Channel Adaptive One Hop Broadcasting for VANETs

Lin Yang, Jinhua Guo, Member, IEEE, and Ying Wu

Abstract—One-hop broadcasting is the predominate form of network traffic in VANETs. Exchanging status information by broadcasting among the vehicles enhances vehicular active safety. Since there is no MAC layer broadcasting recovery for 802.11 based VANETs, efforts should be made towards more robust and effective transmission of such safety-related information. In this paper, a channel adaptive broadcasting method is proposed. It relies solely on channel condition information available at each vehicle by employing standard supported sequence number mechanisms. The proposed method is fully compatible with 802.11 and introduces no communication overhead. Simulation studies show that it outperforms standard broadcasting in terms of reception rate and channel utilization.

I. INTRODUCTION

By enabling vehicles to communicate with one another as well as their environments, vehicular ad hoc networks (VANETs) will increase the overall safety and efficiency of national transportation systems. Given the emphasis on supporting safety applications, broadcasting will be the predominate form of network traffic in VANETs. Some of the uses for broadcast messages are: sending emergency warning messages, periodically broadcasting vehicle state information, etc. For this purpose, one-hop broadcasting is a natural choice [4] [5]. The lower layer used in VANETs will be a variant of IEEE 802.11a technology [1], namely, 802.11p [2]. However, the 802.11 is known for not being able to manage the medium resources very efficiently, especially in the case of broadcasting. Thus, providing reliable delivery of broadcast messages in VANETs introduces new challenges:

- **Highly dynamic channel condition**: The channel condition of VANETs is highly dynamic due to the high mobility of vehicles as well as frequently changing road conditions. To improve the system performance, a sender must select appropriate communication parameters (such as transmission power, data rate, etc) and dynamically adapt its decision to the time-varying and location-dependent channel quality. The fundamental challenge is that adaptive broadcasting protocols must accurately estimate the channel condition despite the presence of various dynamics caused by fading, mobility, and hidden terminals.

- **Potential channel congestion**: The periodical transmission of safety messages by all vehicles in a dense traffic environment may cause severe network congestion. However, in contrast to unicast, 802.11 broadcasting has no collision detection or avoidance mechanism. As a result, broadcast works poorly in congested environments where the collision probability is high. It has been shown that the probability of reception rate of broadcast frames can be as low as 20% at distances of 100 meters to the sender and even lower for larger distance under saturation conditions [15].

- **Difficulty in detecting failed broadcasting transmissions**: A failed unicast transmission is detected by the lack of acknowledgment (ACK) from the receiver. However, it is not practical to receive an ACK from each node for a broadcast message. If ACKs were used, a problem known as the “ACK explosion problem” would exist.

Our objective is to develop a channel adaptive one-hop broadcasting mechanism capable of ensuring the successful reception of status information from surrounding nodes in VANETs. This paper is the continuation of our work [6], in which the reliability of one-hop broadcasting is increased by means of dynamic contention window size adjustment. However, the impact of this method is limited. Rather than inappropriate channel scheduling, the collisions caused by hidden terminals is the major cause of low reception rates in VANETs. In this contribution, we are interested in how to alleviate the possibility of collision. Specifically, an 802.11 compatible channel adaptive transmit power control scheme is proposed. Since we exploit the sequence number mechanism, which is built into 802.11 standards and ready to use, no communication control overhead is involved.

Power control in both infrastructure and ad hoc wireless networks has been intensively studied recently [8] [10] [11]. However, most of these studies address a unicast environment and intend to improve spatial reuse or energy consumption, thus are not valid to satisfy VANETs’ specific paradigms and its main goal of safety. The most related study to our work is performed by Torrent-Moreno et al. in a series of [15] [16] and [17]. They first identified the primary reason of low reception rate as the hidden terminal problem, and then implemented a distributed fair power adjustment mechanism to improve the reception rate. Their method relies on active channel monitoring, where nodes are required to send, relay and collect extra information, while ours is fully compatible with 802.11 standards and introduces no extra overhead.

This paper is organized as follows. In Section II, we introduce the channel adaptive one hop broadcasting scheme. In Section III, we discuss channel adaption principles and then present our adaptive algorithm. Performance studies are given in Section IV. We conclude this paper in Section V.
II. RECEIVER-BASED CHANNEL MONITOR

A. Sequence Numbers

According to IEEE 802.11 [1] standards, a two-byte sequence control field is contained in an 802.11 MAC header. The sequence control field consists of two subfields, a 12-bit sequence number and a 4-bit fragment number. First, each frame passed down to the MAC is assigned a 12-bit sequence number. The sequence number was originally intended to detect duplicate frames. In effect, the sequence number acts as a modulo-4096 counter and is incremented by one for each frame passed down to the MAC. Second, the fragment number is used for defragmentation. If a packet passed down from a higher layer must be fragmented, each frame will contain the same sequence number, but each fragment will be assigned its own fragment number. As presented in [13], the total broadcast safety message size, which includes the message itself and overheads for maintaining its security and privacy, is between 283 and 791 bytes. Therefore, in this situation, fragmentation will not take place.

Since the sequence control field already exists, it could be used to detect collision and traffic load in the network. In other words, our modified adaptive broadcast protocol will analyze the overheard sequence numbers to determine the state of the network.

<table>
<thead>
<tr>
<th>Packets from B</th>
<th>32</th>
<th>34</th>
<th>35</th>
<th>36</th>
<th>37</th>
<th>38</th>
<th>40</th>
<th>41</th>
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</thead>
<tbody>
<tr>
<td>Packets from C</td>
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<td>8</td>
<td>9</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Packets from D</td>
<td>15</td>
<td>16</td>
<td>18</td>
<td>19</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Packets from E</td>
<td>62</td>
<td>63</td>
<td>64</td>
<td>65</td>
<td>67</td>
<td>68</td>
<td>69</td>
<td>70</td>
</tr>
</tbody>
</table>

Fig. 1. Packets that node A received in the last time interval

B. Monitoring Network Traffic

While it is not possible for a sender to detect the collisions of packets sent, it is possible to record the successful delivery of packets by receivers. In VANETs, each node is supposed to periodically broadcast status packets over a single hop to its neighbors several times per second. By analyzing the packets it has received recently, a node is able to detect failed ones and thus determine the network conditions. In specific, the receiver will be able to calculate the exact percentage of packets sent to him from neighboring nodes that are successfully received and record the number of these neighbors. For example, as shown in Fig.1, by hearing transmissions placed on the wireless channel, node A can determine that the percentage of packets sent to it from neighboring nodes that were corrupted in the last update interval is 20% (8 out of 40). This means the average reception rate is 80%. It can also observe that there are at least 5 nodes (including itself) contending for the wireless channel around him. Note that the reception rate we get here is the average rate over all neighboring nodes. This passive motoring method has the capability to record and distinguish each node’s reception rate. Such information will be more meaningful if the positions of transmitters are also presented. However, this requires cross-layer operations to extract location information for the MAC layer. Since it is our intention to make the method fully compatible with the 802.11 standards, only average reception rate is utilized in this paper. This leaves room for improvement in our future work.

We assume that a receiver shares the same or similar network condition with its nearby neighbors. This allows a node to adjust its transmission parameters, such as power and data rate, as a transmitter according to the information it collected as a receiver. In our simulation presented in Section IV, this symmetry is confirmed.

III. CHANNEL ADAPTIVE BROADCASTING

A. Channel Adaption Principles

Our goal is to dynamically optimize network traffic based on current channel load, such that periodical safety messages could be received with high probability where they are relevant. In VANETs, since power is usually assumed as unlimited, to deliver messages as far as possible using higher power is preferred. It makes more nodes aware of the transmitter’s status. On the other hand, these messages are most relevant at distances close to the transmitter. For the vehicles just next to the transmitter, every message is too critical to drop. Thus, in our scheme, the reception rate of receivers at close distances is first guaranteed, more important than the number of nodes the message can reach.

The parameters that can be controlled by a channel adaptation algorithm are transmitting power and data rate. Although the packet length and packet generation rate also have impacts on network traffic load, these factors are dominated by safety applications over MAC layer and out of the scope of this paper. Hence only transmit power and data rate will be considered. To gain sufficient insight into the interaction between parameters we can control and factors we can monitor, we present a simple but helpful model to assist us in concluding strategies for the link adaptation scheme.

A typical highway scenario is illustrated and abstracted into a one-dimensional network in Fig. 2. The distance between parallel lanes is neglected, given the large radius of one-hop broadcasting coverage, which is a maximum of 1000m as suggested in [5]. We choose the vehicle $V_R$ in the middle as receiver and randomly pick another one $V_T$ as the reference transmitter. If we denote the monitored number of neighbors as $n$ and the average reception rate as $r_a$, we have

$$r_a = \frac{n}{n} r_i,$$

where $r_i$ is the reception rate of node $i$ observed by $V_R$. We
assume these \( n \) vehicles are uniformly distributed on the abstract line with \( V_R \) in the middle of them, so \( n/2 \) nodes are located on the same side with \( V_T \) and \( n/2 \) are located on the other side. We assume all nodes have the same transmission and receiving range. As shown in Fig.2, clearly all the nodes on the right side are in \( V_R \) ’s receiving range, as well as \( V_T \) ’s. Nodes in the receiving region of \( V_R \) but out of that of \( V_T \) may cause the well-known hidden terminal problem. We identify this area as a potential hidden node area. Since CSMA mechanism can not coordinate the transmissions between \( V_T \) and nodes in its potential hidden node area, packets simultaneously transmitted will cause collision at \( V_R \). For simplicity, we only consider the worst case, in which all the \( n/2 \) nodes on the left side are considered as \( V_T \) ’s potential hidden nodes.

![Transmissions](image)

**Fig. 3.** Two hosts contending for the channel

We represent the contention in the simplified 802.11 DCF access method as a discrete time stochastic process evolving between three states: an idle contention slot, a transmission without a collision and a collision. Fig.3 illustrates the contention process for two hosts. We also assume all slots have the same durations, denoted as \( t_{slot} \). Denoting the packet size as \( S \), the date rate as \( R \), and the useful lifetime of a packet as \( T \), we can compute the number of slots within the useful lifetime of a packet, denoted \( n_{slots} \):

\[
\frac{n_{slots}}{s} = \frac{T \times R}{s} = \frac{T}{s}.
\]

Consider the event that a host attempting to transmit in a time slot. Denoting the attempt probability by \( P_a \), we have:

\[
P_a = \frac{1}{n_{slots}} = \frac{s}{T \times R}.
\]

We denote the probability that \( V_R \) successfully receives the packet from \( V_T \) as \( P_s \). Taking potential hidden node area into account, we have

\[
P_s = P_{RV} \times P_{HN},
\]

where

\[
P_{RV} = (1 - P_a)^n
\]

is the probability that none of other nodes within \( V_T \) ’s receiving range transmits when \( V_T \) starts transmission and

\[
P_{HN} = ((1 - P_a)^n)^2
\]

is the probability that none of the nodes in \( V_T \) ’s potential hidden node area transmits during the hidden terminal vulnerable period. The duration of this period is \( t_{slot} \times 2 \), since \( V_R \) needs an idle channel when \( V_T \) begins transmitting to avoid possible collision.

Because we don’t take the relative distance between transmitter and receiver into consider, the reception rate of \( n \) transmitters are essentially the same. From formula (1), (3), (4), (5) and (6), we have

\[
r_a = P_s = (1 - \frac{s}{T \times R})^\frac{3n}{2},
\]

which describes the principle between the monitored factor with the adjustable transmit power and data rate. From the above results, several observations can be made:

- The number of receiver \( V_R \) ’s neighboring nodes \( n \) is critical to its average reception rate \( r_a \). The more nodes sharing the channel, the more possible collisions will happen. In general, decreasing the transmission power of one packet limits its capability of reaching further distances, so that decreasing the transmission power of all nearby nodes can reduce the number of nodes sharing the channel.
- When data rate \( R \) is raised, it is less likely that collisions will happen. However, higher data rates suffer higher vulnerability to bit-error and interference. In [17] 3Mbps data rate is chosen due to its lower SINR (Signal to Interference and Noise Ratio) requirement. It is also confirmed in [17] that 3Mbps achieves higher reception rates than 6Mbps in different VANET scenarios. So we fix the data rate at 3 Mbps and only consider power adaptation.
- In reality, when \( n \) is small, it is possible that \( r_a \) drops instead of increases as in (7). In such situation, road traffic density is low and vehicles are relatively far apart, and can fall out of or on the border of each other’s transmission range. So using higher power with lower data rate is more acceptable since collision is no longer the major reason of the low reception rate.
- Besides trying to achieve the high reception rate, we also need to keep vehicles informed. So both the reception rate and number of received nodes are criteria for the proposed channel adaptive scheme. For safety applications, as long as the information is accurate enough, being aware of more vehicles around is preferred. This is a tradeoff between accuracy and awareness.

**B. Proposed Channel Adaptive Algorithm**

The channel adaptation algorithm proposed here makes use of the aforementioned sequence number mechanism. When a certain time interval \( \tau \) expires, every node \( V_R \) in VANETs collects information monitored in the last interval and calculates its current average reception rate \( r_a \). Based on the resulting reception rate \( r_a \) and the number of neighboring nodes \( n \), each node makes its own decision on transmit power \( P_{wr} \) independently, according to the algorithm. It is obvious that a shorter \( \tau \) brings more accurate information about neighbours’ status available at the receiver. The proposed channel adaptive algorithm is summarized in Fig.4.

**Algorithm 1 Channel adaptive power control**

\[
P_{max} \quad \text{and} \quad P_{min}\quad \text{are max and min power supported}\n\]

At the end of every \( \tau \), \( V_R \) calculates \( r_a \) and \( n \)

if \( n > N_{Threshold} \) then

    if \( r_a > R_{Threshold} \) then

        increment \( P_{wr} \) by one level when \( P_{wr} < P_{max} \)

    else if \( r_a < R_{Threshold} \)

        decrement \( P_{wr} \) by one level when \( P_{wr} > P_{min} \)

end if

else if \( n < N_{Threshold} \)

    increment \( P_{wr} \) by one level if \( P_{wr} < P_{max} \)

end if

**Fig. 4.** The algorithm for channel adaptive power control
In the algorithm, two thresholds are defined, they are:

- $N_{\text{Threshold}}$ indicates road traffic load. When $n$ is smaller than $N_{\text{Threshold}}$, sparse topology of VANETs is the major reason of the low reception rate and the channel is not well utilized. Otherwise, the channel is well or over utilized and the chance of collisions occurring is notably increased.

- $R_{\text{Threshold}}$ is the target average reception rate. When $r_a$ is smaller than $R_{\text{Threshold}}$, efforts are made to improve $r_a$ towards it. Otherwise, the algorithm tries to maintain current $r_a$ and make possible improvements.

We assume $P_{\text{wr}}$ can be chosen from certain discrete levels. The maximum and minimum supported power level are $P_{\text{max}}$ and $P_{\text{min}}$ respectively. The algorithm first decides road traffic load using $n$. If low traffic density is estimated, $P_{\text{wr}}$ is raised by one level. Otherwise, when $n$ is larger than $N_{\text{Threshold}}$, one of two opposite adjustments on $P_{\text{wr}}$ is determined using the value of $r_a$. If $r_a$ is larger than $R_{\text{Threshold}}$, power is raised for one level, since room for channel utility improvement can be anticipated. If $r_a$ is smaller than $R_{\text{Threshold}}$, power drops for a level to alleviate network load and collision possibility.

In the algorithm, attempts are made to improve the reception rate or channel utilization when $\tau$ expires. The choice for this time interval $\tau$ depends on the channel dynamics. Small values make transmission parameters keep up with channel variations; larger values avoid premature and ineffective parameter adjustments, when the channel is fluctuating rapidly and doesn’t have sufficient improvement potential. In order to achieve low implementation complexity, we fix it to a relatively small value, i.e., 1s, in our simulation study, considering VANETs are intrinsic fast-changing networks.

When $n$ is lower than $N_{\text{Threshold}}$, the small number of received neighboring nodes is attributed to the sparse road traffic density. We neglect the extreme situation that the node density is so high and network traffic is so saturated that almost all packets are dropped. The field experimental study in [12] shows that even with 100 transmitters in communication range with a frame size of 128 bytes and a data rate of 6Mbps, the mean packet delivery rate for 10 packets per second (pps) per node is about 95% when no hidden nodes are present. Since $N_{\text{Threshold}}$ is a fairly small value, this neglect is viable.

$R_{\text{Threshold}}$ and $N_{\text{Threshold}}$ can be seen as a handle to fine-tune the target channel utility. If these two thresholds appropriately represent the channel’s capability, the algorithm will have better performance. We give a pair of feasible value for them in our simulation and leave the design of a strategy for dynamic value setting, e.g., depending on traffic conditions, as future work.

Another notable issue is that our algorithm describes the adaptation of each individual node in VANETs, in other words, only the microcosmic perspective of VANETs. It is apparent that there is no simple analytical approach to deal with the performance and behavior of VANETs as a whole. But from our simulation study, we note that since nodes in VANETs share similar channel conditions with nearby nodes, each node’s decision affects the behavior of others and eventually tends to equilibrium.

IV. SIMULATION STUDY

A. Simulation Setup

The most up to date version of network simulator, ns-2.33, is utilized in our experiments [3]. One significant improvement of this version over the previous ones is that several new, completely overhauled 802.11 models are introduced for a higher level of simulation accuracy [7]. It now supports cumulative SINR computation, preamble and PLCP header processing and capture, and frame body capture, which former versions don’t.

The choice of an appropriate vehicular movement pattern is important for a convincing simulation. We employ the public available highway patterns and ns traffic trace generation tools presented in [9] to obtain a realistic scenario with a dynamic network topology. The original patterns are generated by means of microscopic traffic simulation and validated against real-world data collected on highways. In particular, we consider a 6 km long highway composed of 6 lanes (3 in each direction) with high traffic density, where in total 523 vehicles pass along the road in both directions with average speed of 120 km/h. All vehicles equipped with wireless communication interfaces. This fast moving, heavy traffic scenario is the most critical for safety VANET applications. In order to avoid border effects, only nodes positioned in the middle 2 km are taken into consideration to compute the statistics.

In order to obtain valuable results, wireless networks simulations should be performed with radio propagation models that include realistic effects, i.e., shadowing and fading. In our simulation the probabilistic Nakagami model with a fading intensity $m = 3$ is used, as suggested in [14]. Furthermore, PHY and MAC layer parameters are carefully configured according to the IEEE 802.11p protocols [2].

![Reception rate without interferences of different power levels](image)

As defined in [5], 1000m is the maximum communication range. Following it, we choose 0 dBm as $P_{\text{min}}$ and 15 dBm as $P_{\text{max}}$ with a step size of 3dBm for each power level in between. In Fig.5, we report the probability of correctly receiving a message without interference as a function of distance for each power level, given the propagation model and

PHY layer parameters used in our simulation study. The data rate is fixed at 3Mbps, where the BPSK modulation is used in a 10 MHz channel.

Two application related parameters are left to be configured. The first one is packet generation rate. We choose the rate of 10 pps, at which 10 beacons are broadcasted every second from each vehicle. This frequency is considered as an acceptable value to provide accurate enough information to the safety system [18]. The next one is packet size. All beacons are 500 bytes long in our simulation. As mentioned before, this is in the approximate middle value of reasonable packet sizes in VANETs [13]. Parameters used in our simulation are summarized in Table I with scenario descriptions. All the simulations presented later follow these parameters.

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<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>PHY</td>
<td>Frequency</td>
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</tr>
<tr>
<td></td>
<td>Channel bandwidth</td>
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</tr>
<tr>
<td></td>
<td>Data rate</td>
<td>3Mbps</td>
</tr>
<tr>
<td></td>
<td>Power monitor threshold</td>
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<tr>
<td></td>
<td>Noise floor</td>
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<tr>
<td></td>
<td>Carrier sense threshold</td>
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<tr>
<td></td>
<td>SINR preamble capture</td>
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<tr>
<td></td>
<td>SINR data capture</td>
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</tr>
<tr>
<td></td>
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<td></td>
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<tr>
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<td>Packet size</td>
<td>500 bytes</td>
</tr>
</tbody>
</table>

B. Simulation and Numerical Results of \( r_a \) and \( n \)

We first verify the idea of sequence number based channel monitoring. In this simulation vehicles are equipped with passive monitor functionality as described in Section II, while channel adaptation is turned off. Transmit power varies from 0dBm to 15dBm to achieve different coverage. High power leads to higher channel load. Fig.6 depicts the relationship between the reception rate and number of neighboring nodes. Numerical results of the model in Section III are also shown in the figure. Since some factors, such as SINR and vehicle’s mobility are not considered in the model, number results don’t perfectly match with simulation results. However they follow the basic trend of the simulation and confirm that by manipulating monitored factors, channel load can be estimated and tuned. Note that when \( n \) is smaller than 30, modeled values begin to deviate significantly from simulated ones. This is because although the channel still has capacity left, sparse traffic density becomes the major cause of low reception rate. Another notable fact is the reception rate spread from 0.2 as minimum to almost 0.6 as maximum. Based on the above observation, we choose 30 as \( N_{Threshold} \) and 0.5 as a conservative \( R_{Threshold} \).

C. Performance of Adaptive Power Control

In order to evaluate our algorithm, we configure two main setups, Non-adaptive and Adaptive. In the Non-adaptive simulation, all beacons are sent at maximum power since no power adaptation is applied. On the other hand, for the Adaptive simulation, beacons are sent at the transmit power obtained from the proposed channel adaptive algorithm. We also compare our algorithm’s performance with that of Distributed Fair Power Adjustment for Vehicular environments (D-FPAV) [17]. D-FPAV needs extra information for computing the optimal transmit power, so beacons are required to piggyback aggregated status information. As the threshold mechanism in our scheme, D-FPAV relies on a presetting Maximum Beaconing Load (MBL) to estimate the channel’s capacity. In the comparison, D-FPAV is set to piggyback the information every 10 beacons and MBL is set to 2.5 Mbps. With this configuration, it achieves the best performance.

The main metric analyzed for performance evaluation is the reception rate of a beacon message with respect to the distance, i.e., the probability that a transmitted message can be successfully decoded by the receiving node at a specific distance from the transmitter. As shown in Fig.7, the Non-adaptive simulation presents low reception rates due to high channel load and resulting packet collisions, below 50% for nodes located at 200m and further. On the other hand, the Adaptive simulation achieves an increased reception rate at distances close to the sender. Comparing Adaptive with D-FPAV, we can see Adaptive is slightly better than D-FPAV within a range of 150m. Additional load in beacons causes a higher number of collisions from close nodes. However, from 150m and further, D-FPAV outperforms Adaptive since it has...
more accurate information about channel load and is able to calculate the more optimal transmit power.

It is also useful to analyze why a transmission has failed. Two categories are differentiated, they are dropping (DRP) for insufficient receiving signal strength and collision (CLS) for hidden nodes or inappropriate channel scheduling. Fig.8 shows the probabilities for them with that of successful receiving (RCV). In the figure, prefix “N” and “A” indicated Non-adaptive and Adaptive respectively. In the worst case, in Non-adaptive, nearly 90% percent of packets collide at 600m, while only 58% collide in Adaptive at distances of around 300m. Much less collisions happen in Adaptive, and channel utility is significantly improved.

Fig. 8. Successful and failed transmission breakdown

D. Fairness of Adaptive Power Control

In VANET safety applications, the concept of fairness claims that a higher transmission power of a sender should not be selected at the expense of preventing other vehicles to send or receive their required amount of safety information [16]. In other word, the most ideal situation is for each vehicle to have the same transmit power as its surrounding vehicles, and that this selection of power makes the wireless channel fully utilized. A snapshot in the middle of Adaptive simulation is shown in Fig.9. Each point in the figure presents the ratio between current transmit power of a particular vehicle and the average value of vehicles around it in a radius of 300m. Although vehicles don’t exactly select the same power, the difference between them is mostly less than one level. Thus, a rough fairness is achieved. It also confirms the similar channel condition assumption we made before.

Fig. 9. Comparison between receiver’s power level and the average around it

V. Conclusion

By adaptively adjusting the transmit power, the proposed one-hop broadcasting protocol increases the reception rate at closer distances and alleviates collision possibility at further distances. It is fully compatible with 802.11 standards, consumes no extra network resource, and has little additional complexity. In the paper, the idea of sequence number based channel monitoring is verified by means of the analytical modeling and simulation study, and shows significant promise. Compared with the existing work, our method achieves the similar performance while having the merit of standard compatibility and low overhead. Our future work will focus on dynamically setting the threshold used in the algorithm.

REFERENCES