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Power Control and Fuzzy Pairing in V2X Communications

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***Abstract*—In this paper, a joint power control, and pairing-based resource allocation problem in the vehicle-to-everything (V2X) network is studied. This V2X network consists of a vehicle-to-infrastructure (V2I) link and a vehicle-to-vehicle (V2V) link. Therefore, the resource allocation problem has been formulated with the objective function of maximizing the V2I link's rate with the constraints of quality of service (QoS). Due to its NP hard nature, the original resource allocation problem is divided into two sub-problems of power control and pairing. The power control sub-problem is transformed into a convex problem using an exponential variable change. A fuzzy decision-making method is exploited to solve the pairing sub-problem to have a highly reliable and stable V2V link. Then, the proposed joint power control and pairing based resource allocation technique is evaluated with a simulated highway and compared with similar pairing algorithms. These performance comparisons reveal that the stability of the proposed resource allocation technique outperforms the other related methods.**

***Index Terms*—V2X Communications, Resource allocation, Decision Making, Fuzzy Probability.**

I. INTRODUCTION

VEHICULAR communications have recently gained significant attention from industry and academia. The different types of communications in vehicular communications are collectively defined as vehicle-to-everything (V2X) communications. They include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N). The primary focus of the vehicular network is to offer safety-critical applications, i.e., applications to avoid accidents and bring road safety. Another objective of them is to provide the infotainment services such as online video gaming and live-streaming for vehicle passengers [1]–[3]. Moreover, V2X communication plays a crucial role in the development of autonomous driving [1], [4].

V2X network relies on two critical technologies: dedicated short-range communications (DSRC), and cellular vehicular-to-everything (C-V2X) communications. DSRC equivalent technology is already employed in Europe in intelligent transport systems (ITS), which is initiated with IEEE 802.11p standard [5]. Although DSRC has its benefits, e.g. low end-to-end latency, some issues, such as short-range, large channel access delay, and low network coverage area still need to be investigated [6]. The 3rd Generation Partnership Project (3GPP) has already started to develop the cellular standards for vehicular communications, first with long-term evolution (LTE), and then 5G/6G cellular networks [7]. The key aims of these studies are to achieve high reliability, low latency communications, and highly efficient V2X connections in the vehicular network [8]. The V2X service was standardized in Rel-14 and Rel-15 of 3GPP, where the four modes for resource allocation in device-to-device (D2D) communications were considered in LTE. In these releases, modes 3 and 4 were assumed for V2X communications. Due to the necessity of higher reliability, and lower latency, the new radio (NR) V2X Rel-16 is studied in [9]. Novel use cases of NR-V2X Rel-16 including autonomous driving and advanced driving in [10] are introduced.

A. Related Works

Resource allocation in vehicular communications is one of the key challenges which needs to be carefully addressed [8]. High channel capacity, reliability, and latency of V2X links are the stringent requirements to realize vehicular communications. In order to guarantee the highlighted network quality of service (QoS), various algorithms and scenarios are proposed. An approach to maximize both the sum and the minimum ergodic capacities of V2I connections is proposed in [11]. In [12] for the reliability safeguard of V2V connections, an outage probability based on SINR approach is presented. Accordingly, the optimization problem is divided into two parts: First, under some of the QoS constraints the power allocation problem is solved, then the resource allocation is addressed through different algorithms. Then for maximizing the sum throughput of V2I links, a centralized deep reinforcement learning (DRL) is developed.

Resource allocation problems can be categorized in literature into two main parts, centralized and distributed resource allocation [8]. While in vehicular communications these are introduced as mode 3 and mode 4, respectively [8]. In other words, although both modes support direct V2V connections, they are different in centralized or decentralized resource allocation. Mode 3 considers a centralized point of

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view. In other words, the resource blocks (RBs) selections are under the control of evolved node base station (eNB). This mode can be under the overlay and/or underlay scenarios of D2D communications [13], [14]. The work in [3] proposed a centralized mode where the V2V pairs reuse the cellular network resources. Then, in order to solve the NP-hard problem, a heuristic algorithm named cluster-based resource block sharing and power allocation (CROWN) is suggested.

In mode 4, the radio resource management (RRM) of side-link channels (i.e. V2V communications) is formed independently. As a consequence, each V2V chooses its RB in a distributed manner whether under the cellular coverage bandwidth or with a non-cellular RB [13]. To derive a robust model, a two-timescale federated DRL algorithm based on mode 4 is suggested [12]. The work in [15] considers a mode 4 based on C-V2X communications. To decrease the packet collisions, resource scheduling based on short-term sensing is suggested. The authors in [14] propose a mode selection for vehicle users between mode 3 and mode 4. It is attempted to solve the power control and resource allocation problems under a light and heavily loaded network. For the light loaded, Vacant Resource Blocks and Power Allocation algorithm are suggested. Under the assumption of the heavily loaded network, Occupied Resource Blocks and Power Allocation algorithm are presented. In [16] to satisfy the latency constraint while minimizing the interference between V2V and V2I links is suggested. In this work, a decentralized resource and power level allocation with deep reinforcement learning is proposed.

Another critical technology that has shown significant improvement in resource allocation problems for V2X communications is D2D communications [17]. Therefore, to increase the network throughput, reliability, energy efficiency, and reduce latency, different methods such as resource allocation management, power control, and mode selection in D2D-based V2X networks are vastly explored [3], [11]–[14], [17]–[19]. Hence, in [17] a resource allocation based on D2D technology with slow fading statistics of channel state information (CSI) is considered. With assumption of an underlay scenario, a graph-based cluster is suggested to avoid high possible V2V interfering links. The problem is reformulated with a weighted 3-D matching problem and solved with different algorithms. Authors in [19] with assumption of preassigned V2I sub-bands tried to solve sub-bands allocation, and power allocation problems with joint-DRL.

Other challenges such as user pairing and fuzzy-based routing in D2D communications are discussed in [20], [21]. An optimal pairing selection based on a fuzzy method in D2D communications is proposed [20]. The fuzzy degree is defined based on the received signal-to-interference-plus-noise-ratio (SINR), and potential D2D transmitter nodes' battery levels. In [22] a joint user pairing and power allocation problem with a factor-graphs method in a D2D-underlay cellular network is solved. In [18], not only a mode selection to choose the D2D or cellular users is proposed but also a pairing selection based on the nearest neighbor for D2D communications is applied. In order to address these challenges, an analytical framework based on stochastic geometry is propounded. A neighbor discovery algorithm determined from a side-link interface is suggested under the underlay case study [23]. To discover adjacent vehicles, authors in [24] considered the status information such as speed, location, and driving direction attempted based on the cooperative awareness messages (CAM). Therefore, in V2X communications despite the attention to user discovery, the user pairing needs more attention.

User pairing in a D2D-based V2X network can be selected randomly, with the nearest transmitter, or with different criteria such as maximizing the total network throughput [18], [22], [25]. In this paper, we aim to select the transmitter of the V2V receiver with respect to a stability factor. By stability factor, we mean a parameter that determines the level of maintenance of a communication connection after its formation. Therefore, another issue in a vehicular network is having a stable connection between users in each time slot. For instance, Alnasser et al. [26] suggest several constraints for selecting a D2D node as a relay node in V2X communications. Furthermore, for selecting the relaying node, three different QoS constraints, capacity, link stability, and end-to-end delay are proposed. The link stability concept as the duration of each connection lasts between two nodes is described, which is calculated by two variables; acceleration and direction. In [27] regarding a D2D-relay network, a new user pairing based on stability is suggested. Instead of only considering the network performance in choosing pairs, what is proposed is a novel metric for the calculation of link stability. Hence, the receivers select the transmitters with a high stability metric.

In vehicular networks due to high-speed vehicles, environmental fluctuations are inevitable. Therefore, some studies have investigated bringing stability using fuzzy logic [28]–[30]. Fan et al. [28] with the aim of solving the environment dynamics problem, identify a mapped fuzzy space where the CSI is interpreted as fuzzy numbers. Then, the optimization problem for joint time-frequency allocation is defined with a two-side many-to-many fuzzy matching game (MM-FMG). Therefore, to solve it the dynamic fuzzy matching learning (DFML) algorithm is applied. In the following two papers [29], [30], for user clustering, novel fuzzy logic schemes are presented. Authors in [29] suggest a new fuzzy logic approach to address several QoS constraints encompassing scalability, stability, and efficient spectrum allocation to choose cluster heads in the proposed scenario. While the latter [30], a fuzzy cluster head selection for issues like security, stability, and reliability in a cognitive radio (CR) VANET system is investigated.

To the best of our knowledge, this paper is the first attempt to solve V2V pairing with a proposed fuzzy method-based stability factor. Here, V2V pairing means considering more than one transmitter for a typical V2V receiver with the assumption that all the transmitters have the requested information. Usually, in literature, it is assumed that the V2V receiver chooses its transmitter randomly or based on the nearest distance. While in this paper we try to select the transmitter based on stability factor. We propose a joint pairing and power control problem in a V2X network in a freeway case study using the Rel-14 of the 3GPP standard. The V2X communications include V2I and V2V pairs, where mode 3 with an underlay scenario is suggested. Also, mode 4 is applicable in this scenario. We study the power control problem for efficient energy consumption in the network. In a V2X network with the assumption of safety-critical applications, having reliable connections is a necessity. We apply this constraint with the outage probability of the received SINR. The main goals of this paper are maximization of V2I throughput and satisfaction of the QoS of V2X links including stability and reliability. Therefore, for the problem formulation, a maximization of V2I throughput is proposed which is an NP-hard optimization problem. Therefore, the problem is decoupled into two steps. In the first step, for power control, a numerical approach is suggested with converting the problem to a convex optimization one. Then, in the second step, for pairing selection, a stability factor is modeled based on a fuzzy membership function. Hence in order to select the more stable and reliable V2V transmitter, two independent network factors including V2V velocity differences and reliability are considered. After the calculation of the fuzzy membership function, a maximum value of the decision-making function is selected. Therefore, with the fuzzy application, we could derive the network parameters straightforwardly.

B. Contributions

The main contributions of this paper are as follows:

- We model a highway with only one V2V and one V2I pair, while the V2V link reuses the V2I RB. In other words, it is an underlay scenario. For the V2V receiver, several transmitters are considered. Hence, we attempt to solve joint pairing (selection of the best transmitter for the V2V connection) and power allocation problems in the modeled network.
- We formulate the problem based on optimizing the V2I throughput, guaranteeing the V2X QoS, and V2V reliability criterion as well as the V2X power control bounds.
- We divide the NP-hard optimization problem into two sub-problems. First, we derive the power of each V2X transmitter regarding converting the non-convex optimization problem to a convex one. Second, we investigate V2V pairing based on a stability factor in vehicular communications.
- We propose a fuzzy based stability factor for the V2V link. Therefore, we consider the V2V receiver and the V2V transmitters velocity difference and the reliability constraint for it. Finally, we employ a stability-based decision-making function to select the most stable V2V transmitter.

C. Paper Organization

The rest of this paper is organized as follows. Section II presents the considered V2X scenario and formulates the joint power control and fuzzy pairing problem. Then, Section III proposes the power allocation scheme. Section IV introduces the concepts of fuzzy pairing and stability-based decision-making. Section V evaluates the performance of the proposed algorithms in the considered scenarios. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

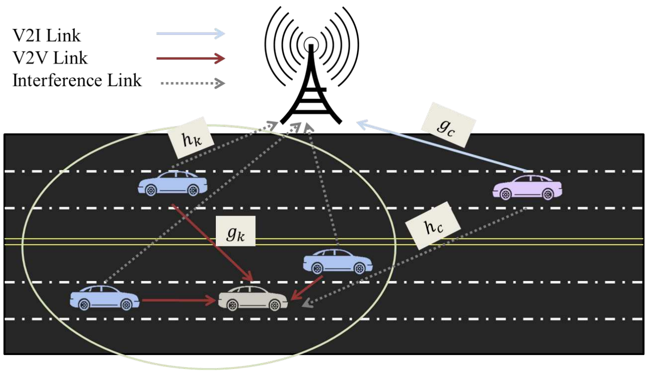

Fig. 1. A freeway case

As shown in Fig. 1, a freeway case study with one eNB, one V2I user (CUE), one V2V receiver (RUE), and multi-V2V transmitters (TUE) is assumed so that the uplink connections are shared. Moreover, the exact RB of CUE is shared in underlay mode with RUE and TUEs. It is assumed that several TUEs are equipped with the presumption of having the requested information of RUE. The notations are summarized in TABLE I.

TABLE I
NOTATION SUMMARY

Notation	**Description**
P_c	The CUE transmitted power
P_k	The k^{th} TUE transmitted power
g_c, h_c	The CUE-BS and CUE-RUE channels
g_k, h_k	The k^{th} TUE-RUE and TUE-BS channels
$a_c, \hat{a}_c$	The CUE small-scale fading and the interfered one
$a_k, \hat{a}_k$	The k^{th} TUE small-scale fading and the interfered one
$q_c, \hat{q}_c$	The CUE large-scale fading and the interfered one
$q_k, \hat{q}_k$	The k^{th} TUE large scale fading and the interfered one
σ^2	The Noise power
ρ_k	The pairing variable of k^{th} TUE
γ_c, γ_k	The SINR of V2I and k^{th} V2V connections
R_{th}	Threshold rate of V2I connection
$\gamma_{th}, \hat{\gamma}_{th}$	Threshold SINR of V2I and V2V connections
$\hat{R}_{th}$	Threshold rate of V2V connection
$\Pr_{\text{out}}$	The outage probability of V2V connection
P_o	The minimum probability to fulfill the V2V reliability
$P_{c(\max)}$	The maximum transmit power of CUE
$P_{\max}$	The maximum transmit power of TUE
Pr_{th}	The outage probability threshold
V_r	The velocity of RUE
V_k	The velocity of TUE

According to the above system model, the SINR of V2I and V2V channels are defined, respectively, as follows.

$$\gamma_c = \frac{P_c \ g_c}{\sigma^2 + \sum_{k=1}^{K} \rho_k P_k h_k}, \tag{1}$$

$$\gamma_k = \frac{P_k \ g_k}{\sigma^2 + P_c \ h_c}, \tag{2}$$

where $k \in \mathcal{K} = \{1, 2, ..., K\}$, and K is the number of available TUEs for a typical RUE. Note that a typical channel h can be formulated as $h = q \ a$, where q models the large-scale fading encompassed path loss and shadowing, and a is the small-scale fading assumed to be exponentially distributed with unit mean. In addition, the pairing variable ρ_k is formulated as follows.

$$\rho_k = \begin{cases} 1; & \text{if } k^{th} \text{ TUEs is paired,} \\ 0; & \text{Otherwise.} \end{cases} \tag{3}$$

A. Problem Formulation

In this section, the problem which is maximizing the V2I throughput, and satisfying the QoS of the V2X connections are formulated as follows.

$$\begin{aligned} \underset{\rho_k, P_k, P_c}{\text{maximize}} \quad & \log_2(1+\gamma_c) && \text{(4a)} \\ \text{subject to} \quad & \sum_{k\in\mathcal{K}} \rho_k \leq 1, \forall k \in \mathcal{K}, && \text{(4b)} \\ & \rho_k, \in \{0,1\}, \forall k \in \mathcal{K}, && \text{(4c)} \\ & \log_2(1+\gamma_c) \geq R_{th}, && \text{(4d)} \\ & \log_2(1+\gamma_k) \geq \hat{R}_{th}, \forall k \in \mathcal{K}, && \text{(4e)} \\ & 0 \leq P_k \leq P_{\max}, \forall k \in \mathcal{K}, && \text{(4f)} \\ & 0 \leq P_c \leq P_{c(\max)}, && \text{(4g)} \end{aligned}$$

We assume that the RUE could be connected only with one TUE. The constraints (4b) and (4c) are related to the pairing variable. Moreover, the quality of service (QoS) of the V2I and V2V pairs are indicated by equations (4d) and (4e), respectively. The constraints (4f) and (4g) ensure the power limitations of k^{th} TUE and CUE, respectively. This optimization problem is NP-hard as it is a mixed integer non-linear programming (MINLP). Therefore, we would solve it with the proposed sub-optimum algorithm in the next section.

In the following, instead of solving the mentioned NP-hard optimization problem, we aim to transform the main problem into two sub-problems. The first sub-problem is the power allocation of V2I and V2V users with the QoS and power constraints, and the second one is the fuzzy pairing of TUEs with their related RUE, regarding reliability and stability constraints.

III. POWER ALLOCATION

The power allocation sub-problem is formulated as follows.

$$\begin{aligned} \underset{P_c, P_k}{\text{maximize}} \quad & \log_2(1+\gamma_c) && \text{(5a)} \\ \text{subject to} \quad & \log_2(1+\gamma_c) \geq \gamma_{th}, && \text{(5b)} \\ & \log_2(1+\gamma_k) \geq \hat{\gamma}_{th}, \forall k \in \mathcal{K}, && \text{(5c)} \\ & 0 \leq P_k \leq P_{\max}, \forall k \in \mathcal{K}, && \text{(5d)} \\ & 0 \leq P_c \leq P_{c(\max)}. && \text{(5e)} \end{aligned}$$

Therefore, for each CUE and all possible TUEs we calculate their powers, since we need their power transmitters for the next step. To solve this problem, as it is still non-convex, a sub-optimum algorithm is proposed. For $\gamma, \gamma_k \gg 1$, the objective and constraints could be rewritten as,

$$\log_2(\gamma_c) \gg 1, \tag{6}$$

$$\log_2(\gamma_k) \gg 1. \tag{7}$$

Despite the simplified assumptions, equations (6) and (7) remain non-convex. Therefore, based on the following lemma, TUEs, and CUE exponential power variables substitution tends the problem to a convex problem.

Lemma 1. The function $\log_2(\gamma)$ is a concave function with an exponential power transformation.

Proof. The lemma is proved in Appendix A. ☐

With respect to Lemma 1, the power allocation sub-problem is simplified as follows.

$$\begin{aligned} \underset{P_c, P_k}{\text{maximize}} \quad & \log_2(\gamma_c) && \text{(8a)} \\ \text{subject to} \quad & \log_2(\gamma_c) \geq \gamma_{th}, && \text{(8b)} \\ & \log_2(\gamma_k) \geq \hat{\gamma}_{th}, \forall k \in \mathcal{K}, && \text{(8c)} \\ & 0 \leq P_k \leq P_{\max}, \forall k \in \mathcal{K}, && \text{(8d)} \\ & 0 \leq P_c \leq P_{c(\max)}. && \text{(8e)} \end{aligned}$$

Accordingly, we evaluate the power variable of each transmitter with respect to existing convex optimization solvers. In other words, the calculated transmitted power will be able to maximize the CUE sum-rate while satisfying the QoS constraints.

In the next section, to select the best TUE for an assumed RUE, the constraint of outage probability of V2V communications is considered. Moreover, in order to have stable connection, another constraint is proposed. Therefore, with these two constraints, the pairing problem could be solved with a fuzzy point of view.

IV. FUZZY PAIRING

In order to guarantee the safety-critical application of the V2X network, what is pivotal for the V2V connection is having a highly reliable and stable connection. Hence, in this section, a fuzzy-decision making method is addressed to refine the stability and reliability of each V2V connection during each data transmission time-step. The fuzzy concept in 1965 for the first time was presented by L. A Zadeh [31] which had broad applications in engineering and computer science. The idea of Zadeh was to introduce a generalization of the classical notion of sets. Hence, in the following to explain our proposed idea, at first the fuzzy sets is presented and then the proposed fuzzy membership function is introduced.

Definition IV.1. [32] Let X be a non-empty set and $\mu : X \to [0,1]$ be a function. A fuzzy set A over the X is defined as

$$A = \{(x, \mu(x)) : x \in X\}, \tag{9}$$

where $\mu(x)$ denotes the membership function of A.

Definition IV.2. [33] A triangular norm (t-norm) is an associative, non-decreasing, and commutative function $T : [0,1] \times [0,1] \to [0,1]$, which $T(x,1) = x$.

t-norms play a vital role in the theory of probabilistic norm spaces and fuzzy mathematics. Moreover, triangular conorms (t-conorms), are defined as the dual operation of t-norms as follows.

Definition IV.3. [33] A t-conorm is a binary function $S : [0,1] \times [0,1] \to [0,1]$, which is commutative, associative, and monotone function with $S(x,0) = x$.

A particular t-conorm, called Einstein sum, would be used in the proposed method. It will be denoted as

$$\tau(x,y) = \frac{x+y}{1+xy}, \tag{10}$$

for all $x, y \in [0,1]$.

Based on the above explanations, the fuzzy membership function will be written as follows. Let $(x,y) \in [0,1] \times [0,1]$, and fix $x_0, y_0 \in (0,1)$. Define membership function $\mu : [0,1] \times [0,1] \to [0,1]$ as

$$\mu(x,y) = \begin{cases} x & ; y_0 \le y \le 1, 0 \le x < x_0 \\ y & ; 0 \le y < y_0, x_0 \le x \le 1 \\ \tau(x,y)\left(x^2 + y^2\right) & ; 0 < x < x_0, 0 < y < y_0 \\ \tau(x,y) & ; x_0 \le x \le 1, y_0 \le y \le 1. \end{cases} \tag{11}$$

Then, the set $S = \{(\mathbf{u}, \mu(\mathbf{u}) : \mathbf{u} \in [0,1] \times [0,1]\}$ is a fuzzy set.

The proposed fuzzy membership function (11) uses two thresholds x_0 and y_0. If one of the inputs (for example x) is smaller than its corresponding threshold (x_0) but the other one is not (i.e. $y > y_0$), then the input below the threshold (i.e. x) is returned as the membership function output. For both $x > x_0$ and $y > y_0$, the Einstein sum ($\tau(x,y)$) is the value of $\mu(x,y)$. Finally, if $x < x_0$ and $y < y_0$, then an attenuation factor ($(x^2 + y^2)$), is multiplied by the Einstein sum to reduce the membership function value.

Now, consider the fuzzy concept of "the set of all stable connections". For each typical transmitter-receiver connection, a number between 0 and 1 can be considered as a degree of stability. With respect to (11), we aim to model this fuzzy set in a V2X communications network. Obviously, when the membership degree approaches 1, the connection will be more stable. For this purpose, we use reliability and velocity parameters as the membership function variables.

A. Reliability and Velocity Parameters

Since high reliability is vital for the V2V connections, here it is tried to select the best TUE based on outage probability and RUE and TUEs velocity differences. So the outage probability is constrained as $\Pr_{\text{out}} \le P_0, \forall k \in \mathcal{K}$, and it is formulated as, $\Pr_{\text{out}} \triangleq \Pr(\gamma_k \le \hat{\gamma}_{th})$. The outage probability is simplified with respect to the next lemma.

Lemma 2. $\Pr_{\text{out}}$ can be derived as a closed form as [11]

$$\Pr(\gamma_k \le \hat{\gamma}_{th}) = 1 - \frac{P_k q_k e^{-\frac{\hat{\gamma}_{th}\sigma^2}{P_k q_k}}}{P_k q_k + \hat{\gamma}_{th} P_c q_c} = 1 - Pr_{th}, \tag{12}$$

where q_k and q_c model the large-scale fading.

Proof. The lemma is proved in Appendix B. ☐

We consider Pr_{th} as the first variable of our membership function which meets the reliability of potential connection. The difference in velocity of both potential V2V nodes is another influential parameter in the communication between them. Therefore, a mathematical model of the mentioned velocity would be proposed as follows.

$$\Gamma(V_r, V_k) = 1 - \frac{e^{\sqrt{|\Delta V|}}}{100 + e^{\sqrt{|\Delta V|}}}, \tag{13}$$

where $\Delta V = V_r - V_k$. It should be noted that ΔV is the velocity difference of the RUE and the k-th TUE. Therefore Pr_{th} and Γ are two independent parameters which will be used in the membership function of each potential V2V pair as follows.

$$\mu_k(\Gamma, Pr_{th}) = \begin{cases} Pr_{th} & ; \Gamma_0 \le \Gamma \le 1, 0 \le Pr_{th} < Pr_0 \\ \Gamma & ; 0 \le \Gamma < \Gamma_0, Pr_0 \le Pr_{th} \le 1 \\ \tau(\Gamma, Pr_{th})\left(Pr_{th}^2 + \Gamma^2\right) & ; 0 < \Gamma < \Gamma_0, 0 < Pr_{th} < Pr_0 \\ \tau(\Gamma, Pr_{th}) & ; \Gamma_0 \le \Gamma \le 1, Pr_0 \le Pr_{th} \le 1 \end{cases} \tag{14}$$

where Pr_0 and Γ_0 are the thresholds of Pr_{th} and Γ, respectively.

Finally, the proposed algorithm with respect to the power allocation optimization problem (8a) and based on the fuzzy pairing method, is presented as follows.

The total computational complexity of the proposed algorithm will be calculated as $\mathcal{O}(K^2 \log_2(K) + K) \simeq \mathcal{O}(K^2 \log_2(K))$, where K is the number of potential TUEs.

V. SIMULATION RESULTS

In this section, the performance of the studied model in terms of stability and network throughput is represented. The model is compared to pairing models based on maximum rate, minimum distance, and random selection. First, the simulation setup is elaborated. Then, the simulation results based on the proposed model are illustrated.

Algorithm 1 : Power Allocation based on Fuzzy Pairing

```
Initialization:
Initialize each vehicle random location, velocity and direction.
Initialize $g_c, h_c, g_k, h_k$.
Power Allocation:
for $t = 1, 2, \ldots, T$ do
    for $k = 1, 2, \ldots, K$ do
        Solve the convex optimization problem in (8a) with CVX, which is a Matlab-based modeling system for convex optimization.
        Return $P_k$ and $P_c$.
        Fuzzy Pairing:
        Calculate $\Gamma$ and $Pr_{th}$ based on the attained $P_k$ and $P_c$.
        Calculate $\mu_k$ and return it.
    end for
    Return $\max \mu_k$.
    Update all vehicles' locations and new $g_c, h_c, g_k, h_k$.
    Repeat this algorithm until the end of assumed time.
end for
```

A. Simulation setup

We consider a multi-lane freeway case defined by the 3GPP TR 36.885 [34] where the eNB is located at the center of the network cell. The crucial simulation parameters are set in Table II. The V2V and V2I channel models are listed in Table III. The vehicles are dropped down randomly with different velocities between $70 - 140 (km/h)$ in which for simplicity we assume that the acceleration of the vehicles is zero.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	2 GHz
Bandwidth	10 MHz
Number of CUE	1
Number of RUE	1
Number of TUEs	3
BS antenna height	25 m
BS antenna gain	8 dBi
BS receiver noise figure	5 dB
Vehicle antenna height	1.5 m
Vehicle antenna gain	3 dBi
Maximum CUE transmit power	23 dBm
Maximum TUE transmit power	23 dBm
Number of lanes	3x2
Lane width	4 m
Noise power σ^2	-114 dBm
Distance between BS and highway	35 m
Vehicle receiver noise figure	9 dB
SINR threshold of CUE γ_{th}	4 dB
SINR threshold of V2V $\hat{\gamma}_{th}$	2 dB
Γ_0	0.3

TABLE III
CHANNEL MODEL OF V2V AND V2I COMMUNICATION LINKS [34]

Parameter	V2I Link	V2V Link
Pathloss model	$128.1+37.6 \log_{10} d$, d in Km	LOS in WINNER + B1
Shadowing distribution	Log-normal	Log-normal
Shadowing standard deviation ζ	8 dB	3 dB
Fast fading	Rayleigh fading	Rayleigh fading

B. The main results of the proposed model

In this section, the main results of the proposed model are explained. Note that the Distance Selection refers to the selection of the closest TUE to the RUE. The MaxRate Selection means the selection of the TUE which causes the maximum sum-rate of the network. Furthermore, Random Selection refers to the random selection of the TUE. In this regard, Fig. 2 and Fig. 3, show two metrics, the μ factor, and the total network throughput, versus the number of TUEs, respectively. As shown in Fig. 2, the proposed V2V pairing model has the highest stability. Besides, the more the number of TUEs gets, the better the suggested model performs, e.g. when the number of TUEs is 4, the stability improvement compared to the other methods is nearly 20 percent. As observed, where the number of TUEs is 4, the μ factor of all the comparative algorithms is dropped, which shows the MaxRate, the Distance and the Random selection do not bring stability in our systems as high as the proposed solution, especially when the number of TUEs leads to an increase.
In Fig.3, the proposed model follows the MaxRate selection as well as the Distance selection method. Hence, not only does the proposed model have the highest stability, but also it follows the network throughput of the MaxRate method. In Fig. 4, the stability factor versus the reliability constraint is considered, where the number of TUEs is 3. As P_0 increases, the stability of the proposed model is maintained, while the stability of other models decreases. The figure shows when P_0 is 10^{-3} it has about 0.98 stability. Finally, the more the outage probability threshold, the more stable connection we get.

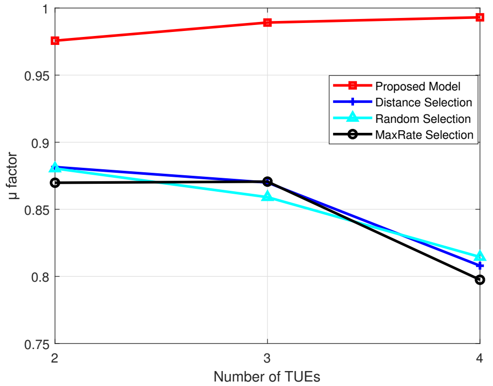

Fig. 2. Stability factor versus number of TUEs.

Fig. 5, shows stability with respect to the SINR threshold γ_{th}, for the V2I connection. Fig. 5 corroborates the proposed method performance, increasing the V2I threshold. As shown, while all the other methods have almost 15 percent worsen

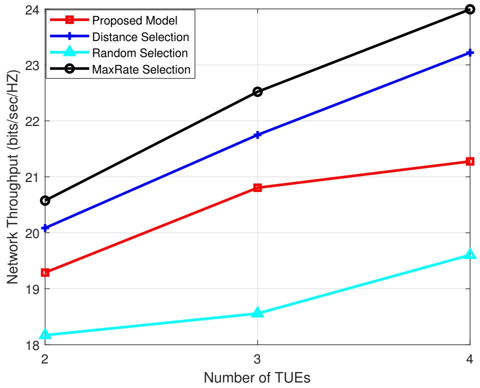

Fig. 3. Network throughput versus number of TUEs for the first time slot.

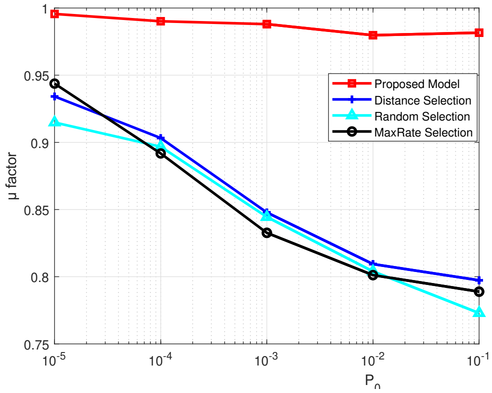

Fig. 4. Stability factor versus the outage probability threshold P_0.

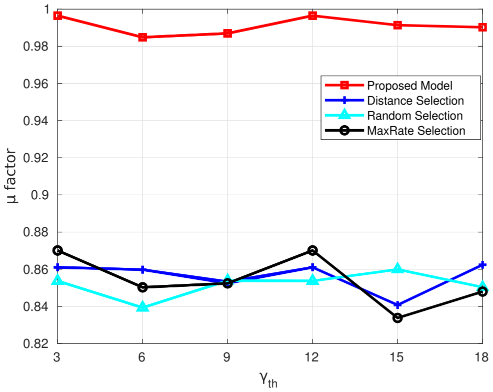

Fig. 5. Stability factor versus γ_{th}.

performance, the proposed model through ascending the γ_{th} has 0.98 of stability. Fig. 6 shows the μ factor versus time, with $100(ms)$ for each time-slot. The figure demonstrates maintaining of the stability factor at a high level, in the proposed method, when the other methods may fail to improve the stability factor during the time.

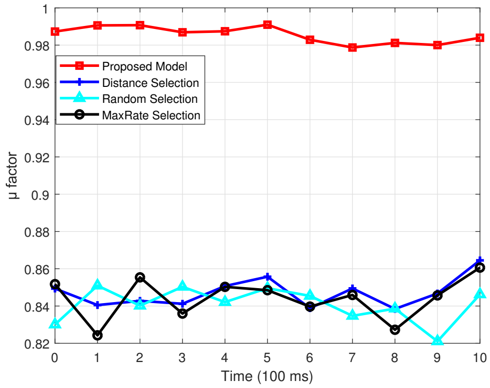

Fig. 6. Stability factor versus time, where each time-slot is equal $100(ms)$.

VI. CONCLUSION

In this paper, an optimization problem for resource allocation in a V2X network is investigated. This issue is divided into two sub-problems of power control and pairing. The power control sub-problem is transformed into a convex problem with an exponential variable change. The pairing sub-problem is presented using fuzzy techniques. For this purpose, the speed of a vehicle and the outage probability threshold of the V2V link are considered as inputs of the fuzzy function. Simulation results show that the proposed fuzzy method provides more stable connections compared with pairing models based on maximum rate, minimum distance, and random selection.

APPENDIX A
PROOF OF LEMMA 1

The approximate throughput of the V2I connection is as

$$\log_2\left(\frac{P_c\ g_c}{\sigma^2+\sum_{k=1}^{K}\rho_k P_k h_k}\right).$$

Assuming that $\alpha_k=\rho_k h_k$ and the exponential transformation of CUE and TUEs are as $P_c = e^{\tilde{P}_c}$, and $P_k = e^{\tilde{P}_k}$. Hence, equation (A) could be rewritten as

$$R(\tilde{P}_c,\tilde{P}_k)=\log_2\left(\frac{e^{\tilde{P}_c}\ g_c}{\sigma^2+\sum_{k=1}^{K}\alpha_k e^{\tilde{P}_k}}\right),$$

while it can be modified as follows:

$$R(\tilde{P}_c,\tilde{P}_k)=\tilde{P}_c\log_2(g_c)-\log_2(\sigma^2+\sum_{k=1}^{K}\alpha_k e^{\tilde{P}_k}),$$

where it is the sum of an affine function $\tilde{P}_c\log_2(g_c)$ and the following function

$$R'(\tilde{P}_k)=-\log_2(\sigma^2+\sum_{k=1}^{K}\alpha_k e^{\tilde{P}_k}).$$

Therefore, if we could prove the concavity of R', the Lemma (1) would be proved, so the first derivative with respect to $\tilde{P}_k$ is

$$\frac{\partial R'(\tilde{P}_k)}{\partial \tilde{P}_k} = -\frac{\alpha_k e^{\tilde{P}_k}}{\sum_k \alpha_k e^{\tilde{P}_k} + \sigma^2},$$

also the second derivative of this function could be

$$H(\tilde{P}_k) = \frac{yy^T - (\sum_k \alpha_k e^{\tilde{P}_k} + \sigma^2)\ diag(y)}{(\sum_k \alpha_k e^{\tilde{P}_k} + \sigma^2)^2},$$

where $y = \left[\alpha_1 e^{\tilde{P}_1}, \alpha_2 e^{\tilde{P}_2}, \ldots, \alpha_k e^{\tilde{P}_k}\right]$ and $H(\tilde{P}_k)$ is a negative definite function due to the later equation so

$$v^T H(\tilde{P}_k) v = \frac{(\sum_k v_k \alpha_k e^{\tilde{P}_k})^2 - (\sum_k \alpha_k e^{\tilde{P}_k} + \sigma^2)(\sum_k v_k^2 \alpha_k e^{\tilde{P}_k})}{(\sum_k \alpha_k e^{\tilde{P}_k} + \sigma^2)^2} \leq 0.$$

The proof of latter inequality could be defined from the Cauchy–Schwarz inequality $(A^T B)^2 \leq (A^T A)(B^T B)$ where we have $A = \left[v_1 \sqrt{\alpha_1 e^{\tilde{P}_1}}, v_2 \sqrt{\alpha_2 e^{\tilde{P}_2}}, \ldots, v_k \sqrt{\alpha_k e^{\tilde{P}_k}}\right]$ and $B = \left[\sqrt{\alpha_1 e^{\tilde{P}_1}}, \sqrt{\alpha_2 e^{\tilde{P}_2}}, \ldots, \sqrt{\alpha_k e^{\tilde{P}_k}}\right]$.

According to the above explanation, the convexity of V2V throughput is similar to this proof, thus we avoid the details for brevity.

APPENDIX B
PROOF OF THE FIRST ZONKLAR EQUATION

$$\begin{aligned}
&\Pr\left\{\hat{\gamma}_k \leq \hat{\gamma}_{th}\right\} \\
=&\Pr\left\{\frac{P_k\ g_k}{\sigma^2 + P_c\ h_c} \leq \hat{q}_{th}\right\} \\
=&\int_0^{\infty} \mathrm{d}\hat{a}_c \int_0^{\frac{\hat{\gamma}_{th}\left(\sigma^2 + P_c \hat{a}_c \hat{q}_c\right)}{P_k q_k a_k}} e^{-(a_k + \hat{a}_c)} \mathrm{d}a_k \\
=&1 - \frac{P_k q_k e^{-\frac{\hat{\gamma}_{th}\sigma^2}{P_k q_k}}}{P_k q_k + \hat{\gamma}_{th} P_c \hat{q}_c} = 1 - Pr_{th} \leq p_0
\end{aligned}$$

where a_k and $\hat{a}_c$ are independent and identically distributed (i.i.d.) exponential random variables with unit mean.

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