On the Reliability and Concurrent Unicast Transmission Node Control of 5G NR-V2X Networks

Ke Li*, Li Li*, Wenpeng Wu*, Xueyan Tang† and Pingzhi Fan*

*Provincial Key Lab of Information Coding & Transmission, Southwest Jiaotong University - Chengdu, China
†School of Computer Science and Engineering, Nanyang Technological University
Email: {keli@swjtu.edu.cn, 253194072@qq.com, vyps@my.swjtu.edu.cn, asxytang@ntu.edu.sg, pzfan@swjtu.edu.cn}

Abstract—In vehicle-to-everything (V2X) communications, reliability is one of the most important performance metrics in safety-critical applications such as advanced driving, remote driving, and vehicle platooning. In this paper, the link reliability of unicast concurrent transmission in mode 1 (centralized mode) of 5G New Radio based V2X (NR-V2X) is analyzed. The closed-form expression of link reliability for concurrent unicast transmission is firstly derived for a highway scenario under a given interference distance distribution. On this basis, according to the macroscopic configuration of the system, a method to control the number of concurrent transmission nodes is proposed, including the communication range, message packet size, and the number of lanes, etc. The results indicate that the proposed method can maximize the system load on the premise of satisfying the link reliability requirements.

Index Terms—Vehicle-to-vehicle communication, New Radio (NR), Reliability, Concurrent unicast transmission.

I. INTRODUCTION

Vehicle-to-Everything (V2X) communication is considered to be an essential basis for achieving road safety, traffic efficiency, and advanced V2X applications such as advanced driving, remote driving, and vehicle platooning [1]. To meet the QoS requirements of these applications, New Radio based V2X (NR-V2X) is proposed by 3GPP [2], which is expected to saliently improve the reliability.

Furthermore, reliability can be measured by packet reception ratio (PRR) [3] or outage probability [4]. Based on these two performance metrics, the existing works for reliability analysis mainly focus on broadcast scenarios with different communication technologies such as IEEE 802.11p [5], D2D based V2X [6], or Cellular based V2X (LTE-V2X) [7]. More specifically, the hidden terminal problem with IEEE 802.11p [5] and the collision problem caused by concurrent transmissions with LTE-D2D [6] or LTE-V2X [7] are highlighted. To overcome the hidden terminal problem, W. Benhaïem et al. [5] introduced the reliability metric PRR and designed a scheme to optimize the number of retransmissions of the emergency messages. Besides, resource allocation optimization is another way to improve reliability [6], [7]. The work in [6] proposed a resource allocation scheme to reduce interference caused by concurrent transmissions among vehicle user equipments(VUEs). Furthermore, the work in [7] presented a way to control the size of resources in the LTE-V2V system. However, there is a lack of link reliability analysis method for NR-V2X networks.

In particular, the NR-V2X networks should also support unicast communication mode, which is different from the broadcast mode in 802.11p and LTE networks. Compared with broadcast communication mode, unicast communication is generally considered to be more reliable. In fact, the link reliability of unicast communication is also a problem for a given time-spectrum resources in which the nodes are allowed for concurrent transmission.

In Figure 1, an NR-V2X network has a cellular infrastructure gNodeB. Three pairs of vehicle transmitter (VUE-TX) and vehicle receiver (VUE-RX) are assigned to the same resource block (RB) by the gNodeB in a highway scenario. In this case, the concurrent transmissions of VUE-TX2 and VUE-TX3 will be the left-hand and the right-hand interferers of the VUE-RX1, respectively. They will result in unreliable message transmissions of the VUE-TX1. It is noticeable that the interferences among Vehicle-to-Vehicle (V2V) pairs still exist even in the unicast concurrent transmission.

In light of the above considerations, the following two questions will be answered in this paper: i) What are the means of quantitative analysis of link reliability for concurrent unicast transmission of NR-V2X Mode 1? ii) Can the reliability of the unicast transmission system be also improved through effective resource allocation? The main contributions of this paper are summarized as follows:

- The closed-form expression of link reliability is obtained on the condition of assuming a Poisson distribution of
arrival VUEs per unit distance. Based on this expression, the relation between the link reliability and the number of concurrent transmission nodes of the system is analyzed.

- The problem of maximizing the number of concurrent transmission nodes (MNCTN) with given the reliability requirements is also proposed, which is formulated as a mathematical programming model and solved by iterative algorithm.

The remainder of this paper is organized as follows. Section II introduces the system model of NR-V2X. Section III formulates the optimization problem and proposes an algorithm to solve it. Section IV presents parameters setting and numerical results, respectively. Section V concludes the paper.

II. SYSTEM MODEL

Under the condition of given NR-V2V resources, the link reliability of concurrent unicast transmission is analyzed. Furthermore, assuming that the disturbance distance obeys a certain distribution, the closed-form expression of link reliability is obtained.

A. NR-V2X Communication

In NR-V2X centralized Mode 1, the gNodeB manages the radio resources and selects vehicles for granting their direct V2V communications within gNodeB’s coverage. All VUEs operated in the NR Mode 1 move on an S lanes and L meters long road.

Assume that $N_{RB}^T$ RBs transmit messages in a subframe (1 ms). So the total available number of RBs in the system is $N = N_{RB}^T \times t_{Tx}$, where $t_{Tx}$ represents the entire transmission duration. A RB contains 14 symbols, then each symbol contains 12 subcarriers, so the number of resource element (REs) in a RB is $12 \times 14 = 168$. Since 16 REs are used for carrying a high density demodulation reference signal (DMRS) owing to the fast-changing channel conditions [8]. The residual number of REs in a RB available for data transmission, namely $N_{RE}$, is reduced to 152. Moreover, it is assumed that each VUE uses a fixed number of bytes to send a message. For a given message size of $N_m$ bytes, the number of RBs $N_{RB}$ [9] is given by:

$$N_{RB} = \left\lfloor \frac{8N_m}{N_{RE} \times n_{pm}} \right\rfloor \quad (1)$$

where $n_{pm}$ is the spectral efficiency of a given MCS and can be obtained from [9]; $\lfloor \cdot \rfloor$ is a ceiling operator.

Furthermore, there are $N_R = k$ available resources for VUEs denoted as $R_1, R_2, \cdots, R_k$. In this case, Eq. (3) is obtained.

$$N_R = \left\lfloor \frac{N}{N_{RB}} \right\rfloor \quad (2)$$

where $\lfloor \cdot \rfloor$ is a flooring operator.

B. Link Reliability

As for the same resource $R_k$, a set of vehicles $J_k$ are assigned to it. In this case, the received signal to interference and noise ratio (SINR) of the VUE–RX, can be written as:

$$\gamma = \frac{PG_r \beta d_i^{-\alpha} g_0}{\sum_{j \in J_k, i \neq j} PG_r \beta d_j^{-\alpha} g_j + N_0} \quad (3)$$

where $P$ is the transmit power of vehicle node; $G_r$ is the antenna gain at the VUE–RX, $\alpha$ is the pathloss exponent; $\beta$ is the pathloss at one meter; $d_i$ and $d_j$ are the distance between VUE-TX and VUE-RX, as well as the $j$-th VUE of resource reuse and VUE–RX, respectively. $g_0$ and $g_j$ are channel gain from VUE–TX and the $j$-th interfering VUE to the VUE-RX, respectively; $N_0$ is the received power of the additive white Gaussian noise.

In [6] and [7], link reliability is equivalently transformed into a constraint of signal-to-interference-noise-ratio (SINR), and the SINR should exceed a given threshold. In essence, if the total number of error-free bits is larger than V2V message, i.e., $8N_m$, it is regarded as a successful transmission of the $N_m$ size message between the transmitter and the receiver. The probability of this successful transmission $p_r$ is given by:

$$p_r = \Pr [\rho \log_2 (1 + \gamma) > 8N_m] \quad (4)$$

where $\rho = N_{RB} \times N_{RE}$ is the number of available resources.

Furthermore, (4) can also be transformed into the form that the value of SINR is larger than the thread $T = 2^{\frac{8N_m}{\rho}} - 1$, i.e.,

$$p_r = \Pr \left[ \frac{PG_r \beta d_i^{-\alpha} g_0}{\sum_{j \in J_k, i \neq j} PG_r \beta d_j^{-\alpha} g_j + N_0} > 2^{\frac{8N_m}{\rho}} - 1 \right] \quad (5)$$

For the sake of analytical simplicity, link reliability expression is reformulated according to the following two assumptions: First, the communication range of each VUE is limited to the $s$-th VUE power, namely $N_{RE}$, $j$-th VUE as well as the $s$-th VUE are almost all of the aggregate interferences in the highway scenario. As for the link-level interferences, concurrent unicast transmission has the same interference pattern as that of broadcast transmission as demonstrated in Figure 1. Accordingly, the $p_r$ in Eq.(5) can be re-written as:

$$p_r = \Pr \left[ \gamma > T \right] \approx \Pr \left[ \frac{PG_r \beta d_i^{-\alpha} g_0}{\sum_{j=1}^{S} PG_r \beta d_j^{-\alpha} g_j + N_0} > T \right] \quad (6)$$

It is assumed that the variable $g_0$, $g_1$ and $g_2$ follow independent exponential distribution with mean value of unity. The link reliability could be described as double integrations expression, which is given by the following theorem.
In a highway scenario, the link reliability performance for the centralized Mode 1 of NR-V2V with concurrent unicast transmission can be expressed as

\[
p_r = \Pr[\gamma > T] 
= \int_0^\infty \int_0^\infty \lambda e^{-\lambda s} g(x) f_{d_1}(x) f_{d_2}(y) \, dx \, dy
\]

where \( f_{d_1}(x) \) and \( f_{d_2}(y) \) are the PDFs of the distances from the left hand side interferer or the right hand side interferer to the receiver, respectively.

C. Analysis of Transmission Nodes \( \xi \)

It is assumed that the random arrival of VUEs within one kilometer obeys Poisson distribution, and its mean is \( \xi = \lambda \times S \), where \( \lambda \) denotes the density of VUEs per unit distance from one lane, \( S \) is the number of lanes, and \( \xi \) is the number of concurrent transmitting VUEs per unit distance. The distance intervals between arrival VUEs follows an Exponential distribution with a mean of \( \frac{\xi}{\lambda} \). Furthermore, the average interference distance from left hand side is \( E[d_1] = \frac{N_R}{\xi} + d_c \); Similarly, from the right hand side is \( E[d_1] = \frac{N_R}{\xi} - d_c \). By replacing the expectation over the entire term with the expectation over each component of \( d_1 \) and \( d_2 \) in the Eq. (7). Finally, a closed-form expression of \( p_r \), is shown in Eq.(8).

\[
p_r = g(\xi) = \frac{d_c^{-2\alpha} \exp\left(-\frac{N_R T_{d_c}^\alpha}{P_{Gr} d_c}\right)}{(d_c^{\alpha} + AT)(d_c^{\alpha} + BT)}
\]

where \( A = \left(\frac{N_R}{\xi} + d_c\right)^{-\alpha} \), \( B = \left(\frac{N_R}{\xi} - d_c\right)^{-\alpha} \). If \( x \geq 0, [x]^+ = x \); otherwise, \( [x]^+ = 0 \).

Therefore, the link reliability \( p_r \) can be characterized by the function \( g(\xi) \) with parameter \( \xi \).

III. PROBLEM FORMULATION AND ALGORITHM

In light of the relation between link reliability \( p_r \) and VUEs density per unit distance \( \xi \), the number of concurrent transmission nodes \( \varphi \) can be easily controlled by unicast communication method in NR-V2X mode 1. We attempt to maximize the number of concurrent transmission nodes (MNCTN) on the condition of satisfying the reliability requirement \( p_r^* \). Accordingly, this optimization problem of MNCTN can be formulated as:

\[
\begin{align*}
\text{Maximize} & \quad E(\varphi) \\
\text{subject to} & \quad g(\xi) \geq p_r^* \\
\varphi & = L \times \xi \quad \varphi, \xi \in N^+
\end{align*}
\]

Because of the complexity of Eq. (11), the exhaustive search method is adopted to find the value of \( \xi \) satisfying the requirement of reliability. The procedure of obtaining the objective value \( \varphi \) is also given in Iterative Algorithm 1. The gNodeB is assumed to have the computing capability to decide the number of concurrent transmission nodes \( \varphi \). The proposed method consists of three steps. First, the gNodeB estimated system parameters such as transmission power \( P \) and noise power \( N_0 \). Second, the gNodeB computes \( \varphi \) by Algorithm 1. Third, the gNodeB reports to the associated VUEs.

Algorithm 1: Procedure for Obtaining \( \varphi \) in the Proposed MNCTN for the Centralized Mode 1 of NR-V2V.

**Input:** message size \( N_m \), transmission time \( t_{Tx} \), communication range \( d_c \), transmission power \( P \), antenna gain \( G_r \), total number of RBs in one subframe \( N_{RB} \), spectral efficiency \( n_{pm} \), pathloss exponent \( \alpha \), pathloss at one kilometer \( \beta \), noise power \( N_0 \), number of lanes \( S \), length of lane \( L \).

**Output:** maximal number of concurrent transmission nodes \( \varphi \).

1. Initialize \( \lambda = 0, p_r = 0, \xi = \lambda \times S \);
2. while \( p_r < p_r^* \) do
   3. \( \lambda += 1 \);
   4. \( \xi = \lambda \times S \);
   5. \( p_r = \text{ReliabilityCompute}(\xi); \quad // \text{Eq. (8)}; \)
6. \( \varphi \leftarrow L \times \xi; \)
7. return \( \varphi \).

IV. NUMERICAL RESULTS

In this paper, python 3.5 is used to program and model the centralized mode in NR-V2X networks. Table I lists the parameters used in this paper [8].

According to the relations between reliability requirements and concurrent transmission vehicles, Table II illustrates the number of concurrent transmission vehicles \( \varphi \) with different reliability requirements \( p_r^* \). The shorter the length \( L \), the fewer vehicles are allowed to be sent messages. For the same length \( L \), the larger link reliability requirements \( p_r^* \), and the lower the number of concurrent transmission vehicles \( \varphi \). Moreover, with the increase of link reliability requirements \( p_r^* \), more and more vehicles fail to send messages, which will cause interference within this distance. For example, under the condition of \( L = 50km \), as the requirement of link reliability increases from \( p_r^* = 0.8 \) to \( p_r^* = 0.95 \), the number of concurrent transmission vehicles decreases by 966, 1,241, and 1,840, respectively. When \( p_r^* \) is increased to 0.99, the number of concurrent transmission vehicles is declined by 3,702.

Furthermore, Fig. 2 illustrates that the number of concurrent vehicles changes with the received message sizes \( N_{rm} \) of the VUEs \( (d_c = 500m \text{ and } t_{Tx} = 100ms) \). The received message sizes \( N_{rm} \) can be calculated using the formula \( p_r^* \times N_m \). On one hand, provided that the resources are determined, more vehicles can be accommodated for message transmission, thus...
TABLE I: System default parameters

| Parameters                        | Value     |
|----------------------------------|-----------|
| Number of RBs per subframe $N^T_{RB}$ | 50 [RBs] |
| Message transmission time $t_{TX}$ | 100 [ms]  |
| V2V message size $N_m$            | 300 [bytes] |
| Communication range $d_c$         | 500 [m]   |
| Pathloss exponent $\alpha$        | 2.75      |
| Pathloss at 1m $\beta$            | -47.86 [dB] |
| Transmission power $P$             | 23 [dBm]  |
| Antenna gain at the receiver $G_r$| 3 [dBm]   |
| Spectral efficiency $n_{om}$       | 1.03      |
| Received power of additive white Gaussian noise $N_0$ | -104 [dBm] |
| Number of lanes $S$               | 3         |

TABLE II: Number of concurrent transmission vehicles $\varphi$ with different reliability requirements $p^*_r$

| $L$ (km) | $p^*_r = 0.99$ | $p^*_r = 0.95$ | $p^*_r = 0.9$  | $p^*_r = 0.85$ | $p^*_r = 0.80$ |
|----------|----------------|----------------|----------------|----------------|----------------|
| 10       | 716            | 1456           | 1832           | 2080           | 2274           |
| 30       | 2148           | 4370           | 5497           | 6242           | 6822           |
| 50       | 3581           | 7283           | 9163           | 10404          | 11370          |

reducing the possibility of conflict in the information transmission process, while the reliability is improved. However, when the number of vehicles reaches a certain level, the number of messages received by each vehicle decreases rapidly. On the other hand, the larger the size of a single message $N_m$, the more resources need to be allocated to each vehicle. In this case, even one additional vehicle that will be allowed to send messages may result in a great impact on the system reliability, and the curve will be steep.

Similarly, Fig. 3 indicates that the longer the message transmission duration, the more resources can be allocated to the vehicles. Thus, under the same reliability condition, the shorter the transmission time, the fewer vehicles can send messages simultaneously.

In general, the reliability describes the link performance between two VUEs, which is normally difficult to obtain. Thus, concurrent transmission nodes control over the V2V network can be used as enhancement means to guarantee link reliability from the perspective of system. Based on these findings, several research topics will be addressed, including the design of reliable V2V messaging schemes, measurement of link reliability in real NT-V2X systems, and in-depth simultaneously optimization of reliability and delay performance.

V. CONCLUSION

The performance of reliability is a crucial performance metric for applications in 5G NR-V2X vehicular networks. This paper analyzes the interference pattern of concurrent unicast transmission with centralized mode of NR-V2X (Mode 1) in highway vehicular networks, and obtains the closed form expression of link reliability under the condition of Possion distribution of arrival vehicle nodes per unit distance. Moreover, this paper presents an optimization problem for maximizing the number of concurrent transmission nodes (MNCTN) and formulates the problem of MNCTN as a mathematical programming model with the constraints of the NR-V2X network’s requirements regarding link reliability, which can be solved by iterative algorithm.

ACKNOWLEDGMENT

This work was supported by NSFC Project (No.61731017), and 111 project (No.111-2-14).

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