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Layer 3 Enhancements for Vehicular Ad Hoc Networks

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Abstract

This paper proposes two improvements to the Network Layer (Layer 3) that improves the performance in Vehicular Ad Hoc Networks or VANETs. Specifically, it describes a new addressing scheme called Zone Based Geographic IPv6 Addressing, and a new routing algorithm called Contention Based Multi-protocol Hybrid VANET Routing. Our addressing scheme incorporates current locations into the IP address and our routing algorithm handles our location-dependent addresses, and also handles queries targeted to a geographic location and not a particular vehicle. We demonstrate using detailed VANET simulations that our proposed algorithms significantly outperform existing algorithms.

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Keywords: Vehicular Ad Hoc Networks; Addressing; Routing; Geographic Routing

1. Introduction

Communication technologies have become an integral part of our society in recent years, After computers and the Internet, wireless communication in the form of cellular networks and wi-fi were major pervasive technologies. The next major area of interest for wireless technology integration is in the vehicle in the form of Vehicular Ad-Hoc Networks (VANETs). Today's cars (can) have wireless communication capabilities in the form of *On-Board Units* (OBU). Also quite feasible are *Road Side Units* (RSU) deployed along roads. The goal of these trends is to develop applications that are classified into safety applications (i.e., to increase driver safety), efficiency applications (e.g., to increase road utilization and improve vehicle mobility) and comfort applications (i.e., to increase passenger enjoyment while on the road through Internet access, social networking, tourist information, advertisements, leisure information and file sharing)[1]. Broadly this set of applications are referred to as an Intelligent Transportation System (ITS) where the VANET is a vital part of the system allowing for communication between vehicles and roadside infrastructure[1].

Vehicular communication may be infrastructure-based, using a cellular or another type of fixed (non-mobile) units, or it may be ad hoc (using a VANET). The latter has the benefits of being very resilient and inexpensive. It is also well-suited for quick spreading of emergency information, as it directly communicates a vehicle's state to all other nearby vehicles. However, the ad-hoc model suffers from inability to reach other networks, and this prevents Internet

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access by vehicles. The hybrid model combines both the ad-hoc and infrastructure models, vehicles may communicate directly with each other (V2V communication) as well as with infrastructure such as cellular towers or RSUs (V2I communication). The hybrid model combines the strengths of the ad-hoc and infrastructure models. Vehicles may dynamically react to failures in the network, routing around issues while maintaining a link to the Internet.

While VANETs are a special case of mobile ad-hoc networks (MANET)[1], studies have shown that protocols developed for MANETs do not perform well in VANET environments[2]. The unique characteristics of VANETs pose significant challenges to MANET protocols[2]. These characteristics include highly dynamic topologies resulting in shortlived link connections, far fewer power constraints compared to MANETs, hard delay constraints, easy access to location data and mobility constrained by roads, traffic lights, speed limits, traffic conditions and driver behaviour.

1.1. VANET Routing and Addressing Literature

Routing algorithms in VANETs may be broadly divided up into five major categories; topology based routing, hybrid, cluster routing, geographic routing and data fusion. We only mention a few here due to space constraints and refer the interested reader to the survey by Milton et al[3]. GPRS[4] is one of the early position based routing protocols explicitly designed with protocol scaling and frequently disconnected networks in mind[4]. GPCR[5] builds on the idea of greedy position based routing. Like in GPRS, nodes exchange periodic beacons to build a model of the on hop topology. Additionally all GPCR nodes contain a complete map of their environments detailing roads and junctions. Contention based forwarding[6] is a position based routing protocol, however unlike position based protocols such as GPRS and GPCR where nodes choose the next hop, neighbours compete to forward packets.

Next, we review some mobile ad hoc network (MANET) protocols that have been extensively tested in VANET environments. AODV[7] is an extremely popular MANET routing protocol frequently evaluated in both MANET and VANET environments. AODV is a reactive topology based protocol, as such it does not maintain an active view of the topology but builds a route each time it is needed. Destination-Sequenced Distance-Vector Routing (DSDV)[8] is a proactive routing protocol which regularly exchanges link state updates and uses distance vector routing. OLSR[9] is a link state proactive protocol.

Relatively little work has been done in VANET addressing schemes. The WAVE standard uses modified router advertisement messages as seen in wired IPv6 networks to advertise network prefixes to nodes. This type of architecture suffers from two main issues; firstly RSUs must use high powered transmissions to reach all nodes within the area and secondly any issues with the RSU will stop nodes from obtaining IP addresses effectively stopping all VANET communication. An alternative to the WAVE addressing scheme is presented in[10].

1.2. Our motivation and contributions

Currently, the physical layer (layer 1) and data link (layer 2) of the network model have been standardized in the form of 802.11p[11] and WAVE[12,13] respectively. In the network layer (layer 3), the V2I model is standardized because it has received attention in industry. Much of the current research focuses solely on V2V traffic but the ad-hoc and hybrid communication models are not standardized. This lack of standardization has been an issue in bringing Internet access to VANET nodes using ad-hoc and hybrid models of communication[3]. Further, it is difficult to make geographical queries (i.e. query a region instead of a node) using the current network layer architectures. This paper attempts to address these gaps. Our proposal for layer 3 functions in VANETs are split into three areas; zone assignment, IP addressing and hybrid routing. Zone assignment is reviewed in section 2.1, next the proposed location-based IP addressing scheme is reviewed in section 2.2 and finally the proposed hybrid routing that works with the location-based addresses is reviewed in section 3.

2. A Novel Addressing Scheme for VANETs

The current standard in VANETs employs a centrally controlled addressing in which nodes are assigned addresses by RSUs. This raises two issues. First, the addressing strategy is centralized and thus more failure-prone. Secondly the addresses assigned contain no inherent location information. Thus additional systems must run on top of VANETs to manage location information. Our proposal seeks to solve both of these issues with a geographic, zone based addressing strategy built on top of the existing standards.

2.1. Zone Assignment

We divide the entire land mass of the earth into discrete geographic zones, with each zone potentially containing a RSU that supports gateway functions and neighbour location services. The total land area of earth is $148,326,000km^2$. Zone assignment must balance location granularity with address space, communication range and cost of infrastructure. Based on these considerations, we assume each zone covers an area of $1km^2$. This implies that each zone can have a unique 28 bit zone id.

Each zone is defined by the locations of its bottom left corner, top right corner, an optional RSU position and IP address. Using 4 bytes for the zone id and 8 byte locations, and 16 byte IPv6 address of the RSU, each zone is fully defined by 68 bytes. This creates a global RSU database of 10 GB, but in reality this is unnecessary. A vehicle in North America may store all zones within North America with a database less than 2 GB in size. Note that a vehicle can determine its zone membership from the zone database using simple geometric calculations. Periodically each node compares its current position to the current zone. If the nodes position does not match the current zone. nodes must begin the re-addressing process as show in section 2.2.

2.2. IP Addressing

Our proposal uses IPv6 addressing as mandated by the IEEE 1609.3 standard, addresses are generated via Stateless Address Auto Configuration (SLAAC) which is a self addressing mechanism specified in 1609.3. It forms a unique 128 bit IPv6 address for a node using (a) a unique 36 bit VANET identifier shared across all VANET nodes, (b) a 28 bit zone identifier and (c) a 64 bit unique host identifier.

This addressing scheme is hierarchical in nature allowing for the crucial route summarization to be used in Internet routers. Since VANET traffic is identified, QoS functionality and application specific behaviour may be implemented. The address directly embeds geographical coordinates with a granularity of $1km^2$. The zone identifier field is common to all nodes within a zone. The 64-bit host identifier can be generated with SLAAC. The zone id can be easily made hierarchical, for example, a 7 bit region ID followed by 21 bits usable for zone identification in each region. Our addressing strategy reserves less than 0.00000000146% of the total IPv6 address space for VANETs.

3. A New Routing Protocol for VANETs

We now introduce our hybrid V2V and V2I routing protocol. Our protocol allows neighbouring nodes to exchange information to facilitate safety and efficiency applications. Additionally, neighbouring nodes are used to route packets toward road side infrastructure allowing VANET nodes to reach both distant VANETs as well as existing networks on the Internet. Building on the hybrid design,our protocol differs from a much of existing work by simultaneously routing multiple types of traffic. We consider three forms of communication:

1. Safety messaging (control and emergency messages) is broadcast to all nodes within a certain area;
2. Internet communication, based on directed unicast transmissions divided into communication toward a known gateway and communication toward a predicted node position, and
3. Infrastructure assisted V2V communication in the form of geographic queries which allow nodes to query locations (e.g. to find out the state of traffic at an intersection) rather than nodes.

Our proposed routing protocol builds on top of the CBF[6] as well as the spatio-temporal multicast protocol presented in[14]. Routing decisions are primarily split into three types of communication; Internet access via a hybrid V2V and V2I model, emergency V2V messages and finally hybrid V2V and V2I zone queries. Due to the unique constraints of emergency messages as opposed to Internet and query messages, these two classes of messages are dealt with separately. Our routing protocol is designed keeping in mind the issues created by location-dependent addresses.

3.1. Safety Message Routing

Safety messages are given absolute priority over all types of messages at the routing layer because of their nature and real-time constraints. Incoming messages (of all types) are first processed by the safety routing unit and outgoing traffic is first generated and queued by the safety routing unit.

The safety message protocol uses a special type of multicast referred to as a *spatio-temporal* multicast or *Mobicast*. Our protocol builds on the ideas in [14] where nodes involved in an emergency dynamically generate an elliptical *Zone Of Relevance* (ZoR) based off of their current velocity and position. Next, using a modified version of contention based routing, the emergency message is propagated throughout the ZoR. This modified version of contention based routing necessitates the exchange of periodic Hello messages informing all neighbours of their positions. Periodic messages are sent with a period of $[T - 1.5T]$, after sending a hello message, nodes choose a random delay from the range of $[T - 1.5T]$ to wait before sending the next hello message. Each transmitted hello message contains the nodes ID and position. Each node maintains a cache containing neighbour information.

The detection of an emergency event triggers the generation of a ZoR, V_e is the node detecting the event and V_i is any point within the ellipse. Figure 1 shows the ZoR generated with the event vehicle at the center of the ellipse. Two virtual vehicles are generated at the left and right apex of the ZoR ellipse, these virtual vehicles are used as targets when disseminating the emergency message. The major axis length a is computed as in [14]. The minor axis length b is set to the width of multiple lanes to increase message dissemination.

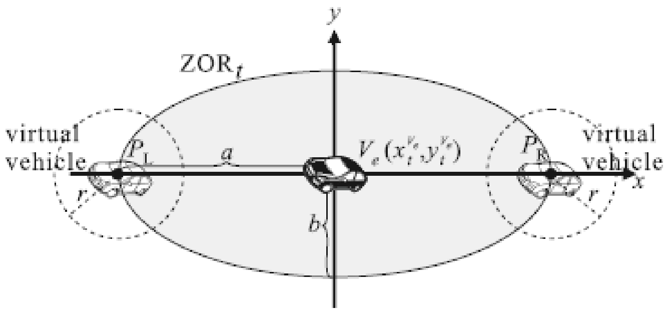

Fig. 1. Zone of Relevance Generation [14]

Emergency messages are composed of three fields; first the ID of the node generating the message, the specifications of the ZoR and the actual message containing the emergency details. All vehicles within transmission range of the original transmission receive the transmission and processes it only if it is within the ZoR of the sending node. It determines the direction of forwarding and starts a backoff-based contention algorithm to send the message.

3.2. Hybrid Routing Protocol

VANETs can use three main types of communication; pure V2V, hybrid V2V and V2I Internet and finally infrastructure-assisted V2V. In our contention-based protocol, nodes do not require knowledge of their local neighbourhood and all nodes contend for the medium.

3.2.1. Hybrid Internet Access: Node to Internet

Hybrid Internet access is achieved through a combination of V2V and V2I communication, and zone based gateways. Each RSU serves as an *intelligent* gateway serving as the border between the VANET and other networks on the Internet. Aside from standard gateway functions each RSU performs two additional functions; mobility prediction and inter-RSU forwarding. Mobility prediction leverages mobility constraints in VANETs in order to predict a nodes position when attempting to send a reply packet into the VANET. Inter-RSU forwarding further builds on mobility prediction to handle cases where nodes move between zones between message transmission and replies. Inter-RSU forwarding allows an RSU to forward a reply to another RSU if the node is predicted to have entered that RSUs zone. Inter-RSU forwarding attempts to reduce the number of hops a packet must make over the less reliable VANET channels by forwarding over reliable point-to-point links to reach a gateway as close to the target node as possible. A complete Internet query is accomplished through the following steps:

1. The node generates a request and sends the packet using multicast to all neighbors within transmission range.
2. All nodes within transmission range receive the packet and check the number of active contention cycles currently running. If the number of active contention cycles is below a set threshold, the effective validation and contention processes may begin. Validation consists of checking the zone of the sending node and making sure that transmission will result in forward progress of the packet toward the gateway. Future work will incorporate less greedy algorithms for routing. Contention is based on a backoff timer proportional to the current nodes distance to the gateway as compared to the transmitting node.
3. Once a node sends a packet, it caches the metadata of the packet to avoid its transmission.
4. When an RSU receives an Internet bound packet from the VANET. it caches the packet origin source address, position, velocity and timestamp. These cached details are used to assist in routing replies. RSUs do the necessary header conversion, and send acknowledgements with the VANET to Internet header. All nodes receiving the RSU acknowledgement update their timers and caches to avoid retransmission.

3.2.2. Hybrid Internet Access: Internet to Node

The Internet reply to a packet sent by a VANET is routed through the following steps:

1. Receive Internet Packet and Predict Destination Zone: The RSU first does header conversion for the packet received from the Internet. It then runs a lookup on its cache and returns the most recent entry for the destination. Then it performs mobility prediction to estimate the position of the destination and determine whether to send the packet to another RSU or a VANET.
2. Gateway to VANET node Routing: This is identical to VANET to gateway routing except for the target destination. Nodes attempt to route the packet toward the predicted position as opposed to a known gateway position. The packet is forwarded until it is dropped due to ineffective transmissions, exceeded hop counts or if it reaches the destination node.
3. Destination Node Receives Packet: The destination node sends an acknowledgement to suppress any remaining transmissions. The acknowledgement is sent via a short acknowledgement packet with a type 6 header and the received information header.

3.3. Geographic Query (GeoQuery) Routing

Geographic query routing referrers to a form of routing where a node attempts to query a specific distant geographic area for information. Two challenges are encountered; first, a sending node may not know the IP address of a node within the geographic area it is attempting to query, and second, the issue of distance is encountered, distant locations require large numbers of hops to reach. Each hop decreases the chances of a packet ultimately reaching its final destination due to increases in contention and chances of collision. Our proposal solves these two issues through V2I assistance and reply contention. A complete GeoQuery is accomplished through the following steps:

1. Upper Layer Query Formation: The upper layers are not required to specify the final destination as that will be determined by reply contention, however the query position must be specified. The network layer does not have access to upper layer data, but the routing protocol requires the geographic position of the query specified in the upper layers. In order to solve this issue we provide a very limited interface allowing upper layers to specify GeoQuery coordinates as the packet is passed down the network stack.
2. Contention Based Routing Towards RSU: Once the routing protocol receives the packet from the upper layer it forms and attaches the appropriate header bits. This stage is very similar to the V2I routing described in section 3.2.1. Upon receiving the GeoQuery packet, the RSU transmits it toward the correct RSU zone and it also transmits an acknowledgement packet; this suppresses any remaining retransmissions. Upon arrival at the query zone RSU the RSU forwards the GeoQuery request packet into the VANET.
3. GeoQuery Reply Contention: Nodes within range of the RSU receive the transmitted GeoQuery request and contend to reply. The successful node passes the request packet up the network stack for further processing.

Upon receiving suppression packet nodes suspend their contention processes and stop transmission. Once the upper layers have successfully processed the request a reply is generated and sent back to the routing protocol. Due to mobility prediction and caching on RSUs, the replying node does not specify the predicted position of destination node. The reply is routed toward the RSU which then routes the packet toward the destination zone.

4. Contention Based GeoQuery Reply Routing: The GeoQuery reply routing is quite similar to Internet based replies presented in Section 3.2.2. Upon receiving the reply packet, the RSU searches its cache for the latest entry on the destination node. It predicts the node's final position based on mobility prediction. If the node is predicted to have moved outside of the RSU zone, the reply is forwarded to the correct zone, otherwise processing continues normally to retransmit the packet. Once a reply has reached the correct zone, the RSU updates the GeoQuery reply header and forwards the reply backed into the VANET. The VANET routes the reply packet toward the predicted position using contention based routing logic identical to that described before for I2V routing. Upon receiving the reply packet the destination node sends an acknowledgement to suppress all other retransmissions. All nodes receiving the acknowledgement stop their retransmission efforts and start a hold down timer after which the cached packet is dropped.

4. Simulation and Performance Evaluation

The proposed routing protocol is implemented and simulated in ns-3 version 3.24 [15]. We used maps from the Open Street Map Database (OSM) [16] that provides detailed topology information on real world maps. The maps were used in the SUMO simulator [17]. SUMO simulates vehicular movements on the map from the OSM database using extremely detailed models of vehicular movements including aspects like acceleration and stopping times. It also utilizes by traffic lights, stop signs, roundabouts and other various conditions encountered on roads.

Due to the lack of VANET protocol support for VANETs in popular simulators we evaluate our protocol against AODV, DSDV and OLSR. These protocols were originally designed for MANETs, however, each of these standards has over a decade of refinement and optimization and thus are the best candidates for comparison for our protocol. We used five evaluation metrics, viz., the average route trip time (RTT), the successful packet delivery ratio (PDR), the average hop count(VANET to RSU), the average hop count (RSU to VANET) and the network throughput.

We used OSM maps of two regions, one urban and one rural, each about approximately 4 km^2. Each region is split into four geographic zones each 1 km^2. An RSU is placed at the center of each zone serving at the gateway from the VANET to both distant VANETs and the Internet. Urban environments are classified by dense roads spaced apart at regular intervals. Density patterns range from low traffic, low density conditions to high traffic, high density periods. Rural environments are classified by spare roads at irregular intervals. Density patterns are expected to reach low and medium density conditions and high density conditions are unlikely. Our protocol is evaluated in firstly with pure Internet bound traffic, then with both safety control messages, safety message dissemination and Internet bound traffic and finally with pure Internet routing, safety message routing and GeoQuery routing.

We used AdHoc-MAC and SUMO-generated traffic and varied the vehicular densities from 25 to 100 vehicles per km^2. Packet payloads are 1kB and transmission power was 25dB. Please note that due to space limitations, we can onloy present a small fraction of our results here.

Results: Urban Environment - High Density. We evaluated the proposed protocol first in a high density urban environment. Each node sends 1-2 packets per second, inter-packet relays are varied between each transmission to ensure transmissions do not become synchronized. Each simulation runs for 120 seconds, nodes do not begin sending packets until 5 seconds into the simulation allowing them to begin their mobility before transmitting.

Figure 2 shows the average successful packet receive rate. It shows that our proposed protocol (on pure Internet and Internet and safety messages) initially has over 20% higher successful receive rates than all other protocols. As the number of transmitting nodes increases, the average successful receive rate gradually decreases, between 45-50% the fraction of successfully received packets reaches parity with OLSR. Between 50 and 100% the proposal protocol experiences rates within 1-3% of OLSR performance. This set of results shows that at high densities the proposal protocol route discovery performs extremely well as it may form multiple paths to the destination. As the number of transmitting nodes increases the performance suffers as contention processes are disrupted. The addition of GeoQuery messages to safety and Internet messages further saturates the channel causing an increase in contention difficulties. We see that our protocol outperforms AODV and DSDV in all evaluation environments.

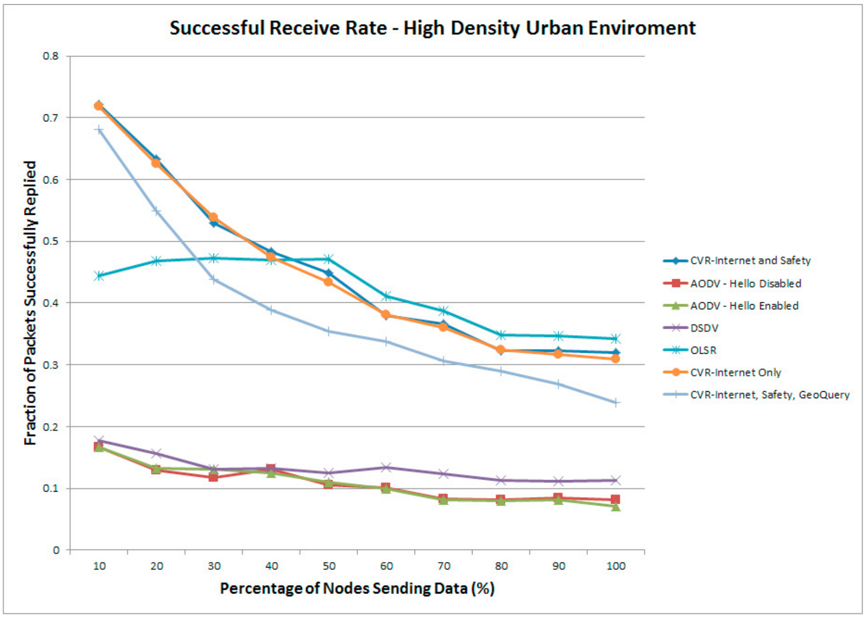

Fig. 2. High Density Urban Environment Average Receive Rate

Results: Rural Environment - Low Density. The following section presents the evaluation of the proposed protocol in a low density rural environment. Each node sends 1-2 packets per second, inter-packet relays are varied between each transmission to ensure transmissions do not become synchronized. Each simulation runs for 120 seconds, nodes do not begin sending packets until 5 seconds into the simulation allowing them to begin their mobility before transmitting.

Figure 3 shows the average successful packet receive rate rate. As before, successfully transmissions are defined by a node sending a request and receiving a reply to that request.

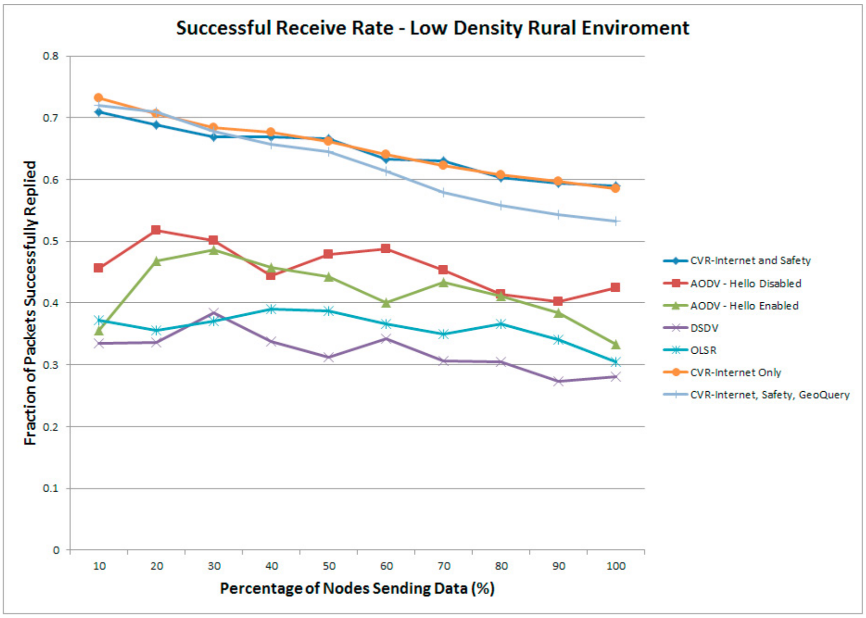

Fig. 3. Low Density Rural Environment Receive Rate

In the low density rural environment, all protocols maintains similar performance to that seen in the urban environment. Our protocol performs between 10 and 30 % better than all other evaluated protocols. The addition of safety and GeoQuery messages lowers the successful receive rate by up to 5 %. However. even with reduced performance, our protocol continues to perform better than all of the tested alternatives. A notable difference between the rural and urban environments is that our protocol seems to perform better. Comparing the urban environment results to the rural environment results, our protocol achieves between a 5 and 15% higher successful packet receive rate. The largest difference is seen with few vehicles transmitting data, as the number of vehicles transmitting data increases the performance of the proposed protocol in the rural environment approaches that of the urban environment. The addition of safety messages does not appear to have a notable affect on the successful receive rate. However, when GeoQuery and safety messages are both introduced the channel becomes more congested causing more contention.

5. Conclusions

Our proposed protocol performs well at low and medium densities in both urban and rural environments when compared to existing work. It achieves much higher successful receive rate using cooperation between nodes and RSUs. For GeoQuery traffic in particular, this form of communication is only possible through cooperation with VANET nodes, RSUs and general Internet infrastructure. At high densities, the main reason for the degradation of our protocol is that the MAC layer queueing mechanism packets result in long times. The long queueing time may cause errors with the contention process creating unnecessary network traffic and creating ineffective routes. Based on our experience, two ways to address this problem are first, to use local neighbourhood estimation to estimate the the active contention threshold, and second to use cross layer coordination. The latter can be done by including a node's position and velocity into RTS and CTS messages. Using the modified RTS and CTS messages source nodes may actively select its preferred forwarder.

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