

## Vehicle-to-Vehicle Channel Simulation in a Network Simulator

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***Abstract***—Recent developments in vehicle-to-vehicle (V2V) communication has increased the need for simulation to test and analyze protocols for this emerging technology. Packet level network simulators lack a realistic V2V channel module that would allow having accurate simulations. An efficient method for generating a V2V channel in a packet level network simulator is discussed. This method, based on V2V channel measurements and models, efficiently generates Nakagami fading whose power spectrum and fading severity change with vehicles' velocities and separation. The small-scale fading envelop is used to modulate a large-scale path loss model. The implementation uses a simple pre-computed lookup table to generate the power envelop with minimal calculations in the simulator.

***Index Terms***—Nakagami fading, network simulator, wireless channel simulation.

### I. INTRODUCTION

VEHICLE-TO-VEHICLE (V2V) communication will be an essential part of Intelligent Transportation Systems (ITS). It will allow nearby vehicles to communicate without the

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dependence on any infrastructure or roadside equipment. One of the major applications of V2V is road safety where it would provide drivers with more information about their surroundings and give them early warnings about potential hazards on the road. A summary of how V2V can improve on-road safety can be found in [1]. V2V will also have various applications that would improve driving experience such as road traffic information, weather conditions, internet access, and automatic highway tolls payment.

Research in V2V has been substantially growing recently after the Federal Communications Commission (FCC) in the United States allocated 75 MHz of spectrum from 5.85 GHz to 5.925 GHz as part of ITS for the use in Dedicated Short Range communications (DSRC) [2]. The IEEE 802.11p standard is currently under development for use with DSRC technology in this band as well as other international allocations. As the DSRC standard is being formed, Vehicular Ad Hoc Networks (VANETs) for V2V communication are gaining more importance. The process of designing, validating, and evaluating network protocols for VANET requires extensive simulations before deployment or testing using expensive hardware. These simulations should give results as close as possible to the real world, requiring simulators to provide a realistic V2V propagation channel model.

Network protocol simulation packages operate on individual packets created in the simulation, and there might be thousands of such packets in one simulation run, making them computationally expensive. The addition of a radio frequency propagation channel module should add a minimal amount to the computational complexity in the simulator. Popular simulators often provide support only to free space path loss and two ray propagation models due to computational efficiency considerations.

This paper describes a simple and efficient method for simulating a Nakagami fading envelop whose time correlation properties are described by the double-ring model for mobile-to-mobile communication [3]. The time correlation, or the power spectrum, of the Nakagami process varies during the simulation run based on the velocities of the transmitter and the receiver. The  $m$  parameter of the Nakagami fading process varies according to the separation distance between the transmitter and receiver.

This is achieved by extending the method described in [4] where a dataset containing the fading process components is pre-computed. The time correlation for each component is obtained by shaping complex Gaussian random numbers with the appropriate power spectra. The simulator then uses the dataset as a lookup table for calculating the fading envelop with the needed power spectrum based on some calculated parameters. The calculation of parameters needs minimal computation. These parameters include the velocity ratio of the receiver and transmitter, maximum Doppler frequency,  $m$  parameter of the Nakagami fading, and the large-scale path loss power. The small scale fading is used to modulate the large-scale path loss.

Section II discusses the V2V channel model that is used in the simulation, Section III describes the method used for computing the dataset and then constructing the fading envelop from the dataset, Section IV verifies the statistics of the simulation results, and Section V concludes the paper.

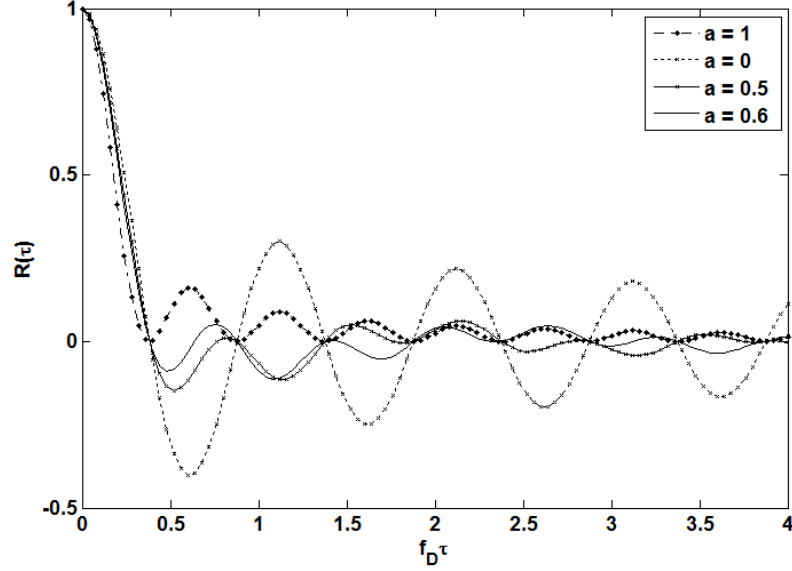


Fig. 1. The autocorrelation function for various values of  $a$ .

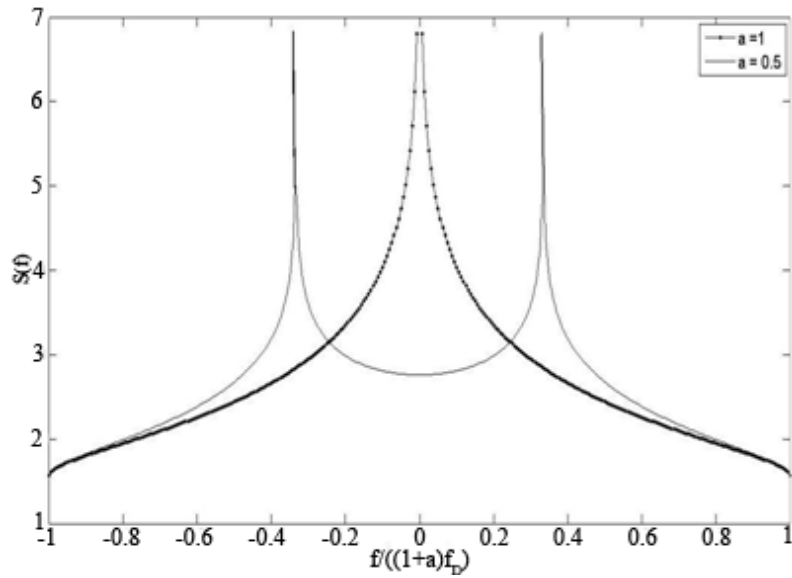


Fig. 2. The power spectrum for different values of  $a$ .

## II. THE CHANNEL MODEL

The growing interest in DSRC technology for V2V has initiated the necessity to understand the behavior of DSRC in V2V propagation environments. This is needed for enabling the design of reliable and practical V2V communication systems.

Channel models for mobile-to-mobile communications have been discussed in [3], [5], [6], [7]. These models are based on the double-ring model, which assumes isotropic scattering and a fading envelop having a Rayleigh distribution. The time correlation function for each of the in-phase and quadrature components of the Rayleigh envelop is found to be:

$$R(\tau) = J_0(2\pi f_D \tau) J_0(2\pi a f_D \tau) \quad (1)$$

where  $a$  is the ratio of the transmitter velocity  $V_t$  and receiver velocity  $V_r$ :  $a = V_t/V_r$ , and  $f_D$  is the maximum Doppler frequency due to the motion of the transmitter:  $f_D = V_t/\lambda$ . The correlation function for various values of  $a$  is shown in Fig. 1. Note that when  $a$  is zero, then the transmitter is stationary, and the autocorrelation function reduces to that given by Clark [8].

The power spectrum of the complex envelop is derived by taking the Fourier transform of the autocorrelation function:

$$S(f) = \frac{1}{\pi^2 f_D \sqrt{a}} K \left[ \frac{(1+a)}{2\sqrt{a}} \sqrt{1 - \left( \frac{f}{(1+a)f_D} \right)^2} \right] \quad (2)$$

where  $K()$  is the complete elliptic integral of the first kind. The power spectrum for different values of  $a$  is shown in Fig. 2.

The assumptions made by the double-ring model might not always be true in a V2V environment, where both of the communicating vehicles are limited to motion on the road. An empirical study of the V2V channel [9] where measurements were taken in real driving conditions, shows that the fading envelop is more accurately modeled by a Nakagami distribution [10]:

$$f_Z(z) = \frac{2m^m z^{2m-1}}{\Gamma(m)\Omega^m} e^{-(m/\Omega)z^2} \quad (3)$$

where  $\Omega = E[Z^2]$  is the expected power of the signal  $Z$ , and  $m = \frac{\Omega^2}{(Z^2 - \Omega)^2} \geq 0.5$ , characterizes the Nakagami fading. For  $m$  less than one, the fading is sub-Rayleigh, for  $m$  equal to one it is Rayleigh, and for  $m$  greater than one it can be approximated by Ricean fading. Fig. 3 shows the Nakagami distribution for different values of  $m$ .

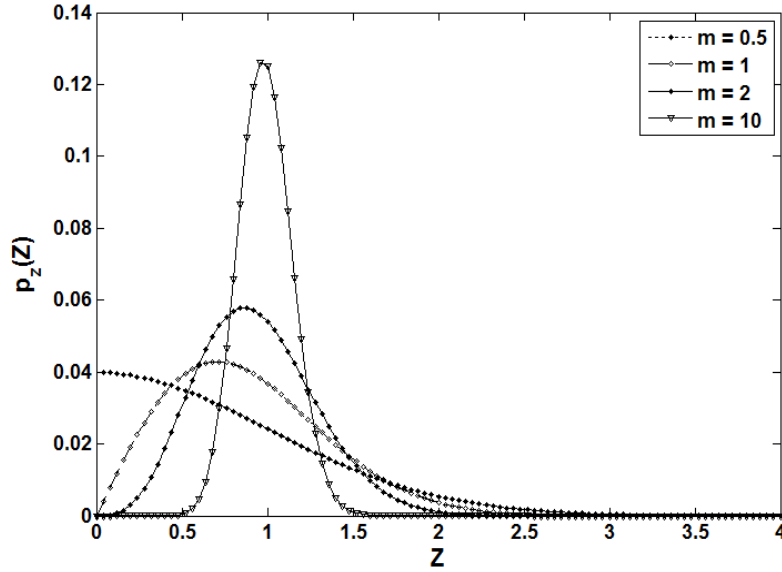


Fig. 3. The Nakagami Distribution for different values of  $m$ .

In V2V environments, the transmitter and receiver are moving at high speeds. This causes different fading statistics depending on the existence of a line-of-sight (LOS). The  $m$  parameter would be changing in inverse proportion with distance since the chance of having LOS decreases as distance increases due to turns or intersections at the road. This results in Rayleigh or Sub-Rayleigh fading. At shorter distances, it is very likely to have a LOS since there would be no obstacles in the road between the vehicles. Reference [9] has shown how  $m$  changes with distance by measuring the received signal strength versus distance, and then dividing the distance into bins, where the amplitude values within each bin are used as the data to fit the Nakagami distribution. Linear regression was then used to get the best fit of the variation of  $m$  with distance:

$$m = -1.3 \log_{10} \left( \frac{d}{d_o} \right) + 3.7 \quad (4)$$

This function will be used by the simulator to dynamically calculate  $m$  during the simulation run to find the fading envelop. This fading envelop is then used to modulate the large-scale path loss. To obtain a realistic path loss model, V2V measurements need to be fitted to a piecewise linear model that shows how the average power changes with distance. Measurements done in [9] were fitted to a dual piecewise linear model:

$$P(d) = \begin{cases} P(d_o) - 10\gamma_1 \log_{10} \left( \frac{d}{d_o} \right) + X_{\sigma_1} & \text{if } d_o \leq d \leq d_c \\ P(d_o) - 10\gamma_1 \log_{10} \left( \frac{d_c}{d_o} \right) - 10\gamma_2 \log_{10} \left( \frac{d}{d_c} \right) + X_{\sigma_2} & \text{if } d \geq d_c \end{cases} \quad (5)$$

where  $\gamma_1$  is a path loss exponent above a reference distance  $d_o$  and up to a critical distance  $d_c$ , and after that the power falls off with path loss exponent  $\gamma_2$ .  $X_{\sigma_1}$  and  $X_{\sigma_2}$  are zero mean normally distributed random variables with standard deviations  $\sigma_1$  and  $\sigma_2$  respectively. They model the scatter in the path loss measurements. The parameters for this model were fitted using linear regression for three different environments: suburban, rural, and highway. The corresponding values are shown in Table I. The next section focuses on generating the small-scale fading using the described channel model.

### III. SIMULATION

#### A. The Nakagami Fading Envelop

When  $m$  is an integer or half integer, a Nakagami process can be decomposed into the amplitude of  $n$  independent and identical Gaussian processes:

$$Z(t) = \sqrt{X_1^2(t) + X_2^2(t) + \dots + X_n^2(t)} \quad (6)$$

where  $X_i(t)$ ,  $i = 1, \dots, n$  are independent and identically distributed (iid) Gaussian processes each with zero mean and variance  $\sigma_X^2$ . The process  $Z(t)$  has a Nakagami pdf with  $m$  parameter  $m = n/2$  and  $\Omega = 2m\sigma_X^2$ . Thus in the case when  $2m$  is an integer,  $X_i(t)$  can be computed with the required time correlation using the inverse discrete time Fourier transform method which will be described below. The dataset would be composed of those  $X_i(t)$  processes. However, this decomposition would make the size of the dataset impractically large to enable simulations with a big value for  $m$ . Moreover, more computation time would be required for summing all the components.

A solution for this problem is to approximate the Nakagami process as a Ricean process when  $m > 1$ , by mapping  $m$  to the Ricean  $K$  parameter [11]:

$$K = m - 1 + \sqrt{m^2 - m}. \quad (7)$$

The Nakagami process then becomes a Ricean process whose envelope is:

$$Z(t) = \sqrt{(X_1(t) + \sigma_X \sqrt{2K})^2 + X_2^2(t)}. \quad (8)$$

The normalized power envelope is then:

$$Z^2(t) = \frac{1}{2\sigma_X(K+1)} [(X_1(t) + \sigma_X \sqrt{2K})^2 + X_2^2(t)]. \quad (9)$$

This eliminates the need to store more than two processes in the dataset, and also allows simulating the Nakagami fading for any real  $m > 1$ . Note when  $m = 1$ , the Nakagami fading becomes Rayleigh fading.



Table I  
The dual-slope piecewise linear model parameters for the V2V channel in urban, rural and highway environments

Parameter	Urban	Highway	Rural
$\gamma_1$	2.05	1.9	2.3
$\gamma_2$	3.9	4.0	4.0
$\sigma_1$ (dB)	4.1	5.9	5.5
$\sigma_2$ (dB)	6.4	6.6	4.7
$d_c$ (m)	100	220	226

A problem still exists when  $m$  is in the range  $0.5 \leq m \leq 1$ . Zhang in [12] solves this problem by defining

$$Z(t) = \sqrt{\alpha X_1^2(t) + \beta X_2^2(t)}, \quad (10)$$

where the coefficients  $\alpha$  and  $\beta$  are given by:

$$\alpha = \frac{2pm + \sqrt{2pm(p+1-2m)}}{p(p+1)} \quad (11)$$

$$\beta = 2m - p\alpha \quad (12)$$

and

$$p = \lfloor 2m \rfloor. \quad (13)$$

The corresponding normalized power envelop in this case would be:

$$Z^2(t) = \frac{1}{\alpha^2 + \beta^2} [\alpha X_1^2(t) + \beta X_2^2(t)]. \quad (14)$$

### B. Generating $X(t)$

Methods for generating a correlated Gaussian process are well known. Since the generated data is stored as a block, it would be most efficient to use the inverse discrete Fourier transform method [13]. This method generates processes with limited time duration. A simulation run with longer time duration can reuse the processes in the pre-computed dataset. This requires the

beginning and end of the each process to be wrapped around so that the signal would be continuous. The power spectrum in Eq. 2 would be used for shaping the generated complex Gaussian random numbers. The need to have a varying spectrum as the velocities of the vehicles change during a simulation run requires storing the same components for different values of  $a$  in the power spectrum in Eq. 2. It is chosen to have spectra with  $a$  at 0.1 intervals for  $0 \leq a \leq 1$ . In the case the power envelope in the simulation has a spectrum with  $a$  not stored in the dataset, the spectrum with the nearest  $a$  is taken. This rounding would not have a significant effect on the correlation properties of the Nakagami fading components. It can be seen from Fig. 1 that the autocorrelation functions for  $a = 0.5$  and  $a = 0.6$  are almost overlapping.

The steps for calculating the dataset are as follows:

1. Specify the maximum Doppler frequency  $f_D$ , the number of samples that will be used to represent the power spectrum, and the frequency spacing (i.e. sampling frequency) of the samples. Note that the power spectrum should be an even function. The inverse of the frequency spacing determines the time duration of the pre-computed fading envelope.

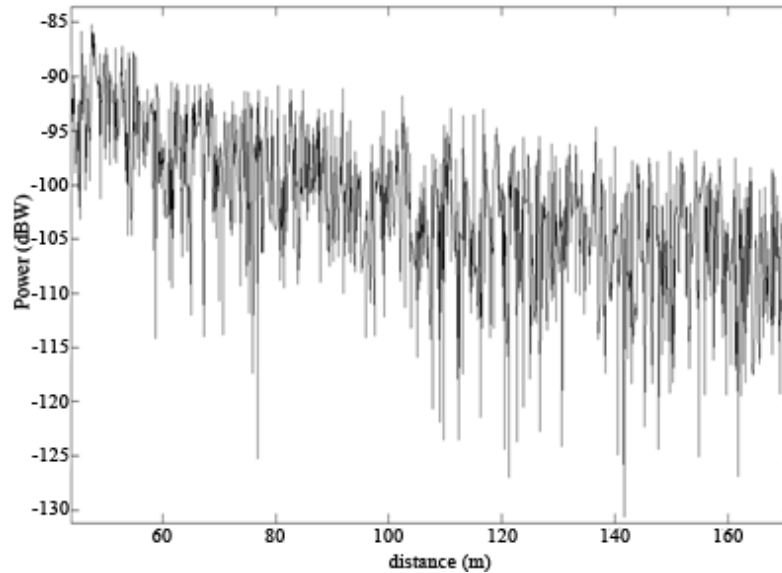


Fig. 4. Simulated power envelope versus distance (transmit power = 0.282 W, antenna heights = 1.5 m).

2. Generate a complex Gaussian random sequence for half the samples representing the positive frequency points. Conjugate this sequence to represent the negative frequency points.
3. Set the value of  $a$  for the power spectrum in Eq. 2 to zero.
4. Evaluate the spectrum from Eq. 2 at the same frequencies as in step 2.
5. Multiply the generated complex Gaussian sequence with the spectrum samples.
6. Perform an IFFT on the resulting sequence and take the real part to obtain the time domain equivalent. The IFFT operation ensures that the dataset is wrapped around so that it can be reused during a simulation run.
7. Increase  $a$  by 0.1 and repeat steps 4 – 7 until  $a = 1$ .
8. Repeat steps 2 – 7 to calculate the other time series.

### C. Using different Doppler frequencies

The dataset contains time series with different spectra for all values of  $a$ . However, when the transmitter changes velocity,  $f_D$  also changes. This imposes the need to do simulations with  $f_D$  different than the value used in constructing the dataset. This can be done by stretching or squeezing the dataset time series [4]. Let  $f_{D_0}$  be the maximum Doppler frequency represented in the dataset,  $f'_D$  be the desired maximum Doppler frequency for simulation, and  $\Delta t$  be the time spacing in the dataset. The time spacing of the simulation would be:

$$\Delta t' = \frac{f_{D_0}}{f'_D} \Delta t. \quad (15)$$

### D. The algorithm

The algorithm for calculating the fading envelop uses a dataset pre-computed as described above, containing  $X_1(t)$  and  $X_2(t)$  with different spectra. The following summarizes the steps of the algorithm:

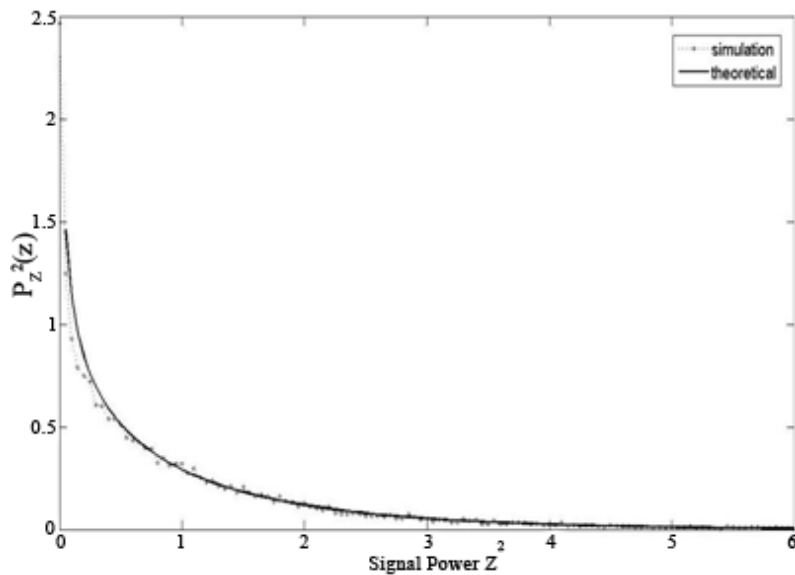


Fig. 5. Theoretical and simulated probability density function for the received signal power.

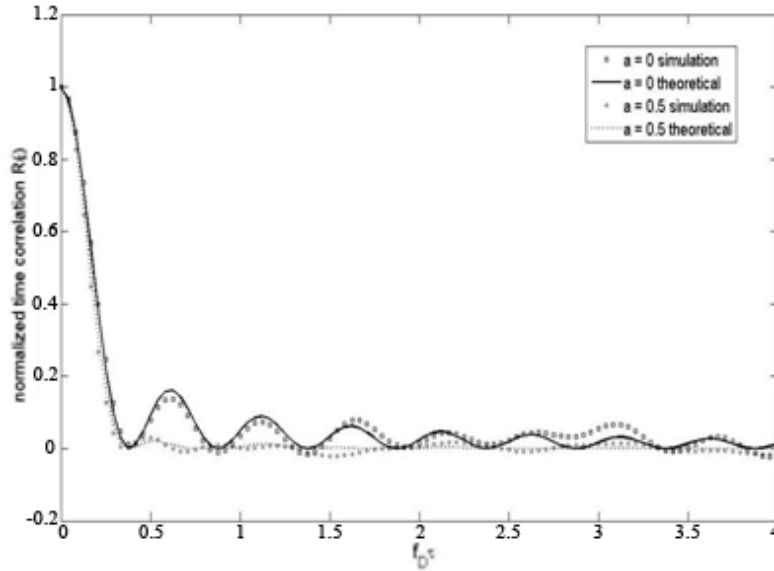


Fig. 6. Empirical and theoretical normalized time correlation functions of the power fading envelop.

1. Get  $V_r$  and  $V_t$  from the simulation scenario. If  $V_t > V_r$ , then  $a = V_r/V_t$  and  $f_D = V_t/\lambda$ , otherwise  $a = V_t/V_r$  and  $f_D = V_r/\lambda$ .
2. If the value of  $f_D$  in the simulation is different than the one in the dataset, expand or squeeze the dataset time spacing using Eq. 15.
3. Depending on the value of  $a$ , select the proper time correlated components  $X_1(t)$  and  $X_2(t)$  from the dataset.
4. In the simulator, calculate  $m$  using Eq. 4. The distance is known from the simulation scenario.
5. If  $m > 1$ , calculate  $K$  using Eq. 7. Otherwise, calculate  $\alpha$ ,  $\beta$  and  $p$ , using Eqs. 11, 12, and 13 respectively.
6. Calculate the fading envelop using Eq. 9 if  $m > 1$ , or Eq. 14 otherwise.

7. Multiply the fading envelop with the calculated large-scale path loss power at the corresponding distance.

#### IV. VERIFICATION

The fact that the statistics of the fading envelope are constantly changing during the simulation makes it difficult to verify the simulation results when the transmitter and receiver are moving and varying their velocities.

Since the power envelope is of interest in the simulation, the distribution of the signal power, which is the square of the signal amplitude, is:

$$p_{Z^2}(r) = \left(\frac{m}{\Omega}\right)^m \frac{r^{m-1}}{\Gamma(m)} e^{-\frac{mr}{\Omega}}. \quad (16)$$

A simulation scenario was conducted where the receiver is constantly moving away from a stationary transmitter. Since  $m$  is changing with distance, then  $m$  is different for each value of  $Z^2$ , depending on the distance. The signal power and the corresponding distance were recorded. Fig. 4 shows the signal envelope. Notice that the fading severity increases as the distance increases. The probability density function of the signal power is shown in Fig. 5. The autocorrelation of the signal can be compared to the theoretical as shown in Fig. 6. Also shown is the time correlation for other scenario when the transmitter is not stationary. It can be seen that the simulated data statistics are very close to the theoretical ones.

#### V. CONCLUSION

An efficient method for having a V2V propagation channel in a network simulator has been presented. Small-scale Nakagami fading is superimposed on a large-scale path loss model based on V2V channel measurements. A Nakagami process was decomposed into two Gaussian components. Each component was replicated several times and then each replica was shaped by

a different spectrum to obtain the time correlation for various values of the vehicles velocities. Those values were then stored to be used during simulation. The dataset can be reused in long simulation runs. A key contribution of this work is the realization of a computationally efficient fading model that can be varied during the simulation run to describe the effects of changing distance between vehicles in a link, and changing vehicle speeds.

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