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Infrastructure-assisted joint power adaptation and routing for heterogeneous vehicular networks☆

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In vehicular networks, protocols and algorithms rely on the in-network status information and its delivery via control messages for their operations. Using the same wireless channel for data and control message transmissions consume significant channel capacity and time, thus resulting in performance degradation. In this paper, a multi-tiered, heterogeneous vehicular network architecture is considered consisting of mainly two radio access technologies, i.e., ad hoc and cellular. Based on the concept of *infrastructure-assistance*, we suggested offloading control messages over the cellular network and data over the ad hoc network. Next, an efficient broadcast algorithm is proposed that exploits predicted connectivity information to decide on transmit power levels for each vehicle. Finally, a joint transmit power adaptation, and routing algorithm is implemented to disseminate data over a multi-hop network. Through extensive simulations, we reported significant performance gains in terms of delay, collision rate, and packet delivery ratio while maintaining lower communication overhead.

1. Introduction

Most of the vehicular networking applications in the domains of active road safety, traffic efficiency, and infotainment rely on efficient dissemination of Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM). These messages are sent via broadcast or geocast towards multiple destinations or an Area of Interest (AOI). Since CAM and DENM are transmitted either periodically or event-based by all the vehicles, predominantly they occupy most of the wireless channel capacity and time. Several Decentralized Congestion Control (DCC) [1] algorithms have been proposed to balance the channel load. However, in Vehicular Ad hoc Networks (VANETs), the channel load is inherently variable and determined by the transmission power, messaging rate, vehicular mobility, and routing strategy. Therefore, the conventional problem of congestion control and routing must be handled jointly with transmit power adaptation and rate control at the physical layer. Moreover, the decentralized nature of VANETs warrants the design and development of efficient and distributed algorithms at all layers of the network protocol stack.

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Typically, channel load is balanced, or congestion is controlled by employing techniques like transmit power and rate adaptation, Medium Access Control (MAC) and routing. Most of these distributed algorithms rely on the frequent exchange of in-network information such as packet reception rate [2], number of neighbors [3], beaconing load [4], and channel utilization rate or Channel Busy Ratio (CBR) [5]. Reliable and timely dissemination of in-network information is critical to the proper functioning of these algorithms. The information is either disseminated locally or globally at network-wide scale using periodic beacons, flooded Route Requests/Reply and other route reconfiguration control messages. For this purpose, transmitting CAM/DENM and control messages within the same wireless channel (i.e., in-band signaling) consume a significant amount of channel capacity [6]. Moreover, due to inherit dynamicity of VANETs where topology changes more frequently and unpredictably and vehicles join/leave the network more often, the control message dissemination results in excessive communication overhead.

The main focus of this paper is on the potential of multi-tiered network architecture, and joint transmission power adaptation and routing algorithms for vehicular networks. Transmit power adaptation has been extensively studied in the context of static ad hoc and sensor networks where the foremost concern is to increase energy efficiency and decrease interferences with less focus on the mobility or connectivity awareness [7]. In VANETs, the transmit power adaptation algorithms either switch back to the default or maximum transmission power levels quickly or more often whenever the required Quality of Service (QoS) conditions are not satisfied. This is particularly true when the power adaptation algorithms take into account multiple performance criteria. Moreover, most of the schemes provide traffic independent assessment of their algorithms without considering vehicular networking specific reference scenarios. Similarly, stateless geographic routing overcomes some of the limitations of topology-based routing protocols that often assume complete or partial topology and map information to make better routing decisions. However, frequent topology changes and high-speed scenarios in vehicular networks leave the topology fragmented for most of the time, thus resulting in severe network performance degradation. A problem common to both transmission power adaptation and routing is their reliance on in-network information on making optimal decisions. Capturing and maintaining the in-network information requires dissemination of control messages over the same communication channel, which further exacerbates the situation.

To this end, we proposed a multi-tiered vehicular network architecture which uses infrastructure either cellular network or road-side (i.e., out-of-band signaling) to update a centralized Intelligent Transportation Systems (ITS) server with the control messages. It has been recently reported that by offloading control message overhead from the ad hoc domain to cellular network infrastructure can significantly improve the network performance [8]. We then designed a framework of control protocols within which congestion control, transmit power control, and routing can be developed in a unified fashion. On receiving the data and control messages, the ITS server is assigned with a task of finding an efficient transmit power level such that it lowers the channel load and congestion. A stable local topology subject to the given constraints regarding the minimum coverage range that application data message must reach is then obtained. The lower collision rate and contention delays are the results of shorter communication range that increases spatial reuse while decreasing the interferences among neighboring vehicles. However, transmit power adaptation often leads to sub-optimal routes selection and a higher number of hop distances among the information sources and sinks. Infrastructure-assistance leverages these issues by mean of the hybrid routing protocol. The two main components of the proposed hybrid routing protocol are (1) proactive, topology-based local forwarding and (2) reactive, location-based and delay-aware global routing.

Following are the main contributions of our work. In this paper, we proposed,

- Multi-tiered vehicular network architecture, where Vehicle-to-Everything or V2X communication is provided by mean of dual-interface enabled On-board Units (OBUs) that include IEEE 802.11p [9] and 4th Generation/Long Term Evolution (4G/LTE) by 3rd Generation Partnership Project (3GPP) [10] interfaces. Here, the main idea is to transmit data over IEEE 802.11p enabled interface and control messages over 4G/LTE cellular infrastructure. The inter-vehicle or Vehicle-to-Vehicle (V2V) communications are performed over IEEE 802.11p interface whereas control messages are routed to and from an ITS server using existing infrastructure. The Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) communications are performed either over cellular network infrastructure or Road-side Units (RSUs).
- Algorithm for transmission power adaptation that limits the range over which CAM/DENM messages are broadcasted based on mobility awareness. The proposed algorithm considers the predicted state of connectivity in ad hoc network topology so that it can proactively and effectively adjust the transmit power during the next period.
- Hybrid routing algorithm which allows each vehicle to maintain a soft topology state locally. The data is forwarded towards the extended neighborhood, using the forwarding table. Route request (RREQ) control messages are only initiated if the intended destination is not found in the forwarding table. On receiving the route request, the ITS server calculates minimum delay, location-based routing paths and update each vehicle on the path with a Route Reply (RREP) control message.
- By integrating transmit power adaptation and data dissemination, the proposed network architecture and protocols are reported to achieve the following goals: (a) improved packet delivery ratio, (b) fewer packet collisions and failed transmission attempts at the MAC layer, (c) minimize end-to-end delays while incurring lower control message overhead.

We performed extensive simulations using benchmark reference scenarios for vehicular networking. The proposed transmit power adaptation algorithm has been evaluated and compared with fixed maximum transmission power using extensive simulation-based studies. The simulation results show that by limiting the transmission range with which vehicles' send a broadcast to its close vicinity only (around 100m) the proposed technique significantly lowers the number of collision per packet transmitted and delay in the presence of a different number of vehicles in the region with varying average speed. The performance of the proposed routing algorithm is evaluated and compared against Ad hoc On-Demand Vector (AODV) [11], Greedy Perimeter Stateless Routing (GPSR) [12] and Mobile Gateway Routing Protocol (MGRP) [13]. The simulation results show that cumulatively the hybrid routing and forwarding scheme is capable of delivering more data packets in comparison with AODV, GPSR, and MGRP respectively with a significantly fewer number of failed transmission at the MAC layer and lower delays while maintaining lower communication overhead.

The rest of this paper is organized as follows. Section 2 describes the related work on state-of-the-art transmit power adaptation techniques in vehicular ad hoc networks and routing protocols over heterogeneous vehicular network architecture. In Section 3, details of the multi-tiered vehicular network architecture are followed by the description of the combined transmit power adaptation and routing algorithms. A performance evaluation study is provided in Section 4. Finally, we conclude the paper in Section 5.

2. Related work

This section gives a brief summary of the transmission power adaptation techniques in vehicular ad hoc networks and data delivery over heterogeneous vehicular networks.

2.1. Transmit power adaptation in vehicular networks

Transmission power adaptation has been extensively studied to improve the performance of wireless ad hoc networks. Generally, power control techniques rely on a variety of in-network information to adapt transmission power according to the changing network conditions. The basic idea is to adjust transmission power to achieve a trade-off among several competing design objectives based on information such as packet/beacon reception rate [2], number of neighbors [3], beaconing load [4], and channel utilization rate [5]. All these metrics are estimated based on the information available from the physical, MAC and network layers, essentially making the power control a cross-layer issue.

In [2], the power adjustment algorithm relied on monitoring the radio channel condition and based on the estimated packet/beacon reception rate adapts its transmission power and beaconing load accordingly. In [3], the proposed algorithm takes a number of neighbors as input and increase or decrease the transmit power as the neighbor count goes below or over the given threshold value. A distributed algorithm is presented in [4] that increases or decreases the transmission power based on the Maximum Beaconing Load (MBL). Marc et al. in [4] presented a distributed power control algorithm based on adjusting the beaconing load. While the authors reported advantages like bandwidth availability for higher priority and fairness, the inputs to the algorithm have to be pre-estimated. Similarly, the algorithm proposed in [5] adjusts the transmit power based on congestion level measured in terms of CBR. The authors in [14] achieve a trade-off between two conflicting design goals, i.e., the ability to communicate reliably over short distances and to reach the neighboring vehicles at longer distances. The decision is based on beacon load, estimated as the sum of the product between beacon size and transmission rate of the nearby vehicles. A randomize power selection algorithm is proposed in [14] to reduce the congestions and the probability of the collisions. The idea was to increase the reception rate by transmitting CAM at higher distances less frequently. In [15], Rawat et al., presented a joint power control and Contention Window (CW) adjustment approach to achieve improved throughput and lower latency. Power control and CW adaptation rely on estimated vehicle density and collision rate information, respectively.

A number of transmission power adaptation algorithm consider awareness based metrics and adapt according to the vehicle's surrounding environment and application requirements. In [16] Kloiber et al. reported visual quality improvement of the video-based overtaking assistance applications when power is adapted according to the wireless channel condition and interference from the other vehicles. In [17], authors turned their focus on perception map applications which demand higher bandwidth where a few packet losses are tolerable, and communication takes place over short distances, i.e., between 50 and 100m. The stringent requirements on capacity posed by these types of safety applications are satisfied by adjusting the power based on signal strength measurements. In [18], the authors proposed a power control algorithm that takes into account application's requirements and channel load in the presence of a variety of different traffic densities and scenarios and adjusts transmission power accordingly. Similarly, Gozalvez et al. in [19] proposed power adjustment mechanism based on vehicle's location information and its nearness to the critical situations such as an intersection.

Primarily, the dual power and rate control algorithms are used to lower the impact of congestion and improve performance in the vehicular networks. In [20], authors compared the effect of no control, only power, only rate, and combined rate and power control on the network. The study reported that the control algorithms effectively mitigated the congestion issue and achieved a considerable performance gain in terms of packet reception rate. Most of the algorithms utilize different in-network information and environment or application context to adjust the transmit power level and message rate control either independently [21] or jointly [22]. Jose et al. [21] proposed rate and power adaptation as two separate sub-problems to enhance performance during the network congestion scenario. Whereas, Aygun et al. [22] proposed Environment and Context-aware, combined Power and Rate control (ECPR) algorithm for congestion control in vehicular ad hoc networks. The algorithm used awareness criterion as a metric to adjust the transmit power and combined it with rate adaptation based on channel utilization information.

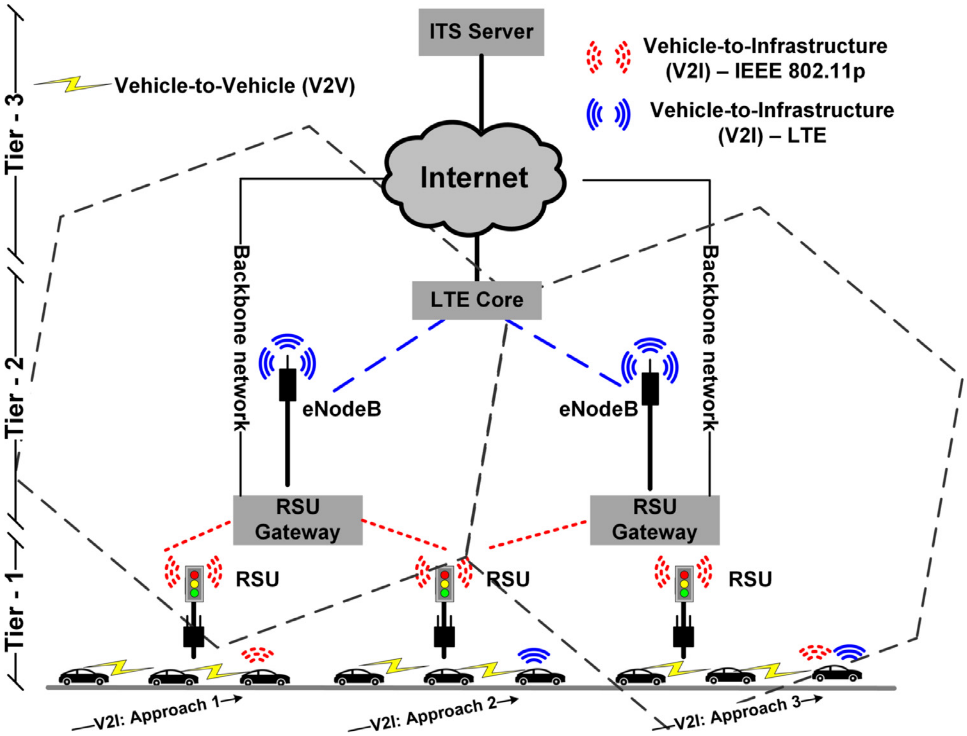


Fig. 1. Multi-tiered vehicular network architecture.

2.2. Data delivery in heterogeneous vehicular networks

The availability of multiple Radio Access Technologies (RATs) led to a bulk of research on data delivery in heterogeneous vehicular networks. Such networks utilize IEEE 802.11p and cellular standards, e.g., WiMAX and 3G/4G as the two primary access technologies. However, predominantly cellular networks are used either as a backup or to offload data [23,24]. In the former case, a message can either be delivered by means of ad hoc transmissions or over the cellular network. Most of the work deals with the appropriate selection of RAT [25] such that it maximizes the performance. Whereas in the latter case only the mobile gateways are directly connected to the cellular network. A mobile gateway uses ad hoc transmissions to collect data from the source and acts as the last hop towards the final destination.

Work that uses explicit route between the source and destination vehicles proposed in [26]. Shafiee et al. suggested a multi-technology routing algorithm which combines position-based routing over WLAN-based links and topology-based routing over WiMAX network. The paper described multi-technology, multihop routing and assume forwarding via ad hoc communications capabilities in both WLAN and WiMAX technology. However, the distributed route selection approach requires excessive broadcast of control messages such as route request and route reply.

Generally, in mobile gateway enabled data dissemination techniques such as MGRP [13], the data is first collected and delivered to the nearby mobile gateway which then offloads the data to a remote server over the 3G cellular interface. The remote server relays the data to another mobile gateway nearest to the destination. The communication between vehicles and the mobile gateway is done over the IEEE 802.11p enabled interface only. The advantages like lower hop distances between the source and destination and improved reliability are achieved at the expense of increased gateways selection algorithm complexity, higher communication overhead, sub-optimal routing decisions, and longer end-to-end delays.

3. Proposed scheme

3.1. Multi-tiered vehicular network architecture

Given numerous vehicular telematics applications and use cases, each with their own set of functional and performance requirements, many endorsed the suitability of multi-tiered network architecture consisting of multiple RATs for the Heterogeneous Vehicular Network (HetVNet) [27]. Fig. 1 illustrates the proposed architecture which combines wireless ad hoc (IEEE 802.11p based) and mobile cellular network (4G/LTE based) infrastructure with a centralized Intelligent Transportation System (ITS) server.

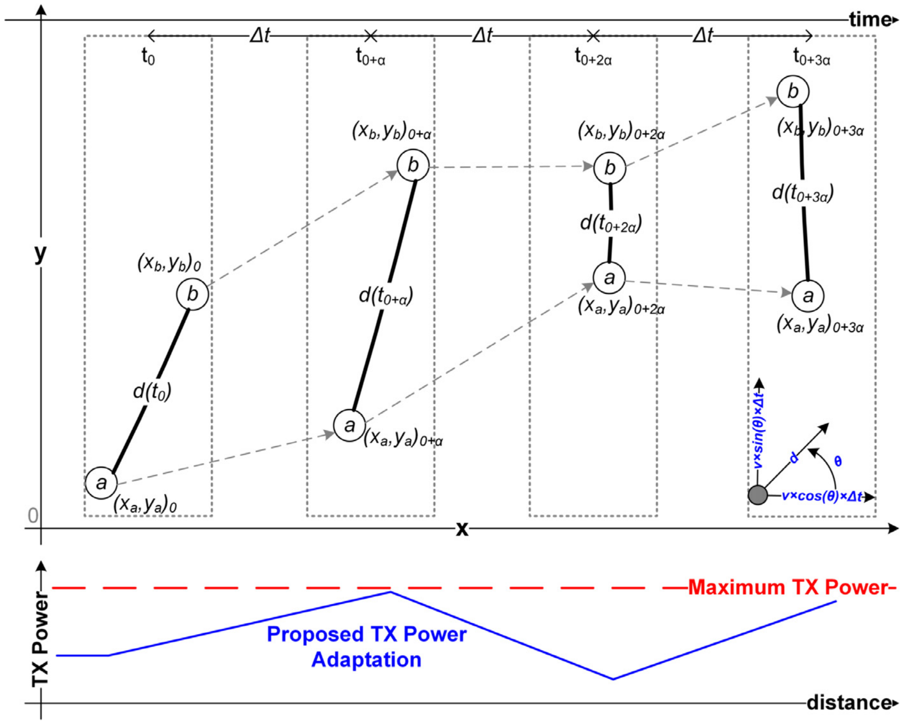


Fig. 2. An example of how vehicular mobility shapes the network topology. The upper part of the figure illustrates several topology snapshots in time and the changing estimated distance between two vehicles *a* and *b*. The lower part of the figure shows a comparison between fixed maximum transmission power level and the proposed power control algorithm that adapts the transmission power levels for both vehicles *a* and *b* based on the predicted distance between the two vehicles.

The first tier consists of vehicles with OBUs to support Vehicle-to-Everything (V2X) communications. The OBUs collect vehicle movement data and other contextual information and periodically share this information with each other, i.e., V2V or with the ITS server, i.e., V2I using one of the three approaches. In the first approach, V2X communications are performed directly in an ad hoc fashion using the IEEE 802.11p enabled interface, only. The second approach utilizes existing mobile network infrastructures such as 3G or 4G/LTE cellular networks. The cellular network interface allows vehicles to exchange data with each other via ITS server easily. The third alternative combines the first two by enabling vehicles to communicate over a dual-interface enabled OBUs. However, this approach requires OBUs with RAT selection and Vertical Handover (VHO) capabilities to provide seamless connectivity.

The second tier performs data relaying between the first and third tier. When IEEE 802.11p standard is utilized, the RSUs are used to collect messages from the vehicles and forward them to the RSU Gateways. RSU Gateways connected through a backbone network act as the network bridge or router. In cellular network approach, vehicles are connected directly with a base station (i.e., Evolved NodeB or eNodeB) which in turn to the mobile core network. Similarly, a backbone network which connects either the RSU gateways or the core network (i.e., Evolved Packet Core or EPC in 4G/LTE) to the Internet and through this to the ITS server constitute the third and final tier.

3.2. Mobility-aware power adaptation algorithm

The transmit power adaptation part of the proposed scheme adjusts the transmit power based on the mobility pattern information. The algorithm decides on the transmit power based on a vehicle's movement information such as position, speed, direction, etc. The fact that vehicle's movement information is already part of the CAM messages for most of the vehicular applications and use cases, the algorithm is capable of adapting its operations without relying on specific messages with road layout or map information. In order to assess the mobility pattern of the surrounding vehicles, it is required to estimate the *Link Connectivity Index (LCI)* metric of all the neighboring vehicles. The proposed transmit power adaptation algorithm has five steps.

1. Initially, at current timestamp t_0, the ITS server collects the raw movement data from the vehicles which include vehicle's position, speed, and direction. The information is sent periodically, which can be piggybacked in the transmitted messages, e.g., in CAM or in data packets. The periodicity depends on the vehicle's speed and application requirements. Fig. 2 shows how vehicular mobility affects the network topology.

2. The ITS server computes the future state (i.e., at time $t_{0+\alpha}$) of the network topology for each vehicle. The parameter α represents any arbitrary time interval in seconds. Consider a two-dimensional plane, a vehicle's future position along the x-axis and y-axis can be estimated based on its current position (x,y), velocity (v) in m/s, direction (θ) in degrees and $\Delta t = t_{0+\alpha} - t_0$ the time difference, using the following two equations.

$$x(t_{0+\alpha}) = x(t_0) \pm v * \Delta t * \cos(\theta) \tag{1}$$

$$y(t_{0+\alpha}) = y(t_0) \pm v * \Delta t * \sin(\theta) \tag{2}$$

   Let v_a and v_b be the magnitude of velocities, θ_a and θ_b be the directions, then the predicted distance between vehicle a and b at time $t_{0+\alpha}$ can be calculated using the following equation.

$$d(t_{0+\alpha})_{ab} = \sqrt{(x_a(t_{0+\alpha}) - x_b(t_{0+\alpha}))^2 + (y_a(t_{0+\alpha}) - y_b(t_{0+\alpha}))^2} \tag{3}$$

   For a vehicle b to be part of the network topology of vehicle a at estimated locations $(x_b(t_{0+\alpha}), y_b(t_{0+\alpha}))$ and $(x_a(t_{0+\alpha}), y_a(t_{0+\alpha}))$, respectively, their predicted distance must be less than the maximum transmission range r (i.e., $d(t_{0+\alpha})_{ab} \leq r$).
3. Next, the *Link Connectivity Index (LCI)* is calculated using the following equation.

$$LCI_{ab}(t_{0+\alpha}) = \frac{d(t_{0+\alpha})_{ab}}{r} \tag{4}$$

   The LCI metric measures the likelihood that the vehicle b will continue to remain in vehicle's a transmission range at time $t_{0+\alpha}$. It is similar in concept with the *Link Expiration Time (LET)* used in [7], to estimate the duration of time two vehicles a and b remain connected, as given below.

$$LET_{ab}(t_{0+\alpha}) = \frac{r \pm d(t_{0+\alpha})_{ab}}{|v_b \pm v_a|} \tag{5}$$

   Here, the plus-minus sign indicates a choice of exactly two possible values, positive when vehicle a and b moves towards each other, and negative when they move in the opposite direction.
4. The ITS server calculates the transmit power, during the next time interval by considering the future distance between the vehicles. The power selection step follows a simple intuition of retaining links with only those neighboring vehicles which are likely to stay together longer. Vehicles traveling either too fast or in the opposite direction have limited connectivity as compared with the vehicles that are traveling towards each other or moving relatively slowly. Therefore, the ITS server shortlists all those neighbors that have higher LCI or residual link expiration duration based on the application requirements or target awareness range [22]. The final transmit power is decided based on the transmission range required to reach the farthest among this subset of vehicles. The ITS server calculates the transmit power $PTX_{ab}(t_{0+\alpha})$ of the vehicle a to reach the neighboring vehicle b for the next time interval. The log-distance path loss model [22] given in the following equation is used, where $PRX_b(t_0)$, λ and η represent received power of vehicle b, signal wavelength and path loss exponent, respectively.

$$PTX_{ab}(t_{0+\alpha}) = PRX_b(t_0) + 10 \times \eta \log_{10}\left(\frac{4 \times \pi}{\lambda} \times d(t_{0+\alpha})_{ab}\right) \tag{6}$$

5. Steps 2,3 and 4 are carried out periodically for all vehicles. The ITS server then unicasts the recommended transmit power to each vehicle. On receiving the message from ITS server, each vehicle sets its transmission power of the IEEE 802.11p interface and broadcast safety messages using the set transmit power.

Fig. 3, exemplifies the above mentioned procedure. Fig. 3(a), shows the initial topology at some arbitrary time t_0. Fig. 3(b) shows the ITS server estimates the LCI at time $t_{0+\alpha}$ and triggers the transmission power selection procedure for the vehicle in red color. Fig. 3 (c) shows that vehicle adjusts the power required to reach the neighboring vehicles that are more likely to stay connected longer, i.e., for the given value of LCI.

3.3. Minimum-delay hybrid routing algorithm

To reach the distant destinations, most of the power control algorithms quickly converge to the maximum transmit power levels. This practice often leads to severe congestion and higher packet collision rates. In this paper, we complement the mobility-aware broadcast algorithm with an infra-structure-assisted routing and forwarding scheme which is based on Dijkstra's shortest path algorithm. The algorithm takes the current link delay and position information as an input. On the one hand, when the destinations are near-by, the scheme takes the connectivity information into consideration while disseminating vehicular data to maximizes the chances of packet delivery. On the other, in scenarios where the destination is located farther away, the routes which provide greater forward progress towards destinations with minimum delay are selected to lower the end-to-end delivery latency.

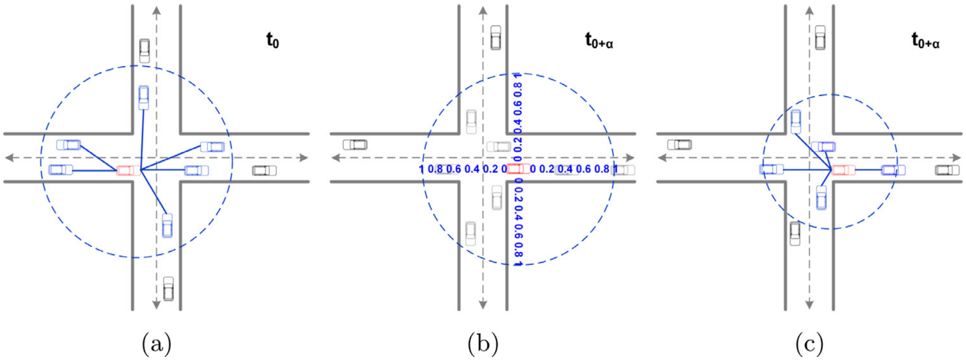


Fig. 3. (a) Initial topology at time t_0. (b) ITS server calculates the link connectivity index (LCI) and assigns it to the vehicle in red color. (c) Topology after the transmission power adaptation is applied at time $t_{0+\alpha}$.

3.3.1. Link delay metric estimation

Vehicles transmit CAM messages either directly in a V2V fashion or indirectly, i.e., delivered via remote ITS server using 4G/LTE or RSU gateway infrastructure in a V2X manner. On receiving the CAM messages, each vehicle maintains a two-hop network topology map which holds information such as position and metrics like LCI and delays about the neighboring vehicles. The ITS server also stores the network topology map for each vehicle either at a single or multi-cell level. This information is then subsequently used by the routing algorithm to calculate routing paths.

The link delay information is estimated during the CAM message exchange without requiring a two-way handshake or time synchronization. The link delay is calculated for both directions, i.e., the uplink and downlink transmissions, i.e., $delay_{UL}$ and $delay_{DL}$, respectively. The downlink delay information can be calculated by using the tag, i.e., tagging the time when a packet was created or sent and reading this tag when a packet is received and estimate the delay using the following equation between vehicle a and vehicle b.

$$delay_{DL}(ab) = Time.Now(b) - tag.GetTxTime(a) \tag{7}$$

The uplink delay is calculated similarly and shared with the upstream neighboring vehicles by piggybacking the information in the transmitted packet.

3.3.2. Route selection algorithm

The infrastructure-assisted network configuration enables an efficient functional split between the routing algorithm and the forwarding strategy by helping in optimizing and implementing the routing decisions independent of the forwarding logic, thus a hybrid approach. We utilized Dijkstra's shortest path algorithm which has been extensively studied in the context of routing protocols. Following is a brief explanation of the route selection procedure.

1. A source vehicle s initiates the route discovery procedure to destination vehicle d by transmitting a Route Request (RREQ) message to the ITS server. On receiving an RREQ message from a source s, the ITS server creates an empty vertex set Q representing the set of vehicles to which there exist a shortest path among all the vehicles V in the network topology map, and initializes Q as:

$$Q = \emptyset \tag{8}$$

2. Initialize the link cost for the source vehicle s, given as L (s) to 0 and add s to Q:

$$\begin{aligned} L(s, s) &= 0 \\ Q &= \{s\} \end{aligned} \tag{9}$$

3. For all the neighboring vehicles i of s set the initial link cost $L(v)$ according to the routing metric $U(s, i)$:

$$L(s, i) = U(s, i) \tag{10}$$

The routing metric assigns a cost to each link characterized by the weighted sum of the link delay and forward progression. The uplink delay and distance to the destination $distance_d$ are normalized by maximum tolerable delay, $delay_{\max}$ and the maximum transmission range r, respectively. The weight factor β is an adjustable parameter such that $0 \le \beta \le 1$. The routing metric is given as:

$$U = \beta\left(\frac{delay_{UL}}{delay_{max}}\right) + (1-\beta)\left(\frac{distance_d}{r}\right) \tag{11}$$

4. While $Q <> V$, repeatedly enlarge Q until it includes all the vehicles in V:

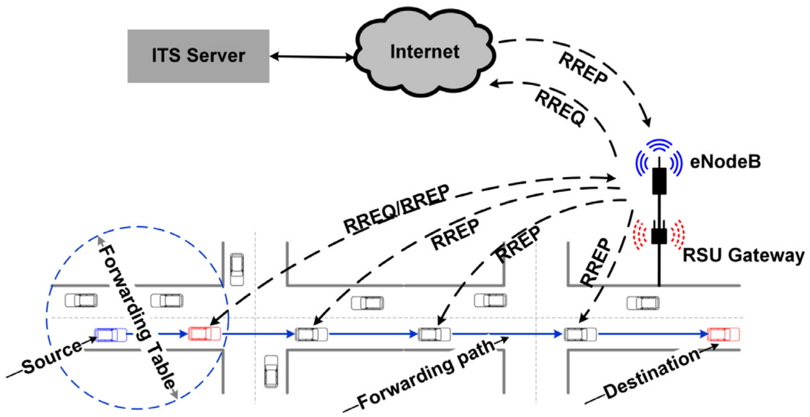
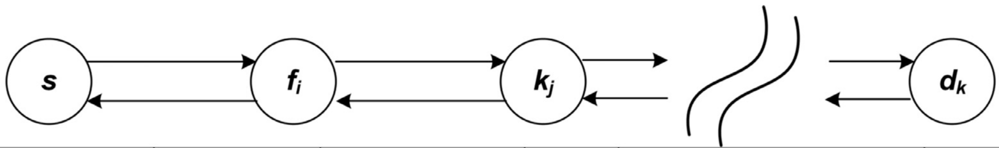


Fig. 4. An example of route request/reply, route dissemination, and the data forwarding procedures between a source-destination pair.



IP/MAC Address	$Delay_{UL}/Delay_{DL}$	Reachable Vehicles	Location	Temporal Reachable Vehicles	Lifetime
f_1	0.1/0.1	k1	x_1,y_1	d_1	5 sec.
f_2	0.5/0.7	k2	x_2,y_2	d_2	3 sec.

Fig. 5. A source s and destinations d_k connected by a multi-hop path consisting of relay nodes f_i and k_j along the selected routing path. Forwarding table at the source s.

(i) Select a vehicle j that is not in Q with the minimum link cost among neighboring i:

$$Find : j \notin Q \wedge min\{L(s,i)\} \tag{12}$$

(ii) Add j to Q:

$$Q = Q \cup \{j\} \tag{13}$$

(iii) For each vehicle k, adjacent to vehicle j:

$$P(s,d) = min(L(s,k), L(s,k) + L(j,k)) \tag{14}$$

$$prev(k) = \Big\{ j, \quad \text{if } L(s,k) + L(j,k) < L(s,k)$$

Here, $P(s, d)$ represents the value of the path cost from source to the destination and $prev(k) = j$ implies that j is the predecessor to k along the path.

5. *return*(Q[], *prev*[])

3.3.3. Forwarding table construction

On calculating an efficient routing path between the source and the destination, ITS server disseminates the Route Reply (RREP) messages to all vehicles that are on the route. Fig. 4, exemplifies the route request/reply, route dissemination, and the data forwarding procedures between a source and a destination. The vehicles on the routing path on receiving the RREP message and maintain a forwarding table with a single forwarding entry for each reachable destination. Each entry in the forwarding table includes information such as the final destination address, immediate next-hop address and expiration time to mark the time duration after which the entry is considered outdated and removed from the forwarding table. The forwarding table is dynamically updated either when the forwarding entry expires or by the remote ITS server when there is a change in the routing path. When a vehicle has data message to send, it looks up the forwarding table to determine the next hop towards the final destination.

Fig. 5, illustrates the set of candidate intermediary vehicles f_i and k_j between a information source s (or origin) and the sinks d_k (or destinations), where $(i, j, k = 1 \ldots n)$. Fig. 5 also shows the forwarding table maintained at vehicle s. The forwarding table holds information such as IP and MAC addresses of the immediate one-hop neighbors (i.e., f_i) of the vehicle s along with the uplink/down delays and current location coordinates. It also contains information regarding extended neighborhood or two-hop neighbors (i.e., k_j) that are reachable via immediate neighboring vehicles. Finally, on receiving the RREP message from the ITS server, each vehicle on the routing path adds the destination d_k in the *temporal reachable* vehicle list along with the route expiration time.

Algorithm 1 Joint transmission power adaptation and routing.

```
1: Initialize: LCI = 0.5; α = 1s ; β = 0.5; delay_max = 500ms; r = 250m; PTX_max = 22dBm;
2: procedure SENDDATA(msg)
3:   while (PTX(t_{0+α}) ≠ PTX_max) ∨ (LCI ≠ 1) do
4:     if Destination(t_0) ⊂ Neighborhood(t_{0+α}) then
5:       PTX(t_{0+α}) ← POWERCONTROL(LCI);
6:       BROADCAST(PTX(t_{0+α}), t_{0+α});
7:     else
8:       LCI ← LCI + +;                                   ▷ Increment by 10%
9:     end if
10:  end while
11:  if Destination(t_0) ∈ FORWARDINGTABLE() then
12:    nexthop ← GETNEXTHOP(Destination(t_0));
13:    UNICAST(PTX_max, nexthop);
14:  else
15:    SENDRREQ(Destination(t_0));
16:  end if
17: end procedure
18: procedure RECVDATA(msg)
19:  if myself f ≠ Destination(t_0) then                  ▷ Overheard the transmission
20:    waitTimer ← RANDOM();
21:    WAIT.START(waitTimer);
22:    if min(waitTimer) then
23:      BROADCAST(PTX_max);
24:    else
25:      WAIT.CANCEL( );
26:      DISCARD(msg);
27:    end if
28:  else
29:    HANDLEDATA(msg);
30:  end if
31: end procedure
32: procedure RECVRREP( )
33:  FWDTABLEUPDATE( );
34: end procedure
```

3.4. Joint transmission power adaptation and routing

Algorithm 1 formally describes the following steps of the joint power control and routing algorithm.

1. Steps 1–10: After parameter initialization, the proposed scheme broadcasts the messages to immediate neighbors. The transmission power level is adapted based on the current Link Connectivity Index (LCI) metric, as described in Section 3.2. Here, it is worth pointing out that increasing the LCI would lead to higher transmit power levels, which is gradually increased in smaller steps until either maximum power level or LCI is not achieved. Thus, LCI value can be used as a tunable parameter based on the application requirements such as target awareness range [22] or environmental factors such as urban scenario and speed. Although by setting higher transmission power levels, a vehicle can potentially send messages to faraway neighbors, this results in significant interferences and higher collision rate. Alternatively, a vehicle may choose to transmit messages (both CAM and data) over carefully selected routes to reach more distant destinations.
2. Steps 11–14: The source vehicle searches for the destination in its local forwarding table. The local forwarding table holds information on all the reachable vehicles at a two-hop distance. If a valid entry towards the destination is found, then it immediately forwards the messages to the next hop. In scenarios where there are multiple next-hop candidate vehicles, then the neighboring vehicle with better LCI value is selected. Each vehicle on the routing path adjusts the transmit power to maximum before further communicating the message.
3. Steps 15–17: For scenarios where the destination lies beyond the reachable neighborhood with no valid entry in the forwarding table, the vehicle initiates the route request to the remote ITS server. On receiving the route request message, the ITS server calculates the route between the source and the destination using the shortest path algorithm as described in Section 3.3. The ITS server calculates the routes using the default maximum transmit power and transmits the route reply messages to all the intermediate vehicles on the selected path.

4. Step 18–31: In order to improve the reliability of data delivery, all nearby vehicles of the forwarding vehicles overhear the neighbor's ongoing data transmissions. If the forwarding vehicles fail to transmit during the given duration of time, a single-hop broadcast is performed. All other vehicles on overhearing the transmission cancel their timers and discard the message.
5. Step 32–34: Once the route update message is received, vehicles on the path maintain a soft forwarding state. Each vehicle adds an entry into its forwarding table with the updated list of reachable destinations. Moreover, the route expiration time is set to some predefined constant value.

4. Performance evaluation

This section presents the simulation results of the proposed scheme. Mainly, two studies are conducted. First part compares the performance of broadcasting over the power-controlled and non-power controlled network topology. The idea is to report on the performance gains attained with mobility-aware power-controlled vehicular ad hoc network. For this purpose, following two networking scenario are considered and compared.

1. Non-power controlled network: Each vehicle operates at the maximum transmission power, i.e., 22 dBm, transmits a message at 250 m transmission range.
2. Power-controlled network: Each vehicle decides on its transmission power level based on the proposed mobility-aware power control algorithm. A vehicle can operate at one of the four transmission power levels, i.e., 22, 16, 10 and 4 dBm.

The performance is evaluated in terms of the following three performance metrics, i.e., average transmission range, average collision rate, and average delay. The results are obtained by increasing the number of vehicles in the region, and message transmission frequency.

1. Average transmission range in meters is defined as the ratio between total transmission range and a number of vehicles in the region.
2. Average collision rate in % is given as the ratio between the sum of all message collisions and the total number of message sent.
3. Average delay in ms is calculated as the ratio between the sum of all delays (i.e., time elapsed between message transmission and reception) and the total number of received messages.

The second part evaluates the performance of the infrastructure-assisted routing protocol and compares it with some competent protocols such as AODV [11], GPSR [12], and MGRP [13]. During the simulations, 30% of the vehicles were randomly selected as mobile gateways. The simulation results describe the impact of single and multiple applications on the following performance metrics.

1. Packet Delivery Ratio (PDR) in %, is defined as the ratio between a number of messages received and the total number of messages sent.
2. Average MediumAccessFail per packet is defined as the ratio between a total number of failed transmissions by the MAC layer and the total number of message sent.
3. End-to-End Delay in ms is given as the sum of all mean delays, averaged over the total number of application sessions.
4. Communication Overhead in log-scale is a number of control messages generated during the simulation time.

4.1. Simulation environment

The simulations are implemented, and experiments are conducted using NS-3 (Version 3.23) network simulator [28]. A 5 × 5 Manhattan grid layout is used to represent a road network, typically an urban scenario. There are total 25 equal sized blocks each 400m × 400 m long wide. These blocks are divided by 6 horizontal and 6 vertical two-lane roads. The entire simulation area is 2000m × 2000m, as illustrated in Fig. 6. The Simulation of Urban Mobility (SUMO) [29] tool is employed, to generate realistic mobility traces. SUMO outputs vehicle's movement pattern based on designated trips and routes between randomly chosen origins and destinations. The speed of each vehicle is arbitrarily selected between 20 km/h to 100 km/h. During the simulation, the number of vehicles in the simulation area is varied between 50 to 200.

For vehicular ad hoc network simulations, IEEE 802.11p MAC/PHY is used with relevant parameters settings. The antenna operates in an omnidirectional mode, and the maximum transmission power level is set to 22 dBm which corresponds to the maximum communication range of 250 m. Among other PHY parameters, the values for parameters EnergyDetectionThreshold and CCAModelThreshold are set according to the IEEE 802.11p standard [9], i.e., −80 dBm and −82 dBm, respectively. We chained Log-distance and Nakagami fading propagation channel modes. The radio operates at 5.8 GHz frequency with data rate set of 6 Mbps. By default, each vehicle transmits 500 bytes CAM message using a UDP based application. As for the simulations of the cellular-based wireless access infrastructure network, LTE-EPC Network SimulAtor (LENA) [30] module for 4G/LTE networks is utilized in NS-3. It consisted of two parts, the Radio Access Network (RAN) consists of a single base station (or eNodeB). Thus there is only one cell operating with a bandwidth of 10 M Hz. The Evolved Packet Core (EPC) consists of single Serving Gateway/PDN Gateway (SGW/PGW) node connected via a point-to-point to a Remote Host (RH) or ITS server. The simulation parameters and their values for both IEEE 802.11p standard and 4G/LTE technology are given in Table 1.

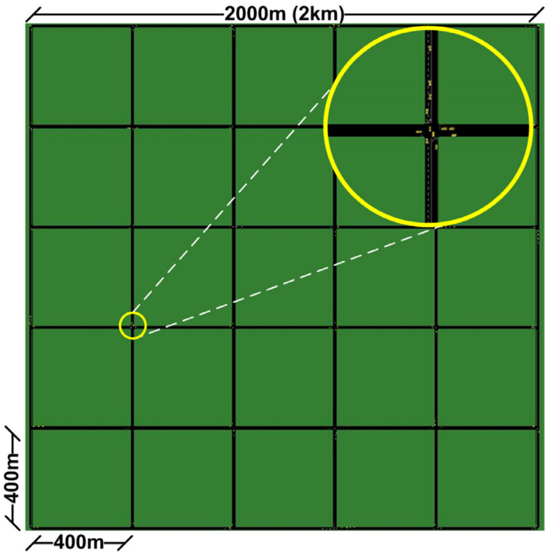


Fig. 6. Road network layout illustrated using SUMO-GUI [29], with 5 × 5 Manhattan grid.

Table 1
Simulation parameters and values.

Parameters	Values
Number of vehicles	50,80,110,140,170,200
Vehicle average speed	20,40,60,80,100 km/h
CAM transmission frequency	1,4,8,12,16,20 Hz
Number of application sessions	10,30,50,70,90
Transmission power levels	22,16,10,4 dBm
Transmission range	250,175,80,50 m
Antenna type	Omni-Directional
Frequency	5.89 GHz
Packet size	512 bytes
Channel bandwidth	10 MHz
Data rate	6 Mbps
EnergyDetectionThreshold	−80 dBm
CcaMode1Threshold	−82 dBm
Simulation area	2000m × 2000m
Simulation duration	300 s
Road network layout	5 × 5 Manhattan grid
Number of eNodeB	1 eNodeB or single cell
Time interval (α)	1 s
Weight factor (β)	0.5
Route expiration time	5 s
Maximum tolerable delay ($delay_{max}$)	500 ms
Maximum transmission power level (PTX_{max})	22 dBm
Maximum transmission range (r)	250 m
Number of mobile gateways	30% of network size
Propagation Models	**Parameter Values**
Log-Distance	Path loss exponent (η): 2.9 Reference Distance: 1m Reference Loss: 47.8423 dB

4.2. Simulation study

Fig. 7 shows the sample topologies at several instances of time during the simulations. NS-3 PyViz [28] simulation visualizer is used for the visualization. Fig. 7(a) shows the topology instance when no power control is applied, in other words, all vehicles operate at a maximum transmission power level, i.e., 22 dBm. Fig. 7(b) and (c) illustrate the output of the proposed transmit power adaptation algorithm with lower and higher values of LCI metric, respectively. Fig. 7 (d) shows the topology obtained as the result of applying joint power control and routing algorithms with several application sessions, among multiple source-destination pairs. There are two simulation studies included.

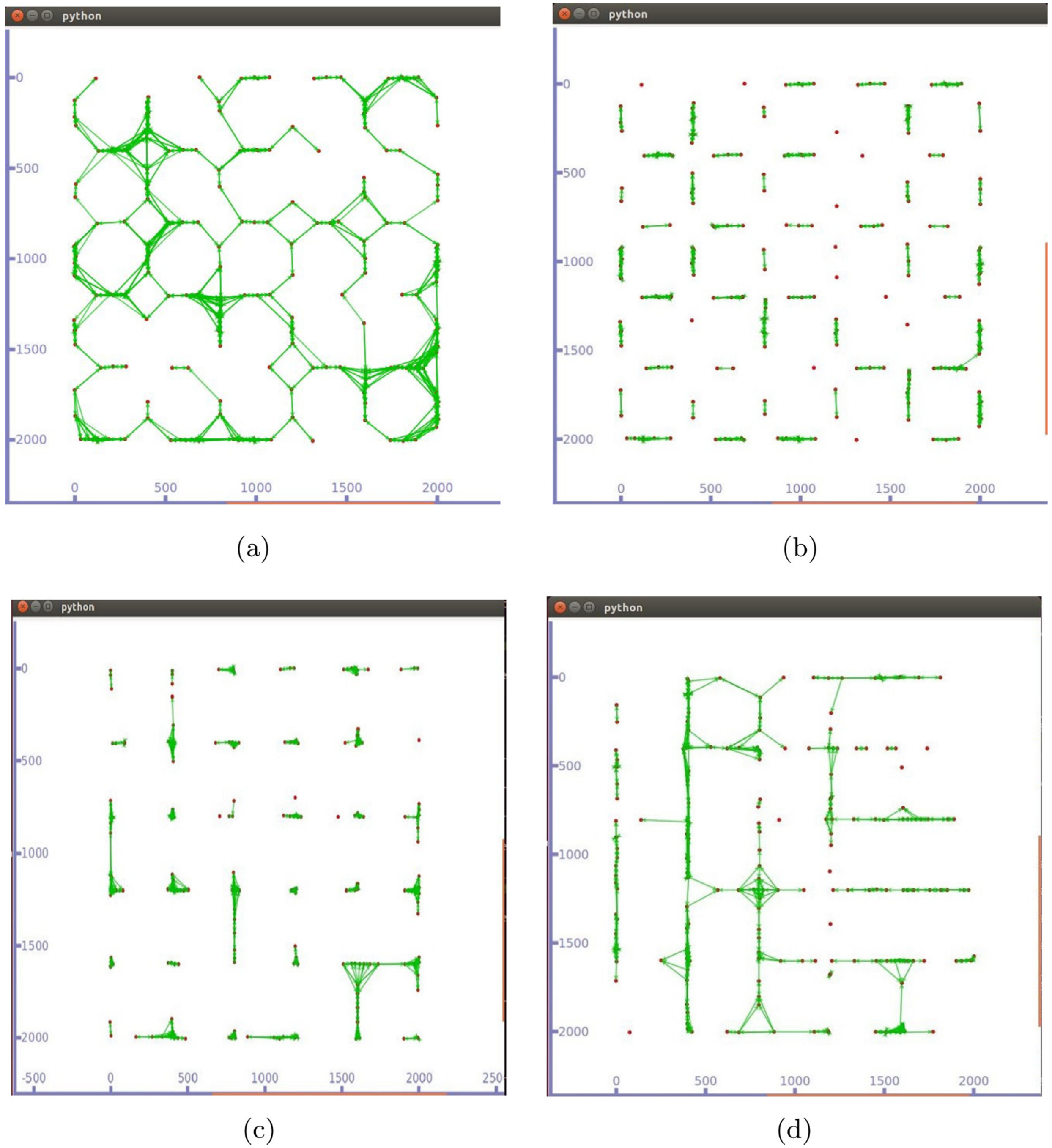


Fig. 7. Sample topology instances with 200 vehicles. (a) Power control disabled. (b) Power control enabled with lower LCI value. (c) Power control enabled with higher LCI value. (d) Joint power control and routing.

4.2.1. Impact of power adaptation on performance metrics

The first set of simulations results measure the efficacy of power control over non-power-control using broadcast traffic. The broadcast message transmission frequency is set to 10 Hz. In the non-power-controlled network, each vehicle operates at maximum transmission power, i.e., 22 dBm, thus a communication range of 250 m. As for the mobility-aware power-controlled network, average vehicles speed considerably influences the transmission range, packet collision rate, and delay. Fig. 8(a) shows that for high-speed scenarios, the nearby vehicles tend to remain connected for shorter durations. Therefore, transmission range has to be extended to account for the smaller link stability index value so that the farthest of the neighboring vehicles can be reached. Conversely, in scenarios where vehicles are moving slowly, the larger link stability

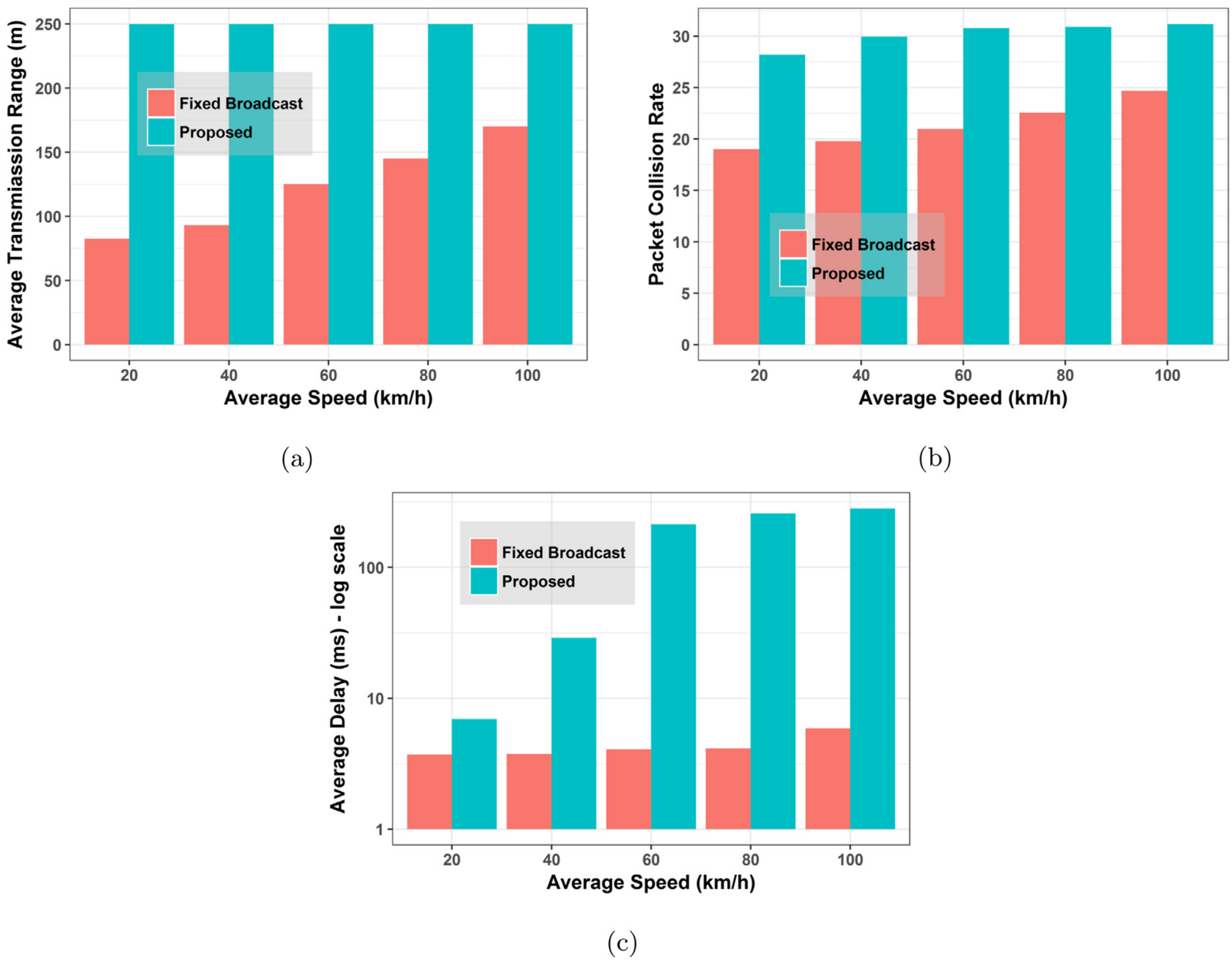


Fig. 8. Impact of average vehicle speed (km/h) on (a) Transmission range (m). (b) Packet collision rate. (c) Delay - log-scale.

index allows vehicles to operate at relatively shorter communication ranges. Consequently, the higher transmission ranges result in a higher collision rate as shown in Fig. 8(b). However, the collision rate increases with the increase in speed, because faster moving vehicles tend to operate at higher transmission power levels as compared with slowly moving vehicles. Fig. 8(c) shows that the delay increase as the average vehicle speed increases. Generally, the channel access time depends on relative vehicle speed, biased towards slowly moving vehicles which get most of the channel access time in comparison with the faster moving vehicles.

Simulations are also performed by increasing the number of vehicles in the simulation area. In these simulation scenarios, messages were sent with 10 Hz frequency, and vehicles move with an average speed of 20 km/h. Fig. 9(a) shows the impact of the network size on transmission range. Vehicles are required to adjust the transmission power to reach only a subset of neighbors with higher Link Connectivity Index (LCI) value results in significantly lower transmission range. However, as the network size increases, the transmission range increases gradually, to reach the farthest of the neighboring vehicles. The collision rate is significantly higher for the fixed transmission range as given in Fig. 9(b). Although with the increase in a number of vehicles the transmission range increase as well for the proposed transmit power adaptation scheme, the average number of collisions per packet sent is significantly low. As Fig. 9(c) shows that for the sparser network topologies the delay is low, On the other hand, the delay increases considerably as the network topology grows denser and the network size increases.

Next, the impact of messaging frequency on performance is explained. Fig. 10(a) and (b) suggest that overall the collision rate and delay increases, as the number of packets transmitted per second increases. In the proposed scheme case, lower transmission ranges result in higher spatial reuse, thus allowing more vehicle to communicate simultaneously with a fewer number of collisions per transmitted packet. Fig. 10(a) shows that, on average, the proposed power control algorithm results in 50% to 150% lesser numbers of collisions. Fig. 10(b) shows that for lower messaging frequencies the performance difference between the fixed and the proposed transmit power control scheme is relatively small in terms of delay. However, as the messaging frequency increase, the gap started to grow significantly. Therefore, for the non-power controlled network,

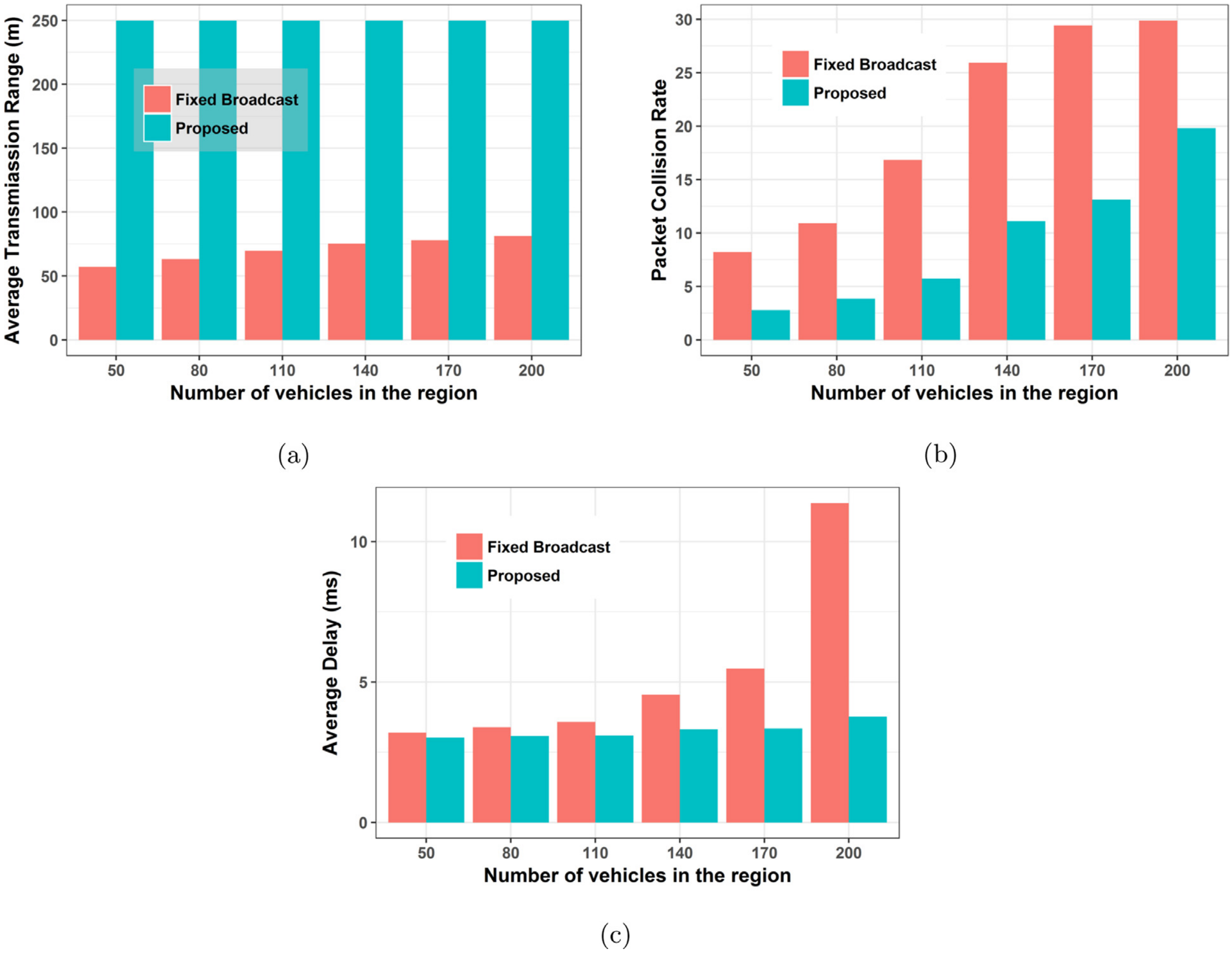


Fig. 9. Impact of network size on (a) Transmission range (m). (b) Packet collision rate. (c) Delay (ms).

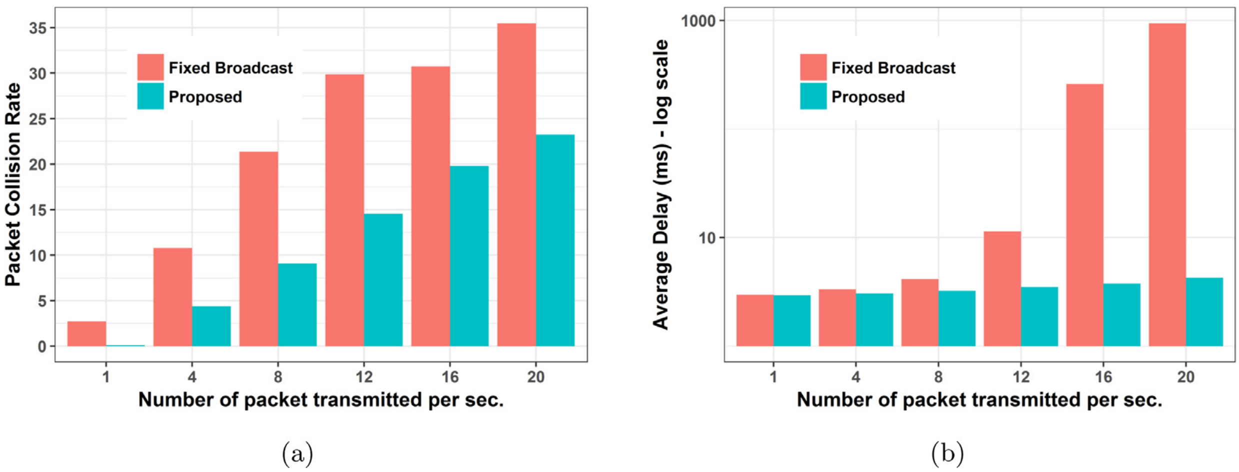


Fig. 10. Impact of packet transmission frequency on (a) Packet collision rate. (b) Delay - log-scale.

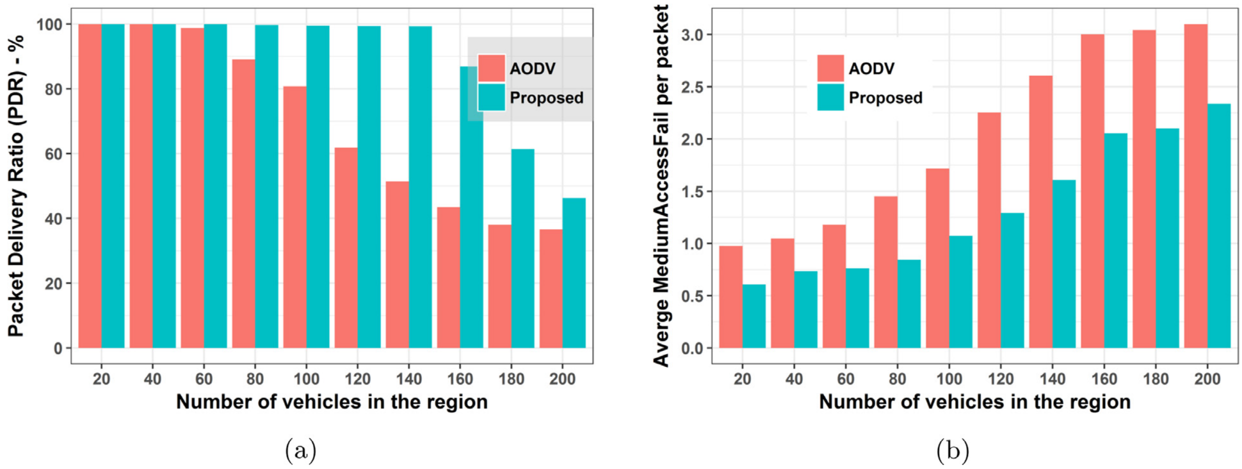


Fig. 11. Impact of network size on (a) Packet Delivery Ratio (%). (b) MediumAccessFail per packet. Single multihop session.

the stringent delay requirements (i.e., < 100 ms) imposed by most of the active road safety applications and use cases are difficult to achieve at higher vehicle densities and messaging frequencies.

4.2.2. Impact of hybrid routing on performance metrics

First, we compared the proposed scheme performance with a topology-based routing protocol. The simulations were performed by varying the number of vehicles in the region with a single, multihop (averaged 3 hops) session between a randomly selected source-destination pair. Fig. 11(a) shows the impact of network density on packet delivery ratio (PDR). As the network size grows, the PDR decreases for both routing protocols. However, for the most part, the performance of the proposed routing scheme remained intact, and the PDR started decreasing only in highly dense scenarios. In AODV, the PDR decrease is considerable even with the medium-sized network of 140 vehicles AODV lost 50% more of the packets as compared with the proposed scheme. By allowing only fewer of the vehicles on the routing path to operate with full transmit power the proposed scheme gain significant in terms of average medium access fails per packet. Fig. 11(b) shows as the network size increases the number of failed attempts at the MAC layer increases for both competing routing protocols. However, as for the AODV, the average number of failed transmission is between 25% to 43% more as compared with the proposed scheme.

Next, we evaluated the performance of the proposed scheme and compared it with relevant routing protocols with and without the infrastructure support. We study the impact of a different number of application sessions on the network performances. Fig. 12(a) shows that for all the routing algorithms, as the number of application sessions increases, the packet delivery ratio decreases. Without the assistance from the cellular network infrastructure, AODV and GPSR protocol reliability decreases considerably as the number of source-destination pairs are increased. In comparison with AODV, GPSR, and MGRP, *cumulatively* the proposed routing scheme is capable of delivering up to 92%, 53%, and 26% more data packets, respectively. In the proposed scheme maintaining lower transmit power levels at vehicles not involved in data forwarding also contributed towards attaining better performance. With infrastructure assistance both the proposed scheme and MGRP performed better than AODV and GPSR regarding reliability. However, MGRP performance is more sensitive to the offered load, especially in high-speed scenarios. Frequent change in local topologies requires regular routing table updates. Therefore, stale or expired routing entries resulted in higher packet losses.

Fig. 12(b) shows the performance of all four routing algorithms regarding delay with varying number of application sessions. In comparison with the proposed routing scheme, on average AODV and GPSR took between 39% and 66% more time to deliver data, respectively. The trend is primarily due to the way each of the competing routing algorithms manages the no-route to the destination scenario. In the case of AODV, the delay associated with route discovery between source-destination pairs increases as the number of applications sessions increases. Similarly, in GPSR whenever a gap in the routing path occurs, it applies the right-hand rule. While this approach is effective in ultimately reaching the destination, the packets have to traverse through longer and sub-optimal paths, thus resulting in higher delays. Conversely, in the proposed scheme a source or relaying vehicle first searches for the destination within its locally maintained forwarding table. Only when entry to the extended and the temporal reachable neighbor is not found, the route requests are sent to the remote ITS server. Moreover, calculating near-optimal routing paths also contributes to lower delays. In the MGRP case, the dynamicity of vehicular networks, i.e., periodic routing table updates, disconnected networks, and channel conditions causes longer delays during the data relaying process. Another contributing factor is that all data has to traverse through the remote ITS server using the cellular infrastructure, even for the nearby destinations. On average, MGRP took 26% more time to deliver data as compared with the proposed scheme.

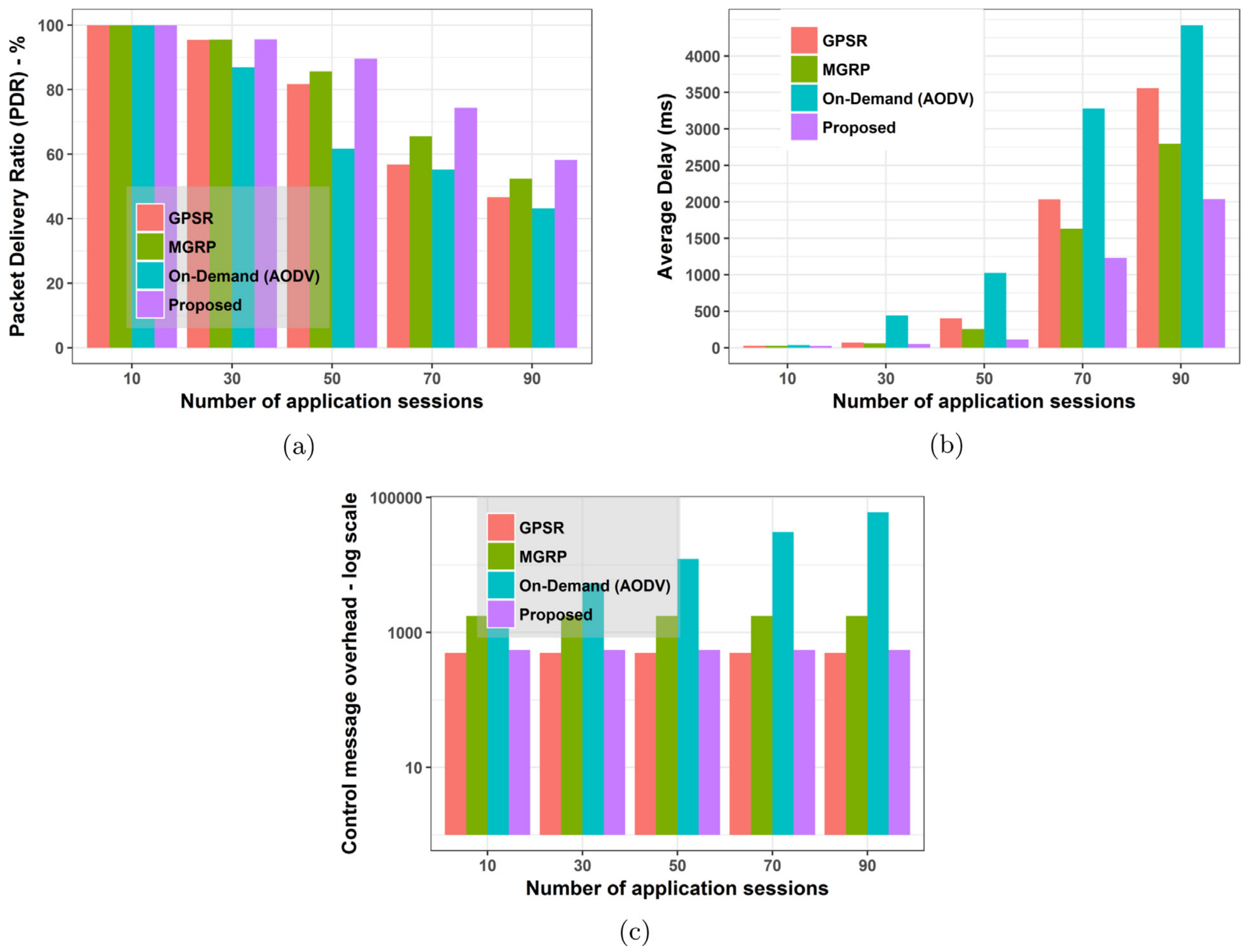


Fig. 12. Impact of number of application sessions on (a) Packet Delivery Ratio (%). (b) Delay. (c) Control message overhead - log-scale.

Fig. 12(c) shows the control message communication overhead in log-scale. The AODV routing algorithm causes a significantly higher number of control messages such as route request/reply to establish routing paths between the source-destination pairs. Consequently, the control message overhead increase as the number of application sessions increases. As for the GPSR and proposed scheme, both send the neighbor discovery messages with the same frequency. The proposed scheme is also required to exchange the route request/update messages, with the remote IT server which resulted in 10% more communication overhead. In MGRP, better reliability comes at the cost of maintaining current routing tables, thus resulting in 69% more communication overhead. Route discovery and maintenance overhead increase considerably as the mobile gateways move at higher speed throughout the simulation area.

5. Conclusion

Distributed protocols and algorithms in vehicular networks rely on control messages to share in-network status information. Once acquired, the status information is subsequently used to make decisions regarding channel access, scheduling, routing, and power or rate control. Simultaneously disseminating control and data traffic using the same channel often led to significant channel capacity consumption and latency. To address these issues, we suggest steering control and data separately over multiple-technology enabled, multi-tiered, heterogeneous vehicular network architecture. Furthermore, based on the infrastructure-assisted protocol design concept, we also implemented a joint power adaptation and hybrid routing algorithm. Two simulation-based studies were conducted to assess the impact of power adaptation and hybrid routing. Simulation results show that by limiting the transmit power at each vehicle based on the predicted connectivity metrics resulted in shorter transmission ranges. Consequently, it outperforms the fixed transmit power approach in terms of average delay and collision rate for a variety of network settings such as different vehicle speed, network sizes, and transmission rate. Similarly, the proposed routing and forwarding algorithm performed significantly better in terms of packet delivery ratio, end-to-end delay and control message overhead as compared with AODV, GPSR, and MGRP routing protocols. The obtained results are consistent for different number of vehicles and application sessions.

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