SINR and Reliability based Hidden Terminal Estimation for Next Generation Vehicular Networks

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ABSTRACT

Safety applications are currently being developed in next generation vehicular networks to provide road safety. Broadcasting of safety messages unveils the need of reliability assessment since there are no request-to-send (RTS)/clear-to-send (CTS) handshaking and acknowledgment packets in broadcast vehicular communications. Therefore, the reliability of broadcast messages suffer from hidden terminal problem, interference and high mobility. To overcome these challenges, Signal-to-Interference-and-Noise Ratio (SINR) estimation is a key solution so that we can foresee the transmission collisions caused by hidden terminals and prevent its transmissions. Then, we can build a model to improve reliability of broadcast messages. Towards this aim, in this paper, we propose a SINR based hidden terminal estimation model. First, we introduce a method to specify hidden terminals and their transmissions, then we estimate accurate SINR level at the receiver in the near future. Second, we formulate the successfully received packets with a heuristic algorithm and, calculate throughput and hidden terminal radius. Our approach enables significant improvement in the reliability of broadcast vehicular communications.

Keywords

SINR estimation, hidden terminal problem, broadcast vehicular communication, reliability

1. INTRODUCTION

Safety applications play an essential role in supporting traffic safety and efficiency in next generation vehicular networks. The efficiency of safety applications depends on the establishment of reliable communication. Thus, mobile vehicles periodically disseminate broadcast messages including position, speed, direction, acceleration informations to nearby vehicles. However, in IEEE 802.11p based broadcast communication, RTS/CTS exchange is disabled since using these packets can be overloaded in the topology, especially, in safety-related messages and enhanced the probability of collision. Moreover, since there is no mechanism for retransmission of broadcasted packets, the failure of packet reception cannot be detected, which leads to a drop on the reliability. Due to the crucial lack in this communication type, challenges of this work are threefold.

Challenge 1: The key problem faced in the dissemination of broadcast messages is hidden terminal problem. The factors affecting system performance are based on data dissemination and the system may not be effective due to the collisions caused by concurrent transmissions. Especially, safety applications are designed to prevent or mitigate potential accidents so that vehicles collaborate with each other. As an example, autonomous vehicles have the capable of collecting and analyzing sensory data and then making decision based on the sensory information. On the other hand, these processes are only accomplished with a reliable information collected by all vehicles, but hidden terminals can cause major risks to obtain and perform broadcast messages.

Challenge 2: The consequences of hidden terminal problem also trigger to increasing interference. Hidden terminals can interfere with the reception of nearby vehicles throughout a communication duration. This results with an intermittent connectivity and decreases throughput. When the density of vehicles increases, there is a strong need to maintain connectivity and guarantee reliable communication.

Challenge 3: Vehicular mobility makes the problem of maintaining network connectivity in vehicular networks challenging. Due to frequently changing vehicle movement, dramatic changes in spatial and temporal behaviors of the network topology occur and such a highly fluctuating network triggers the challenge of channel fading. Thus, there is a need for quick adaption of the network.

To overcome these challenges, SINR estimation is a key solution that especially relevant for predicting communication link quality. It is affected by the noise and transmission of transmitter and interferer. Here, due to the existence of hidden terminals, the impact of interference can range from an increase in the communication disruption to the transmission collisions. Thus, each vehicle will not have the same level of communication link quality. On the other hand, if the communication link quality is estimated in the near future, then we can improve the system's performance by preventing the transmission of hidden terminals.

While there has been considerable research effort for SINR estimation techniques, we encounter a basic difficulty in

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practical usage. Cooperative safety applications actively require knowledge about its environment. Hence, critical issues are twofold: (i) effective and timely sharing of information and (ii) stringent delay requirements. It is difficult to deal with these constraints with the current SINR estimation techniques due to the mobility. Thus, we also present a spatial estimation method for SINR estimation to reflect a realistic vehicular environment.

This work is motivated by the importance of a vehicle's knowledge of SINR in the near future. Towards this aim, we propose a SINR based hidden terminal estimation model and analyze the reliability of broadcast messages for vehicle-to-vehicle (V2V) communications. Consequently, this paper makes the following main contributions.

- We present a novel SINR based hidden terminal estimation model to specify hidden vehicles and their transmissions. Then we estimate reliable and accurate amount of SINR level of vehicles.
- Our proposed model enables to model highly dynamic vehicular environment.
- We present a heuristic algorithm to optimize the reliability of broadcast communication so that we observe the ratio of successfully received packets.
- We evaluate the impacts of hidden terminals and estimation of SINR in terms of throughput and effective range so that we manage the efficiency of the spatial estimation method.

The rest of the paper is organized as follows: Section II briefly describes the related work. Section III defines the network architecture. Section IV gives the proposed system model. Section V defines the problem formulation. Section VI evaluates the performance of the proposed model and finally Section VII concludes the paper.

2. RELATED WORK

IEEE 802.11 MAC protocol addresses hidden terminal problem with RTS/CTS exchange. However, in IEEE 802.11p based broadcast communication, there are no traditional RTS/CTS handshaking to monitor and detect the collisions, acknowledgments as well as packet receptions. Therefore, reliability based on IEEE 802.11p broadcast vehicular communication has been extensively researched in many studies.

In this respect, [1] introduce four reliability metrics including packet reception rate, packet delivery ratio, packet delivery probability and effective range, and evaluate the performance and reliability of broadcast communication for safety applications in Vehicular Ad Hoc Networks (VANETs). [2] analyze the reliability and delay of Dedicated Short Range Communication (DSRC) over control channel (CCH) by considering a new mobility model in safety applications for VANETs. Vehicles change their parameters such as sending rate, communication range, carrier sense range depending on traffic density and speed to increase the success probability. [3] analyze the performance of the broadcast messages in safety applications in terms of probability of packet reception, collision probability, throughput and delay. Both status and emergency packets are evaluated to achieve a certain successful rate by maximizing throughput and minimizing delay. [4] show the relationship between broadcast

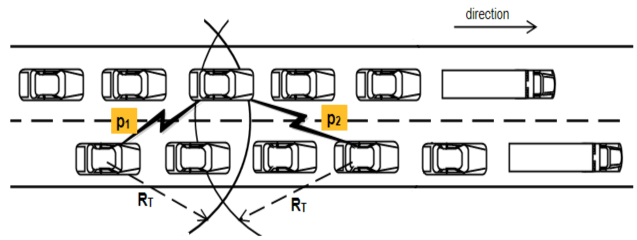


Figure 1: The illustration of vehicle platooning.

reliability and broadcast efficiency, and propose a power control and congestion control mechanism in order to increase broadcast efficiency. [5] propose a technique for transmission power adjustment to ensure reliable transmission with minimum delay and reduce channel congestion.

3. NETWORK ARCHITECTURE

We consider a vehicle platoon consists of N vehicles in two lanes that travel together and cooperate to exchange information with each other. As seen in Fig.1, vehicles are led by two trucks at a constant speed. Vehicles share the local vehicle signals including position, speed, direction with vehicles in the platoon so that the shared signals are used to proposed system model.

The communication between the platoon members is performed over CCH by sending one-hop broadcast messages. As seen in the Fig.1, collision may occur since two packets p_1 and p_2 are generated and sent to a vehicle at the same time. Here, we define that receiver vehicle is within the transmission range of a sender vehicle and hidden vehicle is out of transmission range of the sender vehicle, but within the transmission range of a particular receiver vehicle.

We also make some assumptions to model vehicular network topology so that we can build a more accurate and efficient model to track reliability depending on SINR. These assumptions are as follows:

- Broadcast messages are delivered over CCH that is shared amongst vehicles. Vehicles update and transmit broadcast messages to surrounding vehicles every CCH interval (CCI), 100ms [6].
- Vehicles are located on a 2D urban vehicular environment. Communication requests of vehicles are represented with binary variables in a connectivity matrix. The configuration of topology is predetermined.
- At initial situation of simulation, all vehicles have same transmission range, R_T, and transmission power, P_{max}.
- We interest in the distribution of vehicles within the transmission range of a sender vehicle and then we specify the hidden terminals depending on receivers. Here, we calculate potential hidden terminal area for each vehicle as follows:

$$A(j) = \pi R_T^2 - 2R_T^2 arccos\left(\frac{d_{ij}}{2R_T}\right) + \frac{d_{ij}}{2}\sqrt{4R_T^2 - d_{ij}^2} \quad (1)$$

where $A(j)$ is the potential hidden terminal area of sender vehicle j for receiver vehicle i. R_T is the transmission range that initially defined as constant for all vehicles. d_{ij} is the Euclidean distance between sender and receiver. Thus, a packet can be successfully broadcasted from sender to receivers depending on distribution of vehicles in the potential hidden terminal area.

- In order to avoid unsuccessful transmission due to the hidden terminals, we formalize the successful transmission of sender vehicles [7] as follows:

$$\sum_{i\in\tau_j} a_{ji} = \begin{cases} 1, & \text{if vehicle j broadcasts packet to all vehicles} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Here, we assume that vehicle j represents sender vehicle and may or not broadcast packet to "all vehicles" that are within the transmission range. Depending on this condition, total value of a_{ji} will be equal to 0 or 1. $i \in \tau_j$ represents the set of vehicles that are within the transmission range of vehicle j. Note that a successful transmission depends on the following condition:

$$\sum_{i\in\tau_j} a_{ji} + \sum_{i\in\tau_k} a_{ki} \leq 1 \qquad \forall i,j,k \in N \quad (3)$$

where a_{ki} is the transmission from hidden vehicle to receiver vehicle and N is the total number of vehicles in the topology. It means that hidden vehicle should not interfere to ongoing transmission if the total value of a_{ji} is equal to 1. Thus, $\sum_{i\in\tau_k} a_{ki}$ should be equal to 0 while a sender vehicle j broadcasts to vehicle i.

- Under the proposed model, SINR of vehicles can be varied and this results with different communication ranges. Here, a dynamic SINR based hidden terminal estimation model is devised to warn the vehicles actively and timely so that possible collisions may be prevented. Thus, we schedule the transmissions in each time slot and limit the signal levels of inferred vehicles depending on transmission of sender vehicle [7] as given in Eq.4.

$$P_{ki} \leq \begin{cases} \left(\frac{d_{ki}}{R_T}\right)^{\ell} P_{max}, & \text{if } \sum_{i\in\tau_j} a_{ji} = 1 \\ P_{max}, & \text{otherwise} \end{cases} \quad (4)$$

where P_{ki} is the received signal power sent from hidden vehicle k at the receiver vehicle i and P_{max} is initial transmission power before implementation of the proposed model. d_{ki} and ℓ represent the distance between vehicles, and path loss exponent, respectively.

4. THE PROPOSED SYSTEM MODEL

As it is mentioned, our main objective is to establish a reliable communication and enhance the reliability of broadcast messages in V2V communications. The proposed system model as seen in Fig.2 is applied as follows.

4.1 Connectivity Matrix

We create a connectivity matrix, denoted as $[C]_{NxN}$, to determine communication requests between vehicles. The communication requests are modeled by a directed graph. The graph consists of a set of N vehicles and a set of edges and it is represented with binary variables. An edge between vehicles (i,j) may exist if there is a packet from vehicle i to vehicle j to transmit. Then, the graph is sent to reliability map module to detect hidden vehicles in the topology.

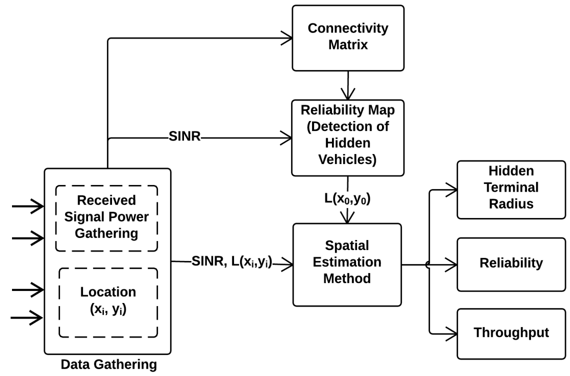


Figure 2: Proposed system model.

4.2 Data Gathering

Total power at the receiver consists of the signal from the sender, interference from undesired senders and noise. Therefore, SINR level is calculated, denoted as $Z(x_i, y_i)$ for receivers at different positions in order to estimate the quality of the link as given in Eq.5.

$$SINR = Z^0(x_i, y_i) = \frac{P_{ji}}{I + P_n} \quad (5)$$

where P_{ji} and I are the transmission power from sender vehicle j to receiver vehicle i, $i \in \tau_j$, and the received interference power within the range of receiver, respectively. P_n is the noise power. Here, transmission power, P_{ji}, and cumulative interference power, I, from simultaneous senders are modeled [7] as given in Eqs.6 and 7, respectively.

$$P_{ji} = \begin{cases} \left[\left(\frac{d_{ij}}{R_T}\right)^{\ell} P_{max}, P_{max}\right], & \text{if } \sum_{i\in\tau_j} a_{ji} = 1 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

and

$$I = \sum_{i\in\tau_k} P_{ki} \quad (7)$$

It is shown that Nakagami distribution is more efficient and flexible than current distributions for urban propagation environments [8]. This distribution can model the rapid fluctuations of the received signal envelope, which is transmitted over fading wireless channel. Since Nakagami fading can reflect many fading condition in a wireless channel, it can provide a better explanation in real-time vehicular applications. Hence, in this work, we use Nakagami-m channel model. The probability density function (Pdf) of received signal power, P_r, for Nakagami-m fading channel [9] is defined in Eq.8:

$$Pdf(P_r) = \frac{2m^m P_r^{2m-1}}{\Omega^m \Gamma(m)} exp(-\frac{mP_r^2}{\Omega}) \quad (8)$$

where the channel amplitude $P_r \geq 0$, Ω =E(P_r^2) is average fading power, $\Gamma(.)$ is gamma function and E(.) is the expectation operator. The parameter m expresses the severity of the fading as described in Eq.9.

$$m = \frac{(E(P_r^2))^2}{Var(P_r^2)} \quad (9)$$

SINR level and vehicles' locations are given as input to the spatial estimation method and reliability map module.

4.3 Reliability Map

This module detects hidden vehicles in order to avoid concurrent transmissions. To achieve this, Algorithm 1 is proposed. As shown in the algorithm, the transmission requests of each vehicle are evaluated and potential hidden terminal area is defined for each receiver as given in Lines 3-5. Then the condition, as given in Line 6, is checked. The details for this condition will be detailed in the next section. After that, the transmission requests are scheduled with Eqs.2 and 3 in order to prevent concurrent transmissions occurred at the same time. Finally, the locations of detected hidden vehicles are sent to spatial estimation method as an input.

Algorithm 1 Reliability Map Creation to Detect the Hidden Vehicles

Require: $[C]_{NxN}$; vehicle locations, $L(x_i, y_i)$
Ensure: $L(x_0, y_0)$
1: **for** $j \leftarrow 1$ to N **do**
2:   **for** $i \leftarrow 1$ to N **do**
3:     **if** $[C]_{jxi} \leftarrow 1$ **then**
4:       Define A(j) in Eq.1
5:       Find $[C]_{kxi} \leftarrow 1 \; \forall$ k $\in$ A(j)
6:       **if** $d_{ij} \leq R_T$ and $P_{ji} d_{ik}^{\ell} \leq Z(x_i, y_i) P_{ki} d_{ij}^{\ell}$ **then**
7:         Vehicle k $\leftarrow$ hidden vehicle
8:         Schedule the transmission with Eqs.2 and 3 for hidden vehicle k
9:         Spatial Estimation Method $\leftarrow L_k(x_0, y_0)$
10:       **end if**
11:     **end if**
12:   **end for**
13: **end for**

In the simulation results, we observe that even if we detect hidden vehicles and then apply the proposed model, we cannot prevent concurrent transmissions at some conditions, such as high vehicle density. Therefore, in the paper, we classify hidden vehicles as discovered hidden terminals and undiscovered hidden terminals. Discovered hidden terminals are defined as the hidden vehicles that successfully sense the ongoing transmission after regulating the SINR level. It means that interference is minimized by scheduling transmission and optimizing signal level. On the other hand, when the number of vehicles increases, the number of receivers within the senders' transmission range shows an increase and this can reduce the reception of broadcast messages due to the undiscovered hidden terminals. Undiscovered hidden terminals are unable to detect sender vehicle's transmission even if SINR levels are calibrated. They initiate the communication with the receiver and collision happens. Hence, one of the critical factors is to discover hidden terminals and then calibrate SINR levels so that the higher the reliability, the lower the undiscovered hidden terminals.

4.4 Spatial Estimation Method

In this paper, we use Ordinary Kriging method as spatial estimation method. Kriging is an interpolation technique which observed values are weighted to estimate the value for an unknown location in geostatistics. Weights are based on the distance between the known locations by estimating spatial distribution of predicted values. We use the distances between vehicles to predict optimum weights. In this module, our aim is to estimate SINR so that we can enhance the reliability and calculate effective range.

Ordinary Kriging estimates the weighted linear combinations of the measured data with the aim of minimizing variance of the errors [10]. This method uses semivariogram analysis to determine the spatial correlation of the obtained signals from surrounding nodes. For further information about this method, [10], [11] can be referred.

We will estimate the SINR by using a weighted linear combination of the available data. We assume that there are N vehicle locations $(x_i, y_i; i = 1, ..., N)$ and a known value $Z(x_i, y_i)$ at this location (x_i, y_i). To keep the estimate unbiased, we need to decide weight of the nearby vehicles. The Kriging estimator calculates by linear combination of the known values as defined in Eq.10.

$$Z^*(x_0, y_0) = \sum_{i=1}^{N} \lambda_i Z(x_i, y_i) \quad (10)$$

where $Z^*(x_0, y_0)$ represents SINR level at location (x_0, y_0). Weight, λ_i, is the Kriging coefficient and $\sum_{i=1}^{N} \lambda_i = 1$ for unbiaseness. However, this unbiaseness condition does not give any information about how to determine the weights. Therefore, mean squared error (MSE) is minimized in order to obtain optimum weights as defined in [10]. The obtained general formulas are given as follows:

$$\begin{aligned} \sum_{j=1}^{N} \lambda_j \gamma(h_{i,j}) + \mu &= \gamma(h_{i,0}) \qquad \forall i \in N \\ \sum_{i=1}^{N} \lambda_i &= 1 \end{aligned} \quad (11)$$

This system of equations can be written in a matrix notation as follows:

$$\gamma(h_{i,j})\lambda_i = \overline{\gamma}(h_{i,0}) \quad (12)$$

Matrix form in Eq.13 is used to determine optimal weights in order to satisfy conditions in Eq.11.

$$\begin{pmatrix} \gamma(h_{1,1}) & \cdots & \gamma(h_{1,N}) & 1 \\ \gamma(h_{2,1}) & \cdots & \gamma(h_{2,N}) & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \gamma(h_{N,1}) & \cdots & \gamma(h_{N,N}) & 1 \\ 1 & \cdots & 1 & 0 \end{pmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_N \\ \mu \end{pmatrix} = \begin{pmatrix} \overline{\gamma}(h_{1,0}) \\ \overline{\gamma}(h_{2,0}) \\ \vdots \\ \overline{\gamma}(h_{N,0}) \\ 1 \end{pmatrix} \quad (13)$$

where γ is the semivariogram which is a function of distance between vehicles. Semivariogram is used to determine spatial covariance of variables as seen in Eq.14.

$$\begin{aligned} \gamma(h_{i,j}) &= \gamma(x_i y_i - x_j y_j) \\ &= \frac{1}{2} E[(Z(x_i, y_i) - Z(x_j, y_j))^2] \end{aligned} \quad (14)$$

To solve the weights, we multiply Eq.12 on the both sides by γ^{-1} and Eq.15 is obtained.

$$\begin{aligned} \gamma(h_{i,j})\lambda_i &= \overline{\gamma}(h_{i,0}) \\ \lambda_i &= \gamma^{-1}(h_{i,j})\overline{\gamma}(h_{i,0}) \end{aligned} \quad (15)$$

In ordinary Kriging, the key approach depends on the selective of semivariogram model. Therefore, most commonly used semivariogram models are analyzed in the proposed model: Exponential model, Gaussian model, Linear model in Eqs.16, 17 and 18 respectively, as follows:

$$\gamma^{exp}(h_{i,j}) = \begin{cases} 0, & h_{i,j} = 0 \\ C_0 + C_1(1 - exp(\frac{-3h_{i,j}}{r}), & h_{i,j} > 0 \end{cases} \tag{16}$$

where C_0 is the nugget effect, which provides a discontinuity at the origin. The semivariogram value at the origin should be zero in theory (C_0=0). r is the range which represents covariance value as constant at a time which the longest Euclidean distance between vehicles. $C_0 + C_1$ is called as sill value, which represents the variogram value for very large distances.

$$\gamma^{gauss}(h_{i,j}) = \begin{cases} 0, & h_{i,j} = 0 \\ C_0 + C_1(1 - exp(\frac{-3h_{i,j}^2}{r^2}), & h_{i,j} > 0 \end{cases} \tag{17}$$

and,

$$\gamma^{lin}(h_{i,j}) = \begin{cases} 0, & h_{i,j} = 0 \\ C_0 + C_1 r h_{i,j}, & h_{i,j} > 0 \end{cases} \tag{18}$$

After weight λ_i^{exp} is calculated for exponential semivariogram model by inserting Eq.16 into Eq.15, the spatially estimated SINR level at location (x_0, y_0), can be expressed as follows:

$$Z^{exp}(x_0, y_0) = \sum_{i=1}^{N} \lambda_i^{exp} Z(x_i, y_i) \qquad \forall i \in N \tag{19}$$

If the signal power is Gaussian distributed, weight λ_i^{gauss} is calculated for Gaussian semivariogram model by inserting Eq.17 into Eq.15. The spatially estimated SINR level at location (x_0, y_0), can be expressed as follows:

$$Z^{gauss}(x_0, y_0) = \sum_{i=1}^{N} \lambda_i^{gauss} Z(x_i, y_i) \qquad \forall i \in N \tag{20}$$

If the signal power is linearly distributed, weight λ_i^{lin} is calculated for linear semivariogram model by inserting Eq.18 into Eq.15. The spatially estimated SINR level at location (x_0, y_0), can be expressed as follows:

$$Z^{lin}(x_0, y_0) = \sum_{i=1}^{N} \lambda_i^{lin} Z(x_i, y_i) \qquad \forall i \in N \tag{21}$$

4.4.1 Mobility Model

The proposed model is built on 2D vehicular environment. N vehicles move on with constant velocity depending on the total number of vehicles on the platoon. It changes between v_{min} and v_{max}. Here, we interest in the distance between all vehicle pairs by considering velocities and directions.

In this paper, to model dynamic vehicular network topology, Kriging estimation method is used. Note that at known locations, $L_1, L_2, ..., L_N$, and the observed values, $Z(L_1)$, $Z(L_2), ..., Z(L_N)$, of nearby data points are weighted depending on spatial covariance values. The covariances and obtained Kriging weights are defined based on vehicle configuration by considering relative speed and direction. Recall that $\overline{\gamma}(h_{i,0})$ in Eq.15 provides a weighted scheme similar to inverse distance method [12]. When the covariance between data samples $(L_1, L_2, ..., L_N)$ and the location being detected, (L_0), increases, the accuracy of the prediction will also increase. In the model, nearest data samples carry significant weights so that the covariance between sender and hidden vehicle enhances.

5. PROBLEM FORMULATION

Reliability is an important measure to analyze broadcast messages in V2V communications. In this paper, reliability is defined as the number of successfully received packets to the total number of all packets sent. It measures successful packet reception rate.

If SINR at the receiver is above a certain threshold, denoted as Z_T, broadcast messages are successfully delivered to the receiver. Thus, the mapping between reliability and SINR, denoted as $\chi_{j,i}$, is equivalent to the following. This shows the successful packet reception from vehicle j to vehicle i.

$$\chi_{j,i} = \begin{cases} 1, & \text{if } Z^0(x_i, y_i) \geq Z_T \\ 0, & \text{otherwise} \end{cases} \tag{22}$$

The signal power of nodes needs to be calibrated so that it reaches to intended receiver while minimizing the interference with other nodes [13]. Therefore, the key contribution of our work is to estimate SINR level dynamically so that SINR at the receiver exceeds the threshold. To this end, interference can be minimized and the reliability can be enhanced. To achieve these, we use the following optimization problem.

$$max \left(\frac{\sum_{j=1}^{N} \sum_{i \in \tau_j} \chi_{j,i} - \beta \sum_{j=1}^{N} P_{ji}}{\sum_{j=1}^{N} \sum_{i=1}^{N} x_{j,i}} \right) \tag{23a}$$

subject to:

$$\chi_{j,i} \in (0,1) \qquad \forall i,j \in N \tag{23b}$$

$$x_{j,i} \in (0,1) \qquad \forall x_{j,i} \in [C]_{NxN} \tag{23c}$$

$$d_{ij} \leq R_T \qquad \forall i,j \tag{23d}$$

$$0 \leq P_{ji} \leq P_{max} \qquad \forall i,j \tag{23e}$$

$$P_{ji} d_{ik}^{\ell} > Z(x_i, y_i) P_{ki} d_{ij}^{\ell} \qquad \forall i,j,k \in N \tag{23f}$$

In the model, a successful transmission from sender vehicle to receiver vehicle depends on the constraints. Vehicle j is the sender and vehicle i (receiver vehicle) is only receiver mode. β is the coefficient for the total power consumption that $\sum_{j=1}^{N} P_{ji}$ will not influence the amount of successful packet reception. β is set to $1/(NP_{max})$ [14]. The variable $x_{j,i} \in (0,1)$ indicates the communication requests in connectivity matrix, $[C]_{NxN}$.

As the problem formulation illustrated, the calculation of the reliability has been proven as NP-hard [15]. Hence, we propose a heuristic algorithm to analyze the reliability of broadcast messages in V2V communications.

5.1 A Heuristic Algorithm for Reliability Optimization

The proposed heuristic algorithm is given in Algorithm 2. This algorithm is responsible from analyzing the reliability of each scheme. The explanation of the algorithm is as follows:

As indicated previously, connectivity matrix is created and then depending on the communication requests, each vehicle, if $\forall(x_{i,j}) = 1$, allocates P_{max} dBm for initialization process as given in Lines 2-3. Because of this initial power value and constant transmission range, hidden terminal problem causes concurrent transmissions and this leads to interference, which has a significant impact on the packet reception. Therefore, SINR value at the receiver is calculated in order to obtain link quality as given in Line 4. In this algorithm, the detection of hidden vehicles is important to operate heuristic algorithm. Thus, Algorithm 1 is run and the location of hidden vehicles are sent to spatial estimation method to estimate optimal signal level of vehicles. A vehicle can interfere if and only if if the following condition is satisfied.

$$P_{ji} d_{ik}^{\ell} \leq Z(x_i, y_i) P_{ki} d_{ij}^{\ell} \qquad \forall i, j, k \in N \tag{24}$$

Therefore, this condition is checked to observe whether the transmission is successful or not as given in Lines 9-15.

Algorithm 2 Heuristic Reliability Algorithm

```
1: Counter ← 0
2: Describe [C]_{NxN}
3: Assign P_init ← P_max        if ∀(x_{i,j}) = 1, ∀i, j ∈ N
4: Calculate Z^0(x_i, y_i)
5: Run Algorithm 1 and find the location of hidden vehicle k, L(x_0, y_0)
6: for i ← 1 to N do
7:    if Z^0(x_i, y_i) < Z_T      ∀i, j, k ∈ N then
8:       Compute optimal SINR level for each scheme with the spatial estimation method, as given in Section IV.D.
9:       Check the condition that P_ji d^ℓ_ik > Z(x_i, y_i) P_ki d^ℓ_ij
10:      if true then
11:         χ_{j,i} = 1
12:         Counter ← Counter+1
13:         Update Z^0(x_k, y_k) ← Z^*(x_0, y_0)
14:      end if
15:      χ_{j,i} = 0
16:   end if
17: end for
```

5.2 Throughput

After the successful packet reception rate is observed, we calculate throughput, c. Throughput is defined as the number of broadcast bits successfully received by all intended vehicles. After the spatially estimated SINR is obtained for each scheme, throughput is evaluated by Eqs.25, 26 and 27, respectively.

$$c^{exp} = W log_2 \left(1 + \sum_{i=1}^{N} \left(Z^{exp}(x_0, y_0) \right) \right) \tag{25}$$

$$c^{gauss} = W log_2 \left(1 + \sum_{i=1}^{N} \left(Z^{gauss}(x_0, y_0) \right) \right) \tag{26}$$

and

$$c^{lin} = W log_2 \left(1 + \sum_{i=1}^{N} \left(Z^{lin}(x_0, y_0) \right) \right) \tag{27}$$

where W is the bandwidth of the channel.

5.3 Hidden Terminal Radius

We determine hidden terminal radius by estimating SINR level of vehicles in order to avoid hidden terminal problem. Hidden terminal radius is defined as effective range of vehicles to communicate nearby vehicles.

As defined previously, after detecting potential hidden vehicles in the topology, instead of assigning a constant transmission range, we calculate hidden terminal radius while minimizing adverse effects of hidden vehicles. Moreover, we take the advantages of power saving by calibrating power and maximizing network reliability.

In the proposed model, SINR of vehicles is calculated by collecting network information as defined in the previous sections. Here, due to the shadowing is a minor effect on the transmission in V2V communications, we concentrate on the impacts of path loss. The theoretical hidden terminal radius, r_{hidden}, is calculated by using two way propagation model as given in Eqs.28, 29 and 30, respectively.

$$r_{hidden}^{exp} = \sqrt[4]{\frac{\sum_{i=1}^{N} (\lambda_i^{exp} (Z(x_i, y_i))(I + P_n) G_t G_r h_t^2 h_r^2}{P_r}} \tag{28}$$

$$r_{hidden}^{gauss} = \sqrt[4]{\frac{\sum_{i=1}^{N} (\lambda_i^{gauss} (Z(x_i, y_i))(I + P_n) G_t G_r h_t^2 h_r^2}{P_r}} \tag{29}$$

$$r_{hidden}^{lin} = \sqrt[4]{\frac{\sum_{i=1}^{N} (\lambda_i^{lin} (Z(x_i, y_i))(I + P_n) G_t G_r h_t^2 h_r^2}{P_r}} \tag{30}$$

where G_t and G_r are antenna gains of sender and receiver, h_t and h_r are sender and receiver antenna heights.

6. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed SINR based hidden terminal estimation model with 3 estimation scheme which are Exponential, Gaussian and Linear Model. We also observe the results when there is no mechanism for SINR estimation, named as Static Case, so that transmission power and transmission range are constant in this case.

Kriging spatial interpolation method is used to estimate SINR level of vehicles. This mechanism prevents hidden terminal problem and collisions caused by concurrent transmission by mitigating interference and increasing reliability. Depending on spatially estimated SINR, reliability, hidden terminal radius and throughput are analyzed as performance parameters.

To validate the proposed model, MATLAB environment is applied for all system modules. DSRC parameters used in the simulation are shown in Table 1. We interest in the scenario where vehicles communicate with each other in a platoon and share a single broadcast channel with one-hop communication link. The medium access behavior is modeled using IEEE 802.11 CSMA/CA protocol with distributed interframe space (DIFS), contention window (CW) parameters. Here, CW is predetermined as fixed value for broadcast packets to regulate the channel access. The packets are broadcasted every CCI, thus the network topology is updated every CCI.

The impacts of hidden terminal problem can be reduced with estimation of SINR. At initial situation of simulation, it is assumed that all vehicles have allocated maximum 33 dBm power in order to use in broadcast message transmission. Recall that transmission power and interference power are

Table 1: Simulation Parameters

Parameter	Value
Carrier frequency	5.890 GHz
Bandwidth	10 Mhz
Noise power	-99 dBm
SINR threshold	15 dBm
Antenna gains of sender and receiver	1
Antenna heights of sender and receiver	1.5m
Number of vehicles	1-50
vehicles' speed	10-40 m/s
Path-loss exponent	2
CW size	32 μs
Slot time	13 μs
DIFS	64 μs
CCI	100 ms
Packet size	64 Bytes

specified in Eqs.6 and 7, respectively. SINR threshold value, Z_T, is equal to 15 dBm. Noise power, P_n, sets to -99 dBm.

We consider 2D urban vehicular environment with varying number of vehicles in two lanes. According to total number of vehicles, we classify the results as low, medium and high traffic density. The number of vehicles varies between 1-15, 15-35 and 35-50 in low, medium and high traffic densities, respectively. We define the transmission range of vehicles as 300m at initial situation for IEEE 802.11p based broadcast vehicular communication. Then, each vehicle adapts the changing network conditions by adjusting the communication range in order to establish reliable and robust broadcast vehicular communication.

6.1 Reliability Analysis

An important parameter in this work is the reliability that measures the successful packet reception by all intended vehicles with respect to number of all packets sent from sender vehicles.

Fig.3(a) demonstrates the increase of reliability with the proposed model depending on total number of vehicles in the topology. Reliability is evaluated for each spatial scheme. When compared to current specifications of DSRC, each model guarantees to reach the broadcast messages with a high reliability. It is shown that in all cases, low traffic density leads to higher reliability due to the high percentage of discovered hidden terminals. As seen in Fig.3(a), Exponential model is more accurate in predicting hidden terminals and obtains the highest reliability with increase of 22% when compared to Static Case.

In addition, in Fig.4, reliability is analyzed in terms of distance between sender and receiver for each estimation method. Here, we consider two analyses, vertical analysis and horizontal analysis.

In vertical analysis, reliability is evaluated in terms of distance between receiver and broadcast sender in each model and static case, separately. From Fig.4(a) to Fig.4(d), it is clearly showed that as distance between receiver and broadcast sender increases, reliability will decrease. On the other hand, proposed model outperforms to static case. When vehicles move away from each other, they need to increase transmission powers in order to obtain information from nearby vehicles and this causes an increase in the coverage area by enabling to access more vehicles. This means that the number of potential hidden vehicles will seriously show an increase by causing degradation of reliability of V2V communications. It is clearly showed that low traffic density achieves more reliable broadcast vehicular communication as observed in each model.

In horizontal analysis, we compare to proposed spatial schemes with each other. Exponential model achieves more reliable communication in each traffic density. In this paper, semivariogram models are used to determine spatial covariance and we only consider to meet the unbiaseness condition in each model. However, the received signal power significantly attenuates at first several meters. Specifically, broadcast senders that far from the receiver significantly impact the reliability and Exponential model slightly better than Gaussian and Linear Model.

6.2 Throughput

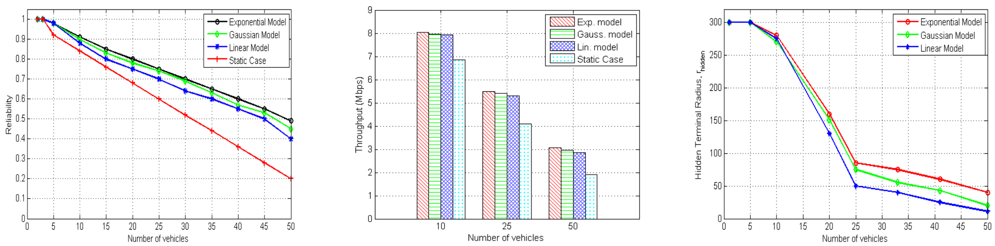
As SINR based hidden terminal estimation model is introduced, we define a metric, throughput, to measure the number of broadcast bits successfully received by all intended vehicles. We demonstrate in Fig.3(b) the behavior of the throughput according to the number of vehicles. It can be clearly seen that although the number of vehicle increases, transmitted packets will not be received successfully by all intended vehicles due to the undiscovered hidden terminals. As it is mentioned in the previous sections, distance between vehicles has another significant effect on the performance in vehicular networks. We note that, the throughput rate drops, especially, when the distance exceeds 250m. Since the undiscovered hidden terminals cannot sense the ongoing transmission, concurrent transmissions occurred at the same time will effect the successful packet reception. Thus, the higher the distance between vehicles, the higher the drop in throughput.

6.3 Adjustment of Hidden Terminal Radius

In this paper, hidden terminal radius is defined as effective range of vehicles to communicate with nearby vehicles. To this end, Fig.3(c) shows the obtained hidden terminal radius, as expressed in Eqs.28, 29 and 30, corresponding to number of vehicles for each scheme. It is evident that as traffic density increases, hidden terminal radius will decrease. Here, SINR effects the communication range and high signal power enables to increase of communication range. However, at the same time, interference occurs by decreasing wireless communication quality. Therefore, Fig.3(c) shows the right amount of communication range depending on the number of vehicles for each scheme.

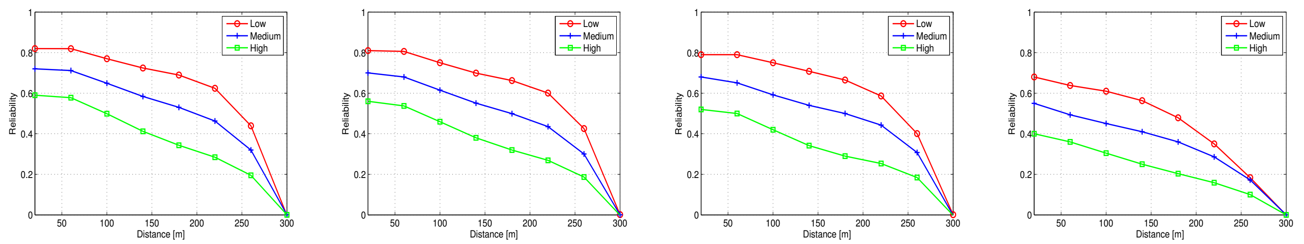
7. CONCLUSIONS

In this paper, we propose a novel SINR based hidden terminal estimation model to enhance the reliability of broadcast messages in V2V communications. By doing this, we take into the consideration of hidden terminal problem, interference and mobility challenges. In the proposed model, we specify hidden vehicles and their transmissions, then we estimate optimal SINR level at the receiver. This estimation is used to analyze the reliability by formulating an optimization problem and calculate throughput. In addition, it is analyzed that how SINR estimation can adjust the hidden terminal radius. Simulation results show the trade-off among network parameters in terms of reliability, hidden terminal radius and throughput with respect to the number



(a) (b) (c)

Figure 3: (a) Reliability (b) Throughput (c) Hidden terminal radius.



(a) (b) (c) (d)

Figure 4: The relationship between reliability and distance between sender and receiver depending on traffic density. (a) Exponential model (b) Gaussian model (c) Linear model (d) Static Case.

of vehicles. We observe that more reliable broadcast communication is achieved in next generation vehicular networks.

8. ACKNOWLEDGMENT

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9. REFERENCES

[1] X. Ma, J. Zhang and T. Wu. Reliability Analysis of One-Hop Safety-Critical Broadcast Services in VANETs, *IEEE Transactions on Vehicular Technology,* 60(8):3933-3946, 2011.

[2] K. A. Hafeez, L. Zhao, B. Ma, and J. W. Mark. Performance Analysis and Enhancement of the DSRC for VANETâĂŹs Safety Applications, *IEEE Transactions on Vehicular Technology,* 62(7):3069-3083, 2013.

[3] K. A. Hafeez, L. Zhao, Z. Liao, B. Ngok-Wah Ma. Performance Analysis of Broadcast Messages in VANETs Safety Applications, *IEEE Global Telecommunications Conference,* Miami, USA, 2010.

[4] F. Ye, R. Yim, S. Roy, J. Zhang. Efficiency and Reliability of One-Hop Broadcasting in Vehicular Ad Hoc Networks, *IEEE Journal on Selected Areas in Communications,* 29(1):151-160, 2011.

[5] O. Chakroun, S. Cherkaoui. Enhancing Safety Messages Dissemination Over 802.11p/DSRC, *in 38th IEEE Local Computer Networks Workshops (LCN Workshops),* Sydney, Australia, 2013.

[6] IEEE Standard for Wireless Access in Vehicular Environments (WAVE) Multi-channel Operation. *IEEE Vehicular Technology Society,* 2011.

[7] Y. Shi and Y. T. Hou. Optimal Power Control for Multi-hop Software Defined Radio Networks, *in 26th IEEE International Conference on Computer Communications,* Anchorage, AK, 2007.

[8] K. A. Hafeez, L. Zhao, Z. Liao, B. Ngok-Wah Ma. The Optimal Radio Propagation Model in VANET, *in 4th IEEE International Conference on Systems and Networks Communications,* Porto, Portugal, 2009.

[9] J. G. Proakis and M. Salehi. *M. Digital Communications,* McGrawHill, New York, USA, 2008.

[10] Isaaks and Srivastava. *An Introduction to Applied Geostatistics,* Oxford University Press, 1989.

[11] D.M. Gutierrez-Estevez, B. Canberk, I. F. Akyildiz. Spatio-Temporal Estimation for Interference Management in Femtocell Networks, *in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,* Sydney, 2012.

[12] N. Cressie. The Origins of Kriging. *Mathematical Geology,* 22(3):239-252, 1990.

[13] P. Gupta and P. R. Kumar. The Capacity of Wireless Networks, *IEEE Transactions on Information Theory,* 46(2):388-404, 2000.

[14] A. Hisham, W. Sun, E. G. Strom, and F. Brannstrom. Power Control for Broadcast V2V Communications with Adjacent Carrier Interference Effects, *in IEEE International Conference on Communications,* Kuala Lumpur, Malaysia, 2016.

[15] M. Andersin, Z. Rosberg, J. Zander. Gradual Removals in Cellular PCS with Constrained Power Control and Noise, *in 6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,* Toronto, 1995.