Packet Forwarding in VANETs, the Complete Set of Results

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Abstract

The discrepancy between real-world radio channel behavior and its standard modeling in simulations (Unit Disk Graph) is a major reason for protocols to perform different – often worse – than predicted when deployed in a real-world setup. As researchers having to deal with real ad hoc networks are aware of, assuming a fixed border for a node's communication range might not only lead to inaccurate results but also to a wrong judgment on the comparison between different protocols. We have set up a simulation study to investigate the effects of realistic channel characteristics on packet forwarding strategies for vehicular ad hoc networks. The contributions of this technical report are threefold: *i)* We provide a performance evaluation of various routing/forwarding strategies under the realistic non-deterministic Nakagami radio propagation model and compare the results with the ones obtained using the standard Two-Ray-Ground model. Validated German highway movement patterns are used to model node mobility. *ii)* We demonstrate that realistic channel conditions present an opportunity and not only a drawback for some forwarding strategies. More specifically, we show that for *contention-based* forwarding (CBF) techniques, realistic channel characteristics provide a positive impact in terms of an increased average hop distance. *iii)* We provide an analytical derivation of the expected hop distance for CBF that provides a basis to optimally adjust CBF parameters.

1 Introduction

Vehicular ad hoc networks (VANETs) are a specific type of mobile wireless ad hoc networks that are currently attracting the attention of researchers around the globe. The joint efforts of governments, standardization bodies, car manufacturers and academia (among others) in several national/international initiatives (DSRC [1] in USA, C2CCC [2] in Europe, InternetITS [3] in Japan or Network on Wheels [4] in Germany, to name a few) aim to make possible that, in a near future, vehicles can benefit from spontaneous wireless communications.

Clearly, safety-related applications will be the most important class of applications in VANETs requiring, primarily broadcast messages. In addition, certain applications for traffic information or access to stationary nodes are envisioned demanding geo-cast communications, i.e., addressing/requesting information to/from a specific region that is few hops away.

VANETs differ from other wireless networks in several aspects. Some of them stress standard routing challenges, such as high node mobility due to the high potential speeds of their nodes. Others, though, can favor the message forwarding strategies, such as 'pre-defined' topologies (limited to the shape of the roads), an 'unlimited' energy source in every node and the increasing availability of positioning systems.

Additionally, vehicular scenarios can present particularly 'adverse' environmental phenomena, not necessarily common in all ad hoc scenarios. Basically, a VANET is composed by multiple static and mobile 'reflecting' nodes and obstacles that can disturb the amplitude of a receiving signal due to multi-path. However, most of previous studies on the mobile world analyze and adjust communication protocols under simplistic assumptions, i.e., Unit Disk Graph [5]. As any researcher that has implemented his/her design in a real testbed knows, to assume a fixed received signal strength for a fixed distance does not reflect reality. While this modeling is very useful for understanding and explaining protocols, it is a major reason for unexpected protocol behavior when moving from theory to reality.

In our aim to determine an appropriate routing/forwarding strategy for VANET highway scenarios we use both realistic highway movements and a realistic – meaning probabilistic – radio propagation model. In addition, we have improved the 802.11 medium access control and changed the 802.11 physical model of ns-2 to reflect 802.11p, which is a certain candidate for use in VANET systems. As candidate geo-addressing schemes we have selected two promising position-based strategies, greedy forwarding with beacons (PBF for Position-Based Forwarding), and CBF (Contention-Based Forwarding). When analyzing the performance of these protocols though, the comparison with a non-position (routing) based approach appears to be interesting. For completeness, we selected Ad hoc On-Demand Distance Vector Routing (AODV) as one of the routing protocols for mobile networks with experimental RFC-status.

The selected protocols are analyzed using both deterministic (Two-Ray-Ground) and probabilistic (Nakagami) radio propagation models in order to evaluate the impact of more realistic radio channel conditions. With the results obtained in our scenarios we first present the good performance in terms of packet delivery demonstrated by *position-based* approaches in all simulated scenarios. In more detail, we can observe that although a realistic propagation model increases the number of collisions in the medium it can also benefit in terms of average hop distance when using a *contention-based* strategy. Finally, we indicate how to adjust CBF, by computing the analytical estimation of its hop distance over probabilistic propagation models, to reduce the number of collisions while keeping an acceptable round trip time.

The remainder of this technical report is organized as follows. In Sec. 2, we introduce the routing strategies and different models utilized in this study pointing to the most relevant research related to our work. In Sec. 3, the results of the simulation study comparing the different routing approaches and settings are explained. The CBF's analytical hop distance computation and potential improvement are developed in Sec. 4. Finally, in Sec. 5 we provide our concluding remarks.

2 Background and Related Work

Here, we briefly explain necessary background information with respect to routing/forwarding protocols, radio propagation models and the realistic highway movement traces utilized. At the end of the section we point to additional related work.

2.1 Routing Protocols

Position Based Forwarding (PBF). (Greedy) Position-Based Forwarding is a long-known [6] method for finding a route through a network utilizing node positions. In this protocol – called Position Based Forwarding (PBF) here – nodes pro-actively send beacon messages containing their node ID and their current location. On the reception of such a message, the receiving node stores triples of the ID, the location and a time stamp in a so-called neighbor table. The removal of neighbor table entries is done by a time-out.

When a node wants to send a packet, it first queries the location of the destination node using a so-called location service unless the application provides the location by itself. A location service is a distributed algorithm that resolves the location of other nodes in the same network. The probably most simple one is RLS [7], which floods a location request, i.e., the location request is propagated over the whole network. When the node whose location is searched receives the request, it answers with a reply already using the corresponding routing/forwarding mechanism (PBF in this case, since the request packet brings the position of the requesting node along).

After the location resolution is done, PBF selects a neighbor from the neighbor table that offers most progress towards destination (the "greedy-constraint"). In our case, a conservative approach to select the next hop has been taken in order to increase the probability that the selected node is able to receive the message, i.e., the furthest nodes inside the neighbor table are not selected to alleviate the effect of interferences, mobility and fading. This means that all nodes in the neighbor table that are possibly out of communication range under the assumption that they move with a defined highest speed v_{max}, set to 234 km/h here, are not taken into account as next forwarders. Additionally, we implemented the *local-link callback* feature: when a node has not received any acknowledgment after the maximum MAC retries it will select another node from the neighbor table (if any) and try it again. While this method does not need the notion of a route, there are network constellations where an existing route to a destination cannot be found. In Highway Scenarios, however, these constellations do not occur due to reasons of geometry [8], meaning that whenever a forwarding path exists and the neighbor tables are sufficiently up-to-date, the path will be found.

Contention-Based Forwarding (CBF). Like PBF, Contention-Based Forwarding [8, 9] does not maintain routes and also assumes that the destination node's position is provided by the application or by a location service. Contrary to the previous scheme though, CBF does not make use of beacons. The sender of a packet will broadcast the message to all its neighbors and these neighbors will find out among themselves the one that will forward the packet. The forwarder is selected by the use of a contention period where all nodes will select a waiting time depending on their distance to the final destination (see Sec. 4). Therefore, the node that offers a maximum progress will select the smallest waiting time, forwarding the message at the end of this period, letting the other nodes know that they should not forward the packet. Note that the main difference with respect to PBF is that CBF does not make use of a unicast flow to forward the packet, i.e., the 'next forwarder' selection is done after the actual transmission of the packet in every hop.

Ad hoc On-Demand Distance Vector (AODV). AODV [10] is a well-established ad hoc routing protocol and fundamentally works as follows: As a reactive protocol it will only be activated when a route is needed. In that case, the originator of the message will flood a route request message. All nodes receiving this request will record the number of hops to the originator and the last hop of this packet as a distance vector to this destination. Then the packet is rebroadcasted after incrementing the hop count. This process is repeated until the final destination is reached, then a route reply will be sent backwards using the just-established list of distance vectors. This creates a bi-directional route from originator to destination. In order not to flood the whole network, AODV broadcasts its route request packets with a – low – limited number of hops, time to live (TTL). If no reply is received a new request with a higher TTL is sent again. Due to the linear geometry of our scenarios, we configured AODV to use the *local repair* mechanism, i.e., when one node in the chain can not reach its next hop, it tries to find a new route to destination itself depending on the distance to the message originator: the originator of the packet is informed if the route break is nearer to sender than to destination; otherwise the node where the route broke tries to find a new route to destination without informing the originator.

Note that several improvements have been proposed for AODV in unidirectional links scenarios, e.g., [11]. However, due to our main goal of studying geo-addressing schemes the default version of the simulator ns-2.28 [12] was utilized.

2.2 Propagation Models

A propagation model tries to approximate the received signal strength (RSS) of a radio transmission, typically using parameters like transmission power, distance between sender and receiver and antenna configurations. This RSS is then used to determine success or failure of a packet's reception.

Two-Ray-Ground (TRG) is a well known deterministic radio propagation model, it always determines the same RSS for a fixed distance between sender and receiver. In consequence, and in absence of interferences, a well defined communication range is experienced, that will be called "intended communication range" in the following. This model is often used in the evaluation and/or design process of wireless communication protocols, its advantage lying in its interpretability.

Several studies, e.g., [13], indicate that the probabilistic two-parameter Nakagami distribution [14] matches the amplitude of a radio signal in a (mobile environment) fading channel at a given distance between sender and receiver. In our studies we make use of the Nakagami propagation model based on the real highway's measurements and analysis performed in [15]. See our previous work [16] and Sec. 4.1 for a more detailed description.

Note in Fig. 1 how the assumptions of *i)* all nodes inside the intended communication range (in the absence of interferences) will receive a specific message and *ii)* all nodes outside will not receive it are only valid for the Two-Ray-Ground model, but not for Nakagami. For example, with a $500m$ communication range, Nakagami's probability of reception with respect to the distance is a decreasing curve with a long tail that is as low as 0.4 at the edge of the intended communication range. Since we cannot claim any communication range for the Nakagami model, the term "intended communication range" always refers to the range that is reached with the Two-Ray-Ground model.

2.3 Highway Traces

The nodes' geographic position at a given time is the major determinant of both channel condition and network topology. Thus – when modeling a multi-hop highway scenario – the mobility model is of high significance. The ones used for this technical report are real-world validated microscopic movement patterns created by DaimlerChrysler for the FleetNet [18] project. The result of this effort was a set of highway

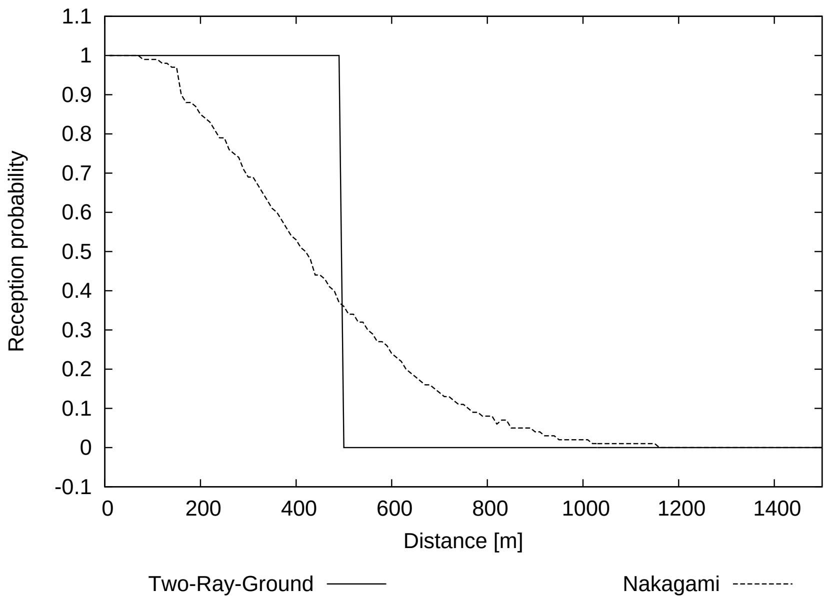

Figure 1: Probability of reception of a message with respect to the distance in absence of other nodes' interferences for Two-Ray-Ground and Nakagami models with an intended communication range of 500m.

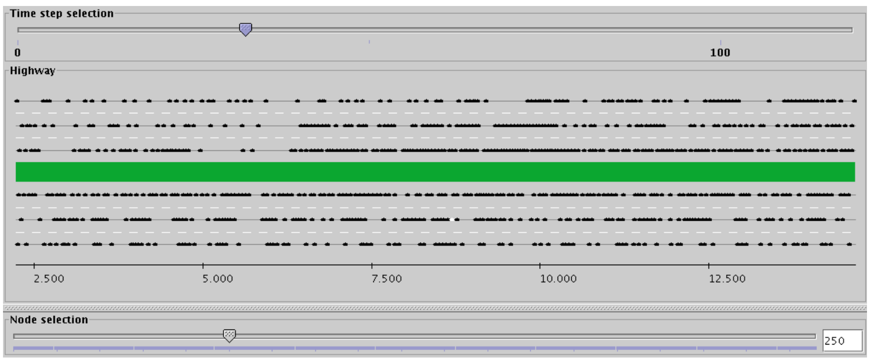

Figure 2: Utilized highway scenario with 3 lanes per direction and 11 cars per km per lane (snapshot of the HWGui [17] software of the FleetNet project).

scenarios with different number of lanes per direction and traffic densities (see [19] for a complete description). Fig. 2 shows a snapshot of such a typical scenario with 3 lanes per direction. The chosen set for our evaluation consists in a $12km$ long highway scenario where vehicles travel at speeds from $50km/h$ to $220km/h$. We have chosen a medium/high traffic density scenario (2 lanes per direction with 12 cars per km traveling in one direction and 22 cars per km in the opposite one) to study in detail the different behavior of the analyzed protocols. Additionally, we have also used a low traffic density scenario (2 lanes per direction with 4 cars per km in one direction and 12 in the other one) and one with high traffic density (3 lanes per direction and 33 cars per km in both directions). Using the three scenarios we cover a wide range of traffic densities what ensures that our results are valid under a variety of traffic conditions.

2.4 Additional Related Work

This work is a continuation of [20], now using a probabilistic channel model and also evaluating CBF for usage on highways. [21] discusses improvements of PBF on similar movement scenarios that we have used for this work.

Also, our technical report is in line with the trend followed by some other studies in the field of ad hoc networking (e.g., opportunistic routing [22]) where the characteristics of a wireless channel are not neglected, but instead, are taken advantage of.

3 Performance Comparison

After pointing out the main differences between the analyzed protocols we will compare their performance under two different settings, i.e., deterministic and probabilistic radio channel models.

3.1 Simulation Set Up

The utilized simulation tool is the network simulator ns-2.28 [12]. However, its MAC/PHY implementation has been adapted to IEEE 802.11p [23], a variant of 802.11a still not standardized, which is the technology the above-mentioned projects have agreed upon. We refer the reader again to a previous work [16] for a more detailed description. Moreover, bugs in the MAC and PHY modules were fixed [24], and the PBF and CBF forwarding modules implemented.

Our intention is to analyze how different distances between sender and receiver, and a different radio propagation model (deterministic and probabilistic) affect the performance of the routing algorithms in both directions of a communication. For this purpose, we simulated the highway scenarios described in Sec. 2.3, where among all possible nodes we selected two specific vehicles (one communication pair) to exchange 10 Ping packets (request/reply). We performed several simulations where we increased the distance between the two nodes forming a communication pair, up to $4500m$. A larger distance results in an increased number of hops since the intended communication range of all nodes is constant during the whole simulation. We selected a $500m$ intended communication range as reasonable 1 hop maximum distance in ideal conditions and absence of interferences (IEEE specifies a range up to $1000m$ [23] for this technology).

In each simulation only one communication pair was selected, while all other vehicles on the road would only be potential intermediate nodes. The communication partners were picked such that they were in theoretical multi-hop range, meaning that when applying a unit disk graph model, the resulting graph contained routes between them during the whole communication time. In addition, they remain within the same distance range ($500m$ wide) during the whole packet exchange. For example, if the studied distance was $3500m$ we can be sure that during the simulation time the two nodes are between $3000m$ and $3500m$ apart and there are always enough vehicles in between to connect them via multi-hop.

In order to have statistical significance, we selected 10 different scenarios (with the same number of lanes and density) from the whole set of traffic patterns. In each scenario we select 10 different communication pairs (originator/destination) and run independent simulations with each one of them. Finally, for each configuration setting, we compute the average and the confidence interval (with 95% confidence level) of the studied metrics, see Sec. 3.2. The main configuration parameters are reported in Table 1. While we have simulated many other settings, we will stick to these to describe the effects found.

3.2 Results

To compare the performance of PBF, CBF and AODV under both types of radio channel models we have plotted different figures representing their behavior when increasing the communication distance with respect to the selected metrics.

Table 1: Configuration parameters

Studied protocols	PBF, CBF, AODV
Radio propagation models	Two-Ray-Ground, Nakagami
Distance between comm. pair	$500m$ to $4500m$
Intended comm. range	$500m$
Ping packets generation rate	4 packets/s
Packet size	64 bytes
Number of Ping packets	10
PBF beaconing interval	$2s$
CBF max. contention time (T)	$20ms$
Vehicle density - 3 bi-directional scenarios - up and down directions	Medium: 12 cars/km up, 22 cars/km down, 2 lanes/dir. Low: 4 cars/km up, 12 cars/km down, 2 lanes/dir. High: 33 cars/km up, 33 cars/km down, 3 lanes/dir.

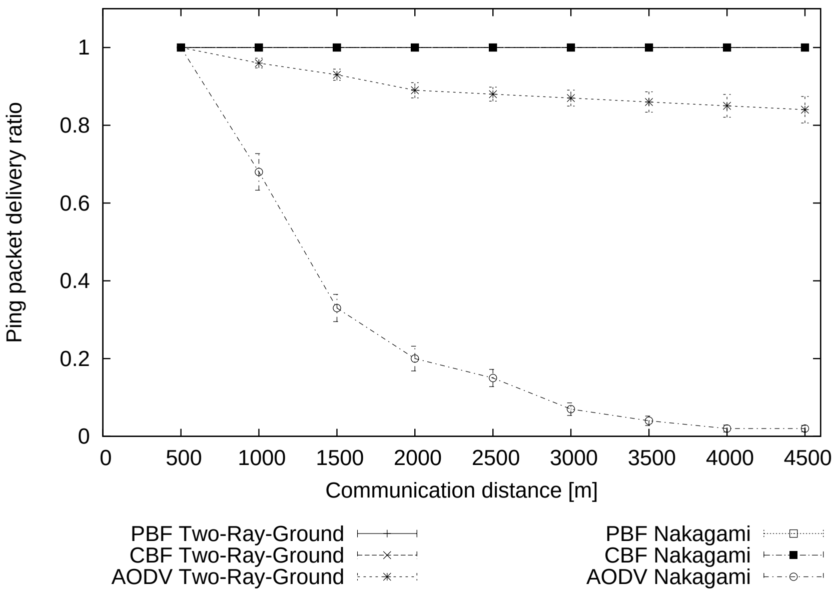

Figure 3: Packet Delivery Ratio of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami. Note that the curves of PBF and CBF for both propagation models and all communication distances all cover each other.

We can observe in Fig. 3 the performance of the different protocols under Two-Ray-Ground and Nakagami. It reports the packet delivery ratio for different distances between sender and receiver. Note that since the intended communication range of all nodes is fixed to $500m$ selecting a destination node $500m$ further from the sender is equivalent to add, at least, one hop to the resulting communication path. As expected, AODV achieves the lowest packet delivery ratio, further decreased under non-deterministic radio propagation. In more detail, we observe that communication fails mainly due to two reasons: *i)* mobility, i.e., some chosen nodes drove far from their previous/next hop significantly decreasing the probability to forward a packet successfully, and *ii)* the random behavior of Nakagami made a too optimistic route choice [25], i.e., some intermediate nodes were ‘quite’ far from each other so the data flow had low probability to reach its destination. When not only mobility but also received signal strength fluctuations are considered the search and use of a fixed route turns to be the worst choice.

Position based routing protocols are robust against both, node mobility and fading. Both schemes show average bidirectional delivery rates higher than 99.7% for all simulated distances and propagation models due to the linear geometry of the studied scenarios.

To better understand the effect of using different propagation models we can take a look at the total load sent into the channel resulting from the different routing algorithms, Fig. 4. First, we observe a good performance of all strategies when dealing with Two-Ray-Ground, only AODV results in a significant increase of load with distance; note a constant higher channel load for PBF due to the utilization of beacons. Second, note the high increment of the experienced channel load of PBF and AODV under Nakagami when

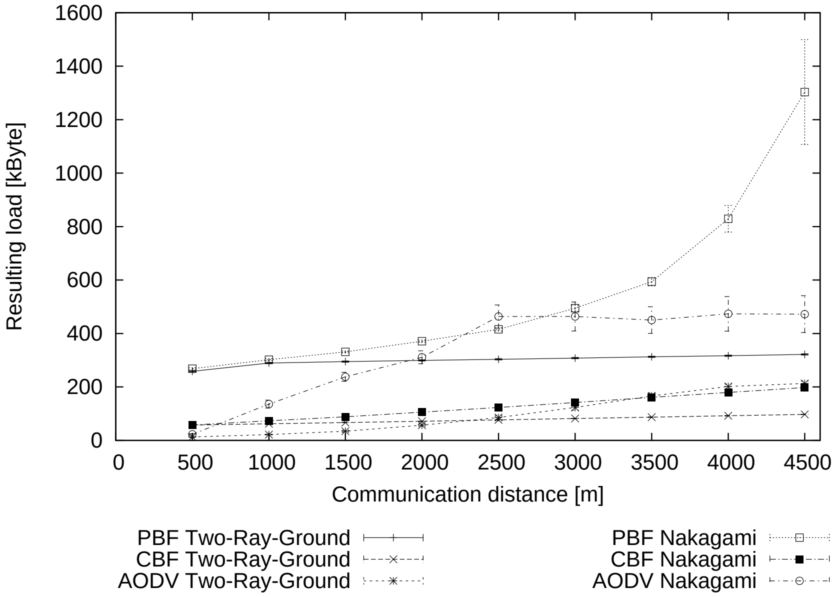

Figure 4: Resulting load in the medium of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami.

increasing the number of hops between the sender and the receiver. The difference between PBF and CBF responsible of their different performance is the strategy to select the next forwarding node. A node using CBF broadcasts a message and just expects that one node, which is closer to destination than itself, receives the packet and forwards it. PBF, on the other hand, selects a specific node from the neighbor table and tries to communicate with it. The use of a non-deterministic propagation model notably increases the risk that a successful data exchange between an intermediate node and its next hop needs more than one MAC retry, or more than one neighbor in a worse case. That explains the high increase of transmitted load w.r.t. the number of hops of PBF with Nakagami. Similarly, AODV increases its resulting load. When AODV routes hold, they tend to need many retries since the neighbors are chosen poorly. On the other hand, when all possible routes break, no more packets are transmitted from the source due to route requests time-outs (distances further than 2500m at Fig. 4). This effect limits the number of packets that are sent at a total resulting load of $500kByte$.

Finally we plotted the round trip time experienced by the different protocols in Fig. 5. We can see how the results are in line with the former figures. The worst performance, i.e., the longest round trip time, corresponds to AODV, specially under the probabilistic propagation model. The reason for this is a combined influence of both mobility and the propagation model. Discovered routes in the request phase may include hops over high distances when the Nakagami model is used. These hops though, may have low probability of successful data transmission and lead to a high number of broken routes and packet losses. Additionally, one single route failure can lead to several packet losses, if these packets already wait in the interface queue and the local repair mechanism does not succeed. If we take a look at the zoom (the square inside Fig. 5), we can see how the performance of PBF under Nakagami is affected when increasing the distance between the communication pairs. Also in the zoom of Fig. 5, we can observe an interesting phenomenon, CBF shows shorter round trip times when considering a non-deterministic propagation model and PBF shows longer ones.

To explain the resulting CBF's round trip time with Nakagami, we also plotted the average number of hops for both protocols for the different communication distances, Fig. 6. Again, we see the benefit of not pre-selecting the next forwarding node in the process of routing a packet when considering a non-deterministic radio model. As mentioned before, PBF selects a node inside its intended communication range and tries to communicate with it. It is reasonable to think that the unreliability of the link results in a longer round trip time, i.e., it will use several MAC layer retries (or even select a new node) before being acknowledged. On the other hand, a node using CBF does not pre-select a node inside its intended communication range as a next forwarder. That way, CBF benefits when a node outside this range receives the packet, what is a possible situation only when considering a non-deterministic propagation model. That explains that, e.g., the average number of hops could be smaller than 8 when the destination is further than $4000m$ and having all nodes an intended communication range of $500m$.

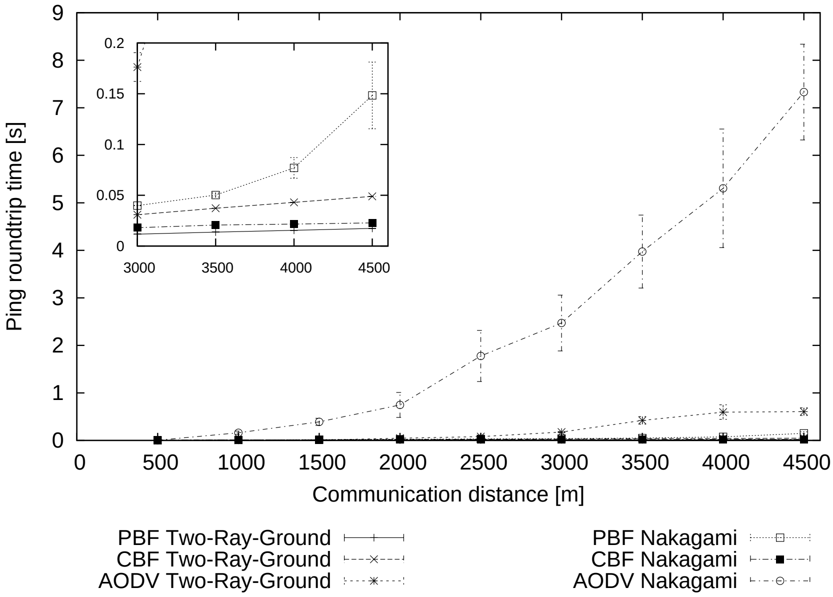

Figure 5: Round trip time of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami.

As a conclusion, we can state that CBF presented the best performance among the routing protocols. Although it presents a higher number of duplicates, CBF's strategy of not selecting a specific forwarder before the actual message transmission is a robust scheme to fight against fading channels.

3.2.1 Low car density

In this subsection we repeat the same experiments presented above when assuming a highway with lower traffic density. In this case, we chose a 4 and 12 cars per per km in each direction of the highway, i.e., a scenario with approximately half the node density as the previous one.

Although most of the results are inline with the ones obtained with a medium/high density, we will also observe few differences with respect to packet delivery ratio and resulting load.

In Fig. 7 we can observe that the packet delivery ratio presents some values below 100% (97% at minimum) for the position based forwarding approaches when using the Nakagami radio propagation model. Remember that the communication partners are chosen so that there is always a possible path between them in ideal conditions, i.e., no interferences and no fading phenomena. However, having a lower number of potential forwarders combined with an unreliable channel due to fading can result in a slight decrease on the packet delivery ratio. Note though, that the position based strategies still present the best choice in terms of successful communication exchange.

Fig. 8 represents a significantly lower resulting load than the previous scenario in all cases. For CBF, the lower load corresponds mainly to the – flooding – location mechanism with a lower node density (see Sec. 3.3). Also in case of AODV, the flooding mechanism used to find the destination is the main reason for a lower load on the medium. For PBF, not only the RLS affects the resulting load on the channel, but mainly the constant exchange of beacons; note how the resulting load is approximately half as before, in accordance with the total number of nodes. Note that although a lower node density has different impact on the different protocols, the relation among them stays mainly unchanged.

Finally, we can observe in Fig. 9 how a lower density of nodes has a minimal impact on the round trip time. Here, as in the case of the packet delivery ratio, having enough nodes in the path, ensures that position based algorithms can provide a good performance in terms of bidirectional data exchange.

3.2.2 High car density

For completeness, we present in this section the results obtained with a high vehicular density scenario, a highway with 3 lanes per direction and 33 cars per km. It can be observed how the results depicted in Figs. 10, 11 and 12, are totally inline with the ones obtained with lower nodes' densities. The only effect

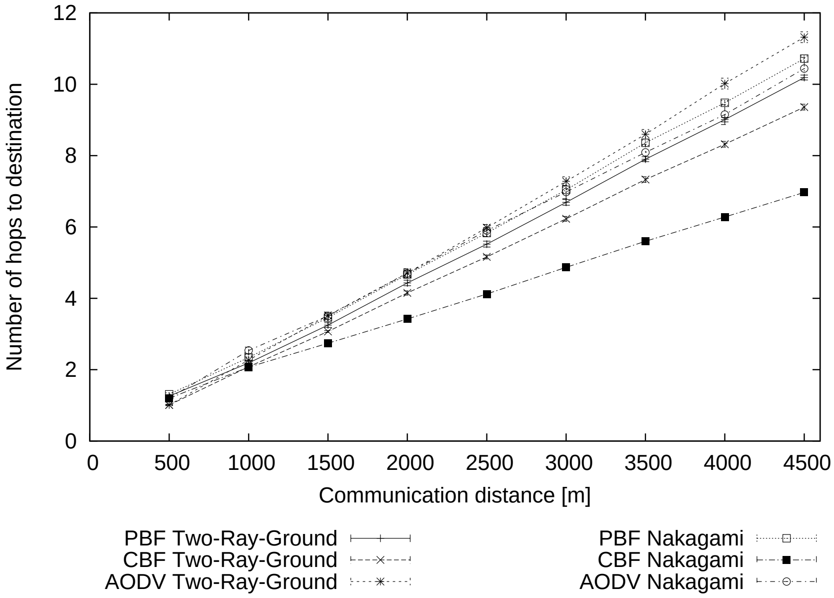

Figure 6: Number of hops to reach destination of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami.

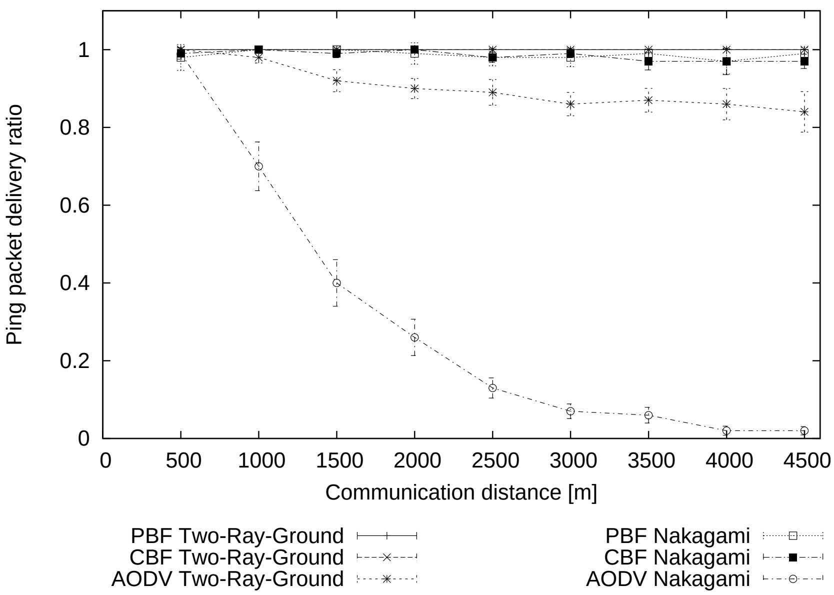

Figure 7: Packet Delivery Ratio of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami under low traffic conditions.

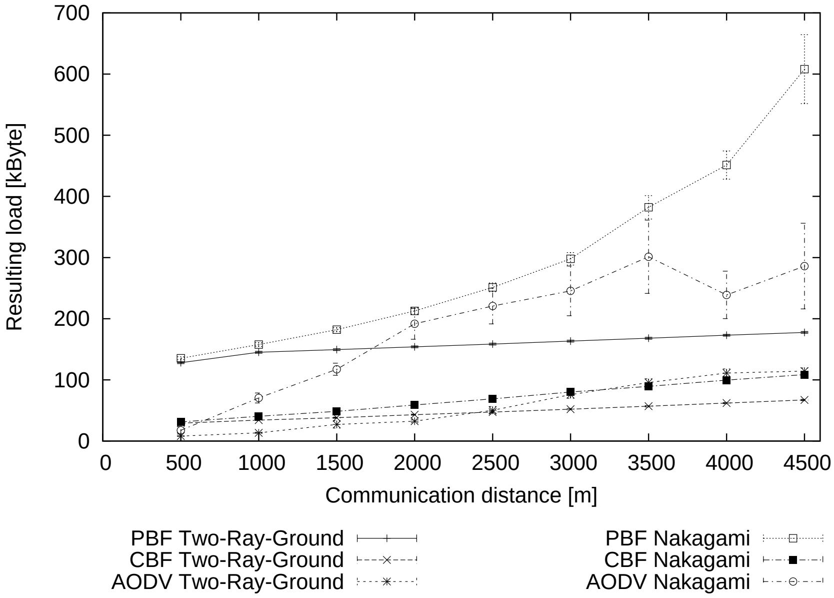

Figure 8: Resulting load in the medium of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami under low traffic conditions.

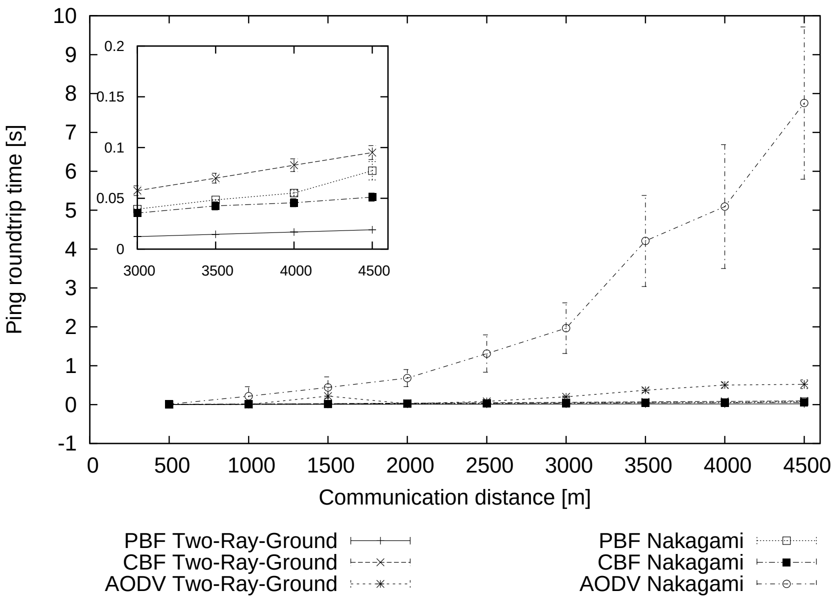

Figure 9: Round trip time of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami under low traffic conditions.

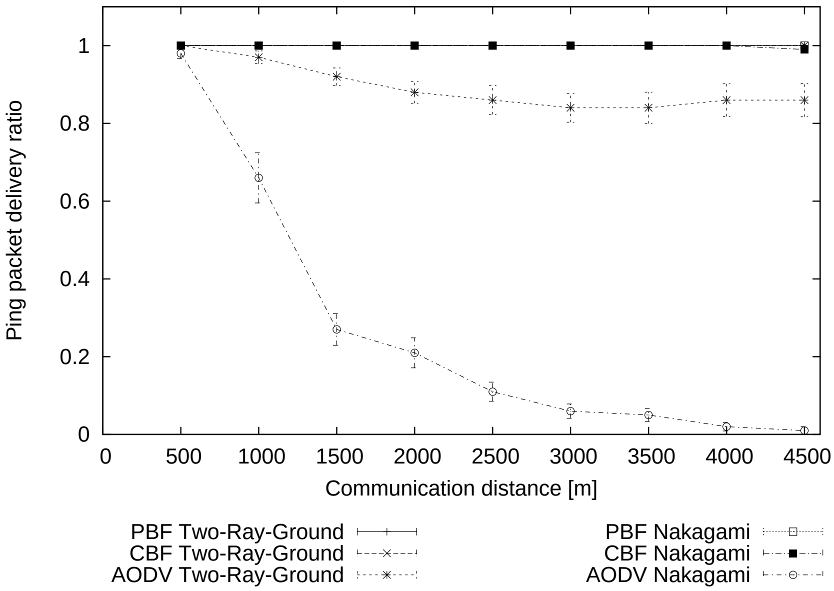

Figure 10: Packet Delivery Ratio of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami under high traffic conditions.

worth commenting from our point of view is the decrease on the packet delivery ratio shown by PBF for high communication distances and Nakagami due to the high resulting load experienced.

3.3 Impact of the Reactive Location Service

Motivated by the existence of geo-addressed applications in VANETs we also studied the performance of the position-based schemes assuming that the application relaying on the routing layer already knows the position of the targeted node, or area, at the moment it generates the first Ping packet. The results obtained in the medium/high traffic density present, as expected, a lower channel load, a shorter round trip time and no change with respect to the packet delivery ratio when RLS is not required.

Figs. 13 and 14 show a constant load increase for all distances and both propagation models when using RLS; except for a 1 hop communication in case of PBF since the source node knows the destination's position due the use of beacons. This constant difference results from the flooding mechanism used by the RLS, i.e., broadcasting location requests over the whole network. Notice also a lower increase of the resulting load in case of PBF when using RLS if we compare it with the increase experienced by CBF. PBF makes use of the position information exchanged by the flooding mechanism to update its neighbor table, hence, saving some beacons to be transmitted to the medium.

Fig. 15 and 16 show the influence of RLS on the experienced round trip time with the Two-Ray-Ground and the Nakagami model. Only the first Ping packet of each communication exchange is taken into account since the RLS is used only before the transmission of this first packet. As expected, we observe an increasing amount of additional RTT for higher communication distances when using RLS in every case. It is also noticeable again that the tendency of longer RTTs for PBF and shorter ones for CBF if the Nakagami model is used instead of Two-Ray-Ground.

4 CBF Analysis and Adjustment

With the Nakagami channel model, CBF shows the best performance w.r.t. resulting load, round trip time and number of hops to destination. In the following, we develop the analytical estimation of CBF's hop distance depending on the vehicular traffic density to evaluate the positive impact that it can have on CBF's performance. First though, we provide some necessary details on CBF's next hop selection procedure in order to understand the later proposal and improvements.

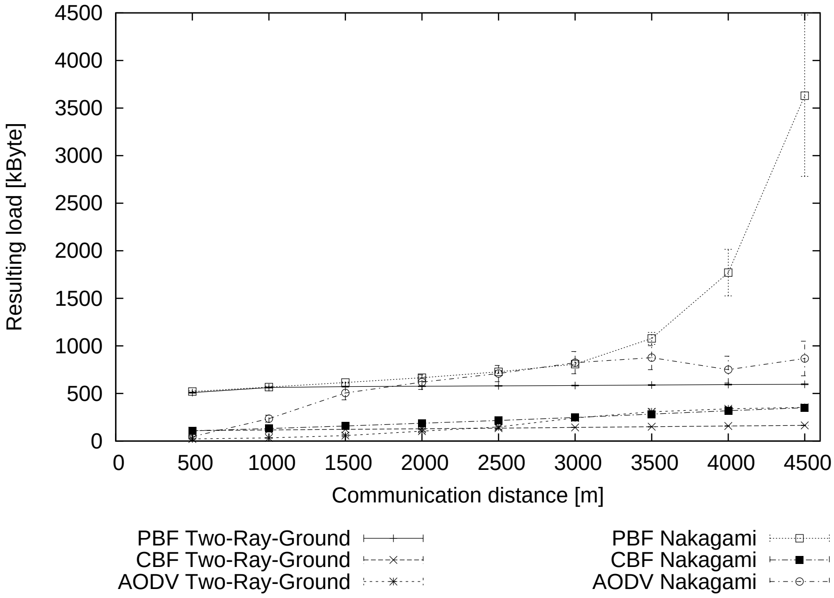

Figure 11: Resulting load in the medium of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami under high traffic conditions.

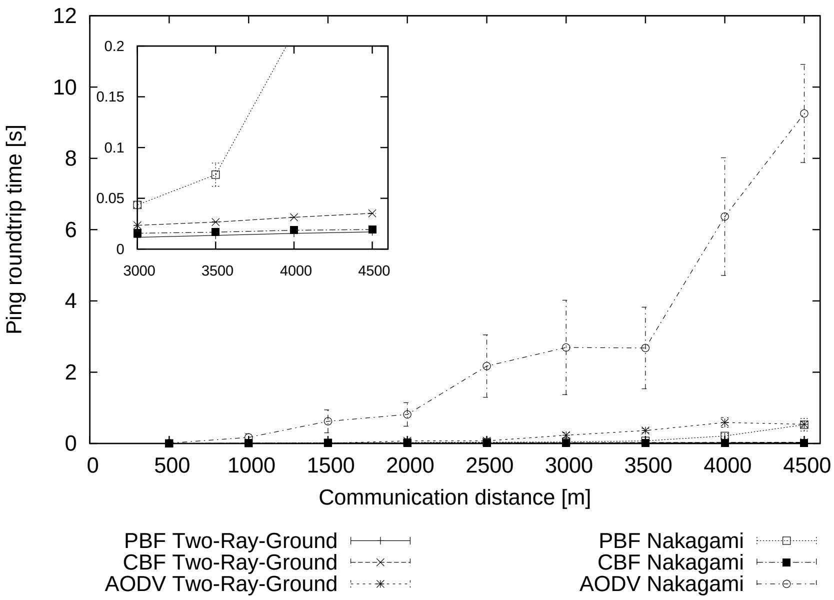

Figure 12: Round trip time of PBF, CBF and AODV when increasing the distance to destination for Two-Ray-Ground and Nakagami under high traffic conditions.

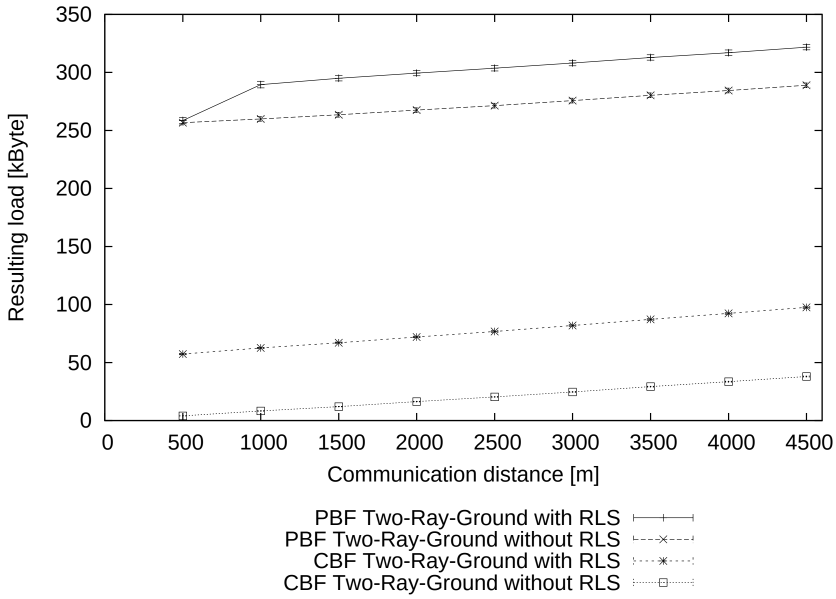

Figure 13: Impact of RLS. Resulting load of PBF and CBF when increasing the distance to destination under Two-Ray-Ground.

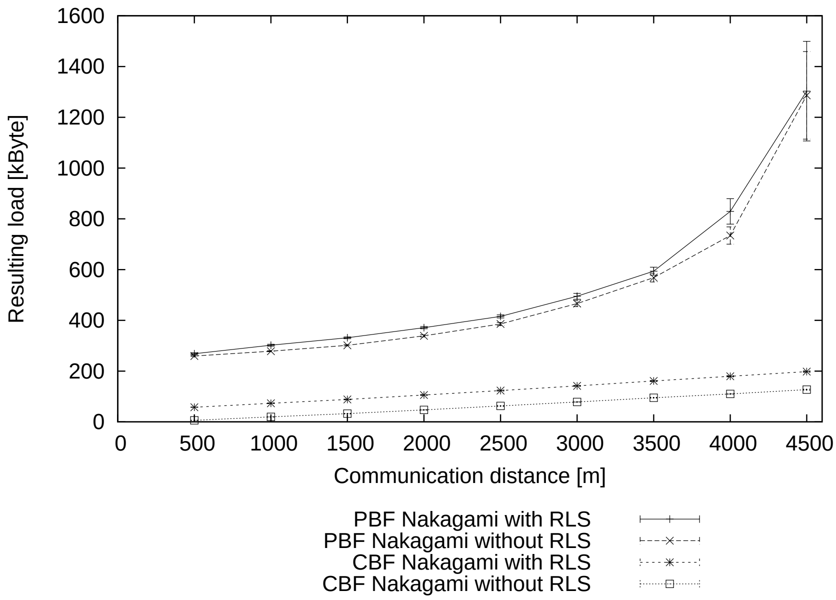

Figure 14: Impact of RLS. Resulting load of PBF and CBF when increasing the distance to destination under Nakagami.

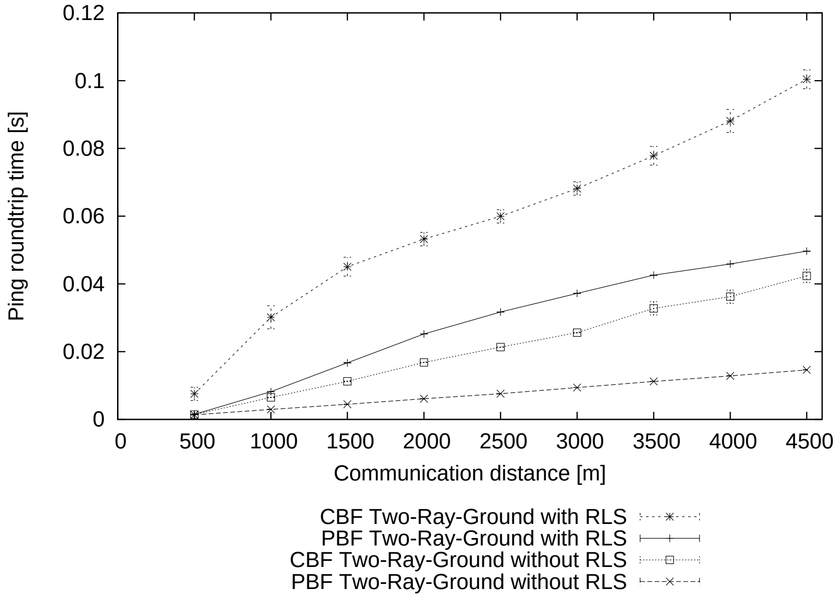

Figure 15: Impact of RLS. Round trip time of PBF and CBF when increasing the distance to destination under Two-Ray-Ground.

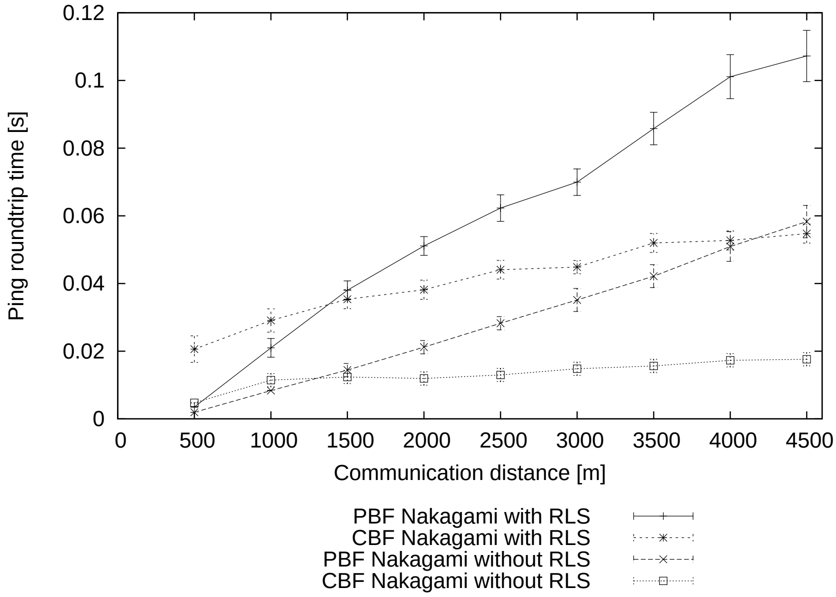

Figure 16: Impact of RLS. Round trip time of PBF and CBF when increasing the distance to destination under Nakagami.

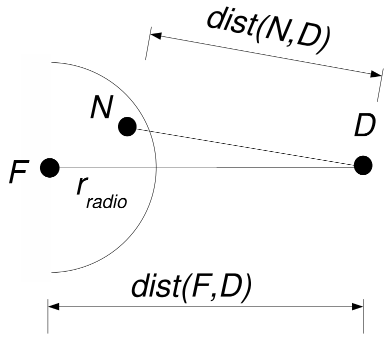

Figure 17: Calculation of CBF's waiting time: F denotes the last forwarder, D the final destination node and N a node receiving the packet. r_{radio} denotes the maximum distance towards destination a message is supposed to travel.

CBF uses contention to implicitly select the next hop in the communication path. Each potential forwarder, i.e., each node receiving the message to forward, computes the time t it must wait before transmitting the packet depending on its suitability, i.e., its progress towards destination:

$$P(F, D, N) = \max\left\{0, \frac{dist\,(F, D) - dist\,(N, D)}{r_{radio}}\right\} \tag{1}$$

$$t(P) = \begin{cases} \max\{0, T \cdot (1 - P)\} & , P > 0 \\ \infty & , else \end{cases} \tag{2}$$

where P is the progress function depending on the positions of the last forwarder F, the final destination node D of the packet and of the receiving node N. The Euclidean distance between two positions is expressed as $dist$, r_{radio} denotes the maximum distance towards destination a message is supposed to travel and T defines the maximum contention time. Fig. 17 illustrates the situation and the parameters used for the calculation. In Two-Ray-Ground, the setting of r_{radio} is as straightforward as using F's communication range, since nodes further than this distance can receive a message with probability 0 (see Sec 2.2). With Nakagami, however, the selection is not trivial since there exists no such border where the probability of reception of a message drops to 0. Note that a short r_{radio} can result in multiple collisions since all nodes located further than r_{radio} that receive the message will forward the message at the same time ($t(P) = 0$ for all of them). On the other hand, a long r_{radio} value results in a longer average forwarding delay.

In a linear network topology, the ideal r_{radio} setting in each case is the distance from F to the location of the furthest receiving node. In the following, we derive an estimation of this value or, in other words, the estimation of the hop distance in a CBF multi-hop communication.

4.1 Analytical estimation of hop distance

The average distance a message can travel in every hop depends on the propagation model, the nodes' density/distribution and the wireless interfaces' configuration.

In order to estimate the hop distance we must first consider the probability that a message is received at a specific distance. The Nakagami probability density function (*pdf*) [26, p. 102] describes the distribution of the power x of a received signal and is given by:

$$f_{pow}(x; m, \Omega) = \frac{m^m}{\Gamma(m)\Omega^m} x^{m-1} \exp\left(-\frac{m}{\Omega}x\right) \tag{3}$$

where Γ is the *Gamma function*, m denotes the *Nakagami m-parameter* and Ω the average received power. m and Ω depend on the distance d between sender and receiver. The *pdf* f_{pow} describes a *Gamma distribution* and as a special case (if $m \in \mathbb{N}$) an *Erlang distribution*. Therefore, in case that the Nakagami-m parameter is an integer, the Nakagami cumulative density function (cdf) can be expressed as:

$$F_{pow}(x; m, \Omega) = 1 - \exp\left(-\frac{mx}{\Omega}\right) \sum_{i=1}^{m} \frac{\left(\frac{m}{\Omega}\right)^{i-1}}{(i-1)!} \tag{4}$$

In our scenarios, assuming that packets travel further than $150m$, (4) simplifies to (using the same Nakagami configuration as in [16], where the m-parameter is set to 1.0 for $d > 150m$):

$$F_{pow}(x; 1, \Omega) = 1 - \exp\left(-\frac{x}{\Omega}\right) \tag{5}$$

The average received power Ω depends on d, the distance between sender and receiver. Assuming the simple *Free Space* model for Ω, this dependency can be expressed as:

$$\Omega(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L} \tag{6}$$

where P_t is the transmission power, G_t and G_r the antenna gains, λ the wavelength and L the path-loss factor (see [27]). Then, the cdf $F_{1,pow}(x; d) := F_{pow}(x; 1, \Omega(d))$ can be expressed as a function of d:

$$F_{1,pow}(x; d) = 1 - \exp\left(-\frac{x}{C} d^2\right) \text{ with } C = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 L} \tag{7}$$

In ns-2, a packet is received successfully if the received signal power is greater than the *Receiving Threshold* R_{xTh}. Thus the probability for successful reception at a certain distance d can be expressed as:

$$\begin{aligned} P_R(d) &= 1 - F_{1,pow}(R_{xTh}; d) \\ &= \exp\left(-\frac{R_{xTh}}{C} d^2\right) \end{aligned} \tag{8}$$

At this point we have an estimation of the probability of successfully receiving a message at a specific distance from the sender (in the absence of other node's interferences). Now, for simplicity reasons and justified by our focus on 'linear' scenarios, we model our road as a line where there is a node every δ[meters] at the moment a message is sent. Thus node n_i is positioned at $x_i = i \cdot \delta$[m], $i \in \mathbb{N}$. In these conditions, the probability that the furthest node receiving a packet sent by n_0 (with position $x_0 = 0$[m]) is node n_i can be expressed as:

$$\begin{aligned} P_F(i; \delta) &= P_R(i \cdot \delta) \prod_{j=i+1}^{\infty} \left(1 - P_R(j \cdot \delta)\right) \\ &= \exp\left(-\frac{R_{xTh}}{C} (i \cdot \delta)^2\right) \prod_{j=i+1}^{\infty} \left(1 - \exp\left(-\frac{R_{xTh}}{C} (j \cdot \delta)^2\right)\right) \end{aligned} \tag{9}$$

Then, the *expected value* of $P_F(\delta)$, $\mathbb{E}P_F(\delta)$, defines the expected average hop distance of a multi-hop communication:

$$\begin{aligned} \mathbb{E}P_F(\delta) &= \sum_{i=0}^{\infty} \left(i \cdot \delta \cdot P_F(i; \delta)\right) \\ &= \sum_{i=0}^{\infty} \left(i \cdot \delta \cdot \exp\left(-\frac{R_{xTh}}{C} (i \cdot \delta)^2\right) \prod_{j=i+1}^{\infty} \left(1 - \exp\left(-\frac{R_{xTh}}{C} (j \cdot \delta)^2\right)\right)\right) \end{aligned} \tag{10}$$

In order to corroborate our analytical estimation and our simulation tool we simulated the idealized road described above, i.e., one car every δ[m]. We can see in Fig. 18 the perfect match of the results obtained for the average hop distance by analysis and simulation for different distances between the cars. The configuration values are summarized in Table 2.

Both results show that lower distances between cars can achieve higher average hop distances. The higher average distance that a message can travel in one hop is the result of a higher number of nodes that can probably receive, and therefore forward, the packet.

Furthermore, given the specific PHY settings (see Table 2) and together with the nodes distribution, it is possible to interpolate the resulting curve. In our case we use a polynomial $p(\delta)$ of degree 3 with a relative error lower than 2% for distances between cars greater than 10 meters:

$$p(\delta) = -0.0005\delta^3 + 0.1191\delta^2 - 11.1337\delta + 968.3044 \tag{11}$$

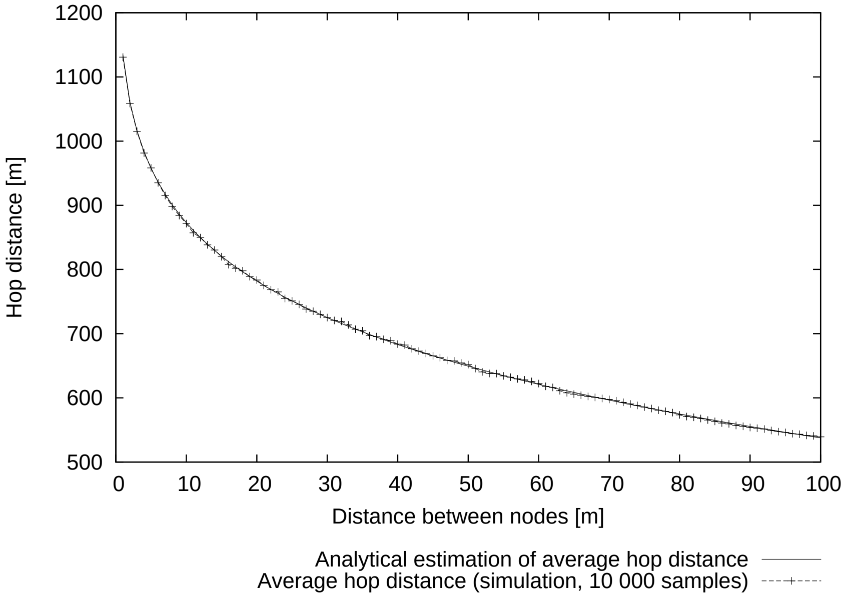

Figure 18: CBF's expected and simulated value of the average hop distance $\mathbb{E}P_F(\delta)$ when increasing the distance δ[meters] between cars positioned in a line.

Table 2: Physical layer parameters

Transmission power (P_t)	$7.6543 \cdot 10^{-4}W$
Reception threshold (R_{xTh})	$3.1632 \cdot 10^{-13}W$
Antenna gains (G_t, G_r)	$4dB$
Carrier frequency (f)	$5.9GHz$
Wavelength (λ)	$50.8mm$
Path-loss factor (L)	1

4.2 CBF's Adjustment

In the simulated scenario of Sec. 3.2, CBF achieved (with high distances to destination, $4500m$) an average hop distance of $681m$. However, if we would use that car density, i.e., 34 cars/km, on the simple model described above, i.e., one car every $29.4m$, we would estimate an average hop distance of $725m$. The difference between the estimated and the achieved hop distance is due to the non-uniform distribution of cars in a realistic highway scenario and the suboptimal r_{radio} setting, i.e., $500m$.

As explained above, a shorter r_{radio} can result in a higher resulting load in the medium due to collisions among the forwarders. In Fig. 19 we can observe how a higher choice of r_{radio} results in a lower resulting load. Note also the remarkable benefit from using $r_{radio} = 725m$, i.e., the expected value using the model from Sec. 4.1, and the little one of extending to $r_{radio} = 1000m$ in terms of resulting load.

On the other hand, if we take a look at Fig. 20 we become aware of the trade-off between decreasing the channel load and increasing the round trip time. In other words, having a higher r_{radio} achieves lower resulting load (less collisions) but results in a higher round trip time due to longer contention periods of all potential forwarders. If we take a look at the achieved average hop distance, Fig. 21, we observe that a higher r_{radio} leads, as expected, to higher average hop distances. Note that the distance traveled for the last hop is not averaged since it is limited by the position of the destination node. As in Fig. 19, we can observe that *i)* increasing r_{radio} until the expected value offers a significant improvement and *ii)* setting r_{radio} to even higher distances results in little benefit.

Taking all observations together, we can state that the expected hop distance, i.e., $725m$, presents a good choice of r_{radio}. It slightly increases the round trip time (by only $40ms$ for a bidirectional communication over $4500m$) but it presents a remarkable improvement with respect to coordination among the intermediate nodes. From our point of view, any improvement in the channel load can result highly beneficial in the future when the technology is developed and there exist a high number of equipped vehicles on the roads.

For completeness, we present in the following the results obtained when adjusting r_{radio} in the low and high nodes density scenarios.

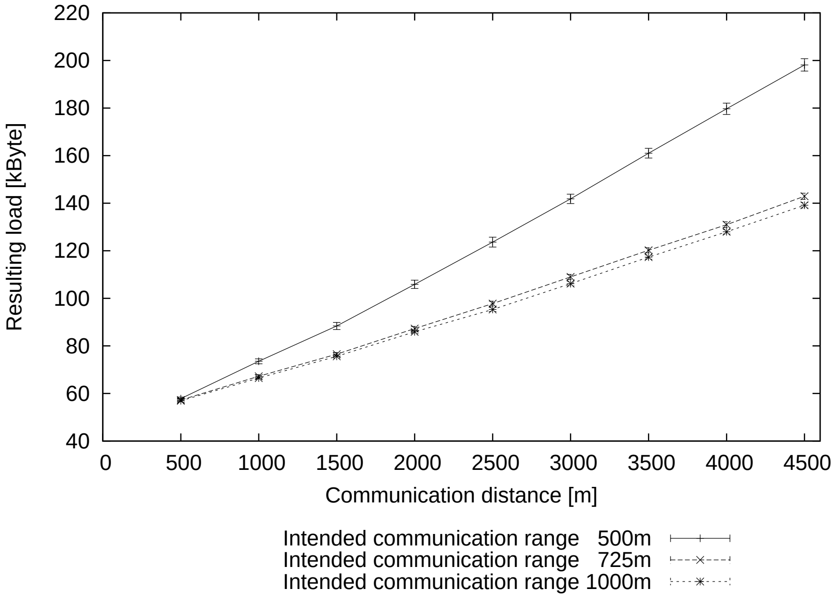

Figure 19: CBF's resulting load in the medium for different values of r_{radio} when increasing the distance to destination under Nakagami.

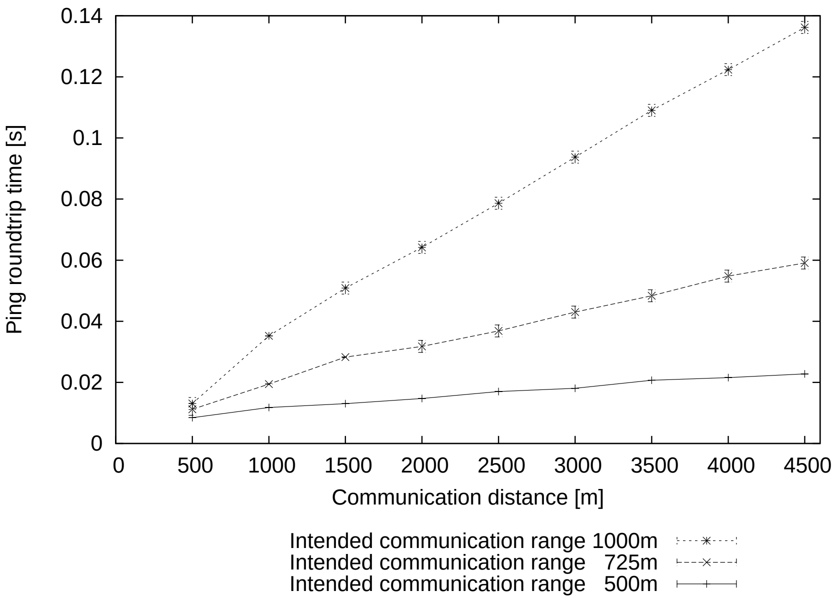

Figure 20: CBF's round trip time for different values of r_{radio} when increasing the distance to destination under Nakagami.

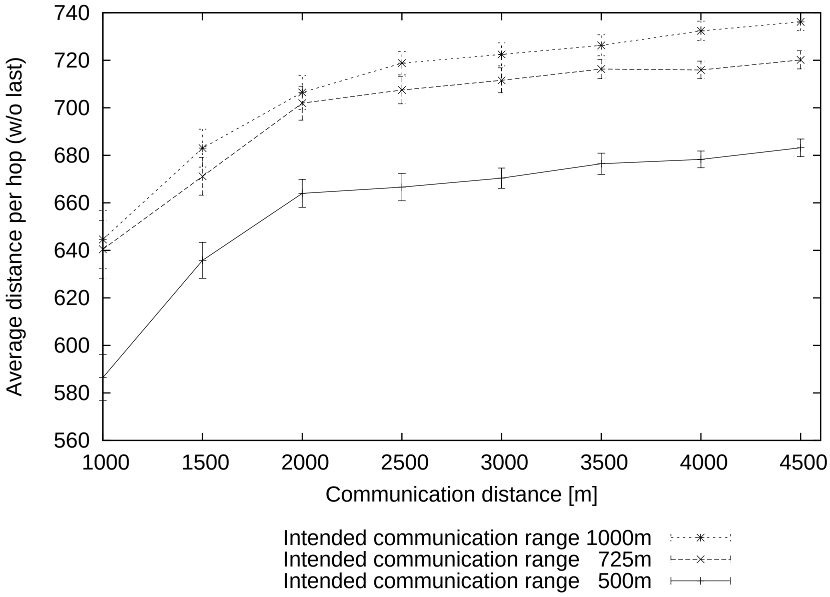

Figure 21: CBF's average hop distance for different values of r_{radio} when increasing the distance to destination under Nakagami.

4.2.1 Low car density

The same observations described before can also be noticed when the scenario with low traffic density is used. In average, there are 24 cars per km, that results in an average car distance of $41.7m$. The expected average hop distance for this car density is $675m$. As we can see in Fig. 22, the impact of adjusting the r_{radio} parameter to its expected value lowers the resulting load by up to 14%, while a higher value for r_{radio} does not improve the situation anymore. Fig. 23 presents the price to pay in terms of RTT when reducing the load on the medium.

4.2.2 High car density

In case of high traffic density the effect of the r_{radio} adjustment can be seen in Figs. 24 and 25. In our case, r_{radio} has been set to $820m$, the theoretical average hop distance.

Again, we can observe the high decrease in the resulting load with $r_{radio} = 820m$ and the little further decrease for $r_{radio} = 1000m$, Fig. 24. On the other hand, the resulting RTT for $r_{radio} = 1000m$ is remarkably higher than for $r_{radio} = 820m$, Fig. 25.

Summarizing, we can state that adjusting the r_{radio} parameter in the way described is a good balance between resulting load and observed Round Trip Time.

5 Conclusions

Some future VANETs applications will most probably require geo-addressing strategies. Motivated by this fact, this paper studies the impact on packet forwarding strategies of multi-path fading, an important characteristic in vehicular environments often neglected in wireless studies. To accomplish our purpose, we have used a simulation setup not only using realistic vehicle movements, but also a probabilistic radio propagation model (Nakagami) adjusted to VANET radio characteristics.

In such a context, we first performed a simulative comparison of two position-based schemes, one with beacons (PBF) and another with a contention-based forwarding strategy (CBF). Additionally, due to completeness we included a topology-based routing protocol (AODV). The three protocols have been analyzed under the assumption of both deterministic (Two-Ray-Ground) and probabilistic (Nakagami) propagation models. From the results obtained we can draw the following conclusions: *i)* the radio propagation model utilized has a great impact on protocol performance, *ii)* probabilistic channel models can not only have a negative impact but also enhance protocol performance in certain aspects *iii)* not selecting a specific node as ‘next hop’ before the transmission of a message is a robust strategy against both unreliable links and dynamic topologies and *iv)* although the explicit pre-selection of a next-hop may lead to almost perfect

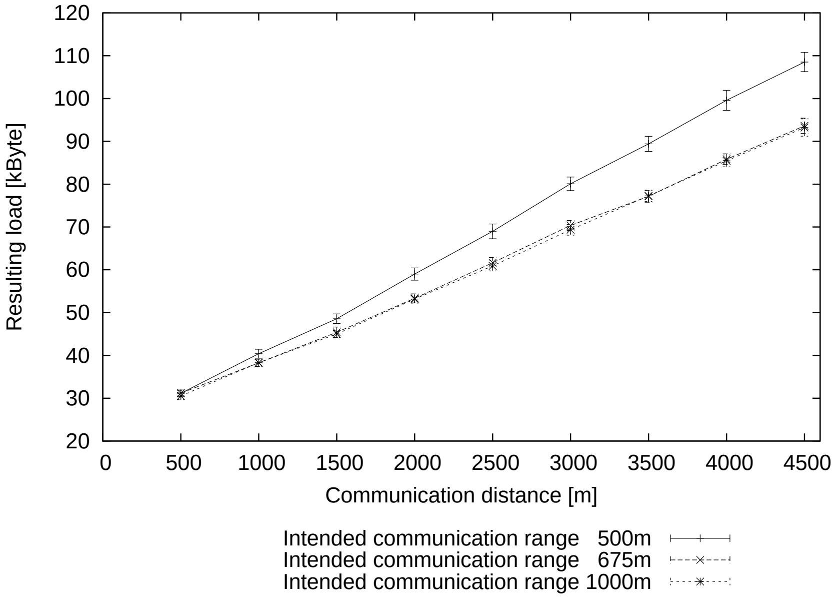

Figure 22: CBF's resulting load for different values of r_{radio} when increasing the distance to destination under low nodes density under Nakagami.

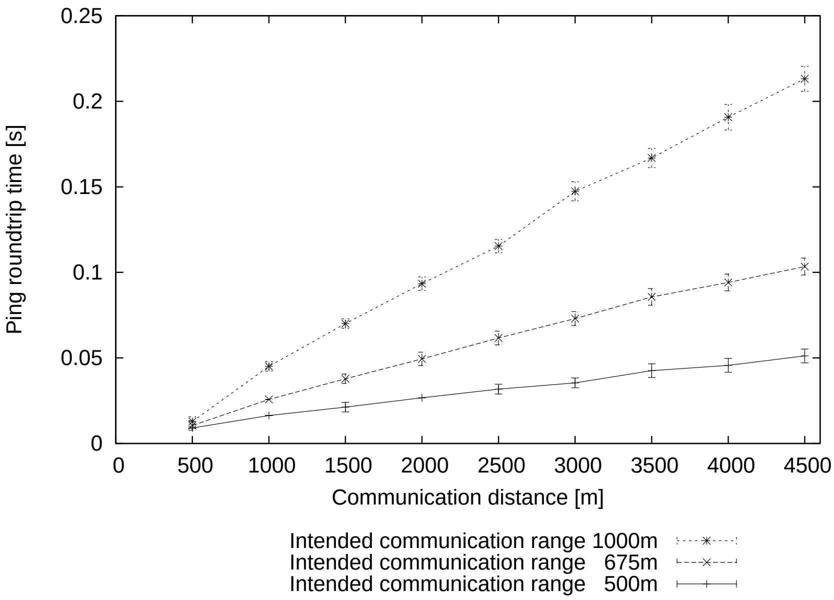

Figure 23: CBF's round trip time for different values of r_{radio} when increasing the distance to destination under low nodes density under Nakagami.

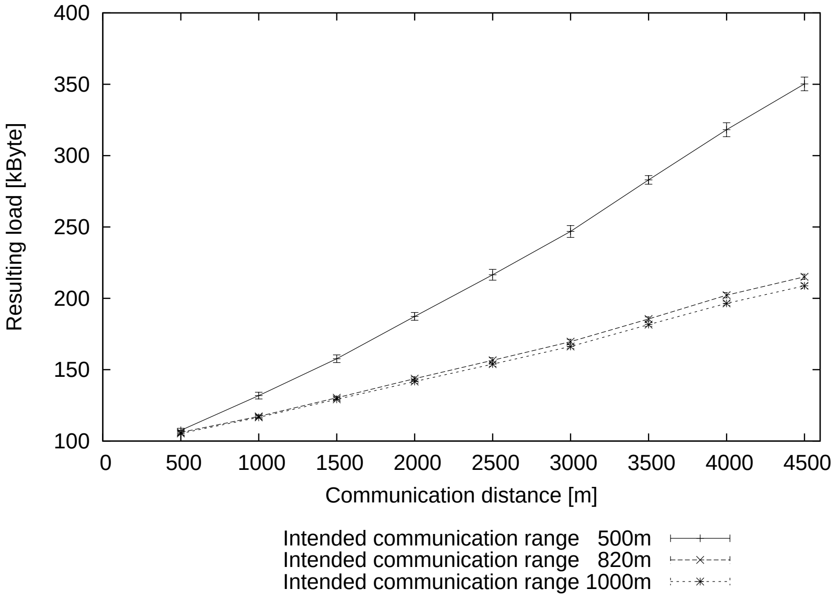

Figure 24: CBF's resulting load for different values of r_{radio} when increasing the distance to destination under high nodes density under Nakagami.

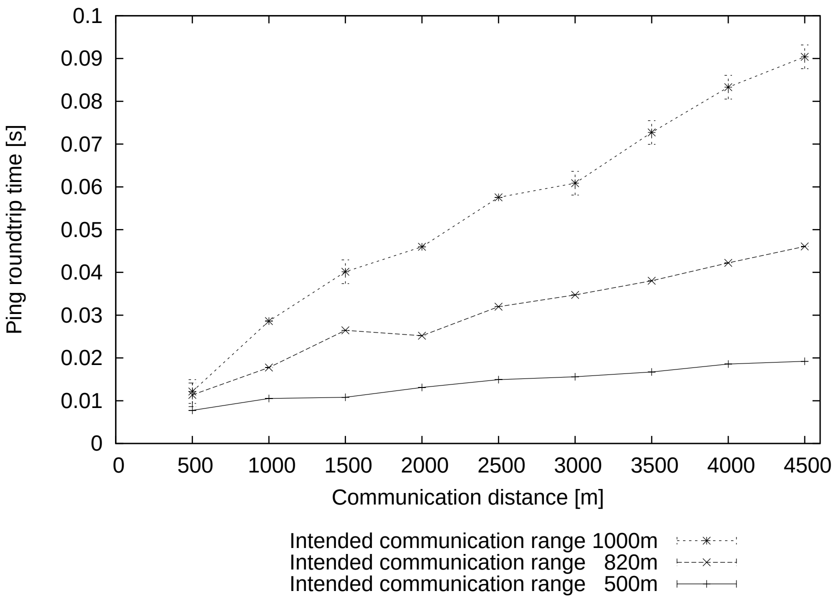

Figure 25: CBF's round trip time for different values of r_{radio} when increasing the distance to destination under high nodes density under Nakagami.

end-to-end packet delivery, the consequential MAC retries induce additional delay and load costs. For these reasons we believe that CBF is a serious candidate to be used in future vehicle-to-vehicle communications.

Second, after understanding the behavior of CBF under a probabilistic radio model we conducted an analytical study of its expected hop distance. Moreover, we corroborated this result with simulations and showed how it can be used in order to improve CBF's performance. The result of this adjustment is a reduction of the number of collisions, i.e., a better synchronization among neighbors, with the only trade-off of a slight increase in delay.

Our current work comprises a broader study of the CBF strategy, including other scenarios, such as sensor network type, and applications, such as robust information dissemination inside a geographical area.

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