Enhancing Connectivity for Spectrum-agile Vehicular Ad hoc Networks in Fading Channels

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Abstract—In Vehicular Ad hoc NETwork (VANET) safety applications, connectivity among vehicles is important to disseminate the upcoming traffic information (e.g., warning messages generated by a source vehicle that detects an accident) to other following vehicles to notify drivers in a timely manner. Because of the highly dynamic VANET topology and the short transmission range mandated for Dedicated Short Range Communication (DSRC) by Federal Communications Commission (FCC), communication links among vehicles are short-lived especially in sparse vehicular density, making the task of establishing (through connection setup process) and maintaining the communications for fast-moving vehicles difficult. Furthermore, when a fixed transmission range is used in dynamically changing VANET, network could be easily suffered by a “broadcast-storm” in dense vehicular density while vehicles in VANET could be disconnected frequently in sparse vehicular density. In addition, when communication channels are overcrowded in VANET, vehicles should be able to switch from one radio frequency (RF) bands to another to make robust communication using spectrum-agile wireless environment. In this paper, we study the connectivity for spectrum-agile VANET in fading channels. Specifically, connectivity enhancement for vehicle-to-vehicle communications for vehicles traveling in opposite directions and for vehicles traveling in same direction is investigated using mathematical analysis and simulation results. Performance of the proposed approach is evaluated using numerical and simulation results.

Index Terms—Vehicle-to-vehicle connectivity, connectivity in VANET, spectrum-agile VANET, adaptive VANET.

I. INTRODUCTION

Vehicular Ad hoc Network (VANET) is emerging as one of the most successful commercial applications of mobile ad hoc networks for intelligent transportation cyber-physical systems. VANET is expected to provide not only road safety and traffic efficiency by exchanging information among vehicles but also infotainment services to passengers. It is expected to use a variety of wireless technologies to forward the traffic information using Vehicle-to-Vehicle (V2V) through VANET and Vehicle-to-Roadside-to-Vehicle (V2R2V) communications. Because of the possible high delay introduced by V2R2V communication and the cost (licensing fee associated with licensed bands or installation cost of roadside units throughout the road to use unlicensed bands), V2V communication through VANET is one of the best alternatives for safety application to forward upcoming traffic information or warning messages generated by a source vehicle that detects an accident to other following vehicles to notify drivers in a timely manner. Performance of VANET depends on connectivity among vehicles since reliable connectivity for single hop or multi-hop communication is very important to forward time-critical information. Connectivity in VANET is directly related to density of vehicles, (relative) speed of the vehicles, and transmission range and frequency bands used by vehicles.

Recent related work concerning the network connectivity in VANET includes [1]–[11]. Connectivity in one dimensional VANET is presented in [1], [2], analysis for connectivity-aware routing in VANET is presented in [3], [7], and connectivity for both highway and urban roads is presented in [4]. Note that the existing methods in [1]–[3], [7] consider the connectivity among vehicles that are traveling in same direction only. To improve the connectivity, an extra vehicle is introduced as a mobile base station (BS) in [5], [6] and roadside BSs are used in [9]. It is difficult to introduce a reliable mobile BS in highly dynamic VANET. Furthermore, installation of roadside BSs throughout the highways is not economically viable option. Connectivity analysis is presented for both one-way and two-way scenarios in [11]. However, the work in [11] considers that all vehicles maintain constant speeds which doesn’t consider the effect of random speed of vehicles and dynamic adaptation of transmission range. Furthermore, dynamic spectrum access in cognitive radio enabled VANET is proposed in [12]–[15]. None of the methods in [12]–[15] considers adaptation of transmission range and the effect of sensing and connection setup time for V2V communications.

Note that none of the work available in the state-of-the-art literature considers the VANET connectivity for both one-way traffic flow and two-way traffic flow where vehicles travel with random speeds and in different vehicle densities. Furthermore, existing methods in the literature do not consider the spectrum-agile systems (where, for instance, vehicles switch channels between 5GHz/2.4GHz ISM band and 5.9 GHz DSRC band) with variable speed and range where vehicles switch channels from one frequency (DSRC) band to another (ISM) for V2V communications. In one-way traffic flow, the relative speed of vehicles is low which results in long duration for connectivity and information exchange (since time = $\frac{tx-range}{relative-speed}$). Whereas, in two-away traffic flow, time duration is short since the relative speed is high when vehicles travel in opposite directions.

In this paper, we study the V2V connectivity for vehicular communications in fading channels where we explicitly consider vehicles traveling in opposite directions as well as in same direction. We show that the connectivity in VANET can be enhanced by adapting the transmission range based on the estimated local vehicle density (and speed) and by switching...
frequency band to less congested one. Mathematical analysis is supported by numerical results obtained from simulations.

The remainder of the paper is organized as follows: the VANET model for V2V connectivity is presented in Section II followed by the analysis in Section III. Simulation results are given in Section IV. Finally, Section V concludes the paper.

II. VANET SYSTEM MODEL AND PROBLEM STATEMENT

Vehicles are assumed to be equipped with computing and communication devices according to the U.S. National Highway Transportation Safety Administration (NHTSA) ruling [16] to participate in vehicular communications. We assume that these devices are also capable of switching back and forth between 5.9 GHz DSRC band and 5GHz or 2.4GHz ISM bands and periodically broadcasting vehicle status information (location, speed, direction, etc.) in VANET [17]. For V2V communications, we consider: i) vehicles traveling in same direction as shown in Fig. 1 (a) and ii) vehicles traveling in opposite directions as shown in Fig. 1 (b).

![Image](a) One-way Two-lane Road Section

![Image](b) Two-way Two-lane Road Section

Fig. 1. Vehicular ad hoc networks with vehicles (e.g., V_i and V_j) with their corresponding transmission ranges (e.g., R_i and R_j).

As mentioned, time duration for vehicles to communicate with each other depends on their transmission ranges and their relative speed. In other words, when the relative speed is smaller (larger), vehicles remain within communication range for longer (shorter) time and they have longer (shorter) time for connection setup and information exchange using V2V communication. Note that when the vehicles travel in opposite directions at highway speeds, they remain within communication range of each other for a short amount of time which might not be enough for successful connection setup and information exchange.

Our goal in this setup is to enhance the VANET connectivity for V2V communications in both one-way and two-way traffic flows where the transmission range/power of each vehicle is adapted based on its local vehicle density (and vehicle arrival rate) in fading channels, and the RF bands are switched between DSRC and ISM based on the channel condition.

III. ANALYSIS FOR CONNECTIVITY IN VANET

A. Connectivity Probability, Vehicle Density and Range

The inter-arrival times of vehicles on a road-segment are exponentially distributed with parameter \( \lambda \) for a traffic flow of \( \lambda \) vehicles/sec [1]. When vehicles are assumed to be entering on the road with \( M \) discrete levels for the speed \( v_i, i = 1 \ldots M \), and with a rate of arrival of vehicles at each level of speed as \( \lambda_i, i = 1 \ldots M \), the probability of each speed level is \( P_i = \lambda_i/\lambda \). Then, the inter-vehicle distances are i.i.d and exponentially distributed with a parameter \( \rho = \sum_{i=1}^{M} \lambda_i/\rho_i = \lambda \sum_{i=1}^{M} P_i/\rho_i \). The CDF of inter-vehicle distance \( X = x \) is given by [1]

\[
F_X(x) = 1 - e^{-\rho x}, \quad x \geq 0
\]

Note that the speeds of different vehicles in free flow state is a Gaussian distribution [18], and for \( v_{min} = \mu_v - 3\sigma_v \) and \( v_{max} = \mu_v + 3\sigma_v \) as minimum and maximum level of the vehicle speed, the PDF is given by [1], [19]

\[
g_V(v) = \frac{f_V(v)}{\int_{v_{min}}^{v_{max}} f_V(v)dv}
\]

where \( f_V(v) = \frac{1}{\sigma_v \sqrt{2\pi}} \exp \left( \frac{-(v - \mu_v)^2}{2\sigma_v^2} \right) \) is the Gaussian PDF with a average speed \( \mu_v \), and standard deviation \( \sigma_v \). Then, we can write \( g_V(v) \) as

\[
g_V(v) = \frac{2f_V(v)}{\text{erf} \left( \frac{v_{max} - \mu_v}{\sigma_v \sqrt{2}} \right) - \text{erf} \left( \frac{v_{min} - \mu_v}{\sigma_v \sqrt{2}} \right)}, \quad v \in [v_{min}, v_{max}]
\]

where \( \text{erf}(.) \) is the error function [19]. The expected value of speed can be computed as

\[
E[V] = \int_{v_{min}}^{v_{max}} v g_V(v)dv
\]

Then, the average vehicle density on the road is given by

\[
\rho = \frac{1}{E[V]} = \lambda \sum_{i=1}^{M} P_i \mu_i = \frac{\lambda}{E[V]}
\]

Finally, average number of vehicles on a road segment \( L \) is computed as

\[
N_v = L \rho
\]

We note that \( N_v \) can also be estimated based on received periodic broadcast status messages [20]. The vehicles are said to be connected if their transmission ranges are larger than their separation distance. The distance between any two vehicles on the highway is exponential with parameter \( \rho \) and the probability that two vehicles are connected when they are within the range \( R \) is given as [18], [19], \( P(R) = 1 - \exp(-\rho R) \), and a given vehicle can be connected to \( N_v - 1 \) other vehicles with a probability given by

\[
P_{con} = [1 - \exp(-\rho R)]^{N_v - 1}
\]

The number of vehicles that can be present on a given road segment of length \( L \) is expressed as [20]

\[
N_v = \frac{L}{Sd} N L_n
\]

where \( Sd \) is the safety separation distance between vehicles, \( N L_n \) is total number of lanes on the road. Thus, a vehicle could estimate the normalized vehicle density as

\[
K_v = \frac{N_v}{N_l}
\]
Then, based on the estimated normalized vehicle density, each vehicle can adapt its transmission range as [20]

\[ R = \min\{L(1 - K_c), \sqrt{\frac{L \ln L}{K_c} + \alpha L}\} \quad (10) \]

where \( 0 < \alpha < 1 \) is traffic flow constant [18] and \( L = 1000\text{m} \) in DSRC standard. However, once the range is estimated by a vehicle, it is mapped with suitable transmit power in a fading channel as mention in the following section.

B. Transmit Power vs. Range in Fading Channels for Spectrum-agile VANET

We assume that there are \( K \) independent channels (e.g., 7 channels in 5.9GHz DSRC band and 11 channels in 2.4 GHz ISM band), each with bandwidth \( W_k \), which are used in vehicular communication in VANET. For a given transmit power \( p_t \), the received power \( p_r \) at distance \( z \) can be calculated as [21]

\[ p_r = p_t G_r G_t h_t h_r \frac{(1/4\pi)^2 \lambda_w^2}{z^\alpha_p} = p_t G_r \frac{\lambda_w^2}{2\pi z^\alpha_p} \quad (11) \]

where \( h_t \) and \( h_r \) are respectively height of transmit and receive antenna, \( G_r \) and \( G_t \) are respectively transmit and receive antenna gains, \( \lambda_w \) is the wavelength (e.g., \( \lambda_w = 5.08\text{cm} \) for 5.9GHz DSRC band and \( \lambda_w = 12.50\text{cm} \) for 2.4GHz ISM band), and \( \alpha_p \in [2, 4] \) is the path loss exponent. For a given transmission range in (10), i.e., \( z = R \), in spectrum-agile VANET, the transmit power from (11) is expressed as [21]

\[ p_t = \frac{p_r}{G_r \lambda_w^2} R^\alpha_p \quad (12) \]

Transmit power \( p_t \) also depends on the frequency (5.9GHz DSRC or 5.2/4 GHz ISM) band that the vehicular users choose to communicate in spectrum-agile VANETs. Then, the signal-to-noise ratio (SNR) can be computed as

\[ \gamma_{i,j} = \frac{p_r}{N_0 W_k} = \frac{p_t G_r \lambda_w^2}{2\pi z^\alpha_p N_0 W_k} \quad (13) \]

where \( N_0 \) is the power spectral density of the noise and is given by \( N_0 = kT \) for a receiver system temperature \( T \) and Boltzmann constant \( k = 1.38e^{-23}W/K \).

Note that when instantaneous SNR \( \gamma_{i,j} \) falls below desired minimum SNR \( \tau_{i,j} \) (i.e., \( \gamma_{i,j} < \tau_{i,j} \)) outage occurs. To measure the performance, considering the probability density function of the instantaneous SNR \( f(\gamma_{i,j}) \) as exponential for considered i.i.d. Raleigh fading channels, the probability of an outage event occurring can be calculated as [19]

\[ P_{out}^{i,j} = \text{Prob}[\gamma_{i,j} < \tau_{i,j}] = \int_0^{\tau_{i,j}} f(\gamma_{i,j}) d\gamma_{i,j} \]

\[ = \frac{1}{\tau_{i,j}} \exp\left(-\frac{\gamma_{i,j}}{\tau_{i,j}}\right) d\gamma_{i,j} \]

\[ = 1 - \exp\left(-\frac{\gamma_{i,j}}{\tau_{i,j}}\right) \quad (14) \]

where \( \gamma_{i,j} \) is the time-average of SNR values. For maximum allowed outage probability, \( P \), the \( \tau_{i,j} \) can be calculated using

\[ P_{out}^{i,j} \leq P \text{ is satisfied as } \tau_{i,j} \geq \frac{-\gamma_{i,j}}{\ln(1-P)} \]

Note that the transmissions with low SNR will create unnecessary interference to other active vehicular users (and waste battery life of a mobile device even though battery power in vehicular network is not a concern). Thus the user should be dropped from the systems if a required SNR threshold is not satisfied.

The CDF of transmission range is given by

\[ F_R(z) = \text{Prob}[R \leq z] = 1 - \text{Prob}[R > z] = 1 - \text{Prob}[\gamma_{i,j} \geq \tau_{i,j}] = 1 - \exp\left(-\frac{\tau_{i,j}}{\gamma_{i,j}}\right) = 1 - \exp\left(-\frac{\tau_{i,j}}{\tau_{i,j}^2 N_0 W_k} \right) \quad (15) \]

Then, the average transmission range can be computed as

\[ E[R] = \int_0^\infty [1 - F_R(z)] dz = \frac{1}{\alpha_p} \left[ \frac{p_t G_r \lambda_w^2}{\tau_{i,j} N_0 W_k} \right]^{1/\alpha_p} \quad (16) \]

C. V2V Connectivity in Two-way Traffic Flow

The vehicles, traveling in opposite directions, remain within the communication range of each other for short period of time and the time duration depends on their relative speed and transmission ranges. During this limited time duration, communication devices mounted in the vehicles should be able to setup the connection and exchange the information for successful single-hop communication.

Let \( A, B \) and \( C \) be, respectively, association time\(^2\) (includes channel sensing and switching time), data exchange time (time left after successful association) and total available time for given transmission range in V2V communication. For successful association and data exchange, \( A + B \leq C \) condition must be satisfied. Probability of successful association and data exchange between vehicles can be expressed as \( P_s = P_r\{A + B \leq C\} \). Then \( 1 - P_s \) gives the probability of unsuccessful data exchange which represents, in our case, partial or no messages being exchanged between vehicles. The total available duration for V2V communication for vehicles with speed \( v_i \) and \( v_j \) can be computed as

\[ C = \left\{ \begin{array}{ll} \frac{z}{v_i + v_j}, & z \leq \min\{R_i, R_j\}, \forall v_i, v_j \\ 0, & \text{Otherwise} \end{array} \right. \quad (17) \]

where \( z = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \) is the distance between vehicles located at \((x_i, y_i)\) and \((x_j, y_j)\) positions. Obviously, \( z \leq \min\{R_i, R_j\} \leq 1000\text{m} \) should satisfy for the vehicles with transmission ranges \( R_i \) and \( R_j \) to be able to communicate with each other.

We assume that communication range overlapping process between vehicles is random process and it does not depend on the time and range overlap of the previous vehicles. A Poisson distribution with parameter \( \lambda \) [23, Ch. 8] [18] is used to represent a process for vehicles being within the communication range of each other. Then, we analyze how

\(^2\)Note that the association time depends on technologies such as typical association time for ZigBee is about 30 milliseconds, Wi-Fi is about 600 milliseconds and so on [22].
association (connection setup or switching from one channel to another in spectrum-agile systems) time can influence the data exchange in V2V communications. Assuming that the \( C \geq 0 \) is the random variable representing the total time duration available for device association and data exchange between vehicles which follows the Poisson distribution with parameter \( \beta \), the CDF for a random variable \( C \) is defined as [23] \( F_C(C) = 1 - e^{-\beta C} \), \( C \geq 0 \) and the CDF of random variable \( B \) is as \( F_B(B) = 1 - e^{-(B+A)/\beta} \). Thus the pdf of \( B \) is

\[
f_B(B) = \beta e^{-(B+A)/\beta}
\]

(18)

Finally, the expected value of time for data exchange is computed as

\[
\mathbb{E}[B] = E[B] = \int_0^{\infty} B \beta e^{-(B+A)/\beta} dB = \frac{\beta}{\beta} e^{-A/\beta}
\]

(19)

To be able to exchange the complete information of size \( S \) bits should satisfy the following condition

\[
B \leq \mathbb{E}[B]
\]

where \( B \) is the time needed to transmit the given message of size \( S \) successfully with a data rate \( D_r \) in V2V communication and is given by

\[
B = \frac{S}{D_r}
\]

(20)

Probability of successful information exchange, which depends on association time and data rate of a given technology, relative speed of communicating vehicles, and size of the message to be transmitted, is given as

\[
P_s = Pr\{A + \mathbb{E}[B] \leq C\}
\]

(21)

If the condition \( A + \mathbb{E}[B] \leq C \) is not satisfied, vehicles would not be able to exchange the complete message of size \( S \) using a single-hop communication. We consider this as a failure of communication since exchange of partial information may not make any sense in VANET and the vehicles traveling in opposite directions will not be within the communication range of each other for long (or quite some) time.

D. V2V Connectivity Link for One-way Traffic Flow

The relative speed of the vehicles is small (or zero when they have same speed) for the vehicles traveling in the same direction. Vehicles could be within the communication range of each other for a long period of time. However, this time duration depends on the distance traveled by vehicles (relative speed or acceleration of the vehicles for a given period of time) and the transmission range. Note that when the difference in distances traveled by two vehicles is greater than their transmission ranges, the link between them will be broken and they cannot communicate with each other using single-hop communication. When they come within the communication range, they may need to go through the connection setup process before exchanging the actual information. The probability distribution of existence of a link between two vehicles separated by a distance \( z \) is log-normal and is given by [19], [24]

\[
F(z) = P\{X \leq z\} = \frac{1}{2} + \frac{1}{2} \text{erf}\left(\frac{z - \mu_z}{\sigma_z \sqrt{2}}\right)
\]

(22)

where \( X \) is the random variable for inter-vehicle distance. Again, vehicles to be able to reach using single hop communications in DSRC standard, the distance between two vehicles should satisfy

\[
z \leq \min\{R_i, R_j\} \leq 1000m
\]

and note that the transmission ranges \((R_i \text{ and } R_j)\) for individual vehicles are adapted dynamically using (10).

Once two vehicles are within the communication range, we can check whether or not they are reachable after certain time \( t \) by using their speeds (speeds that they had when they initially met), their acceleration and time interval. For a given vehicle of initial speed \( v(0) \), the instantaneous speed \( v(t) \) at time \( t \) is defined as

\[
v(t) = v(0) + \int_0^t a(y)dy
\]

(23)

where \( a(y) \) is the acceleration of a vehicle at time \( y \). Using (23), the distance traveled by a given vehicle for a given time interval \([0, t]\) is defined as

\[
D(t) = \int_0^t v(y)dy
\]

(24)

Thus, using (24) for a time interval \([0, t]\), we can compute the distances traveled by the vehicles \( i \) and \( j \) respectively as \( D_i(t) \) and \( D_j(t) \). Then the distance between the vehicles \( i \) and \( j \) for the interval \([0, t]\), where vehicle \( i \) is following \( j \) and initial separation distance between them was \( z \), is given by

\[
D_e = I(i,j)[-D_i(t) - D_j(t)] + z
\]

where \( I(i,j) \in \{1,-1\} \), i.e., if \( D_i(t) > D_j(t) \), \( I(i,j) = -1 \), otherwise \( I(i,j) = 1 \).

After time \([0, t]\), the vehicles to be able to reach wirelessly, the distance traveled in time \( t \) should not be greater than the overlapping range and this should not exceed 1000-m (upper limit in DSRC standard), that is,

\[
D_e \leq \min\{R_i, R_j\} \leq 1000m
\]

If above condition is not satisfied, vehicles would not be able to communicate with each other using single-hop communication. After the link is disconnected, when vehicles reach again within the communication range of each other, they will have to restart the connection setup process before they can exchange the information.

IV. NUMERICAL AND SIMULATION RESULTS

In order to illustrate the performance of the analytical model presented in previous section, we have presented the numerical results obtained from simulations. We consider a highway segment of length 5 km where a Poisson process with arrival rates \( \lambda \) vehicles/sec is used to generate vehicles that are entering the road segment. Each vehicle enters the road segment with a non-negative average speed \( \mu \) miles/hour and standard deviation \( \sigma \) miles/hour.

In Fig 2, we plotted the variation of normalized local vehicle density against the arrival rate for different average speeds and standard deviations. Normalized vehicle density increases when arrival rate increases as in Fig 2. However, the
density decreases when average speed increases. Note that, as expected, vehicle density on the road is high when vehicles move slowly and their arrival rate is high.

In Fig. 3, we have plotted the variation of network connectivity probability against different values of transmission range\(^3\) for different vehicle-arrival-rates, speeds and standard deviations. The results in Fig 3 show that, for a given arrival rate, network connectivity probability decreases when average speed of vehicle and its standard deviation increase. This happens because vehicle density on the road becomes sparse when the arrival rate is fixed and vehicles move fast with different speeds. Similarly, for given average speed and standard deviation, network connectivity probability increases when arrival rate increases because the vehicle density increases with greater arrival rate for vehicles.

We then plotted the variation of total time duration that is available for V2V communications against the relative speed of vehicles for 1000 m (upper limit in DSRC) and 25 m (lower limit to cover the two-way traffic separated by a median) as shown in Fig 6. For vehicles traveling in opposite directions with a relative speed of 141 mph, for a single-hop communication, total time duration (that is available for both communication setup and information exchange) is 1596 milliseconds when overlapping transmission-range is 1000 meter and 398.9 milliseconds when overlapping transmission-range is 25 meter. Note that when relative speed decreases, the total time duration increases for a given transmission range as in shown in Fig 6. When vehicles travel with smaller relative speed they remain within the communication range for a long time to setup a connection and to exchange the actual information.

It is important to point out that the time duration between vehicles traveling in the same direction will be longer depending on their relative speed and communication range. When vehicles travel in same direction with almost constant speeds, the relative speed is almost zero, they could remain within communication range for long time (virtually for infinite time).

The wireless access in vehicular environments for DSRC bands is introduced to support communications with very short latency (approximately 100 microseconds to 50 milliseconds) [17] and the complete transaction must be completed in less than 100 ms. We assume that the time needed for successful connection setup (including channel sensing) is between 30 to 100 milliseconds depending on the communication environment in VANET. Note that communication setup time includes the switching time between bands (e.g., from 5.9 GHz DSRC band to 2.4 GHz ISM band or vice versa). After successful connection setup, variation of total transfer size of the information is plotted in Fig. 5 for the minimum (3 Mbps) and maximum (27Mbps) data rates in DSRC standard. Transfer size obtained in simulation is lower than that for analytical because of the effect of speed of fast-moving vehicles.

We also plotted the variation of successful exchange of information against the simulation time for three different scenarios as shown in Fig. 6. We assume that the vehicles travel with a average speed of 50 mph and standard deviation of 20 mph. When we considered 300 meter as a fixed transmission range for all vehicles, the probability of successful data exchange is dropped from 99% to 0 after certain time because of the network disconnection among fast-moving vehicles with different speed and standard deviation. Similarly for 700 meter as a fixed transmission range, there was successful exchange with probability 99% for longer time than that for a range of 300 meter.

\(^3\)Note that 1000 meter is the maximum allowed transmission range in 5.9GHz DSRC band.

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Fig. 2. Normalized local vehicle density vs. arrival rate for different average speed and standard deviation.

Fig. 3. Variation of connectivity probability versus the transmission range for different speeds and arrival rates.

Fig. 4. Lower bound (with transmission range = 25 meter) and upper bound (with maximum allowed DSRC transmission range = 1000 meter) of link duration for different relative speeds when vehicles travel in opposite direction.
When we implemented dynamic adaptation of transmission range (without exceeding 1000 meter in DSRC standard) based on the estimated local vehicle density, vehicles were able to successfully exchange information for longer time than the previous cases as shown in Fig. 6. When vehicles adapt their transmission range, there is small drop in successful probability because vehicles may take fraction of millisecond to switch channel or adjust the transmission range on the fly.

V. Conclusion

We have presented an analysis for connectivity in VANET for fading channels where the communication links among vehicles are short-lived especially in sparse vehicular density, making the task of establishing and maintaining the communication links for fast-moving vehicles. Transmission range and frequency bands are adapted dynamically based on the operating conditions of the vehicular network. We have shown that the connectivity in VANET, for vehicles traveling in opposite directions as well as for vehicles traveling in the same direction, can be enhanced by adapting the transmission range based on the estimated local vehicle density and by switching to suitable the frequency bands. We have evaluated the performance of VANET connectivity through numerical examples obtained from simulations.

![Graph showing variation of data transfer for different relative speeds.](image1)

**Fig. 5.** Variation of size of data transfer for different relative speeds.

![Graph showing successful probability (P_s) vs. simulation time for fixed transmission range and variable transmission range.](image2)

**Fig. 6.** Successful probability (P_s) vs. the simulation time for the fixed transmission ranges and variable transmission range ≤ 1000meter.

REFERENCES


