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Trust Aware V2V Relay Assisted Content Distribution in Cellular V2X Networks

Muhammad Saleh Bute, *Student Member, IEEE,* Pingzhi Fan, *Fellow, IEEE,* Gang Liu, *Member, IEEE,*
Li Zhang, *Senior Member, IEEE*

***Abstract*—The vehicular networks are envisioned to support the future intelligent transportation system (ITS). Content dissemination is vital to achieving efficient data traffic management and real-time decision-making. Limited resources constrain the vehicles and edge network, but the vehicle-to-vehicle (V2V) communication technology can support the conventional cellular communication link in content dissemination. To explore the full benefit of V2V, relay vehicles can be selected to support direct V2V links in situations where direct communication is not feasible due to distance or shadowing. However, not all vehicles will agree to participate in relaying without any reward. To counter this problem, we introduce an incentive mechanism to entice vehicles to assist in relaying. The trustworthiness between users is considered when establishing a V2V communication link. We jointly consider the content distribution mode and relay selection problems to maximize system utility. Moreover, improved auction algorithms were proposed to improve user utility. The proposed scheme is compared against some closely related baseline schemes.**

***Index Terms*—Relay, vehicle to everything (V2X), cellular, content, system utility, incentive.**

I. INTRODUCTION

WITH the massive growth in vehicular communication technologies, vehicular networks generate a lot of network traffic, which puts more burden on the existing network infrastructure [1], [2], [3]. The vehicular network is a major driving force in future intelligent transportation systems (ITS), supporting road safety and enhancing traffic efficiency [4], [5]. However, the increasing number of resource constrained connected vehicles and the proliferation of resource demanding vehicular applications such as augmented reality (AR) assisted driving poses a challenge for future networks in terms of data explosion and content dissemination [6], [7], [8]. To counter these problems, the direct device-to-device (D2D) enabled vehicular network can improve content dissemination efficiency and network traffic management [9], [10]. Direct vehicle-to-vehicle (V2V) communication can assist in content dissemination with higher reliability and data rates. However, direct V2V communication limits the advantages of V2V in the sense that vehicles will not be able to engage in direct V2V communication in some circumstances because of long communication distances or poor channel conditions due to channel fading, link obstruction, and shadowing caused by other vehicles in the network [11]. To tackle this problem, a relay vehicle can be selected to assist in content delivery. Relay supported content dissemination can improve network performance, reliability, and data rates [12].

Although some research has been conducted on relay-aided content delivery in cellular vehicle-to-everything (V2X) networks [2], [3], [4] where idle vehicles are selected as relays to assist in content dissemination, the selection of optimal relay vehicles is still a challenge. Several factors have an impact on relay selection [13], [14], such as willingness to assist in relaying contents, trustworthiness, transmission capability, mobility, and user satisfaction. However, it is difficult to choose the proper relay vehicle in polynomial time because it is subjected to several constraints. For example, a vehicle requesting content via direct V2V communication might be blocked by a moving truck, thereby obstructing the transmission link. Similarly, V2V communication can be obstructed by long distances due to high relative velocity. In such cases, direct V2V content dissemination cannot be completed. However, with the aid of a relay vehicle, such a transmission can be successful. Novel solutions are required to address the aforementioned problems in order to design an efficient content dissemination scheme.

Most of the existing work on relay selection focuses on energy efficiency [1], system sum rate [6], and system utility. Essential user attributes such as trustworthiness, incentive, willingness, and transmission capability are not considered. Few works integrate relay selection and user attributes in content dissemination. However, the joint mode selection for direct V2V and relay-assisted V2V considering trust and incentives has not been fully exploited. Therefore, there is a need to design an efficient content dissemination scheme while encouraging vehicles to participate in relaying when the need arises.

In this work, we propose a relay-assisted content dissemination scheme that jointly achieves the following goals: ascertaining the trustworthiness of vehicles that engage in content dissemination; introducing an incentive mechanism to motivate vehicles to assist in content relaying [15]; and maximization of system utility. Moreover, we apply an improved auction model, where vehicles use optimal bidding to compete. For spectral efficiency, we consider the underlay cellular network, where resource blocks are shared between cellular and V2V users. Power allocation is considered to avoid excessive mutual

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M. S. Bute, P. Fan, and G. Liu are with the Key Lab of Information Coding & Transmission, Southwest Jiaotong University, Chengdu 610031, China (e-mail: msbute@my.swjtu.edu.cn; pzfan@swjtu.edu.cn; gangliu@home.swjtu.edu.cn).

L. Zhang is with the Institute of Communication and Power Networks, School of Electrical and Electronic Engineering, University of Leeds, Leeds LS2 9JT, U.K (email: l.x.zhang@leeds.ac.uk).

interference. The main contributions of the proposed scheme are as follows:

- A relay-assisted content distribution scheme is proposed that jointly considers content transmission mode and relay selection. An improved auction model is designed to maximize system utility and provide incentive mechanisms to motivate vehicles to participate in relaying.
- A relay vehicle selection model is introduced to support vehicles that cannot establish direct V2V communication link due to poor channel conditions or a long communication distance.
- Social trust between users is obtained based on direct and indirect observation by applying Bayesian inference and Dempster-Shafer theory, respectively.
- The performance of the proposed scheme has been evaluated through simulations. The result shows that the proposed scheme can efficiently disseminate contents and improve system utility.

The remainder of this article is divided into the following sections: A concise review of the related works is provided in Section II. Section III describes the proposed system model. Section IV presents the problem formulation. Section V explains the proposed V2V relay-assisted content distribution scheme. Section VI presents performance evaluations and simulations. Finally, Section VII concludes the paper.

II. RELATED WORK

With the increasing demand for efficient content dissemination schemes in cellular networks due to the data traffic explosion, many researchers have recently focused on content dissemination schemes. Liu et al. [16] present relay-assisted D2D communication to support data dissemination in cellular networks. They propose an algorithm to solve joint relay selection and resource allocation problem optimally. The work in [4] studied intelligent content dissemination in vehicular edge networks; fuzzy logic was applied in selecting relaying vehicles. The dual importance evaluation approach was exploited in determining the priority of vehicles based on content and vice versa. Li et al. [1] proposed an energy-efficient multiple relaying-aided computation offloading and a low complexity online algorithm was explored to minimize execution cost. In [17], the authors proposed a content delivery framework for vehicular clouds where content is cached on selected relay vehicles for further dissemination to the requesting vehicles based on a hierarchical name model. The work in [18] presents multicarrier relay-aided offloading in mobile edge networks and develops a framework that supports simultaneous data transfer and parallel execution. Qin et al. [19] studied computation and relaying in mobile edge computing. They proposed a relaying scheme that can enhance the throughput of uncompressed data using the Lambert function. In contrast with the above schemes, we consider social relationships among users for content dissemination. [1], [3], [10], [11], [12], [13] consider only the physical attributes of users in relay selection. However, social ties among users can improve trust, reliability, and willingness to support users in need of relay, which will improve overall system utility and user satisfaction.

Zhao et al. [20] proposed a social and mobility-assisted content dissemination scheme in which relay nodes were selected based on physical and social graphs. The authors exploit the Girvan Newman algorithm to determine the edge betweenness of the nodes. In [21], socially aware relaying in a vehicular content-centric network was proposed. The relaying vehicles were chosen based on social similarity, mobile trajectory, and centrality. The work in [6] presented a socially assisted relay selection scheme with the aim of maximizing energy efficiency. The authors apply the concept of dynamic peer selection while considering spectrum and power trading in the cellular network. Li et al. [2] studied energy-efficient relay selection based on social relationships; social ties among users were used for participation in cooperative communication. The optimization problem was solved using game theory, aiming at minimizing energy consumption and mutual interference. The work in [22] aims at improving content dissemination by considering social trust and battery level in relay selection. Unlike the works presented in [2], [4], [14], [15], [16] where only direct observation is considered in deriving social ties between users. However, direct observation has some limitations in some cases, where a user might be biased against others. Therefore, in the proposed scheme, we consider both direct and indirect observation in the evaluation of trustworthiness among users. Also, to motivate users to assist in relaying, we introduced an incentive mechanism through an auction.

Moreover, few works propose an incentive-based content relaying scheme. Due to the selfish nature of users, the works in [23], [24] explore incentives to motivate users to support relaying. Different from these schemes, an improved auction model is designed based on heterogeneity. The bid of users in the model considers factors such as data rate, social trust, incentive, cost, and competition among users. In this paper, we propose an efficient V2V relay selection scheme in a cellular V2X network, where we consider social trust and incentive in relay selection. Due to spectrum sharing between cellular and V2V users, power allocation is also considered. Based on this, an optimization problem is formulated to maximize system utility and improve content dissemination.

III. SYSTEM MODEL

In the proposed scheme, we consider a base station with M cellular users in the set $CU = \{cu_1, cu_2, cu_3, ..., cu_M\}$, N V2V pairs in the set $VU = \{vu_1, vu_2, vu_3, ..., vu_N\}$, and each V2V pair consists of a transmitter vt and a receiver vr. A set of relay vehicles is presented in the set $RU = \{ru_1, ru_2, ru_3, ..., ru_K\}$. We consider an underlay cellular network where cellular users and V2V users share the uplink spectrum, each link can only be reused by one V2V user, and each relay vehicle can only support one V2V pair. Time is divided into slots $\tau \in \Psi$, where $\Psi = \{1, 2, 3, ..., \tau_F\}$. For each relay vehicle, the requesting vehicle presents its request as a bid, denoted as bd_j. A bid is proposed based on the valuation of the prospective relay vehicles. The relay vehicle will in turn present its asking price A_k which is also known as the reserve price [25]. The V2V vehicle valuation for each

TABLE I: Key Notations

Parameter	Definition
CU	the set of cellular users
VU	the set of V2V users
RU	the set of relay vehicles
τ	time slot
$\gamma v_{i,j}$	SINR of V2V link in direct V2V mode
$\gamma c_{i,j}$	SINR of cellular link in direct V2V mode
$RD_{i,j}$	data rate of a transmission link in direct V2V mode
$\gamma^a v_{i,j}$	SINR of V2V link in relay mode (phase one)
$\gamma^a c_{i,j}$	SINR of cellular link in relay mode (phase one)
$\gamma^b v_{i,j}$	SINR of V2V link in relay mode (phase two)
$\gamma^b c_{i,j}$	SINR of cellular link in relay mode (phase two)
$RR_{i,j}$	data rate of a transmission link in relay mode
$\gamma^v_{\min}$	minimum SINR for V2V users
$\gamma^c_{\min}$	minimum SINR for cellular users
$P^c_{\min}, P^c_{\max}$	minimum and maximum transmit power of cellular users
$P^d_{\min}, P^d_{\max}$	minimum and maximum transmit power of V2V users
$P^r_{\min}, P^r_{\max}$	minimum and maximum transmit power of relay vehicles
$\hat{P}d_i$	optimal transmit power of V2V users
$\hat{P}c_m$	optimal transmit power of cellular users
$\hat{P}r_k$	optimal transmit power of relay vehicles
$Ts_{i,j}$	trust value of users
$\alpha_{i,j}$	binary variable indicating content dissemination in direct V2V mode
$\beta_{i,j}$	binary variable indicating content dissemination in relay mode
ve_i	valuation of transmission link in direct V2V mode
vd_i	valuation of transmission link in relay mode
py_i	charges paid by V2V users
px_k	payment received by relay vehicle
U^{total}	system utility
bd_j	bid submitted by a buyer
bd_η	least submitted bid
A_k	asking price of a seller
A_μ	median asking price
RU_w	the set of wining sellers
VU_w	the set of wining buyers

relay vehicle differs due to several metrics, such as data rate, distance, and trust value. The relay vehicles give a uniform price for buyers since their objective is to receive payment for their services. At the base station, a central controller is responsible for coordinating content dissemination. Vehicles send in their details, such as vehicle ID, driving direction, position, velocity, etc. These details are updated periodically and reactively when necessary [9], [10]. When a content request is sent in, based on the demand and available resources, the controller will determine the content dissemination mode, either through direct V2V mode or relay mode. Privacy and security are essential features for secured wireless services and content dissemination. In the proposed scheme, we introduce trust-based V2V discovery and pairing in order to improve reliability and content delivery success. The trust value denoted as $Ts_{i,j} \in [0, 1]$ of each vehicle is computed; only vehicles with trust values equal to or above the threshold can participate in content dissemination.

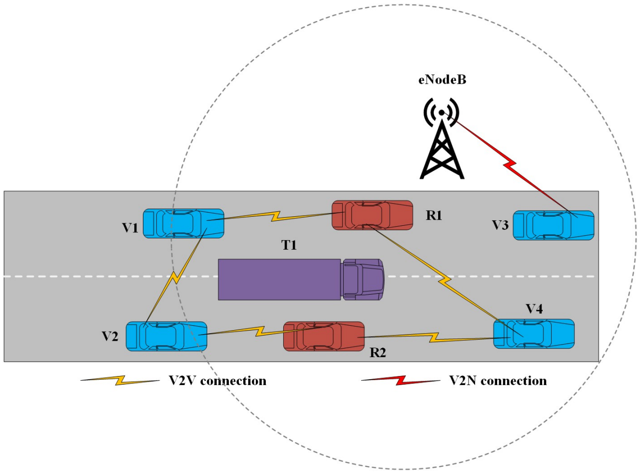

Fig. 1: System Model

As illustrated in Fig. 1, Vehicles V1 and V2 appeared to be at the edge of the network coverage of eNodeB, where the communication signal to eNodeB is low. Therefore, an intermittent link is not suitable for receiving content from the eNodeB. For V1 to engage in direct V2V communication to receive content from V4, it is impossible due to shadowing or blockage from truck T1. Therefore, vehicle R1 is selected as a relay to support communication between V1 and V4. Similarly, vehicle V2 will not be able to receive content directly from vehicle V4 due to the long communication distance. Therefore, vehicle R2 is selected as a relay vehicle to aid communication between vehicles V2 and V4. Vehicle V3 communicates with the eNodeB through a cellular link. Similarly, V1 and V2 can engage in direct V2V communication.

A. Physical Layer

In this section, we consider physical layer data for content transmission using the uplink channels. In channel modeling, we consider both small-scale fading and large-scale fading. The channel gain between two vehicles vt_i and vr_j can be expressed as $g_{i,j} = \ell \Phi_{i,j} z_{i,j} \partial_{i,j}^{-\Delta}$, where ℓ denotes the path loss constant, $\Phi_{i,j}$ denotes fast fading with exponential distribution, $z_{i,j}$ denotes small-scale fading with lognormal distribution, $\partial_{i,j}$ is the distance between the vehicles, and Δ denotes the path loss exponent [1].

1) Content Transmission Rate in Direct V2V Mode

In direct V2V mode, the signal to noise ratio (SINR) of the V2V link and cellular link on a channel can be expressed as [26].

$$\gamma v_{i,j} = \frac{Pd_i g_{i,j}}{Pc_m g_{m,j} + N_0} \tag{1}$$

where Pd_i is the transmission power of the V2V transmitter, $g_{i,j}$ denotes the channel gain between the V2V pair, Pc_m is the transmission power of the cellular user cu_m, $g_{m,j}$ denotes the interfering channel gain between cellular user cu_m and V2V receiver vr_j, and N_0 denotes the noise power.

$$\gamma c_{i,j} = \frac{Pc_m g_{m,b}}{Pd_i g_{i,b} + N_0} \tag{2}$$

where $g_{m,b}$ is the channel gain between the cellular user m and the base station. $g_{i,b}$ denotes the interfering channel gain between the V2V transmitter vt_i and the base station. Therefore, the achievable data transmission rate of a V2V link and a cellular link can be expressed as

$$\begin{aligned} Rv_{i,j} &= w_0 \log_2(1 + \gamma v_{i,j}) \\ Rc_{i,j} &= w_0 \log_2(1 + \gamma c_{i,j}) \end{aligned} \tag{3}$$

where w_0 denotes the allocated bandwidth. The total achievable data transmission rate in direct V2V mode can be expressed as

$$RD_{i,j} = Rv_{i,j} + Rc_{i,j} \tag{4}$$

2) Content Transmission Rate in Relay Mode

In the relaying mode, we consider the decode and forward (DF) technique. The data transmission period is divided into two intervals. In the initial phase, content is transferred from the V2V transmitter to the relaying vehicle. In the second phase, the content is forwarded from the relay vehicle to the V2V receiver. The SINR of the V2V link and the cellular link, respectively, in phase one can be expressed as

$$\begin{aligned} \gamma^a v_{i,j} &= \frac{Pd_i g_{i,k}}{Pc_m g_{m,k} + N_0} \\ \gamma^a c_{i,j} &= \frac{Pc_m g_{m,b}}{Pd_i g_{i,b} + N_0} \end{aligned} \tag{5}$$

where Pd_i and Pc_m are the transmission powers of V2V transmitter vt_i and cellular user cu_m respectively, $g_{i,k}$ denotes the channel gain between V2V transmitter vt_i and relay vehicle ru_k, $g_{m,k}$ denotes the interfering channel gain between cellular user cu_m and relay vehicle ru_k, $g_{m,b}$ is the channel gain between the cellular user cu_m and the base station, $g_{i,b}$ is the interfering channel gain between the V2V transmitter vt_i and the base station, and N_0 denotes the noise power. The SINR of the V2V link and the cellular link, respectively, in phase two can be expressed as

$$\begin{aligned} \gamma^b v_{i,j} &= \frac{Pr_k g_{k,j}}{Pc_m g_{m,j} + N_0} \\ \gamma^b c_{i,j} &= \frac{Pc_m g_{m,b}}{Pr_k g_{k,b} + N_0} \end{aligned} \tag{6}$$

where Pr_k and Pc_m are the transmission powers of relay vehicle ru_k and cellular user cu_m respectively, $g_{k,j}$ denotes the channel gain between the relay vehicle ru_k and the V2V receiver rv_j, $g_{m,j}$ is the interfering channel gain between the cellular user cu_m and the V2V receiver vr_j, $g_{m,b}$ denotes the channel gain between the cellular user cu_m and the base station, $g_{k,b}$ is the interfering channel gain between the relay vehicle ru_k and the base station, and N_0 denotes the noise power. Therefore, The data transmission rate of a V2V link in relaying mode can be given as

$$Rv_{i,j}^{ab} = \tfrac{1}{2} w_0 \log_2 \left(1 + \min\left(\gamma^a v_{i,j}, \gamma^b v_{i,j}\right)\right) \tag{7}$$

Since data transmission in relay mode includes transmitting data from the source vehicle (V2V transmitter) to the relay vehicle and from the relay vehicle to the destination vehicle (V2V receiver), the transmission time in relay mode is divided into two halves, which are denoted by $\frac{1}{2}$ in the equation above. w_0 denotes the allocated bandwidth, $\gamma^a v_{i,j}$ is the SINR of the V2V link between the source vehicle and the relaying vehicle, and $\gamma^b v_{i,j}$ is the SINR of the V2V link between the relaying vehicle and the destination vehicle. The data transmission rate of a cellular link in relaying mode can be given as

$$Rc_{i,j}^{ab} = \left(\tfrac{1}{2} w_0 \log_2 \left(1 + \gamma^a c_{i,j}\right) + \tfrac{1}{2} w_0 \log_2 \left(1 + \gamma^b c_{i,j}\right)\right) \tag{8}$$

The data transmission in relaying mode is in two halves. The first term is transmission rate of the cellular link in the first phase, and the second term is data transmission of the cellular link in the second phase. $\gamma^a c_{i,j}$ denotes the SINR of the cellular link in the first phase, $\gamma^b c_{i,j}$ denotes the SINR of the cellular link in the second phase, and w_0 is the allocated bandwidth. The total data transmission rate in the relaying mode can be expressed as

$$RR_{i,j} = Rv_{i,j}^{ab} + Rc_{i,j}^{ab} \tag{9}$$

B. Social Layer

In this section, we consider the social trust among users through their engagements. Social trust is the degree of belief in the behavior of a user; where the trust level determines the reliability of the user for content dissemination [27], the trust value $Ts_{i,j}$ of a user is evaluated within the range of $[0, 1]$. In the proposed scheme, we jointly consider direct observation and indirect observation in ascertaining the trust value between users. In direct observation, the trust value of a user is obtained by estimating the degree of trustworthiness from direct communication with other users in the past. However, the subjectiveness of a direct connection may be biased. Integration of observations from other indirect connections can improve the accuracy of trust evaluation [28]. The trust value between users can be denoted as

$$Ts_{i,j} = \theta T^d + (1-\theta)T^i, \text{ where } 0 \leq \theta \leq 1 \tag{10}$$

where T^d is the trust value of direct connection, T^i denotes the trust value of indirect connection, and θ denotes the weight that adjusts between direct observation and indirect observation.

1) Direct Observation

In this section, we assume that the observing user overhears contents transferred by the observed user in order to identify the observed user's malicious behavior, such as halting content transfer by discarding, incomplete transfer, or modification of the original data. By conducting several observations on the observed user, we can apply Bayesian inference to evaluate the trust value of the observed user.

(i) Bayesian Framework

The Bayesian technique allows the incorporation of personal belief or opinion in decision-making, which is a well-suited solution to stochastic problems. In the proposed Bayesian framework, the trust of a user is defined as a continuous random variable [29], which is denoted as η with a variable ε that takes a value within the range of $[0,1]$. Consider that η follows a beta distribution $\eta \sim Beta(x,y)$ which can be expressed with parameters x and y.

$$Beta(x,y) = \frac{\varepsilon^{x-1}(1-\varepsilon)^{y-1}}{\int\limits_0^1 \varepsilon^{x-1}(1-\varepsilon)^{y-1}d\varepsilon} \tag{11}$$

where η follows beta distribution. Therefore, the trust value can be defined by the parameters x and y. The belief of the trust η is iteratively updated as more observations are obtained. Assuming the pdf of the prior observation is known, the posterior distribution at the tth observation can be expressed as

$$f_t(\varepsilon) = \frac{f_t\left(a_t|\varepsilon, b_t\right) f_{t-1}\left(\varepsilon\right)}{\int\limits_0^1 f_t\left(a_t|\varepsilon, b_t\right) f_{t-1}\left(\varepsilon\right) d\varepsilon} \tag{12}$$

where a_t is the number of packets that have been correctly transmitted at the tth observation, b_t denotes the number of packets received by the user at the tth observation, $f_t\left(a_t|\varepsilon, b_t\right)$ denotes the likelihood function, which obeys the binomial distribution and can be expressed as

$$f_t\left(a_t|\varepsilon, b_t\right) = \binom{a_t}{b_t} \varepsilon^{a_t}(1-\varepsilon)^{b_t-a_t} \tag{13}$$

Therefore, the prior distribution $f_{t-1}\left(\varepsilon\ \right)$ also follows the beta distribution since the likelihood function follows the binomial distribution. Given that the posterior distribution $f_t\left(\varepsilon\ \right)$ and prior distribution $f_{t-1}\left(\varepsilon\ \right)$ follows beta distribution, where $f_{t-1}\left(\varepsilon\ \right) \sim Beta\left(x_{t-1}, y_{t-1}\right)$ and the parameters a_t, b_t are obtained from the tth observation, then we have

$$f_t\left(\varepsilon\right) \sim Beta\left(x_{t-1}+a_t, y_{t-1}+a_t-b_t\right), \ t \geq 1 \tag{14}$$

Due to the lack of prior information in the early stages of the observation, we assume η follows a uniform distribution $f_0\left(\varepsilon\ \right) \sim Beta\left(1,1\right)$. Therefore, $f_t\left(\varepsilon\ \right)$ follows $Beta\left(x_t, y_t\right)$ with the following parameters

$$\begin{aligned} x_t &= x_{t-1}+a_t, \text{ where } x_0 = 1 \\ y_t &= y_{t-1}+b_t-a_t, \text{ where } y_0 = 1 \end{aligned} \tag{15}$$

Consequently, after the tth iteration, trust value based on direct observation can be expressed as the expected value of ε with respect to $f_t(\varepsilon)$

$$T^d = \frac{x_t}{x_t+y_t} \tag{16}$$

Therefore, the initial trust value of a user can be continuously updated through follow-up observation.

2) Indirect Observation

Indirect observation is also crucial in evaluating the trustworthiness of a user. Indirect observation will ensure fairness by curtailing user sentiments in a situation where an observed user is honest with one user but dishonest with others. Consider that the observing user obtains observations from other users and integrates their opinions into its decision. However, the third-party opinion may be unreliable. The Dempster Shafer method can be applied to handle uncertainty from third-party observers effectively [30]. In indirect observation, we assume that there is more than one third-party observing user and that their evidence is mutually independent.

(i) Belief Function

Belief function is a mathematical probability to quantify subjective verdicts or judgments. In the proposed scheme, we consider a third-party observation on the trustworthiness of a user, the observation verdict can be given as to whether the user is trustworthy or untrustworthy. For example, consider that user A gives a verdict that user C is trustworthy, the hypothesis can be given as G, and the basic probability is given as ρ_1. If user A gives a verdict that user C is untrustworthy, the hypothesis can be given as $\bar{G}$ and the basic probability is given as 0. If user A gives a verdict that user C is either trustworthy or untrustworthy (uncertain), the hypothesis can be given as U, and the basic probability is given as $1-\rho_1$. Therefore, if user A believes that user C is trustworthy, then the basic probability assignment can be defined as

$$\begin{aligned} h_1\left(G\right) &= T_1^d \\ h_1\left(\bar{G}\right) &= 0 \\ h_1\left(U\right) &= 1-T_1^d \end{aligned} \tag{17}$$

where T_1^d denotes the trust value of user A through direct observation of user C and the value of T_1^d ranges within [0,1].

$h_1(G)$ is the probability of the hypothesis that a user is trustworthy, $h_1(\bar{G})$ is the probability of the hypothesis that a user is untrustworthy, and $h_1(U)$ is the probability of the hypothesis a user is neither trustworthy nor untrustworthy (uncertain). However, if user A considers user C untrustworthy, the basic probability assignment can be defined as

$$\begin{aligned} h_1\left(G\right) &= 0 \\ h_1\left(\bar{G}\right) &= T_1^d \\ h_1\left(U\right) &= 1 - T_1^d \end{aligned} \tag{18}$$

where T_1^d denotes the trust value of user A through direct observation of user C and the value of T_1^d ranges within [0,1]. $h_1(G)$ is the probability of the hypothesis that a user is trustworthy, $h_1(\bar{G})$ is the probability of the hypothesis that a user is untrustworthy, and $h_1(U)$ is the probability of the hypothesis a user is neither trustworthy nor untrustworthy (uncertain). Let φ be the universe of discourse, and φ= $\{trustworthy, untrustworthy\}$ represent the possible states considered in the model. The power set $2^{\varphi} = \{\emptyset, \{trustworthy\}, \{untrustworthy\}, \varphi\}$ defines the set of all subsets of φ. Let hypothesis Q_i be a subset of 2^{φ} and be mapped into basic probability $h\left(Q_i\right)$, which represents the proportion of the total belief given to hypothesis Q_i, the following condition has to be satisfied: $h\left(\emptyset\right) = 0$ and $\sum_{Q_i \subseteq \varphi} h\left(Q_i\right) = 1$. The belief function can be expressed as

$$blv\left(C\right) = \sum_{Q_i \subseteq C} h\left(Q_i\right) \tag{19}$$

(ii) Integration of Belief Functions

The Dempster-Shafer method can be used to combine multiple user's beliefs based on independent evidence. For example, consider that $blv_1\left(C\right)$ and $blv_2\left(C\right)$ are belief functions under φ. The sum of $blv_1\left(C\right)$ and $blv_2\left(C\right)$ can be expressed as follows

$$\begin{aligned} blv\left(C\right) &= blv_1\left(C\right) \oplus blv_2\left(C\right) \\ blv\left(C\right) &= \frac{\sum_{i,j,Q_i \cap Q_j = C} h_1\left(Q_i\right) h_2\left(Q_j\right)}{\sum_{i,j,Q_i \cap Q_j \neq \emptyset} h_1\left(Q_i\right) h_2\left(Q_j\right)} \end{aligned} \tag{20}$$

where $Q_i, Q_j \subseteq \varphi$, and $h_1(Q_i) > 0,\ h_2(Q_j) > 0$. The basic probability of the hypothesis Q_i is denoted by $h_1(Q_i)$, and the basic probability of the hypothesis Q_j is denoted by $h_2(Q_j)$. The integrated degrees of belief of two users can be obtained as follows

$$\begin{aligned} h_1\left(G\right) \oplus h_2\left(G\right) =& \frac{1}{L} h_1\left(G\right) h_2\left(G\right) + h_1\left(G\right) h_2\left(U\right) \\ & + h_1\left(U\right) h_2\left(G\right) \end{aligned} \tag{21}$$

$$\begin{aligned} h_1\left(\bar{G}\right) \oplus h_2\left(\bar{G}\right) =& \frac{1}{L} [h_1\left(\bar{G}\right) h_2\left(\bar{G}\right) + h_1\left(\bar{G}\right) h_2\left(U\right) \\ & + h_1\left(U\right) h_2\left(\bar{G}\right)] \end{aligned} \tag{22}$$

thus, we have

$$h_1\left(U\right) \oplus h_2\left(U\right) = \frac{1}{L} [h_1\left(U\right) h_2\left(U\right)] \tag{23}$$

where L is defined as

$$\begin{aligned} L =& [h_1\left(G\right) h_2\left(G\right) + h_1\left(G\right) h_2\left(U\right) + h_1\left(U\right) h_2\left(U\right) \\ & + h_1(U) h_2(G) + h_1\left(U\right) h_2(\bar{G}) + h_1(\bar{G}) h_2(\bar{G}) \\ & + h_1(\bar{G}) h_2\left(U\right)] \end{aligned} \tag{24}$$

Using the combination of belief techniques, we can integrate multiple degrees of belief from other users, and the trust value of indirect observation can be defined as

$$T^i = h_1\left(G\right) \oplus h_2\left(G\right) \oplus h_3\left(G\right) ... \oplus h_h\left(G\right) \tag{25}$$

IV. PROBLEM FORMULATION

In the proposed scheme, the V2V links augment the cellular links in content distribution. V2V can disseminate content either through direct V2V mode or relaying mode. The major aim is to successfully deliver content to requesting vehicles; the system utility is used to represent gain and cost in the process of content delivery. To maximize the system's utility, we have to maximize the sum of the utilities of all vehicles. When content is disseminated in direct V2V mode, the binary indicator can be given as

$$\alpha_{i,j} = \begin{cases} 1, & \text{direct V2V mode} \\ 0, & \text{otherwise} \end{cases} \tag{26}$$

Likewise, when content is disseminated in relay mode, we have

$$\beta_{i,j} = \begin{cases} 1, & \text{relay mode} \\ 0, & \text{otherwise} \end{cases} \tag{27}$$

The valuation of a transmission link ve_i between vehicle vt_i and vr_j in direct V2V mode can be given as $ve_i = Ts_{i,j} RD_{i,j}$, where $Ts_{i,j}$ denotes the trust value between users, and $RD_{i,j}$ is the data rate of the transmission channel between vehicle vt_i and vr_j in direct V2V mode. Thus, the utility of V2V users in direct V2V mode can be given as $U^v = ve_i - ct_i$, where ct_i is the content transmission cost.

The valuation of a transmission link vd_i between vehicle vt_i and vr_j in relay mode can be given as $vd_i = Ts_{i,j} RD_{i,j}$, where $Ts_{i,j}$ denotes the trust value between users, and $RR_{i,j}$ is the data rate of the transmission channel between vehicle vt_i and vr_j in relay mode. The utility of V2V users in relay mode can be given as $U^d = py_i - vd_i$, where py_i denotes the payment for resources leased by the relay vehicle. The utility of the relay vehicle can be given as $U^r = A_k - px_k$, where px_k denotes the payment received by the relay vehicle. Therefore, the total system utility can be expressed as

$$U^{total} = U^v \alpha_{i,j} + (U^d + U^r) \beta_{i,j} \tag{28}$$

Since the content request and content dissemination modes are independent in any two time slots. We consider a single time slot, where $|\tau|$ denotes duration of a slot; thus, to maximize the total system utility, the optimization problem can be formulated as

Problem P1:

$$
\begin{aligned}
\underset{\{P,\alpha,\beta\}}{\text{maximize}} \quad & \frac{1}{|\tau|}\sum_{m=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{K}U^{total} \\
\text{subject to} \quad & C1: \gamma v_{i,j} \geq \gamma_{\min}^{v}; \gamma^{a} v_{i,j}, \gamma^{b} v_{i,j} \geq \gamma_{\min}^{v}, \forall i \in N \ , \\
& C2: \gamma c_{i,j} \geq \gamma_{\min}^{c}; \gamma^{a} c_{i,j}, \gamma^{b} c_{i,j} \geq \gamma_{\min}^{c}, \forall j \in M \ , \\
& C3: 0 \leq Pd_{i} \leq P_{\max}^{d}, \forall i \in N \ , \\
& C4: 0 \leq Pc_{m} \leq P_{\max}^{c}, \forall m \in M \ , \\
& C5: 0 \leq Pr_{k} \leq P_{\max}^{r}, \forall k \in K \ , \\
& C6: \alpha_{i,j} \in \{0,1\}, \beta_{i,j} \in \{0,1\}, \forall i \in N \ , \\
& C7: \sum_{j=1}^{N}\alpha_{i,j} + \sum_{k=1}^{K}\beta_{i,j} \leq 1, \forall k \in K
\end{aligned}
\tag{29}
$$

where constraints C1 and C2 denote the minimum SINR requirement of the V2V and cellular links. C3-C5 ensures that the transmit power of V2V, cellular, and relay vehicles does not exceed the maximum limit. C6 is a binary variable indicating data transmission mode. C7 ensures that vehicles can receive content in either direct V2V mode or relay mode. The formulated optimization problem is NP-hard [4], where the complexity of the problem increases with the large number of vehicles in the network. To solve the problem, we decompose it into two subproblems: power allocation and relay selection.

Theorem 1: Problem P1 is NP-hard to solve unless $NP = ZPP$

Proof: The theorem is proved by reducing the maximum independent set problem (MISP), and problem P1 will be built from the MISP. To define MISP, consider a graph $Gr = (Vx, Ee)$ an independent set Υ is a maximum independent set if for $vx \in Vx$ one of these conditions has to be satisfied: $vx \in \Upsilon$ or $N(vx) \cap \Upsilon \neq \emptyset$. Where $N(vx)$ are the neighbours of vx. In the formulated problem, it is assumed that edge Ee is the set of relay vehicles (sellers) RU, and vertex Vx denotes a set of V2V pairs requesting for a relay (buyers) VU. For any two winners $\{vu_1, ru_1\}$ and $\{vu_2, ru_2\}$ from the set of winning sellers RU_w and winning buyers VU_w, must satisfy that $\{vu_1, ru_1\} \cap \{vu_2, ru_2\} = \emptyset$. Therefore, the vertex Vx is independent of the graph. The system utility is the same size as that of the set; this implies that the optimal system utility is at least Π if and only if there exists an independent set of size Π. Hence, MISP, which is NP-hard, is reduced to problem P1. Therefore, problem P1 is NP-hard.

V. THE PROPOSED V2V RELAY-ASSISTED CONTENT DISTRIBUTION SCHEME

A. Power Allocation

For content dissemination in direct V2V mode, the power allocation problem can be given as

Problem P2:

$$
\begin{aligned}
\underset{\{Pd_i, Pc_m\}}{\text{maximize}} \quad & RD_{i,j} \\
\text{subject to} \quad & C1.1: \gamma v_{i,j} \geq \gamma_{\min}^{v}, \gamma c_{i,j} \geq \gamma_{\min}^{c} \ , \\
& C2.1: 0 \leq Pc_{m} \leq P_{\max}^{c} \ , \\
& C3.1: 0 \leq Pd_{i} \leq P_{\max}^{d}
\end{aligned}
\tag{30}
$$

Let $\hat{P}d_i$ and $\hat{P}c_m$ denote the optimal transmission power for V2V users and cellular users, respectively. To achieve the optimal data rate, either $\hat{P}c_m$ or $\hat{P}d_i$ have to be equal to the maximum transmit power as proved [16]. However, when $\hat{P}c_m = P_{\max}^{c}$ problem P2 is convex within the range $0 \leq Pd_i \leq P_{\max}^{d}$. Also, when $\hat{P}d_i = P_{\max}^{d}$ problem P2 is convex within the range $0 \leq Pc_m \leq P_{\max}^{c}$. Therefore, $\left(\hat{P}d_i, \hat{P}c_m\right)$ can be chosen from a feasible set of solutions ψ [16].

$$
\left(\hat{P}d_i, \hat{P}c_m\right) = \begin{cases} (0,0), & \psi = \emptyset \\ \underset{(Pd_i, Pc_m) \in \psi}{\arg\max} RD_{i,j} \ , & \text{otherwise} \end{cases}
\tag{31}
$$

where $\psi = \psi_a \cup \psi_b$

$$
\psi_a = \begin{cases} \{(P_{\max}^{c}, Za), (P_{\max}^{c}, Zb)\}, & Za \leq Zb \\ \emptyset, & \text{otherwise} \end{cases}
\tag{32}
$$

$$
\psi_b = \begin{cases} \left\{\left(Zc, P_{\max}^{d}\right), \left(Zd, P_{\max}^{d}\right)\right\}, & Zc \leq Zd \\ \emptyset, & \text{otherwise} \end{cases}
\tag{33}
$$

Also, as proved in [42] we have

$$
\begin{aligned}
Za &= \max\left\{0, \frac{\gamma_{\min}^{v}\left(P_{\max}^{c} g_{m,j} + N_0\right)}{g_{i,j}}\right\} \\
Zb &= \min\left\{P_{\max}^{d}, \frac{\left(P_{\max}^{c} g_{m,b} - \gamma_{\min}^{c} N_0\right)}{g_{i,j}\gamma_{\min}^{c}}\right\} \\
Zc &= \max\left\{0, \frac{\gamma_{\min}^{c}\left(P_{\max}^{d} g_{i,b} + N_0\right)}{g_{m,b}}\right\} \\
Zd &= \min\left\{P_{\max}^{c}, \frac{\left(P_{\max}^{d} g_{i,j} - \gamma_{\min}^{v} N_0\right)}{g_{m,j}\gamma_{\min}^{v}}\right\}
\end{aligned}
\tag{34}
$$

Therefore, the optimal system data rate in direct V2V content dissemination can be expressed as

$$
\begin{aligned}
\hat{R}D_{i,j} = & \left[w_0 \log_2\left(1 + \frac{\hat{P}c_m g_{m,b}}{\hat{P}d_i g_{i,b} + N_0}\right)\right] \\
& + \left[w_0 \log_2\left(1 + \frac{\hat{P}d_i g_{i,j}}{\hat{P}c_m g_{m,j} + N_0}\right)\right]
\end{aligned}
\tag{35}
$$

where $\psi = \emptyset$, when the transmit power of both V2V and cellular links cannot fulfill the constraints in equation (29), the optimal data rate of the channel is zero. For content dissemination in relay mode, the power allocation problem can be given as

Problem P3:

$$\begin{aligned} \underset{\{Pd_i, Pc_m, Pr_k\}}{\text{maximize}} \quad & RR_{i,j} \\ \text{subject to} \quad & C1.2 : \gamma^a v_{i,j}, \gamma^b v_{i,j} \geq \gamma^v_{\min} , \\ & C2.2 : \gamma^a c_{i,j}, \gamma^b c_{i,j} \geq \gamma^c_{\min} , \\ & C3.2 : 0 \leq Pd_i \leq P^d_{\max} , \\ & C4.2 : 0 \leq Pc_m \leq P^c_{\max} , \\ & C5.2 : 0 \leq Pr_k \leq P^r_{\max} \end{aligned} \tag{36}$$

where $\hat{P}d_i$, $\hat{P}c_m$, and $\hat{P}r_k$ denote the optimal power for V2V users, cellular users, and relay vehicles, respectively. It is proved that problem P3 can only achieve optimum if $Pc_m = P^c_{\max}$, $Pr_k = P^r_{\max}$ or $Pd_i = P^d_{\max}$ and $\gamma^a v_{i,j} = \gamma^b v_{i,j}$ [16].

- **Case 1**: When $Pc_m = P^c_{\max}$

Problem P4:

$$\begin{aligned} \underset{\{Pd_i, Pr_k\}}{\text{maximize}} \quad & fc(Pd_i, Pr_k, P^c_{\max}) \\ \text{subject to} \quad & C1.3 : \left(\frac{Pd_i g_{i,k}}{P^c_{\max} g_{m,k} + N_0} \right) = \left(\frac{Pr_k g_{k,j}}{P^c_{\max} g_{m,j} + N_0} \right) , \\ & C2.3 : \left(\frac{Pr_k g_{k,j}}{P^c_{\max} g_{m,j} + N_0} \right) \geq \gamma^v_{\min} , \\ & C3.3 : \left(\frac{P^c_{\max} g_{m,b}}{Pd_i g_{i,b} + N_0} \right) \geq \gamma^c_{\min} , \\ & C4.3 : \left(\frac{P^c_{\max} g_{m,b}}{Pr_k g_{k,b} + N_0} \right) \geq \gamma^c_{\min} , \\ & C5.3 : 0 \leq Pd_i \leq P^d_{\max} , \\ & C6.3 : 0 \leq Pr_k \leq P^r_{\max} \end{aligned} \tag{37}$$

Then,

$$\begin{aligned} f\left(Pd_i, Pr_k, P^c_{\max}\right) = & \left(1 + \frac{Pr_k g_{k,j}}{P^c_{\max} g_{m,j} + N_0}\right) \\ & \left(1 + \frac{P^c_{\max} g_{m,b}}{Pd_i g_{i,b} + N_0}\right) \\ & \left(1 + \frac{P^c_{\max} g_{m,b}}{\mathrm{Pr}_k g_{k,b} + N_0}\right) \end{aligned} \tag{38}$$

where constraints C2.3-C4.3 shows that $Pr_k \in \left[P_r^{\min}, P_r^{\max}\right]$. From constraint C1.3, Pd_i can be defined as a linear function of Pr_k. Thus, the objective function in P4 can be presented as a function of Pr_k

$$fc = \left(\frac{av_3 Pr_k^3 + av_2 Pr_k^2 + av_1 Pr_k + av_0}{bv_2 Pr_k^2 + bv_1 Pr_k + bv_0} \right) \tag{39}$$

where coefficients av and bv are obtained using the expand function. The problem can be transformed into a fractional optimization, which can be optimally solved using the Dinkel-Bach technique.

- **Case 2**: When $Pr_k = P^r_{\max}$ or $Pd_i = P^d_{\max}$. In this case $Pr_k = P^r_{\max}$ and $Pd_i = P^d_{\max}$ are similar and can be solved using the same method by simply changing parameters. Thus, we show a solution for the case where $Pr_k = P^r_{\max}$.

Problem P5:

$$\begin{aligned} \underset{\{Pd_i, Pc_m\}}{\text{maximize}} \quad & fr(Pd_i, Pc_m, P^r_{\max}) \\ \text{subject to} \quad & C1.4 : \left(\frac{Pd_i g_{i,k}}{Pc_m g_{m,k} + N_0} \right) = \left(\frac{P^r_{\max} g_{k,j}}{Pc_m g_{m,j} + N_0} \right) , \\ & C2.4 : \left(\frac{P^r_{\max} g_{k,j}}{Pc_m g_{m,j} + N_0} \right) \geq \gamma^v_{\min} , \\ & C3.4 : \left(\frac{Pc_m g_{m,b}}{Pd_i g_{i,b} + N_0} \right) \geq \gamma^c_{\min} , \\ & C4.4 : \left(\frac{Pc_m g_{m,b}}{P^r_{\max} g_{k,b} + N_0} \right) \geq \gamma^c_{\min} , \\ & C5.4 : 0 \leq Pd_i \leq P^d_{\max} , \\ & C6.4 : 0 \leq Pc_m \leq P^c_{\max} \end{aligned} \tag{40}$$

Then,

$$\begin{aligned} f\left(Pd_i, Pc_m, P^r_{\max}\right) = & \left(1 + \frac{P^r_{\max} g_{k,j}}{Pc_m g_{m,j} + N_0}\right) \\ & \left(1 + \frac{Pc_m g_{m,b}}{Pd_i g_{i,b} + N_0}\right) \\ & \left(1 + \frac{Pc_m g_{m,b}}{P^r_{\max} g_{k,b} + N_0}\right) \end{aligned} \tag{41}$$

Thus, constraint C1.4 can be expressed in terms of Pd_i as

$$Pd_i = \left(\frac{g_{k,j}\left(Pc_m g_{m,k} + N_0\right)}{g_{i,k}\left(Pc_m g_{m,j} + N_0\right)} P^r_{\max} \right) \tag{42}$$

where constraint C6.4 guarantees that $Pc_m \in [P^c_{\min}, P^c_{\max}]$. By replacing Pd_i as a function of Pc_m in the objective function of problem P5, we have

$$fr = \left(\frac{ak_4 Pc_m^4 + ak_3 Pc_m^3 + ak_2 Pc_m^2 + ak_1 Pc_m + ak_0}{bk_2 Pc_m^2 + bk_1 Pc_m + bk_0} \right) \tag{43}$$

where coefficients ak and bk are obtained using the expand function, and the optimal solution can be obtained using the Dinkel-Bach algorithm.

B. Auction Based Relay Selection

We applied an improved auction model for relay selection. V2V users are the buyers of relaying services from the relay vehicle, which is the seller in the auction game. The buyers submit their bids while the seller sets an asking price for their services [32], [33]. At each time slot, V2V users submit their bid to the auctioneer, and the relay vehicles also submit their asking price. A sealed bid double auction is designed to allocate relay vehicles to V2V users. For each buyer $vu_j \in VU$ its bid can be defined as $BB_j = \{bd_1, bd_2, bd_3, ..., bd_n\}$, and the bid vector of all buyers can be given as $BD = \{BD_1, BD_2, BD_3, ..., BD_n\}$. Each seller $ru_k \in RU$ has an asking price denoted as A_k, and the ask vector of all relay vehicles can be given as $A = \{A_1, A_2, A_3, ..., A_l\}$. Subsequently, by applying the auction model, the auctioneer can obtain the winning set of buyers $VU_w \subseteq VU$, and the winning set of sellers $RU_w \subseteq RU$. The matching of a winning seller and a winning buyer can be defined as $\chi : \{k : ru_k \in RU_w\} \rightarrow \{j : vu_j \in VU_w\}$. The winning seller, $ru_k \subseteq RU_w$ is rewarded with a payment of px_k, and a winning buyer, $vu_j \subseteq VU_w$ is charged py_j as the payment for services rendered. The auction model designed can be denoted as $\Omega = \{VU, RU, A, BD\}$, the auctioneer follows the auction model to determine the auction winners. An effective model has to satisfy the economic properties of auctions as follows [34], [35].

- Budget Balance: The total charges paid by all winning buyers should not be less than the total payment received by all winning sellers $\sum\limits_{vu \in VU_w} py_j \geq \sum\limits_{ru \in RU_w} px_k$.
- Individual Rationality: A winning seller should not be paid a reward less than its asking price; likewise, a winning buyer will not be charged more than its bid. For each matching between a winning buyer and winning seller, we have $py_j \leq bd_j$ and $px_k \geq A_k$.
- Truthfulness: An auction is truthful if no buyer can improve its utility through a false bid, which means every bidder should submit its true valuation. A bid vector $BD_j = B\bar{D}_j$, where $B\bar{D}_j$ denotes the true bids of a buyer.
- Computational Complexity: A computation-efficient auction model has to be executed and terminated within polynomial time.
- System Efficiency: An auction is system efficient if social welfare is maximized, which is defined as the total utility of all agents in the auction.

Due to the peculiarity of relay selection in vehicular networks, the existing auction models cannot be directly applied in our proposed scheme as they will not satisfy the economic properties of the auction. The Vickery double auction model is not able to jointly achieve truthfulness, budget balance, and rationality. Similarly, the McAfee auction is also not applicable to our proposed scheme due to its homogeneity [36], [37]. To suit our problem, we introduced an improved auction model that satisfied the economic properties of auctions.

1) Auction Winners Determination Procedure

- Construct a sorted list of buyers bids in descending order VU' where $bd_j > 0$, and a sorted list of sellers asking prices RU' in ascending order.
- Obtain the median ask A_μ from the sorted list of sellers, where $\mu = \frac{m+1}{2}$. In some cases, μ is not necessarily the median; rather, the threshold can be determined by the system in order to improve efficiency.
- Determine the least bid bd_η from the sorted bidding list, such that $bd_\eta < A_\mu$.
- For each buyer $vu_j \in VU$, if its bid $bd_j \geq bd_\eta$ and the asking price of the seller $A_k < A_\mu$. Then buyer vu_j is a winning buyer and $vu_j \in VU_w$.
- If $A_k < A_\mu$. Thus, seller ru_k is a winning seller $ru_k \in RU_w$.

2) Greedy Based Auction (GRD)

For relay selection, the GRD algorithm operates as follows: If seller ru_k receives only one bid bd_j from buyer vu_j, then buyer vu_j wins seller ru_k. The auctioneer will charge the buyer the clearing price bd_η. If more than one buyer bids for seller ru_k, then the buyer with the highest bid wins seller ru_k. The auctioneer will charge the winning buyer the second highest bid. When a tie occurs, two bids emerge as the highest bids. The auctioneer randomly selects one among the highest bids; the winning buyer is then charged the same amount as its bid. The winning seller ru_k will receive the median ask price A_μ as payment.

Algorithm 1: Greedy Based Auction Algorithm (GRD)

```
inputs: $RU'$, $VU'$, $BD$, $A$, $bd_\eta$, $A_\mu$
output: $RU_w$, $VU_w$, $py_j$, $px_k$
initialization: $RU_w \leftarrow \emptyset$ , $VU_w \leftarrow \emptyset$
$px_k \leftarrow \emptyset$, $py_j \leftarrow \emptyset$
foreach $ru_k \in RU'$ do
    $bd_j \in BD$
    $px_k = A_\mu$
    if the number of received bid ==1 then
        $VU_w \leftarrow VU_w \cup \{bd_j\}$
        $py_j = bd_\eta$
    else
        the number of received bid $> 1$ $arrange$
         received bids in descending order
        $\{bd_{j1}, bd_{j2}, bd_{j3}, ..., bd_{jm}\}$
        if the two highest bids are equal then
            a tie exists
            randomly $select$ any $bd_j$ from the list
        else
            $select$ the buyer with highest bid
            $VU_w \leftarrow VU_w \cup \{bd_j\}$
            $py_j = bd_{j2}$
        end
    end
    $return$ $RU_w$, $VU_w$
end
```

(i) The Economic Properties of the GRD Algorithm

Theorem 2: GRD is individual rational

Proof: Each winning seller is paid px_k for its services, where $px_k = A_\mu$ and $A_\mu > A_k$ the payment is greater than the seller's asking price. As for the winning buyers, two conditions might arise: if buyer vu_j wins a seller ru_k without competition from other bidders, the buyer is charged $py_j = bd_\eta$ and $bd_\eta \leq bd_j$, the amount charged is less than or equal to the bid. On the other hand, if a buyer vu_j wins a seller ru_k with competition from other bidders, the buyer is charged an amount equal to the second highest bid, where $py_j \leq bd_{j2}$. Thus, individual rationality holds for all winners.

Theorem 3: GRD is budget balanced

Proof: Each winning buyer $vu_j \in VU_w$ assigned to a winning seller $ru_k \in RU_w$. Where the amount charged from a buyer is $py_j \geq bd_\eta$, and each seller receives payment $px_k = A_\mu \geq bd_\eta$. Similarly, it can be expressed as $\sum(py_j - px_k) \geq 0$. Hence, GRD is budget-balanced since no seller is paid less than its ask, and no buyer is charged more than its bid.

Theorem 4: GRD is truthful

Proof: Each winning buyer $vu_j \in VU_w$ can achieve maximum utility if $U > 0$. For $vu_j \notin VU_w$ bids truthfully but loses the auction since the utility generated is $U < 0$. Similarly, if the buyer vu_j bid untruthfully, two conditions might occur. If the untruthful bid is less than the true bid, then the result of the auction will not change. However, even if the buyer vu_j wins the auction, it cannot improve its utility since $U = 0$. Hence, the theorem holds since no buyer can improve its utility through false bidding.

Theorem 5: GRD is computational efficient

Proof: To obtain the winning agents of the auction, which include k sellers and n buyers, using the GRD. The process involves sorting, price determination, and winners' assignments. The worst-case complexity can be given as $O\left(nk(k + \log_n)\right)$.

3) Improved Maximum Matching Auction Algorithm (IMM)

In the proposed GRD, relay vehicles are assigned to V2V users using a greedy technique, which may produce lower utility for V2V users and relay vehicles. To this end, the relay vehicles may refuse or be reluctant to offer their services. We propose another improved auction algorithm based on maximum matching. However, the maximum matching technique incurs high computational complexity. Hence, we apply the two-approximation method to minimize the complexity of the algorithm. The IMM algorithm constructs a bipartite graph of V2V users and relay vehicles, and relays are selected based on maximum utility. The relay selection procedure is described in Algorithm 2.

VI. PERFORMANCE EVALUATION

To validate the proposed scheme, all simulations were conducted using MATLAB and NS3 simulators. We consider a cell where the eNodeB is located by the roadside. A real-world vehicular traffic dataset as described in [38], [43] is used to conduct the simulations. The GAIA dataset contains DiDi taxi mobility traces for Xian City for 30 days over several districts and roads. The traces of 100 vehicles were selected for the simulations. A list of simulation parameters has been given in Table II [38], [39].

A. Simulation and Discussions

Here, we evaluate the performance of the proposed scheme in terms of system data rate, system utility, social welfare, system throughput, time complexity, convergence, and trust value. For the evaluation, the values of $M = 5$, $K = 5$, and N vary from 10-100. All other simulation parameters remain the same as given in Table II unless otherwise stated. The proposed scheme is compared against some closely related baseline schemes as follows:

- Cellular scheme (C-V2N): In this scheme, the eNodeB provides contents to the requesting vehicles. Contents can only be shared via the V2N communication link. There is no spectrum reuse; resource blocks are exclusively allocated to cellular users [7].
- Direct V2V scheme (D-V2V): Aside from cellular communication, contents can only be shared through direct V2V communication. To improve spectral efficiency, the resource blocks allocated to cellular users are re-used by V2V users [40], [10].
- Random relaying scheme (RRD): This scheme explores relaying techniques to support V2V content dissemination. However, the relay vehicles are selected using a random approach, which might not produce optimal system utility [41].

Algorithm 2: Improved Maximum-Matching Auction (IMM)

```
inputs: $RU'$, $VU'$, $BD$, $A$, $bd_\eta$, $A_\mu$
output: $RU_w$, $VU_w$, $py_j$, $px_k$
initialization: $RU_w \leftarrow \emptyset$ , $VU_w \leftarrow \emptyset$
$px_k \leftarrow \emptyset$, $py_j \leftarrow \emptyset$
$\Gamma \leftarrow \emptyset$, $\zeta \leftarrow \emptyset$
$design$ a bipartite graph $Z = \{RU, VU, \Gamma, \vartheta\}$
$\vartheta(vu_j, ru_k) = \{bd_j - A_k\}$
$U = \{bd_j - A_k\}$
if $U \geq 0$ then
    $\zeta \leftarrow matching(\Gamma)$
else
    the utility $generated$ is negative
end
while $\zeta \neq \emptyset$ do
    foreach $(vu_j, ru_k) \in \zeta$ do
        $RU_w \leftarrow RU_w \cup \{ru_k\}$
        $VU_w \leftarrow VU_w \cup \{vu_j\}$
        $update$ $\bar{\Gamma} \leftarrow \Gamma \backslash \{ru_k, vu_j\}$
        $\bar{Z} = \{V\bar{U}, R\bar{U}, \bar{\Gamma}, \vartheta\}$
        $\bar{\zeta} \leftarrow matching(\bar{\Gamma})$
        $px_k = A_\mu + \iota$
    end
    $return$ $RU_w$, $VU_w$
end
```

TABLE II: List of Simulation Parameters

Simulation Parameter	Value
Simulation Area	4200m x 2000m
Bandwidth	10Mhz
Communication Range	250m
Number of V2V Users	10-100
Number of Cellular Users	5-20
Number of Relay Vehicles	5-20
Max Transmit Power of Cellular users	43dBm
Max Transmit Power of V2V users	21dBm
Trust value	[0,1]
Noise Power	-114dBm
Number of Lanes	4
SINR Threshold for Cellular Users	10dBm
SINR Threshold for V2V Users	15dBm

1) *The System Data Rate*

The system data rate is the total sum of achievable rates of content transmission in a network. The system data rate is evaluated against the number of V2V users and cellular users minimum SINR thresholds, respectively. As illustrated in Fig. 2, the system data rate is proportional to the number of V2V users in all schemes. Except for the C-V2N scheme, it can only disseminate content through the cellular link. For the other schemes that support V2V content dissemination, the increase in the number of active V2V links improves the system data rate. The proposed R-V2V scheme performs better than the other schemes because relays are selected based on maximum utility to support V2V content dissemination in the system.

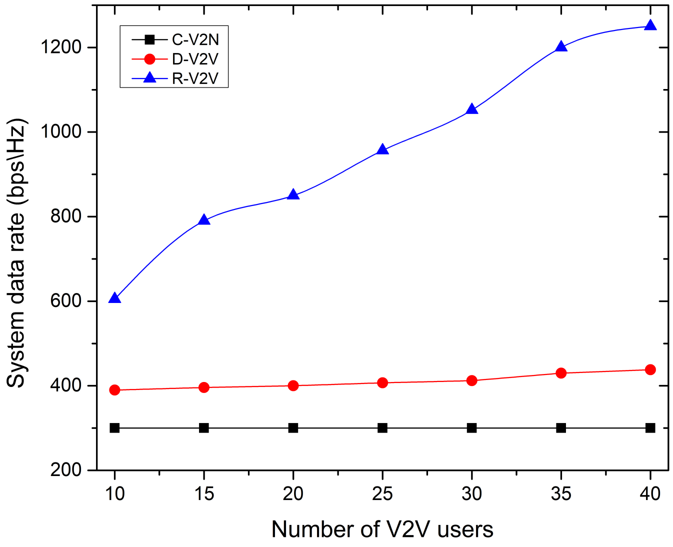

Fig. 2: System data rate over the number of V2V users

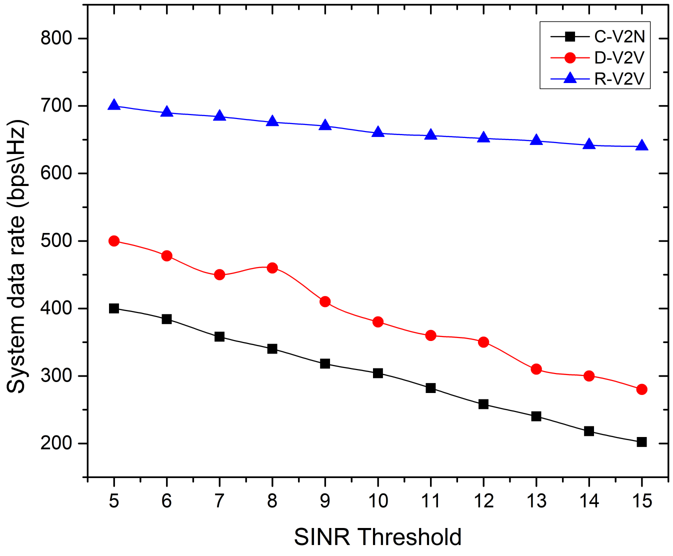

Fig. 3: System data rate over SINR threshold

Fig. 3 depicts the system data rate with respect to the minimum SINR threshold for cellular users. The system data rate is inversely proportional to the larger SINR requirement in all schemes. Due to the increase in the minimum SINR threshold, cellular user's limited interference tolerance is the cause of the performance degradation. Which affects the allowable transmit power of all users; hence, the system data rate is reduced.

2) *The system Utility*

Utility is the payoff or gain of each agent in a combination of strategies. The utility of V2V users and the utility of relay vehicles are evaluated against the different numbers of V2V users in the network. The IMM algorithm performs better than the GRD and RRD algorithms. The V2V utility for GRD and RRD schemes does not show any significant increase after the number of V2V users exceeds 70, except for the IMM scheme, which improves steadily with an increase in the number of V2V users even when the number of V2V users is above 70. This is because the IMM algorithm selects relays based on the maximum utility of the system, while the GRD and RRD schemes select relays greedily.

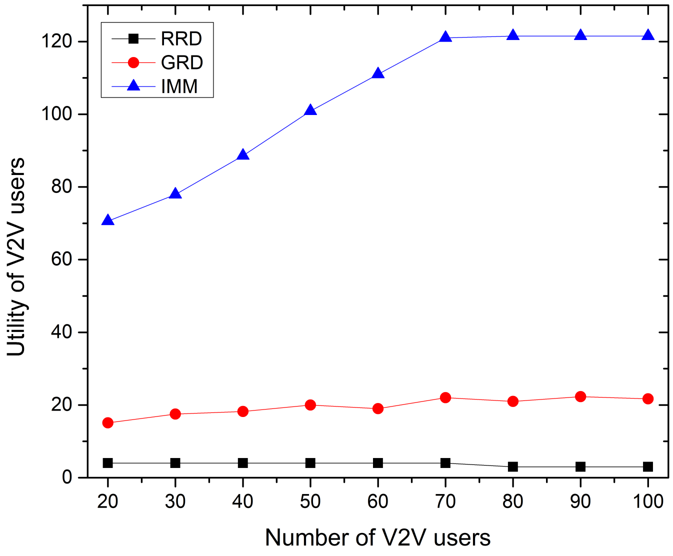

Fig. 4: Utility of V2V users over the number of V2V users

Fig. 5 depicts the relationship between the utility of relay vehicles and the number of V2V users. The utility of relay vehicles increases with the increase in the number of V2V users in the network for all schemes. The proposed GRD and IMM algorithms perform better than the RRD scheme. However, the utility starts degrading gradually when the number of V2V users is above 90, and no significant increase in utility is noted. This happens because when the network is dense, most of the contents can be disseminated through direct V2V without the assistance of relay vehicles.

3) *The social welfare*

Social welfare is the total sum of the utilities of all agents involved in an auction. Fig. 6 shows the obtainable social welfare in the system. The proposed GRD and IMM algorithms are better because, in the proposed auction schemes, we consider sum utility maximization in the relay selection phase. The RRD scheme generates the lowest social welfare because relays are arbitrarily selected without considering utility.

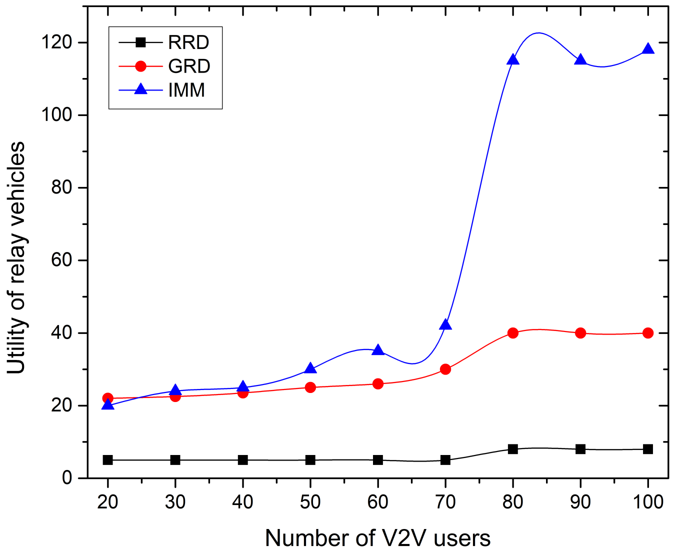

Fig. 5: Utility of relay vehicles over the number of V2V users

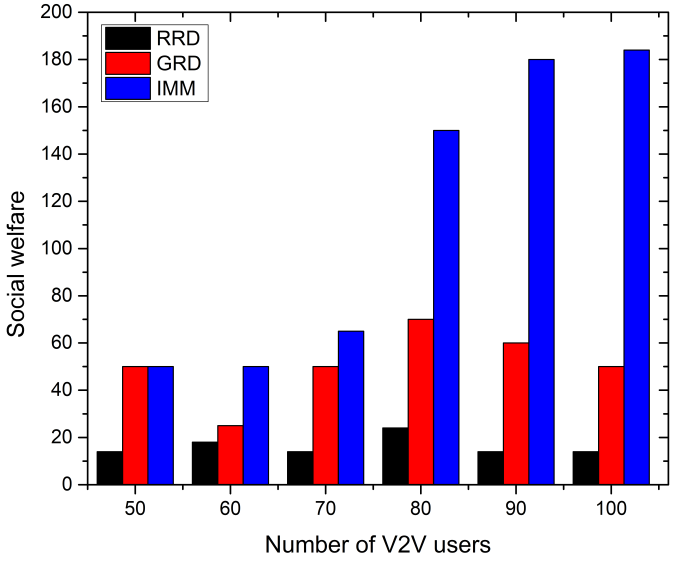

Fig. 6: Social welfare over the number of V2V users

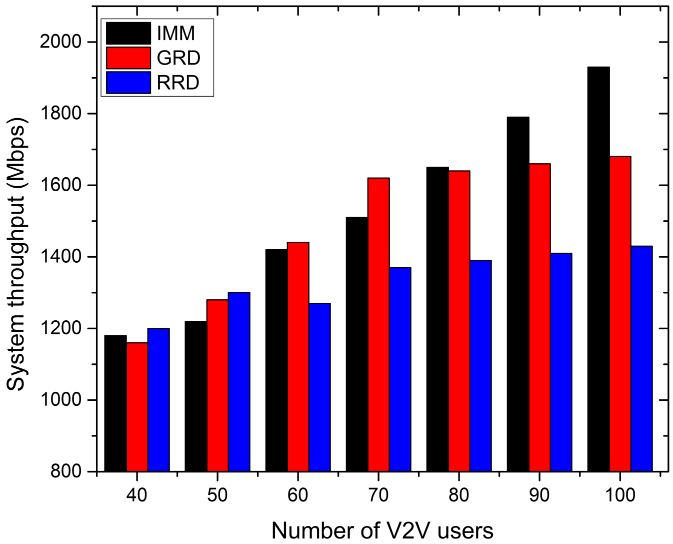

Fig. 7: System throughput over the number of V2V users

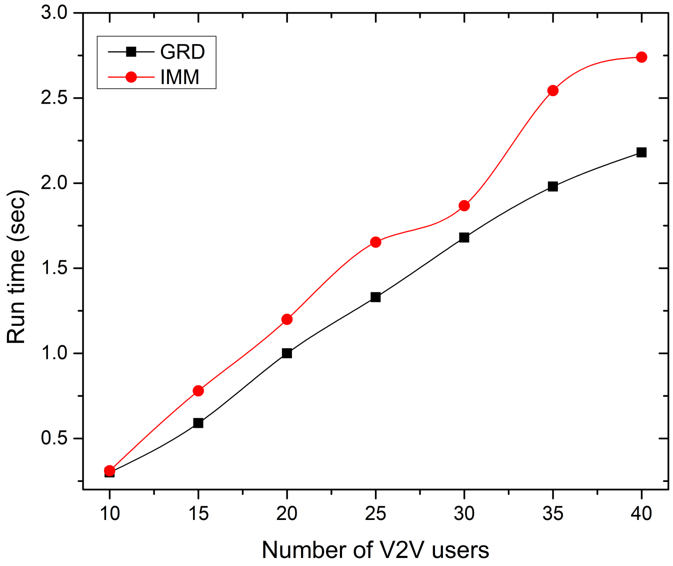

Fig. 8: Complexity against the number of V2V users

4) The system throughput

Throughput is the content delivery rate over a transmission link within a specified period. Fig. 7 shows the variation in system throughput against the number of V2V users in the network. The system's throughput is proportional to the increase in the number of V2V users for all schemes. The increase in V2V users provides more links for content dissemination, thus improving the system throughput.

5) Time Complexity

Computational complexity is the time taken for an algorithm to complete execution. Fig. 8 illustrates the time complexity of the proposed algorithms against the number of V2V users in the system. As the number of users increases, the runtime increases for all schemes. The runtime of IMM is higher than that of GRD because IMM maximizes system utility using the maximum matching technique, which incurs much more runtime than the greedy method explored by GRD.

6) Convergence

To evaluate the convergence of the proposed algorithms, the parameters are set at $N = 30$, $M = 5$, $K = 5$. Since the optimization problem is NP-hard, it is not possible to obtain the optimal solution in polynomial time. It is difficult to obtain the optimality gap of the proposed algorithms theoretically. Therefore, optimality is analyzed through simulations. The optimal auction is obtained using a centralized algorithm where the auction details of all bidders are known to the auctioneer. The winning buyers and sellers are matched based on an exhaustive search. The optimal scheme generates maximum utility since the winners are paid exactly as per their bid, where $bd_j = px_k$. However, the complexity of the optimal scheme is very high due to excessive communication and computation overhead.

As illustrated in Fig. 9, all the algorithms converge between 14 and 30 iterations. The optimal scheme converges faster with the highest utility; in the optimal scheme, the auctioneer is aware of the details of all bids, and the winners are paid exactly as their bid; however, the optimal auction scheme lacks economic truthfulness because, by knowing all the details of the bidders, the auctioneer can be biased. The proposed IMM performs better than the other two algorithms and is very close to the optimal algorithm in terms of convergence and utility because the scheme selects auction winners based on maximum payoff and maximum matching. The proposed IMM is far less in complexity and closer to optimal in terms of performance. GRD records a fair performance in convergence and utility because of the greedy approach used in the scheme. The RRD trails behind with the lowest performance because auction winners are selected randomly.

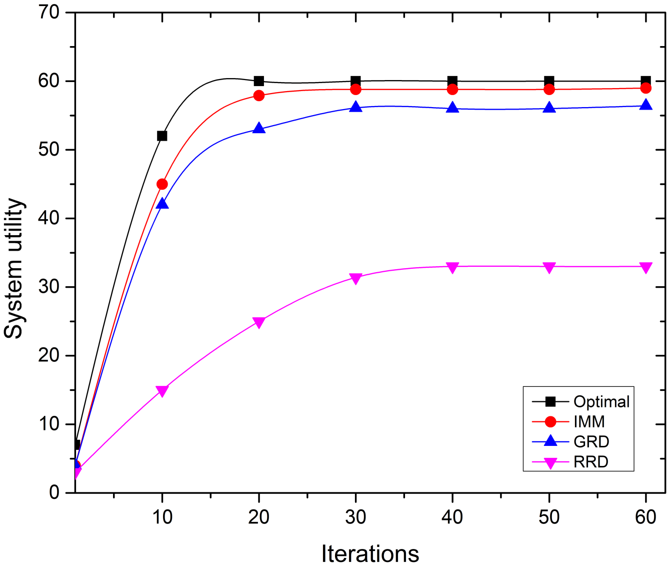

Fig. 9: Convergence of algorithms

7) *Trust Evaluation*

To evaluate the effectiveness of the proposed trust scheme, the trust value of the vehicles is set within [0,1], and the trust threshold is set at 0.5. Vehicles with a trust value below 0.5 are likely untrustworthy and capable of distorting or refusing to forward contents. As shown in Fig. 10, the proposed scheme generates the highest throughput because the model can accurately select vehicles with higher trust values for content distribution because of the integration of direct and indirect observations in trust evaluation. The direct trust scheme trails behind the proposed scheme because the method considers only direct observation in trust evaluation, and the accuracy of the direct observation is lower than the proposed scheme. Due to this, untrustworthy users might be selected for content dissemination, which affects the system throughput because untrustworthy users will not forward the content completely or modify it. The trust unaware scheme records the lowest throughput because it does not consider trust in content distribution; hence, untrustworthy users will be saddled with content distribution, which affects the performance of the system.

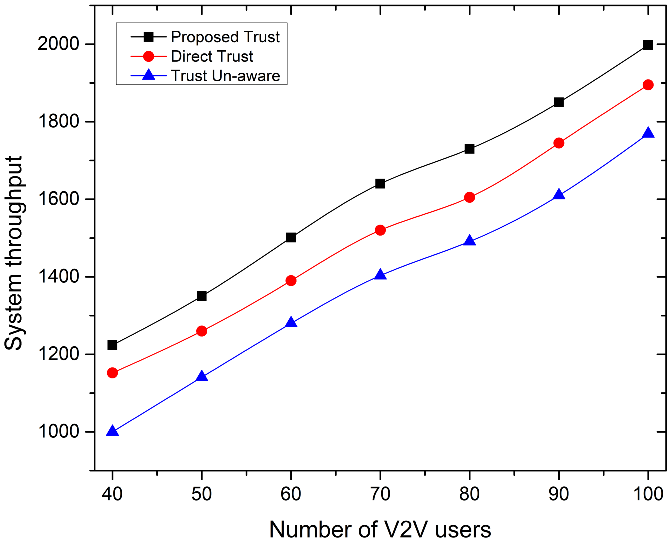

Fig. 10: Impact of trust on system performance

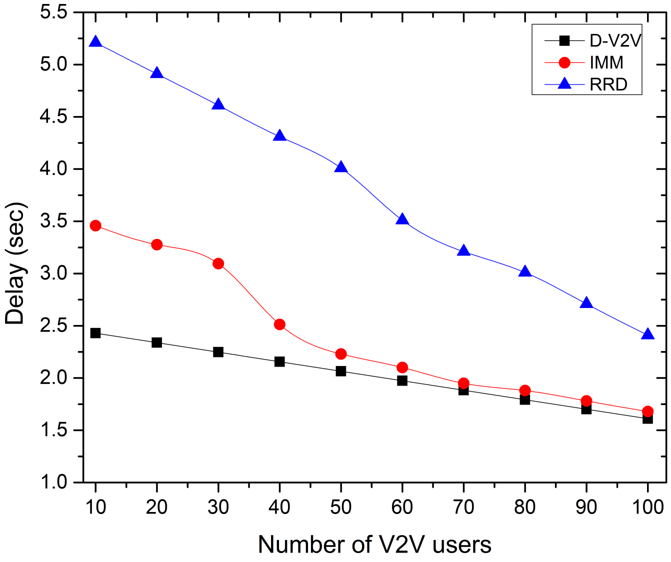

Fig. 11: Content dissemination latency

8) *Latency*

To analyze the latency of the algorithms, we consider a content of 3MB in size. As shown in Fig. 11, content transmission delay is inversely proportional to the number of vehicles in all schemes. The D-V2V scheme records the lowest content transmission delay because it only shares content via direct V2V links. However, the scheme records the lowest throughput because contents are shared only through direct V2V since the scheme does not use relay services, which minimizes its transmission delay. The IMM scheme records a fair transmission delay, and the content transmission delay reduces drastically when the number of vehicles increases above 40 because there will be many vehicles available to select the optimal relay vehicles to assist in content transmission. Also, when the vehicle traffic is dense, there will be more available V2V links to carry out content dissemination, therefore reducing the content transmission latency. Moreover, the IMM scheme generates the highest throughput because contents are disseminated through relays in situations where direct V2V is not feasible. The RRD schemes record the highest content transmission latency because relay vehicles are randomly selected, which affects the transmission delay.

VII. CONCLUSIONS AND FUTURE WORK

In this work, we investigated content dissemination in cellular vehicle-to-everything (V2X) networks. We proposed a relay assisted V2V content distribution scheme that considered content dissemination mode and relay selection. An incentive mechanism is designed based on auctions to motivate vehicles to participate in content relaying. To maximize system utility, we formulate an optimization problem with comprehensive consideration of trust value and data rate. We also consider power allocation due to channel sharing between V2V and cellular users in order to minimize mutual interference. The simulation results show that the proposed scheme performs better than the existing schemes in terms of system sum rate, utility, social welfare, computational complexity, convergence, and trust evaluation. In the future, the work can be extended by considering content size in relay selection and dissemination, and the impact of content size on performance metrics can be analyzed as well. Also, optimizing the time interval between two consecutive rounds of auctions can further improve performance.

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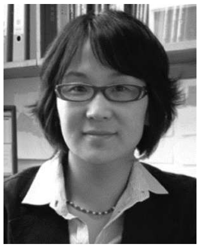
Muhammad Saleh Bute (Member, IEEE) received an M.Sc. degree in Computer Science from the University of Ilorin, Kwara State, Nigeria, in 2014. He is currently pursuing a Ph.D. degree with the Key Laboratory of Information Coding and Transmission, School of Information Science and Technology, Southwest Jiaotong University, Chengdu, China. He is also an academic staff with the Computer Science Department, Gombe State University, Gombe State, Nigeria. His research interests include mobile edge computing (MEC), vehicular ad-hoc networks (VANETs), 5G/6G technologies, C-V2X technology, intelligent transportation system (ITS), game theory, fuzzy systems, auction theory, radio resource management and federated learning for wireless networks. Muhammad is a member of the IEEE Young Professionals, IEEE Vehicular Technology Society (VTS) and The Nigeria Computer Society (NCS). He is also an active reviewer of the IEEE Transactions on Mobile Computing, IEEE Internet of Things Journal and the IEEE Vehicular Technology Conference.

Pingzhi Fan (M'93-SM'99-F'15) received the M.Sc. degree in computer science from Southwest Jiaotong University, China, in 1987, and the Ph.D. degree in electronic engineering from Hull University, U.K., in 1994. He is currently the director and distinguished professor of the Institute of Mobile Communications, Southwest Jiaotong University, China, and a visiting professor of Leeds University, UK (1997-), a guest professor of Shanghai Jiaotong University (1999-). He served as an EXCOM Member for the IEEE Region 10, IET (IEE) Council and the IET Asia Pacific Region. He is a recipient of the UK ORS Award (1992), the National Science Fund for Distinguished Young Scholars (1998, NSFC), IEEE VT Society Jack Neubauer Memorial Award (2018), IEEE SP Society SPL Best Paper Award (2018), IEEE WCSP 10-Year Anniversary Excellent Paper Award (2009-2019), IEEE/CIC ICCC Best Paper Award (2020), and IEEE WCSP2022 Best Paper Award. He served as a chief scientist of the National 973 Plan Project (National Basic Research Program of China) between 2012.1-2016.12. His research interests include high mobility wireless communications, massive random-access techniques, signal design & coding, etc. He is an IEEE VTS Distinguished Speaker (2019-2025), a fellow of IEEE, IET, CIE and CIC.

Gang Liu (Member, IEEE) is currently an Associate Professor at the School of Information Science and Technology, Southwest Jiaotong University (SWJTU), Chengdu, China. He received the Ph.D. degree in Communication and Information Systems from Beijing University of Posts and Telecommunications (BUPT) in 2015, and the B.S. degree in Electronics and Information Engineering from Sichuan University (SCU) in 2010. He was also with the University of British Columbia and Carleton University as a visiting Ph.D. student from Nov. 2013 to Nov. 2014. His current research interest lies in resource management and protocol optimization in the next generation cellular networks, connected vehicle networks and massive IoT networks.



Li Zhang (Senior Member, IEEE) received her PhD in Communications at the University of York in 2003. Currently she is an Associate Professor and leads the Wireless Communication Group at the school of Electronic and Electrical Engineering, University of Leeds, UK. Her research interest is focused on wireless communications and signal processing techniques, such as massive MIMO, mmWave communications, Heterogeneous Network, Device to Device communications and 5G systems etc. She has served on the Technical Programme Committees of most major IEEE conferences in communications since 2006 and also an associate editor of IEEE journal. She has been selected as a member of the prestigious UK EPSRC Peer Review College since 2006, and regularly helps reviewing grant applications for Research councils and book proposals. She has been PhD examiner for numerous Universities. In 2005, she received a Nuffield award for a newly appointed lecturer. In 2006, she became a fellow of Higher Education Academy. In 2011, she was awarded as IEEE exemplary reviewer and in 2012 she was promoted as senior IEEE member.