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Congestion Game With Link Failures for Network Selection in High-Speed Vehicular Networks

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ABSTRACT Network selection is of critical importance for heterogeneous vehicular networks. However, it still faces network congestion and reliability challenges in high-speed vehicular networks, which are caused by users' selfishness and link failures, respectively. To address these challenges, we propose a scheme called enhanced congestion game with link failures (E-CGF) to achieve optimal network selection. In E-CGF, a hidden Markov model is utilized to formulate the link failure probability. Considering link failures, users can use more than one radio network simultaneously to improve throughput performance by redundant transmission, which leads to an increase of transit cost. Accordingly, the goal of E-CGF is to make a compromise between achieved throughput and transit cost. We first prove the existence of Nash equilibrium in E-CGF and construct an efficient algorithm to find the optimal strategy. We then evaluate the effect of different parameters on the utility based on numerical analysis. Finally, we carry out extensive experiments based on real-world traces of link states from high-speed rails and compare with three typical algorithms. The results demonstrate that E-CGF outperforms others by alleviating network congestion and improving transmission reliability with a moderate trade-off between achieved throughput and transit cost.

INDEX TERMS Congestion game, link failures, network selection, redundant transmission, high-speed vehicular networks.

I. INTRODUCTION

With the development of wireless technologies, the integration of Heterogeneous Vehicular Networks (HVNs) is regarded as a promising solution for intelligent transport systems [1]–[3]. In HVNs, vehicles can communicate to infrastructure (V2I), vehicles (V2V), and everything (V2X) by using roadside Wi-Fi, cellular networks, Dedicated Short Range Communications (DSRC) and other radio technologies [1], [4]. Traditionally, in a rough definition, HVNs consist of different wireless protocols and communication systems. For example, the combination of DSRC and LTE forms HVNs [1]. The components of HVNs are vehicular ad hoc network and wireless metropolitan area network [5]. In a fine-grained definition, HVNs can be extended as an integration of multiple Radio Access Networks (RANs) with different network states. From the point of service performance, RANs with different states of network characteristics (e.g., bandwidth-delay product, round-robin time, bandwidth, etc) can generate a significant distinction [6]. As shown in Figure 1, roadside radio networks within different Mobile Network Operators (MNOs) form heterogeneous high-speed vehicular networks, which are specific vehicular networks [7]. As proved by [8] and [9], RANs within different deployments of MNOs have distinct states of network characteristics along high-speed rails.

Thanks to the coexistence of multiple radio access technologies in HVNs, many excellent works have been done for solving the network selection problem [10]–[12]. The network selection problem is one of the most important tasks in heterogeneous networks. Users generally choose the 'best' network to satisfy requirements of their selection benchmarks, which is called as Always-Best-Connected (ABC) selection principle [12]. The selection benchmarks are diverse. Considering Figure 1 as an example, in the selection process, UE_1 aims to improve network throughput [13]; UE_2 wants to secure network [14];

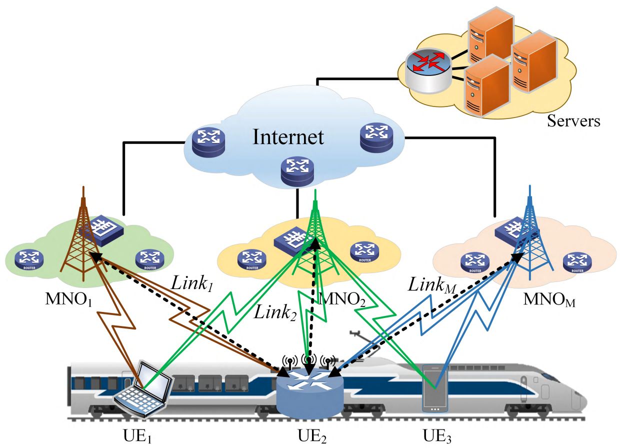

FIGURE 1. An example of heterogeneous high-speed vehicular networks.

UE_3 focuses on transmission efficiency and security [15]. In vehicular networks, transmission reliability and vehicle mobility are also taken into consideration before making the network selection decision [5], [16]. However, the selection decision based on 'ABC' principle might not be the actual 'best' due to users' selfishness and link failures. First, depending on 'ABC', selfish users tend to choose the same network, which will lead to network congestion [17]. Second, radio link failures are intermittent happened in mobile networks, which will result in communication interruptions. Taking an example from Figure 1, the RAN within MNO_2 is the 'best' network for all users (i.e., UE_1, UE_2 and UE_3) in terms of signal strength, network delay and non-congestion loss at this time. But, this RAN will become congestion caused by selfish selections or even be unavailable due to vehicle mobility. Consequently, all the users selecting this RAN receive very low (or, even zero) throughput.

To deal with users' selfishness and link failures, Congestion Games with Failures (CGFs) are introduced into the network selection problem [18]. Congestion games are noncooperative games in which a collection of users compete for a finite set of network resources. Considering resource competition, congestion games seek the coordination between users' payoff and costs. Since failures are inevitable in real applications, CGFs should be taken into consideration. Generally, failures in CGFs vary depending on the perspective: resource failures [19], [20] and agent failures [21], [22]. **Resource failures** are interpreted as **link failures** in this paper, which represents the unavailability of wireless channels. **Agent failures** are caused by the outage of terminal devices. Both types of failures can bring about communication interruptions. In another perspective, the failure probability could be correlated [21] or uncorrelated [19] in CGFs depending on the application scenario. Since the failure probability is one of key parameters in CGFs and is also an important metric for applications (e.g., IPTV [23]), it's critical to establish the probability model of link failures or player failures.

While the existing studies show promising benefits of CGFs for network selection, two main challenges, i.e., network congestion and reliability, still remain to be addressed in high-speed vehicular networks. In particular, link failures are extremely terrible in high-speed vehicular networks [24], [25]. For evidence, the network delay and non-congestion loss of wireless channels are up to 500 ms and 10%-30%, respectively [11], [25]. Such higher values of network characteristics will increase the probability of link failures. In addition, the link handover among base stations of the same MNO also promotes link failures. According to statistics, the event of link handovers occurs with an interval of [20,40] seconds at a vehicle speed of 250 km/h. These features of heterogeneous high-speed vehicular networks create changeable link failures, resulting in network congestion and low transmission reliability. Still taking an example from Figure 1, UE_2 connects M RANs through $Link_1$ to $Link_M$, and their failure probabilities are up to 30%. By using CGFs, UE_2 selects $Link_2$ to execute tasks according to its strategy. Unfortunately, network congestion is regarded as the cause of high probability of failures, which will come into poor performance of UE_2 according to its congestion control mechanism. Considering the mobility of vehicles, link failures of M links intermittently appear as time goes by. Consequently, the selection strategy of UE_2 with $Link_2$ based on current states may be obsolete, since a better strategy is $Link_M$ based on the following states of RANs.

To solve the above-mentioned problems, we propose an Enhanced Congestion Game with link Failures (E-CGF) scheme to achieve optimal network selection. In E-CGF, we utilize Hidden Markov model (HMM) to formulate the probability of link failures in high-speed vehicular networks. In consideration of link failures, users can connect to more than one RAN and use them simultaneously to improve throughput performance by redundant transmission, which will lead to an increase of transit cost. The throughput of each user also increases since he sends duplicates simultaneously through different RANs to his communication peer, but it's not his practical achieved throughput. In this paper, we focus on the achieved throughput of each user, which is defined as the maximum throughput obtained from those RANs successfully completing his tasks, rather than his throughput. Accordingly, the goal of E-CGF is to make a compromise between achieved throughput and transit cost. To seek the optimal strategy, we prove the existence of Nash equilibrium and construct an efficient algorithm, which is promising to find the Nash equilibrium. We then evaluate the effect of link failures and number of users on the utility based on numerical analysis. Finally, we carry out extensive simulation experiments based on real-world traces of link states along high-speed rails to evaluate network performance of our model. Three typical algorithms are exploited for comparison. Results demonstrate that E-CGF outperforms other algorithms by alleviating network congestion and improving transmission reliability with a moderate trade-off between achieved throughput and transit cost.

The main contributions are summarized as follows:

- We propose a novel scheme named E-CGF to address network congestion and reliability in high-speed vehicular networks. Different from traditional CGFs that only use one RAN for each user executing his task, it can improve the reliability by using redundant transmission.
- We analyze the causes of HMM along high-speed rails, and estimate the probability distribution by learning from massive datasets collected along dozens of high-speed rail lines in China.
- We redefine the goal of E-CGF with achieved throughput and transit cost, and prove the existence of Nash equilibrium. Numerical analysis and simulation experiments are both performed for evaluation.

The rest of this paper is organized as follows. Section II summarizes the state-of-the-art congestion game with link failures and redundant transmission solutions. Section III presents our system model, including our network model, link failure model and the utility function. Section IV proves the existence of Nash equilibrium and constructs an algorithm. Section V performs a numerical analysis to discuss the effect of different parameters on the utility. Section VI evaluates users' throughput performance. Finally, we make conclusions in Section VII.

II. RELATED WORK

Here, we briefly review the state-of-the-art congestion game with link failures and redundant transmission solutions.

A. CONGESTION GAME WITH LINK FAILURES

In CGF models, the goal is to minimize or maximize each user's expected disutility or utility. Since their disutility and utility functions are different, the work of congestion game with link failures can be divided into three types.

Penn *et al.* took the lead in studying network resource failures in congestion games, and they mainly focused on uncorrelated failures in CGFs [19]. Its basic CGF model aims at minimizing the disutility function, which is the sum of incompletion cost and completion cost. Since users only utilize the RAN with the minimum expected cost to complete their tasks, the completion cost is the minimum service cost for a user to complete his task. The service cost of a user using any RAN is a nonnegative nondecreasing function of the total number of users using this RAN. However, the failure probability is constant which is not suitable for practical applications, and this game model is great different from ours.

To model more practical applications, Li *et al.* presented the analysis of congestion games with correlated resource failures [18]. They assume resource failures abide by a probability distribution. Similar to [19], the completion cost of this model is the minimum service cost. However, this model is still not suitable for our application scenarios. In our model, the cost should be the total cost of selected RAN(s) since users utilize all the selected RAN(s) to transfer data simultaneously.

Penn *et al.* further discussed load-dependent failures with identical resources in CGFs [26]. In this model, the failure probability of a RAN and the cost of users selecting it both depend on the number of users using this RAN. The utility function in [26] is similar to ours, which is the difference between his benefit from successful task completion and the total cost. Nevertheless, it concentrates on identical resources that are not suitable for practical heterogeneous networks.

B. REDUNDANT TRANSMISSION

The study of redundant transmission solutions mainly aims to increase communication reliability in lossy and changeable networks [27]–[30].

Redundant transmission was utilized to improve performance over ALOHA networks [27] and lossy network control systems [28]. The goal modeled in [27] is to maximize communication capacity within a maximum permissible delay. Communication protocols designed in [28] attempted to find a balance between stability performance and communication rate. However, such communication policies and protocols are designed for ALOHA networks and network control systems, respectively, which are not suitable for our applications.

In traditional TCP/IP communications, the multiple-copy redundant transmission mechanisms were primarily designed in TCP layer over high-speed railway communication systems [29], [30]. Lopez *et al.* [29] enhanced the reliability of railway transportation systems by designing redundant Multipath TCP (MPTCP) strategy. Redundant MPTCP uses a full-copy method to schedule packets to all paths. Nonetheless, it will lead to network congestion since the full-copy method excessively increases the total number of transmitted data. Zhang *et al.* [30] presented a link prediction based reliable transmission scheme for high-speed railways. It jointly considers the transmission overhead of multiple copies and performance, and replicates data moderately for transmission. However, it will still obtain a poor success rate when the link failure probability of the selected path is very high, since all copies are transmitted to the same path.

III. SYSTEM MODEL

In this section, we discuss the system model for network selection in high-speed vehicular networks. We first describe the network model in Section II-A and HMM of link failures in Section II-B. Then, we present the utility function of each user in Section II-C.

A. NETWORK MODEL

As shown in Figure 1, there exists $\mathcal{M} = \{1, 2, ..., M\}$ radio networks along the high-speed rail. They belong to M mobile network operators. On-board smart devices with multiple wireless interfaces can connect to these networks at the same time. In the high-speed rail environment, most of these wireless networks are cellular networks. Therefore, M generally is 3 indicating the three major MNOs in China. We suppose that these RANs are also heterogeneous since their network states, especially the link failure probability, are different as time changes during train travel.

The set $\mathcal{N} = \{1, 2, ..., N\}$ stands for identical users. In terms of the number of users, we have two cases: high-dense urban areas and sparsely populated rural areas. In high-dense urban areas, especially at train station, there are nearly 5000 people on average. In sparsely populated rural areas, the majority of users are passengers on a train, and the number is up to 600 on a Chinese high-speed train. According to statistics, about a quarter of users are active at the same time who have data in the scheduling queue of a LTE eNobeB. Therefore, N is almost in [150, 1250] range.

The throughput function of user i selecting RAN j is denoted by w_{ij} (Mbps), where w_{ij} is a non-increasing function of the number K_j of users selecting RAN j. As [31] concluded, w_{ij} can be calculated by formula (1),

$$w_{ij} = \begin{cases} R_j/K_j, & \text{3G/4G} \\ L/\sum\limits_{k\in K_j} \dfrac{L}{R_{k,j}}, & \text{Wi-Fi} \end{cases} \quad (1)$$

where R_j is the data rate when only one user uses this RAN, and L is the packet size. Hence, the throughput allocated to users depends on their selection strategies.

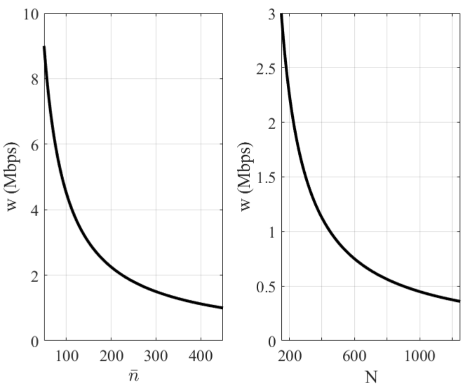

FIGURE 2. The throughput w of LTE with different numbers of users when $\bar{n}$ = [50, 416] and N = [150, 1250].

We demonstrate the impact of two different strategies on throughput. The strategy of $\bar{n} = N/3$ means that N users are evenly distributed to three RANs. The strategy of N means that all users select the same RAN. Here, $R = 3 * 150$ Mbps when the LTE eNobeB utilizes 3 × 20 MHz and 2 × 2 Multi-Input Multi-Output (MIMO). As shown in Figure 2, the throughput becomes less when all the users (N) select one RAN. It's only 0.36 Mbps in high-dense areas. Fortunately, in light of the development of micro-cell, pico-cell, femto-cell and other technologies [32], the congestion in high-dense areas can be solved. In rural areas, on-board users can receive a better throughput logically. However, the throughput performance has been proved to be extremely terrible in high-speed vehicular networks [25]. The redundant transmission should be taken into consideration in such environments. In the following, we focus on the network selection of high-speed vehicular networks in rural areas.

B. LINK FAILURE MODEL

We utilize hidden Markov model to formulate the link failure probability f in high-speed vehicular networks. Note that the link failure is not just the meaning of interruption, but represents the unavailability of wireless channels that cannot support a minimum service requirements. Except for special explanations, these two words, i.e. failure(s) and unavailability, are used interchangeably in this paper.

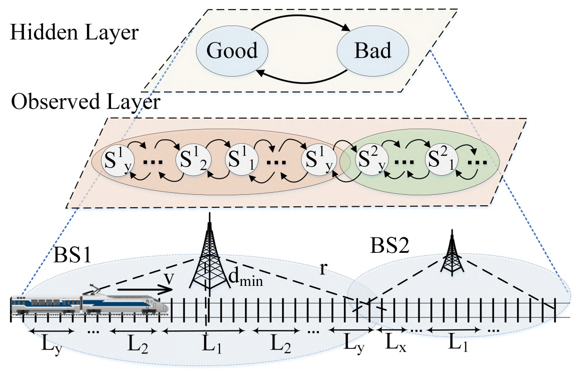

FIGURE 3. The hidden Markov model along a high-speed rail.

As Figure 3 depicts, the link state is dynamically changing when the train passes through two Base Stations (BSes). To describe the state transition, two layers are established to model the state of network unavailability (or, availability conversely): the observed-layer (S_p^q={ $p = 1, 2, ..., y$; $q = 1, 2$}) and the hidden-layer (s={ '*Good*', '*Bad*'}). In the observed-layer, the value $\max(y)$ is 6, which indicates six levels of network unavailability. Our previous work [33] has already explained this according to real-world data collected from high-speed rails. Among these, S_6 represents the highest unavailability, and S_1 indicates the smallest. Users on the train may experience these six states when the BS is close enough. In the hidden-layer, the state s tends to be 'Bad' when the majority of observed periods are S_6, S_5. For the sake of explanation, we describe it as a two-dimensional state $S_{p,s}^q = \{p = 1, 2, ..., y; s = 0, 1\}$ while $s = 0$ for 'Bad' state and $s = 1$ for 'Good' state, respectively.

However, observed states among these BSes are usually non-identical since the length d_{min} between BS and high-speed rail line differs. Note that $\lim\limits_{d_{min}\to 0} S_1^q = S_1$, and $\lim\limits_{d_{min}\to 0} S_y^q = S_6$. That is to say, the state set of $(S_1^2, ..., S_y^2)$ may be distinct from the set of $(S_1^1, ..., S_y^1)$. In addition, considering the switch condition between BSes, S_y^2 and S_y^1 are approximate, and the availability of S_y^2 is not inferior than that of S_y^1. Therefore, a concrete example of HMM state transition can be shown in Figure 4. It can be seen that, $S_1^1 = S_{1,1}$, $S_y^1 = S_{6,1}$, and $S_1^2 = S_{4,0}$, $S_y^2 = S_{6,0}$. The state transition experiences the process from BS1 to BS2 by step 1 to step 4.

To obtain the state transition probability matrix P of high-speed rail lines, massive datasets collected along high-speed rail lines are used for training and leaning. Benefiting from data measurements along dozens of high-speed rail lines,

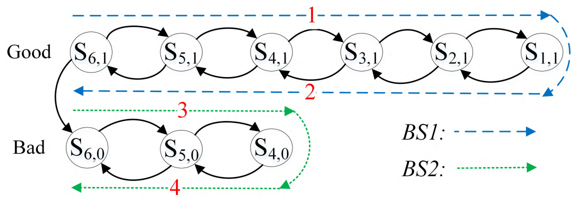

FIGURE 4. A concrete example of state transition in hidden Markov model.

including Beijing-Shanghai, Beijing-Tianjin, Beijing-Fuzhou and Zhengzhou-Xi'an in China, the transition probability matrix P for each tested high-speed rail line is calculated as:

$$P_{2\times 6} = A_{2\times 2} * B_{2\times 6},$$

where, A and B correspond to the transition probability matrix of hidden states and observed states, respectively. Then, the next link failure probability f could be estimated by P and its history states.

C. UTILITY FUNCTION

As mentioned above, $\mathcal{N}$ users compete for $\mathcal{M}$ RANs with failure probability $f = \{f_1, \ldots, f_M\}$ to complete their tasks. Due to link failures, each user connects more than one RAN and utilizes these RANs simultaneously for redundant transmission. As a result, the congestion level and the transit cost will increase accordingly. Here, we present the utility function from a given strategy profile Σ.

The set of pure strategies Σ_i for user i is the power set of the resource set: $\Sigma_i = 2^M$. Thus, $\Sigma = \Sigma_1 \times \Sigma_2 \times \cdots \times \Sigma_N$ is the set of pure strategy profiles, and $\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_N) \in \Sigma$ is a combination of pure strategies of these users. The $|\mathcal{M}|$-dimensional congestion vector corresponding to σ is $h^\sigma = (h_j^\sigma)_{j\in\mathcal{M}}$, where $h_j^\sigma = |\{i \in \mathcal{N} | j \in \sigma_i\}|$ representing the number of users connecting to RAN j.

Given a strategy profile σ, the utility $U(\sigma)$ of any user is calculated as the difference between his benefit from achieved throughput and transit cost per second. Since each RAN has its failure probability, the achieved throughput of user i is the maximum throughput obtained from those successfully completing his tasks. Let α_{ij} represent the throughput revenue (per Mbps) that user i obtains from RAN j. Then, the expected benefit per second can be represented as $\sum_{A\in 2^{\sigma_i}\backslash\emptyset} [\max_{j\in A}(\alpha_{ij} w_{ij})] \prod_{j\in A}(1-f_j) \prod_{j\in\sigma_i\backslash A} f_j$, where A stands for the survival set. In terms of transit cost per second, we assume RANs employ the common usage-based pricing. Therefore, the monetary transit cost per second for user i selecting RAN j is calculated as $P_{j_1} * w_{ij} + P_{j_2}$, where P_{j_1} is a price per unit of usage for using RAN j, and P_{j_2} is a fixed price. Hence, the expected utility of user i from a strategy profile σ is calculated as follows:

$$U_i(\sigma) = \sum_{A\in 2^{\sigma_i}\backslash\emptyset} [\max_{j\in A}(\alpha_{ij} w_{ij})] \prod_{j\in A}(1-f_j) \prod_{j\in\sigma_i\backslash A} f_j - \sum_{j\in\sigma_i}(P_{j_1} w_{ij} + P_{j_2}). \quad (2)$$

where, $U_i(\emptyset) = 0$. The utility of a selected strategy σ for each user should be greater than zero, i.e. $U_i(\sigma) > 0$. In addition, the maximal congestion level h_j^* can be calculated by the following formula:

$$\alpha_j w_{ij}(h_j) \geq P_{j_1} w_{ij}(h_j) + P_{j_2}, \quad (3)$$

where the equality is established only if $h_j = h_j^*$. Let $N \leq \sum_{j\in\mathcal{M}} h_j^*$ to avoid overcrowding.

IV. ENHANCED CONGESTION GAME WITH LINK FAILURES

In this section, we detail our enhanced congestion game with link failures scheme. The selection behavior of each user to maximize his own utility is presented in Section IV-A. We then prove the existence of its equilibrium in Section IV-B. The construction of our algorithm is outlined to find the optimal strategy in Section IV-C.

A. SELECTION BEHAVIOR

Initially, the strategy set of each user is $\emptyset$. We suppose that only one user changes his strategy each iteration, and his changing action benefits to himself. More specifically, there are three kinds of actions to increase the utility: i) *'A-move'*, means adding a RAN to a user's strategy; ii) *'D-move'*, means dropping a RAN from one's strategy; iii) *'S-move'*, means switching a RAN with another. For any user, only one action can be performed at each iteration. For example, user i intends to add RAN $e \in \mathcal{M}\backslash\sigma_i$ when the utility $U_i(\sigma_{-i}, \sigma_i \bigcup \{e\})$ of the strategy $\sigma_i^a = \sigma_i \bigcup \{e\}$ satisfies that:

$$\Delta U_a = U_i(\sigma_{-i}, \sigma_i^a) - U_i(\sigma_{-i}, \sigma_i) > 0.$$

Similarly, ΔU_d and ΔU_s can be obtained below, where $\sigma_i^d = \sigma_i\backslash\{b\}$, and $\sigma_i^s = (\sigma_i\backslash\{b\}) \bigcup \{e\}$.

$$\Delta U_d = U_i(\sigma_{-i}, \sigma_i^d) - U_i(\sigma_{-i}, \sigma_i).$$
$$\Delta U_s = \Delta U_d + \Delta U_a.$$

However, this *'A-move'* will influence the utilities of users who have chosen RAN e before. As a consequence, the utilities of these users might decline while $w_e(h_e + 1) < w_e(h_e)$. Then, they will take *'D-move'*, *'S-move'*, or, another *'A-move'* to increase their utilities. Such *'A-move'*, *'D-move'*, *'S-move'* iterations will continue until the game reaches a NE point if NE exists.

B. EXISTENCE OF EQUILIBRIUM

First of all, we present the definition of NE as below:

$$\forall i \in \mathcal{N}, \quad \sigma_i \in \Sigma_i : U_i(\sigma_i^*, \sigma_{-i}^*) \geq U_i(\sigma_i, \sigma_{-i}^*), \quad (4)$$

where, σ_i and σ_{-i} are the strategy sets of user i and all users expect user i, respectively. Below we describe the procedure of seeking NE and prove the existence of NE.

Theorem 1: The E-CGF model possesses a Nash equilibrium.

Proof: Our method of proof is similar to [26]. As denoted in formulation (4), a strategy profile is equilibrium if and only if it stops *'A-'*, *'D-'*, *'S-'* moves, which is called *'A-'*, *'D-'*, and *'S-'* stable.

Note that the different characteristics of RANs in E-CGF contain price (P_1, P_2), rate (R), the maximum congestion level (h^*), and failure probability (f). The designed parameter α is utilized to eliminate the price difference and unify user's throughput and cost. Since RANs along high-speed rails are 4G cellular networks, we assume the designed parameter α, and price P_1, P_2 are the same to simplify the analysis. $\omega = R_j/h_j^*$ becomes a constant for every RAN. In consideration of these characteristics in E-CGF, we redefine the light or heavy resources, and *(nearly-)* **even** as follows.

Definition 2: RAN $e \in \sigma$ is a light resource if $h_e^\sigma \in \arg\max_{e\in\mathcal{M}} \frac{h_e^*}{h_e^\sigma}$, and is a heavy one otherwise. A strategy profile σ is **even** when it has no heavy resources, and it's *nearly-***even** when $\forall e, g \in \mathcal{M}$ always exists $\lceil|\frac{h_e^*}{h_e^\sigma} - \frac{h_g^*}{h_g^\sigma}|\rceil \leq 1$.

Note that the initial strategy profile $\sigma^0 = \{\emptyset, \emptyset, ...\}$ is both 'D-' and 'S-' (called 'DS-') stable and **even**. There exists non-empty strategy profiles that are 'DS-' stable and *(nearly-)* **even**. Thus, we can prove Theorem 1 if we find a 'DS-' stable that is also 'A-' stable. By contradiction, we first assume that the non-empty set Σ^0 of even and 'DS-' stable strategy profiles always exists a beneficial 'A-move'. In view of the development trend of selection behaviors, we focus on the subset of Σ^0 with maximum congestion level and maximum sum of utilities in the following.

Let $\Sigma^1 = \arg\min_{\sigma\in\Sigma^0} |\{e \in \mathcal{M} : \text{e is a } \sigma\text{-heavy}\}|$ with a common congestion level h^*/h^σ, $\Sigma^2 = \arg\min_{\sigma\in\Sigma^1} h^*/h^\sigma$ with maximum congestion level, and $\Sigma^3 = \arg\max_{\sigma\in\Sigma^2} \sum_{i\in\mathcal{N}} U_i(\sigma)$ with maximum sum of utilities.

Primarily, $x = \{\emptyset, ..., \emptyset\}$ is 'DS-' stable and **even**. Then, $\Sigma^1 = \Sigma^2 = \Sigma^3 = \{x\}$ if no other strategy matches the definitions. In this case, another 'DS-' stable profile y can be obtained after a series of 'A-move' performed on x. Then, $h^y > h^x = 0$ that contradicts with $x \in \Sigma^2$.

Then, let $x \in \Sigma^3$ with $h^x \geq 1$, and x' is obtained from x with the 'A-move' of RAN a by user i. Since x is 'DS-' stable, the 'D-move' of RAN a will be executed by another user l if it's profitable. Let $x'' = (x'_{-l}, , x'_l \backslash \{a\})$. As a consequence, $x'' \in \Sigma^2$ since $h_a^{x''} = h_a^x$. It's found that $U_N(x'') > U_N(x)$ that contradicts $x \in \Sigma^3$. Then, Theorem 1 is proved.

C. CONSTRUCTION OF GAME

We construct an efficient algorithm in Algorithm 1 by taking consideration of dynamics and failure model. The algorithm adjusts the upper congestion limit of each RAN based on the total number of users and its maximal congestion level, shown in lines 1-10. M RANs are sorted by their failure probabilities in lines 11-12. $\mathcal{M}^{pre}$ in line 13 and $\mathcal{M}^{tmp}$ in line 17 are used for comparing the alteration of RAN order in adjacent periods. In lines 14-38, an optimal strategy is decided at each period. More explicitly, in lines 15-16 of Algorithm 1, the link prediction function is utilized to estimate the next state of each RAN first, and then RANs are sorted by these predicted results. In lines 18-27, the algorithm filtrates the RANs with order changed and removes them from the strategies of whom have selected them before. In lines 28-36, the algorithm re-selects strategies for changed RANs.

Algorithm 1 E-CGF

Require: $\forall\, i \in \mathcal{N}, \sigma_i := \emptyset$;
1: **for** $j \in \mathcal{M}$ **do**
2: $h_j^* = max\{h_j|\alpha_j w_j(h) > P_{j_1} w_j(h) + P_{j_2}, h_j{=}0, 1, ...\}$;
3: **if** $N \geq \max_{j\in\mathcal{M}} h_j^*$ **then**
4: $h_j^+ = h_j^*$;
5: **else if** $\min_{j\in\mathcal{M}} h_j^* \leq N < \max_{j\in\mathcal{M}} h_j^*$ **then**
6: $h_j^+ = h_j^* * N / \max_{j\in\mathcal{M}} h_j^*$;
7: **else**
8: $h_j^+ = h_j^* * N / \min_{j\in\mathcal{M}} h_j^*$;
9: **end if**
10: **end for**
11: Permutation function $\phi : \mathcal{M} \longrightarrow \{1, ..., M\}, j \longmapsto j = \phi(j)$;
12: $\forall a, b \in \mathcal{M}, f_a < f_b \Longrightarrow j_a = \phi(a) < \phi(b) = j_b$;
13: $\mathcal{M}^{pre} = \mathcal{M}$;
14: **while** each period **do**
15: $\mathcal{M} \leftarrow LP(f)$; /* link prediction function */
16: $\mathcal{M} \leftarrow \phi(j)$; /* sort RANs */
17: $\mathcal{M}^{tmp} = \emptyset$;
18: **for** $j \in \mathcal{M}^{pre}$ **do**
19: **if** $\mathcal{M}^{pre}(j) \neq \mathcal{M}(j)$ **then**
20: $\mathcal{M}^{tmp} = \mathcal{M}^{tmp} \cup \{\mathcal{M}(j)\}$;
21: **end if**
22: **end for**
23: **for** $i \in \mathcal{N}$ **do**
24: **if** $\exists k \in \sigma_i, k \in \mathcal{M}^{tmp}$ **then**
25: $\sigma_i := \sigma_i \setminus \{k\}$;
26: **end if**
27: **end for**
28: **for** $j \in \mathcal{M}^{pre}$ **do**
29: Permutation function $\varphi_j : \mathcal{N} \longrightarrow \{1, ..., N\}, i \longmapsto i_j = \varphi_j(i)$;
30: $\forall k, i \in \mathcal{N}, size(\sigma_i) < size(\sigma_k) \Longrightarrow i_j = \varphi_j(i) < \varphi_j(k) = k_j$; /* sort users */
31: **for** $i_j \in \mathcal{N}$ **do**
32: **if** $i_j \leq h_j^+$ **then**
33: $\sigma_i := \sigma_i \cup \{j\}$;
34: **end if**
35: **end for**
36: **end for**
37: $\mathcal{M}^{pre} = \mathcal{M}$;
38: **end while**

V. NUMERICAL ANALYSIS

In this section, we perform a numerical analysis of our model to discuss the utility under different network states. The effect parameters include link failure probability, number of users and the designed parameter α.

Here, we set N and f as variables to analyze the effect on utility. Let $N = [100, 200, 500, 1000, 1500]$ and $f = [0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 0.8, 0.9, 1]$. Let $M = 3$, $R = 450$ and other parameters be constant. Therefore, these RANs have a common maximum congestion h^*. We select three adjacent failure probabilities from f for RANs in turn, i.e. f_i, f_{i+1}, f_{i+2} while $i = 1, 2, ..., 7$. Results in Fig 5 reveal that the utility of each user becomes lower when the number of users augments. The utility is also lower when the failure probability increases. We also observe that the values of user's utility are very close when link failure probabilities are $\{f_3, f_4, f_5\}$ and $\{f_4, f_5, f_6\}$, respectively. This shows that the effect of link failures can be ignored when link failure probabilities are not all high.

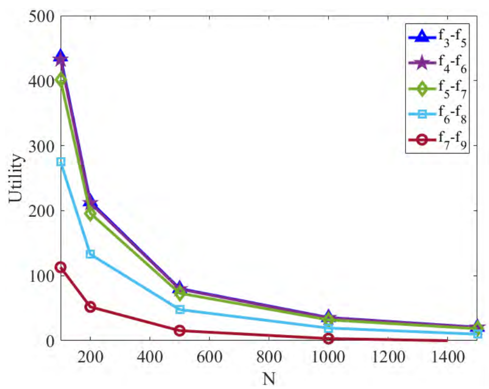

FIGURE 5. The utility with different N and f while $R = 450$.

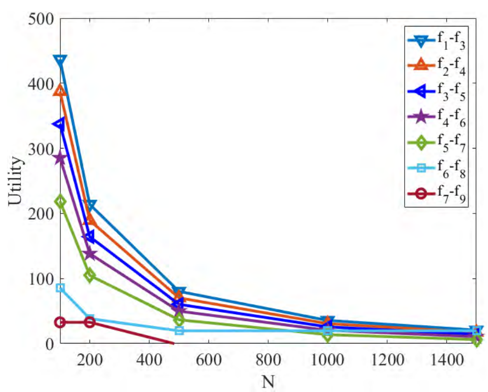

FIGURE 6. The utility with different N, f and R.

Further, we set R as a variable too. Let $R = [450, 400, 350, 300, 250, 150, 50, 10, 1]$ corresponding to $f = [0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 0.8, 0.9, 1]$. Then, h^* gets smaller as R decreases. Fig 6 illustrates an evident decline of utilities compared with Figure 5 since R decreases. In addition, the failure probability has little effect on the utility when $N \geq 1000$. Even worse, users gain nothing ($U = 0$) when $N \geq 500$ and the failure probabilities of RANs are $\{0.8, 0.9, 1\}$.

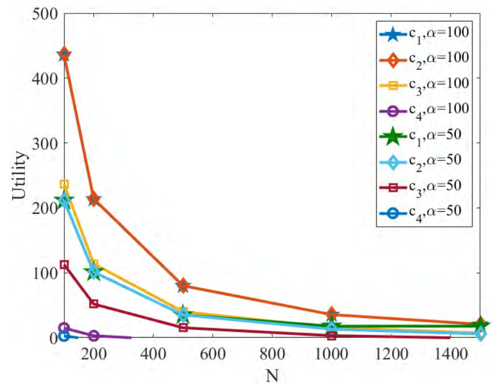

FIGURE 7. The utility with different N and configurations c_1, c_2, c_3, and c_4.

To reveal the impact of considerable differences among three RANs, they are configured with $f = \{0.01, 0.2, 0.8\}$ and $R = \{450, 250, 50\}$ (named c_1), and $\alpha = 100/50$. For comparison, we also configure them with c_2 ($f = \{0.01\}$ and $R = \{450\}$), c_3 ($f = \{0.2\}$ and $R = \{250\}$) and c_4 ($f = \{0.8\}$ and $R = \{50\}$). The results are shown in Figure 7. We observe that the adjustment of α greatly affects the utility. In some practical applications, the user can adjust this parameter according to his own preference. For example, α can be set smaller for overhead-sensitive users. Another finding is that c_1 receives better results than c_2 when $N \geq 1000$ and $\alpha = 50$ although the utilities of c_1 and c_2 are substantially the same. The reason is that the overall congestion level of three RANs with c_1 is lighter than that with c_2. All RANs with c_2 have the maximum congestion level h^* that excite users to choose more. However, in the case of $\alpha = 50$ and $N \geq 1000$, the transit cost of adding a RAN grows faster than the throughput.

VI. PERFORMANCE EVALUATION

In this section, we evaluate our network selection mechanism, E-CGF, based on real-world data collected along high-speed rails. We introduce our simulation setup in Section VI-A and present three algorithms for comparison in Section VI-B. Results are analyzed to demonstrate our advantages in Section VI-C.

A. SIMULATION SETUP

We use ns3 simulator [34] to perform our experiments. The simulation topography conforms to Figure 1. Let $w = R/h$ and $M = 3$ be three 4G cellular networks along the Beijing-Shanghai high-speed rail line. We further scale down the number of users N, rate R and congestion upper limit h^* of RANs to reduce unnecessary simulation tasks. Let $h^* = 3$, and then $N \leq 3 \times 3$. Since we try to explain the impact of each user's strategy using different selection methods on the results, let $N = 7$ and all users generate TCP flows for data transmission tasks. R is scaled down according to formula (3) and Figure 2.

In our simulation setup, a tunnel encapsulation technology is exploited to achieve transparent transmission since the

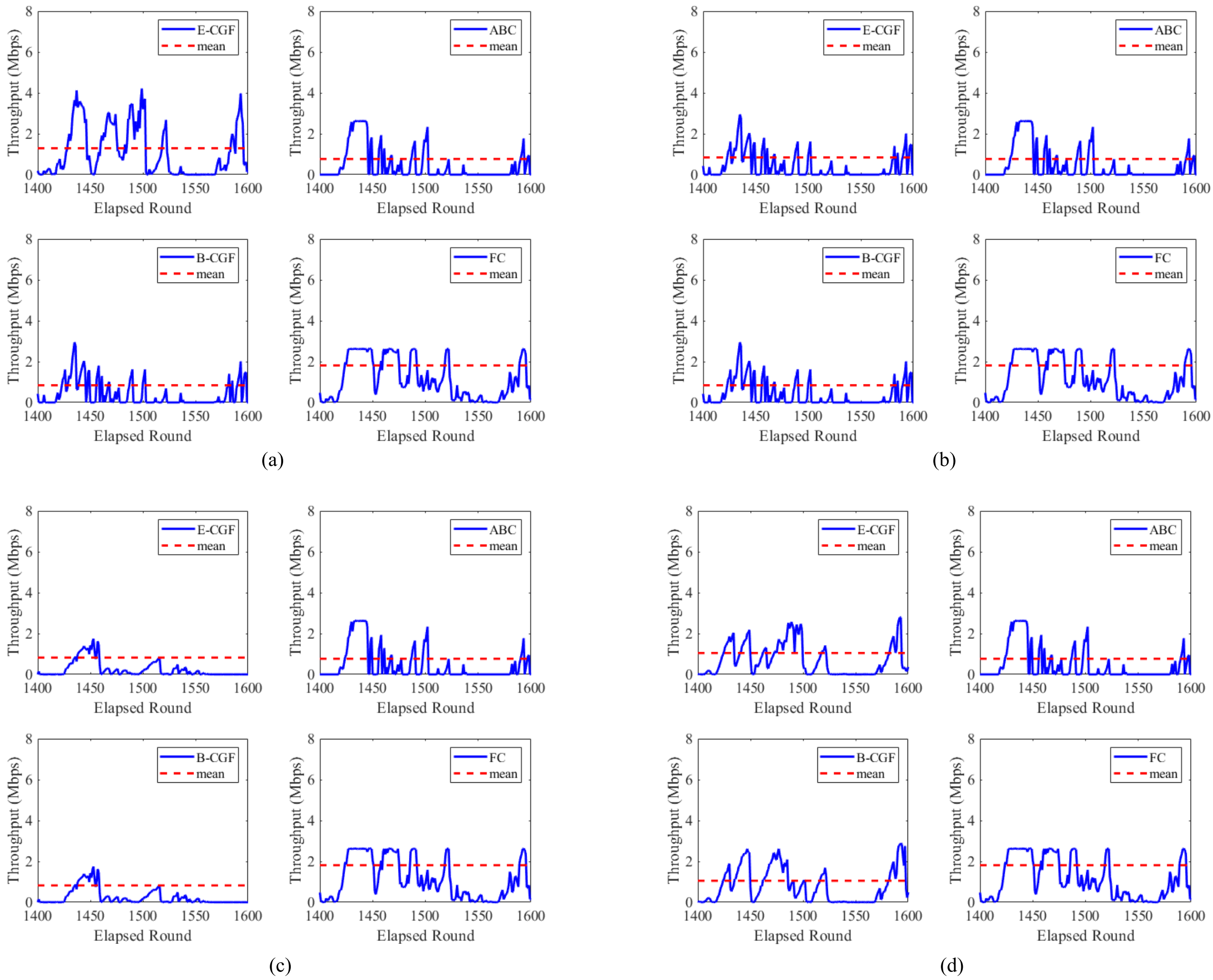

FIGURE 8. **An episode of users' throughput using E-CGF, ABC, B-CGF and FC solutions. (a) an episode of user 1. (b) an episode of user 3. (c) an episode of user 4. (d) an episode of user 4.**

replication process is operated at the network layer. Then, packets are copied and transferred through this tunnel according to a selected strategy profile σ. The peer of this tunnel only accepts the first arrival to avoid duplicate ACKs. In addition, we perform the simulation for about 6000 seconds each time, corresponding to 2000 rounds (3 seconds per round).

B. COMPARISON SOLUTIONS

As mentioned in Section I and Section II, three solutions are introduced for comparison.

1) ABC: Every user using ABC scheme always selects the best RAN to complete his task.

2) B-CGF: Different from E-CGF, Basic CGF (B-CGF) only utilizes the RAN that has the maximum throughput among those successfully completing his task. Therefore, its utility function can be shown in (5).

$$U_i(\sigma) = \sum_{A \in 2^{\sigma_i} \setminus \emptyset} [\max_{j \in A}(\alpha_j w_{ij})] \prod_{j \in A}(1 - f_j) \prod_{j \in \sigma_i \setminus A} f_j - \sum_{j \in \sigma_i}(P_{j_1} w_{ij} + P_{j_2}) f_j, \quad (5)$$

3) FC: Full-Copy is similar to [29] that user's data will be replicated to the same number as selected RANs, and these copies are transmitted through all selected RANs.

C. RESULTS

Here, we carefully observe the strategy profile and throughput results of each user. The strategy profile σ of these four solutions can be derived as below.

$$\sigma = \begin{cases} \{(1,3),(1,3),(1),(2),(2),(2),(3)\}, & \textit{E-CGF} \\ \{(1),\ldots,(1)\}, & \textit{ABC} \\ \{(1),(1),(1),(2),(2),(2),(3)\}, & \textit{B-CGF} \\ \{(1,2,3),\ldots,(1,2,3)\}, & \textit{FC} \end{cases} \quad (6)$$

Note that the values of $(1, 2, 3)$ are the sort result of these RANs by their link failure probabilities. The smaller the value, the better the network quality, and the lower the failure probability conversely. Hence, we analyze the throughput results of users with different strategies.

First of all, we observe an episode of users' throughput by using E-CGF, ABC, B-CGF and FC solutions, respectively.

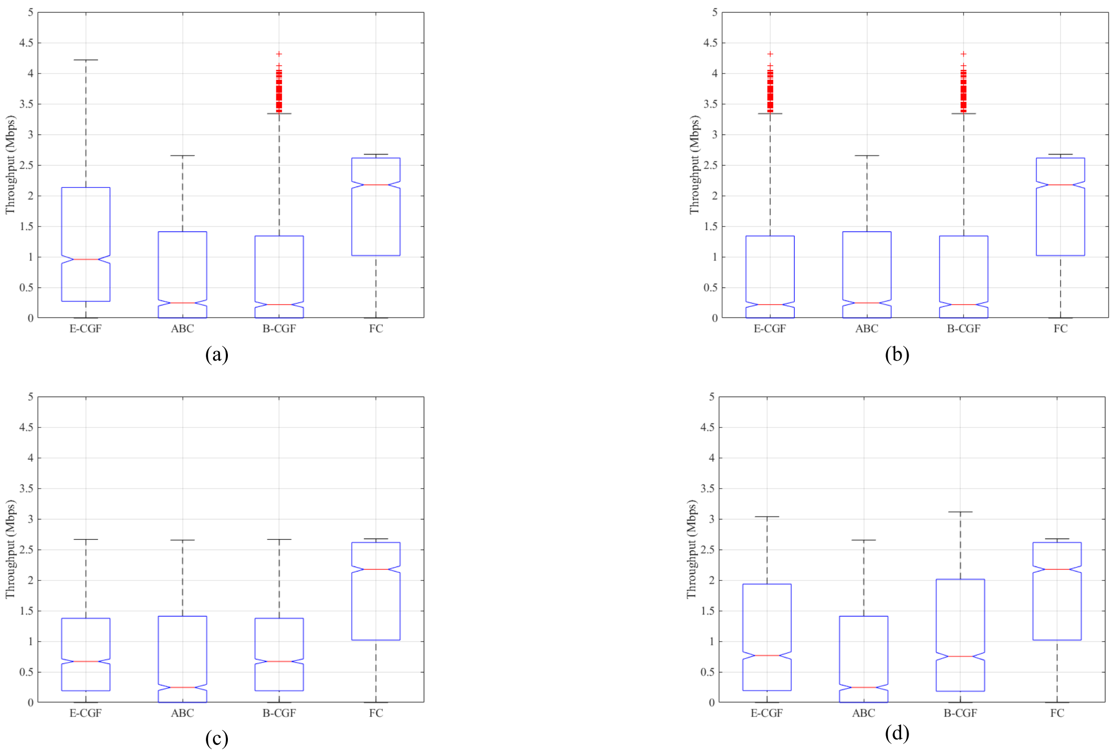

FIGURE 9. **The median and outlier values of users' throughput using E-CGF, ABC, B-CGF and FC solutions. (a) user 1. (b) user 3. (c) user 4. (d) user 7.**

We can see from Figure 8 that users obtain higher throughput peak values by using E-CGF and B-CGF than those using ABC and FC. This is because the congestion levels of the former two (E-CGF and B-CGF) are relatively lighter than the latter two (ABC and FC). Users will be assigned a higher rate while the congestion is lighter. As a result, throughput peak values of user 1 using E-CGF and B-CGF are 6.12612 and 4.31659, respectively. The values of user 7 using E-CGF and B-CGF are 3.0359 and 3.11452, respectively. Correspondingly, the values of user 1 and user 7 using ABC and FC are 2.67428 and 2.65284, respectively. We also observe from Figure 8 that, the redundant transmission of E-CGF and FC can alleviate the performance degradation caused by link failures. During the range of [1450,1500] on x-axis in Figure 8 a), the majority of results exceed 1 Mpbs by using E-CGF and FC, whereas most of them are below 1 Mbps by using ABC and FC. Besides, the throughput of user 1 evades the link failures during the range of [1450,1500] rounds by using E-CGF and FC, while it becomes zero by using ABC and B-CGF.

Further, we observe the average and median values of throughput results from Figure 8 and Figure 9. We can see from Figure 8 a) and Figure 9 a), user 1 using E-CGF achieves better throughput than using ABC and B-CGF. Relatively, he receives a higher throughput by using FC. Comparing their median values of user 1 in Figure 9 a), the result obtained by E-CGF is up to 2.90 times higher than that obtained by ABC, and is up to 3.38 times higher than that obtained by B-CGF. The result obtained by FC is up to 1.27 times higher than that obtained by E-CGF. But the transit cost is excessive when user 1 uses FC, and his utility will become negative ($U < 0$). We also observe Figure 8 c) and d) that, user 4 and 7 using E-CGF seem have no advantage than using ABC and B-CGF. Actually, we can see Figure 9 c) and d), the median values of user 4 and 7 obtained by using E-CGF are higher than those obtained by using ABC and B-CGF. Comparing their median values of user 7, the result obtained by E-CGF is up to 2.12 times higher than that obtained by ABC, and up to 1.9% higher than that obtained by B-CGF. In addition, we compare the results of different users using E-CGF in Figure 9. It's found out that user 1 has the best results, and user 7 has the second. The reason for user 1 is the benefit from redundant transmission ($|\sigma_i| \geq 1$), and the reason for user 7 is the benefit from fewer switches of his selection strategy during the simulation. Since the states of these RANs are changing during the simulation, users' selection strategy might be switched. As the statistics from simulation results of 2000 rounds, the numbers of switch round are 583 for user 7, 739 for user 3 and 836 for user 4. As a result, user 7 obtains a better throughput performance.

Finally, we analyze the sum of users' throughput in Figure 10. In terms of median value, the results are the same as those summarized above. The median value obtained by E-CGF is up to 2.57 times higher than that obtained by ABC, and is up to 1.36 times higher than that obtained by B-CGF. The median value of total throughput obtained by FC is up to 1.48 times higher than that obtained by E-CGF. In terms of standard deviation value, E-CGF gains the lowest.

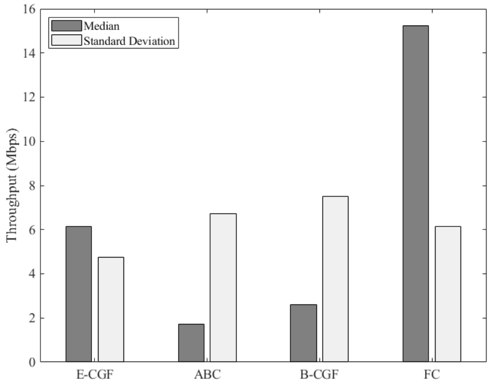

FIGURE 10. The median and standard deviation of total throughput using different solutions.

This reflects that our scheme has the ability to achieve more convergent results compared with other three solutions.

From these simulation results, we summarize the advantages of E-CGF: *(i)* E-CGF can avoid the congestion caused by user's selfishness to improve users' throughput. *(ii)* E-CGF can alleviate the performance degradation caused by link failures and high-speed mobility. *(iii)* E-CGF can achieve a more convergent outcome.

VII. CONCLUSION AND DISCUSSION

In this paper, E-CGF is proposed to address network congestion and reliability challenges of network selection in high-speed vehicular networks. Since the link failure plays a critical role in E-CGF, we take advantage of a hidden Markov model to establish the link failure probability in high-speed vehicular networks. Generally, users compete for RANs to maximize their own throughput. However, each user may utilize multiple radio networks simultaneously for redundant transmission, so as to an increase of his total transit cost. Therefore, the goal of E-CGF is to make a compromise between them. We prove the existence of Nash equilibrium of our game and construct an efficient algorithm to find the optimal strategy. We then perform a numerical analysis of E-CGF to evaluate the effect of different parameters on users' utilities. Finally, we carry out extensive experiments based on real-world traces of network states along high-speed rails. Results demonstrate that our scheme outperforms other algorithms by alleviating network congestion and improving transmission reliability with a moderate trade-off between throughput and transit cost. In our future work, we focus on the research of TCP congestion control mechanism in high-speed vehicular networks by taking multipath redundant transmission into consideration.

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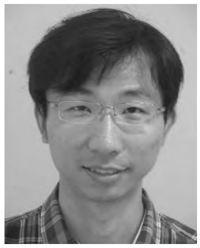

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