Design and Implementation of an active safety system for Vehicular Ad-Hoc Networks(VANETs)

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***Abstract*— Vehicular communication, underpinned by IEEE 802.11p/WAVE-based Vehicle Ad-hoc Networks (VANETs), is instrumental in the seamless functioning of intra-vehicle exchanges. However, a comprehensive assessment of these systems reveals suboptimal efficiencies at the data layer, specifically regarding default broadcast intervals. Such inefficiencies lead to escalated packet collisions and subpar utilization of the delay time counter—factors that undermine the synergistic interplay between Active Safety Systems (ASS), such as Adaptive Cruise Control (ACC), and their passive safety counterparts. To address these intricacies, this research proposes an innovative mathematical framework tailored for the IEEE 802.11p MAC layer. We propose a model that elucidates the intricate dynamics of the delay time counter and offers refined broadcast intervals buttressed by robust algorithmic strategies. Empirical evaluations, conducted in meticulously simulated vehicular environments, validate the prowess of the proposed paradigm, highlighting a decline in packet collision instances. Quantitative findings from this research evince a notable decrease in packet collision rates and a commensurate enhancement in communication reliability, pivotal for advanced vehicular systems. Such technical augmentations directly elevate the operational reliability of cutting-edge safety mechanisms, exemplified by systems like the Toyota Pre-Crash Safety System.** **Keywords—VANET, BSM, road, safety, MAC, PHY, OBU, V2V.**

I. Introduction

Active road safety systems are designed to avoid accidents on the roads. Such systems collect data about the vehicle itself and a certain distance around it, and analyze the data collected during the movement of the vehicle in order to determine the presence of a hazard [1,2]. Informing vehicle drivers occurs with the help of targeted safety systems that use sensors to collect data, the collected data is processed and then given to the driver. In order to expand the processed data, communication technologies are additionally used. To study such problems, many researchers consider only a narrow focus, for example, only the link level, part of computer vision, interference in such communications and etc. Of course, they do this to justify their developments in these parts of the overall system. In this study, unlike others, we will consider the entire system, from high levels to the very physical level, and basically all this will be considered on the basis of recognized world standards.

II. Active road safety systems

A. Safety systems

These systems are designed to help the vehicle driver perform their duties more efficiently, and also allow the vehicle driver to quickly receive information about the situation around the vehicle. Typically, active safety systems (ASS) prevent accidents by notifying the driver of the vehicle, while the system itself can perform independent actions, such as steering. An example of the first manifestations of ASS is adaptive cruise control (ACC), designed to maintain a distance between cars using radar sensors [3]. ASS can be interconnected with passive safety systems, i.e., for example, an unavoidable collision can be detected using radar technology, and in advance, resulting in a reduction in the severity of injury to the driver of the vehicle, an example is the Toyota Pre-Crash Safety System [4].

The application of ASS can be divided into two, depending on the type of delivery to the driver of the vehicle:

- information delivery systems: issuing a warning message. These systems provide the driver with the necessary information about the situation and allow him to take appropriate action;
- automatic control systems: separation of powers between the vehicle and its controller. These systems are aimed at providing additional assistance to the driver of the vehicle by performing automatic actions by the vehicle. In such systems, care must be taken in the allocation of authority, as unknown technical or other problems may arise.

Since the main purpose of ACC is to avoid vehicle crashes, vehicles must be equipped with sensors that can detect the presence of obstacles around them. Another technology used to improve road safety is computer vision. Applications developed on the basis of this technology provide safety by viewing special road markings [6] or lane markings [7]. In such applications, stereo cameras are used to observe the vehicle's surroundings, and dangerous situations are identified through the processing of captured images, for example, a situation when the vehicle is dangerously close to the edge of the road [8].

However, the sensors have a limited detection range, for example, the sensors may not work at full capacity when the vehicle is at an intersection. To solve such problems for vehicles, communication technologies are needed. Vehicles use communication systems to obtain information about other vehicles and objects that cannot be detected by sensors or computer vision. Accordingly, it also increases the possibility of collecting vehicle data. Taking into account the above, communication with vehicles has a significant impact on the development of ASS [9]. The concept of interaction of vehicles within the framework of safety is presented in Fig. 1.

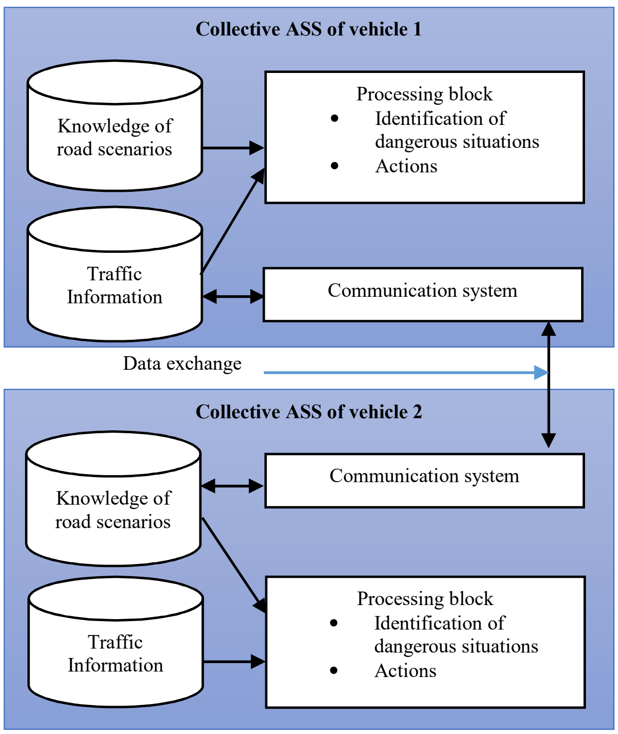


Fig. 1. Vehicle communication concept

The "communication system" element is intended for the exchange of data between vehicles (speed, location, direction) and describing the road (road level, slip coefficient). This information is entered into a database that stores traffic information. The knowledge base of traffic scenarios contains possible accidents, information about which is used to identify dangerous situations that may occur while driving. Such information, being semi-static, can also be updated at any time. The data update can be performed dynamically using continuous technical monitoring or the vehicle's communication system. Such applications use the IEEE 802.11p/WAVE standard to create a vehicle safety system.

B. *Literature review*

Researchers are extensively studying VANET broadcasting, focusing on aspects like network performance, throughput, latency, and message reliability. Some research divides the VANET network into parts or considers it error-prone, examining different layers such as physical, link, or network. In their study, the authors of [10] categorized and compared various VANET broadcast protocols, assessing their performance via simulation. They concluded that efficient broadcasting aims to optimize bandwidth use by minimizing retransmissions while ensuring high availability and minimal latency. The study [11] introduces a VANET broadcasting algorithm prioritizing vehicle safety messages. It assumes a congestion-free network and guarantees reliable communication. The research in [12] proposes a model outlining the quality of service (QoS) for safety messages, suggesting that this model ensures high chances of receiving vehicle warning messages. However, debates persist on certain message relay aspects. A related study [13] emphasizes swift relaying of short messages with minimal delays. In [14], the authors analyzed intelligent solutions for VANET challenges using artificial intelligence and machine learning. They highlighted the need for a comparative framework to transparently design and select future vehicle routing protocols, emphasizing a lack of consensus in protocol evaluation.

In conclusion, VANET broadcasting remains a focal point for academia and industry. Numerous protocols and methods have emerged to facilitate efficient message distribution across VANETs. Still, many studies neglect detailed insights into the fundamental vehicle safety messaging process, an issue addressed in the subsequent section.

III. An Analytical Performance Model of IEEE 802.11p MAC in Vehicle Communications

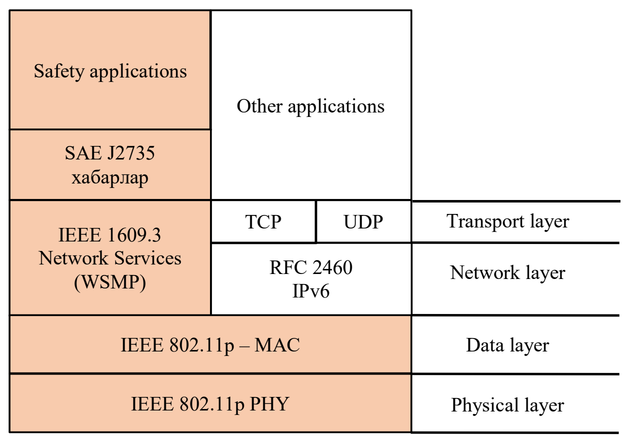


Fig. 2. Vehicle communication concept

The IEEE 802.11p MAC standard operates at the data layer, that is, it implements link resource management. By default, 178 channels are reserved for safety applications (which are considered the control channel), while the remaining channels are reserved for non-safety applications. When using this standard in vehicle security applications, broadcast transmission has the differences such as the inability to send ACK messages (acknowledgment message), as this mechanism will lead to an ACK storm [15]. Secondly, there are no protection mechanisms for broadcast packets such as RTS/CTS as opposed to unidirectional communication. In addition, broadcast mode failures are not detected by the transmitting node. As a result, the number of packet collisions increases, which requires consideration of the performance of the safety application data exchange process over vehicle networks.

The IEEE 802.11p MAC node keeps track of the link state with the new information to send. A node may transmit its data when the channel idle period reaches the DIFS allocated interframe space. Otherwise, i.e. if the channel is transmitting, the node checks the status of the channel until it reaches DIFS. The node generates a random delay before transmitting and waits until the delay time counter drops to zero. The delay time is given by the following equation:

$$T_{del} = Rand(0, w-1) * \sigma \quad (1)$$

where w – is the size of the CW, σ – is the size of the time interval. The value set for w does not change because retransmission is not performed in a broadcast. The delay counter is frozen when the channel is determined to be idle and decremented when it is determined to be busy. The node transmits data as soon as the delay counter reaches zero.

In vehicles, safety information is transmitted periodically, that is, the broadcast period T=1/λ, each node has a deterministic packet generation rate λ. Vehicles connected to the network obey the distribution of Poisson point processes. In VANET, the vehicle density β veh/km and the transmission/reception distance of vehicles are R, and the presence of a vehicle i at a distance of 2R is given by the following equation:

$$P(i, 2R) = \frac{(2\beta R)^i e^{-2\beta R}}{i!} \quad (2)$$

Since there is no acknowledgment or re-request in the event of a failed broadcast, the standard 2D Markov model must be changed to a 1D Markov model by adding an additional state when there are no packets waiting to be transmitted in the buffer.

Let us assume that the process $b(t)$ is stochastic and represents the node's waiting counter at time t. The numbers inside the circle represent the state of the node, their values are the same as the values of the delay time counter in the interval 0, 1, …W-1. A state marked with an E indicates that the node is empty. p_0 is the probability that the node's buffer is free, and p_I is the probability that the channel will be empty during the node's delay time. If $p_0 = 0$ means that the buffer is not empty. $b_k = \lim_{t\to\infty} P\{b(t) = k\}, k\epsilon[0, W-1]$ — stationary distribution of the chain, then b_0 – stationary distribution of packet transmission after the delay, the time counter reaches zero probability. In this steady state, the following equations are obtained from the Markov chain:

The probability of a non-zero one-step transition is determined by the following formula:

$$\begin{cases} P\{k|k+1\} = p_I, & k\epsilon[0, W-2] \\ P\{k|k\} = 1 - p_I, & k\epsilon[1, W-1] \\ P\{k|0\} = (1-p_0)/W, & k\epsilon[0, W-1] \\ P\{k|E\} = (1-p_0)/W, & k\epsilon[0, W-1] \\ P\{E|0\} = p_0, & \\ P\{E|E\} = p_0, & \end{cases} \quad (3)$$

$$b_0 = \frac{(b_0+b_E)(1-p_0)}{W} + b_1 p_I \quad (4)$$

$$b_{W-1} p_I = \frac{(b_0+b_E)(1-p_0)}{W} \quad (5)$$

$$b_k p_I = \frac{(b_0+b_E)(1-p_0)}{W} + b_{k+1} p_I, \quad k\epsilon[1, W-2] \quad (6)$$

(4) and (6) have the following equations:

$$b_0 = (b_0 + b_E)(1 - p_0) \quad (7)$$

$$b_k = \frac{(b_0+b_E)(1-p_0)(W-k)}{W\, p_I} \quad (8)$$

Based on (7) and (8) and the following fact

$$\sum_{k=0}^{W-1} b_k + b_E = 1 \quad (9)$$

the element b_0 specializes in (10).

$$b_0 = \frac{2p_I(1-p_0)}{(W-1)(1-p_0)+2p_I} \quad (10)$$

Assume that τ is the stationary probability of a node transmitting a broadcast packet in an arbitrarily chosen time interval. Considering that translation is performed when the node delay time counter reaches the end, the τ can be defined as b_0.

$$\tau = b_0 = \frac{2p_I(1-p_0)}{(W-1)(1-p_0)+2p_I} \quad (11)$$

If we do not take into account the hang of the delay time counter, then the probability p_I is equal to 1 and t can be expressed as

$$\tau = b_0 = \frac{2(1-p_0)}{(W-1)(1-p_0)+2} \quad (12)$$

$$p = p_b \times (1 - p_t) \quad (13)$$

$$p_b = 1 - (1-\tau)^n \quad (14)$$

Considering the Poisson process assumption used for vehicles on the road described above, and applying formula (2), one can change the probability value p_b as follows:

$$p_b = 1 - \sum_{i=0}^{\infty} (1-\tau)^i \frac{(2\beta R)^i e^{-2\beta R}}{i!} \quad (15)$$

and the probability p_t

$$p_t = \frac{2\beta R\tau e^{-2\beta R\tau}}{1-e^{-2\beta R\tau}} \quad (16)$$

$$p = 1 - (1 + 2\beta R\tau) e^{-2\beta R\tau} \quad (17)$$

Since the rate of creation of broadcast packets λ is deterministic, the packets are serviced exponentially, and the service of each node can be modeled as a discrete time system $D/M/1$. If the timeout of a generated packet waiting to be serviced in the node buffer is T_w, the packet service time is T_s, and the packet timeout is T_{so}, then $f_w(t)$, $f_s(t)$ and $f_{so}(t)$ are T_w, T_s and T_{so}, respectively, can be defined as functions of the probability density. Based on this, the packet buffering time is $T_{so} = T_w + T_s$. The packet generation probability density function for the queue at a node is defined as $a(t) = \delta(t - T)$, $\delta(t)$ – impulse function. The packet maintenance time T_s – exponential variable obtained from the probability density function $f_s(t) = \mu e^{-\mu t}$, where μ – average time of service. The waiting time probability density T_w can be obtained as follows:

$$f_w(t) = (1-a)\delta(t) + \mu a(1-a) e^{-\mu(1-a)t} \quad (18)$$

$$a = A(\mu - \mu a) = e^{-T\mu(1-a)} = e^{-(1-a)/\rho} \quad (19)$$

In (19) $\rho = \lambda/\mu$ and a have a value in the range (0,1) under the condition $\rho < 1$. Taking into account the independence of T_w and T_s, the probability density function of the sojourn time T_{so} is as follows:

$$f_{so}(t) = f_w(t) * f_s(t) = \mu(1-a) e^{-\mu(1-a)t} \quad (20)$$

$$E(T_{so}) = \int_0^\infty f_{so}(t) \cdot tdt = \frac{1}{\mu(1-a)} \quad (21)$$

Equation (21) and solution a in (19) show that the average service time, consisting of the following parts: average latency and time to packet transmission, explicitly depends on $1/\mu$. If we define the change in the value of the delay time counter from i to $i-1$ as $T_{i,i-1}$, then the average delay time, defined as T_b, will change to the following form:

$$T_b = \sum_{i=0}^{W-1} \frac{i}{W} \cdot T_{i,i-1} = \sum_{i=0}^{W-1} \frac{i}{W} \left(\sigma p_I + T_r(1-p_I) \right) = \frac{W-1}{2} [\sigma p_I + (1-p_I)T_r] \quad (22)$$

where T_r – packet transmission time. As a result, the average latency $1/\mu$ is as follows:

$$\frac{1}{\mu} = \frac{W-1}{2} [\sigma p_I + (1-p_I)T_r] + T_r \quad (23)$$

If the freezing of the delay counter is not taken into account, then the probability p_I is equal to 1, the average service time:

$$\frac{1}{\mu} = \frac{\sigma(W-1)}{2} + T_r \quad (24)$$

$$T_r = \frac{L_H + L_P}{r} + DIFS + \delta \quad (25)$$

where r is the information transfer rate in the channel, δ is the propagation delay.

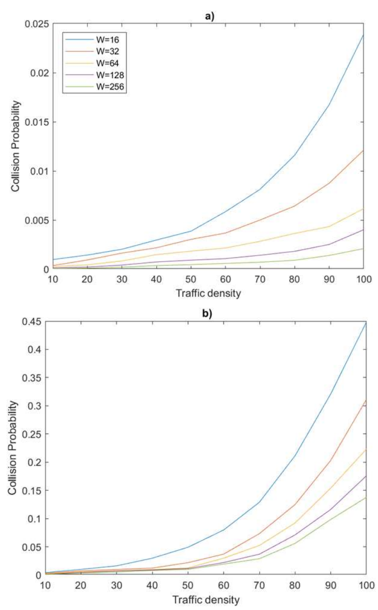


Fig. 3. The probability of a collision of periodically transmitted data in the VANET network, a) T = 0.1 seconds; b) T = 0.05 seconds

In VANET, the correct and timely reception of safety-related messages is important for vehicles, and bandwidth is important for the transmission of non-safety-related messages. Therefore, the CP (collision probability) and APD (Average Packet Delay) indicators are chosen to evaluate the safety messaging performance at the MAC layer of the VANET. The broadcast mode does not have mechanisms that increase the probability of packet loss, such as acknowledgment and retransmission mechanisms. Therefore, the expressions expressing the CP (17) and expressing the APD time (21) are very important in evaluating the broadcast of safety application data at the MAC layer. On Figure 3 shows the probability of a broadcast data collision when the vehicle broadcast periods are T = 0.1 seconds and T = 0.05 seconds. Each curve represents the results at the fitted CW values. These results show that as the number of vehicles increases, the probability of a collision increases accordingly. In addition, it can be seen that at large sizes of the CW, the probability of collision is small. This is because hosts with broadcast packets are less likely to set the same delay time when transmitting packets.

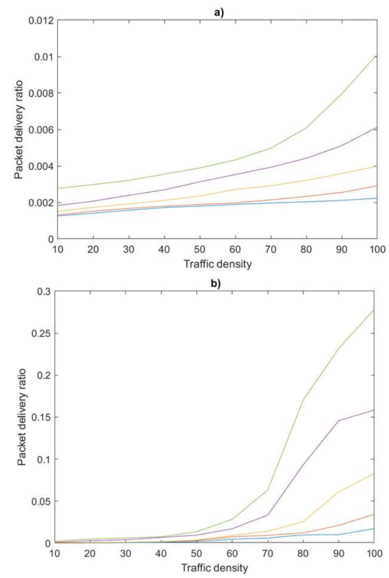


Fig. 4. The average delay of a periodically transmitted packet in the VANET network, a) T = 0.1 seconds; b) T = 0.05 seconds

On Figure 4 also shows the APD for the corresponding settings in Figure 3. According to the results, as the number of vehicles increases, the APD increases due to the increase in the delay time at each node in the broadcast. In addition, the larger the CW size, the more useful to reduce the probability of collisions, the more the APD will increase. The results shown in Figures 3 and 4 above show relatively low CP and APD for a short periodic data transmission time interval (T = 0.1 s). But as the number of vehicles increases, this shows the opposite results. In conclusion, it is possible to achieve good results in broadcast transmission based on IEEE 802.11p MAC due to long transmission time and reduction in data update time related to vehicle safety.

IV. IEEE 802.11p PHY Vehicle Connection Performance Analytical Model

The nature of vehicles requires extensive testing and evaluation. In this regard, several international scientists have proposed analytical models of vehicle communication based on the IEEE 802.11p PHY. Physical layer uses Orthogonal Frequency Multiplexing (OFDM) technology with of 10 MHz. It has data rates from 3-27 Mbps, uses 1⁄2, 2⁄3 or 3⁄4 cyclic coding for coding and QPSK, BPSK, 64-QAM or 16-QAM for modulation. IEEE 802.11p technology, like other network technologies, has the problem of packet loss. This problem can be described as follows: the signal power of the received packet is lower than the detection power (Low Signal Level - LSL), because of this the packet is lost; the receiving node is busy decoding during packet transmission (Device Busy Decoding - DBD), subsequently the packet is lost; packet loss due to insufficient Signal to Interference + Noise

Ratio (SINR), i.e. due to spread effects (Packet Loss due to noise - PLN); a packet may be lost due to other causes such as interference or packet collisions (Packet Loss due to Collisions, etc. - PLC). Other possible packet loss is referred to as PLC in the following.

If none of the above losses occur, the packet is considered to be received correctly. Based on this, the packet delivery ratio (PDR) can be expressed as follows:

$$PDR(d_{t,r}) = (1 - \delta_{\text{LSL}}(d_{t,r})) \cdot (1 - \delta_{\text{DBD}}(d_{t,r})) \cdot (1 - \delta_{\text{PLN}}(d_{t,r})) \cdot (1 - \delta_{\text{PLC}}(d_{t,r})) \quad (26)$$

where d is information; t is the transmitter; r - receiver.

Alternatively, the normalized probability of each loss type can be expressed as:

$$PDR(d_{t,r}) = 1 - \hat{\delta}_{\text{LSL}}(d_{t,r}) - \hat{\delta}_{\text{DBD}}(d_{t,r}) - \hat{\delta}_{\text{PLN}}(d_{t,r}) - \hat{\delta}_{\text{PLC}}(d_{t,r}) \quad (27)$$

here

$$\hat{\delta}_{\text{LSL}}(d_{t,r}) = \delta_{\text{LSL}}(d_{t,r}) \quad (28)$$

$$\hat{\delta}_{\text{DBD}}(d_{t,r}) = \left(1 - \delta_{\text{LSL}}(d_{t,r})\right) \cdot \delta_{\text{DBD}}(d_{t,r}) \quad (29)$$

$$\hat{\delta}_{PLN}(d_{t,r}) = \left(1 - \delta_{\text{LSL}}(d_{t,r})\right) \cdot \left(1 - \delta_{\text{DBD}}(d_{t,r})\right) \cdot \delta_{\text{PLN}}(d_{t,r}) \quad (30)$$

$$\hat{\delta}_{\text{PLC}}(d_{t,r}) = \left(1 - \delta_{\text{LSL}}(d_{t,r})\right) \cdot \left(1 - \delta_{\text{DBD}}(d_{t,r})\right) \cdot \left(1 - \delta_{\text{PLN}}(d_{t,r})\right) \cdot \delta_{\text{PLC}}(d_{t,r}) \quad (31)$$

$$0 \le \delta_{\text{LSL}}, \delta_{\text{DBD}}, \delta_{\text{PLN}}, \delta_{\text{PLC}} \le 1 \quad (32)$$

$$0 \le \hat{\delta}_{\text{LSL}} + \hat{\delta}_{\text{DBD}} + \hat{\delta}_{\text{PLN}} + \hat{\delta}_{\text{PLC}} \le 1 \quad (33)$$

According to expression (32), each loss probability is in the range from 0 to 1, the sum of the loss probabilities (33) is equal to or less than 1. The PDR in (26) is obtained by substituting the probabilities of equations (28)-(31) into equation (27). To calculate the packet delivery ratio, you first need to determine the probabilities of each type of loss between transmitter and receiver. To this end, the transmitting vehicle is designated as v_t and the receiver as v_r. Vehicle density β is a vehicle that is $1/\beta$ meter apart. Vehicles generate 1 packet/s with a power of P_t, the packets contain B bytes of payload, and are also transmitted at a DR rate.

LSL loss. This loss P_{LSL}. These losses are dependent on transmitter power, detection power limit, transmitter/receiver distance, and channel access scheme. The LSL loss probability is calculated based on the source. For this purpose, P_r is the signal power at the receiving device:

$$P_r(d_{t,r}) = P_t - PL(d_{t,r}) - SH \quad (34)$$

P_t - transmit power, $PL(d_{t,r})$ is the path loss at $d_{t,r}$, and SH – shading dispersion (σ), which is a lognormal random distribution with a modeled mean of zero. The probability that P_r is less than the detection limit P_{LSL} is:

$$\delta_{LSL}(d_{t,r}) = \int_{-\infty}^{P_{SEN}} fP_r\, d_{t,r}(p)dp \quad (35)$$

$$fP_r d_{t,r}(p) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\left(\frac{P_t - PL(d_{t,r}) - p}{\sigma\sqrt{2}}\right)^2\right) \quad (36)$$

$$\delta_{LSL}(d_{t,r}) = \frac{1}{2}\left(1 - erf\left(\frac{P_t - PL(d_{t,r}) - P_{LSL}}{\sigma\sqrt{2}}\right)\right) \quad (37)$$

DBD loss. If the received signal strength is above the detection limit, the packet can be decoded. Decoding occurs only when the receiver is not busy with this process. DBD loss occurs under the following circumstance when a packet sent by v_t is received by v_r with the required signal power, but air interface v_r is busy processing a packet sent by vehicle v_i. The DBD loss probability is defined as $\delta_{DBD}^{i}(d_{t,r}, d_{t,i}, d_{i,r})$ because when air interface v_r receives a packet sent by v_t, the packet sent by any vehicle v_i is busy reception. The probability depends on the distances from the receiver to the transmitter v_t and v_r, v_t and v_i, v_r and v_i. Vehicle v_i will not cause loss DBD is calculated from $\prod_i (1 - \delta_{RXB}^{i}(d_{t,r}, d_{t,i}, d_{i,r}))$. So the DBD loss can be calculated by taking the reciprocal of this probability:

$$\delta_{DBD}(d_{t,r}) = 1 - \prod_i (1 - \delta_{DBD}^{i}(d_{t,r}, d_{t,i}, d_{i,r})) \quad (39)$$

$$\delta_{DBD}^{i}(d_{t,r}, d_{t,i}, d_{i,r}) = p_{DBD,HT}^{i}(d_{t,i}, d_{i,r}) + p_{DBD,CT}^{i}(d_{t,r}, d_{t,i}, d_{i,r}) \quad (40)$$

$$p_{DBD,HT}^{i}(d_{t,i}, d_{i,r}) = p_{SIM,HT}(d_{t,i}) \cdot p_{DET}(d_{i,r}) \quad (41)$$

$$p_{DET}(d_{i,r}) = PSR(d_{i,r}) \quad (42)$$

$$p_{SIM,HT}(d_{t,i}) = \lambda \cdot T \cdot \frac{1 - PSR(d_{t,i})}{\Omega(d_{t,i})} \quad (43)$$

$$\Omega(d_{t,i}) = 1 - CBR \cdot R_{PSR}(d_{t,i}) \quad (44)$$

$$R_{PSR}(d_{t,i}) = \sum_{j=-\infty}^{+\infty} PSR\left(\left|\frac{j}{\beta} + d_{t,i}\right|\right) \cdot PSR\left(\left|\frac{j}{\beta}\right|\right) \quad (45)$$

$$p_{DBD,CT}^{i}(d_{t,r}, d_{t,i}, d_{i,r}) = \begin{cases} p_{SIM,CT}(d_{t,i}) \cdot p_{DET}(d_{i,r}) & if \quad d_{i,r} < d_{t,r} \\ 0 & if \quad d_{t,i} \ge d_{t,r} \end{cases} \quad (46)$$

$$p_{SIM,CT}(d_{t,i}) = \lambda \cdot \tau \cdot \frac{PSR(d_{t,i})}{\Omega(d_{t,i})} \quad (47)$$

PLN losses. A packet may be lost if the Signal to Noise Ratio (SNR) is not enough for the receiver for successful packet decoding. The occurrence of PLN loss depends on the level of PHY in the receiving device. The performance of the PHY layer is modeled using frame error rate (FER) curves as a function of E_b/N_0. These curves are obtained taking into account the time-varying multidirectional channel. The SNR at the receiver is modeled as a random value expressed in dBm:

$$SNR(d_{t,r}) = P_r(d_{t,r}) - N_0 = P_t - PL(d_{t,r}) - SH - N_0 \quad (48)$$

$$\delta_{PLN}(d_{t,r}) = \sum_{s=-\infty}^{+\infty} FER(s) \cdot f_{E_b/N_0|P_r > P_{LSL}, d_{t,r}}(s) \quad (49)$$

$$f_{E_b/N_0|P_r > P_{LSL}, d_{t,r}}(s) = \begin{cases} \frac{f_{E_b/N_0, d_{t,r}}(s)}{1 - \delta_{LSL}} & if \quad P_r > P_{LSL} \\ 0 & if \quad P_r \le P_{LSL} \end{cases} \quad (50)$$

$$\delta_{PLC}(d_{t,r}) = 1 - \prod_i (1 - \delta_{PLC}^{i}(d_{t,r}, d_{t,i}, d_{i,r})) \quad (51)$$

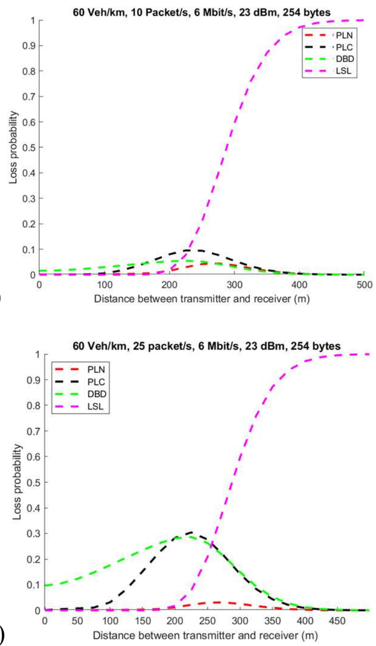
$$p_{SINR}(d_{t,r}, d_{i,r}) = \sum_{s=-\infty}^{+\infty} FER(s) \cdot f_{SINR|P_r > P_{LSL}, d_{t,r}, d_{i,r}}(s) \quad (52)$$

$$p_{INT}(d_{t,r}, d_{i,r}) = \frac{p_{SINR}(d_{t,r}, d_{i,r}) - \delta_{PLN}(d_{t,r})}{1 - \delta_{PLN}(d_{t,r})} \quad (53)$$

$$p^{i}_{PLC,CT}\left(d_{t,r}, d_{t,i}, d_{i,r}\right) = \begin{cases} p_{SIM,CT}\left(d_{t,i}\right) \cdot p_{INT}\left(d_{t,r}, d_{i,r}\right) & if \;\; d_{i,r} \geq d_{t,r} \\ 0 & if \;\; d_{i,r} < d_{t,r} \end{cases} \quad (54)$$

$p_{SIM,CT}\left(d_{t,i}\right)$ is calculated by expression (47), and $p_{INT}\left(d_{t,r}, d_{i,r}\right)$ by expression (53).

The losses discussed above are implemented below in the Matlab environment.



a)

b)

Fig. 5. Loss probability for parameters a) 6 Mbit/s and 10 packets/s; b) 6 Mbps and 25 packets/s

According to the results in Figure 5(a) obtained from the Matlab environment, with the input parameters, data rate of 6 Mbps and intensity of 10 packets/s, the loss probability starts to increase when the distance between vehicles is 200 meters. The fact that LSL loss in the figure occurs at a distance of 200 meters suggests that all other losses occur, that is, packets are lost due to insufficient signal strength. According to the results in Figure 5(b), at a burst rate of 25 packets/s, LSL loss starts to occur after 200 meters, and PLC and DBD loss begins to occur at a distance of 50-200 meters.

Conclusion

In this research paper on the packet exchange process containing road safety data, all layers from the application layer to the physical layer have been described in detail. The conducted study demonstrates the structure of road safety applications and the analytical models considered in the final part make it possible to select the optimal network parameters for such applications. Using these results in the future, it is possible to develop various data transmission algorithms for VANET networks.

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