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Using Tall Vehicles as Next Relay Hops in VANET Multi-Hop
Communication Protocols

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1. Introduction

Vehicle-to-vehicle (V2V) communication is the main message exchange paradigm for a number of applications proposed for Intelligent Transportation Systems (ITS), ranging from safety to traffic management and infotainment [KaA11]. Vehicular networking serves as one of the most important enabling technologies required to implement a myriad of applications related to vehicles, vehicle traffic, drivers, passengers and pedestrians. A Vehicular Ad-hoc Network (VANET) is a vehicular network that allows for V2V communication. The V2V communication approach supports the communication between vehicles, while Vehicle to Infrastructure (V2I) communication approach supports the communication between Vehicles and Infrastructure. The proposed technology to perform this information exchange is the IEEE 802.11p technology [IEEE802.11p-2010], which is a member of the Wireless LAN family adapted for use in vehicular environments. Communication between vehicles can for example be used to realize driver support and active safety services like collision warning, up-to-date traffic and weather information or active navigation systems [EiSc06]. Figure 1 shows a scenario, where a car accident occurred in an intersection, and where VANET is used as a V2V communication network to inform vehicles in the neighborhood about this accident. With such benefits, researches are motivated to study the behaviors of vehicles and vehicular networks.

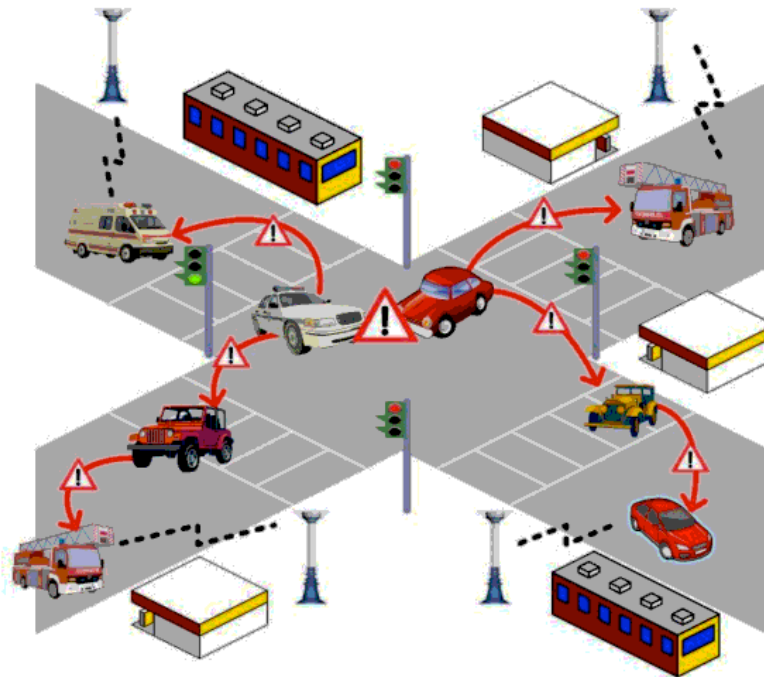


Figure 1 Vehicle Ad hoc Networks, copied from [POSTECH]

VANET supports data communications among nearby vehicles and between vehicles and nearby fixed infrastructure, generally represented as roadside units (RSUs). VANET turns every participating car into a wireless node, allowing cars to connect to each other and, in turn, create a network with a wide range. As cars fall out of the signal range and drop out of the network, other cars can join in, connecting vehicles to one another so that a mobile Internet is created. Communication between vehicles in VANET is performed by direct connection or through multiple vehicles, acting as hop relays. Despite extensive

research in networking, many challenges remain in the study of VANET including development of multi-hop routing techniques.

1.1 Research Challenges

In this section we argue that the performance of multi-hop networks can be improved by exploring enhancement in routing techniques at major network layers. The main motivation for this approach comes from the disconnected nature of vehicular ad hoc networks, and the frequently obstruction to line of sight (LOS) between communicating entities caused by either static (e.g., building, hills) or mobile (other vehicles on the road) objects [BoVi11].

There exist a wide variety of experimental studies dealing with the propagation aspects of V2V communication. Many of these studies deal with static obstacles, often identified as the key factors affecting signal propagation (see [BaKr06] [ChCa05]). Also, it has been shown in some papers that other non-communicating vehicles often block the LOS between the communicating vehicles due to the relatively low height of antennas on the communicating vehicles, thus significantly attenuating the signal. This results in a significant reduction in the received power level and effective communication range [MeBo10] [BoVi11]. In [QiWo12], the impact of vehicles' height is explored. Specifically, an extended evaluation of the impact of Tall vehicles on V2V communication has been presented. In particular, [QiWo12] presented extensive simulation studies in which (i) the effect of Tall vehicles on V2V communication and (ii) the benefit of choosing a Tall vehicle as a next hop are investigated when different vehicle densities, percentages of Large vehicles, transmission power, DSRC data rates (i.e., modulation types and minimum sensitivity threshold) are used. It has been concluded that for different network topologies the communication links that are using Tall vehicles as transmitter and/or receiver perform consistently and significantly better than the communication links that use Short vehicles, from the point of average LOS probability, received power level and packet success rate. Besides, it has been shown that Tall vehicles are significantly better relay candidates than Short vehicles.

However, these benefits of Tall vehicles are only explored for single-hop packet forwarding in [QiWo12]. And it is reasonable to expect that Tall vehicles could provide more benefits on system level performance. Therefore, in this assignment, we intend to design a way to enhance the current existing routing techniques by using the information of vehicle heights.

1.2 Research Questions

The goal of this assignment is to enhance existing VANET multi-hop communication algorithms and protocols by exploiting system level benefits of Tall vehicles, and investigate the performance, in terms of hop count and end-to-end delay. In order to extend the benefits of Tall vehicles into multi-hop communication networks, we plan to design large-scale simulations, which apply the action of selecting Tall vehicles as next hop to multi-hop routing protocols in VANET. This gives insights in how the single-hop benefits observed in [QiWo12] will translate into the system level performance benefits in a multi-hop vehicular environment.

Motivated by above, this assignment extends the research work accomplished in [QiWo12], based on a propagation model that can be applied in V2V communications scenarios, when the communication: 1) is using 802.11p Dedicated Short Range Communication (DSRC) standard, 2) consider vehicles as obstructions. With extensive simulation studies, the system level benefits of Tall vehicles are investigated when different road topologies, vehicle densities, percentages of Large vehicles are used. The main research question that has to be answered by this assignment is:

- How could existing VANET multi-hop communication algorithms and protocols benefit when applying the action of selecting tall vehicles as next relay hops?

Sub-questions are:

- 1) Which VANET multi-hop communication algorithms and protocols should be considered in this assignment? Why?
- 2) How could the action of selecting tall vehicles as next relay hops be applied into the existing VANET multi-hop communication algorithms and protocols?
- 3) To what extent could the existing VANET multi-hop communication algorithms and protocols benefit from the action of selecting Tall vehicles as next relay hops?

1.3 Outline of this report

This report is organized as follows. Chapter 2 gives a detailed comparison of different VANET routing techniques. For simplicity, only one of them will be considered in this assignment. The reason for the decision of position-based routing will also be presented in Chapter 2. Thus Chapter 2 answers research sub-question (1). In Chapter 3, the basic existing algorithms described in the standardization of position based routing are introduced. Next Chapter 4 presents the Tall vehicle-aware position based routing which applying selection of Tall vehicles as next hops into basic algorithm. This chapter solves research sub-question (2). Chapter 5 indicates the simulation environment, simulation topology in the experiments, and description of performance metrics first. Then the performance comparison and evaluation of the basic algorithms and the modified algorithms are discussed, which answers research sub-question (3). In the simulation, different scenarios are determined based on the research goal in this assignment. After that, the simulation results are obtained and analyzed. Finally, Chapter 6 concludes the assignment and provides recommendations and future works.

2. Survey of Routing Techniques in VANET

The design of routing techniques in VANETs is an important and necessary issue for supporting the smart ITS. A lot of papers have proposed routing protocols for MANETs, mainly two types: proactive and reactive routing protocols, e.g. [LiMi04][GoNi06]. However, VANETs are fundamentally different than MANETs, from the point of the special mobility patterns (i.e., high vehicle velocity) and rapid changing road topology. Proactive routing protocols require that every node maintain a routing table. In order to update the routing tables, huge amount of information exchange is needed, making large overhead a burden for the network. In a VANET with high mobility, the overhead is even larger because of the increased routing table update failure probability. As their counterpart, reactive routing protocols discover and establish routes only when there is a packet need to send. This kind of routing protocols saves unnecessary information exchanges and brings down the overhead cost. Nevertheless, rapid changed road topology makes establishing a stable route from the source to the destination much more difficult, see e.g. [WaXi07]. Because of these key differences, the existing routing techniques on MANETs cannot be directly applied into VANETs. Suitable routing techniques are proposed to deal with the highly dynamic nature of VANET, classified into various categories: topology based, position based, cluster based, geocast, and broadcast, see e.g. [NaKh11][SuNa11].

In this chapter, the five categories of the existing VANET multi-hop routing techniques are described briefly first in section 2.1. Since any routing protocol is a compromise between simplicity and efficiency, the purpose of section 2.2 is to select a routing protocol that is simple enough to be tractable from an implementation point of view, yet still able to forward the packet from source to destination efficiently and correctly when considering the essential vehicular network characteristics, mainly high mobility. Therefore, a comparison in terms of scalability, reliability, complexity, standardization and suitable road scenario is given in section 2.2, in order to show which protocol/algorithm is most potential to be extended in the future for VANET, thus most suitable to be considered in this assignment. The contents in this chapter answer the first sub-question.

2.1 Routing Techniques in VANET

This section describes the main routing techniques used in VANETs.

2.1.1 Topology based routing

Topology based approaches, which are further divided into three subcategories: proactive, reactive and hybrid, use information about links to forward the packets between nodes of the network. The descriptions presented in this subsection are strongly based on [SiSu10][KaJo12].

Compared to the connectionless schemes for traditional datagram networks, proactive (table-driven) routing protocols work in a similar way in which they utilize classical routing strategies, such as distance-vector routing and link-state routing, in which any changes in the link connections are periodically updated by exchanging control messages. Examples of this kind of routing protocols are Destination Sequenced Distance Vector (DSDV, see [MaRa09]) and Optimized Link State Routing (OLSR, see [JaMü01]). By periodically exchanging control messages, routing information about all the available paths in the network can be obtained and maintained for each node, even though they are not currently used. This procedure may occupy a large amount of the available bandwidth for periodic updates of topology if the network topology changes frequently, which is the main disadvantage of this kind of protocols. However, when there are packets needs to be transmitted, a best route could be found quickly and directly from the topology table. Thus this kind of protocols does not have initial route

discovery delay. Considering the high dynamic nature of VANETs, proactive protocols may not always be suitable for highly mobile networks such as VANETs.

Reactive (on-demand) routing protocols utilize an approach in which mobile nodes in the network only discover routes to destinations when there is packets on-demand. In this kind of protocols, only the routes that are currently in use are maintained. Therefore, when there packets needed to be transmitted, typically a route discovery process is performs to find the best route to the destination before packets can be exchanged between nodes. Examples of this kind of protocols are Ad hoc On-Demand Distance Vector (AODV, see [RFC3561]) and Dynamic Source Routing (DSR, see [JaMa03]). The advantage of this kind of protocols is that the burden on the network is reduced when only a few of available routes in in use. Thus less bandwidth is consumed compared to proactive protocols. However, the disadvantage of reactive protocols is that the initial route discovery delay in determining the route to the destination may be very large. Another disadvantage is that the route maintenance may generate a significant amount of network traffic if the network topology changes frequently, thus affects the packet delivery success rate.

Hybrid routing protocol (e.g. Zone Routing Protocol, see [ZhJa03]) combines both proactive and reactive approaches to achieve a higher level of efficiency and scalability. However, it is still needed to maintain available routes to destinations in the network, even though the proactive and the reactive approaches are combined.

Furthermore, VANETs differ from other networks by its highly dynamic topology. Many simulation results showed that most of the topology based routing protocols suffer from highly dynamic nature of vehicular node mobility because they tend to have poor route convergence and low communication throughput, see e.g. [RaSa11].

2.1.2 Position based routing

Position is one of the most important data for vehicles. In VANET each vehicle wishes to know its own position as well as the positions its neighboring vehicles. A routing protocol using position information is known as the position based routing protocol. Position-based routing (e.g. Location-Aided Routing, see [KoVa00]) requires some information about the physical or geographic positions of the participating nodes. To acquire the position information of neighboring nodes, each node periodically sends its own position information to all the direct neighbors, using HELLO control messages or beacons. In position based routing, the packet generated by the source is sent to the one-hop neighbor closest to destination without any map knowledge. The routing decision for next hop forwarding packets at each node is not based on a routing table but the positions of its neighboring nodes and the position of the destination node. There is no need to create and maintain global viewable possible routes from the source node to the destination node.

Position based routing protocols are more suitable for VANETs since the vehicular nodes are known to move along established paths. Since routing tables are not used in these protocols no overhead is incurred when tracing a route. Besides, one of the main advantages of using position based routing is that they are not requiring maintenance of routes, which is very appropriate for highly dynamic networks such as VANETs, see e.g. [RaSa11].

2.1.3 Geocast based routing

Geocasting, a variant of the conventional multicasting problem, distinguishes itself by specifying hosts as group members within a specified geographical region, i.e., the geocast region. In geocast based routing protocols, the nodes eligible to receive packets are implicitly specified by a physical region. Membership in a geocast group changes whenever a mobile node moves in or out of the geocast region.

The main objective of geocast based routing protocols is to deliver the packet from the source node to all the other nodes within a specified geographical region Zone of Relevance, see e.g. [YoNi02][HuKh11].

2.1.4 Cluster based routing

By using this kind of routing technique, the network is divided into clusters while each cluster has one cluster-head, which is responsible for intra and inter-cluster management functions. Intra-cluster nodes communicate each other using direct links, whereas inter-cluster communication is performed via cluster headers. In cluster based routing protocols the formation of clusters and the selection of the cluster-head are important issues. In VANET due to high mobility dynamic cluster formation is a towering process. The routing process itself is performed as source routing by flooding the network with a route request message. Due to the clustered structure there will be less traffic, because route requests will only be passed between cluster-heads, see e.g. [NaKh11].

2.1.5 Broadcast based routing protocols

Broadcast routing (see [LaWa09]) is employed to distribute information about traffic, climate, emergency situations and condition of roads between different vehicles. Flooding is mainly used in these types of routing techniques for message forwarding, but it causes bandwidth problems as the network size increases, see e.g. [RaSa11].

2.2 Routing Protocols Comparison

Various qualitative based routing protocols of VANET have been discussed in section 2.1. Comparing the various features is absolutely essential to come up with new proposals for VANET. This section presents the comparison of different categories of VANET routing protocols. The criteria used for comparison, including scalability, reliability, simplicity, standardization and road scenarios, are described as the following.

- **Scalability:** scalability is the ability of the protocols to scale well in a network with a large number of nodes. We define here that the scalability of a VANET multi-hop routing protocol refers to the change of the number of states in the network when network size becomes larger.
- **Reliability:** we define here that the reliability of a VANET multi-hop routing protocol refers to the packet delivery rate in V2V communication networks. Thus the fast movement and dynamic nature of nodes in VANET are considered as important factors, see e.g. [JéFe06][HuKh11].
- **Simplicity:** we define that the complexity of a VANET multi-hop routing protocol refers to the simplicity of the algorithm used to forward the packet in the network. More specifically, this includes 1) whether the location or link information is used or not, 2) whether a global topology table or a routing table is created and updated periodically, see e.g. [SuNa11][BiMd11].
- **Standardization:** this criterion indicates whether the routing techniques in the categories are standardized or not.
- **Road scenarios:** this criterion presents the road environment that the routing techniques are suitable for.

Based on above comparison criteria, we compare the various categories of VANET multi-hop routing techniques described in section 2.1, shown in Table 1.

Table 1 Routing protocols comparison

Routing Protocols Criteria	Proactive	Reactive	Position Based	Cluster Based (CBRP)	Geocast routing	Broadcast routing
Scalability	–	--	++	+	+	--
Reliability (PDR)	+	–	++	+	+	--
Simplicity (Less complexity)	–	–	+	–	+	++
Standardized	OLSR (RFC3626)	AODV (RFC3561) DSR (RFC4728)	[ETSI TS 102 636-4-1 V1.1.1]	CBRP (internet draft)	GPS-Based Addressing and Routing (RFC2009)	NO
Scenario	Urban	Urban	Urban & Highway	Urban & Highway	Highway	Highway

Considering scalability, when the network size becomes larger, the number of states in the network for proactive/reactive/broadcast routing protocols becomes obviously larger. However, in geocast routing protocols normally a forwarding zone (where it directs the flooding of packets) is defined so that the message overhead and network congestion are reduced, and the number of states in the network is also reduced. As to cluster based routing, more nodes in the network lead to higher complexity of the cluster formation. But it is only limited inside the cluster, while the exchange of information between clusters is performed via cluster heads. Thus this kind of routing protocol can scale well in a larger network. Considering position based routing, it uses the location information of neighbor nodes instead of link information, and a packet is sent only to the one hop neighbor closest to destination. Thus there is no need to create and maintain global viewable routes from the source to the destination. Furthermore, the message overhead and the number of node states are significantly reduced, see e.g. [SiSu10][YoNi02].

As to reliability and simplicity, to achieve better reliability proactive/reactive/cluster routing protocols need to exchange control messages frequently thus the information of neighbors could be updated in time. However, the overhead of control messages in the network would become large. Position based and geocast routing protocols do not have this problem since they are using position information and they are also simple enough to forward packet from source to destination without any map information.

Regarding to the standardization, the standards for topology based routing and geocast routing could be found in [RFC] for OLSR (see [RFC3626]), AODV (see [RFC3561]), DSR (see [RFC4728]), and GPS-based addressing and routing (see [RFC2009]). The description for position based routing is presented in [ETSI TS 102 636-4-1]. For cluster based routing, only an Internet draft has been found for CBRP. While no standard for broadcast routing is found.

Considering the road scenario, topology based routing is suitable to be applied in urban environment, as the vehicle mobility is relatively low and a stable topology table could be maintain easier compared to highway environment. Broadcast routing are better performed in highway scenarios, because that relative low vehicle density leads to fewer control message overheads. Since position based and geocast routing are using geographical information of nodes in the network, they could perform well in both highway and urban environment.

From the above comparison we can conclude that position based routing techniques, which are routing protocols using geographic information of routers in the network, have been identified to be most suitable for VANETs because of frequently changed network topology and highly dynamic nature of vehicular nodes. Therefore, the position based routing techniques will be considered and investigated further in this assignment.

3. Position Based Routing Techniques

A number of use cases in ITS communications involve the dissemination of information in a particular geographic region. This ITS requirement has led to the development of the concepts of location-based addressing and routing of data (packets). In this document, "geodissemination" is used to refer to the basic functionality of dissemination of information within a prescribed geographic area, while the term "GeoNetworking" is used to refer to the ITS station networking and transport layer protocols specified in the standards currently being developed at ETSI, also known as the position based routing techniques in this assignment, see e.g. [EU US ITS12].

3.1 Overview

A network layer geodissemination protocol is currently being specified inside ETSI TC ITS as a routing technique ("GeoNetworking") for ITS stations that specifies mechanisms for packet forwarding in an ad hoc collection of ITS stations. The current set of ETSI standards ([ETSI TS 102 636-4-1]) mandates GeoNetworking implementations in all ITS stations, and mandates its use for communications over 5.9 GHz in Europe including for the periodic transmission of safety-related (CAM/DENM) messages.

Related to the geodissemination in GeoNetworking, we introduce the communication scenarios supported in GeoNetworking architecture, when road traffic hazard information is being transmitted to all vehicles located in the targeted geographic areas. From an IPv6 GeoNetworking perspective, communication scenarios are classified according to 1) the sender and the receiver communication endpoints (vehicle, roadside), 2) their communication mode, i.e. whether only the vehicles (infrastructure-less), or the vehicles and the roadside are involved, 3) the destination range: is the destination a single communication endpoint or multiple communication endpoints? This results in some typical scenarios, including Vehicle/Roadside-based Unicast/Anycast/Broadcast. The Unicast addressing uses a one-to-one association between destination address and network endpoints: each destination address uniquely identifies a single receiver endpoint. The Anycast addressing routes datagrams to a single number of a group of potential receivers, all of which are identified by the same destination address. This is a one-to-one-of-many association. The Broadcast addressing uses a one-to-many association, datagrams are routed from a single sender to multiple endpoints simultaneously in a single transmission. The network automatically replicates datagrams as needed for all network links that contain an eligible receiver, see e.g. [GeoNet-D.1.2-v1.2].

Figure 2 is used as an example to explain the typical scenarios. In this example, there are two targeted areas, one being the section of roadway in the immediate vicinity of the hazard and the second being the section of roadway used by vehicles approaching the hazard. In Figure 2, RSU1 (Roadside Unit) connects to a Control Centre and subsequently to RSU2 using fixed infrastructure (e.g. the internet).

In the example of Figure 2, vehicle A detects the hazard on the road and informs all the other cars within its transmission range about this traffic hazard immediately. As a result vehicle B receives the message and then further forwards the same message to other vehicles and the message reaches vehicle C. In this way, the traffic hazard information is forwarded (GeoBroadcast) as long as there are vehicles within the theoretical limited geographical area. In addition, the vehicles that are not following immediately but heading to the same spot could still benefit from the road hazard information, since the information will be valid for a while. In this case, a traffic road Control Center server would thus receive this information from vehicle A by using GeoUnicast to reach the RSU and then through the Internet access provided by RSU1. The road traffic Control Center server determines an appropriate geographic area for dissemination of a warning, and this warning is dispatched periodically to RSUs serving that area (RSU2

in this case). RSU2 then transmits the warning to all cars located in the target geographic area (vehicles D, E, F).

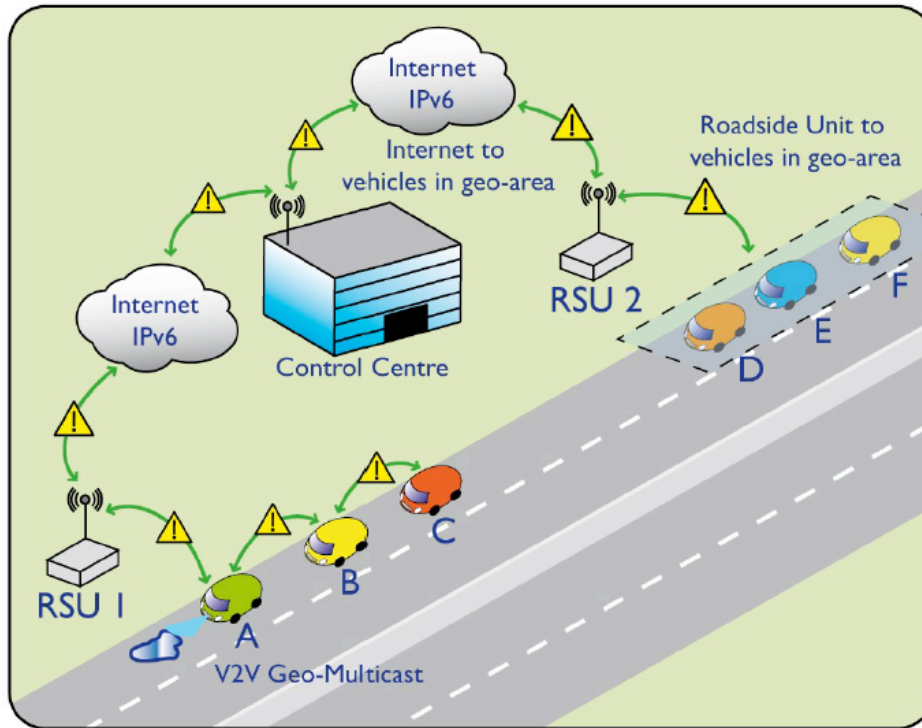


Figure 2 Geodissemination of road traffic hazard information, copied from [GeoNet-D.1.2-v1.2]

This example of Figure 2 illustrates three different geodissemination scenarios: (1) GeoBroadcast: Information sent by a vehicle to all vehicles in an immediate geographic area around the vehicle. (2) GeoUnicast: Information sent by a vehicle to a server in the Internet for subsequent dissemination in a geographic area is a Roadside-based GeoUnicast. If a vehicle acts as the receiver in this information dissemination, it is a Vehicle-based GeoUnicast. (3) Multicast: Information sent by a server in the Internet to all vehicles in a given geographic area.

In this assignment, only the Vehicle-based Unicast is taken under consideration. The endpoints in the scenarios are vehicles, in which the destination is a single vehicle endpoint of known identity whose position and identity are known through received beacons and/or a location service. The Vehicle-based Unicast can be used in cases, like road safety (transmission from a vehicle announcing to a peer vehicle behind that it is decreasing speed), infotainment (delay-tolerant gaming between two vehicles with known identities), etc. The theoretical study for GeoUnicast could be easily extended to GeoBroadcast and GeoAnycast situations when analyzing the system level benefits of Tall vehicles.

While not discussed in details herein, The GeoNetworking protocol is also intend to support point-to-point ("unicast") communication between pairs of ITS stations based on geographical locations for packet transport as well as the dissemination of packets in geographical areas [ETSI TS 102 636-4-1]. A GeoNetworking packet is part of the overall frame/packet structure depicted in Figure 3. MAC addresses are used to address peer stations either in broadcast mode or in unicast mode. The MAC header is not specified in this report. However, the GeoNetworking protocol sets the MAC address, or more generally the link-layer address, in order to define and identify the next hop of a GeoNetworking packet. An LLC header is used to direct the network layer protocol data unit to the appropriate networking protocol. In

Figure 3, the specification of GeoNetworking security header is outside the scope of the present document. The optional payload represents the user data that are created by upper protocol entities. Some GeoNetworking packets do not carry a payload, such as Beacon. The GeoNetworking header is the header of the GeoNetworking packet as defined in this report, which comprises a Common header and an extended header, shown in Figure 4.



Figure 3 GeoNetworking packet structure, copied from [ETSI TS 102 636-4-1]

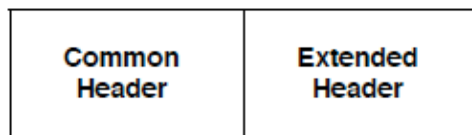


Figure 4 GeoNetworking header structure, copied from [ETSI TS 102 636-4-1]

The common header is 36 octets in length, which contains the geographical location (24 octets) of the sender of the packet, see e.g. [ETSI TS 102 636-4-1]. The content of the extended header depends on the functionality (GeoUnicast, GeoAnycast, GeoBroadcast, etc.). The two main packets distinguished in the Vehicle-based Unicast are BEACON and GeoUnicast packets. A BEACON packet shall consist of a common header only. For GeoUnicast header, besides the common header it has 1) a sequence number which indicates the index of the sent GeoUnicast packet and is used to detect duplicate GeoNetworking packets, 2) lifetime field which indicates the maximum tolerable time a packet can be buffered until it reaches its destination, 3) position vector of the source, 4) position vector of the destination. The Vehicle-based Unicast operations related to the two kinds of packets can be specified in the following Table 2.

Table 2 Vehicle-based Unicast operations [ETSI TS 102 636-4-1]

Network Management	<ul style="list-style-type: none"> – Address configuration – Local position vector and time update – Beaconsing – Location service
Packet Handling	<ul style="list-style-type: none"> – Greedy Forwarding – Contention Based Forwarding

In this assignment report, brief descriptions of each network management operation will be presented in section 3.2. The details of packet handling operations are described in section 3.3.

3.2 Network Management

This section specifies the network management operation briefly, and the detailed functionalities are specified in the standard [ETSI TS 102 636-4-1].

- Address configuration

At start-up, each GeoAdhoc router in the network shall have a self-assigned initial GeoNetworking address. This address shall be used in the header of a GeoNetworking packet and identify the communicating GeoNetworking entities. The format of the GeoNetworking address is specified in clause 6 of [ETSI TS 102 636-4-1].

- Local position vector (LPV) and time update

A GeoAdhoc router shall maintain a local data structure that holds position-related information for the local GeoAdhoc router, i.e. the Local Position Vector (LPV). The data elements of a location table entry include geographical position, speed, heading, timestamp that indicating when the geographical position was generated, and the related accuracies. At start-up, all data elements of the LPV shall be initialized with 0 to indicate an unknown value. The LPV shall be updated with a minimum frequency (1000ms). Local position and time are set by the Network and Transport Layer Management entity.

- Beacons

Beaconing is used to periodically advertise a GeoAdhoc router's position vector to its neighbors. A BEACON packet should be sent periodically unless another GeoNetworking packet carrying the GeoAdhoc router's local position vector is generated and sent. Typically, this periodically transmission of beacons is achieved by implementing a timer that depends on transmission of any GeoNetworking packets. This means that for every sent GeoNetworking packet the GeoAdhoc router shall reset the timer of beaconing. If a GeoAdhoc router receives a BEACON packet, it shall update the position vector for the sender in the Location Table Entry (LocTE) with the sender position vector fields of the Common Header.

- Location service

The location service is used if a GeoAdhoc router needs to determine the position of another GeoAdhoc router. For example, when a GeoAdhoc router acting as the source is in the process to send a GeoUnicast packet to another GeoAdhoc router acting as the destination, and the source does not have the position information of the destination in its location table, the source will firstly process the location service. The execution of a location service is fully transparent to protocol entities of higher layers.

3.3 Packet Handling

The GeoUnicast forwarding algorithm is executed by a GeoAdhoc router to relay a packet to the next hop. The present document [ETSI TS 102 636-4-1] defines two GeoUnicast forwarding algorithms for packet handling operation: Greedy Forwarding (GF) algorithm and Contention-based forwarding (CBF) algorithm. When a source/forwarder receives a GeoUnicast packet request, it generates/processes the packet and determines the forwarding algorithm based on an attribute field. The default algorithm is greedy forwarding algorithm.

3.3.1 Greedy forwarding

Greedy algorithm is defined as an algorithm that always takes the best immediate solution while finding an answer. For some optimization problems, the overall optimal solution is found by using greedy algorithm. However, the solution may be less-than-optimal when some instances of other problems are considered.

In the Greedy Forwarding (GF) algorithm, all the GeoAdhoc routers shall send beacons to each other periodically, in order to exchange the position vectors of other GeoAdhoc routers. In this assignment it is considered that each beacon packet needs to carry for each vehicle, the network address for the GeoAdhoc router entity in the ITS station, position (longitude, latitude) of the GeoAdhoc router, and the speed of the GeoAdhoc router. With beaconing in the Greedy Forwarding (GF) algorithm, every node in

the network creates and maintains a location table that indicating the information of neighbors. With a GeoUnicast packet request, the current GeoAdhoc router uses the location information of the destination carried in the GeoUnicast packet header and selects one of the neighbors in the location table as the next relay hop. Specifically, the algorithm applies the most forward within radius policy, which selects the neighbor with the smallest geographical distance to the destination, thus providing the greatest progress when the GeoUnicast packet is forwarded. The pseudo-code of the greedy forwarding algorithm is shown in the Figure 5. We can see that the current GeoAdhoc router looks over all the entries in its location table (LocT) and finds the vehicle closest to the destination, with the distance expressed as MFR in the code. If the MFR is smaller than the distance between the current GeoAdhoc router and the destination, meaning that the node closest to the destination is not the current router itself, then the link layer address of the next hop is set to the link layer address of the node closest to the destination.

```

-- P is the GeoUnicast packet to be forwarded
-- i is the i-th LocTE
-- NH is the LocTE identified as next hop
-- NH_LL_ADDR is the link layer address of the next hop
-- LPV is the local position vector
-- PVp is the destination position vector in the GeoNetworking packet to be forwarded
-- PVi is the position vector of the i-th LocTE
MFR = DIST(PVp, LPV)
FOR (i ∈ LocT)
    IF (i.IS_NEIGHBOUR) THEN
        IF (DIST(PVp, PVi) < MFR) THEN
            NH ← i
            MFR ← DIST(PVp, PVi)
        ENDIF
    ENDIF
ENDFOR
IF (MFR < DIST(PVp, PVLPV)) THEN
    SET NH_LL_ADDR = NH.LL_ADDR
ELSEIF
    LOCAL OPTIMUM
    SET NH_LL_ADDR = 0
ENDIF

```

Figure 5 Pseudo-code of greedy forwarding algorithm, copied from [ETSI TS 102 636-4-1]

Figure 6 is shown as an example to explain how the greedy forwarding algorithm works in VANET. In the example of Figure 6, assume that the source wants to send a warning datagram or other kind of datagram to the destination shown in the figure. The position vector of the destination vehicle is known by the source by the location service, and the greedy forwarding algorithm is applied. However, the destination vehicle is not located in the theoretical maximum communication range of the source vehicle. The datagram need to be forwarded by several intermediate vehicles. Since only vehicle A and vehicle B in this example are located inside the communication range of the source vehicle, by sending beacons periodically the source can obtain the position vectors of the two vehicles. Then the source calculates the geographical distances to the destination from vehicle A and vehicle B, and we can see from the figure that vehicle A is closer to the destination. Therefore, vehicle A in this example is selected by the source as the next hop to relay the datagram in the greedy forwarding algorithm, and the datagram is forwarded closer to the destination.

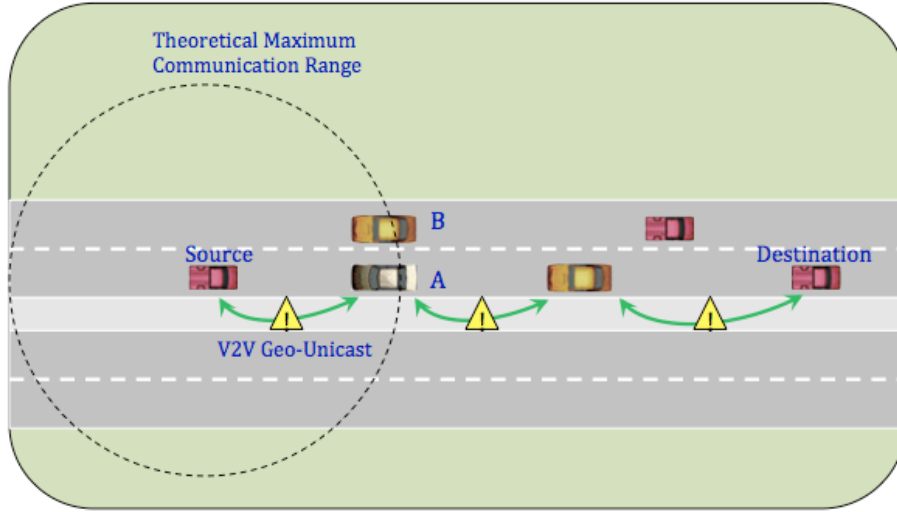


Figure 6 An example of greedy forwarding algorithm in VANET

3.3.2 Contention based forwarding

With the Contention-based forwarding (CBF) algorithm, a receiver decides to be a forwarder of a GeoUnicast packet. This is in contrary to the sender-based forwarding scheme specified in section 3.2.1, where the sender determines the next hop. The general idea of CBF is to base the forwarding decision on the current neighborhood as it exists in reality and not as perceived by the forwarding node. This requires that all suitable neighbors of the forwarding node are involved in the selection of the next hop.

CBF works in two steps: timer-based contention and suppression. In the first step, the forwarding node transmits the packet as a single-hop broadcast to all neighbors. It utilizes timer-based re-broadcasting with overhearing of duplicates in order to enable an implicit forwarding of a packet by the optimal node. The neighbors compete with each other for the "right" to forward the packet. During this contention period, a node determines how well it is suited as a next hop for the packet. Secondly, the node that wins the contention suppresses the other nodes and thus establishes itself as the next forwarding node. The operation of CBF could be expressed with an activity diagram, shown in Figure 7. Associate with Figure 7, we describe in detail how contention can be realized on the basis of biased timers in the following. Furthermore, we present the suppression strategies, see e.g. [HoJö03].

- **Timer-based contention**

The decentralized selection of one node out of a set of nodes is a common problem encountered in many areas of computer networks. A standard approach for this selection is by means of timers. With CBF, the GeoAdhoc router broadcasts the GeoUnicast packet. All neighbors, which receive the packet, process it: The GeoAdhoc router adds the packet into its CBF packet buffer if it receives the packet the first time, and then starts a timer, shown as the left branch of [Flow 1] in Figure 7. To use such a simple timer-based mechanism for the forwarding decision, all nodes that receive the packet shall check if they are closer to the destination than the forwarding node. In [ETSI TS 102 636-4-1], the value for the timers is determined based on how much progress a node provides toward the destination, which is inversely proportional to the distance between the GeoAdhoc router's local position and the destination's positions. The calculation of timeout for buffering packets in the CBF packet buffer for GeoUnicast, expressed as TO_CBF_GUC , is shown as following Equation 1.

$$TO_CBF_GUC = \begin{cases} TO_CBF_MAX + \frac{TO_CBF_MIN - TO_CBF_MAX}{DIST_MAX} \cdot PROG & \text{for } PROG \leq DIST_MAX \\ TO_CBF_MIN & \text{for } PROG > DIST_MAX \end{cases}$$

[Equation 1]

where:

- TO_CBF_MIN: is the minimum duration the packet shall be buffered in the CBF packet buffer.
- TO_CBF_MAX: is the maximum duration the packet shall be buffered in the CBF packet buffer.
- PROG: is the forwarding progress of the local GeoAdhoc router towards the destination, i.e. the difference between the sender's distance and GeoAdhoc router's local distance from the destination.
- DIST_MAX: is the theoretical maximum communication range of the wireless access technology.

When the PROG is smaller than the theoretical maximum communication range of the current GeoAdhoc router, the timeout is inversely proportional to PROG (the maximum timeout subtracts the PROG multiplied by a time factor). If the GeoUnicast packet is transmitted outside the theoretical maximum communication range by accidently, the timeout for the current GeoAdhoc router is default to be the minimum timeout. Note that for $PROG = DIST_MAX$, TO_CBF_GUC becomes TO_CBF_MIN . For the (theoretical) $PROG = 0$, TO_CBF_GUC becomes TO_CBF_MAX . The default values for TO_CBF_MIN , TO_CBF_MAX and $DIST_MAX$ are specified in [ETSI TS 102 636-4-1].

- Suppression

Let us now assume that all neighbors of the forwarding node have set their contention timer according to their respective distances to the destination. After the first of those timers expires, a suppression algorithm aims to cancel the timers in all other nodes to prevent multiple next hops and thereby packet duplication.

The most basic conceivable suppression mechanism, which is also specified in [ETSI TS 102 636-4-1] and implemented in this assignment, works as follows: Upon expiration of the timer, the GeoAdhoc router assumes that it is the next hop, then fetch the GeoUnicast packet from the CBF packet buffer and re-broadcasts the packet if the location table is not empty, shown as [Flow 2] in Figure 7. When another GeoAdhoc router receives this broadcast and still has a timer running for the packet, the router will inspect its CBF packet buffer, stops the timer and removes the GeoUnicast packet from the CBF packet buffer, shown as the right branch of [Flow 1] in Figure 7.

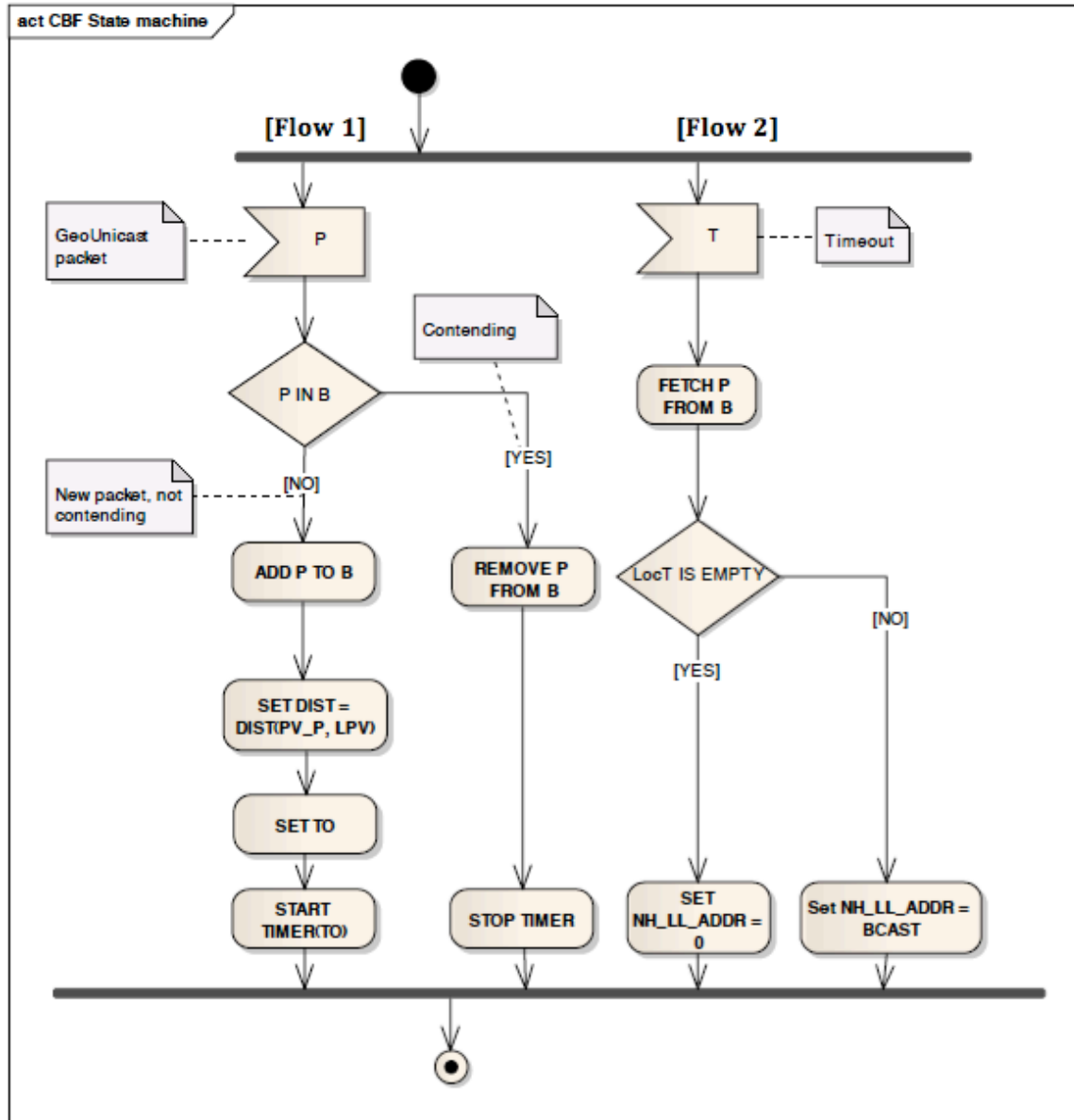


Figure 7 CBF activity diagram, copied from [ETSI TS 102 636-4-1]

Figure 8 is shown as an example to explain how the contention based forwarding algorithm works in VANET. In the example of Figure 8, assume that the source wants to send a warning datagram or other kind of datagram to the destination shown in the figure. The position vector of the destination vehicle is known by the source by the location service, and the contention based forwarding algorithm is applied. However, the destination vehicle is not located in the theoretical maximum communication range of the source vehicle. The datagram need to be forwarded by several intermediate vehicles. Since only vehicle A and vehicle B in this example are located inside the communication range of the source vehicle, the source broadcasts the datagram to vehicle A and vehicle B. Then vehicle A and vehicle B buffer this datagram and set a timeout based on the above Equation 1. According to the geographical information of the two vehicles and the destination, we can see that the forwarding progress towards the destination provided by vehicle B is larger than that provided by vehicle A. Thus vehicle B has a less timeout, and re-broadcasts the datagram first. This is the suppression step in the contention based forwarding

algorithm. When vehicle A receives the duplicate datagram, it cancels its own timeout and removes the datagram from its buffer. In this way, vehicle B in this example is selected as the next hop to relay the datagram in the contention based forwarding algorithm, and the datagram is forwarded closer to the destination.

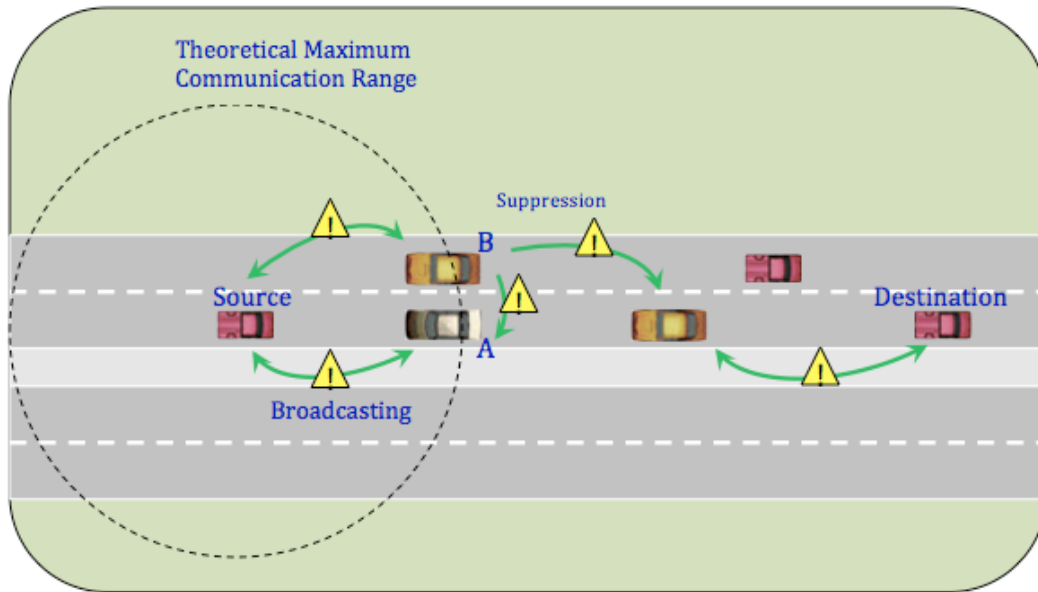


Figure 8 An example of contention based forwarding algorithm in VANET

Compared to the GF algorithm, CBF has an implicit reliability mechanism at the cost of larger forwarding delay and additional processing. The reliability mechanism ensures that a packets is re-forwarded by an alternative forwarder if the theoretically optimal forwarder does not receive the packet, e.g. due to wireless link errors.

4. Tall Vehicle-Aware Position Based Routing Techniques

From the position based routing techniques described in the previous chapter, we can see that there are a number of considerations being involved in selecting the next hop optimally. In spite of finding a shortest way to reach the destination, the transmission power consumed during routing, the protocol overhead, the packet delivery delay and thus the number of intermediate relay hops should also be taken into account. Obviously, the overhead caused by control messages and data packets and sequentially the power consumed due to these overheads become much larger, when there are more intermediate relay hops between the source and the destination, see e.g. [MuSi05].

For a single hop consideration, it has been concluded in [QiWo12] that if distinguishing Tall and Short vehicles in the network, for different network topologies the communication links that are using Tall vehicles as transmitter and/or receiver perform consistently and significantly better than the communication links that use Short vehicles, from the point of average LOS probability, received power level and packet success rate. Furthermore, it has been shown that Tall vehicles are significantly better relay candidates than Short vehicles, since Tall vehicles could provide larger communication range than Short vehicles. Motivated by these findings, we intend to extend the benefits of Tall vehicles performed in single hop path into the position based routing techniques to improve the system level performance. Therefore, this assignment concentrates on how the number of intermediate relay hops between the source and the destination could be decreased by utilizing the information of Tall vehicles. The methods proposed in Sections 4.1 and 4.2 are enhancing the greedy forwarding and the contention based forwarding algorithms, respectively, introduced in Sections 3.3.1 and 3.3.2 respectively.

4.1 Tall vehicle-aware greedy forwarding

In order to utilize the information of vehicle heights, we distinguish two types of vehicles: Tall and Short, in the modified greedy forwarding with applied "Tall Vehicle-Aware" method. The pseudo-code of the Tall vehicle-aware greedy forwarding is shown in Figure 9, and the following steps explain how it works:

- Firstly, the current GeoAdhoc router that have a GeoUnicast packet needs to be forwarded looks over all the entries in its location table (LocT) and finds the closest neighboring Tall and closest neighboring Short vehicle to the destination. The distances from this Tall and this Short vehicle to the destination are expressed as MFR_T and MFR_S , respectively, in the pseudo-code.
- Next, we compare MFR_T and MFR_S obtained in the first step. The difference between them is defined as $DIST_diff$, which equals to $(MFR_T - MFR_S)$.
- Finally, a distance threshold $D_threshold$ is defined as the key parameter in this algorithm, which is the difference between a Tall vehicle's theoretical maximum communication range and a Short vehicle's theoretical maximum communication range. If the $DIST_diff$ calculated in step two is larger than the distance threshold, then select the Short vehicle as next hop; Else, select the Tall vehicle as next hop.

```

-- P is the GeoUnicast packet to be forwarded
-- i is the i-th LocTE
-- NH is the LocTE identified as next hop
-- NH_T is the LocTE identified as the Tall vehicle closest to destination
-- NH_S is the LocTE identified as the Short vehicle closest to destination
-- NH_LL_ADDR is the link layer address of the next hop
-- NH_T_LL_ADDR is the link layer address of the Tall vehicle closest to destination
-- NH_S_LL_ADDR is the link layer address of the Short vehicle closest to destination
-- LPV is the local position vector
-- PVp is the destination position vector in the GeoNetworking packet to be forwarded
-- PVi is the position vector of the i-th LocTE
-- D_Threshold is the difference between the theoretical maximum transmission ranges
of a Tall vehicle and a Short vehicle

MFR_T = MFR_S = DIST(PVp, LPV)
FOR (i ∈ LocT)
    IF (i.IS_NEIGHBOUR) THEN
        IF (i.IS_TALL) THEN
            IF (DIST(PVp, PVi) < MFR_T) THEN
                NH_T ← i
                MFR_T ← DIST(PVp, PVi)
            ENDIF
        ELSEIF
            IF (DIST(PVp, PVi) < MFR_S) THEN
                NH_S ← i
                MFR_S ← DIST(PVp, PVi)
            ENDIF
        ENDIF
    ENDIF
ENDFOR

IF (MFR_S < MFR_T) THEN
    IF (MFR_T - MFR_S < D_Threshold && MFR_T < DIST(PVp, PVLPV)) THEN
        SET NH_LL_ADDR = NH_T_LL_ADDR
    ELSEIF
        SET NH_LL_ADDR = NH_S_LL_ADDR
    ENDIF
ELSEIF
    IF (MFR_T < DIST(PVp, PVLPV)) THEN
        SET NH_LL_ADDR = NH_T_LL_ADDR
    ELSEIF
        LOCAL OPTIMUM
        SET NH_LL_ADDR = 0
    ENDIF
ENDIF
ENDIF

```

Figure 9 Pseudo-code of Tall vehicle-aware greedy forwarding algorithm

In order to compare this enhanced algorithm with the original greedy forwarding for realistic cases in a better way, we use Figure 10(1) as an example. In Figure 10(1), D refers to destination, T refers to the Tall vehicle closest to the destination with the distance MFR_T and S refers to the Short vehicle closest to the destination with the distance MFR_S. D_{diff} is the difference between MFR_T and MFR_S. In the original greedy forwarding algorithm, the source will select node S as the next relay hop as node S is the node closest to the destination. However, in the Tall vehicle-aware greedy forwarding algorithm, the source finds node T (closest Tall vehicle to destination) and node S (closest Short vehicle to destination) respectively, and the choice of next hop decision changes when $0 < D_{diff} < D_{threshold}$. In the cases when $0 < D_{diff} < D_{threshold}$ then the node T is selected as next hop to relay the GeoUnicast packet.

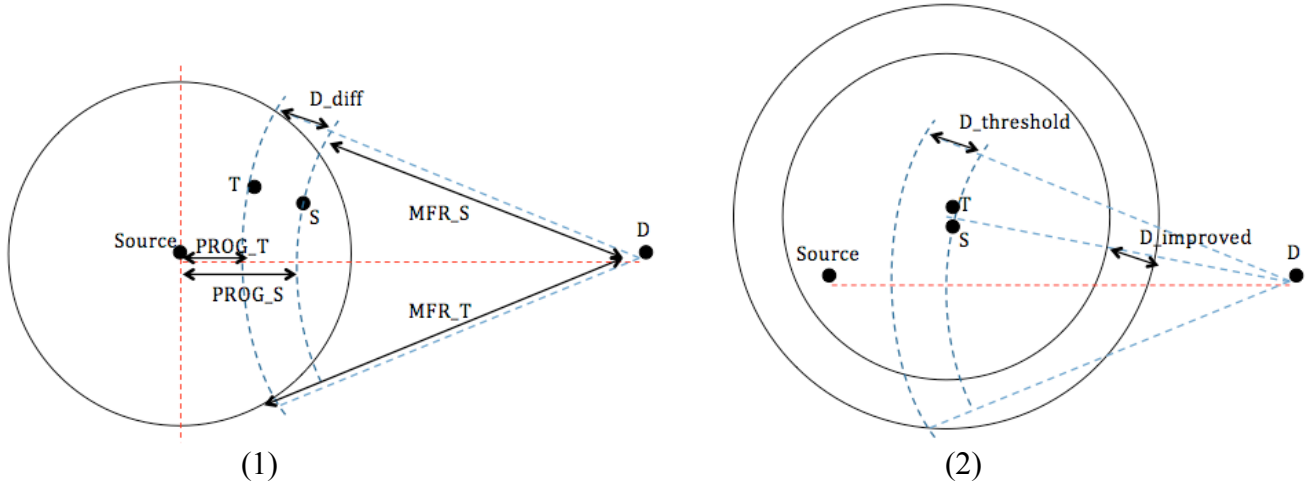


Figure 10 Examples for position based routing techniques: (1) Tall vehicle-aware greedy forwarding (2) Tall vehicle-aware contention based forwarding

4.2 Tall vehicle-aware contention based forwarding

Considering that the contention based forwarding uses timeout to measure the next hop to relay packet, we can use a different value of timeout for taller vehicles, thus exploit the advantage of Tall vehicles. The way to apply the Tall vehicle-aware algorithm is that Tall vehicles will have less waiting time (timeout) to re-broadcast packets.

Now in the Tall vehicle-aware contention based forwarding, for cases that the GeoUnicast packets are received inside the theoretical maximum communication range, we can distinguish Tall and Short vehicles. A Tall vehicle has larger theoretical maximum communication range than a Short vehicle, defining this difference as $D_threshold$. In a theoretical study, when comparing a Tall vehicle and a Short vehicle inside the communication range of the sender, we take into account the forwarding progress of the vehicle itself towards the destination, i.e. the difference between the sender's distance and GeoAdhoc router's local distance from the destination, which are shown as $PROG_T$ and $PROG_S$ in Figure 10(2). A critical position is defined when the result of the Short vehicle's forwarding progress subtracting the Tall vehicle's forwarding progress ($PROG_S - PROG_T$) equals to the distance threshold $D_threshold$. At this position, the waiting times for the Tall and the Short vehicles should be the same. Thus for a Tall vehicle located at the same place as a Short vehicle, the waiting time for the Tall vehicle should be smaller. This optimal case is shown in Figure 10(2), where T and S in the figure are the Tall and the Short vehicle respectively, while D is the destination. By defining a less waiting time for the Tall vehicle, the Tall vehicle will re-broadcast the GeoUnicast packet earlier, thus an improved forwarding distance can be obtained. Note that in the optimal case, the improved forwarding distance equals to the distance threshold $D_threshold$. The difference of the waiting time between a Tall vehicle and a Short vehicle is related to the difference of the Tall vehicle's forwarding progress and the Short vehicle's forwarding progress, which is expressed as TO_sub and is defined in Equation 2.

$$TO_sub = \frac{TO_CBF_MAX - TO_CBF_MIN}{DIST_MAX} * D_threshold$$

[Equation 2]

where:

- TO_CBF_MIN : is the minimum duration the packet shall be buffered in the CBF packet buffer.

- TO_CBF_MAX: is the maximum duration the packet shall be buffered in the CBF packet buffer.
- DIST_MAX: is the theoretical maximum communication range of the wireless access technology.
- D_threshold: is the difference between a Tall vehicle's theoretical maximum transmission range and a Short vehicle's theoretical maximum transmission range.

Therefore, in the Tall vehicle-aware contention based forwarding algorithm, when the nodes outside the theoretical maximum communication range of the sender receive GeoUnicast packets by accident, the timeout value is considered to be the minimum timeout value. For the GeoAdhoc routers inside the communication range, the waiting time for a Short vehicle is the same as the one in original algorithm. But for a Tall vehicle, the waiting time is changed. The formula used for Tall vehicles' timeout, TO_CBF_GUC_T, is defined in Equation 3:

$$TO_CBF_GUC_T = \begin{cases} TO_CBF_MAX - \frac{TO_CBF_MAX - TO_CBF_MIN}{DIST_MAX} \cdot (PROG + D_threshold) & \text{for } PROG \leq DIST_MAX \\ TO_CBF_MIN & \text{for } PROG > DIST_MAX \end{cases}$$

[Equation 3]

where:

- TO_CBF_MIN: is the minimum duration the packet shall be buffered in the CBF packet buffer.
- TO_CBF_MAX: is the maximum duration the packet shall be buffered in the CBF packet buffer.
- PROG: is the forwarding progress of the local GeoAdhoc router towards the destination, i.e. the difference between the sender's distance and GeoAdhoc router's local distance from the destination.
- DIST_MAX: is the theoretical maximum communication range of the wireless access technology.
- D_threshold: is the difference between a Tall vehicle's theoretical maximum transmission range and a Short vehicle's theoretical maximum transmission range.

5. Performance Evaluation

In this chapter, the simulation environment used in this assignment is introduced firstly in section 5.1. Next, the network topology implemented in the simulation for the experiments is described in section 5.2. Then, the performance metrics are presented in section 5.3. After that, experiments scenarios are described in section 5.4. In section 5.5, the performance evaluations of the Tall vehicle-aware position based routing techniques are discussed. A conclusion about the simulation results is presented in section 5.6.

5.1 Simulation Environment

For the simulations accomplished in this research work the OMNeT++ network simulator v4.1 [Omnetpp] combined with the MiXiM framework v2.1 [MiXiM] is used. To model the behavior of the IEEE 802.11p protocol as accurately as possible we have altered the IEEE 802.11 medium access module in such a way that all parameters follow the IEEE 802.11p specification [IEEE802.11p-2010].

5.1.1 OMNeT++

OMNeT++ (Objective Modular Network Tested in C++) is an extensible and modular component-based C++ simulation library and framework that is running on different operating systems such as Linux, Mac OS X, Unix-like systems and Windows. Primarily, OMNET++ is developed for building network simulators. The simulator can be used for traffic modeling of telecommunication networks, protocol modeling, queuing networks modeling, multiprocessors and other distributed hardware systems modeling, hardware architectures validating, evaluating performance aspects of complex software systems and modeling any other systems where the discrete event approaches are suitable [Omnetpp].

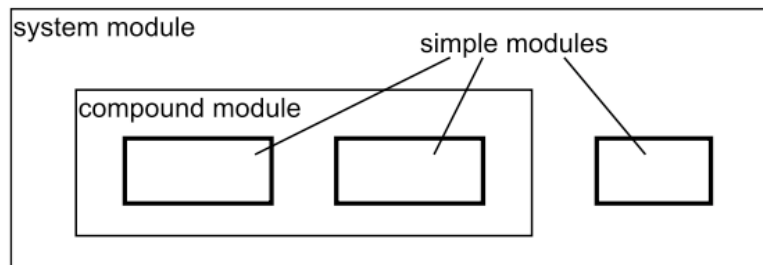


Figure 11 Component-architecture for models in OMNeT++ [Omnetpp_manual]

OMNeT++ provides a component-architecture for models. These components programmed in C++ are nested hierarchically and simpler components can assemble to compound components and models using a high-level language—NED (Network Description), see Figure 11. NED lets the user declare simple modules, and connect and assemble them into compound modules. The user can label some compound modules as networks. These compound models are self-contained simulation models. Communication channels can be defined as another component type, whose instances can also be used in compound modules. The NED language has several features which let it scale well. Therefore, it can be used to model large communication topologies [Omnetpp_manual]. These features are:

- Hierarchical: The traditional way to deal with complexity is by introducing hierarchies. Any module which would be too complex as a single entity can be broken down into smaller modules, and used as a compound module.

- **Component-Based:** Simple modules and compound modules are inherently reusable, which not only reduces code copying, but more importantly, allows component libraries (like MiXiM) to be reused.
- **Interfaces:** Module and channel interfaces can be used as a placeholder where normally a module or channel type would be used, and the concrete module or channel type is determined at network setup time by a parameter.
- **Inheritance:** Modules and channels can be subclassed.
- **Packages:** The NED language features a Java-like package structure, to reduce the risk of name clashes between different models.
- **Inner types:** Channel types and module types used locally by a compound module can be defined within the compound module, in order to reduce namespace pollution.
- **Metadata annotations:** It is possible to annotate module or channel types, parameters, gates and submodules by adding properties.

Reusability of models makes building certain models flexible. Also, the depth of module nesting is not limited, which allows the user to reflect the logical structure of the actual system in the model structure. In particular modules:

- can communicate with message passing. Messages can contain arbitrarily complex data structures.
- can send messages either directly to their destination or along a predefined path, through gates and connections.
- can have parameters which are used for three main purposes: to customize module behaviour; to create flexible model topologies (where parameters can specify the number of modules, connection structure etc); and for module communication, as shared variables.
- at the lowest level of the module hierarchy are to be provided by the user, and they contain the algorithms in the model.

During simulation execution, simple modules appear to run in parallel, since they are implemented as co-routines (sometimes termed lightweight processes). To write simple modules, the user does not need to learn a new programming language, but he/she is assumed to have some knowledge of C++ programming.

Therefore, an OMNeT++ model is combined by simple modules by using the NED language while the simple modules themselves are programmed in C++. The simulation system provides two components: simulation kernel containing the code that manages the simulation and the simulation class library; user interfaces. Graphical, animating user interfaces are highly useful for demonstration, while command-line user interfaces are best for batch execution.

Thus, the way of how OMNeT++ is used is as follows. First, the NED files are compiled into C++ source code, using the NEDC compiler which is part of OMNeT++. Then all C++ sources are compiled and linked with the simulation kernel and a user interface to form a simulation executable.

5.1.2 MiXiM

MiXiM (a MiXed siMulator) is an OMNeT++ modelling framework created for mobile and fixed wireless networks, such as wireless sensor networks, body area networks, ad-hoc networks, vehicular networks, etc. [MiXiM]. MiXiM provides detailed models and protocols, as well as a supporting infrastructure. These can be divided into five groups [KöSw08]:

- Environment models: in a simulation, only relevant parts of the real world should be reflected, such as obstacles that hinder wireless communication.
- Connectivity and mobility: when nodes move, their influence on other nodes in the network varies. The simulator has to track these changes and provide an adequate graphical representation.
- Reception and collision: For wireless simulations, movements of objects and nodes have an influence on the reception of a message. The reception handling is responsible for modeling how a transmitted signal changes on its way to the receivers, taking transmissions of other senders into account.
- Experiment support: the experimentation support is necessary to help the researcher to compare the results with an ideal state, help him to find a suitable template for his implementation and support different evaluation methods.
- Protocol library: last but not least, a rich protocol library enables researchers to compare their ideas with already implemented ones.

The base framework of MiXiM provides the general functionality needed for almost any wireless modeling. And since every module in OMNeT++ can be replaced, we can easily implement another module using different protocol.

To model the behavior of the IEEE 802.11p protocol as accurately as possible we have altered the IEEE 802.11 medium access module in such a way that all parameters follow the IEEE 802.11p specification [IEEE802.11p-2010]. In particular, the used carrier frequency is set to 5.9 GHz. The header length in each layer becomes different from the Mac80211 example used in [MiXiM].

5.2 Simulation Topology

Since we are going to extend the benefits of Tall vehicles found in the previous work [QiWo12], the simulation topology used in [QiWo12] is applied into this assignment, of which the parameters are based on a real highway presented in [BoVi11]. It is a north-south motorway Portuguese highway A28 with length of 12.5km. Due to the fact that the aerial photography of the Portuguese highway A28 in [BoVi11] limits the analysis to only a predefined vehicle density with a certain percentage of Tall vehicles, we decided to realize the road topology in simulation environment OMNET++ where a variety of scenarios can be evaluated.

The topology used in the performed simulations is a 4-lane road, see Figure 12. Note that a bold black line in Figure 12 represents the center of a lane. The length of this road is 5 Km. The inter-lane distance is defined according to Trans-European North-South Motorway (TEM) Standards [TEM]. The used values are shown in Figure 12.

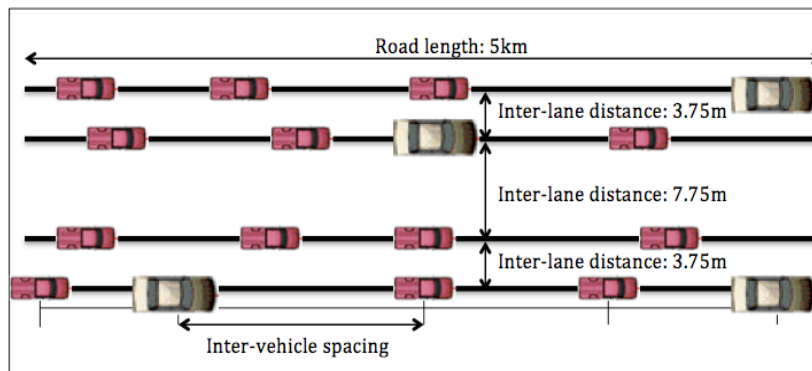


Figure 12 Simulation topology

The vehicles are placed on the road based on:

- *number of vehicles on the road*: depends on the vehicle density
- *inter-vehicle spacing*: the distance between two adjacent vehicles moving on the same lane, see Figure 12. It is defined using an exponential distribution, see [BoVi11]
- *type of vehicles*: two types of vehicles are distinguished, Tall, and Short vehicles, see [BoVi11]
- *dimensions of vehicles*: this represents the length, width and height of both Tall and Short vehicles, see Table 3. These dimensions are random variables, but their values are set before placing the vehicles on the road.

The vehicles are carrying transmitter/receiver antennas on their roofs, see [BoVi11]. In particular, each Small vehicle is carrying one antenna that is located on top of the vehicle and in the middle of the roof. Each Large vehicle is carrying two antennas on the roof, one in the front and another in the back of the vehicle, see [BoMe11]. The height of each antenna is set to 10 cm and the antenna gain is set to 3dBi.

Table 3 Dimension of vehicles

Type	Parameters	Estimate
Small	Width	Mean: 175cm; Std. deviation: 8.3cm
	Height	Mean: 150cm; Std. deviation: 8.4cm
	Length	Mean: 500cm; Std. deviation: 100cm
Large	Width	Mean: 250cm
	Height	Mean: 335cm; Std. deviation: 8.4cm
	Length	Mean: 1300cm; Std. deviation: 350cm

After the vehicles are placed on the road, simulation experiments are run in the following way. During one simulation run, one GeoAdhoc vehicle is performed as the destination permanently, and all the other vehicles placed on the road will be transmitting GeoUnicast packets in a sequential order at different (1 second) time intervals. This means that during a time interval of 1 second only one vehicle acting as the source starts to transmit one GeoUnicast packet, while other vehicle will successfully receive it only if the power of the received signal is higher than a minimum sensitivity threshold. The power of the received signal is measured at each receiving vehicle at the physical layer module incorporated in the OMNET++/MiXiM framework.

As indicated that this assignment is an extension research to [BoVi11] and [QiWo12], and deciding whether a vehicle receives a GeoUnicast packet correctly or not is based on the power of the received signal, the same propagation model as in [BoVi11] and [QiWo12] is applied. According to [BoVi11] and [QiWo12], three main types of model are discussed, including non-geometrical stochastic models, geometry-based deterministic models, and geometry-based stochastic models. The non-geometrical stochastic models are based on an extensive series of measurements. And then for a certain environment, it obtains the predications of signal transmission based on a series of results, which are linked to the environment and the parameters of the measurement. These models reduce computational cost significantly, but not realistic and not accurate. The geometry- based deterministic models are based on sufficient environment information and road traffic. All components (direct component, reflection, diffraction, etc.) affecting the electromagnetic field arriving at receiver are considered in these models. These models are highly realistic and accurate, but achieved at the expense of high computational complexity and location-specific modeling. The geometry-based stochastic models are the combination of deterministic models and statistics of various parameters (environment information). Sufficient

environment information and road traffic are given, but the vehicles positions as well as other objects are distributed randomly. Then various measurements are analyzed.

Since any channel model is a compromise between simplicity and accuracy, Boban et al. in [BoVi11] constructs a propagation model that is simple enough to be tractable from an implementation point of view, yet still able to emulate the essential V2V channel characteristics. The propagation model, proposed by Boban et al. in [BoVi11] and also implement in [QiWo12] and this assignment, is a simplified geometry-based deterministic propagation model, in which the free space path loss and the effect of vehicles as obstacles on signal/wave propagation are isolated and quantified. The effect of other static obstacles (i.e., buildings, overpasses, etc.) and other propagation effects (i.e. reflection, delay dispersion, etc.) are not taken into account since their work mainly focused on and intended to analyze how much side-effects the vehicles as obstacles could cause on the signal strength. Based on the facts, i.e., realistic features, reduced computation, and concentration on mobile obstacles, the propagation model implemented in [BoVi11] and [QiWo12] is also suitable to apply in this assignment. More specifically, for the received power level, the impact of obstacles can be represented by signal attenuation. The attenuation on a radio link increases if one or more vehicles intersect the Fresnel ellipsoid corresponding to 60% of the radius of the first Fresnel zone, independent of their positions on the transmitter-receiver (Tx-Rx) link. This increase in attenuation is due to the diffraction of the electromagnetic waves. To model vehicles obstructing the LOS, we use the knife-edge attenuation model, see [ITU-R07]. When there are no vehicles obstructing the LOS between Tx and Rx, we use the free space path loss model, see e.g., [WirelessComm.96]. If only one obstacle is located between Tx and Rx, then the single knife-edge model described in ITU-R recommendation [ITU-R07] is used. For the case that more than one vehicles (i.e., more than one obstacles) are located between Tx and Rx, the multiple knife-edge model with the cascaded cylinder method, proposed in [ITU-R07], is used.

In the greedy forwarding algorithm, beacons are sent periodically at a certain frequency before GeoUnicast packets start. The current draft standards for cooperative awareness applications specify that each vehicular ITS station broadcasts a basic safety/cooperative awareness message (BSM/CAM, mentioned as beacons in this report) on a 10 MHz safety channel on the order of 10 times per second, see e.g. [EU-US ITS12]. However, this frequency used in the simulation for testing the proposed new algorithm would cause huge number of controls messages and overhead, and would take too much time to finish the experiments. Thus at the beginning, 1 Hz for the beacons exchanging frequency is used, and 10Hz for beacon frequency can be implemented in the further experiments. In order to obtain a stable location table of neighbors for GeoAdhoc routers, the GeoUnicast packets start after 30 beacons/node are sent. The entry of the location table (LocTE) can only last for duration of 2 beacons, meaning that the entry will be deleted after 2 seconds in the simulation. In the contention based forwarding algorithm, no location table needs to be created and no beacons needs to be sent, thus the start time of GeoUnicast packets is not so important. The fixed parameters utilized in the simulation experiments are indicated in the following table 4.

Table 4 Fixed parameters in the simulation

Parameter Name	Values
Length of road	5km, useTorus: false (not round road)
Number of lanes	4 lanes
Type of vehicles	Tall and Short
Speed	Normal distribution mean: 106 km/h, std. deviation: 21.09 km/h
Mobility update	0.1s
Beacon start	0s
Beacon rate	1Hz (1beacon/s)
LocTE timeout	2*beacon rate (2s)
Destination	One vehicle determined to be the destination permanently
Source	Other vehicles act as the source one by one
Packet start	After 30 beacons sent (30*beacon rate, 30s)
Number of packet sent by source	1 packet/source
Transmission power	1996mW (=33dBm)
Sensitivity	-82dBm, 6Mbps

5.3 Experiment Scenarios Description

In addition to the parameters used to emulate the IEEE 802.11p behavior and to determine the simulation topology in section 5.2, additional parameters are used to define different scenarios, which are specified in this section. Since there are Tall and Short vehicles distinguished in the network, in order to study the system level performance benefits of Tall vehicles when varying vehicles density and the mixes of Tall and Short vehicles, the scenarios 1 to 5 are defined, see Table 5. The inter-vehicle spacing mean in Table 5 indicates the mean value of the exponential distribution for the spacing among GeoAdhoc routers in the network. In reality, generally the number of Short vehicles is larger than the number of Tall vehicles. So we never define more than 50% for Tall vehicles. Each vehicle density with five Tall vehicle percentages is defined as one scenario.

Based on the two seconds time headway rule for driving on highway, we calculate the corresponding vehicle density as the reference (100% density in Table 5) for each scenario in the following way. For a certain percentage (x) of Tall vehicles, we can approximate the largest number of vehicles per kilometer on the highway by using highway 2s rule, shown in Equation 4.

$$Density_ref(one_lane) = \frac{1000}{(Dist_2s + vehLen_L) * x + (Dist_2s + vehLen_S) * (1 - x)} (veh / km / lane)$$

[Equation 4]

$$Density_ref(four_lanes) = 4 * Density_ref(one_lane) (veh / km)$$

$$Dist_2s = vehSpeed * 2(m)$$

For the reason that ‘vehicle density’ is hard to measure in the simulation, we vary the mean of the inter-vehicle spacing distribution to achieve the required vehicle densities values. By collecting total number of active vehicles within defined road length 5km, and dividing this number by 5 (km) and 4 (lanes), the vehicle density values in Table 5 are calculated. Note that the vehicle density is indirect proportional to

the inter-vehicle spacing, meaning that when the vehicle spacing is increasing then the vehicle density is decreasing and vice versa.

Table 5 Scenario Parameters

	Inter-vehicle Spacing Mean (Corresponded Vehicle Density)	Tall Vehicle Percentage
Scenario 1	500m (2veh/km/lane)	{10%, 20%, 30%, 40%, 50%}
Scenario 2	250m (4veh/km/lane)	
Scenario 3	125m (8veh/km/lane)	
Scenario 4	75m (13veh/km/lane)	
Scenario 5	50m (20veh/km/lane) (100% vehicle density)	

In the experiments, the scenarios are firstly simulated in static environment, in order to obtain the maximum improvement that could be achieved by Tall vehicles. This set of the simulation results for the optimal situations is regarded as the reference for further mobile experiments. Then the mobile environment is implemented in the simulation. The vehicle mobility is based on the realistic value on the Portuguese highway A28, on which the speed of vehicles can be indicated as a normal distribution with a mean equals to 106 km/h, shown in Table 4.

5.4 Performance Metrics

Two performance metrics are defined, i.e., hop count and end to end delay, in order to investigate (i) the system level performance benefits provided by Tall vehicle when greedy forwarding algorithm is applied and (ii) the system level performance benefits provided by Tall vehicle when contention based forwarding algorithm is applied in VANET routing, when different road topologies are implemented, where various vehicle densities, percentages of Tall vehicles are utilized.

1. Hop Count

The Hop Count is defined as the count of intermediate hops to relay GeoUnicast packets between the source and the destination. In the GeoUnicast packet header a field named HL is defined as the hop limit number, and the default value is set to 10, meaning that the maximum number of hops a packet travels is 10. When a forwarder or a receiver receives the GeoUnicast packet, it decrements the value of the HL field by one. If HL is decremented to zero, the GeoUnicast packet will be discarded. The final value of *the Hop Count* performance measurement equals 10 subtracts the final value of the HL field in the GeoUnicast packet.

2. End-to-End Delay

The End-to-End Delay is defined as the total value of the delays the GeoUnicast packet travels from the source to the destination. This delay is expressed in ms. In the greedy forwarding algorithm, it is calculated as the travelling time of the signal in transmission between GeoAdhoc routers. Thus it is actually dependent on the hop count number. However in contention based forwarding algorithm, besides the travelling time of the transmission signal there is a waiting time before transmitting the GeoUnicast packet. This waiting time depends on the forwarding progress from the local GeoAdhoc router towards the destination (see, section 3.3.2). The total value of the delays is independent with the hop count number.

Note that in order to guarantee a high statistical accuracy of the obtained performance results, multiple runs for the scenarios described in section 5.3 have been performed and confidence intervals have been calculated. After collecting the results for all the simulation runs, a large numbers of samples (the values

of the Hop Count and the End-to-End Delay measurements) at different distances from the source to the destination will be available. Thus the average values of the performance measurements at a certain distance from the source to the destination are calculated and presented. To guarantee the accuracy, double-sided 90% confidence intervals have been calculated. This means that for all performed experiments, the calculated confidence intervals are lower than the $\pm 5\%$ of the shown calculated mean values. The confidence intervals in the form of upper and lower bars around their associated average values are not shown in the following evaluation results, since the lines of the average values in the graphs are too close to each other. However, all the confidence intervals for the obtained evaluation results are presented in Appendix A.

5.5 Evaluation of Tall Vehicle-Aware Greedy Forwarding Algorithm

This section evaluates the system level performance benefits of Tall vehicles when used in the greedy forwarding algorithm, by comparing the performance of the original greedy forwarding and the Tall vehicle-aware greedy forwarding, when various vehicle densities and Tall vehicle percentages are applied in the network. The observed performance measurements are: *Hop Count and End-to-End Delay*.

The simulation environment utilized in the investigation of the system level performance benefits of Tall vehicles consists of STATIC and MOBILE situations. For each performance measurement, the five scenarios described in section 5.3 are simulated in both static and mobile environment, and the results of these scenarios are presented for both static and mobile environment.

5.5.1 Hop Count

In this set of experiments the Hop Count measure is investigated. For both static and mobile scenarios, two types of experiments are performed.

The goal of the first type of experiments is to investigate the Hop Count when the parameters of the realistic road are applied. In particular, the Hop Count versus the distance from the source to the destination is investigated for the case where the vehicle density is 8 veh/km/lane when the inter-vehicle spacing mean is 125m, and the Tall vehicle percentage is 20%. The results in static environment are presented in Figure 13, while the results in mobile environment are shown in Figure 14. The basic GF in the figures refers to the original Greedy Forwarding algorithm, while the TVA GF means the Tall Vehicle-Aware Greedy Forwarding algorithm. This is accomplished for a sub-scenario of Scenario 3, shown in Table 5.

From this type of experiments it can be concluded that for both static and mobile environment when the distance from the source to the destination becomes larger, it takes larger number of intermediate GeoAdhoc routers to forward the GeoUnicast packets. In static environment, for small distances (smaller than 3000m) from the source to the destination, we can hardly see a difference between the results of the original greedy forwarding and the Tall vehicle-aware greedy forwarding. For distances from the source to the destination larger than 3000m, there is a slightly improvement caused by the Tall vehicle-aware greedy forwarding. However, this small difference is not useful in realistic cases. In mobile environment, the largest distance from the source to the destination collected from the simulation is less than 5000m because of the mobility of vehicles in the network. From Figure 14, we can see that there is nearly no difference between the two algorithms. The reason that Tall vehicle-aware greedy forwarding didn't provide much benefits is that there are only two out of ten Tall vehicle in this network, and the probability that the decision of next relay hop changes is quite small. The details of this problem will be discussed in section 5.7.

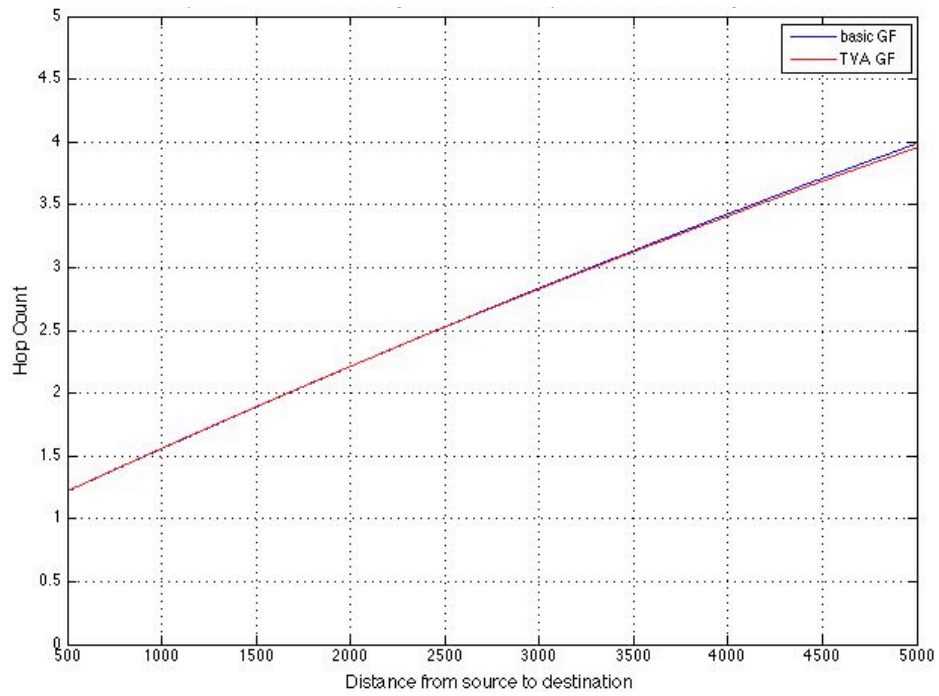


Figure 13 STATIC: Hop count for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

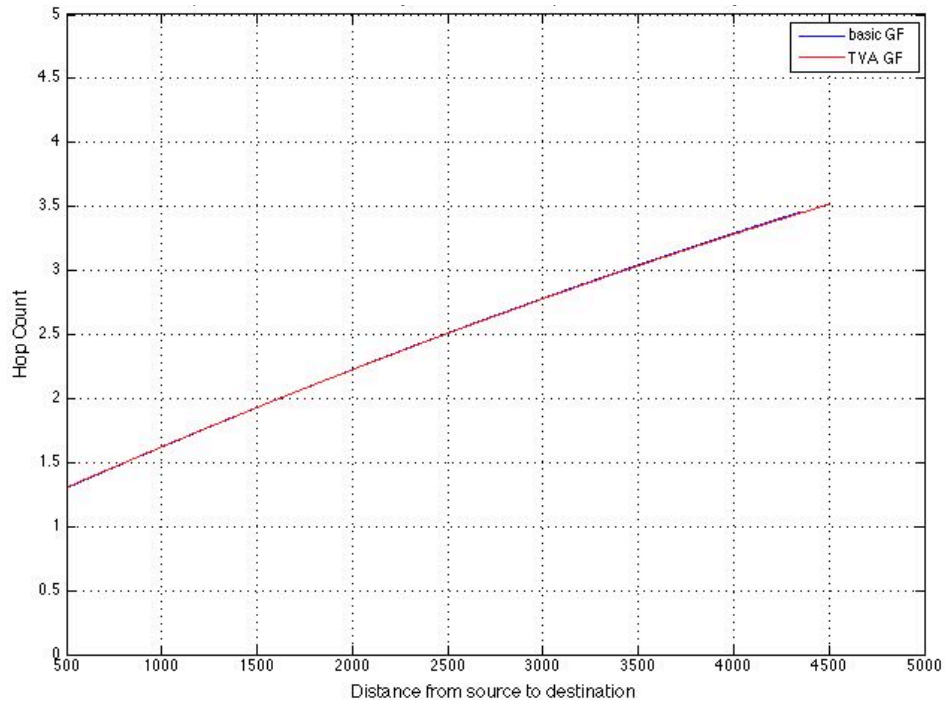


Figure 14 MOBILE: Hop count for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

The goal of the second type of experiments is to investigate the Hop Count when various Tall vehicle percentages and various vehicle densities are applied. In this type of experiments, the Hop Count when the distance from the source to the destination equals to a certain value is investigated for the five vehicle densities with (i) the five Tall vehicle percentages presented in Table 5, (ii) the static

environment results shown in Figure 15 and (iii) the mobile environment results shown in Figure 16. This is accomplished for Scenarios 1, 2, 3, 4, and 5, shown in Table 5. The distance from the source to destination for both static and mobile environment is chosen to be 4000m, since using this distance a slightly difference between the Tall vehicle-aware greedy forwarding algorithm and the basic greedy forwarding algorithm can be seen, and the hop count value obtained for this distance is easier to observe and compare.

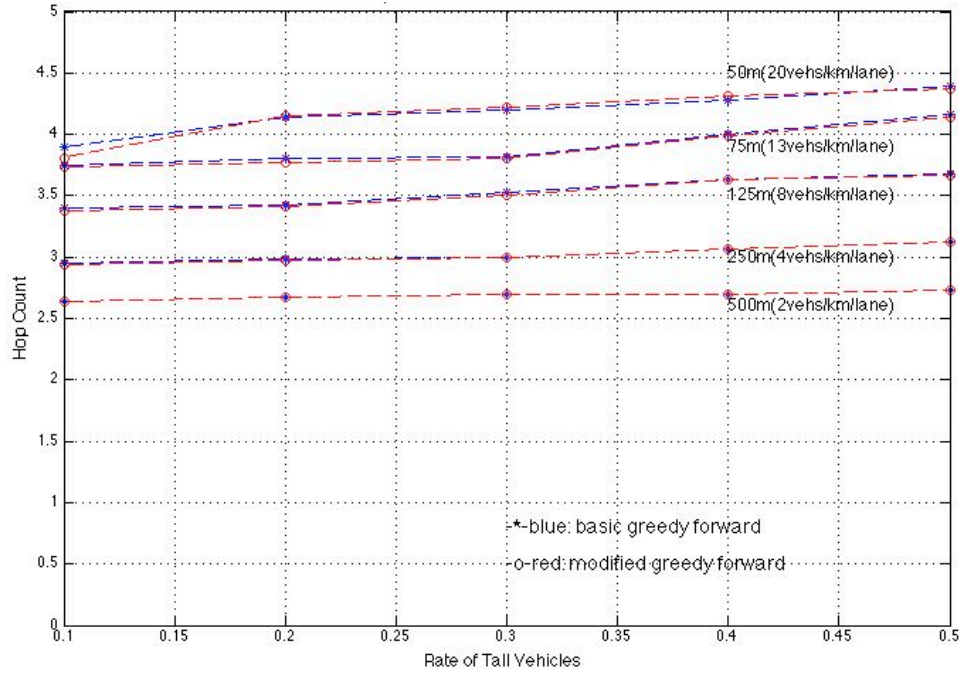


Figure 15 STATIC: Hop count for the five scenarios given in Table 5

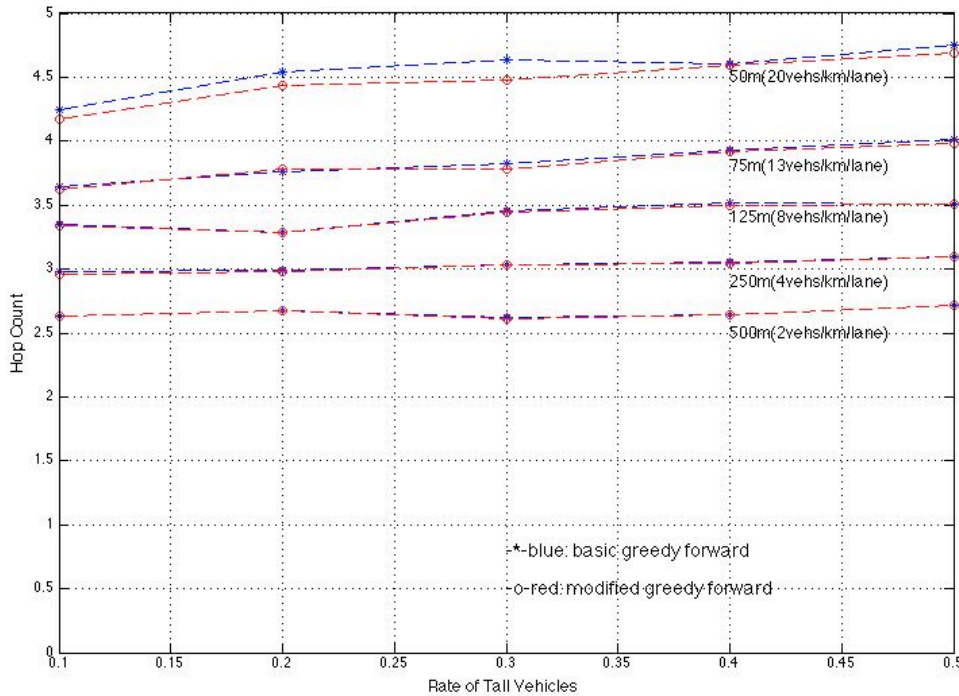


Figure 16 MOBILE: Hop count for the five scenarios given in Table 5

In Figure 15 and Figure 16, a pair of a blue dash lines and a red dash line with five points stands for the hop count results for a certain vehicle density (one scenario in Table 5) with five Tall vehicle percentages at the distance from the source to the destination equal to 4000m. Each point with star or circle on the blue/red dash line refers to the number of intermediate relay hops needed for a certain vehicle density and a certain Tall vehicle percentage, when the distance from the source to the destination is 4000m. From Figure 15 and Figure 16, it can be concluded for both static and mobile environment simulations that:

- 1) all the Hop Count values associated with the Tall vehicle-aware greedy forwarding algorithm are similar as all the Hop Count values associated with the original greedy forwarding algorithm.
- 2) all the Hop Count values associated with both the Tall vehicle-aware greedy forwarding and the original greedy forwarding algorithm are slightly increasing, when the Tall vehicle percentage in the network becomes larger while the vehicle density remains the same. The reason of this observation is that the transmission signal is more likely to be blocked when there are more Tall vehicles, since taller vehicles can obstruct the transmission signal easier. The fact that more Tall vehicles can cause smaller theoretical maximum communication range has been proven in [QiWo12]. In this type of experiments, more Tall vehicles thus smaller communication range needs more relay hops to forward GeoUnicast packets to the destination from the source.
- 3) all the Hop Count values associated with both the Tall vehicle-aware greedy forwarding and the original greedy forwarding algorithm becomes larger, when the vehicle density increases while the Tall vehicle percentage in the network remains the same. The reason of this observation is that the transmission signal is more likely to be blocked when there are larger number of vehicles in the network, since more vehicles can act as obstructions to obstruct the transmission signal. The fact that larger vehicle density can cause smaller theoretical maximum communication range has been proven in [QiWo12]. In this type of experiments, larger vehicle density thus smaller communication range needs more relay hops to forward GeoUnicast packets to the destination from the source.

Note that the results for a different distance from the source to the destination and when various vehicle densities and various Tall vehicle percentages are applied can also be obtained and compared. We predict that the conclusions derived by these new performance experiments will be similar as the ones derived by the experiments described in this section.

5.5.2 End-to-End Delay

In this set of experiments the End-to-End Delay performance measure is investigated. For both static and mobile scenarios, two types of experiments are performed.

The goal of the first type of experiments is to investigate the End-to-End Delay when the parameters of the realistic road are applied. In particular, the End-to-End Delay versus the distance from the source to destination is investigated for the case where (i) the vehicle density is 8 veh/km/lane, (ii) the inter-vehicle spacing mean is 125m, and (iii) the Tall vehicle percentage is 20%. The results associated with the static environment are presented in Figure 17, while the results in mobile environment are shown in Figure 18. The basic GF in the figures refers to the original Greedy Forwarding algorithm, while the TVA GF refer to the Tall Vehicle-Aware Greedy Forwarding algorithm. This is accomplished for a sub-scenario of Scenario 3, shown in Table 5.

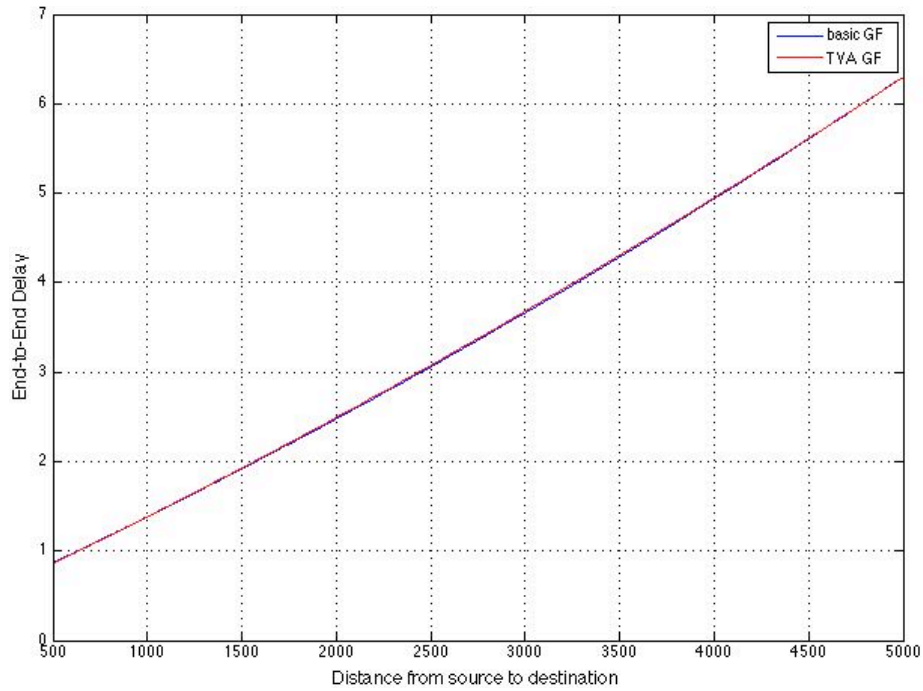


Figure 17 STATIC: End-to-End Delay for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

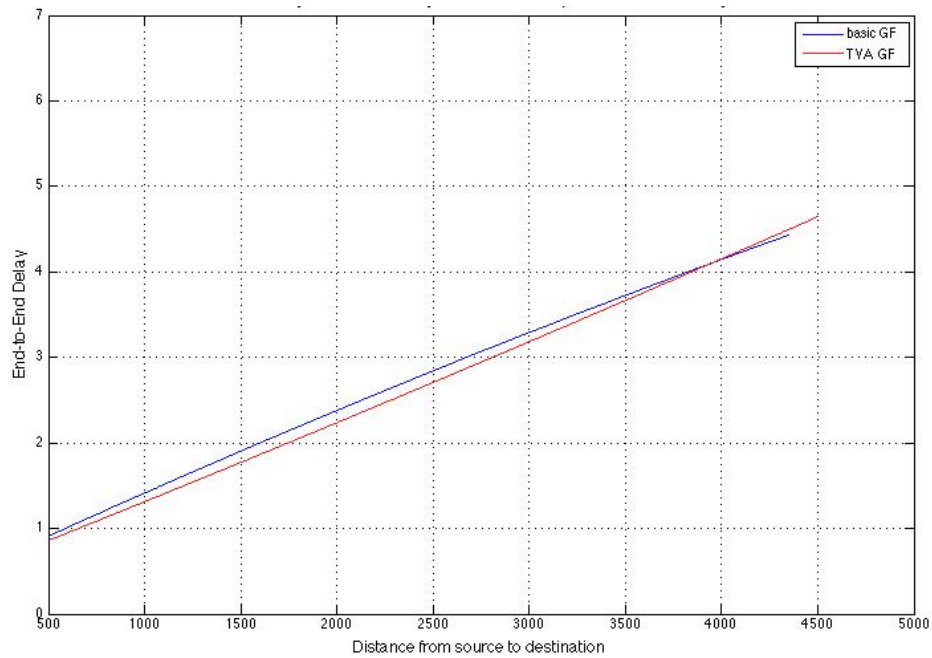


Figure 18 MOBILE: End-to-End Delay for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

From this type of experiments it can be concluded that for both static and mobile environment when the distance from the source to destination becomes larger, it takes larger number of intermediate GeoAdhoc routers to forward the GeoUnicast packets. In the static environment, we can hardly see a difference between the results of the original greedy forwarding and the Tall vehicle-aware greedy forwarding. In the mobile environment, the largest distance from the source to the destination collected from the simulation is less than 5000m because of the mobility of vehicles in the network. From Figure 18, se can

see that there is a difference between the two algorithms, but not useful in practical cases. Besides, the End-to-End Delay values in mobile environment are smaller than those in static environment. The reason could be that the vehicle speed of the source/forwarders is relatively larger than the vehicle speed of the destination sometimes, thus the traveling distance from the source to the destination becomes smaller than the original distance in static environment. This leads to a decrease in the End-to-End Delay results. When comparing the original greedy forwarding algorithm and the Tall vehicle-aware greedy forwarding algorithm in mobile environment, the difference is quite small. The reason that Tall vehicle-aware greedy forwarding is not providing much benefits is that there are only two out of ten Tall vehicle in this network, and the probability that the decision of the next relay hop changes is quite small. The details associated with this issue will be discussed in section 5.7.

The goal of the second type of experiments is to investigate the End-to-End Delay when various Tall vehicle percentages and various vehicle densities are applied. In this type of experiments, the End-to-End Delay when the distance from the source to the destination equals to a certain value is investigated for the five vehicle densities with the five Tall vehicle percentages presented in Table 5, with (i) the static environment results shown in Figure 19 and (ii) the mobile environment results shown in Figure 20. This is accomplished for Scenarios 1, 2, 3, 4, and 5, shown in Table 5. The distance from the source to the destination for both static and mobile environment is chosen to be 4000m, the same as the distance value when investigating the Hop Count measurement.

In Figure 19 and Figure 20, a pair of a blue dash lines and a red dash line with five points stands for the hop count results for a certain vehicle density (one scenario in table 5) with five Tall vehicle percentages at the distance from the source to the destination equaling 4000m. Each point with star or circle on the blue/red dash line refers to the number of intermediate relay hops needed for a certain vehicle density and a certain Tall vehicle percentage, when the distance from the source to the destination is 4000m. From Figure 19 and Figure 20, it can be concluded for both static and mobile environment simulations that:

- 1) all the End-to-End Delay values associated with the Tall vehicle-aware greedy forwarding algorithm are similar as all the End-to-End Delay values associated with the original greedy forwarding algorithm. The difference is not significant in realistic situations.
- 2) all the End-to-End Delay values associated with both the Tall vehicle-aware greedy forwarding and the original greedy forwarding algorithm are increasing, when the Tall vehicle percentage in the network becomes larger while the vehicle density remains the same. The reason of this observation is that the transmission signal is more likely to be blocked when there are more Tall vehicles, since taller vehicles can obstruct the transmission signal easier, thus a different route towards the destination with more delays of the GeoUnicast packet might be chosen.
- 3) all the End-to-End Delay values associated with both the Tall vehicle-aware greedy forwarding and the original greedy forwarding algorithm becomes larger, when the vehicle density increases while the Tall vehicle percentage in the network remains the same. The reason of this observation is that the transmission signal is more likely to be blocked when there are larger number of vehicles in the network, since more vehicles can act as obstructions to obstruct the transmission signal. A fast way to reach the destination becomes more difficult, thus leads to an increase in the End-to-End Delay results.
- 4) the difference between the End-to-End Delay values associated with original greedy forwarding and those values associated with Tall vehicle-aware greedy forwarding becomes larger, when the vehicle density becomes larger while a certain Tall vehicle percentage is applied. The

improvements provided by Tall vehicles in static environment are better than that in mobile environment.

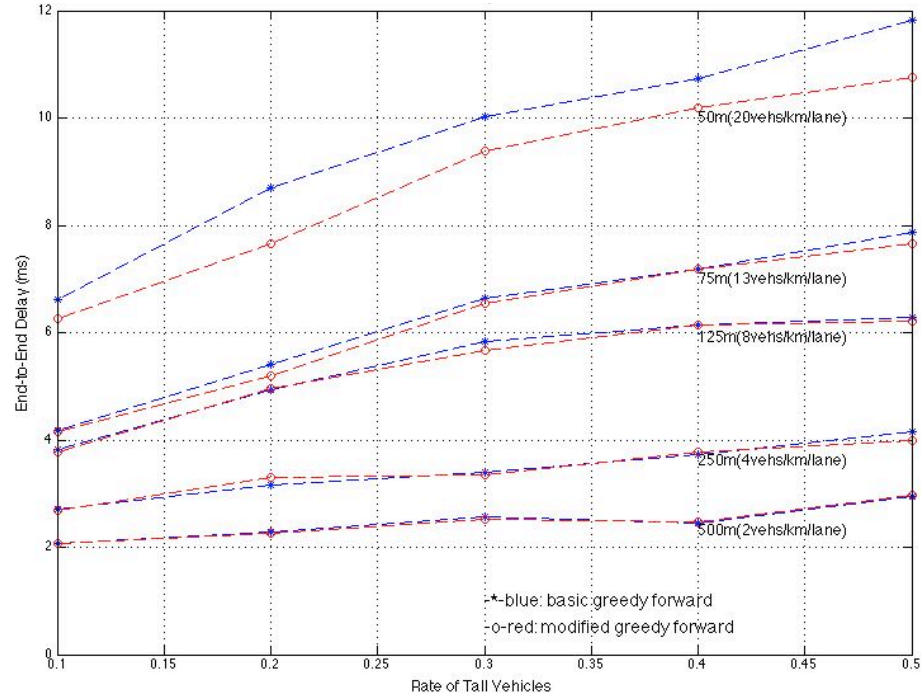


Figure 19 STATIC: End-to-End Delay for the five scenarios given in Table 5

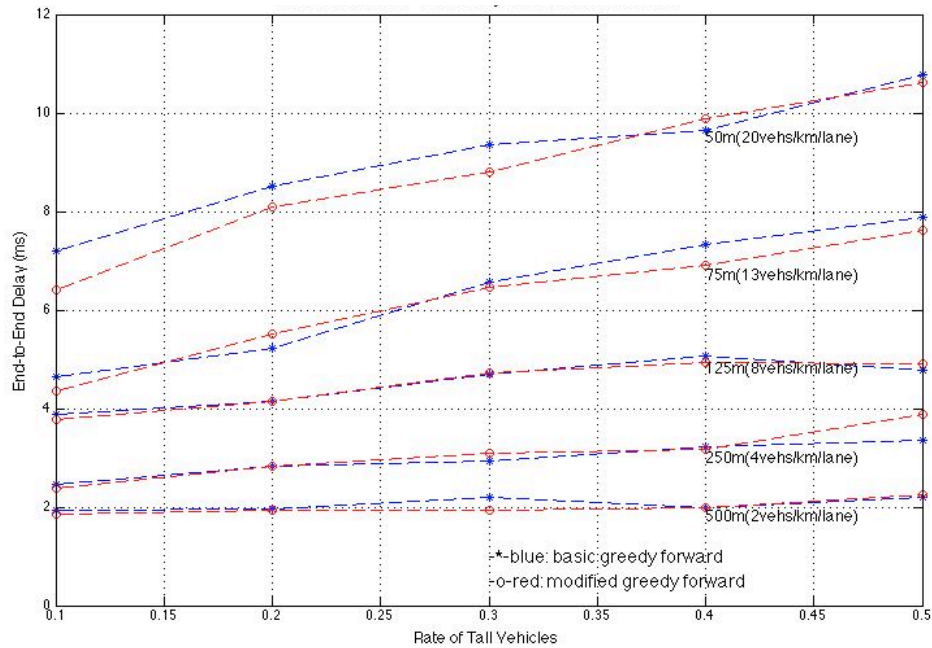


Figure 20 MOBILE: End-to-End Delay for the five scenarios given in Table 5

We can conclude from the above performance results that the Tall vehicle-aware algorithm does not provide much practical enhancement in greedy forwarding, in terms of the Hop Count and the End-to-

End Delay. Single-hop benefits of Tall vehicles as next hops to relay packets do not achieve significant improvements in system level performance.

5.6 Evaluation of Tall Vehicle-Aware Contention Based Forwarding Algorithm

This section evaluates the system level performance benefits of Tall vehicles in contention based forwarding algorithm, by comparing the performance of the original contention based forwarding and the Tall vehicle-aware contention based forwarding, when various vehicle densities and Tall vehicle percentages are applied in the network. The observed performance measurements are: *Hop Count* and *End-to-End Delay*.

The same as the evaluation of greedy forwarding algorithm described in section 5.5, for each performance measurement, the five scenarios described in section 5.3 are simulated in both static and mobile environment, and the results of these scenarios are presented for both static and mobile environment.

5.6.1 Hop Count

In this set of experiments the Hop Count measure is investigated. For both static and mobile scenarios, two types of experiments are performed.

The goal of the first type of experiments is to investigate the Hop Count when the parameters of the realistic road are applied. In particular, the Hop Count versus the distance from the source to the destination is investigated for the case where the vehicle density is 8 veh/km/lane with (i) the inter-vehicle spacing mean is 125m, and (ii) the Tall vehicle percentage is 20%. The results associated with the static environment are presented in Figure 21, while the results in mobile environment are shown in figure 22. The basic CBF in the figures refers to the original Contention Based Forwarding algorithm, while the TVA CBF means the Tall Vehicle-Aware Contention Based Forwarding algorithm. This is accomplished for a sub-scenario of Scenario 3, shown in Table 5.

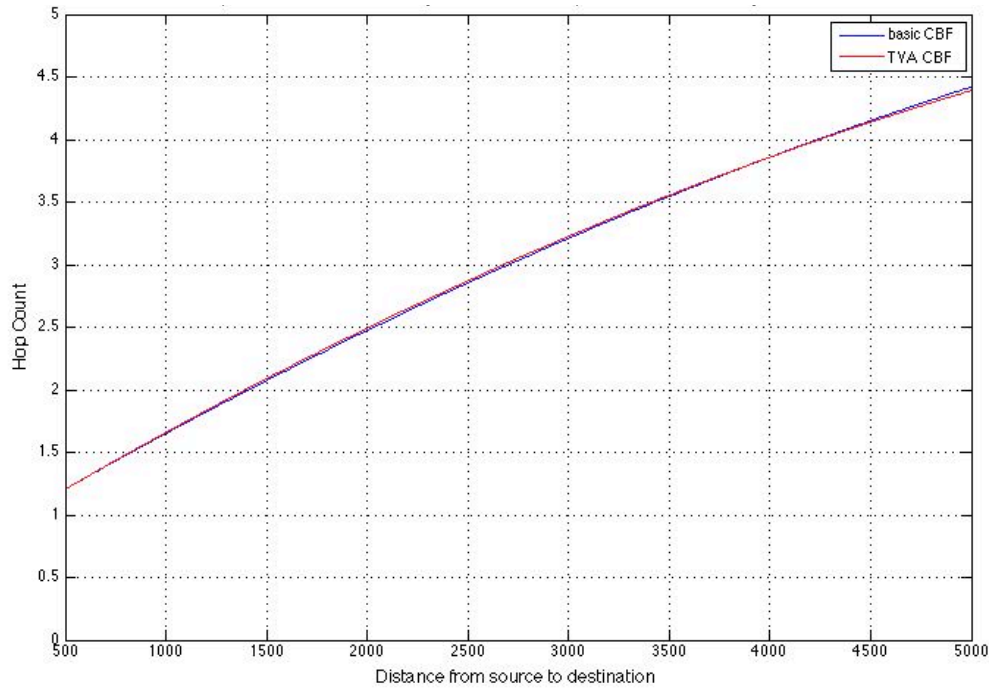


Figure 21 STATIC: Hop count for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

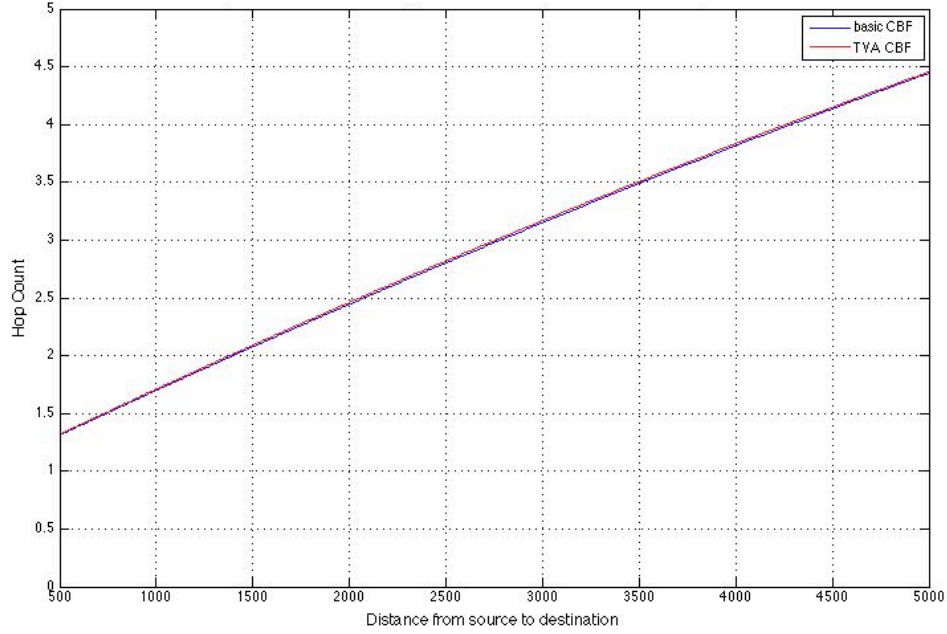


Figure 22 MOBILE: Hop count for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

From this type of experiments it can be concluded that for both static and mobile environment when the distance from the source to the destination becomes larger, it takes larger number of intermediate GeoAdhoc routers to forward the GeoUnicast packets. We can hardly see a difference between the results of the two algorithms in both static and mobile environment.

The goal of the second type of experiments is to investigate the Hop Count when various Tall vehicle percentages and various vehicle densities are applied. In this type of experiments, the Hop Count when the distance from the source to the destination equals to a certain value is investigated for the five vehicle densities with (i) the five Tall vehicle percentages presented in Table 5, (ii) the static environment results shown in Figure 23 and (iii) the mobile environment results shown in Figure 24. This is accomplished for Scenarios 1, 2, 3, 4, and 5, shown in Table 5. The distance from the source to destination for both static and mobile environment is chosen to be 4000m, the same as the distance value when investigating the Hop Count measurement in greedy forwarding algorithm.

In Figure 23 and Figure 24, a pair of a blue dash line and a red dash line with five points stands for the hop count results for a certain vehicle density (one scenario in Table 5) with five Tall vehicle percentages at the distance from the source to the destination equaling 4000m. Each point with star or circle on the blue/red dash line refers to the number of intermediate relay hops needed for a certain vehicle density and a certain Tall vehicle percentage, when the distance from the source to the destination is 4000m. From Figure 23 and Figure 24, it can be concluded for both static and mobile environment simulations that:

- 1) all the Hop Count values associated with the Tall vehicle-aware greedy forwarding algorithm are similar as all the Hop Count values associated with the original greedy forwarding algorithm.
- 2) all the Hop Count values associated with both the Tall vehicle-aware greedy forwarding and the original greedy forwarding algorithm are slightly increasing, when the Tall vehicle percentage in the network becomes larger while the vehicle density remains the same. More Tall vehicles in the network thus smaller communication range needs more relay hops to forward GeoUnicast packets to the destination from the source.

- 3) all the Hop Count values associated with both the Tall vehicle-aware greedy forwarding and the original greedy forwarding algorithm becomes larger, when the vehicle density increases while the Tall vehicle percentage in the network remains the same. Larger vehicle density thus smaller communication range needs more relay hops to forward GeoUnicast packets to the destination from the source.

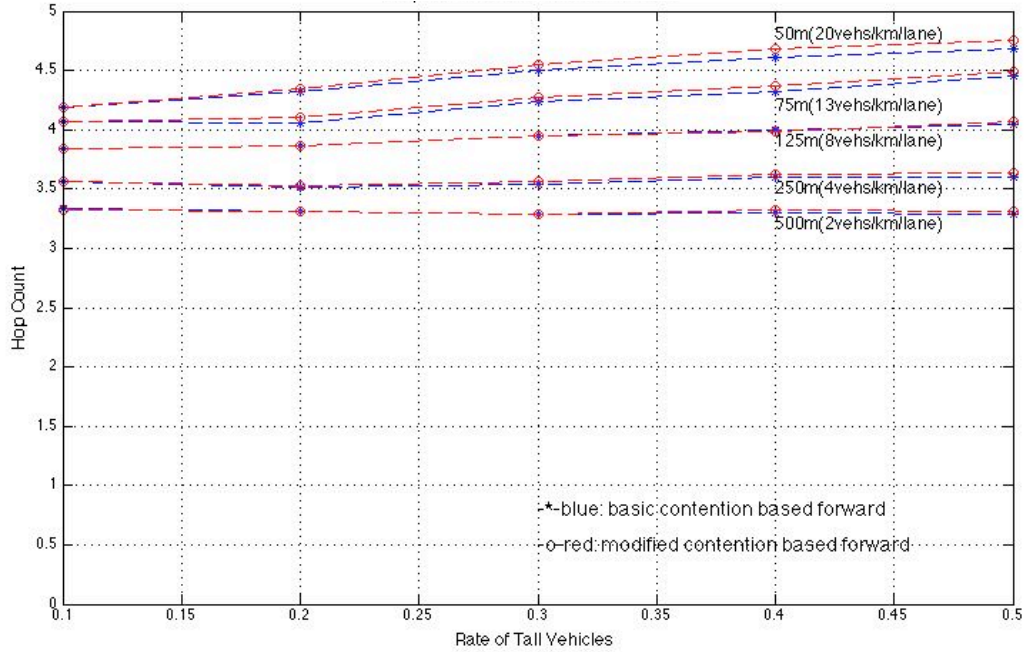


Figure 23 STATIC: Hop count for the five scenarios given in Table 5

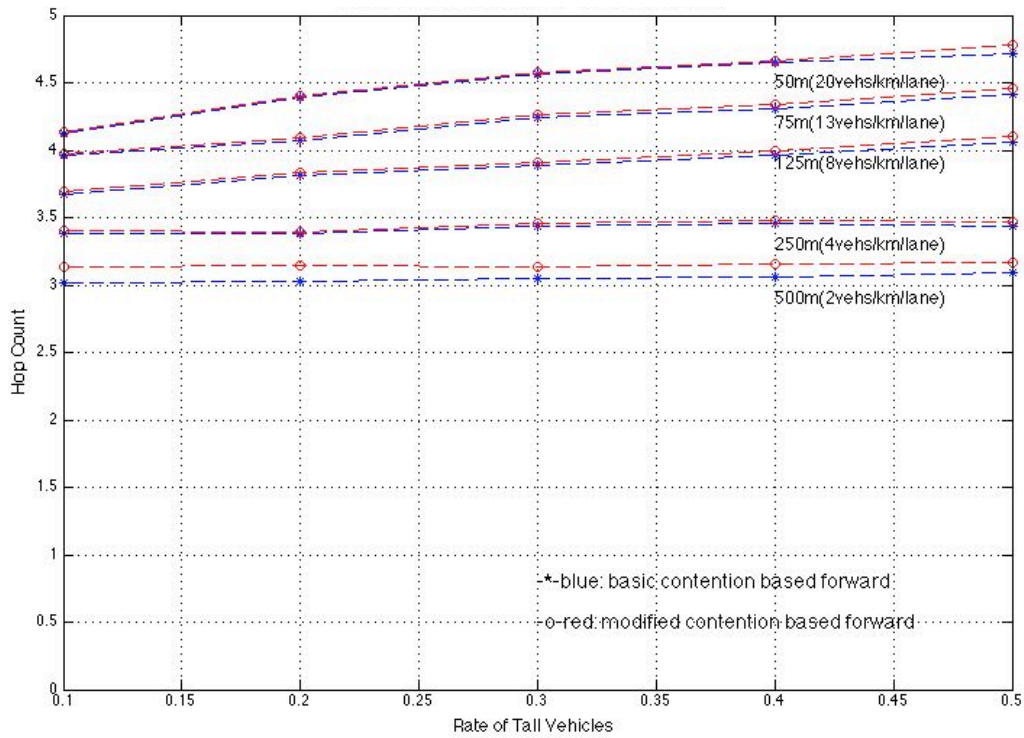


Figure 24 MOBILE: Hop count for the five scenarios given in Table 5

5.6.2 End-to-End Delay

In this set of experiments the End-to-End Delay measure is investigated. For both static and mobile scenarios, two types of experiments are performed.

The goal of the first type of experiments is to investigate the End-to-End Delay when the parameters of the realistic road are applied. In particular, the End-to-End Delay versus the distance from the source to the destination is investigated for the case where the vehicle density is 8 veh/km/lane with (i) the inter-vehicle spacing mean is 125m, and (ii) the Tall vehicle percentage is 20%. The results in static environment are presented in Figure 25, while the results in mobile environment are shown in Figure 26. The basic CBF in the figures refers to the original Contention Based Forwarding algorithm, while the TVA CBF refers to the Tall Vehicle-Aware Contention Based Forwarding algorithm. This is accomplished for a sub-scenario of Scenario 3, shown in Table 5.

From this type of experiments it can be concluded that for both static and mobile environment when the distance from the source to the destination becomes larger, it takes larger number of intermediate GeoAdhoc routers to forward the GeoUnicast packets. In static environment, we can see an obvious difference between the results of the original contention based forwarding and the results of the Tall vehicle-aware contention based forwarding. Compared with the results associated with the static environment, the End-to-End Delay values become larger at the same distance from the source to the destination in mobile environment, and also the difference between the results of the two algorithms becomes quite small.

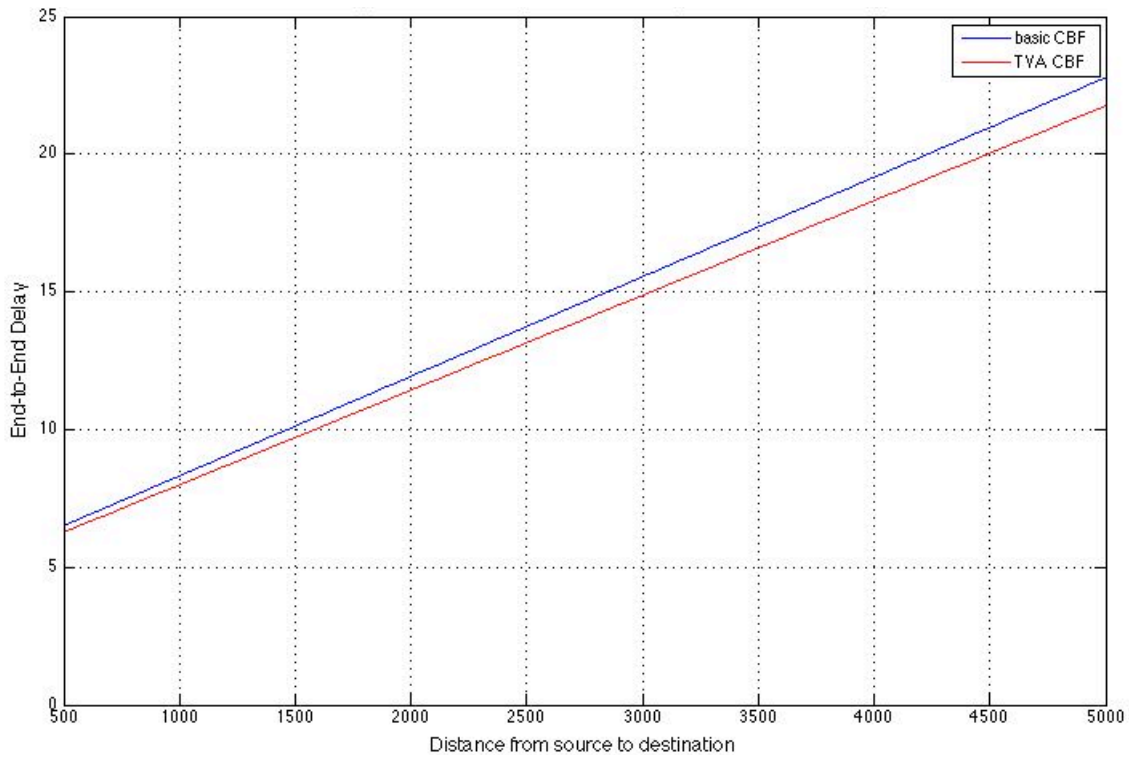


Figure 25 STATIC: End-to-End Delay for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

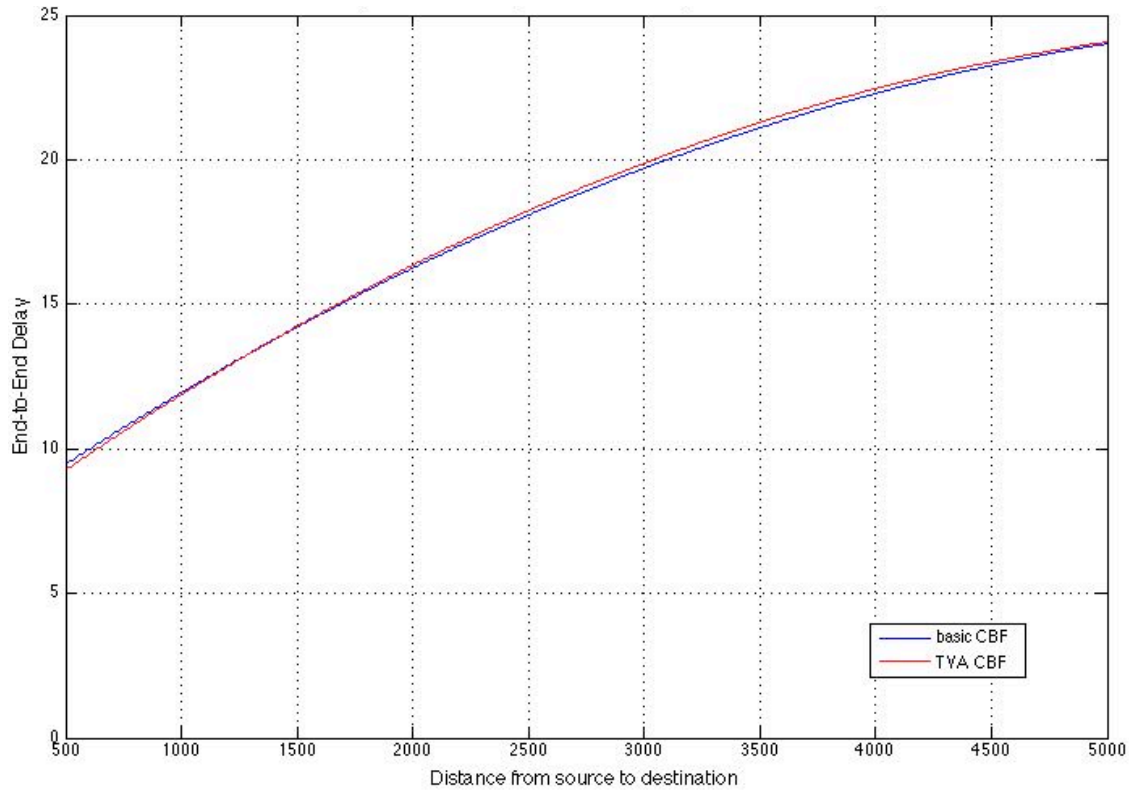


Figure 26 MOBILE: End-to-End Delay for vehicle density: 8 veh/km/lane, Tall vehicle percentage: 20%

The goal of the second type of experiments is to investigate the End-to-End Delay when various Tall vehicle percentages and various vehicle densities are applied. In this type of experiments, the End-to-End Delay when the distance from the source to the destination equals to a certain value is investigated for the five vehicle densities with the five Tall vehicle percentages presented in Table 5, with the static environment results shown in Figure 27 and the mobile environment results shown in Figure 28. This is accomplished for Scenarios 1, 2, 3, 4, and 5, shown in Table 5. The distance from the source to the destination for both static and mobile environment is chosen to be 4000m, the same as the distance value when investigating the End-to-End Delay measurement in greedy forwarding algorithm.

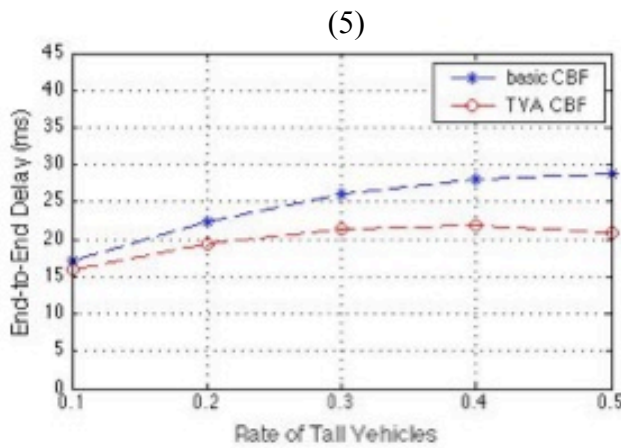
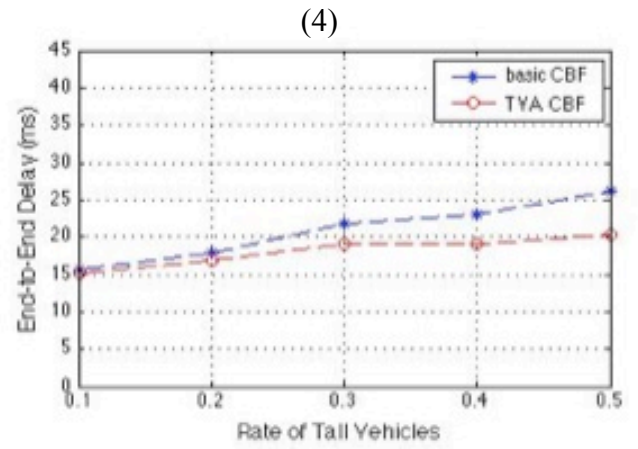
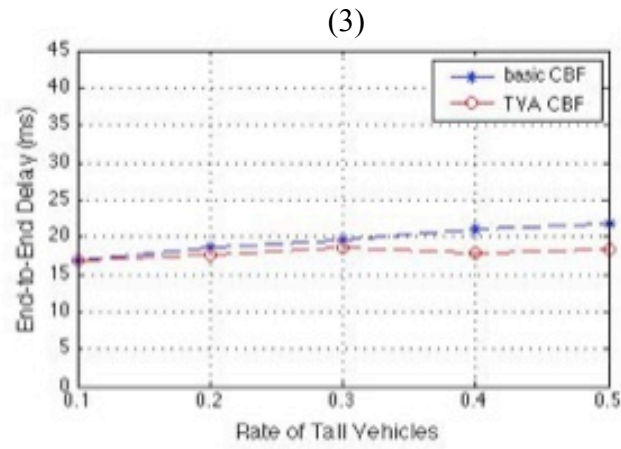
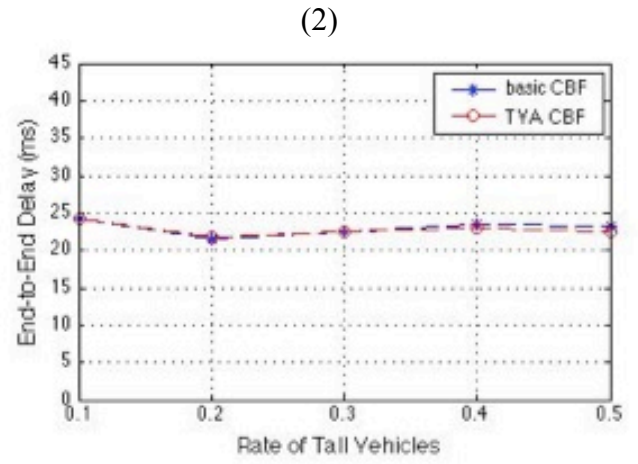
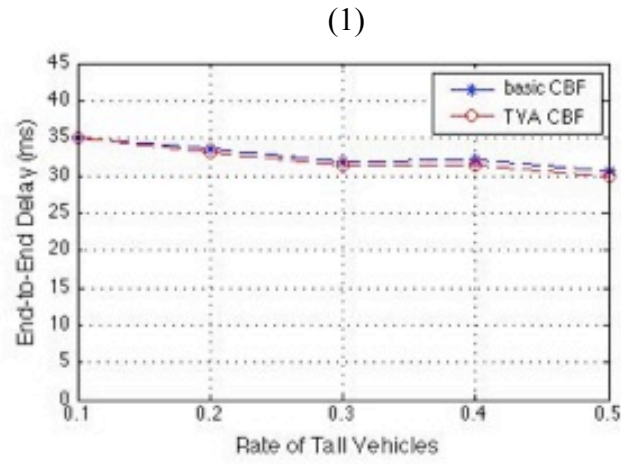


Figure 27 STATIC: End-to-End Delay for the five scenarios given in Table 5: (1) 500m (2veh/km/lane) (2) 250m (4veh/km/lane) (3) 125m (8veh/km/lane) (4) 75m (13veh/km/lane) (5) 50m (20veh/km/lane)

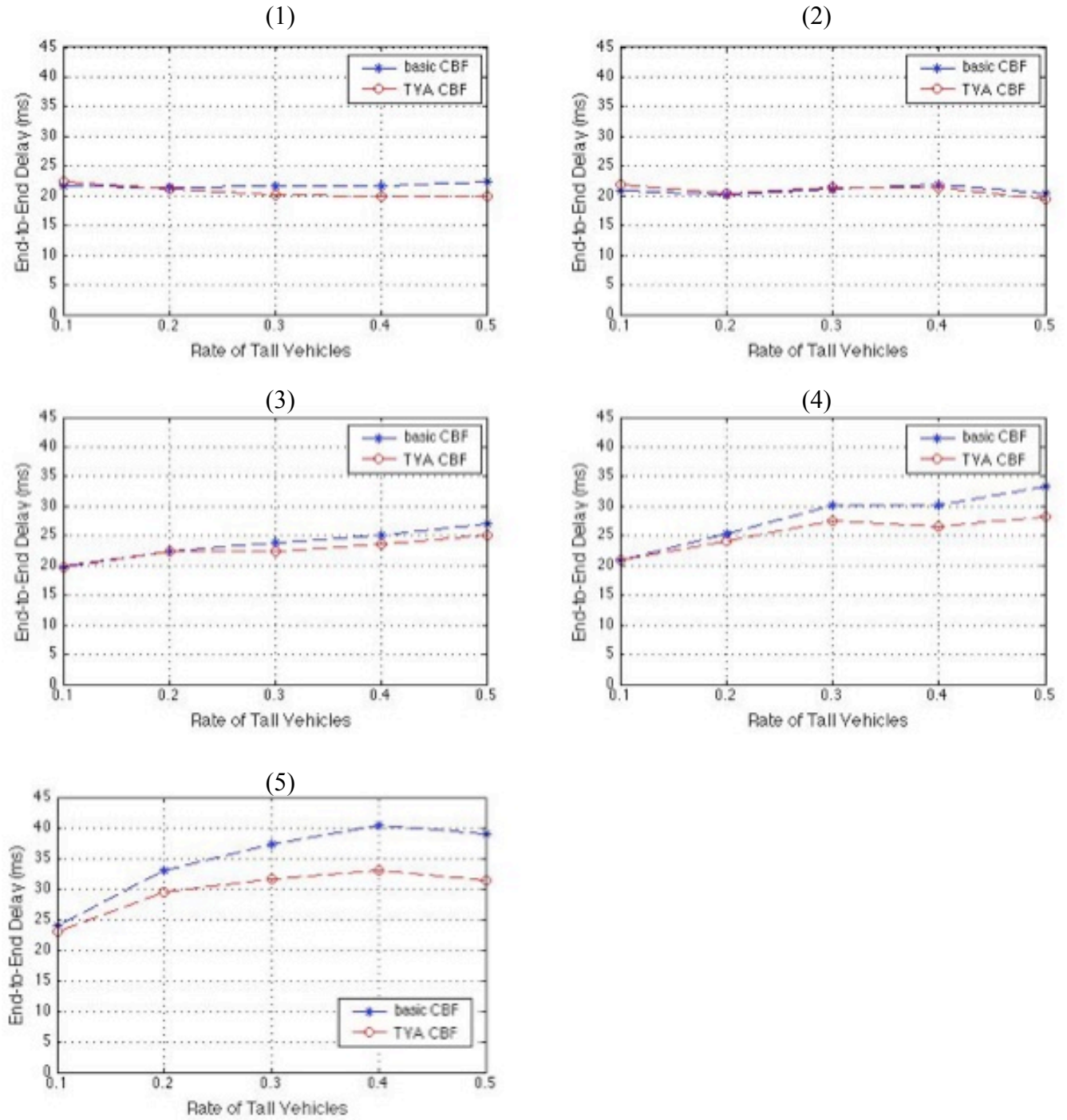


Figure 28 MOBILE: End-to-End Delay for the five scenarios given in Table 5: (1) 500m (2veh/km/lane) (2) 250m (4veh/km/lane) (3) 125m (8veh/km/lane) (4) 75m (13veh/km/lane) (5) 50m (20veh/km/lane)

In Figure 27 and Figure 28, a pair of a blue dash lines and a red dash line with five points stands for the hop count results for a certain vehicle density (one scenario in Table 5) with five Tall vehicle percentages at the distance from the source to the destination equaling 4000m. Each point with star or circle on the blue/red dash line refers to the number of intermediate relay hops needed for a certain vehicle density and a certain Tall vehicle percentage, when the distance from the source to the

destination is 4000m. From Figure 27 and Figure 28, it can be concluded for both static and mobile environment simulations that:

- 1) all the End-to-End Delay values associated with the Tall vehicle-aware contention based forwarding algorithm are smaller than the End-to-End Delay values associated with the original contention based forwarding algorithm, when a certain vehicle density and a certain Tall vehicle percentage are applied.
- 2) for large vehicle densities in the considered scenarios, all the End-to-End Delay values associated with both the Tall vehicle-aware contention based forwarding and the original contention based forwarding algorithm are increasing, when the Tall vehicle percentage in the network becomes larger while the vehicle density remains the same. The reason of this is that taller vehicles can obstruct the transmission signal easier, thus a different route towards the destination with more delays of the GeoUnicast packet might be chosen.
- 3) all the End-to-End Delay values associated with both the Tall vehicle-aware contention based forwarding and the original contention based forwarding algorithm becomes larger, when the vehicle density increases while the Tall vehicle percentage in the network remains the same. The reason of this observation is that the transmission signal is more likely to be blocked when there are larger number of vehicles in the network, since more vehicles can act as obstructions to obstruct the transmission signal. A fast way to reach the destination becomes more difficult, thus leads to an increase in the End-to-End Delay results.
- 4) the difference between the End-to-End Delay values associated with original contention based forwarding and those values associated with Tall vehicle-aware contention based forwarding becomes larger, when the vehicle density becomes larger while a certain Tall vehicle percentage is applied.
- 5) the difference between the End-to-End Delay values associated with original contention based forwarding and those values associated with Tall vehicle-aware contention based forwarding becomes larger, when the Tall vehicle percentage becomes larger while a certain vehicle density is applied.

We can conclude from the above performance results that when applying the contention based forwarding, the Tall vehicle-aware algorithm does provide some enhancement in the End-to-End Delay measurement, but not in the Hop Count measurement, since the contention based forwarding algorithm mainly measures waiting time of next hops to forward the GeoUnicast packets. Single-hop benefits of Tall vehicles as next hops to relay packet do achieve a small improvement in the system level performance, when considering End-to-End Delay measurement.

5.7 Problem Analysis

According to the performance evaluation results and conclusions in the previous section 5.6, it is concluded that the Tall vehicle-aware method proposed in this assignment does not provide much enhancement on the existing position based routing techniques, e.g. greedy forwarding and contention based forwarding. The single-hop benefits of Tall vehicles observed in [QiWo12] do not achieve significant improvement in the system level performance. To analyze the reasons of this fact, we firstly define several concepts for better understanding of the explanation.

- *stand-by Tall vehicle*: the Tall vehicle found by the local GeoAdhoc router that is closest to the destination in Tall vehicle-aware greedy forwarding algorithm; the Tall vehicle found by the

local GeoAdhoc router that has the largest forwarding progress towards the destination in Tall vehicle-aware contention based algorithm.

- *stand-by Short vehicle*: the Short vehicle found by the local GeoAdhoc router that is closest to the destination in Tall vehicle-aware greedy forwarding algorithm; the Short vehicle found by the local GeoAdhoc router that has the largest forwarding progress towards the destination in Tall vehicle-aware contention based algorithm.
- *Dist_Tall*: in Tall vehicle-aware greedy forwarding, it is the distance from the stand-by Tall vehicle to the destination; in Tall vehicle-aware contention based forwarding, it is the forwarding progress towards the destination from the stand-by Tall vehicle.
- *Dist_Short*: in Tall vehicle-aware greedy forwarding, it is the distance from the stand-by Short vehicle to the destination; in Tall vehicle-aware contention based forwarding, it is the forwarding progress towards the destination from the stand-by Short vehicle.
- *Dist_diff*: the difference between *Dist_Tall* and *Dist_Short* in both Tall vehicle-aware greedy forwarding algorithm and Tall vehicle-aware contention based forwarding algorithm.
- *Dist_threshold*: the distance threshold defined in the Tall vehicle-aware method, proposed in this assignment, which is the theoretical maximum communication range difference between a Tall vehicle and a Short vehicle.
- *Dist_improved*: by changing the decision about next relay hops from a Short vehicle to a Tall vehicle, the next hop could reach further towards the destination, as a Tall vehicle provides larger communication range than a Short vehicle. This additional achieved distance is defined as *Dist_improved*.

The main idea of the Tall vehicle-aware method proposed in this assignment is that the decision about the next relay hop is changed from a Short vehicle to a Tall vehicle, thus the next hop can reach further towards the destination. In both greedy forwarding and contention based algorithm with Tall vehicle-aware method applied, the condition of changing the decision about the next relay hop is that $0 < Dist_diff < Dist_threshold$. Details could be found in Chapter 5. The reasons of the fact that not significant improvement is achieved by Tall vehicle-aware method is due to the following limitations:

- Limitation 1: Probability to change next hop decisions is small. The condition described in the Tall vehicle-aware method is actually a small probability case in the network, since normally the Tall vehicle percentage is low and it is hard to ensure that a stand-by Tall vehicle and a stand-by Short vehicle have a distance difference smaller than the distance threshold. In the simulation experiments of this assignment, the Tall vehicle percentage in the network varies from 10% to 50%, meaning that up to 5 out of 10 are Tall vehicles. This means, when distinguishing Tall and Short vehicles in the network, and considering the case as an example that, (i) 10 intermediate hops are needed to reach the destination, (ii) the Tall vehicle percentage is 50% in the network, then in the 10 intermediate hops there are in average 5 Tall vehicles and 5 Short vehicles that are chosen as next hop relays. Only the existing decisions of Short vehicles are possible to be changed in the Tall vehicle-aware method. Now considering the Tall vehicle-aware method is applied, we can not ensure that the *Dist_diff* in the each of the five next hop decision processes is smaller than the *Dist_threshold*. Thus the probability of changing next hop decisions is quite small.
- Limitation 2: Total *D_improved* is not large enough. As discussed above the probability of changing the decisions about next hops is small, in this limitation analysis we take the example mentioned in the first limitation into account that (i) 10 intermediate hops are needed to reach the destination, (ii) Tall vehicle percentage is 50% in the network, (iii) in the 10 intermediate hops

there are in average 5 Tall vehicles and 5 Short vehicles that are chosen as next relay hops. When deciding the next relay hop and comparing a *stand-by Tall vehicle* and a *stand-by Short vehicle*, the optimal situation is shown in Figure 29, where the two stand-by vehicles are located at the same distance to the destination. In this case, the changing of the next hop decision from a Short vehicle to a Tall vehicle will provide the largest improved distance, which equals to the communication range difference between a Tall vehicle and a Short vehicle (also equals to $Dist_threshold$ in Figure 29). For easier understanding, we consider an extreme case that all of the 5 Short vehicles as next relay hops in the example are changed to Tall vehicles. Thus the total improved distance (total $Dist_improved$) caused by the decision changing is proximately 500m, as the distance threshold defined in the Tall vehicle-aware method is 100m. From previous study ([QiWo12]) that one vehicle's theoretical maximum communication range is about 1000m when the transmission power and the data rate in this assignment is applied. Only when total $Dist_improved$ is larger than 1000m, one intermediate vehicle as next hop can be saved. Therefore, even though in the example all intermediate hops become Tall vehicles, no obvious difference could be observed for Hop Count between the simulation results of Tall vehicle-aware algorithms and the original algorithms in position based routing techniques, since the total improved distance is not large enough in the simulation.

- Limitation 3: The best next hop algorithm in [QiWo12] is not applied completely. In [QiWo12], the best next hop works based on the following steps: (i) for current GeoAdhoc router, find the farthest neighboring Tall and the farthest neighboring Short vehicle, (ii) determine which of the two has the largest number of new neighbors (second hop neighbors), (iii) the one with the largest number of new neighbors is selected as next relay hop. In the Tall vehicle-aware method proposed in this assignment, the number of second-hop neighbors is not collected and is not considered as a factor to decide the next relay hop. This is because that in order to know the second-hop neighbors for the current GeoAdhoc router, it is necessary to include a table of the neighbor information in the beacon header in the Tall vehicle-aware greedy forwarding algorithm (No neighbor information is used in contention based forwarding). However in this way, the beacon structure in the original algorithm, i.e. greedy forwarding, will also be modified, which is not good in the research. Therefore, the benefits of Tall vehicles in this assignment might be slightly different with the single-hop benefits of Tall vehicles found by using the best next hop algorithm in [BoVi11] and [QiWo12].

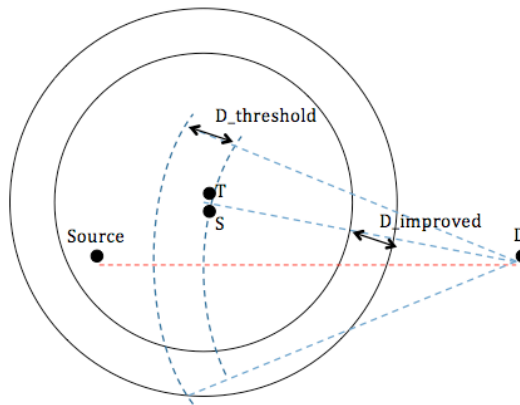


Figure 29 Examples for results analysis

6. Conclusion and Future Work

6.1 Conclusions

In this article we have presented an extended evaluation of the system level performance benefits of Tall vehicles on multi-hop VANET communication, based on the single-hop benefits of Tall vehicles presented in [BoVi11] and [QiWo12]. In order to apply the action of selecting Tall vehicles as next relay hops in a proper and potential VANET multi-hop communication algorithm/protocol, various existing VANET multi-hop routing techniques are investigated and compared. The one that is most likely to be developed in the future is chosen to be implemented in this assignment, which is the position-based routing techniques, with greedy forwarding algorithm and contenting based forwarding algorithm to handle transmission packets. For simplicity, only GeoUnicast is taken into account in this assignment. However, the action of selecting Tall vehicles as next relay hops could also be extended into other communication scenarios (GeoAnycast, GeoBroadcast, etc.). After that, an appropriate method to apply the action of selecting Tall vehicles as next relay hops into position based routing techniques is proposed, which is the Tall vehicle-aware method. In the Tall vehicle-aware method, a key parameter called $Dist_threshold$, which equals to the difference between the theoretical maximum communication range difference of a Tall vehicle and that of a Short vehicle, is defined as an additional factor to decide the next intermediate hop to relay packets to the destination. To evaluate the system level performance benefits of Tall vehicles by comparing the original algorithms and the Tall vehicle-aware algorithms in position based techniques, extensive experiment studies regarded to the research question are simulated in OMNET++, in which the effects of the Tall vehicle-aware method is investigated when various vehicle densities and various percentages of Tall vehicles are applied in the network. The research questions in this assignment could be answered as the following:

- 1) Which VANET multi-hop communication algorithms and protocols should be considered in this assignment? Why?

Answer: The one that is most likely to be developed in the future is chosen to be implemented in this assignment, which is the position-based routing techniques, with greedy forwarding algorithm and contenting based forwarding algorithm to handle transmission packets.

- 2) How could the action of selecting tall vehicles as next relay hops be applied into the existing VANET multi-hop communication algorithms and protocols?

An appropriate method to apply the action of selecting Tall vehicles as next relay hops is proposed in this assignment, which is called Tall vehicle-aware method. The details could be found in Chapter 4.

- 3) To what extent could the existing VANET multi-hop communication algorithms and protocols benefit from the action of selecting Tall vehicles as next relay hops?

To evaluate the Tall vehicle-aware method proposed in this assignment, huge number of simulations has been done in OMNET++. The results indicate that this method does not improve a lot to the original routing techniques.

Based on the extensive simulation results, we can see that almost all cases in the simulation experiments suggest that, either increasing vehicle density (decrease the mean of the inter-vehicle spacing exponential distribution), or increasing the percentage of Tall vehicles, cause a slightly increase in the results of average Hop Count, End-to-End Delay values versus the distance from the source to the destination. Besides, we can conclude for the main research question that,

- 1) in position based routing techniques, both greedy forwarding and contention based forwarding applied Tall vehicle-aware method perform almost the same as the original algorithms in terms of Hop Count and End-to-End Delay,
- 2) when considering the End-to-End Delay measurement, the Tall vehicle-aware contention based forwarding performs slightly better than the original algorithm,
- 3) in both greedy forwarding and contention based forwarding, the difference of the Hop Count and End-to-End delay results between Tall vehicle-aware algorithm and the original algorithm becomes larger, when increasing the vehicle density or increasing the Tall vehicle percentage in the network,
- 4) in the position based routing techniques, e.g. greedy forwarding and contention based forwarding, both the Tall vehicle-aware algorithm and the original algorithm performs better in the static environment than in the mobile environment. The largest improvement caused by Tall vehicle-aware algorithm is achieved in the static environment.

All in all, the hypothesis stated in research study that, Tall vehicles as next relay hops might provide significant system level performance advantages in multi-hop VANET communication, is not tenable in realistic cases.

6.2 Future Work

Based on the conclusions derived in this assignment several recommendations for future activities have been identified as following:

- The sensitivity of the system level performance to the key parameter defined in the Tall vehicle-aware method, i.e. `Dist_threshold`, which equals to the communication range difference between a Tall vehicle and a Short vehicle, could be investigated. Since the theoretical maximum communication ranges of a Tall vehicle and a Short vehicle set in the simulation are approximate values from the research work in [QiWo12], the distance threshold does not have a fixed value. When the distance threshold becomes larger, the probability of a Tall vehicle selected as the next relay hop becomes higher according to the Tall vehicle-aware method proposed in this assignment. Thus we can predict that the system level performance will have larger improvement caused by Tall vehicles.
- Other methods of enhancements could be proposed for multi-hop communication in VANET. For example, the speed of vehicles in the network could be considered and then the position of other vehicles could be predicted by the vehicle act as the local GeoAdhoc router. In this way, the source/forwarders may know which neighboring vehicle will be closer to the destination after a certain time interval, and select it as the next relay hop.

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Appendix A: Confidence Intervals For Simulation Results

This appendix describes the double-sided 90% confidence intervals calculated for the average results of the experiments provided in Chapter 5. In order to calculate these confidence intervals, a large number of simulation runs (where each of them uses a different random seed) have been accomplished for each experiment described in section 5.3. This means that for each point in each curve presented in the figures given in section 5.5 and section 5.6, a large number of samples are found, where their average value is used to calculate the two-sided 90% confidence interval.

A $(1 - \alpha)$ confidence interval (CI) for the mean is an interval such that the mean of the population, μ , is inside it (i.e. $a < \mu < b$) with $(1 - \alpha)$ "confidence". According to [Jain91], the formula of the confidence interval for sample sizes larger than 30 and sample sizes smaller than 30 is different. Since the collected number of samples is higher than 30, in order to find the double-sided 90% confidence intervals, the formula used for the calculation is shown as the following:

$$\bar{x} - 1.96 \frac{s}{\sqrt{n}} < \mu < \bar{x} + 1.96 \frac{s}{\sqrt{n}}$$

Here, \bar{x} is the sample mean, s is the sample standard deviation, while n represents the number of samples and μ is the mean of the population.

In order to be able to show that how large the confidence intervals are below/above their associated average value, we decided to calculate and plot the ratios between each confidence interval and its associated average value. For experiments defined for both Tall vehicle-aware greedy forwarding and Tall vehicle-aware contention based forwarding, we calculated the ratio of half of the CI range and its associated average value. However, for the simulation results shown in section 5.5 and section 5.6, the following only presents the confidence intervals for Hop Count and End-to-End Delay results associated with the case that when the vehicle density is 8veh/km/lane (inter-vehicle spacing mean is 125m) since the confidence intervals of other cases in other scenarios are similar and there are too many figures of the confidence intervals. The confidence intervals corresponding to Figure 13 and Figure 14, where the Hop Count measurement is investigated for Tall vehicle-aware greedy forwarding (TVA GF in the figure) and the original greedy forwarding (GF in the figure) in static and mobile environment respectively, are shown in Figure 30 and Figure 31. The confidence intervals corresponding to Figure 17 and Figure 18, where the End-to-End Delay measurement is investigated for Tall vehicle-aware greedy forwarding and the original greedy forwarding in static and mobile environment respectively, are shown in Figure 32 and Figure 33. Furthermore, the confidence intervals corresponding to Figure 21 and Figure 22, where the Hop Count measurement is investigated for Tall vehicle-aware contention based forwarding and the original contention based forwarding in static and mobile environment respectively, are shown in Figure 34 and Figure 35. The confidence intervals corresponding to Figure 25 and Figure 26, where the End-to-End Delay measurement is investigated for Tall vehicle-aware contention based forwarding and the original contention based forwarding in static and mobile environment, are shown in Figure 36 and Figure 37.

Note that the red solid line in each figure points out the ratio of half confidence interval and the the mean value of the population at the distance from the source to the destination equaling 4000m, where for each case in the scenarios described in section 5.4 the results of Hop Count and End-to-End Delay are collected. Since the confidence intervals for other cases look similar (the ratio of half CI and average

is also under 5%), the ratios of half confidence intervals and average values for other figures presented in section 5.5 and section 5.6 are also under 5%.

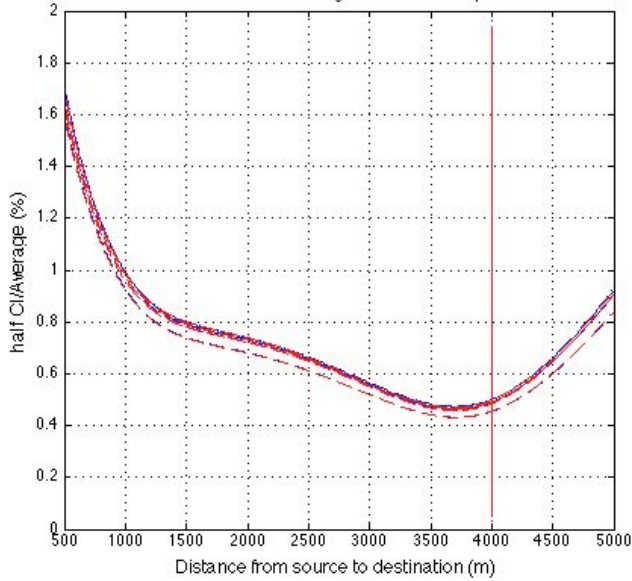


Figure 30 half CI/Average ratio for Hop Count associated with GF and TVA GF in static environment

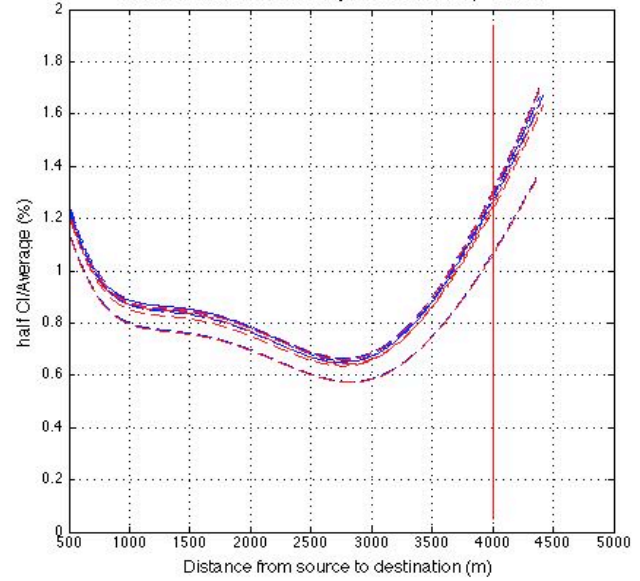


Figure 31 half CI/Average ratio for Hop Count associated with GF and TVA GF in mobile environment

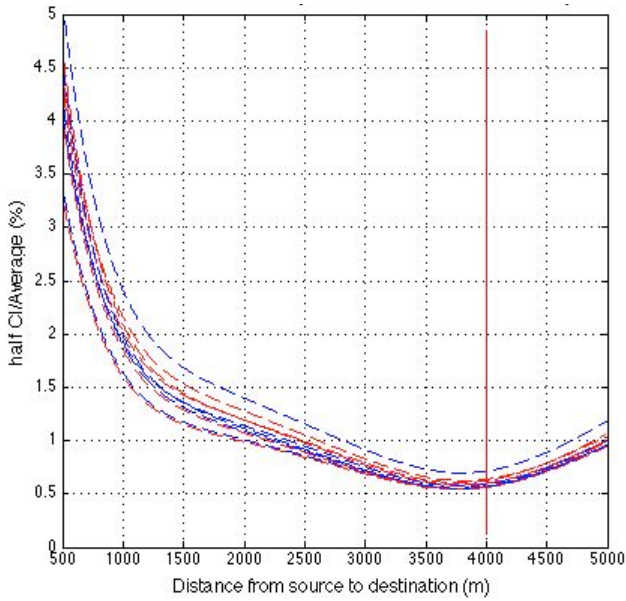


Figure 32 half CI/Average ratio for End-to-End Delay associated with GF and TVA GF in static environment

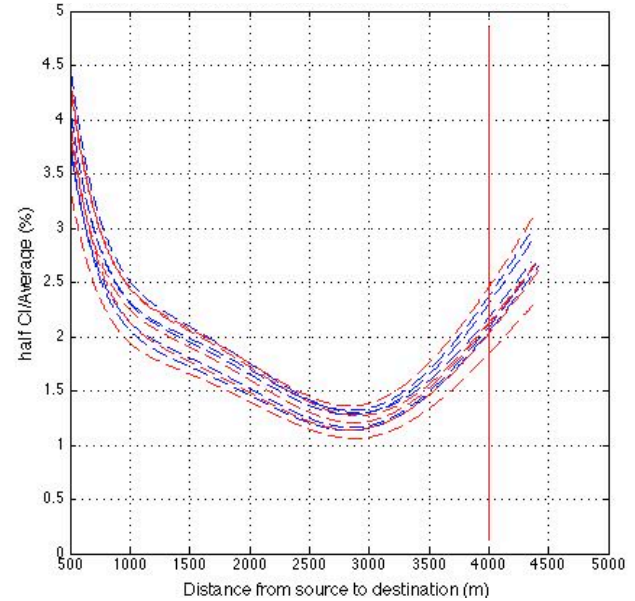


Figure 33 half CI/Average ratio for End-to-End Delay associated with GF and TVA GF in mobile environment

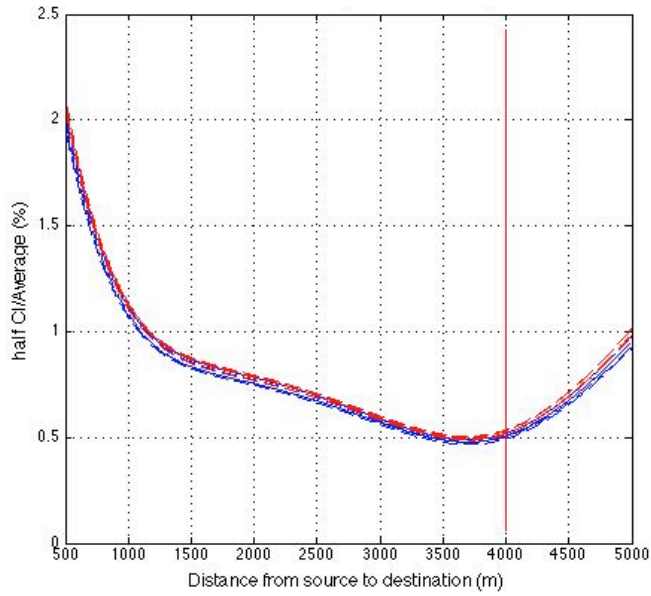


Figure 34 half CI/Average ratio for Hop Count associated with CBF and TVA CBF in static environment

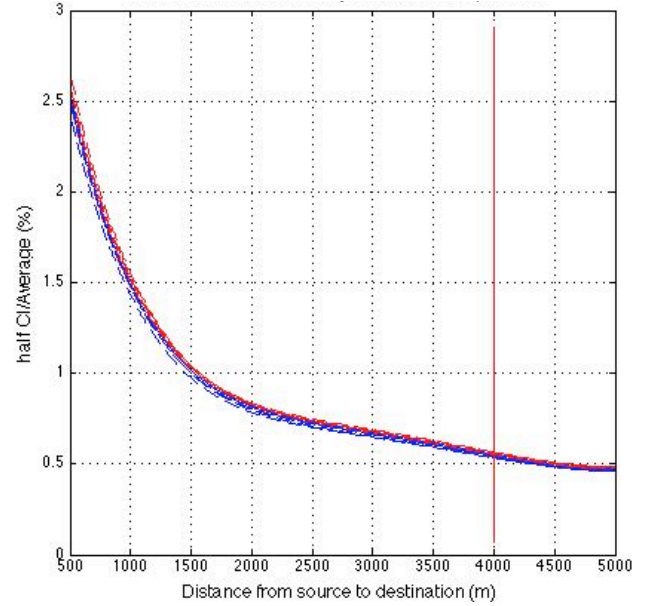


Figure 35 half CI/Average ratio for Hop Count associated with CBF and TVA CBF in mobile environment

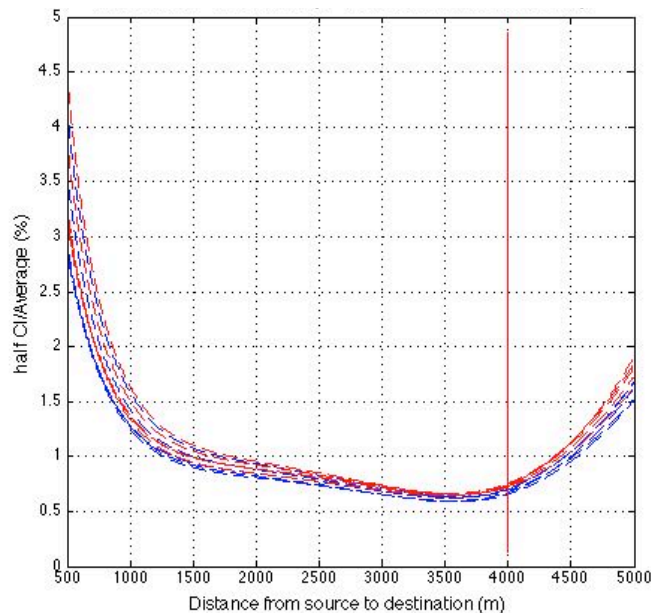


Figure 36 half CI/Average ratio for End-to-End Delay associated with CBF and TVA CBF in static environment

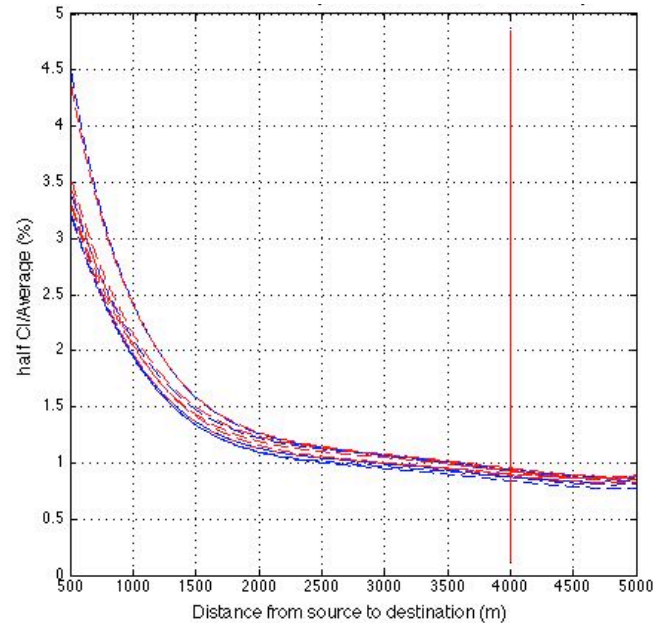


Figure 37 half CI/Average ratio for End-to-End Delay associated with CBF and TVA CBF in mobile environment