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Tracking the position of neighboring vehicles using wireless communications

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ABSTRACT

We investigate four communication schemes for Cooperative Active Safety System (CASS) and compare their performance with application level reliability metrics. The four schemes are periodic communication, periodic communication with model, variable communication, and variable communication with repetition. CASS uses information communicated from neighboring vehicles via wireless network in order to actively evaluate driving situations and provide warnings or other forms of assistance to drivers. In CASS, we assume that vehicles are equipped with a GPS receiver, a Dedicated Short Range Communications (DSRC) transceiver, and in-vehicle sensors. The messages exchanged between vehicles convey position, speed, heading, and other vehicle kinematics. This information is broadcast to all neighbors within a specified communication range. Existing literature surmises that in order for CASS to be effective, it may need a vehicle to broadcast messages periodically as often as every 100 ms. In this paper, we introduce the concept of running a kinematic model in-between message transmissions as a means of reducing the communication rate. We use traffic and network simulators to compare the performance of the four schemes. Our performance measure metrics include communication losses as well as average position errors.

1. Introduction

This paper explores communication schemes that will enable a vehicle to track the position of its neighboring vehicles. We envisage vehicles equipped with GPS and WiFi (or DSRC) broadcasting GPS position, speed, and heading, so that each vehicle may use these messages to detect possible collisions and warn its driver. This concept is known in the literature as Cooperative Active Safety Systems (CASS).

CASS evolved from Active Safety Systems (NHTSA, 1997). An Active Safety System is an in-vehicle system that provides warnings or other forms of assistance to drivers based on in-vehicle sensors such as radar or lidar that offer information about the motion of vehicles within their field of view. It has been argued that this class of applications may reduce over 75% of the nation's crashes (Godbole et al., 1998). CASS aims at accomplishing this goal by using technology alternatives, such as GPS and Dedicated Short Range Communications (DSRC), thus offering the potential to provide information from vehicles that may be occluded from direct line of sight. CASS is now a well established concept in the literature (Broqua et al., 1991; Schubert et al., 1994; Asher and Galler, 1996, 1997; Yang et al., 2000; Passmann et al., 2000; Oloufa and Radwan, 2001; Kato et al., 2002; Muller et al., 2003). Likewise several industry and government-led CASS efforts are also underway.

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The 2004 ruling by the Federal Communications Commission (FCC) provides bandwidth for CASS communications in the DSRC spectrum (FCC, 2003). The DSRC band plan consists of seven channels which include one control channel (Ch. 178) to support high priority safety messages and six service channels to support non-safety applications. The bandwidth of each DSRC channel is 10 MHz. The most advanced CASS prototype to date is the one opened to the public by General Motors at the 2006 ITS World Congress (Press Release, 2006, 2005, 2006). This extended an earlier prototype built and tested by PATH (Misener et al., 2005; Sengupta et al., 2007). The automotive industry, as a whole, and USDOT are working on CASS under the aegis of the Vehicle Safety Communications Consortium (VSCC).

VSCC has extensively investigated the types of information that may be usefully communicated by CASS vehicles (VSCC, 2005). The recommended minimum communication rate and range for all but two applications is a message every 100 ms per vehicle up to a range of 150 m. The general motion data causes the bulk of the messages generated by CASS. It is produced all the time. The other messages are produced in rare traffic conditions.

There are two main technical challenges associated with the general motion data. The first is the reliable estimation of a vehicle's GPS position and its localization with respect to the roadway. In this paper, we focus on the second challenge, which rests in the reliable transmission of these motion messages through the channel to their intended recipients with low latency and high probability. For the first problem see references Rezaei and Sengupta (2007) and the references therein. This paper is about the second problem.

The problem of communicating of CASS messages is an active area of research in the vehicular ad-hoc networking community. The literature has several evaluations of the delivery of CASS messages (ElBatt et al., 2006; Xu et al., 2004; Torrent-Moreno et al., 2004; Bana and Varaiya, 2001; Lee et al., 2001; Yang et al., 2004; Yin et al., 2004). The most relevant to our research is ElBatt et al. (2006), which presents a performance evaluation study of cooperative collision warning applications using DSRC wireless standard. They define a new performance measure, packet inter-reception time (IRT) at the neighbor vehicle for packets sent by a given sender, which provides insight on the impact of interference and successive packet losses on application performance. All other evaluations in the literature are based on packet-level reliability metrics. In Xu et al. (2004), the authors study the impact of the rapid repetition of broadcast messages on the reception failure probability of random access protocols using analysis and simulation. In Torrent-Moreno et al. (2004), the authors quantify the channel access time and probability of reception under deterministic and statistical channel models.

In this paper, we design communication schemes based on application level measure of performance. We show that packet loss rate is neither a necessary, nor sufficient condition for application reliability. The warning systems on board the receiving vehicle consume data on the positions and speeds of neighboring vehicles. Therefore our performance measure is the error in these quantities at the receiver. Our aim is to find communication schemes that reduce the position error, in both the lateral and longitudinal directions.

We focus on two statistics of the error: mean square of the total position error and tail probability. The first is widely used in estimation and control. We define the second statistic as the probability that at least one of the lateral or the longitudinal errors crosses its predefined corresponding limit. This measure is motivated by factors particular to CASS (Sengupta et al., 2007; Shladover and Tan, 2006). The lateral component of the error need only be known to accuracy sufficient to correctly assign the lane of a vehicle. The longitudinal component of the error need only be known to accuracy sufficient to compute the time to collision with an in-lane vehicle with acceptable precision. The analyses in Shladover and Tan (2006) suggest the accuracy requirements on standard deviation of the lateral and longitudinal components of position error are nominally 0.5 m and 0.75 m.

These performance measures have motivated us to develop and evaluate the following communication designs:

(1) *Periodic communication*: Here each vehicle broadcasts GPS position, speed, and heading periodically (e.g., every 100 ms) with enough power to reach a target range (e.g. 150 m). The receivers assume the position of the sender remains constant at the last received value until reception of the next message. Most analyses in the literature assume this scheme. Here the only way to reduce position error is to increase the size of the channel and broadcast more frequently. We evaluate this scheme to establish a baseline.
(2) *Periodic communication with model*: This scheme is the same as the previous on the sender side. On the receiver side, the received data is input to a model-based estimator that estimates states of the sender based on the model and data received from the sender.
(3) *Variable communication with scheduler*: This scheme is the same as above on the receiver side. However, it is different from both previous schemes on the sender side. In this scheme, data transmitted by a sender is input to a model-based estimator that estimates states of the sender, based on the model and data sent by the sender. The errors of these estimates are calculated by a scheduler and are used to trigger communication should they exceed fixed, predetermined thresholds. The sender broadcasts only when it believes the lateral or longitudinal position errors to exceed their respective thresholds.
(4) *Variable communication with repetition*: This scheme is the same as the previous one, with the exception that the sender repeats its message a few times within a short time window.

Scheme 3 has advantage versus Scheme 2 because it has a sense of timing. It communicates when it is necessary to communicate, i.e. when the motions of the vehicle are such as to cause the error to grow large. However, Scheme 2 can have redundancy benefit if the period of communication is sufficiently small. Scheme 3 does communicate at the right time, but does not communicate enough. The channel does throw away some of its messages, causing the error to exceed the thresholds. At the same time, if the channel can actually bear more information, Scheme 4 will do better. Scheme 4 emerges as the best, as it tries to combine the sense of timing of Scheme 3 with communicating as much as the channel will bear.

This approach to vehicle communication in CASS is motivated by ideas in the control systems literature on control with limited feedback. Yook, Tilbury, and Soparkar were the first to show that the communication rate can be reduced by only transmitting data when the remote estimation error becomes large (Yook et al., 2002). They proved bounded input-bounded output stability of controlling such a system with limited feedback. Schenato et al. (2004), Seiler (2001) and Liu and Goldsmith (2004) addressed the Kalman filtering problem with intermittent observations. All assume that the communication losses are Bernoulli distributed. Hespanha et al. (Xu and Hespanha, 2005, 2004) have rigorously argued the optimality of a design like this one based on threshold crossings. Xu and Hespanha (2005) assumes instantaneous acknowledgement of packet arrival and communication loss is modeled as a Bernoulli random variable. Xu and Hespanha (2004) consider the estimation error as one part of an objective function to be minimized. The other part is the average communication load.

The paper is organized as follows. We describe the designs in Section 2. Section 3 describes the evaluation methods. The performance results are described in Section 4.

2. Designs

In this section we present the four communication designs. For the rest of this paper, "SV" refers to the subject vehicle and "OV" represent the other (neighboring) vehicle.

2.1. Periodic communication

Fig. 1 shows the block diagram for this simple design. Each vehicle has an extended Kalman filter, called the "Self Estimator" that estimates its own position, speed, and heading, by integrating differential GPS and the vehicle sensors (including speed, steering angle, and yaw rate sensors). These quantities collectively constitute the vector $\hat{\vec{X}}(k)$, which is the best available estimate of the state of the vehicle at time k. The information stored in $\hat{\vec{X}}(k)$ is broadcast to all neighboring vehicles at a predetermined fixed rate. The details of the Self Estimator can be found in Rezaei and Sengupta (2007). For the rest of the discussion, we refer to $\hat{\vec{X}}(k)$ of the Self Estimator as the state of the vehicle at time k.

2.2. Periodic communication with model

This design builds upon the previous one by incorporating a "*Neighbor Estimator*" into each vehicle, as indicated in Fig. 2.

The Neighbor Estimator receives messages reporting the state $\hat{\vec{X}}(k)$ of each vehicle that is in the neighborhood of SV. In the figure, OV receives the messages of SV. The Neighbor Estimator operates a simple kinematics model to provide its vehicle with an estimate of the state of SV for times in-between message receptions from SV. We keep the model simple because each vehicle may need to operate many Neighbor Estimators, depending on traffic flow conditions. The equations for the model are as follows:

$$\begin{aligned}
&\tilde{X}(k+1) = \tilde{X}(k) + \tilde{V}(k) \times \cos(\tilde{\phi}(k)) \times \Delta T;\\
&\tilde{Y}(k+1) = \tilde{Y}(k) + \tilde{V}(k) \times \sin(\tilde{\phi}(k)) \times \Delta T;\\
&\tilde{V}(k+1) = \tilde{V}(k);\\
&\tilde{\phi}(k+1) = \tilde{\phi}(k) + \tilde{\dot{\phi}}(k) \times \Delta T;\\
&\tilde{\dot{\phi}}(k+1) = \tilde{\dot{\phi}}(k);
\end{aligned} \tag{1}$$

The state vectors $\hat{\vec{X}}(\cdot), \tilde{\vec{X}}(\cdot)$ consist of positions X, Y (in the universal GPS coordinate frame with a local origin), speed V, and heading angle ϕ. Symbols with (^) on top refer to the Self Estimator's estimates and symbols with ($\sim$) on top refer to the Remote Estimator's estimates. Whenever SV receives a message, it updates the above parameters to reflect the values provided in the transmitted message.

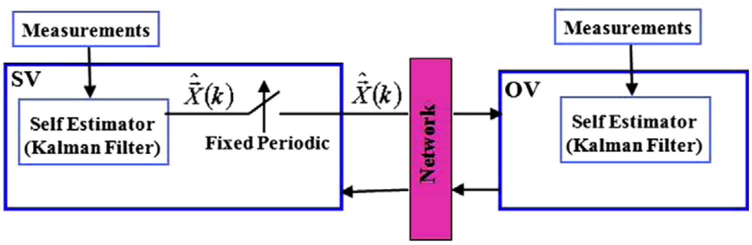

Fig. 1. Design block diagram for periodic communication without model.

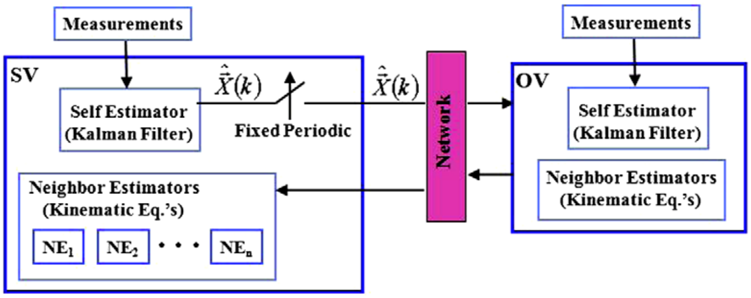

Fig. 2. Design block diagram for periodic communication with model.

The outputs of the vehicle Self Estimator and the Neighbor Estimators for all the neighboring vehicles drive the responding applications in the vehicle. If a SV has n neighbors (OV's) it will run n Neighbor Estimators.

2.3. Variable communication with scheduler

This design builds upon the previous model by adding two new components, the "*Remote Estimator*" and the "*Scheduler*." The Remote Estimator stores a copy of the most recent information it has broadcast to its neighbors regarding its own motion. Let the Remote Estimator of vehicle i be denoted by RE_i. Let the Neighbor Estimator run by neighbor j for vehicle i be denoted NE_{ji}. The purpose of RE_i is to estimate the output of all the NE_{ji}'s. It is an estimator of all the Neighbor Estimators. Fig. 3 shows the design block diagram.

A vehicle's decision to communicate at any time instance is made by the Scheduler. The Scheduler receives inputs from both the Self Estimator and the Remote Estimator. It uses Eq. (2) to calculate the longitudinal and lateral errors. These errors are defined in Fig. 4.

The position error in the longitudinal and latitudinal directions is calculated as follows:

$$\begin{aligned} \varepsilon_{long.}(k) &= |(\tilde{X}(k) - \hat{X}(k)) \times \cos(\hat{\phi}(k)) - (\tilde{Y}(k) - \hat{Y}(k)) \times \sin(\hat{\phi}(k))|; \\ \varepsilon_{lat.}(k) &= |(\tilde{X}(k) - \hat{X}(k)) \times \sin(\hat{\phi}(k)) + (\tilde{Y}(k) - \hat{Y}(k)) \times \cos(\hat{\phi}(k))|; \end{aligned} \tag{2}$$

At time k, if $\varepsilon_{long.}(k+1)$ or $\varepsilon_{lat.}(k+1)$ exceed their respective thresholds at any time k, SV broadcasts $\hat{\vec{X}}(k)$ as specified by the following policy:

$$\begin{aligned} &u(k) = 1 \quad if\,(\varepsilon_{long.}(k+1) > Tr._{long.} \vee \varepsilon_{lat.}(k+1) > Tr._{lat.}) \\ &u(k) = 0 \quad Otherwise \end{aligned} \tag{3}$$

where

k	is the time index
$u(k)$	is the scheduler's decision on communication at time k (1 means communication and 0 means no communication)
$\varepsilon_{long.}(\cdot)$	is longitudinal tracking position error
$\varepsilon_{lat.}(\cdot)$	is lateral tracking position error
$Tr._{long.}$	is the threshold on the longitudinal error
$Tr._{lat.}$	is the threshold on the lateral error

The value of the Remote Estimator is reset to that of the Self Estimator whenever the SV broadcasts a message.

Shladover and Tan (2006) have derived the accuracies required in position, speed, and heading estimates to produce warnings of reasonable accuracy and consistency. We use their work to set the thresholds for the evaluations in Section 4.

Fig. 5 shows how the scheme works. In between broadcasts, the error rises. When the error crosses either threshold, a new message is broadcast. If it is received, the error at the receiver resets to zero.

If the communication channel has no loss or delay, the Remote Estimator estimates exactly what each neighboring vehicle estimates as the state of vehicle i. This is because each time the vehicle sends a message reporting $\hat{\vec{X}}(k)$ to its neighbors; it also sends it to its own Remote Estimator as shown in Fig. 3. We also have the Remote Estimator run the same model as that run by the Neighbor Estimators. Thus identical equations driven by identical inputs will produce identical outputs. Moreover the difference between the state of the vehicle at time k and a neighbor's perception of it at time k is always less than the threshold used to trigger the next broadcast of $\hat{\vec{X}}(k)$. Assuming the threshold is chosen to be small enough to be tolerated by the responding applications, the design would provide applications in CASS with a sufficiently accurate estimate of the state of the sender at all times.

These arguments hold when there is no communication loss or delay. Since in reality some messages will be lost, the difference between $\hat{\vec{X}}(k)$ and the neighbors' estimate of $\hat{\vec{X}}(k)$ will sometimes exceed the threshold used to trigger messages. This

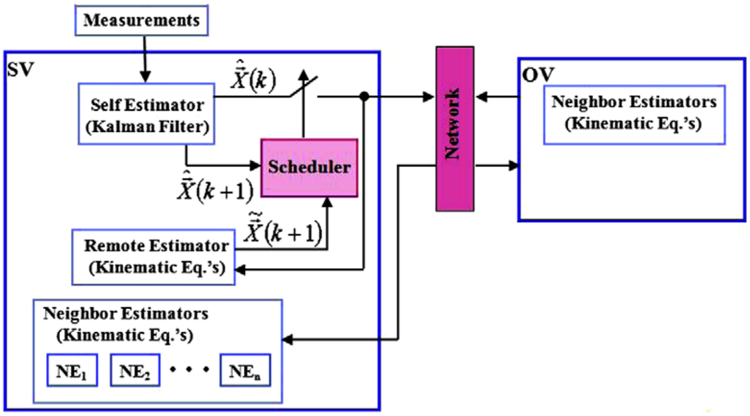

Fig. 3. Design block diagram for variable rate.

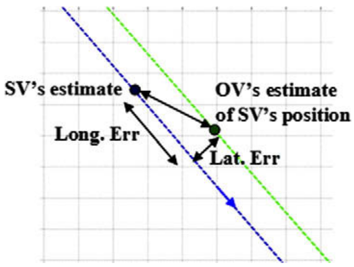

Fig. 4. Longitudinal and lateral position errors.

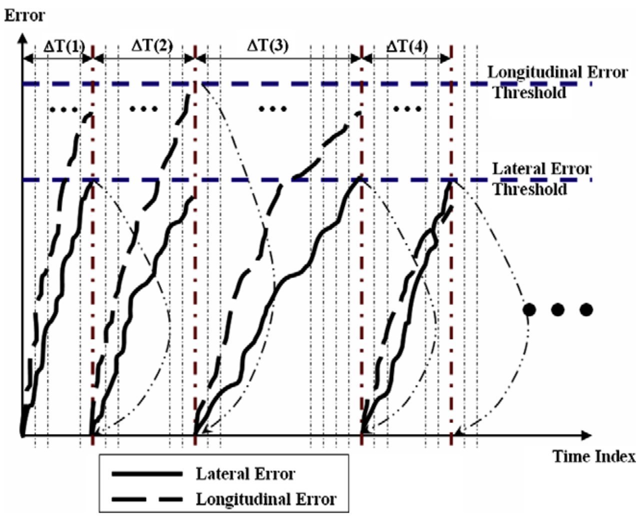

Fig. 5. Communication rate control scheme bounds the longitudinal and lateral error while maximizing the time interval between communications.

threshold violation may result in violation of the position accuracy required by some applications. This violation is captured by our tail probability measure.

Communication delays also cause threshold violations. If the difference between the Self Estimator and Remote Estimator outputs crosses the threshold at time t, it will trigger a broadcast of $\hat{\vec{X}}(k)$ that may be received at time $t + \delta$ by a neighbor. During the interval δ, the error in the neighbor's estimate will not satisfy the application requirement. However, if δ is 50 ms, accuracy will be off by 0.024 m at most, assuming the maximum deceleration of a vehicle to be limited to 1 g. Such a threshold violation would be insignificant, as GPS errors themselves are likely to be much larger. Communication loss is the more significant concern.

2.4. Variable communication with repetition

In an effort to address the effect of packet loss, we have modified the variable rate scheme to incorporate redundancy. The distinguishing feature of this design is the retransmission of each message within a 50 ms window following the creation of a message by the Scheduler. The 50 ms window is divided into time slots of 1.5 ms (equivalent to three times 0.5 ms, which is the time taken to transmit a 300 bytes packet at 6 Mbps rate). In the case of a single retransmission, each message is randomly assigned one time slot in which to resend its message, as shown in Fig. 6. If multiple retransmissions are required, multiple time slots are assigned to a particular message.

3. Evaluation method

Fig. 7 shows a flow diagram for our evaluation technique.

3.1. Traffic simulator

The rate at which messages are produced by the variable rate design depends on vehicle dynamics. If the state of a vehicle is relatively constant, the kinematic equations run by neighbors will accurately predict the state of the vehicle. Consequently, the differences between the Self and Remote Estimator outputs will remain small and few messages will be produced. On the other hand, fast changing dynamics will result in more frequent messages.

To evaluate the communication rates produced by our design, we have incorporated it into a vehicular traffic simulator. We have then simulated different traffic patterns to understand which scenarios might generate the highest rates of communication. In this section we describe the simulation tools.

We use the Ruby SHIFT (Homepage, XXXXa) and Paramics (Homepage, XXXXb) traffic simulators. SHIFT has been developed by California PATH at the University of California at Berkeley. Fig. 8 is a snapshot of a typical simulated section.

The maximum traffic flow per lane of our simulator is around 2250 vph (vehicles per hour). This corresponds to an average inter-vehicle gap of 1.1 s. At this flow, the average inter-vehicle distance is about 30 m, density is 55 vpm (vehicles per mile) per lane, and the average speed is 27 m/s.

Inputs to the simulator are roadway parameters such as the length of sections, number of lanes, desired vehicle inflows, speeds, and inter-vehicle gaps. Vehicles are capable of changing lanes. The output of the simulator is a log file of X and Y-coordinate positions and speed (V) of vehicles, updated at 20 Hz. We assume these are the true values of these quantities. Vehicles change lanes instantaneously in the traffic simulator, which is not realistic. In order to better model for lane changes, we adjust the vehicle's trajectory for the duration of the lane change in order to make it smooth. For each lane

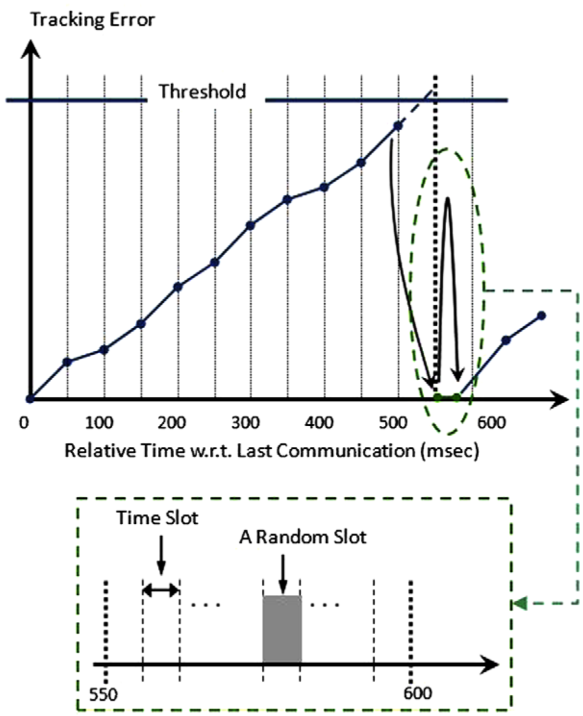

Fig. 6. An example of single repetition scheme.

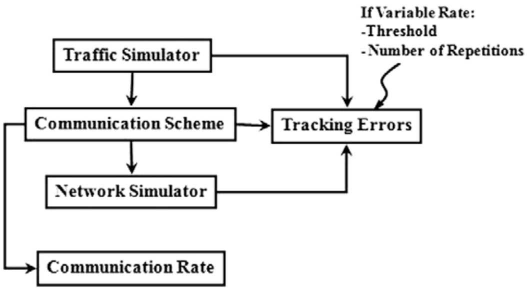

Fig. 7. Evaluation tools flow diagram.

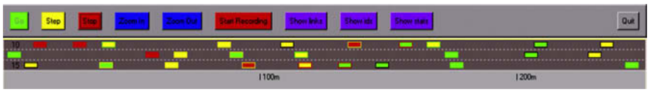

Fig. 8. Snapshot of Ruby SHIFT traffic simulator.

change, we pick a random number (uniform distribution) between 2 and 3 s to be the lane change duration. Fig. 9 shows how the design is modeled as a block diagram.

Based on the true position, heading, and speed of vehicles output by the simulator, we model the Self and Remote Estimators' estimates as follows:

(1) We add colored Gaussian noise to X, Y, V, H, and the heading rate ($\dot{H}$) in order to simulate errors in the output of the Self Estimator. Standard deviations of noise are 0.2 m, 0.2 m, 0.2 m/s, 1°, and 0.3°/s, respectively. These numbers match experimental data (Rezaei and Sengupta, 2007). The additive noises are correlated by a first order autoregressive (AR) model. This is because our experimental data shows the Self Estimator errors are colored rather than white. We use the same AR model for the four states. The model for the noise denoted by w, is:

$$\begin{aligned} &w(k+1) = \alpha w(k) + \beta z(k); \\ &\alpha = 0.9; \quad \beta = 0.436; \quad z(k) = N(0, \sigma_w) \end{aligned} \tag{4}$$

where, $z(k)$ is zero mean white Gaussian noise with standard deviation equal to the standard deviation of 'w' in steady state.

(2) Calculate the Remote Estimator's estimation of states using Eq. (1).
(3) Calculate the longitudinal and the lateral tracking errors using Eq. (2) and generate a message if at least one of the errors exceeds the related threshold.
(4) Log all the time traces of the messages produced by all the vehicles and use them to produce the results in Section 4.

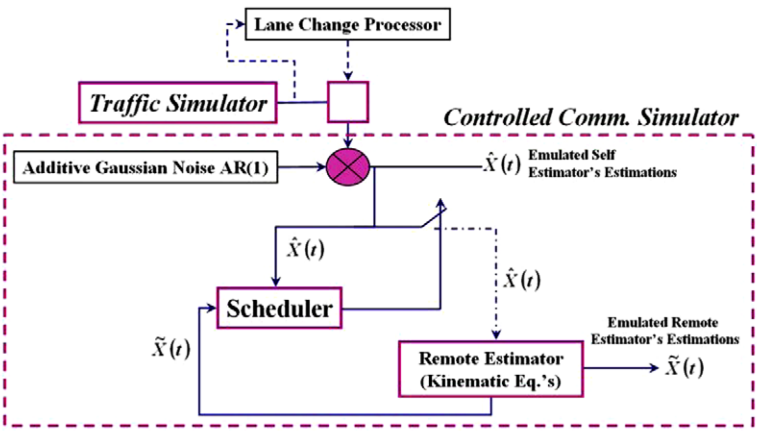

Fig. 9. Rate control scheme implementation using traffic simulator data.

3.2. Network simulator

We have used the OPNET network simulator (Homepage, XXXXc) to determine the relative improvement associated with our inter-vehicle communication design. Data regarding the instantaneous position and speed of cars, obtained from the traffic simulator, is used to dictate node movement in OPNET. The vehicular traffic flow used here matches our regular freeway simulation. Also, we produce the time instances of communications of the cars for both variable and fixed rate schemes. By incorporating both the time instances of communication and motion of the vehicles into the network simulator, we preserve and capture their correlation.

We simulate in OPNET using its 802.11a communication model. The DSRC band plan consists of seven channels which include one control channel (Ch. 178) to support high priority safety messages and six service channels to support non-safety applications. The bandwidth of each DSRC channel is 10 MHz. Prioritizing safety over non-safety applications is an open problem that started to receive attention in the literature and is closely related to the problem of multi-channel coordination. Aside from these differences, the DSRC MAC follows the original IEEE 802.11 MAC (IEEE, 1999) and its extensions (e.g. IEEE 802.11e QoS).

For our purposes, we modified the 802.11a model (IEEE, 1999) to represent DSRC in accordance with the ASTM draft standard (ASTM, 2003), as follows. The carrier frequency is set to 5 GHz (as the closest frequency in OPNET to the DSRC 5.9 GHz frequency) and the channel bandwidth is 10 MHz. We focus on the single channel operation of DSRC (control channel supporting safety applications). The problem of DSRC multi-channel operation, for supporting the coexistence of safety and non-safety applications, lies out of the scope of this paper and is a subject of ongoing research. The messages and repetitions produced by the Scheduler are passed to CSMA, which then controls the broadcast.

The propagation model is,

$$P(d) = P_T - 10 \times \gamma \times \log_{10}(d) - 20 \times \log(4 \times \pi) \tag{5}$$

where $P(d)$ and P_T are the receiving power at distance d and the transmission power (in dB). γ is the path loss exponent and it is equal to 2.75. We do not include fading in the model, as our purpose is to compare the communication schemes to each other and fading would affect them all similarly. The receiver sensitivity is −87 dbm and the data rate is 6 Mbps. We choose the transmission power to be 100 mW, which secures the transmission range up to 150 m, which according to VSCC final report is the smallest range required by most applications (VSCC, 2005).

We assume a nominal payload size of 300 bytes, which is within the 200–500 byte range discussed in the literature (VSCC, 2005; Xu et al., 2004).

4. Results

In this section we present two sets of results. First, we quantify the communication load generated by our design. Then we quantify the improvement in communication performance that might be expected from the design. Section 4.1 quantifies communication rates. Section 4.2 quantifies the tracking errors in the presence of communication loss.

4.1. Communication rate

We present simulation results for three vehicular traffic scenarios: regular freeway, freeway with a merge lane, and intersection. We use the Ruby SHIFT simulator for the first two scenarios and the Paramics simulator for the last.

We use 0.5 m and 0.3 m as values for the longitudinal and lateral error thresholds, respectively, unless stated otherwise. Using smaller threshold values trivially results in faster communication, while larger threshold values require less frequent communication. We conservatively chose 0.3 m for the lateral error threshold because warning applications require the standard deviation of the lateral error to be smaller than 0.5 m (Shladover and Tan, 2006).

Our performance measure is the number of messages per second per meter. To avoid fractions we calculate the number of message per 300 m/2 s at every point along the roadway. This is because the capacity of a wireless network is better understood in bit-meters/second. The bit per second per vehicle measure does not capture the workload created by increasing communication range.

4.1.1. Regular freeway

Fig. 10 presents the spatial density of communication for a straight section of a freeway with our design at different traffic flow conditions.

Specifications of these tests are:

Road length: 6 km
Sampling rate: 20 Hz
Average flow: varying between 400 and 2100 vph per lane

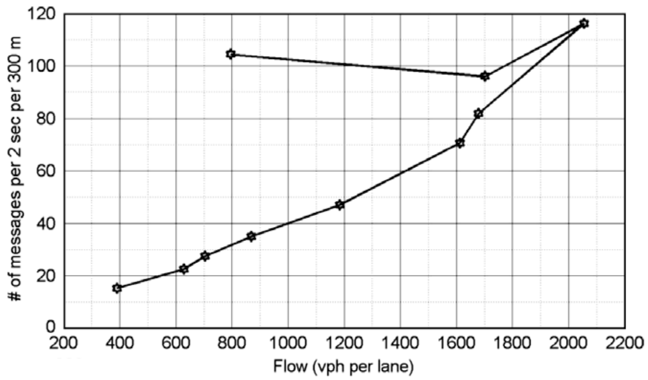

Fig. 10. Communication density in a regular four lane freeway.

Average inter-vehicle gap: 1.1 s
Number of lanes: 4
Longitudinal error threshold: 0.5 m
Lateral error threshold: 0.3 m

When average flow is 1900 vph per lane, the average inter-vehicle distance is 40 m. Hence, the density is 40 m per vehicle per lane. The maximum flow density is 29.3 m per vehicle per lane (55 vehicles per mile per lane). Thus, the traffic is flowing freely. If periodic communication were happening at 10 Hz (i.e. without rate control), within a 300 m distance window and 2 s time window, the number of messages produced per 300 m and per 2 s would be 600, as calculated below:

$$600 = \frac{300\ \text{m}}{40\ \text{m}} \times 4[\text{lanes}] \times 2\ \text{s} \times 10\ \text{samples/s}$$

As shown in Fig. 10, the same number with this design is less than 100 messages at this traffic flow, which reduces the communication load by 1/6th. The figure also shows this number for other traffic flows.

Fig. 11 shows how the average communication message time interval per vehicle is changing at different traffic flow conditions. The flow values cover both free flow and jammed traffic conditions. When entering the jammed region, flow is decreasing while density is increasing. The arrows indicate, the traffic condition switching from freely flowing to jammed condition.

Communication is triggered when either the longitudinal or the lateral error exceeds the threshold. Fig. 11 shows, there is small variation in the average time interval between messages in the free flow traffic region. Its mean is at 0.520 s and its standard deviation is just 0.0267 s. This is because at higher flow there is more net acceleration (i.e. average absolute value of acceleration per vehicle) which results in faster growth of the longitudinal error, triggering more crossings of the longitudinal error threshold as indicated by the circles. In the freely flowing region, as flow increases there is less space available for lane changes. This reduces the number or lane changes. Speed also reduces at higher flows. The two reductions minimize

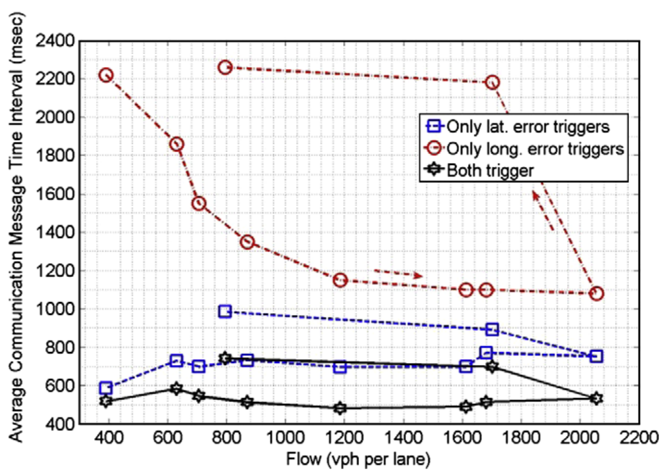

Fig. 11. Variation of the average communication message time interval versus traffic flow.

the number of lateral threshold crossings as indicated by the squares. The increasing rate of longitudinal threshold crossing and reduced rate of lateral threshold crossings counter balance each other to result in an average time interval between messages of about 500 ms in the free flow region regardless of traffic flow.

Fig. 12 shows how speed and acceleration are changing with flow. One can see the maximum acceleration conditions occur as the traffic transitions from freely flowing to jammed. This shows the transition point should represent the highest rate of longitudinal threshold crossing.

In the jammed case, even less communication is required because there is very little net acceleration in the system, speed is small, and lane changes are rare. Thus, jammed traffic is not the highest communication scenario.

The size of the threshold value is inversely proportional to the communication rate. As shown in Fig. 13, the relationship between threshold value and the average time interval between messages is almost linear. In the figure, threshold factor is the ratio of the threshold values used to determine the average message time interval and the nominal values. The nominal values are 0.5 m and 0.3 m for the longitudinal and lateral error thresholds, respectively.

4.1.2. Merge

Fig. 14 presents results for a three lane freeway with an added merge lane. The merge lane joins the freeway at 1000 m. Specifications of this test are:

Road length: 7 km
Sampling rate: 20 Hz
Average flow: 1700 vph per lane (including the merge lane)
Average inter-vehicle gap: 1.1 s

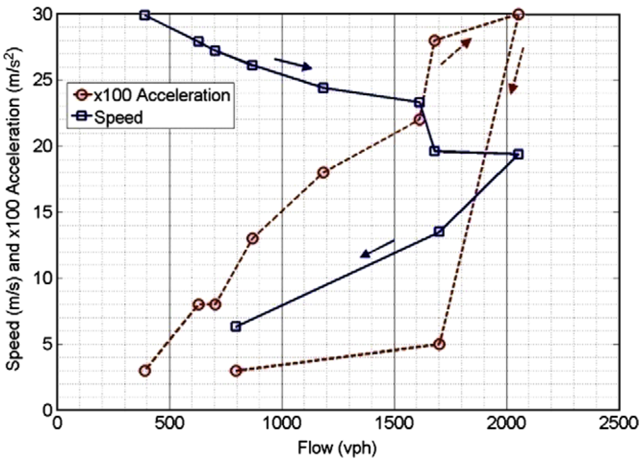

Fig. 12. Variation of average speed and net acceleration versus flow.

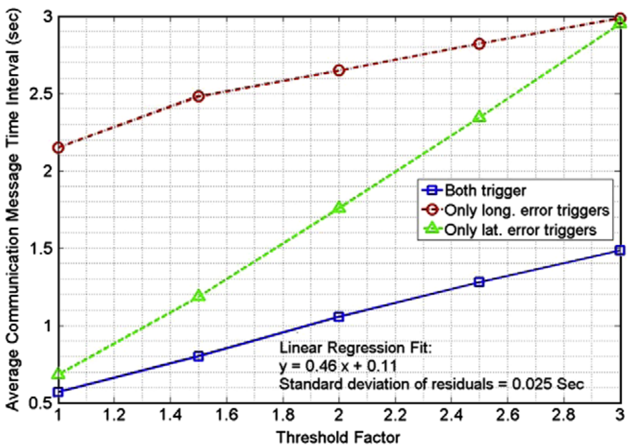

Fig. 13. Variation of the average communication message interval versus threshold value factor.

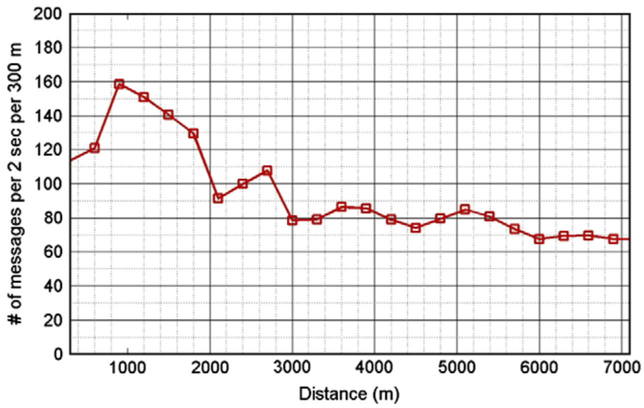

Fig. 14. Communication density in a freeway with a merge lane.

Number of lanes: three plus one merge lane
Longitudinal error threshold: 0.5 m
Lateral error threshold: 0.3 m

The average flow is 1700 vph per lane across four lanes. When lane four merges with lane three the flow becomes $1700 * 4/3 = 2267$ vph per lane. This is the maximum flow condition. Hence we have simulated this scenario. Moreover, merges may result in larger numbers of lane changes.

For this run, the average inter-vehicle distance is 37 m near the merge zone (i.e. around 1000 m). If the communication was happening at 10 Hz (i.e. without our design), within the 300 m distance window and 2 s time window of Fig. 14, on average 645 messages would be produced as calculated below:

$$645 = \frac{300\ \text{m}}{37\ \text{m}} \times 4[\text{lanes}] \times 2\ \text{s} \times 10\ \text{samples/s}$$

Using the design we see even at the merge zone less than 160 messages are generated.

4.1.3. Intersection

Finally, we simulate a suburban intersection. We do this for two reasons. It has been argued that the braking and acceleration of vehicles caused by the change of the traffic light may result in many messages. Secondly, suburban roads can carry a lot of traffic.

Fig. 15 is a snapshot of an intersection simulated using Paramics.

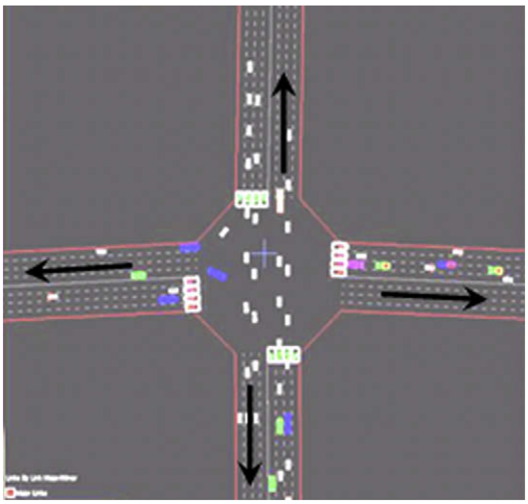

Fig. 15. Simulation of a typical intersection with Paramics.

Specifications of this test are:

Road length: 1 km
Sampling rate: 20 Hz
Average flow: 1700 vph per lane
Number of lanes: 4
Number of approaches: 4
Number of departures: 4
Traffic light duration: 50 s (20 s green → 3 s yellow → 2 s all red → 20 s red → 3 s yellow for other direction → 2 s all red → 20 s green → ...)
Speed limit: 50 km/h
Longitudinal error threshold: 0.5 m
Lateral error threshold: 0.3 m

Fig. 16 shows the average communication density at different distances from intersection. There are four approaching directions and four departing direction (departing directions are shown in Fig. 15). Distance is measured from the intersection. Negative distance means car approaches the intersection and positive distance refers to a departing motion. For this run, the average inter-vehicle distance is 10 m. If periodic communication were at 10 Hz (i.e. without this design), within a 100 m distance window and 2 s time window used, 800 messages would be produced on average, as calculated below:

$$800 = \frac{100\text{ m}}{10\text{ m}} \times 4[\text{lanes}] \times 2\text{ s} \times 10\text{ samples/s}$$

In contrast, Fig. 16 shows that our design reduces the number of messages to fewer than 60. As one may expect, the greatest quantities of messages are generated right near the intersection when vehicles depart the intersection, since the acceleration action necessitates an increase in communication. The communication rate dips as the vehicles move away and rises again some distance later. The rise is most likely associated with the increase in vehicle speed, as also observed in our regular freeway simulation.

4.2. Tracking errors

We determine the probability of message loss at a randomly chosen receiver within the communication range. To be more precise, let packet i be sent with target range R_i, and at the time instant of transmission, let there be n_i nodes within the range R_i, out of which m_i nodes receive the packet successfully. The loss rate for packet i, $P_i = 1 - (m_i/n)_i$. The overall packet loss rate is the average of each of these per packet quantities. However, we do not use the probability of message loss as the performance measure.

We compute the tracking position errors in the presence of loss at the place of neighbors of each sender every 50 ms. For all n_i nodes within the range R_i, we determine m_i nodes that receive the packet successfully and the $(n_i - m_i)$ nodes that lose the packet. The nodes that lose a packet do not get updated, hence their tracking errors of the sender accumulate until the time they have a successful reception for a packet sent by the sender, at which point their errors drops to zero. The overall absolute position error is the average over all tracking errors of the senders at the places of their instantaneous neighbors. We use this value as one of the performance measures.

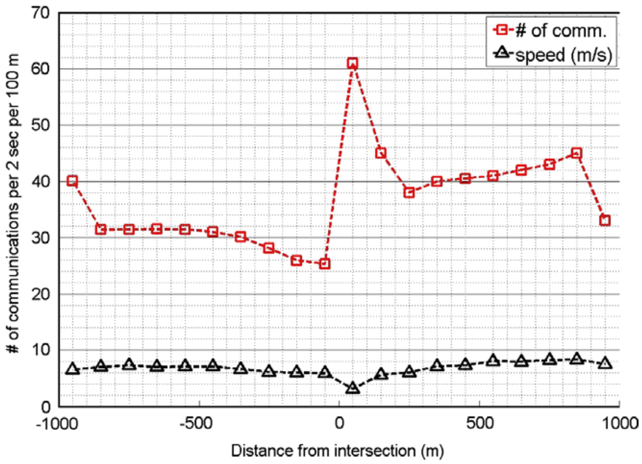

Fig. 16. Average communication density versus distance from the intersection.

The other performance measure we use is the probability that at least one of position tracking errors (lateral or longitudinal) violates the corresponding threshold. We designate this as the tail probability. We compute the tail probability by counting all threshold violation instances and then dividing the sum by the total number of error values. In the example shown in Fig. 17, the combined tail probability is the probability of a random error being in at least one of the dark-shaded zones.

Table 1 quantitatively compares performance of the four different designs. In this table, "VR" refers to variable rate control scheme. "Average distance error" is the average of all tracking errors measured as Euclidean distance between the true and the tracked positions. "ACTI" is the average communication time interval, and is defined as the reciprocal of the average number of communications in 1 s.

Loss rate alone is not a good measure to compare the overall performance. Table 1 shows that the loss rate is 49.4% for variable rate with five repetitions, while it is 16.1% for fixed 600 ms (10 Hz). However, average distance error and tail probabilities are both much smaller in the variable rate case.

In Figs. 18 and 19, we have shown performances of the schemes in the same plot. The variable communication with repetition can optimize both average distance error and tail probabilities. Figs. 20 and 21 present variation of mean distance error and tail probability versus number of repetitions for the variable rate communications. In this set of results, the variable rate communication with one and two repetitions results in best tail probability and average distance error, respectively. In this paper, we do not address the problem of determining appropriate number of repetitions. However, we

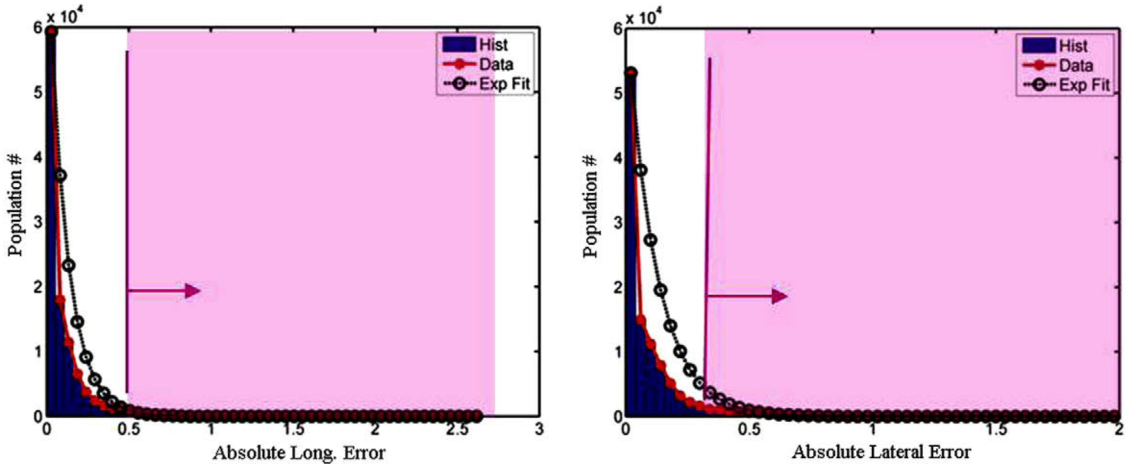

Fig. 17. Tail probability.

Table 1
Performance comparison of four communication designs.

Design	Scenario	ACT1 (ms)	Total loss rate (%)	Average distance error (m)	Stdev distance error (m)	Tail probability (100×)
VR	Without repetition	468	3.8	0.206	0.153	1.31
VR, with repetition	One repetition	240	5.8	0.178	0.151	1.12
	Two repetitions	162	7.3	0.174	0.159	2.03
	Three repetitions	123	13.6	0.177	0.165	3.45
	Four repetitions	99	28.1	0.187	0.177	5.60
	Five repetitions	80	49.4	0.197	0.177	6.27
Periodic, with model	25 ms	25	93.6	0.341	0.431	32.1
	50 ms	50	88.7	0.202	0.237	18.8
	75 ms	75	53.2	0.181	0.197	13.1
	100 ms	100	32.4	0.185	0.264	14.0
	200 ms	200	25.4	0.259	0.339	17.8
	300 ms	300	20.9	0.368	0.534	22.7
	400 ms	400	19.5	0.461	0.712	27.2
	500 ms	500	17.7	0.506	0.807	29.6
Periodic, without model	100 ms	100	31.8	1.05	1.23	68.1

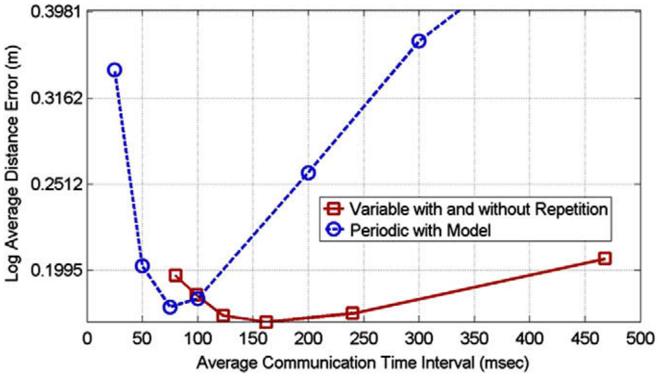

Fig. 18. Variation of mean distance error for variable communication (with and without repetition), and for periodic communication with model.

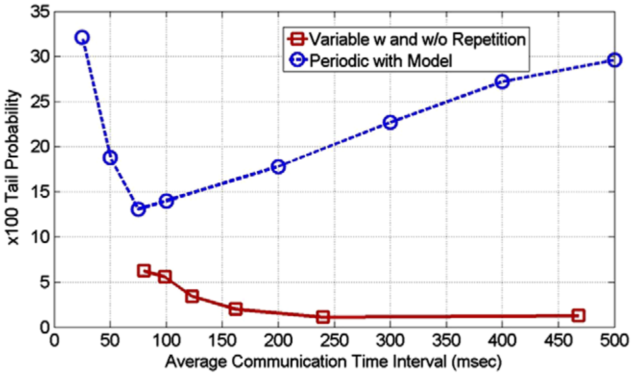

Fig. 19. Variation of tail probability for variable communication (with and without repetition), and for periodic communication with model.

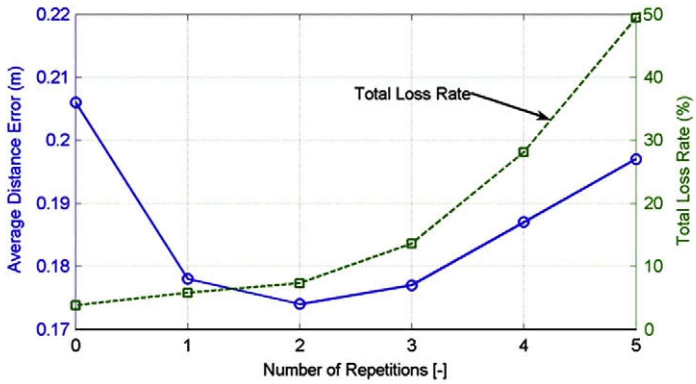

Fig. 20. Variations of mean distance error and total loss rate versus number of repetitions.

suffice to say that optimal number of repetitions is correlated with number of neighboring vehicles of a subject vehicle. Using the information derived by the neighbor estimators, an estimate of number of neighboring vehicles interfering with communications of the subject vehicle can be made and based on that number, number of repetitions can be throttled to increase reception probability of the repetitions.

In the variable rate communication without repetition, by using threshold values of 0.3 m and 0.5 m for the lateral and the longitudinal errors, the average communication time interval is 500 ms. Table 1 shows that fixed communication at 500 ms results in much poorer performance in terms of both mean distance error and tail probabilities.

The above results are all based on one set of threshold values. Of course, by changing the threshold values, numbers will change. However, the relative performance will not change.

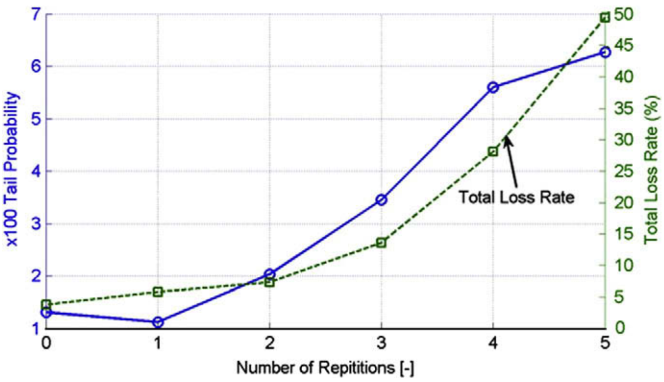

Fig. 21. Variations of combined tail probability and total loss rate versus number of repetitions.

5. Conclusion and future work

In this paper, we studied four communication schemes for position tracking in CASS. Beside the periodic communication scheme, which is widely used in the literature, we proposed three new schemes, including: periodic communication with model, variable communication, and variable communication with repetition. The variable communication schemes aimed to bound the longitudinal and lateral position tracking errors relative to other communicating vehicles within predefined bounds required for application functionality. Using the Ruby SHIFT and the Paramics traffic simulator, we have evaluated the performances of the four schemes using a number of simulations based on a variety of driving environments.

We used OPNET network simulator in order to evaluate performance of the schemes in the presence of communication losses. We showed that the total packet loss rate is neither a necessary, nor a sufficient measure to evaluate application level performance of a communication scheme. Instead we proposed new performance metrics, based on tracking errors in the presence of communication losses. Using the new performance measures, we concluded that variable communication with repetition results in the best performance.

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