Insights into Sidelink Resource Allocation: A Performance Study in 5G NR-V2X

Mahmoud Elsharief [1], Saifur Rahman Sabuj [2], and Han-Shin Jo [1]
[1] Department of Automotive Engineering, Hanyang University, South Korea
[2] Department of Electrical and Electronic Engineering, Brac University, Bangladesh
mahmoud@hanbat.ac.kr, s.r.sabuj@ieee.org, and hsjo23@hanyang.ac.kr

***Abstract*— In its recent release, the Third Generation Partnership Project (3GPP) has focused on sidelink resource allocation for vehicle-to-everything (V2X) autonomous mode. It assigns Mode 2 for enabling advanced driving applications in the fifth generation (5G) New Radio (NR). In this paper, we analyze the NR-V2X Mode 2 performance. Specifically, the study provides an analytical model for the average packet delivery ratio (PDR) as a function of multiple parameters, such as the number of vehicles and the probability of keeping resources. In addition, the analytical framework is validated by running extensive simulations. Furthermore, we study how altering various parameters impacts the system's performance to help improve its existing settings.**

***Index Terms*— 5G NR, 5G-V2X, NR-V2X, autonomous resource allocation, sidelink, vehicle-to-everything.**

I. INTRODUCTION

Vehicle-to-everything (V2X) communication is crucial for cooperative autonomous driving, enabling vehicles to communicate with nearby objects and navigate their surroundings. The third-generation partnership project (3GPP) has completed the final stages of the release 16 process for enhanced V2X use cases in the 5G-V2X standard [1]. Resource allocation in NR-V2X Mode 2, vehicles choose sidelink resources independently using channel sensing techniques. In Mode 2, vehicles use sensing-based semi-persistent scheduling (SPS) or dynamic schemes for independent radio resource allocation. However, SPS faces resource allocation conflicts, especially for broadcast without receiver feedback, threatening future NR-V2X networks' scalability and reliability [2][3].

Recent articles have analyzed the performance of NR-V2X elements quantitatively, focusing on PHY layer performance without investigating MAC dynamics. An open-source system-level simulator evaluates Mode 2 performance, incorporating 5G NR flexible numerology, physical layer elements, and sidelink resource allocation options [1]. The authors of [4] proposed a receiver grant-based resource allocation for the NR-V2X distributed mode, enabling the receiver to send a grant via the sidelink feedback channel. This design improved transmission reliability in collision ratio but is only used for unicasting and groupcasting.

This study presents:

- An analytical model to evaluate packet delivery ratio (PDR) in NR-V2X Mode 2 based on vehicle and resource numbers.
- The model investigates the impact of configuration parameters like vehicle density, NR numerology, and keeping resource probability on PDR. Extensive simulations are conducted to ensure the modeling's effectiveness.

II. SYSTEM MODEL AND PERFORMANCE ANALYSIS ON PDR

This study develops an analytical model of the PDR of NR-V2X in a highway scenario with multiple lanes. The vehicles are uniformly distributed, reducing the two-dimensional situation to a one-dimensional finite-line scenario. Each vehicle broadcasts λ packets per second, with a transmission power of P_t. The vehicles' location remains constant for a short time, and they have the same sensing range, d_s [5].

In NR-V2X, radio resources (RRs) extend over the time and frequency spectrum, organized in frames, subframes, and slots. The lowest time-domain resource allocation unit is a slot, denoted by τ. The subcarrier spacing (SCS) determines slot time duration, decreasing as the numerology increases. RRs are divided into three categories in the frequency domain: resource elements (REs), physical resource blocks (PRBs), and subchannels, M. A subchannel is the smallest allocation unit in the frequency domain, and the number of usable subchannels varies with SCS and PRB bandwidths. Each transmission utilizes a single time slot and one or more contiguous subchannels. The total amount of system resources used in one second is calculated using the formula $N = 1000\frac{M}{\tau\lambda}$. In NR-V2X Mode 2, a resource is chosen randomly from the remaining available resources, and resources corresponding to those subchannels are reserved at regular intervals called resource reservation intervals (RRIs). The discrete reselection counter (RC) determines the number of transmission periods before reevaluating the resource. The duration of transmission periods is equal to RRI times RC, with RC decreasing by one after a packet is sent. As soon as RC reaches zero, the resource is replaced with probability $(1-p)$, where $p \in [0, 0.8]$ [1], [2].

To develop an analytical model for PDR, let $PDR = 1 - P_c$, where P_c is the collision probability. To determine P_c, as in [6] firstly, let the probability that k out of $\mathcal{V}$ vehicles change their resources according to

$$P_r(k) = \binom{\mathcal{V}}{k}\left(\frac{1-p}{T_p}\right)^k\left(1-\frac{1-p}{T_p}\right)^{\mathcal{V}-k}, \qquad (1)$$

where T_p is equal to RRI times RC, and $\mathcal{V}$ is the average number of vehicles in a 2-hop distance of the transmitted vehicle, v_i. In the beginning, let's consider the access collision probability. When k vehicles choose to modify their resource allocations simultaneously with v_i, the probability that at least one of the k vehicles collide with v_i is given by

$$P_s(k) = 1 - \left(1 - \frac{N_R}{N_F}\right)^k. \qquad (2)$$

Here, N_R is the average amount of resources that one vehicle needs to occupy before colliding v_i. $N_F \in N$ is the number of available free resources after excluding the utilized resources, N_U. In this study, we assumed that vehicles are uniformly distributed. This

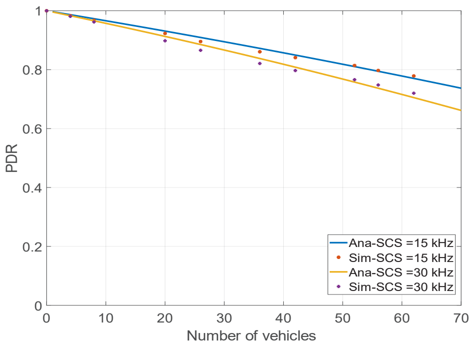

Fig. 1. PDR as a function of number of vehicles (SCS =15 and 30 kHz).

means that all vehicles have the same number of available resources. Therefore, within a region of $2\,d_s$, $N_F = N - \sum_{j=1}^{2d_s\beta} N_{Rj} v_j$.Thus, the resource selection collision probability is:

$$P_C = \sum_{k=0}^{\mathcal{V}} P_r(k) P_s(k)\,. \qquad (3)$$

Using the binomial theorem and substituting (1) and (2) into (3), The access collision probability can be obtained by

$$P_C = 1 - \left[1 - \frac{(1-p)N_R}{T_p N_F}\right]^{\mathcal{V}}. \qquad (4)$$

Then, we substitute and get the following equation that demonstrates the system PDR.

$$PDR = \left[1 - \frac{(1-p)N_R}{T_p N_F}\right]^{\mathcal{V}} \qquad (5)$$

Considering (5), to make PDR improved, p is a vital parameter to guarantee an acceptable range of the PDR and optimize the value of $\mathcal{V}$. Eq. (6) shows the relation between the $\mathcal{V}$ and the targeted PDR, PDR_t, and p. When vehicle density increases, it is recommended to choose a higher value of p to keep the PDR at the desired value. Proof; (6) is calculated by adding log(.) for both sides of (5).

$$\mathcal{V} = \frac{\log(PDR_t)}{\log\left(1 - \frac{(1-p)N_R}{T_p N_F}\right)} \qquad (6)$$

III. SIMULATION AND ANALYTICAL RESULTS

The study uses a system-level NR V2X standard-compliant simulator (5G-LENA) [7] to verify the analytical framework for NR-V2X Mode 2 and assess the impact of various variables on the system's efficiency. The scenario involves a V2X highway deployment with four lanes, a vehicle density of 50 vehicles per kilometer, and a 15 kHz SCS with 10 MHz bandwidth. Fig. 1 demonstrates the analytical model of PDR to be accurate compared to simulation results. It shows the model and simulation for different vehicle ranges, calculating the average number of vehicles using the formula $\mathcal{V} = 4d_s\beta - 1$. The PDRs produced by the suggested model agree with the simulation results, and the PDR decreases dramatically with the growing number of vehicles. In addition, Fig. 1 shows that PDR is slightly improved using 15 kHz SCS compared to 30 kHz SCS. This is due to the unique combination of subchannel availability and slot durations. With a packet size of 300 bytes, 15 kHz numerology offers maximum flexibility in the frequency domain. Moreover, to demonstrate the relationship between vehicle density and p, we have fixed the PDR to 0.9. As shown in Fig. 2, a higher value of p is recommended to maintain quality service for more vehicles.

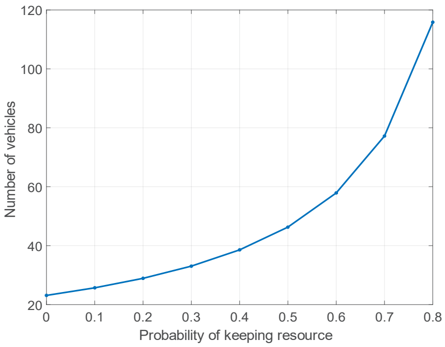

Fig. 2. Number of vehicles as function of keeping resource probability.

IV. CONCLUSION

This paper analyzes resource allocation performance in NR-V2X Mode 2 and presents an analytical model for the system's PDR. Validated with various traffic volumes and configuration parameters, the results show that PDR decreases with increased vehicle or resource numbers while it grows with consistent resource usage. Additionally, the proposed analytical framework has potential future extensions for application in vehicle edge and cloud computing. It offers insights for optimizing resource allocation and communication between vehicles and edge/cloud servers, considering factors like latency, communication overhead, and energy efficiency.

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