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Vehicle-to-Vehicle Connectivity and Communication Framework for Vehicular Ad-Hoc Networks

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***Abstract*—Vehicle-to-Vehicle (V2V) communication in Vehicular Ad hoc Networks (VANETs) is one of the key ingredients in the Intelligent Transportation System (ITS) where vehicles receive relevant traffic information using wireless communications from their peers. Forwarding traffic information to drivers can assist with the tasks of avoiding traffic accidents and related congestion. In this paper, we investigate the effect of association time (*a.k.a.* connection setup time), relative speed of vehicles, transmission range and message/data size in short range based V2V communications. The analysis is illustrated with the numerical results obtained from simulations.**

***Index Terms*—Vehicle-to-vehicle communications, VANET, short range vehicular communications**

I. Introduction

Traffic accidents are one of the largest societal problems facing not only the US but also all over the world. A report published by the U.S. National Highway Traffic Safety Administration (NHTSA) [1] in 2012 estimates that in the U.S, a person dies in a traffic accident every 15 minutes outnumbering any deadly diseases or natural disasters. Studies [2] show that "about 60% roadway collisions could be avoided if the operator of the vehicle was provided warning at least one-half second prior to a collision." The number of death, injuries and the excessive cost of traffic collisions could be significantly lowered if the drivers were provided with traffic information in a timely fashion [3], [4]. Devising an automatic mechanism for communicating traffic information in a timely manner can help drivers make informed travel decisions and avoid hazardous situations.

Vehicular Networking is an emerging concept for Intelligent Transportation System (ITS) to enhance passenger comfort, traffic efficiency, safety of passengers and so on, by forwarding upcoming traffic information in a timely manner. One of the main goals of wireless communications in VANET is to automate message propagation using vehicle-to-vehicle (V2V) and/or vehicle-to-roadside (V2R) with possible roadside-to-roadside (R2R) communications. In V2R communications, vehicles send messages to road side units and the road side units propagate the information to target vehicles. This process can cover large area but introduces delay in message propagation since roadside unit works as a relay between senders and receivers. This type of communication is not suitable for time-critical or emergency messages. In V2V communication, each vehicle works as a source, a destination and/or a router to disseminate traffic related information. Thus, the use of V2V communication can help reduce the delay introduced by roadside unit(s). Furthermore, most of the safety-related applications (such as collision warning, road merging, emergency braking, etc.) need quick exchange of messages which can be achieved by using short range V2V communications. Furthermore, studies [5] have also claimed that if each car could tell every other car, 'Here I am,' vehicular networking systems could prevent cars from colliding each other. For instance, message such as brake applied by driver traveling in front of a given vehicle should be transmitted as quickly as possible so that following drivers could adjust their speed accordingly.

The U.S. Federal Communications Commission (FCC) has allocated 75 MHz RF spectrum in 5.850 GHz to 5.925 GHz band as the Dedicated Short Range Communication (DSRC) to enable wireless communication in VANETs for safety and infotainment applications [6], [7]. The maximum transmission range recommended by DSRC is 1000 meter. A longer transmission range would cover larger area and could transmit traffic-related information to a large number of vehicles. However, when a long transmission range is used, attackers sitting by the road side may inject malicious messages intended to mislead the traveling public. With the implementation of short range based V2V communication, we can easily avoid this type of problems.

Short-range wireless communication for VANET was proposed in [8]–[12]. The work in [10] proposes NOTICE architecture where sensor belts mounted under the road every mile or so collect and transmit traffic-related messages. Vehicles are assumed to be equipped with two wireless radios (one for association and the other for message transmission). Using standard technologies association and message exchange for NOTICE architecture have been analyzed in [13]. In [12], authors have proposed so called "cat's eye" architecture in which roadside units are involved in message collecting and forwarding in vehicular network. It is worth noting that both of these architectures are based on V2R communications and do not provide insight of association (connection setup), physical layer specifications, effect of data size, data rate, etc. Further-

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more, work in [8], [9] focus on V2V based communication without considering association time, relative speed, data size, etc.

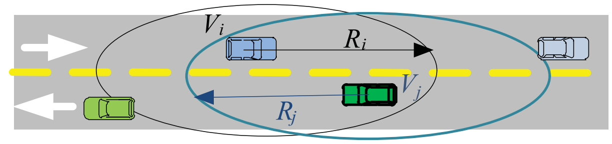
The main contribution of this work is to investigate a short range V2V communication architecture to provide notication about related traffic information/conditions. We analyze the effect of association (connection setup) time, message size[1], transmission range and relative speed of vehicles for successful message forwarding in vehicular network and present analytical and numerical results for V2V communications. Simulation results corresponding to technologies such as Wi-Fi, ZigBee, etc. suitable for short range V2V communication are also presented. When a short transmission range is used for data exchange in V2V communication, attackers sitting by the roadside may not be within the communication range and may not be able to alter/insert the messages, and thus our proposed work provides VANET security as an important byproduct [14]–[16].

The remainder of the paper is organized as follows: we present the system model and formally state the problem in Section II followed by an estimation of the expected value for successful message exchange in Section III. We illustrate our analytical results by simulation and numerical results obtained from simulations in Section IV, and present final conclusions in Section V.

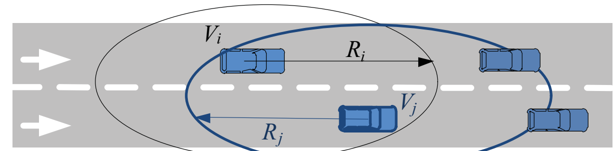
II. V2V Communication System Model

We assume that the vehicles are traveling on the road are equipped with computing and communication devices according to the U.S. National Highway Transportation Safety Administration (NHTSA) ruling [3]. Using those computing and communication devices, vehicles can communicate with each other using V2V based communications. We also assume that vehicles periodically broadcast their geolocations, speeds, etc. information in VANET.

Broadly speaking, there are two types of scenarios for V2V communications: (i) vehicles traveling in *opposite* directions as shown in Fig. 1 (a) and (ii) vehicles traveling in *same* direction as shown in Fig. 1 (b). Note that the time interval during which two vehicles can communicate directly depends in their relative speed. It is clear that the time for information exchange using V2V communication, for a given transmission range r and relative speed v_{rel}, can be computed using $t = \frac{r}{v_{rel}}$. This implies that for a given transmission range the time interval during which the vehicles can communicate decreases when their relative speed v_{rel} increases and vice versa. In other words, when the relative speed is smaller, vehicles remain within communication range for long time and they have longer time for information exchange using direct communication. It is worth noting that the relative speed of vehicles becomes smaller (zero) when vehicles move in same direction (with equal speed). In the case of zero relative speed V2V communication is similar to communication in



(a) Two Way Two-lane Road Section



(b) One Way Two-lane Road Section

Fig. 1. Vehicular ad hoc networks with vehicles (e.g., v_i and v_j) moving in their corresponding directions and with their corresponding transmission ranges (e.g., R_i and R_j).

static peer-to-peer network. However, when vehicles move in opposite direction, their relative speed is high since the relative speed is the sum of the speeds of two communicating vehicles and thus V2V network becomes highly *dynamic* ad hoc network. Note for a given transmission range and relative speed, there will be a fixed time during which vehicles remain within communication range of each other. This time must be used for both association and data exchange.

In V2V communication, wireless devices that are mounted in vehicles should be associated before exchanging the actual information or messages. That is, after successful association, vehicles are ready to exchange messages. When the vehicles travel in the same direction, because of small (or zero) relative speed, devices have sufficient time to get associated and to transmit messages. However, when the vehicles travel in opposite directions at highway speeds, they remain within communication range for a short amount of time which might not be enough to get associated and for a meaningful exchange the messages. It is well documented that different wireless technologies (such as Wi-Fi, ZigBee, Bluetooth, UWB, etc.) have different association times and data rates. These parameters play a major role in successful communication in VANET.

In the next section, we investigate the effect of association time, data rate, transmission range and relative speed of vehicles for successful V2V communications.

III. Analysis for Successful Data Exchange using V2V Communication

Let A, X and L be, respectively, association time[2], 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, $A + X \leq L$ condition must be satisfied. Probability of successful association and data exchange between vehicles can be expressed as $P_s = Pr\{A+X \leq L\}$. Then $1-P_s$ gives the

[1]Note that without exchanging a complete message in vehicular network, it has no meaning. Thus message size affects the successful data exchange in V2V communication.

[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 [17].

probability of unsuccessful data exchange which represents, in our case, partial or no messages being exchanged between vehicles. Value of total available time for V2V communication can be computed as

$$L = \begin{cases} \frac{D_{v_i,v_j}}{v_{rel}}, & D_{v_i,v_j} \leq min\{R_i, R_j\} \quad \forall v_i, v_j \\ 0, & \text{Otherwise} \end{cases} \tag{1}$$

where D_{v_i,v_j} is the distance between vehicles v_i and v_j. Assuming that the two vehicles are located at (x_i, y_i) and (x_j, y_j), we can compute D_{v_i,v_j} as

$$D_{v_i,v_j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{2}$$

Obviously, for the vehicles to be able to communicate, we must have $D_{v_i,v_j} \leq min\{R_i, R_j\}$. From equation (1), it is clear that when $v_{rel} \to 0$, the value of $L \to \infty$. This implies that when the vehicles move at constant speed in the same direction while exchanging their information, they will have very long time (theoretically ∞) to get associated and exchange the messages.

Based on the analysis above, we present the algorithm for time calculation as **Algorithm 1**:

Algorithm 1 : V2V communication time (L)

Input: geographic locations of vehicles (v_i and v_j) and their transmission ranges (R_i and R_j).
for each vehicle pair, v_i and v_j **do**
  for $v_{rel} = 1$ to 140 miles/hour **do**
    Compute D_{v_i,v_j} using equation (2)
    if $D_{v_i,v_j} \leq min\{R_i, R_j\}$ **then**
      Compute $L = \frac{D_{v_i,v_j}}{v_{rel}}$
    else
      $L = 0$
    endif
  end for
end for
Output: time (L) for different relative speeds

Once we have the total time for V2V communication, we can compute the time for message exchange (that is the time left after successful association of devices) and amount of data that could be exchanged between vehicles using **Algorithm 2**.

Algorithm 2 : Message size calculation

Input: time (L) from **Algorithm 1**, association time (A) and data rate (D_r).
if $0 < L$ **then**
  Compute $X = max\{0, L - A\}$
  Compute message size with header $MSH = D_r \times X$
  Actual message size $MS = MSH - Header\text{-}Size$
endif
Output: Message size (MS)

Furthermore, without transmitting a complete message, the message would have no meaning in VANETs. Note that when partial message is exchanged in V2V communication, receiving vehicle may not be able to understand the actual semantic/meaning of the message unless it gets a copy of the message from other vehicles. Thus, we consider that the complete message of size S has to be transmitted with given data rate D_r for successful V2V communication. The time X needed to transmit given message of size S is given by

$$X = \frac{S}{D_r} \tag{3}$$

Because of dynamic nature of VANET topology, it is important to estimate the time (available for data exchange) after successful association of wireless devices. Note that this value depends on various parameters such as relative speed of vehicle, transmission range, association time of technology being used, etc.

Estimation of expected time for data exchange: We assume that communication range overlap between vehicles is random process and it does not depend on the time and range overlap of the previous vehicles. We consider distribution of vehicles being within a communication range of each other as Poisson distribution with parameter β [18, Ch. 8] to analyze how association time can influence the data exchange in V2V communications. Note that $\boldsymbol{L} \geq 0$ is the random variable representing the total time/duration available for device association and data exchange between vehicles for V2V communications which follows the Poisson distribution with parameter β. Thus the cumulative distribution function (cdf) for a random variable $\boldsymbol{L}$ is defined as [18]

$$F_{\boldsymbol{L}}(L) = 1 - e^{-\beta L}, \qquad L \geq 0 \tag{4}$$

Then we can find probability distribution function (pdf) as

$$f_{\boldsymbol{L}}(L) = \begin{cases} \beta e^{-\beta L}, & L \geq 0 \\ 0, & \text{Otherwise} \end{cases} \tag{5}$$

Using total time available $\boldsymbol{L}$ and association time $\boldsymbol{A}$, we can write time for data exchange (after connection setup) as

$$\boldsymbol{X} = [\boldsymbol{L} - \boldsymbol{A}]^+ \tag{6}$$

Where $[b]^+ = max\{0, b\}$. Note that $\boldsymbol{X}$ is also a random variable and should be positive to be able to transmit messages using V2V communication. Then we can write probability of successful message exchange for given time X as

$$\begin{aligned} F_{\boldsymbol{X}}(X) = P\{\boldsymbol{X} \leq X\} &= P\{\boldsymbol{L} - A \leq X\} \\ &= P\{\boldsymbol{L} \leq X + A\} \\ &= F_{\boldsymbol{L}}(X + A) \end{aligned} \tag{7}$$

Now, we can write cdf as

$$F_{\boldsymbol{X}}(X) = 1 - e^{-(X+A)\beta} \tag{8}$$

and then pdf as

$$f_{\boldsymbol{X}}(X) = \beta e^{-(X+A)\beta} \tag{9}$$

Then the expected value of time X can be computed as

$$
\begin{aligned}
\overline{X} = E[\mathbf{X}] &= \int_0^\infty X\beta e^{-(X+A)\beta}dx \\
&= \int_0^\infty X\beta e^{-X\beta}e^{-A\beta}dx \qquad (10)\\
&= \tfrac{1}{\beta}e^{-A\beta}
\end{aligned}
$$

Note that (10) gives the expected value of usable time as a function of successful association time when we consider $\boldsymbol{X}$ as a random variable and there is no boundary in the transmission range. In our case, transmission range is given by (2). Considering factors such as distance between vehicles, data rate, data size, etc, we compute ratio of time, P_r, as

$$P_r = min\left\{1, \left[\frac{\left(A + \frac{S}{D_r}\right)}{\left(\frac{v_{rel}}{D_{v_i,v_j}}\right)}\right]\right\} \qquad (11)$$

It is worth noting that ratio P_r values is bounded by [0, 1] and its value is 1 when relative speed is zero (this happens when two vehicles travel with equal speed in the same direction). Then, the expected time $\overline{X}$ becomes

$$
\begin{aligned}
\overline{X} &= \tfrac{1}{\beta}e^{-A\beta} \times P_r \\
&= \tfrac{1}{\beta}e^{-A\beta} \times min\left\{1, \left[\frac{\left(A+\frac{S}{D_r}\right)}{\left(\frac{v_{rel}}{D_{v_i,v_j}}\right)}\right]\right\} \qquad (12)
\end{aligned}
$$

Note that the expected time $\overline{X}$ for data exchange for given association time and data rate of the technology, and overlapping of transmission range and relative speed of communicating vehicles. From (12), it follows that when relative speed is zero, P_r becomes 1 and the expected value $\overline{X}$ depends only on association time A for a given β.

Using (1) and (12), the probability of successful data exchange is expressed as

$$P_s = Pr\{A + \overline{X} \leq L\} \qquad (13)$$

This probability depends on association time and data rate of a given technology, relative speed of communicating vehicles and size of the message to be transmitted.

IV. Evaluation and Numerical Results

In this section we present simulation setup and numerical results obtained from simulations. We considered that the overlap of communication range between vehicles is Poisson distribution process with the parameter $\beta = 1$ vehicle/second, and overlap in range does not depend on the time and range overlap of the previous vehicles. Relative speed of vehicles varied from 0 mile/hour to 140 miles/hour.

In the first experiment, using **Algorithm 1**, we plotted the variation in available time for given transmission range (varying from 10 meter through 1000 meter) and different *relative speeds* of vehicles (varying from 1 mile/hour through 140 miles/hour[3]) as shown in Fig. 2. As expected for a given transmission range, when relative speed of vehicles increases, available time for communication decreases. For a given relative speed (e.g. 40 miles/hour), time increases when transmission range increases. Observe that the sum of association time and the time needed for message/data exchange cannot exceed the line in Fig. 2 for a given transmission range and relative speed.

In the second experiment, we have considered three scenarios where vehicles are assumed to be equipped with Bluetooth, Wi-Fi, ZigBee/xBee devices[4] for short range V2V commu-

Algorithm 3 : P_s calculation

Input: geographic coordinates of vehicles (v_i and v_j), their transmission ranges (R_i and R_j), A, S, D_r, β, simulation time and success = 0.
repeat
  for each vehicle pair, v_i and v_j **do**
    for $v_{rel} = random(70 \pm 70)$ **do**
      Compute D_{v_i,v_j} using equation (2)
      if $D_{v_i,v_j} \leq min\{R_i, R_j\}$ **then**
        Compute $L = \frac{D_{v_i,v_j}}{v_{rel}}$
      else
        $L = 0$
      endif
      Compute $\overline{X}$ using (12).
      if $A + \overline{X} \leq L$ **then**
        success = success + 1
      endif
    end for
  end for
until end of trials or simulation time
$P_s = \frac{\text{success}}{\text{trials}}$
Output: P_s

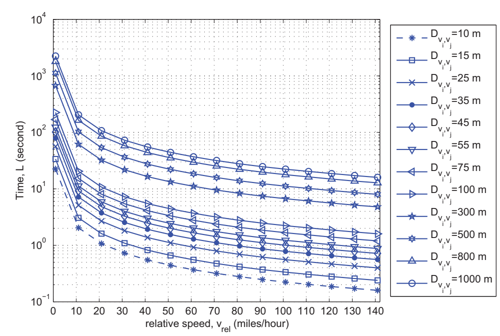


Fig. 2. Upper limit of total communication time (L) for vehicles v_i and v_j for different *relative* speeds (starting from 1 miles/hour through 140 miles/hour) and communication ranges of D_{v_i,v_j} (starting from 10 meters through 1000 Meters - DSRC recommended maximum range).

[3]Posted speed of the US roads/highways is not greater than 70 miles/hour. Thus the relative speed of 140 miles/hour is for vehicles moving with 70 miles/hour in opposite direction.

[4]Note that to make typical wireless technologies such as Bluetooth, Wi-Fi, ZigBee/xBee, etc. suitable for V2V communications, specifications such as transmission range/power could have to be changed to meet the needs for V2V communications.

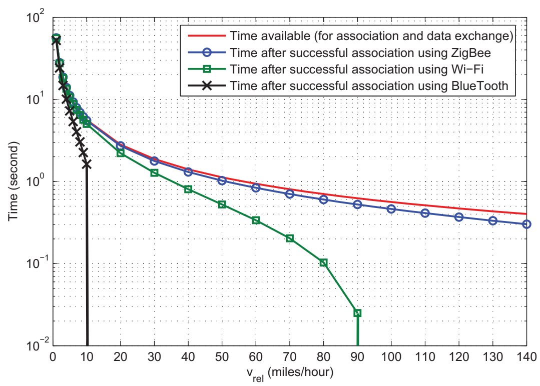


Fig. 3. Total time and time left after successful association between vehicles v_i and v_j for different relative speeds and communication range equal to $D_{v_i,v_j} = 25$ meter.

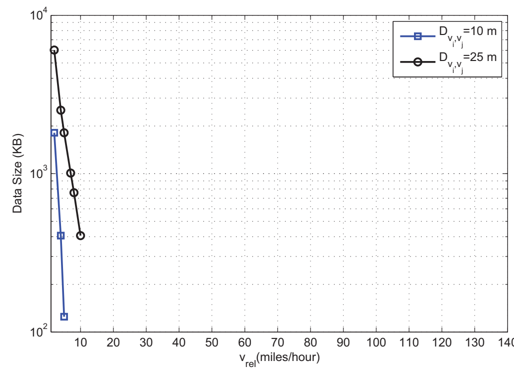
nications. We calculated the total available time for given transmission ranges and relative speeds of vehicles and plotted both total time and time remaining after successful association in Fig 3. Note that Bluetooth, Wi-Fi and ZigBee devices take, respectively, about 4 seconds, 600 milliseconds and 30 milliseconds for association or connection setup [17]. After successful association, devices exchange actual information. Fig 3shows that the vehicles with Bluetooth devices had no time left when their relative speed is greater than 10 miles/hour since Bluetooth devices could not be associated or they spent all of the available time for association. As a result, vehicles could not exchange messages when they traveled with a relative speed greater than 10 miles/hour as shown in Fig 4 (a). Note that the size of the message transmitted is about 4000 Kilobytes when relative speed is about 10 miles/hour.

Next, we assumed that each vehicle was equipped with a Wi-Fi device. When the relative speed was not greater than 90 miles/hour, Wi-Fi devices exchanged messages using V2V communications as shown in Fig 4 (b). For a relative speed of 90 miles/hour, vehicles exchanged 6 Kilobytes of messages. Note that the size of a typical one-page message with 568 words is about 5 Kilobytes.

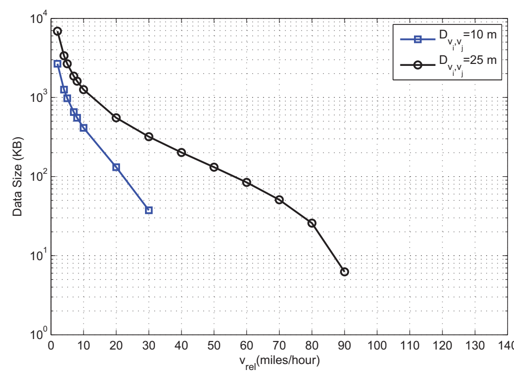
Finally, we assumed that individual vehicles were equipped with ZigBee devices. ZigBee devices were able to transmit messages of size 90 Kilobytes even when their relative speed was 140 miles/hour.

It is noted that for a given transmission range of 25 meter and relative speed not greater than 90 miles/hour, Wi-Fi devices could be used for successful V2V communications. Similarly, Bluetooth devices could be used only when relative speed is not greater than 10 miles/hour. However, ZigBee devices could be used to exchange messages even when relative speed is about 140 miles/hour or even higher.

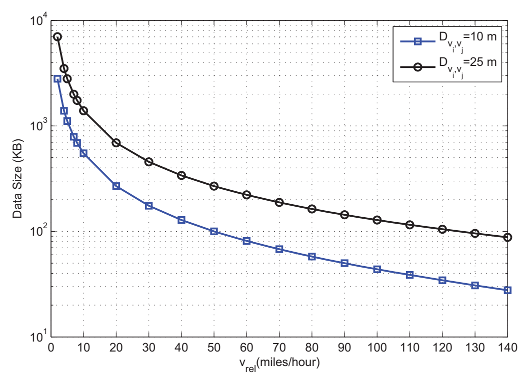
To see the effect in message exchange, we then changed the transmission range from 25 meter to 10 meter for all three cases and plotted the data exchanged for given relative speeds as shown in Fig 4. We noted that vehicles could not exchange data when they move with relative speed higher than 5 miles/hour and 30 miles/hour using Bluetooth and Wi-Fi devices respectively. Furthermore, message size decreased significantly when we decreased the transmission range to 10 meter in all cases as shown in Fig 4 (a). (b) and (c). It is noted that tradeoff between transmission range and message should be considered.



(a) Bluetooth Technology



(b) Wi-Fi Technology



(c) ZigBee/XBee Technology

Fig. 4. Upper bound of message size that could be transmitted with a given data rate of 250Kbps for different relative speed of vehicles and communication range $D_{v_i,v_j} \in \{10, 25\}$ meter.

Finally, we computed probability of successful data exchange in V2V communication using **Algorithm 3** and plotted

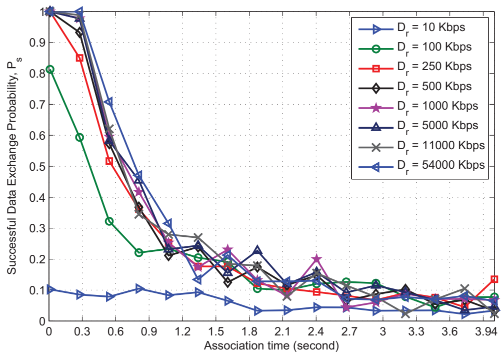


Fig. 5. Effect of Association Time for given message size (e.g. the size of a typical one page message with 568 words is about 5 Kilobytes) and data rate on successful data exchange probability for V2V based communication when the communication range equal to $D_{v_i,v_j} = 25$ meter.

it for given message size of 5 Kilobytes (typical size of one page message of 568 words) using different data rates and association time by averaging 1000 trials. Relative speeds of vehicles were generated randomly in the range 70 ± 70 miles/hour. This represents both low and high relative speeds ranging from 0 miles/hour to 140 miles/hour. From Fig 5, note that as expected, when association time increases, probability of successful data exchange decreases. It is worth noting that for given transmission range and relative speed, there is a fixed time during where vehicles remain within communication range of each other. The overlap time is used for both association and data exchange, when association time increases, time left for data exchange decreases resulting in unsuccessful data exchange. Again, note that unsuccessful data exchange in our case is partial or no information is exchanged at all. Furthermore, to exchange typical one page message (i.e., 5 Kilobytes), there is no significant difference in probability P_s value when data rate is higher than or equal to 100 Kbps.

We conclude that V2V communication requires fast association between wireless devices for successful message exchange between communicating vehicles to forward messages.

V. Conclusion

In this paper, we presented the analysis for successful information exchange using V2V communication for vehicular network. Successful data exchange in V2V communication relied on the technology being used (or association time and data rate of the technology), transmission range and relative speed of vehicles. For a given transmission range, to exchange the information using V2V communication, ZigBee devices could be used when relative speed is high (e.g. 140 miles/hour), Wi-Fi devices could be used when relative speed is not greater than 90 miles/hour and Bluetooth could be used when relative speed is not greater than 10 miles/hour. It is noted that V2V communication provides fast association and low communication latency between communicating vehicles to forward safety related messages. Thus for time-sensitive emergency messages, short range based V2V communication is suitable. It is noted that the selection of wireless technology depends on the services that the vehicular communication is envisioned to support.

VI. Acknowledgments

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