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大規模都市環境におけるブロードキャスト型車車間通信方式のモンテカルロ解析

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車両の位置や速度の情報を車両間で共有してドライバに注意を喚起する，安全運転支援のためのブロードキャスト型車々間通信技術への期待が高まっている．これまでは車々間通信方式の性能をシミュレーションで評価する場合，数 100m 四方の範囲で数 100 台程度の車載端末が分布する環境までが限界であり、それ以上の規模では計算時間が多くかかり評価は困難であった．本稿では，統計的手法を用いることで計算時間を大幅に短縮し，大規模都市環境での車々間通信方式の評価を容易にするモンテカルロ計算方法を紹介する．この方法を用い，2 万台の車両が 2km 四方に存在する大規模都市環境での CSMA/CA と, CDMA をベースとした MAC 方式として筆者らが提案している MM-SA の二種類の通信プロトコルの性能比較評価を行った．その結果，大規模都市環境での MM-SA の高い耐干渉性能が示された．なお，CSMA/CA のパラメータは IEEE802.11p を考慮して設定した．

Monte-Carlo Analysis Of Inter-Vehicle Broadcast Protocols In Large Scale Urban Environments

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We have developed a Monte Carlo method to compute statistical properties of periodic wireless broadcast methods in complex environments. In this paper, we describe the principles of this method and its application to the comparison of inter-vehicle broadcast protocols in a large scale urban street grid. In particular, we compare performance of protocols based on CSMA/CA and MM-SA, a CDMA-based protocol, in a collision scenario with up to 20,000 vehicles distributed in a surrounding 2km x 2km street area. We show that the MM-SA protocol exhibits superior performance in the case of many surrounding vehicles.

1. Introduction

Inter-vehicle wireless broadcast technology has the potential to enable fast sharing of position and motion information which can be used to warn drivers of possible vehicle collisions. The speed and reliability of the information broadcast which is possible with inter-vehicle broadcast depends on both the intrinsic physical quality of wireless signals and the logical coordination of packet broadcasts to avoid packet collisions. The evaluation of inter-vehicle broadcast schemes in realistic scenarios is an urgent topic to understand the fundamental and practical limits of reliable performance, the resources (particularly, valuable spectral resources) that will be needed to achieve reliable performance, and the related issues for standardization.

Various broadcast methods have been proposed aimed at reliable inter-vehicle data exchange, including methods based on CSMA/CA, as in IEEE802.11p [1][2], and methods based CDMA, such as MM-SA [3][4][5]. Various studies are now underway to evaluate these methods in realistic situations. In particular, one difficult task in evaluating the performance of the proposed protocols is evaluating the effect of interference from many vehicles distributed over many streets and intersections. The complexity of wireless propagation and protocol dynamics make this a difficult computation task in general. A common computation approach is to use a standard packet-wise network simulator in combination with a ray-tracing method to capture radio-wave propagation effects. However, the computation load of this approach makes it difficult to consider very large numbers of vehicles. The use of statistical models is one way to avoid the heavy computations of more detailed packet network simulators and provide insights into key effects. However, in order to make the computation tractable, it is typically necessary to invoke simplifying assumptions regarding the spatial shape of the signal strength distributions and the dynamics of the protocol.

We propose the use of a Monte Carlo approach to compute results for statistical models of inter-vehicle broadcast systems. This method allows us to evaluate broadcast methods in more complex situations. In this paper, we describe the Monte Carlo method and its application to the comparison of inter-vehicle broadcast protocols in a large scale urban grid. In particular, we compare inter-vehicle broadcast protocols based on CSMA/CA and MM-SA.

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2. Related Works

Comparison of PDR performance for CSMA/CA and MM-SA protocols has been analyzed using the QUALNET or NS-2 network simulator [3][4][7]. However, the number of vehicles has been limited due to the heavy computation load from detailed handling events of packet transmission and reception by all vehicles.

Recently, Imai et al. [8] have used statistical model approach to estimate the performance of inter-vehicle broadcasts in a street grid for a CSMA/CA-based protocol. The statistical analysis was successfully applied to analyze inter-vehicle broadcasts with large numbers of vehicles, and obtain important insights into essential effects of distributed signal strengths and hidden terminals. This work introduced drastic simplifying assumptions about the spatial distribution of signal strengths, and the operation of the protocol, in order to make the model tractable.

The Monte Carlo method is often used to obtain approximations of solutions in complex physical science and engineering, including financial engineering. However, the Monte Carlo method has had only limited application so far in wireless networks. Kwon et al. [9] propose a coverage calculation method using Monte Carlo simulation in wireless sensor networks. Wang et al. [10] use a Monte Carlo simulation to evaluate a protocol for wireless sensor networks. To our knowledge, the Monte Carlo method has not been previously applied to the analysis of inter-vehicle communications.

3. Monte Carlo Method

In this paper, we present an analysis approach based on calculating the Packet Delivery Ratio (PDR) as a function of Signal-Noise Ratio (SNR). The model focuses on just one representative pair of transmitter and receiver, and treats all other simultaneous transmissions as interference which contribute to the reduction of the Signal-Noise Ratio (SNR).

3.1 Statistical Approach

When the probability distribution of the SNR, p(SNR), is known explicitly, the average value of PDR can be obtained as

$$\mathrm{PDR} = \int F[x]\ p(x)\,dx \tag{1}$$

where x represents SNR values, and F is the functional dependence of PDR on SNR. However, in many practical situations, the probability distribution is not known explicitly, or is too complex to compute.

3.2 Monte Carlo Computation

In cases where Eqn (1) cannot be computed explicitly, the Monte Carlo method can be used to numerically estimate the expected value of PDR by taking the average of multiple random trials. Specifically, our Monte Carlo model calculates the average PDR for various cases of interference by using situation-dependent probabilities to randomly generate trials. Our Monte Carlo model for PDR, is written as,

$$\mathrm{PDR} = \frac{1}{J\,M}\sum_{j=1}^{J}\sum_{m=1}^{M} F\left[\frac{P_0}{\frac{1}{g}\sum_{i=1}^{n} A_{j,m,i}P_{j,i} + N}\right] \tag{2}$$

Here the variables P_0, $Pk_{,i}$ correspond to received power of signal and interferences (i =1,n) in vehicle location trial j, N is intrinsic noise power, g is coding gain, n is total number of vehicles, J is number of vehicle location trials, and M is number of time trials. $A_{j,m,i}$ is an activity index (1=active, 0=inactive) indicating the presence of signal from interference source i in trial (j, m).

The main steps in the numerical computation using the Monte Carlo method are as follows:

1. Determine signal strengths $\{P_{j,i}\}$
2. Determine activity indices $\{A_{j,m,i}\}$
3. Calculate SNR
4. Calculate PDR from SNR.

These steps are repeated many times to obtain the average value of PDR.

The key point for implementing this computation method is the creation of algorithms to generate instances of the sets of signal strengths $\{P_{j,i}\}$ and activity indices $\{A_{j,m,i}\}$ which are consistent with the system conditions and protocol dynamics. Algorithms for generation of signal strengths can be obtained using models of radio signal loss depending on the locations of the nodes and the physical environment. Algorithms for activity indices are more difficult, depending on the dynamics of the wireless protocols. In our method, we determine activity indices using probabilistic rules of the type:

$$A_{j,m,i} = \begin{cases} 1 & \text{if} \quad (\text{random } (1) < X\ ) \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

where random (1) is a random number uniformly generated between 0 and 1, and X is a constant which depends on the protocol parameters. Typically, the rule may be expressed as a combination of multiple separate rules.

3.3 Packet Delivery Ratio (PDR)

In this paper, first the SNR is calculated, then the Bit-Error Rate (BER) is calculated from the SNR using a given BER function, then the PDR is calculated from the BER considering the number z of bits in a packet,

$$\mathrm{PDR} = (1\text{-}\mathrm{BER})^{z} \tag{4}$$

This method invokes a drastic assumption that the signal strength and SNR is constant for each packet, and ignores the details of incomplete overlap of packets in time. The method could be extended a step further to treat SNR varying within a packet by considering BER as a function of SNR with the assumption that SNR is constant during each bit. However, for the purpose of this paper, the assumption of packet-wise constant SNR allows an effective estimate of PDR with greatly reduced computation load.

3.4 Packet Relay

Inter-vehicle packet relay can be most easily treated within a statistical framework by assuming the PDR calculation for each hop is statistically independent. Then, we can calculate the PDR as the compound probability that a packet is received via *any* of the possible relay paths. To illustrate the procedure, we describe an example for just one relay node. First, we separately calculate the PDR for the direct path PDR_d, and each of the two hops, PDR_{r1} and PDR_{r2}. Then the compound PDR is obtained as

$$\mathrm{PDR} = \mathrm{PDR}_d + (\mathrm{PDR}_{r1} * \mathrm{PDR}_{r2}) - (\mathrm{PDR}_d * \mathrm{PDR}_{r1} * \mathrm{PDR}_{r2}) \tag{5}$$

4. Probabilistic Models for Periodic Broadcast Protocols

In this section we present probabilistic models for periodic broadcast using the protocols CSMA/CA and MM-SA. These models can be considered as the simplest models for each protocol. We note that the details of the numerical results reported later depend on the simplifying assumptions used to obtain these probabilistic models. The Monte Carlo analysis could be further advanced to obtain more accurate estimates by replacing these basic models with more complex probabilistic models, such as multi-state Markov models.

4.1 Periodic Broadcast

First let us consider a simple random broadcast protocol. We assume that there is a certain probability X of a node transmitting at the same time as the target transmitter. This probability X can be used to generate the activity indices as in Eqn. (3). For example, for random periodic broadcast, the probability can be estimated as a function of packet time length L and broadcast period T as follows,

$$X = L / T \tag{6}$$

4.2 CSMA/CA

In the case of CSMA/CA, the activity indices for different nodes in each trial are not statistically independent, but are correlated due to the carrier sense interaction mechanism. It is necessary to incorporate the effect of blocking of nearby transmissions due to carrier sensing, and re-scheduling due to back-off. This is done by using the probabilities shown in Table 1, using the back-off window size CW as an additional parameter.

In each Monte Carlo trial, the activity indices are set sequentially for nodes chosen in a random order. In Table 1, the condition “carrier-sensed = True” means that the strength of the signals from previously set nodes with nonzero activity index exceeds a specified carrier-sense threshold. In this case the single node packet generation rate is reduced by a factor of CW. The non-zero probability of transmission when “carrier-sensed = True” models the effect that a node will transmit if its back-off counter reaches zero at the same time as the target transmitter.

Table 1 CSMA/CA model probabilities

Condition	Probability X
carrier sensed = False	L / T
carrier sensed = True	(L / T)*(1/CW)

4.3 CDMA

A CDMA transmission can be most simply modeled by just including a non-zero value of the coding-gain parameter g in Eqn. 2. Further details depend on the particular CDMA-based scheme, as described in regard to MM-SA below. The increase of g usually requires a tradeoff reduction in bit rate, in order to keep the same communication bandwidth. This results in an increase of packet length L in the periodic broadcast scheme.

4.4 MM-SA

MM-SA protocol is a CDMA-based protocol which includes additional features which enhance the reliability for delivery of collision warning signals. The details of the protocol are described in [4]. Here we describe briefly the key features which are considered in our probabilistic model.

Multi-channel Spread Aloha: Transmissions use one of a small set of spreading codes, and one of a small set of frequency channels. Vehicles in the same road lane, and traveling in the same direction, transmit in the same frequency channel. Each vehicle has multiple matched filters, which allows it to receive any of the signals or codes used by other vehicles.

Packet Relay: We assume that packets are only forwarded by vehicles travelling in a limited area ("relay-zone") in front of the target vehicle. Each vehicle relays packets for other vehicles if it is in their relay zone.

Transmission Scheduling: Vehicles use adaptive transmission scheduling to delay their primary transmissions with respect to the vehicles preceding them on the road. The delay is characterized by an integer parameter C>1 which determines the length of the delay in terms of packet lengths. This means that vehicles broadcast with a timing according to their sequential order of their position on the road. We denote the order by s and the corresponding timing of primary broadcast transmission is given by s (mod T/CL). An interval of time of length (C-1)L after a primary transmission is used for relay transmissions.

In order to specify a probabilistic model for MM-SA, we assign vehicle timing according to the order of the vehicles on the road and introduce a relay probability V. Specifically, in this paper we estimate V as

$$V = K/Q \tag{7}$$

where K is an estimate of the number of vehicles in a relay zone, and Q is the number of packet slots available for relay. Q is obtained as

$$Q=(C-1)*T/CL \tag{8}$$

With the above considerations, the probabilities used for generating activity indices in the MM-SA model can be specified as in Table 2 below.

Table 2 MM-SA model probabilities

Condition		Probability X
Source Vehicle	Channel AND Timing are same	1
	Channel OR Timing is not same	0
Relay Vehicle	Channel AND Timing are same	V
	Channel AND Timing are same	0

5. Physical Models

5.1 Radio Signal Loss

The signal strengths P_i are obtained using models for propagation loss depending on the locations of the nodes. For simplicity, we use a model which gives loss as a function of relative position in the road system, as used in [7]. This is based on a form of the Ichitsubo loss model [11] with a distance r defined in terms of the distances x and y along cross streets,

$$r^k = |x|^k + |y|^k \tag{9}$$

For index k=2, the distribution of signal strength is an isotropic circle. For k=1 it is a diamond. Values of k smaller than unity give concave diamond shapes [7]. A concave diamond shape captures the effect of non-line-of-sight (NLOS) dependence on direction for vehicles on cross streets [12,13].

In the evaluation below we adopt the model of [7] with the frequency and road width parameters adjusted to the particular scenario. Moreover, we adjust the index k from the value of k=0.6 used in [7] to the value k=0.255, so as to match empirical measurements of signal strength in cases with low antenna heights and dense roadside obstacles [3]. We also assume signal is cut-off in parallel streets, ie. the path between transmitter and receiver passes around at most one corner. The above assumptions result in a significant reduction in the range of the NLOS transmissions compared to [7].

5.2 Bit-Error Functions (BER)

The BER function depends on the physical layer modulation scheme. Here we give two examples which are used in the simulations below, QPSK and 16QAM with convolution coding and hard-detection.

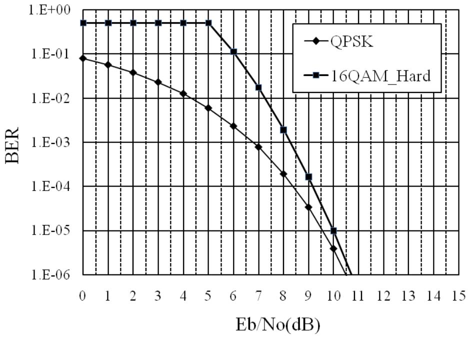


Fig. 1 BER models used in simulations

5.3 Device Noise Power

It is necessary to specify the value of the device noise parameter N in Eqn 2. Assuming device factor of 10 and operating temperature of 300K, we can express the value of the intrinsic device noise intensity as

$$N = F * kT * R \tag{10}$$

where kT is the thermal noise per hertz, F is the device noise factor and R is the bit rate. Assuming T = 300k, F =10, and letting r be the rate in units of Mbps, we can express the intrinsic noise power as

$$N\ (\mathrm{dBm}) = -\ 103.8 + 10 * \log r \tag{11}$$

The receiver sensitivity depends on a combination of this device noise power and the BER function.

6. Simulation Conditions

In this section we specify a specific set of conditions for evaluation, including road scenario, and the values of physical and protocol parameters.

6.1 Simulation Scenario

As a typical example of a collision scenario, we consider an encounter collision at an intersection in a road system with a rectilinear grid structure. Specifically, the road grid has 100 streets in a 2km x 2km square area. Street spacing is 50m with lane structure as follows: the two central cross streets have 3 lanes, every 200m there is a two-lane street, and all other streets have one lane [7].

As a particular collision scenario, we consider collision scenario of two vehicles at the intersection of a one-lane and two-lane street, as in Fig. 2. One vehicle (the receiver of broadcasts) is on the one-lane street, set back from the intersection. The other vehicle (the target transmitter) is approaching along the two-lane street. Tx and Rx are the horizontal coordinates of the transmitter and receiver, respectively. Similarly, Ty and Ry are the corresponding vertical coordinates. Specifically, the position of the receiving vehicle relative to the center of the 2km x 2km road grid system is (50m, -212m). The trajectory of the approaching target vehicle relative to the receiving vehicle is (150m~0m, 9m). Other vehicles are distributed randomly over the surrounding 2km x 2km road system. It is assumed that all vehicles broadcast packets including their position, speed and motion direction every 100ms.

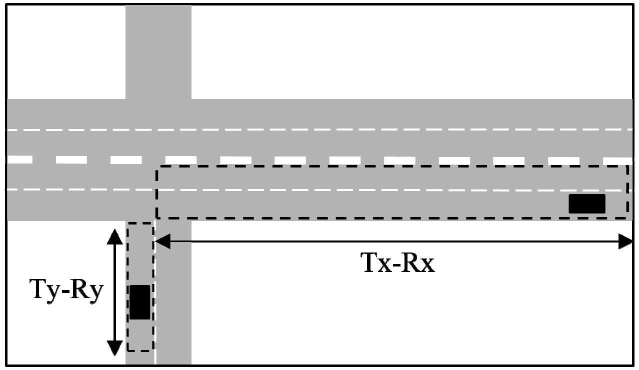


Fig. 2 Collision scenario at cross-roads

6.2 Protocol Parameters

In Table 3 below we summarize the values of parameters used in the evaluation below. It is assumed that the two protocols use the same total spectral bandwidth. The choice of parameter values for CSMA/CA were based on IEEE802.11p.

Table 3　Protocol Parameters

Parameter	**Protocol**	
	CSMA/CA	**MM-SA**
radio frequency	5.8 GHz	
signal loss model	concave diamond (k=0.255) with cutoff	
packet size	139 bytes	
broadcast interval (T)	100 msec	
Channels	1	4
Bandwidth	20 MHz	4 MHz
transmission power	20 dBm	10 dBm
BER function	16QAM (w/ convolution)	QPSK
bit rate	24 Mbps	585 kbps
packet length (L)	0.047 ms	1.95 ms
intrinsic noise ($N_{0)}$	-94 dBm	-106 dBm
maximum backoff (CW)	256 slots	--
carrier sense threshold	-85 dBm	--
spreading-gain (g)	--	7
relay zone	--	120 m
transmission scheduling (C)	--	3

7. Simulation Results

In this section we present specific results obtained using the Monte Carlo computation. We computed the PDR characteristics for two particular versions of inter-vehicle broadcast protocols based on CSMA/CA and MM-SA. The Monte Carlo method was implemented in combination with a multi-agent spatial simulation platform [14] which allows the real-time visualization of vehicle motion and signal strength distributions.

First, in Fig. 3 we show snapshots of signal strength distributions. Black areas show locations around a transmitting vehicle with power above the indicated threshold strength when transmit power is 20dBm.

Next, in Fig. 4 we show an example of a snapshot corresponding to a single Monte Carlo trial of CSMA/CA when many surrounding vehicles are broadcasting. The snapshot shows the road system with signals from concurrently transmitting vehicles. The overlap of signal distributions is manifestation of the so-called “hidden terminal problem”, that is, collisions between transmissions from transmitters which are not within carrier-sense range.

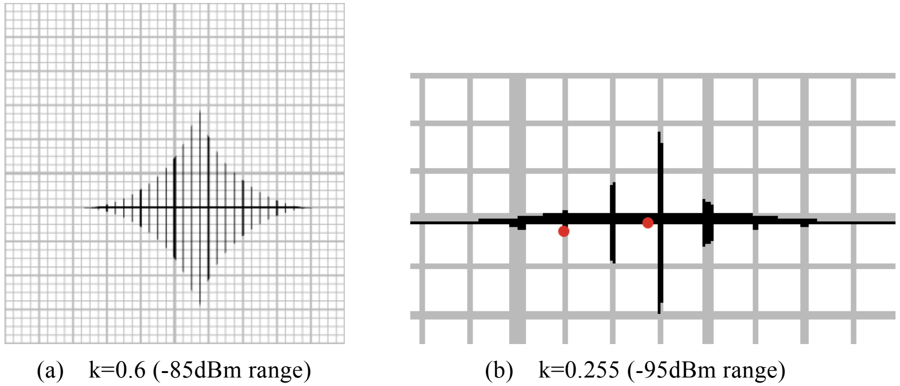

(a)　k=0.6 (-85dBm range)
(b)　k=0.255 (-95dBm range)

Fig. 3 Signal strength distributions

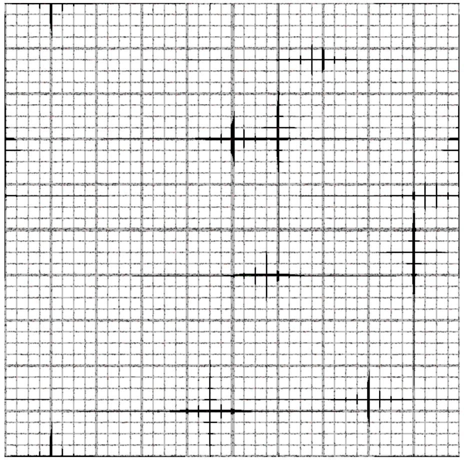


Fig. 4 Snapshot showing transmission footprints of simultaneous transmissions in a single Monte Carlo trial for CSMA/CA (n=20,000, k=0.255).

Finally, Fig. 5 shows plots of the PDR for broadcasts from the approaching vehicle as a function of distance from the intersection. In Fig. 5a there are no other vehicles, so the communication range is determined just by the transmission strength and transmission bandwidth. Fig. 5b shows two cases of 10,000 and 20,000 vehicles. The vehicles are distributed randomly in the surrounding 2km x 2km street grid. The average vehicle spacing in each lane is 42m for 10,000 and 21m for 20,000 vehicles.

First we note that the shorter range of CSMA/CA apparent in Fig. 5a is due to the higher bit rate, which affects the intrinsic noise power, and also the due to the difference in BER which is characteristic of the modulation scheme.

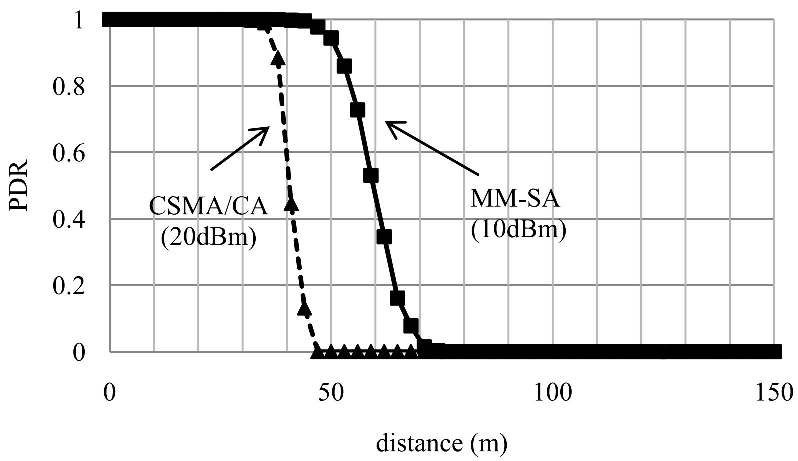
Comparing Fig. 5 (a) and (b) it can be seen that the PDR of the CSMA/CA deteriorates with increase of number of vehicles. On the other hand, the MM-SA protocol has better performance for higher vehicle density. In particular, values of PDR exceeding 80% at 90 m from the intersection are achieved by the MM-SA protocol. This supports the claims made in [3][4] that the performance of the proposed protocol MM-SA is scalable and potentially capable of satisfying expected reliability criteria.

8. Conclusions

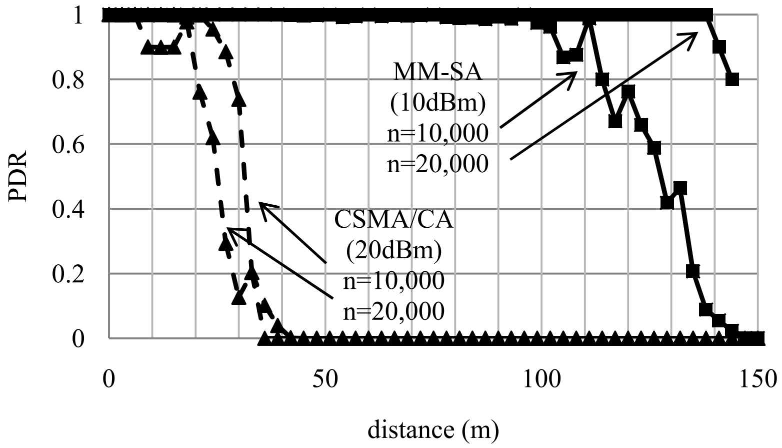
The Monte Carlo method allows probability of delivery of warning messages to be quickly estimated, allowing rapid identification of key effects and important parameter domains. We have applied it to a comparison of two methods based on CSMA/CA and CDMA.for a collision scenario with up to 20,000 vehicles distributed in a surrounding 2km x 2km multi-lane road system, with average inter-vehicle spacing per lane of 21 meters.

It was seen that the performance of the CSMA/CA-based deteriorated severely when the number of surrounding vehicles increased. This is a serious issue for proposed future schemes based on IEEE802.11 standards which use CSMA/CA. On the other hand, the recently proposed MM-SA protocol, which is based on CDMA, showed reliable packet delivery even in the case of 20,000 surrounding vehicles. This superior large-scale performance of the MM-SA protocol is due to the effective combination of CDMA with packet relay and transmission scheduling mechanisms aimed specifically at collision-warning applications.

The probabilistic models used here are relatively simple, but capture key basic features of the scaling behavior of the protocols in large road systems. As mentioned earlier, the Monte Carlo analysis could be further advanced by replacing these basic models with more complex probabilistic models, including multi-state Markov models. Also, extensions of the propagation loss models, for example considering propagation around multiple corners, shadowing by vehicles, and three dimensional road structures would be feasible.



(a) No interfering vehicles



(b) Large numbers of interfering vehicles

Fig. 5 Packet Delivery Ratio (PDR) dependence on distance (Tx-Rx) from the intersection.

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