Improving Network Performance and Coverage Using Contract-based Incentivized V2V Communications

Sepideh Saraydar ¹, Foroogh Tabataba ², and Mohammad Javad Omidi ¹

¹Affiliation not available
²Isfahan University of Technol

October 31, 2023

Abstract

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Abstract—In recent years, there has been a significant increase in vehicles, resulting in areas that are unable to supply online connectivity, due to the lack of infrastructure development, and high construction costs. This, in turn, can cause vehicle outages. Therefore, this paper proposes a method to improve coverage using V2V communication and designing promotional contracts for relay vehicles. Relay vehicles are rewarded according to the contract, and the aim of this system model is to select the appropriate relay, allocate power, determine the optimal amount of data to transmit, evaluate of the relay reward, and ultimately maximize the utility of the base station. The paper considers half-duplex (HD) and full-duplex (FD) relays separately. However, optimization problems are NP-hard problems, and to solve this issue, the paper uses successive convex approximation and Taylor expansion to approximate the problem. Additionally, the paper presents an algorithm for relay selection using a simulated annealing algorithm. The simulation results examine the amount of data provided by two models, rewards and objective functions, and the results show that the FD model outperforms the HD one. Furthermore, the system is extended and solved for multi target and multi relay vehicles.

Index Terms—V2V communication, relay vehicles, half duplex model, full duplex model, network coverage, contract designing, reward.

I. INTRODUCTION

The main purpose of communication systems in vehicles is to improve safety, eliminate excessive costs due to traffic accidents, and control traffic [1]. Vehicular adhoc networks (VANETs) have attracted the attention of many researchers in recent years [2], [3]. Dramatic changes in vehicle mobility are affecting network topologies, making it difficult to maintain stable end-to-end paths [4], [5]. Increased vehicle numbers lead to more traffic, weather pollution, and accidents, causing numerous casualties and becoming a significant social and health issue. New vehicle communication technologies, in addition to safety technologies like airbags and seat belts, are improving vehicle safety. Apart from safety applications, these technologies also increase transportation efficiency by reducing traffic volume, increasing passenger comfort and convenience, and providing in-vehicle internet access [6]. The V2V communication mechanism is one of the key components of VANETs that can improve network coverage [2], for example by choosing vehicle as relays to buffer the data and then deliver the data to vehicle suffering from lack of coverage, due to this, we can expand the coverage and improve the performance [7], [8], [9].

For effective communication between vehicles, each vehicle must be equipped with a wireless device or on-board unit (OBU) [2]. Depending on the available infrastructure in the environment, vehicles can connect to various options such as roadside units (RSUs), Wi-Fi, and cellular networks. V2V communication is much more flexible as it doesn’t require any infrastructure [10]. As mentioned earlier, the vehicle can communicate with RSUs or base stations (BS). Unlike mobile ad-hoc networks (MANETs), which have low node mobility and stable connections, VANETs have high node mobility and no continuous connectivity. Additionally, due to the cost of deploying RSUs and BSs, it is challenging to provide uniform coverage, and the vehicles that experience an outage are called target vehicles. These problems and faults can be eliminated or minimized using vehicles as relays [11], [12]. The resulting vehicle networks from this specification are known as intermittently connected vehicular networks (ICVN) [13].

In [14], a store-carry-forward method is used to minimize outage time in uncovered areas by selecting relays to buffer data and deliver it to target vehicles. This article compares the HD and FD models to maximize the ergodic capacity of the link and achieve optimal power allocation. Also in [15], [16], [17] multi-hop store-carry forward relaying is used to minimize or even diminish outage time. On the other hand, [13] describes a system with several RSUs on the road that have backhaul connections to each other. The road is bi-directional, and the RSU first selects the appropriate relay for the target vehicle. When the target vehicle loses connection, the second RSU notices this and selects another relay vehicle from the other side of the street to assist the target vehicle. In [18], multiple-input multiple-output (MIMO) cooperation in cluster to cluster (C2C) communication is investigated to improve quality of service and reduce power consumption. A vehicle in a cluster can perform V2V communication with one hop or multi-hop if a vehicle in that cluster needs to communicate with another vehicle. In [20], the connection between the source and destination is split into multiple hops to improve coverage, reliability, and reduce power consumption. This work investigates time and frequency selective fading. On the other hand, [2] considers vehicular delay tolerant networks (VDTN) and selects relay candidates based on the size of the data to be delivered and the effective
communication time (ECT), which is the length of time that reduces the outage time of the target vehicle. The vehicle with the highest ECT is selected as the relay. [3] full-duplex (FD) communication is used to improve the system throughput, actually resource allocation is a problem in this paper and the writer suggest to use a dual graph coloring-based interference management (DGCIM) scheme to solve the problem. Also, cellular vehicle-to-everything (C-V2X) communications have attracted attentions because they can improve safety in driving and efficiency. However, resource allocation schemes would be more difficult due to mobility of vehicle due to this, some heuristic algorithms are proposed which can improve spectrum efficiency [21]. In [22], due to challenge of resource allocation, a multiagent double deep Q-networks scheme to make the system stable, and maximize the sum-capacity of the vehicle-to-infrastructure (V2I) links and making the V2V links reliable, has proposed.

As mentioned earlier, VANETs may have areas with no coverage due to vehicle mobility, high infrastructure costs, and long distances between BSs or RSUs. The lack of seamless connectivity and the presence of outages can cause user dissatisfaction and delays. However, choosing vehicles as relays can mitigate problems caused by outages. Encouraging vehicles to act as relays is beneficial to both vehicles and operators. One way to encourage this is through contracts that offer rewards for tasks performed by vehicles [18], [26].

In light of the aforementioned discussion, this paper proposes a contract-based approach to incentivize vehicles to act as relays. Our objective is to maximize the utility of the base station (BS) by determining the optimal amount of data to deliver, allocating rewards to relay vehicles, selecting appropriate relays, and distributing power between the BS and vehicles.

The main contributions of this paper are:
- Proposal of a contract and calculation of rewards to encourage the participation of relay vehicles.
- Proposing the utilities of the base station and relays to formulate the optimization problem in which the utility of the base station is maximized under the power and relay utility constraints.
- Investigating the impact of increasing the number of selected relays and target vehicles on the system model.

Since the optimization problem involves non-convex functions, we approximate them using Taylor series and utilize successive convex approximation (SCA) and then we present an algorithm for relay selection.

The rest of the paper is organized as follows. The next section describes the system model in detail. Section III presents how to solve optimization problem. Section IV shows the effect of increasing the number of relay and target vehicle on system model. Section V presents numerical results. Finally, Section VI concludes with a summary of the main findings.

II. SYSTEM MODEL AND PROBLEM FORMULATION

This section presents, the system model and problem formulation. The system model considers two base stations (BS) located at a distance $d_{BS}$ from each other along a one-way road. Due to the high deployment costs of BS, there may be areas with no coverage, resulting in outages for vehicles in those areas (target vehicles). Relay vehicles can help mitigate the outages by providing assistance to target vehicles.

The system model assumes that there are $N_r$ potential relay vehicles and $N_t$ target vehicles on the road, and all vehicles can operate in full duplex (FD) mode, i.e., they can simultaneously transmit and receive data. Figure 1 illustrates the operation of FD mode, where the relay vehicle buffers and delivers data to the target vehicle when it reaches an uncovered area, with a time of $t_{r_i,t_j}$.

In the coverage area of the BS, the channel gain between the $i$th relay and the $j$th target vehicle is defined as

$$h_{r_i,t_j} = d_{r_i,t_j}^{-\alpha} u$$

where $d_{r_i,t_j}$, $\alpha$, and $u$ represent the distance between the relay and the target vehicle, path loss exponent, and small scale fading modeled as Rayleigh fading, respectively. Similarly, we can represent the channels between the $i$th relay and the BS, and the $j$th target and the BS as $h_{b,r_i}$ and $h_{b,t_j}$, respectively.

In coverage scenario where all the vehicles are in coverage, we assume that when a vehicle communicates with the BS, it only receives data and does not transmit data. The signal-to-noise ratio (SNR) is calculated as follows:

$$SNR_{r_i}^b = \frac{P_{r_i} h_{b,r_i}}{\sigma^2}$$

where $P_{b,r_i}$ denotes the transmit power used by the BS in the downlink, while $\sigma^2$ represents the zero-mean additive white Gaussian noise (AWGN). The (SNR) of the connection between the target and the BS can be expressed as shown in (2). Due to the mobility of the vehicle, all calculations should be performed in different time slots, denoted by $k$. The average data rate received by the $i$th relay vehicle from the BS in coverage can be formulated as follows:

$$R_{r_i}^b = wE[log_2(1 + SNR_{r_i}^b)]$$

where $E[.]$ denotes the expected value and is used to evaluate (2) with (3). If the target vehicle reaches an uncovered area, the connection will be lost, and the relay will have to deliver the buffered data to the target vehicle. If the relay is still in range at this stage, it can send and receive data simultaneously. The data rate of the $i$th relay is given by:

![System model of FD relay](image)
The self-interference suppression coefficient is denoted by $\beta$ and modeled as the noise coefficient ($\sigma^2$) i.e., $\beta = \eta \sigma^2$, which $\eta$ is reversible interference [23]. $a_{r_i,t_j}$ represents the entry of the assignment matrix, where if $a_{r_i,t_j} = 1$, the connection between relay $r_i$ and target $t_j$ is established. Otherwise, the connection will not be established. Also the average data rate between the $i$th relay vehicle and $j$th target vehicle can be formulated as follows:

$$R_{k}^{b,r_i,j} = a_{r_i,t_j} wE[\log_2(1 + \frac{p^{b,r_i,j}h^{b,r_i,j}}{\beta p^{r_i,t_j} + \sigma^2})]$$

(4)

In this section, we define the duration of time and the number of time slots that the relay and target vehicles are in coverage [14]. Additionally, we calculate the duration of time that target vehicles lose connection. Assuming that the vehicles enter the BS coverage from the reference point, we can determine the distance of each vehicle from the BS. Thus, the duration of being in coverage for the $i$th relay is given by:

$$T_{r_i} = \frac{2r_o - d_{r_i}}{v_{r_i}}$$

(6)

Here, $r_o$ denotes the BS coverage radius, $d_{r_i}$ represents the distance from the reference point, and $v_{r_i}$ is the average velocity of the $i$th relay. We can determine the number of the time slots of being in coverage for the $i$th relay by considering the time slot length $T_s$, which can be formulated as follows [14]:

$$t_{r_i} = \left\lfloor \frac{T_{r_i}}{T_s} \right\rfloor$$

(7)

Similarly, we can calculate the duration of in-coverage periods and the number of time slots for the target vehicles, denoted by $T_{t_j}$ and $t_{t_j}$, respectively.

If the target vehicle reaches an uncovered area, we can determine the distance between the $i$th relay and the $j$th target using the following formula [14]:

$$d_{r_i,t_j} = (2r_o - (T_{t_j}v_{r_i} + d_{r_i}))$$

(8)

However, as stated in equation (8), the duration during which the relay can still communicate with the target vehicle while within range is important to consider.

$$T_{r_{r_i,t_j}} = \frac{d_{r_i,t_j}}{v_{r_i}}$$

(9)

The number of time slots are:

$$t_{r_{r_i,t_j}} = \left\lfloor \frac{T_{r_{r_i,t_j}}}{T_s} \right\rfloor$$

(10)

The amount of data a relay can buffer for a destination is given by the formula:

$$D_{buf}^{r_i} = D_{b,r_i} - D_{r_i}$$

(11)

Where $D_{r_i}$ represents the amount of data requested from the relay vehicle, and $D_{b,r_i}$ represents the maximum amount of data that can be received within the coverage formulated below.

$$D_{b,r_i} = \sum_{k=1}^{t_{r_i} - tr_{r_i,t_j}} R_{k}^{b,r_i,j} T_s + \sum_{k=t_{r_i} - tr_{r_i,t_j} + 1}^{t_{r_i}} R_{k}^{b,r_i,j} T_s$$

(12)

Here, the duration during which the relay and the target vehicle are within communication range is calculated as described in [2].

If $v_{r_i} > v_{t_j}, d_{r_i,t_j} \geq 0$

$$T_{r_i,t_j} = \frac{r_o + d_{r_i,t_j}}{v_{r_i} - v_{t_j}}$$

(13)

If $v_{r_i} > v_{t_j}, d_{r_i,t_j} < 0$

$$T_{r_i,t_j} = \frac{r_o - |d_{r_i,t_j}|}{v_{r_i} - v_{t_j}}$$

(14)

If $v_{r_i} \leq v_{t_j}, d_{r_i,t_j} \geq 0$

$$T_{r_i,t_j} = \frac{r_o - d_{r_i,t_j}}{v_{t_j} - v_{r_i}}$$

(15)

The number of time slots during which $r_i$ and $t_j$ are within communication range:

$$t_{r_i,t_j} = \left\lfloor \frac{T_{r_i,t_j}}{T_s} \right\rfloor$$

(16)

If the vehicle speeds of the relay and target are equal, they are perpetually within communication range. In this scenario, the duration of their communication is infinite, and equals the time the target vehicle spends in the uncovered area. Using this information, we can calculate the amount of data that can be delivered to the target vehicle as follows:

$$D_{del}^{r_i} = \sum_{k=1}^{t_{r_i,t_j}} R_{k}^{r_i,j} T_s$$

(17)

It should be noted that the relay vehicle cannot deliver more data to the target vehicle than what it has buffered. So the amount of delivered data is limited to two values $D_{del}^{r_i}$ and $D_{buf}^{r_i}$:

$$D_{r_i,t_j} = \min\{D_{buf}^{r_i}, D_{del}^{r_i}\}$$

(18)

A. Contract Designing

In this section, we propose the contract. As mentioned earlier, to encourage relay vehicle to participate in delivering data, based on a contract, they should receive a reward which is calculated according to the contract. The contract is defined by the BS, taking the idea from [26].

$$C = \{(D_{r_i,t_j}, b_{r_i}), \forall i = 1, 2, \ldots, N_r, j = 1, 2, \ldots, N_t\}$$

(19)

Here, $b_{r_i}$ represents the reward received by the relay for delivering data to the target vehicle. This reward can be in the form of monetary compensation, or the operator may set...
a specific amount of data as the reward. The benefit received by the BS after delivery of $D_{r,t_j}$ is defined as follows:

$$bn_{BS} \triangleq B_{BS} \times D_{r,t_j}$$  \hspace{1cm} (20)$$

where $B_{BS}$ is the unit of benefit for the BS, as defined by the operator. Consequently, the utility of the BS is given by:

$$U_{BS} \triangleq \sum_{i=1}^{N_r} \sum_{j=1}^{N_t} a_{r_i,t_j} [bn_{BS} - bn_{r_i}]$$ \hspace{1cm} (21)$$

The utility of relays can be expressed as:

$$U_{r_i}(p^{r_i,t_j}, bn_{r_i}) \triangleq Q_{r_i} bn_{r_i} - \sum_k \sum_{t_j} a_{r_i,t_j} p_k^{r_i,t_j}$$ \hspace{1cm} (22)$$

Here, $Q_{r_i}$ represents the weight parameter, and the reward amount must be positive to incentivize the relay to participate in data delivery to the target vehicle, and $p_k^{r_i,t_j}$ is the power consumption of relay vehicle when delivering data to target vehicle which is $0 \leq p_k^{r_i,t_j} \leq p_k^{\text{max}}, k = 1, 2, \ldots, t_{r_i,t_j}$.

Now, in order to select a suitable relay and its reward, find a suitable amount of data which should be delivered, and allocate power, the optimization problem can be defined as follows:

$$\max_{a_{r_i,t_j}, bn_{r_i}} U_{BS}(D_{r_i,t_j}, bn_{r_i})$$ \hspace{1cm} (23a)$$

Subject to:

$$\sum_i a_{r_i,t_j} = 1, \quad a_{r_i,t_j} \in \{0, 1\}, \quad j = 1, \ldots, N_t$$ \hspace{1cm} (23b)$$

$$\sum_j a_{r_i,t_j} \leq 1, \quad a_{r_i,t_j} \in \{0, 1\}, \quad i = 1, \ldots, N_r$$ \hspace{1cm} (23c)$$

$$Q_{r_i}, bn_{r_i} - \sum_k \sum_{t_j} a_{r_i,t_j} p_k^{r_i,t_j} \geq 0, \quad k = 1, 2, \ldots, t_{r_i,t_j}$$ \hspace{1cm} (23d)$$

$$bn_{r_i} \geq 0,$$ \hspace{1cm} (23e)$$

$$D_{r_i,t_j} \leq \sum_{k=1}^{t_{r_i,t_j}} R_k^{r_i,t_j} T_s,$$ \hspace{1cm} (23f)$$

$$D_{r_i,t_j} \leq \sum_{k=1}^{t_{r_i,t_j}} R_k^{b,r_i,t_j} T_s + \sum_{k=t_{r_i,t_j}+1}^{t_{r_i,t_j}} p_k^{b,r_i,t_j} T_s - D_{r_i},$$ \hspace{1cm} (23g)$$

Constraints (23b) and (23c) are utilized to assign appropriate relays to the target vehicle, indicating that one relay can be selected for a target vehicle. Constraint (23d) enforces the constraint that the utility of the relay must always be positive, thereby encouraging the relay to participate in the relaying process. Constraint (23e) requires that the relay reward must also be positive. Constraints (23f) and (23g) demonstrate that a delivered data is dependent on the two boundary conditions described in equation (18). Finally, Constraints (23h) and (23i) indicate the upper and lower transmission power limits for both the BS and the relay vehicles.

### B. Half Duplex Model

If the relay vehicle is operating in half-duplex (HD) mode, it will simply buffer the data until the target vehicle reaches an uncovered area. Since the relay cannot receive and send data simultaneously, it must deliver the buffered data to the target as soon as possible once it is within range. Figure ?? shows the HD model, where the relay vehicle delivers the data to the target at time $t_{r_i,t_j}$ once the target vehicle reaches the uncovered area. The amount of buffered data for the HD model is given by:

$$D^{busr,HD}_{r_i,t_j} = D^{HD}_{r_i,t_j} - D_{r_i}$$ \hspace{1cm} (24)$$

The variable $D_{r_i}^{busr,HD}$ represents the maximum amount of data that the relay can buffer within its coverage area, while $D_{r_i}$ represents the data that the relay has requested. The amount of data that can be provided is calculated as follows:

$$D^{del,HD}_{r_i,t_j} = \sum_{k=1}^{t_{r_i,t_j}} R_k^{r_i,t_j} T_s$$ \hspace{1cm} (25)$$

Like FD model, the amount of delivered data is limited between two values $D^{del,HD}_{r_i}$ and $D^{busr,HD}_{r_i}$:

$$D^{HD}_{r_i,t_j} = \min \{ D^{busr,HD}_{r_i}, D^{del,HD}_{r_i} \}$$ \hspace{1cm} (27)$$

In the case of an HD relay, the contract is similar to that of an FD relay. The optimization problem remains the same as (23a), with the exception of constraint (23g).

$$\max_{a_{r_i,t_j}, bn_{r_i}} U_{BS}(D^{HD}_{r_i,t_j}, bn_{r_i})$$ \hspace{1cm} (28a)$$

Subject to:

$$\sum_i a_{r_i,t_j} = 1, \quad a_{r_i,t_j} \in \{0, 1\}, \quad j = 1, \ldots, N_t$$ \hspace{1cm} (28b)$$

$$\sum_j a_{r_i,t_j} \leq 1, \quad a_{r_i,t_j} \in \{0, 1\}, \quad i = 1, \ldots, N_r$$ \hspace{1cm} (28c)$$

$$Q_{r_i}, bn_{r_i} - \sum_j a_{r_i,t_j} p_k^{r_i,t_j} \geq 0, \quad k = 1, 2, \ldots, t_{r_i,t_j}$$ \hspace{1cm} (28d)$$

$$bn_{r_i} \geq 0,$$ \hspace{1cm} (28e)$$

$$D^{HD}_{r_i,t_j} \leq \sum_{k=1}^{t_{r_i,t_j}} R_k^{r_i,t_j} T_s,$$ \hspace{1cm} (28f)$$

$$D^{HD}_{r_i,t_j} \leq \sum_{k=1}^{t_{r_i,t_j}} R_k^{b,r_i,t_j} T_s - D_{r_i},$$ \hspace{1cm} (28g)$$
0 \leq p_{k}^{t_{ri}} \leq p_{\text{max}}, k = 1, 2, \ldots, tr_{ri,tj} \quad \text{(28h)}
0 \leq p_{k}^{t_{rj}} \leq p_{\text{max}}, k = 1, 2, \ldots, tr_{ri,tj} \quad \text{(28i)}

III. SOLVING OPTIMIZATION PROBLEM

In this section, we propose a method to solve optimization problems (24i) and (28a). Problem (24i) has a nonlinear objective function, and constraints (24i), (25i), and (25g) are also nonlinear. Therefore, it is an NP-hard mixed-integer nonlinear programming (MINLP) problem. To solve it, we divide it into two sub-problems. First, we assume that the system is using maximum power, then we find a suitable relay and calculate the data and reward, respectively. In the second stage, we optimize the power of the selected relay. This process is repeated until the problem converges.

However, the presence of the logarithmic function in the constraints makes the problem non-convex. To solve this, we first use the following approximation: $E(\log(1 + SNR)) \approx \log(1 + E(SNR))$. Next, we rewrite constraints (24i) and (25g) as:

$$D_{ri,tj} = w \sum_{k=1}^{tr_{ri,tj}} \log_2(1 + \frac{P_{tr_{ri,tj}} d_{r_{i,tj}}^{-\alpha}}{\sigma^2}) T_s + D_{ri} \leq 0 \quad \text{(29)}$$

and,

$$D_{ri,tj} = \sum_{k=1}^{tr_{ri,tj}} w \log_2(1 + \frac{P_{b,r_i} d_{b,r_i}^{-\alpha}}{\sigma^2}) T_s - \sum_{k=tr_{ri,tj}+1}^{tr_{rj}} w \log_2(1 + \frac{P_{b,r_i} d_{b,r_i}^{-\alpha}}{\beta P_{r_i,tj} + \sigma^2}) T_s + D_{ri} \leq 0 \quad \text{(30)}$$

Since the logarithm is a concave function, its negative is a convex function. In equation (29), the presence of a negative sign means that the constraint is convex. However, in equation (30), the first logarithm is convex, but the second is not due to the optimization variable in the denominator. To solve this, we use the identity $\log_2(1 + \frac{x}{y}) = \log_2(x + y) - \log_2(y)$.

$$D_{ri,tj} = \sum_{k=1}^{tr_{ri,tj}} w \log_2(1 + \frac{P_{b,r_i} d_{b,r_i}^{-\alpha}}{\sigma^2}) T_s - \sum_{k=tr_{ri,tj}+1}^{tr_{rj}} w \log_2(\beta P_{r_i,tj} + \sigma^2 + P_{b,r_i} d_{b,r_i}^{-\alpha}) T_s + w \log_2(\beta P_{r_i,tj} + \sigma^2) T_s + D_{ri} \leq 0 \quad \text{(31)}$$

All the terms in equation (31) except for $w \log_2(\beta P_{r_i,tj} + \sigma^2) T_s$ are convex. To approximate the non-convex term, we use successive convex approximation (SCA) [27] and Taylor expansion. The approximation for $w \log_2(\beta P_{r_i,tj} d_{r_{i,tj}}^{-\alpha} + \sigma^2) T_s$ is given by:

$$D_{ri,tj} = \sum_{k=1}^{tr_{rj}} \log_2(1 + \frac{P_{b,r_i} d_{b,r_i}^{-\alpha}}{\sigma^2}) T_s
- \sum_{k=tr_{ri,tj}+1}^{tr_{rj}} w \log_2(\beta P_{r_i,tj} + \sigma^2 + P_{b,r_i} d_{b,r_i}^{-\alpha}) T_s + w \log_2(\beta a + \sigma^2) T_s + D_{ri} \leq 0 \quad \text{(32)}$$

Now all terms in (32) are convex with respect to power variables that can be solved efficiently.

A. Relay Assignment

This section presents a method for relay assignment. Specifically, we propose an algorithm for relay selection based on the simulated annealing (SA) algorithm [29]. The algorithm works as follows:

First, a random relay $S_n$ is selected and the objective function value is calculated using equation (21). Then, another relay $S_{n-1}$ is randomly selected, and the objective function is computed again using equation (21). If the difference between the two objective function values is positive or $\exp(-\frac{\Delta}{\delta})$ is less than a random number $x$, the new scheme is accepted. Otherwise, the old scheme is accepted. The algorithm continues until its temperature is lower than the final temperature [30].

Using this approach, Algorithm 1 can achieve near-optimal results for relay selection in the optimization problem (2.5a).

**Algorithm 1** Simulated annealing algorithm for relay assignment

1: Initialization: Initial temperature $T = T_0$, set of relay vehicles $\{S_1, S_2, S_n, \ldots\}$, $S_{n-1}$, final temperature $T_{final}$ and annealing coefficient $\alpha_{SA}$.
2: Choosing $S_n$ from the set of relay vehicles randomly.
3: Calculating $U_{BS}(S_n)$ from (22).
4: Repeat
5: Choosing $S_{n-1}$ from the set of relay vehicles randomly.
6: Calculating $U_{BS}(S_{n-1})$ from (22).
7: $\delta = U_{BS}(S_{n-1}) - U_{BS}(S_n)$.
8: Producing a random number between 0 and 1 as $x$.
9: If $\delta > 0$ or $\exp(-\frac{\Delta}{\delta}) < x$ then
10: $S_{opt} = S_{n-1}$.
11: End if.
12: $T = \alpha_{SA} T$.
13: Until $T \leq T_{final}$.
14: Output: $S_{opt}$.

Once an appropriate relay vehicle is selected, we optimize the power of the vehicles using equations (20) and (22) instead of (24i) and (25g) to solve the sub-problem. In the first stage, we assume that the vehicles have maximum power and use algorithm 1 to choose a relay. Then, in the second stage, knowing the relay vehicle, after approximation, we calculate the delivered data, reward and optimize the power of the vehicles. This iterative process is continued until the problem converges.

IV. INCREASING THE NUMBER OF RELAYS AND TARGET VEHICLES

In this section, we investigate the impact of increasing the number of relays and target vehicles on the optimization
problem. When there are multiple target vehicles on the road, equations (23f) and (23g) need to be modified. Here is a quick fix for equation (23f). For instance, if there are two target vehicles on the road, constraints (23f) and (23g) can be transformed as follows:

\[
\sum_{i} a_{r_i, t_j} = 1, \quad \sum_{i} a_{r_i, t_j} = 1 \quad (33)
\]

\[
\sum_{j} a_{r_j, t_i} \leq 1 \quad (34)
\]

Above constraints do not add to the complexity of the assignment subproblem, thus the problem (23f) can be simplified by knowing the values of \( a_{r_i, t_j} \) in the assignment matrix. The optimization of the assignment matrix values is designed to maximize the performance assuming maximum power for the vehicles. We will show that the objective function is repeated for each target vehicle in the problem, and each of these functions is a function of the provided data, the reward, and the associated power, calculated separately for each relay assigned to each target. In conclusion, we can solve the problem separately for each target vehicle with the knowledge of the assignment matrix and denote the sum of the resulting functions as the overall goal solution. For example, for two targets and two relays, the objective function knowing \( a_{r_i, t_j} \) can be written as follows:

\[
U_{BS}(D_{r_i, t_j}, b_{r_i}) = \sum_{i=j=1}^{2} [b_{BS} - b_{r_i}] \quad (35)
\]

Eventually:

\[
U_{BS}(D_{r_i, t_j}, b_{r_i}) = \frac{(B_{BS} \times D_{r_i, t_j} - b_{r_i})}{f_1(D_{r_i, t_j}, b_{r_i})} + \frac{(B_{BS} \times D_{r_i, t_j} - b_{r_i})}{f_2(D_{r_i, t_j}, b_{r_i})} \quad (36)
\]

In fact, both \( f_1 \) and \( f_2 \) are functions of the data sent and the reward, where \( b_{r_i} \) and \( D_{r_i, t_j} \) themselves depend on the power of the relay to the target and the base station power to the relay. As the optimization variables and constraints are independent, it is possible to perform separate optimization for each objective and merge the final optimal values into the objective function. For example, the optimization of \( f_1 \) can be expressed as (37a), and the optimization of \( f_2 \) follows a similar procedure. Finally, the sum of the objective function values is calculated.

Maximize \( \max_{b_{r_i}, D_{r_i, t_j}} f_1(D_{r_i, t_j}, b_{r_i}) \) subject to:

\[
Q_{r_i} b_{r_i} - \sum_{k} p_{r_i, t_i}^{r_i, t_i} \geq 0, \quad k = 1, 2, \ldots, t_{r_i, t_i} \quad (37a)
\]

\[
b_{r_i} \geq 0, \quad (37b)
\]

\[
D_{r_i, t_i} \leq \sum_{k=1}^{t_{r_i, t_i}} R_{k}^{r_i, t_i} T_s, \quad (37c)
\]

\[
0 \leq p_{r_i, t_i}^{r_i, t_i} \leq p_{r_i, t_i}^{r_i, t_i}, \quad k = 1, 2, \ldots, t_{r_i, t_i} \quad (37d)
\]

If the system has multiple relay vehicles and a single target vehicle, the optimization problem (23f) differs slightly. In this scenario, the constraints (23f) and (23g) in task (23f) are modified to account for the presence of multiple relay vehicles. For instance, if two relay vehicles were selected for the same target, the actual modification of constraints (23f) and (23g) would become:

\[
\sum_{i} a_{r_i, t_j} = 2 \quad (38)
\]

\[
\sum_{j} a_{r_i, t_j} \leq 1 \quad (39)
\]

To solve this problem when multiple relay vehicles are present, the constraints in problem (23f) must be repeated for each relay vehicle. The problem (23f) must be rewritten accordingly, and the assignment matrix with maximum power values should be pre-specified for the relays. The optimization problem (23f) can be solved separately for each relay, with the relay having the highest objective function value selected first. Assuming there are two relay vehicles in the system, the optimization problem (23f) for known \( a_{r_i, t_j} \) can be expressed as:

Maximize \( \max_{b_{r_i}, D_{r_i, t_j}, p_{r_i, t_i}^{r_i, t_i}} U_{BS}(D_{r_i, t_j}, b_{r_i}) \) subject to:

\[
Q_{r_i} b_{r_i} - \sum_{k} p_{r_i, t_i}^{r_i, t_i} \geq 0, \quad k = 1, 2, \ldots, t_{r_i, t_i} \quad (40a)
\]

\[
Q_{r_i} b_{r_i} - \sum_{k} p_{r_i, t_i}^{r_i, t_i} \geq 0, \quad k = 1, 2, \ldots, t_{r_i, t_i} \quad (40b)
\]

\[
b_{r_i} \geq 0, \quad (40c)
\]

\[
D_{r_i, t_i} \leq \sum_{k=1}^{t_{r_i, t_i}} R_{k}^{r_i, t_i} T_s, \quad (40d)
\]

\[
b_{r_i} \geq 0, \quad (40e)
\]

\[
D_{r_i, t_i} \leq \sum_{k=1}^{t_{r_i, t_i}} R_{k}^{r_i, t_i} T_s, \quad (40f)
\]
We conducted 150 simulations with randomly distributed vehicles in each realization. The simulation parameters are presented in Table 1, and vehicle speeds were randomly assigned in the range of $v \in [50, 90] \text{km/h}, d_c \in [0, 300] \text{m}$.

To start, we must determine the suitable values of $Q$ and $B_{BS}$. We begin by examining the impact of these parameters on the reward, delivered data, and objective function. For this analysis, we simulate a system with 10 relay vehicles and 1 target. Figure 4 illustrates the effect of $Q$ on the reward for different values of $B_{BS}$. According to equation (22), the reward $(b_{r,t})$ decreases as the value of $Q$ increases. Figure 5 demonstrates the effect of $Q$ and different $B_{BS}$ values on the amount of the delivered data. Increasing the value of $Q$ results in more data being delivered. It is important to note that changes in $Q$ can also affect the power allotted, which can have an impact on the amount of the delivered data, according to equation (22). Figure 6 depicts the effect of different $B_{BS}$ and $Q$ on the objective function. As the value of $Q$ increases, the amount of objective function also increases. This is because, as mentioned in equation (21), the value of the reward decreases as $Q$ increases, leading to a greater emphasis on the value of $Q$ in the objective function. Therefore, the system model performs better with larger values of $Q$. Similar findings were observed for the FD model.

Figures 3, 4, and 5 compare the performance of FD and HD models with $Q = 1 \times 10^{-4}$ and $B_{BS} = 1 \times 10^{-5}$. The system models predict that FD models will transmit more data than HD models due to their ability to buffer more data over a longer time. Consequently, the FD model allocates more rewards to company vehicles, and the objective function (24) also increases. If the operator wants to allocate more rewards to relays and provide more data, they should adopt the FD model. On the other hand, if the operator wants to minimize their spending on rewards or does not mind having a smaller objective function value, they can choose the HD model. Overall, our results show that the FD model outperforms the HD model.

Figure 8 illustrates the performance of different relay selection methods for different numbers of vehicles. The optimal solution is shown at the top of the diagram, where the performance of all vehicles is first optimized, and then the appropriate relay is selected. It means that the power of the vehicles is first optimized, and then the vehicle which has the best utility, will be chosen as a relay. In practice, the exhaustive search method is used to select the most suitable relay, which is more accurate but significantly slower. The next diagram in Figure 8 shows the proposed algorithm based on simulated annealing. This algorithm uses initial temperature $T = 10$, final temperature $T_{final} = 1$, and annealing coefficient $\alpha_{SA} = 0.8$. At the beginning, SA algorithm chooses a vehicle and then, the power of the selected relay is optimized and process is repeated until the problem solution converges. When the number of vehicles is small, the algorithm examines more modes to reach the optimal solution due to the relay’s maximum power. However, as the number of vehicles increases, the algorithm randomly selects vehicles, and the probability of selecting vehicles with better objective functions increases. The efficiency of the algorithm highly depends on the input values. Similar results were obtained for the FD mode.

Figure 9 demonstrates the impact of increasing the number of relay vehicles in the FD model. As anticipated, the system’s performance improves as the number of relay candidates increases.

Figure 10 illustrates the impact of varying the number of target vehicles on the FD and HD models. In practice, the number of target vehicles will vary, and the number of relay vehicles will be equal to the number of target vehicles. This implies that each target will be assigned a relay. Due to the

![Table I](image)

**Table I**

<table>
<thead>
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<th>Parameters</th>
<th>Amounts</th>
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<tr>
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Fig. 2. The effect of $Q$ in different $B_{BS}$ on reward in proposed HD model

Fig. 3. The effect of $Q$ in different $B_{BS}$ on delivered data in proposed HD model

Fig. 4. The effect of $Q$ in different $B_{BS}$ on objective function in proposed HD model

Fig. 5. Comparing delivered data of FD and HD schemes

Fig. 6. Comparing rewards of FD and HD schemes

Fig. 7. Comparing objective functions of FD and HD schemes
Fig. 8. The performance of different relay vehicle selection method in HD model.

Fig. 9. Effect of increasing number of selected relay vehicle on FD model.

Fig. 10. Effect of changing the number of target vehicles on FD and HD model.

Fig. 11. Effect of self interference cancellation on delivered data.

buffering and delivery of more data by the relay vehicles in the FD model, it offers greater rewards and ultimately more objective features compared to the HD model.

In the FD model, there are several time slots in which a vehicle can transmit and receive simultaneously. However, in these time slots, interference from the receiver link on the transmitter is present. To eliminate this interference, we must include the parameter $\beta$ in (4), with a value of $0 \leq \beta \leq 1$. The closer the value of $\beta$ is to zero, the more interference is suppressed. Figure 11 illustrates the effect of self-interference cancellation on the distributed data. As $\beta = \eta \sigma^2$, we can observe changes by varying $\eta$ while keeping $\sigma^2$ fixed. For instance, if $\eta = 40$ dB, the delivered data will be the highest compared to other values of $\eta$.

VI. CONCLUSION

In summary, the proposed model and algorithm provide a useful framework for selecting relay vehicles on highways and improving network performance. The consideration of rewards for relays and the use of FD technology are notable features that can lead to improved network utility. Additionally, the proposed algorithm using simulated annealing provides a faster solution compared to the optimal method. Simulation results demonstrate that FD relays offer greater utility, deliver more data, and receive greater rewards than HD relays. It is also shown that the performance improves as the number of selected relays increases. Furthermore, the study also examined the impact of increasing the number of target vehicles. It is shown that given knowledge of mapping matrix, the problem becomes separable in this state. Finally, the problem can be solved independently and separately for multiple targets. Future work can be built on these results by considering more complex network topologies and incorporating additional factors, such as energy consumption and congestion into the model.
REFERENCES


