Analysis of a Receiver-based Reliable Broadcast Approach for Vehicular Networks

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***Abstract*—The Intelligent Transportation Systems (ITS) concept provides the ground to enable a wide range of applications to improve traffic safety and efficiency. Innovative communication systems must be proposed taking into account, on the one hand, unstable characteristics of vehicular communications and on the other hand different requirements of applications. In this article a reliable (geo-)broadcasting scheme for vehicular ad-hoc networks is analyzed. This receiver-based technique aims at fulfilling the received message integrity yet keeping overhead at a reasonably low level. The results are compared to simulation observations carried out in the Network Simulator-3 (NS-3) simulation environment and they demonstrate good fit to each other.**

I. Introduction

Forwarding and transport protocols are among the main design principles of vehicular communication systems [1]. Forwarding of data packets, as part of a routing protocol, is classified into four types in the vehicular communication domain. They are Geographical Unicast (i.e., direct or multi-hop unidirectional transport of data from a single node to a single node using geographic addresses); Topologically-Scoped Broadcast (TSB) (i.e., transport of data packets from a single node to all nodes of a vehicular network); Geographical Broadcast (i.e., transport of data packets from a single node to all nodes in a geographical region), and Geographical Anycast (i.e., transport of data packets from a single node to any of the nodes in a geographical region) [1]. The transport protocol of a vehicular communication system must meet applications requirements, which in turn affect its design [1]. Here, we consider reliability as the one relevant to our approach. Reliability here refers to assuring that a message has reached the highest possible number of intended receivers. Due to the inherently unreliable nature of vehicular environments, it is very challenging to design an end-to-end reliable (geo-)broadcast protocol guarantying delivery of packets to all intended receivers of a vehicular network and it could considerably degrade the performance. For instance, lack of a couple of packets from the set of packets constituting big messages such as maps, at the receiver-side makes the whole message useless. Providing end-to-end reliable delivery for (geo-)broadcast is an open area of research and in this paper, we describe a novel receiver-based end-to-end reliability assurance scheme in the context of geographically scoped broadcast in vehicular networks. According to this scheme, every packet, as part of a message, is marked with a sequence number, in an increasing order. By sequence checking, the missing packets from a message are detected at the receiver-side and requested afterwards to the neighbors, from which those possessing the desired packet will reply by broadcasting it. In order to avoid collisions as a result of concurrent requests and replies, a back-off timer-based policy is further considered. This approach is not developed with a specific kind of application in mind and could be fitly applied in scenarios with large (e.g., maps) and small (e.g., regular awareness) sized messages.

The main contributions of this paper are as follow. (i) The first sketch of the end-to-end (geo-)broadcast reliability assurance mechanism, which is proposed in the framework of the MOBILITY 2.0 FP7 project [2], is extended with more complementary and reformative specifications. (ii) We model the approach and analytically analyze its functionality. (iii) Further, utilizing NS-3 [18], we validate observations from the analytical analysis.

The rest of the paper is organized as follows. At First, Section II provides a look at the related work. Section III introduces the proposed reliable (geo-)broadcasting approach. Following Section III, Section IV is devoted to the analytical modelling and analysis of the scheme. Numerical results derived from implementing the model in Mathematica and model simulation are presented in Section V. The last section concludes the paper.

II. Related Work

There are plenty of ITS applications demanding to address a group of vehicles falling into the same geographic location. Geocasting is the routing protocol fitting to this demand. However, unreliability of vehicular environments makes it quite challenging to guarantee end-to-end (geo-)broadcast reliability and it could be of significant importance based on application types (e.g., safety applications). Various mechanisms for (geo-)broadcasting and proposals introducing reliability to the scope have emerged in the literature. In general, (geo-)broadcasting reliability approaches could be divided into two main categories as multi-hop and one-hop and further into sender-based (i.e., the recovery action is initiated by the sender such as regular repetitions, also known as implicit recovery) and receiver-based (i.e., the recovery action is initiated by the receiver, such as acknowledgement, also known as explicit recovery) approaches. Here, we refer to those mechanisms and protocols related to our approach.

In [14] [20] [15] [28] overhearing of rebroadcasted messages is considered as an implicit acknowledgement for the sender and all the vehicles with pending rebroadcasts. Besides that, in [17] if the most recent forwarder hears the rebroadcast of a packet, it sends an explicit ACK to the former forwarder to stop further unnecessary rebroadcasts. In [11] while distance-based timers are applied to rebroadcast, overhearing of rebroadcasts is considered as implicit acknowledging. Two kinds of short interval and long interval rebroadcasts are considered to cope with communication losses and network fragmentation, respectively. [5] and [25], both are overhearing based suppression schemes with rebroadcast back-off timers, inversely proportional to the distance between the vehicles and the sender, to ensure longer packet traverse distances. The geocasting protocol in [3] is also a timer-based rebroadcast approach with the difference at back-off time assign criteria, which is preferential for the vehicles at intersections. Such schemes in general improve hop-by-hop and not end-to-end traverse reliability at the cost of increased overhead and redundancy.

The approach in [12] is based on two schemes as Slotted Restricted Mobility Based (SRMB) scheme and the Pseudo-ACKnowledgements (PACK) scheme. While SRMB is responsible for data dissemination over a specified distance, PACK assures multi-hop dissemination reliability by interpreting overheard rebroadcasts as a measure of successful transmission. In [16] besides the distance between the current receiver and the previous forwarder, the number of the local copies of the message at each receiving vehicle, is considered to take the rebroadcast decision. This approach is based on acknowledging the received messages to assure reliable delivery by indexing the copy of the messages. In [21] an end-to-end geocast acknowledgement scheme is proposed, in which individual ACKs are accumulated into larger messages in an aggregator. The approach in [19] is based on the Connected Dominant Set (CDS) scheme and Neighbour Elimination Scheme (NES) [23] [22] for reliable data dissemination. Vehicles possessing the message of interest set a back-off timer, such that the vehicles in the CDS choose a shorter back-off timer, and rebroadcast it upon timer expiration if discovering their neighborhood is not fully covered. Identifiers of the recently received messages are included in beacons as ACKs. In [30], each sender sets a receive ACK window, which is divided into many adaptive slots proportional to the number of neighbors. The retransmission will be started if any ACK from a neighbor in the table of neighbors is missing upon expiration of the ACK window. The approach in [6] is an ACK-based approach such that a couple of packets to be transmitted are combined at first based on a symbol combining algorithm and then transmitted to the intended receivers. It is assumed to deploy an error detection code at the receiver end able to detect any loss pattern and send a negative ACK to the sender side, otherwise a positive ACK will be sent.

The approaches in [7] and [13] both propose a repetition-based scheme for increase reliability assurance, while keeping it efficient by computing efficient rebroadcast intervals based on the vehicle speed, transmission range and the number of the planned repetitions. In [24] rebroadcast decision is based on neighbor detection. That is, upon reception of a packet by a vehicle, if it is connected to its vicinity, it is assumed that most probably the neighbors have also received the same packet and a broadcast suppression mechanism [27] is applied afterwards. However, if the vehicle is sparsely connected, it can immediately rebroadcast the received packet. If the vehicle is totally disconnected, it stores the packet till it expires and then rebroadcasts it once connected again. The approach in [4] proposes to divide the geobroadcast target area into sub-areas and to use different message dissemination techniques in each of them to enhance reliability. Still, end-to-end transfer may not be satisfied. [29] encompasses two phases as initialization and maintenance. The latter is considered for reliability improvement by keeping rebroadcasting at regular time intervals, within a smaller area than the target area to be less redundant and cost-efficient. As a result, this approach fails to guarantee end-to-end reliability for all the intended receivers. The approaches in [26] [9] improve loss recovery performance compared to simple repetition by XOR coding a packet with other packets received from other vehicles and repeatedly transmiting the XORed packet. However, there is still no explicit demand from the receiver side for such, possibly redundant, retransmissions.

Summarizing, sender-based mechanisms cannot provide delivery assurance, as they do not rely on explicit knowledge from the receiver-side. Receiver-based approaches are mostly acknowledgement-based and inefficiently overload the network with acknowledgement packets. In this work, a receiver-based approach is described for one-hop (geo-)broadcast, in which receivers are able to detect lost packets and explicitly ask for them.

III. THE END-TO-END RELIABLE GEOCAST PROTOCOL

The work introduced here is an end-to-end reliability assurance mechanism for (geo-)broadcast in vehicular environments which is proposed in the framework of the MOBILITY 2.0 FP7 project. This receiver-based approach enables loss detection and correction by implementing a sequence checking functionality and is suitable for a wide variety of ITS applications demanding strict requirements on message dissemination. Before proceeding with the system description, it is worth pointing out that here we assume that the underlying ETSI/ITS standard geo-networking infrastructure [8] is functionally available, providing the basis to implement such a facility.

The sequence number checker module works as follows. At first, the packets to be broadcasted are sequentially numbered. Further, a unique session identifier is assigned to the packets constituting a single message and flags to identify the first and last packets of a message are set as well. Hence, the receiving side can detect any inconsistency in the sequence of received messages. If any missing packet is detected, a back-off timer randomly set from 0 up to a few milliseconds is started. Upon expiration of this timer, a Single-Hop Broadcast (SHB) query is initiated to fetch the missing packet from any neighbor, by encompassing the relevant sequence number in the request. The aim of such a random back-off timer is to prevent many duplicate requests from different receivers for the same packet and consequently collisions. During the countdown period as any received broadcast of that packet cancels the timer, any received query for the same packet causes extension of this pending query, up to limited number of times. Such functionality gives a break to the neighbor with pending request to get the packet of interest as a result of heard query and if it is not the case, it will broadcast its own query to give a try to get that packet. Upon broadcasting the request, the vehicle starts a randomly set back-off timer to get the reply. During the countdown if the vehicle does not get the reply, it will rebroadcast a request to try once more to get the desired packet. When the source of the packet or any other neighbor already having the packet receives the retransmission request for the packet, it verifies whether it has in its data cache the missing packet. If it is found, a randomly set back-off timer having value from 0 up to a few milliseconds is started, after which the packet is single-hop broadcasted, if it is not broadcasted by another vehicle before timer expires. Again, this waiting procedure is designed to prevent numerous duplicate retransmissions and collisions. Note that even by utilizing single-hop broadcast of the request packet in the current version of the scheme, it is of high probability that the packet will finally reach a vehicle possessing the requested packet after some time, because of a predefined number of regular request broadcasts.

IV. MODELLING AND ANALYSIS

The focus of this section is on analyzing the functionality of the proposed reliable (geo-)broadcast approach through analytical modelling. The Table I summarizes the notation used throughout the analysis.

TABLE I: The analysis notation

Parameter	Definition
K	The number of the packets constituting a message
N	The number of the receivers
L	The number of the retransmission requests allowed
D	The number of steps till absorption of the Markov chain
$T_{timeout}$	Constant waiting time to receive the reply after a request
T_T	Transmission time of a data packet over the channel
T_R	Transmission time of a request packet over the channel
p_T	Data packet loss probability
p_R	Retransmission request packet loss probability
$1/r_T$	Mean number of time slots prior sending a data packet
$1/r_R$	Mean number of time slots prior sending a request packet
T_{slot}	Duration of a time slot
$E[T_i]$	Mean time spent in the state i of the chain
$E[T]$	Mean time spent in transient set of states till absorption
$E[T_i\|F]$	Mean time spent in the state i, conditioned with failure

In the following subsections, it is considered that all stations can hear each other and the station 0 is the source of broadcast. The simplified system for performance modelling operates as follows. First, the sender transmits a packet by choosing a random access delay, as a means to avoid potential collisions. Geometric distribution is found to be suitable to mimic this delay as it models the number of trials until the first success. Hence, a geometric distribution with mean $1/r_T$ is considered for this purpose. The probability of the data packet loss due to wireless channel conditions is considered to be independent, identically distributed (i.i.d) for all the stations and equal to p_T. Upon receiving a data packet, the stations will detect possible previously lost packets by checking the sequence number of the received packet. Given that the stations, say i out of N, may have not received data packets correctly at the first transmission, they will all choose a certain back-off value from the geometric distribution with parameter r_R independently of each other to broadcast a retransmission request for each lost packet. Requesting stations will then start a time out to receive the packet of interest, otherwise they will resend the request. If no collision happens as a result of concurrent transmission of requests, the request for the packet is received correctly at $N - i$ stations having the original data packet, with probability $1 - p_R$. Here again it is assumed that the request packet loss probability due to wireless channel conditions is i.i.d for all the stations and equal to p_R. Assuming that j stations out of $N - i$ have received the request, they all will choose a certain back-off value from the geometric distribution with parameter r_R to reply with the packet of interest. If no collision happens, the queried packet is correctly received at i stations with probability $1 - p_T$. The procedure repeats itself until all the stations have received the data packet correctly or the number of allowed retransmission requests exceeds.

In order to evaluate the performance of the proposed scheme, we model the system functionality using an Absorbing Markov chain [10], which well suits to the case as described below.

1) Absorbing Markov Chains: Most of the analysis performed in this paper is based on direct application of an absorbing Markov chain. That is, it contains one or more states that, once entered, cannot be left. The absorbing states are accessible from any other state, called transient. Considering the system operation specification, we reasonably model the process of packet distribution from originator to N recipients using the discrete-time absorbing Markov chain with the state space $\{S(n) \in 0, 1, ..., N\}$, where the state number $S(n)$ describes the number of stations not yet having the packet of interest by time n. The process behaves as follows. At the original transmission attempt the chain enters a state $i = 0, 1, ..., N$. If it is not immediately absorbed in the state 0 then it jumps between transient states for some amount of time slots as a result of retransmission requests and replies and finally gets absorbed in the state 0, where all the stations have the packet of interest. Since the number of stations having the packet after the next retransmission attempt depends only on the number of stations having it right now, the process is Markovian. Notice that in our scenario the system start point is considered after the first original transmission of the packet. Hence, the initial state distribution of the system is given by the number of stations successfully receiving the packet at the first transmission attempt. In most models below there is only one absorbing state. Let it be labelled as $S(0)$.

A Markov chain with N transient states and one absorbing state is characterized by a transition matrix T [10] as

$$T = \begin{bmatrix} 1 & \overrightarrow{0^T} \\ \overrightarrow{q} & Q \end{bmatrix} , \tag{1}$$

where Q is an $N \times N$ matrix whose elements, $q_{ij}, i, j = 1, 2, ..., N$ define transition probabilities between transient states of the absorbing Markov chain, $\overrightarrow{0^T}$ is the vector of zeros, and $\overrightarrow{q} = (q_{10}, q_{20}, q_{30}, ..., q_{N0})$ is the vector containing transitions between the transient and absorbing states. Hence, we could reform the canonical form of the Markov chain into the following form

$$q_i + \sum_{j=1}^{N} q_{ij} = 1, \ i = 1, 2, ..., N \ , \tag{2}$$

in which q_i is the probability of going to the absorbing state immediately from the state i. Equivalently, in the short matrix form we have

$$\overrightarrow{q} + Q\overrightarrow{e} = 1 \ , \tag{3}$$

where $\overrightarrow{e}$ is a vector of ones of size N. Consequently, the model is completely characterized by Q.

In what follows for a Markov chain defined in (1) we are interested in computing the probability of absorption in no more than k steps. Absorption of a Markov chain could be modelled with a First Passage Time (FPT) distribution expressing the number of steps required to take in order to get into the absorbed state $S(0)$ from the set of all transient states $1, 2, ..., N$. Let D denote the random variable describing the number of system steps till absorption. The Cumulative Distribution Function (CDF) is immediately given by

$$F_D(k) = Pr(D \leq k) = 1 - \overrightarrow{h}(Q^k)\overrightarrow{e} \ , \tag{4}$$

where $\overrightarrow{h}$ is the initial state probability vector. The CDF provides the probability that the chain absorbs in no more than k steps and it gives us the probability we are looking for. According to the definition of the transition probability matrix Q, it is inferrable that the probability of transition from the state i to the state j in exactly k steps is the (i, j)th entry of $\overrightarrow{Q^k}$. A basic property of an absorbing Markov chain is the fundamental matrix of the chain defined as summation of $\overrightarrow{Q^k}$ over all k's [10] as

$$Z = \sum_{k=0}^{\infty} \overrightarrow{Q^k} = (I - Q)^{-1} \ , \tag{5}$$

where I is the identity matrix of size $N \times N$. The (i, j)th entry of the fundamental matrix Z represents the expected number of visits to a transient state j prior to absorption, assuming the system starts at a transient state i.

To parameterize an absorbing Markov chain with N transient states we should provide three parameters as the $N \times N$ transition probability matrix Q between transient states, the $1 \times N$ vector $(q_1, ..., q_N)$ containing transitions between transient and absorbing states, and the $1 \times N$ vector $(h_0, h_1, ..., h_N)$ providing the initial distribution of states of the system.

As already mentioned, the initial state distribution of the system is given by the number of stations successfully receiving the packet of interest at the first transmission attempt. Letting p_T be the probability of incorrect reception of a data packet we have

$$h_i = \binom{N}{i} p_T^i (1 - p_T)^{(N-i)}, \ i = 0, 2, ..., N \ , \tag{6}$$

which is binomial distribution with parameters p_T and N. From now on we will use the notation $B(p, i, N)$ to denote binomial probabilities.

In order to find $q_{ij}, i, j = 1, 2, ..., N$ consider an arbitrary state i. Notice that the only transitions allowed for the state i are those leading to states $j = 0, 1, ..., i$. The actual probabilities of transitions depend on the probabilities of incorrect reception of data and retransmission request packets, denoted by p_T and p_R, respectively.

The probability that a retransmission request for a missing packet of interest is successfully received by at least one station having the packet is denoted by $p_{success}$ and given by

$$p_{success} = \sum_{k=1}^{N-i} \binom{N-i}{k} p_R^{(N-i-k)} (1 - p_R)^k \ , \tag{7}$$

where k denotes the number of receiving stations. All stations that have received a retransmission request correctly, will start a (geometrically distributed) timer to reply. When the shortest timer expires, a reply is sent and the system may transit to another state j as a result of this reply. It implies that $i - j$ stations out of i stations have received the reply packet correctly, while the remaining j stations have not received it due to transmission loss and it is given by binomial distribution as

$$B(p_T, j, i) = \binom{i}{i-j} p_T^j (1-p_T)^{(i-j)} \ . \quad (8)$$

Such probability demands that at least one station having the original packet has correctly received the retransmission request packet at first. Therefore, it is conditioned on $p_{success}$. Consequently, we get the probability of the system transition from the state i to the state j as

$$q_{ij} = \sum_{k=1}^{N-i} \binom{N-i}{k} p_R^{(N-i-k)} (1-p_R)^k \binom{i}{i-j} \times \times p_T^j (1-p_T)^{(i-j)}, \quad (9)$$

where $i = 0, 1, \ldots, N$ and $j = 0, 1, \ldots, i-1$. Note that there is still a chance that no station get the data packet correctly at the end of the retransmission attempt. Obviously from the last equation, it is given by the probability

$$q_{ii} = p_R^{(N-i)} + \sum_{k=1}^{N-i} \binom{N-i}{k} p_R^{(N-i-k)} (1-p_R)^k p_T^i \ , \quad (10)$$

where $i = 0, 1, \ldots, N$ and it is the probability of remaining in the same state.

Finally, the elements of $\overrightarrow{q}$ are obtained observing that the only way to approach the state 0 from any arbitrary transient state i is receiving the data packet correctly by all i stations and the corresponding probability is given by

$$q_{i0} = \sum_{k=1}^{N-i} \binom{N-i}{k} p_R^{(N-i-k)} (1-p_R)^k (1-p_T)^i \ , \quad (11)$$

which completes parameterization of the model.

The mean transmission delay consists of the time required to perform the initial transmission followed by the time spent for all consecutive requests and replies until all the stations correctly receive the packet. During this time the system traverses from the initial state to the absorbing state by passing through transient states. Therefore, at first we need to know the probability of visiting either of system states and later the amount of time spent in each of them till absorption, which may vary from state to state. The probability of visiting any arbitrary transient state j of an absorbing Markov chain when starting at a transient state i [10], is given by the (i, j) element of the following matrix

$$W = (Z - I)(Z_D)^{-1} \ , \quad (12)$$

where, Z_D is the diagonal matrix derived from the fundamental matrix Z by setting all its elements to zero, except the diagonal elements.

Recalling q_{ii} as the probability of staying in the state i, we see that the time in a state of the Markov chain is geometrically distributed with parameter q_{ii}. Further, as each requester station sets a constant time out, $T_{timeout}$, to receive the reply, we get the mean total duration of time it takes to perform retransmission attempts given that they fail, denoted by $E[T_i|F]$, as:

$$E[T_i|F] = \frac{1}{q_{ii}} T_{timeout} \ . \quad (13)$$

Recalling from equation (6) and as all $i = 0, 1, 2, \ldots, N$ stations, missing the packet of interest, back off with the same geometric distribution to send a retransmission request, the number of time slots to access the channel is again geometrically distributed with parameter

$$r_R^* = 1 - \prod_{l=1}^{i} (1 - r_R) = 1 - (1 - r_R)^i \ . \quad (14)$$

We approximate the number of time slots before sending a reply by assuming that all $N - i$ stations that have the packet do receive the request. Analogous to the equation (14), the number of time slots to access the channel is again geometrically distributed with parameter

$$r_T^* = 1 - \prod_{k=1}^{N-i} (1 - r_T) = 1 - (1 - r_T)^{N-i} \ . \quad (15)$$

Now, recalling that T_T and T_R are the transmission time of a data packet and a request packet respectively, we could find the overall delay of the system at the arbitrary state i denoted by $E[T_i]$ as

$$E[T_i] = E[T_i|F] + (T_{slot}(1/r_R^*)) + T_R + (T_{slot}(1/r_T^*)) + T_T, \quad (16)$$

where, the first component counts for the time spent due to $\frac{1}{q_{ii}}$ time failures and the rest count the time spent to leave the state i successfully. That is, the time prior to access the channel to send a request as $1/r_R^*$ times T_{slot} plus transmission time of the request packet (T_R) providing that at least one station possessing the packet, receives the request. Then after, it is summed up with the time prior to access the channel to send a reply as $1/r_T^*$ times T_{slot} plus transmission time of the reply packet (T_T) providing that at least one station missing the packet, receives the reply. Summing up this equation over all system states gives us the overall mean system delay till absorption as

$$E[T] = T_T + \sum_{i=1}^{N} \sum_{j=1}^{N} (W_{ji}) E[T_i] \ , \quad (17)$$

where T_T is the time taken for the first original transmission of the packet and W_{ji} is the probability of visiting the arbitrary state i, providing starting from the arbitrary state j of the chain.

V. NUMERICAL RESULTS AND VALIDATION

We have tested various scenarios to assess the performance of the protocol after implementing the system model in Wolfram Mathematica. The metrics of interest are the Probability Mass Function (PMF) of the number of steps required to distribute a data packet to all the stations, its 0.95 quantile and the mean end-to-end transmission delay till absorption of the system. The mean end-to-end transmission delay refers to the mean time taken from the moment the packet is transferred from the application layer in a node to the underlying layers, till it is delivered at the application layer of the receiving node.

As it is a receiver-based approach based on requests sent by receivers, it is of significant importance to know in how many request trials the packet is successfully received by receivers and/or the probability of successful reception of the packet by all the receivers in case of limited number of retransmission trials. Therefore, the PMF of the number of steps required to distribute a data packet to all the stations is a critical measure of interest. To validate the model we also implemented the system in NS-3 network simulator. In this section we highlight the results.

A. Validation by Simulation

To validate our model we implemented the protocol described in Section III in NS-3 environment. Rather than evaluating the reliable broadcast protocol in a realistic vehicular network, we aim at validating the analytical model, given that abstractions we applied in the modelling. Considering model assumptions, a wireless network with one-hop communication model has been set up with the constant position mobility model. Propagation loss and delay are considered negligible. Transmission delay and probabilistic packet loss for data packets and retransmission request packets have been implemented at the application level to set up conditions similar to the analytical model. Sequence numbering/checking have been implemented at the application level on all nodes.

Figure 1a shows in logarithmic scale the comparison of the protocol simulation with the results obtained using the analytical model. The metric of interest is the mean packet distribution delay as a function of the number of receivers in the system ($L = 30$, $p_R = 0$, $r_T = r_R = 0.5$, $T_{slot} = 0.0001$, $T_T = 0.01$, $T_R = 0.001$, $T_{timeout} = 0.012$). The data packets loss probability was set to $p_T = 0.1$. The confidence limits were estimated assuming level of significance $\alpha = 0.1$ (two-sided symmetric test, $\alpha/2 = 0.05$). As one may observe, the analytical results slightly overestimate the delay, although they seem to be within the confidence limits for almost all considered values of N. For other values of p_T and p_R the model follows the simulations closely as well. In Figure 1b, the mean packet distribution delay as a function of the data packet loss probability, p_T, is demonstrated in logarithmic scale for the same set of numerical values. The number of receivers was set to $N = 5$ and the confidence limits were estimated assuming $\alpha = 0.1$. As one may observe the analytical results are within the confidence limits for almost all values of the data packet loss probability, p_T. The model follows the simulations for other values of N. Thus, in what follows, studying the qualitative and quantitative behavior of the system, we will use the developed analytical model only.

B. Analytical System Performance

In this section we provide the results obtained from analytical modelling. Note that different numerical settings are used and the details of each evaluation scenario are described in the corresponding part. Logarithmic scales are used for all results to be reasonably fitted.

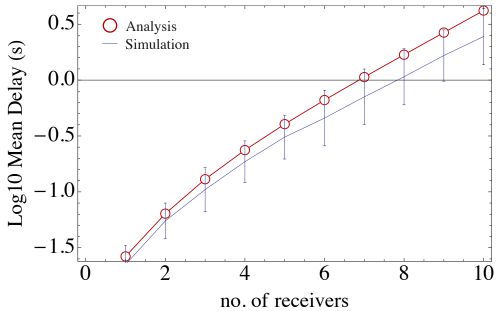
Figure 2 demonstrates PMFs of the number of steps till a broadcast packet is successfully received by all the receivers for $N = 5, 15, 30$ and different data packet loss probabilities, p_T. Note that the probability of incorrect reception of the retransmission request packet is set to zero. Recall, that principally, this distribution is a first passage time (FPT) till absorption in a discrete time Markov chain. As one may observe, for small values of p_T the PMF nearly follows geometric distribution. When p_T or N or both get higher the distribution is no longer geometric and resembles the properties of binomial distribution. For all the input parameters the probability of absorption exponentially decreases when the number of steps increases implying that the considered system is characterized by a lightweight tail distribution.

Figure 3 quantifies the effect of input parameters on the mean delay response of the system (logarithmic scale) with the same set of the mentioned numerical values ($L = 30$, $r_T = r_R = 0.5$, $T_{slot} = 0.0001$, $T_T = 0.01$, $T_R = 0.001$, $T_{timeout} = 0.012$). In particular, the mean delay as a function of the number of receivers for three different data packet loss probabilities is shown in Figure 3a. As expected, the mean packet delay increases nearly exponentially as the number of receiving nodes N increases. The effect of the data packet loss probability is also exponential for small values of p_T as shown in logarithmic scale in Figure 3b. However, for larger values of p_T the mean delay increases linearly rather than exponentially for all considered values of the number of receiving stations. It reveals that the number of nodes failing to successfully receive the packet increases as either the number of nodes or the data packet loss probability increases. Accordingly, higher number of nodes back off to send retransmission requests. For all the missing nodes to receive the packet, higher number of retransmission requests are sent, resulting in the increased mean end-to-end delay. Note that in Figure 3a and 3b the retransmission request packet loss probability is set to zero. Finally, Figure 3c demonstrates the mean delay as a function of the data packet loss probability for three different retransmission request loss probabilities and $N = 10$. As one may observe, the effect is similar to that of the data packet loss probability p_T. Additionally, when p_T and p_R are both not zero the effect is qualitatively similar.

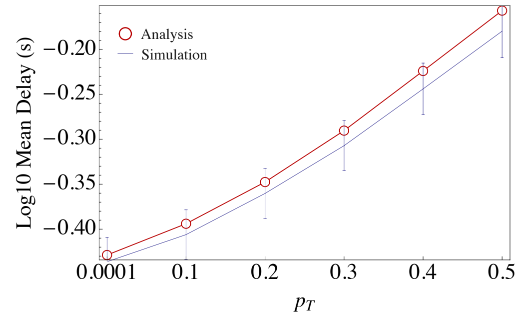
Figure 4 demonstrates the 0.95 quantile of the number of steps till a broadcast packet is successfully received by all the receivers, as a function of the number of receivers and data packet loss probabilities. It is important to highlight that even for rather large number of nodes (e.g. $N = 10$) at most three attempts are needed to distribute a packet. Also, observing Figure 4 one may notice that the 0.95 quantile of number of steps till a packet is successfully received is not increasing largely with the increase in the data packet loss probability.

VI. CONCLUSIONS AND FUTURE WORK

We developed an analytical model of a receiver-based reliable broadcast approach and demonstrated that it allows to predict performance of a packet distribution among several nodes in a network. The model takes the number of nodes,

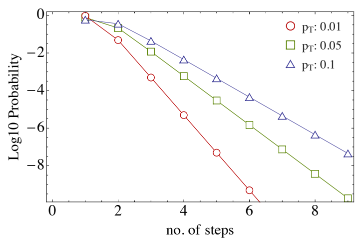


(a) $p_T = 0.1$ and $p_R = 0$.

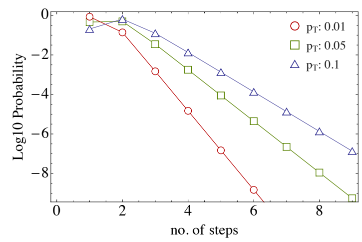


(b) 5 receivers.

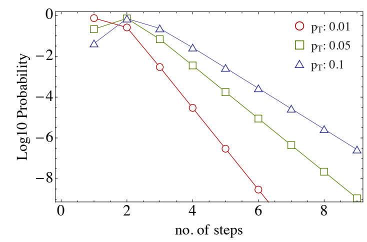
Fig. 1: Mean transmission delay.



(a) 5 receivers.

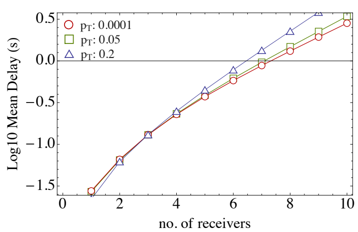


(b) 15 receivers.

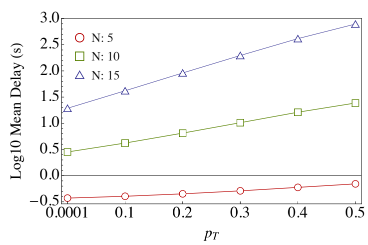


(c) 30 receivers.

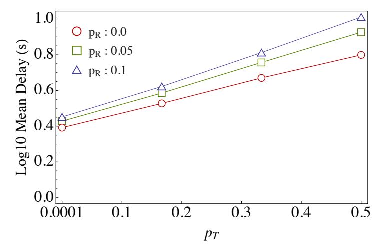
Fig. 2: PMF of the number of steps for different number of receivers.



(a) Different p_T.



(b) Different no. of receivers.



(c) Different p_R.

Fig. 3: Mean transmision delay.

data packet and request packet loss probabilities, the maximum number of allowed requests, packet transmission times and back-off timers into account and gives PMF of the number of retransmission requests to successfully deliver a packet to all the nodes and also the mean end-to-end delay. The proposed model is general enough and can take into account additional improvements in protocol design.

Our main performance metric is end-to-end delay and the model demonstrates that the delay performance of the system scales exponentially with the increase in the number of stations and data and retransmission request packet loss probabilities. Hence, where sender-based reliability approaches do have scalability problems due to storms of acknowledgements, this receiver-based approach is also limited in its scalability if full reliability is to be achieved. It becomes also apparent from our analysis that even with high number of receivers and high packet loss probabilities, data can be reliably distributed within a limited number of retransmission attempts.

However, the described reliable broadcast approach leaves room for further improvement, particularly, in higher network densities and packet loss probabilities, resembling real world scenarios. For example, the proposed mechanism could be extended to further optimize its functionality by intelligently setting timers based on their relative distance to the source such that the shorter the distance is, the shorter the waiting time to send a retransmission request would be. Such a policy would make the protocol more reliable and efficient as the vehicle closer to the source will send its request at first leading to the increased chance for the source to get the request prior to move out of the coverage area of the requesting vehicle in more realistic scenarios. The current model contains some assumptions, mainly it takes the effect of collisions into account only through a load-independent loss probability. For systems with low number of nodes (up until approximately 20) and/or large contention windows the proposed system demonstrates results close to simulations. However, when these requirements are not satisfied we have to explicitly take collisions into account. Besides, the current model applies for

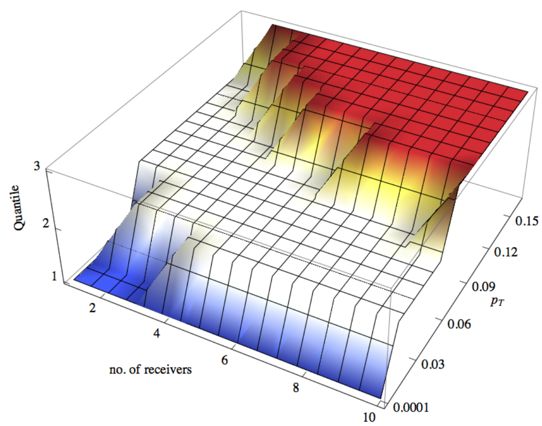


Fig. 4: 0.95 quantile of the number of steps.

the one-hop communication scenario. Modelling the protocol behaviour in a multi-hop communication scenario and further taking into account the effect of collisions are the topics of ongoing work.

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