

Full-Duplex Store-Carry-Forward scheme for Intermittently Connected Vehicular Networks

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Abstract—We consider intermittently connected vehicular networks (ICVNs) in which base stations (BSs) are installed along the highway to connect moving vehicles with internet. Due to the deployment cost, it is hard to cover the entire highway with BSs. To minimize the outage time in the uncovered area (UA), several cooperative store-carry-forward (CSCF) schemes have been proposed in which a vehicle is selected to act as a relay by buffering data to be relayed to a target vehicle in the UA. In this paper, we propose an energy-efficient full-duplex (FD) CSCF scheme that exploits the relay ability to receive and transmit simultaneously to improve the effective communication time, T_e , between the relay and the target vehicle. Accordingly, it can minimize the outage time and deliver more data to the target vehicle. In addition, the power allocation that minimizes the transmission cost (TC) under the required rates constraints is found. The problem is formulated as a geometric program (GP) and globally solved using the interior-point method. As compared to the half-duplex CSCF scheme, simulation results show that the proposed FD scheme offers more effective time, more successfully delivered data in the UA and lower TC.

I. INTRODUCTION

In certain vehicular environments, such as highways, it is hard to provide seamless connectivity due to geographical conditions or deployment cost. Vehicular communication networks (VCNs) in which the distance between neighboring base stations (BSs) is large such that there are uncovered areas (UAs) between successive BSs is known as intermittently connected vehicular networks (ICVNs) [1] or as vehicular delay tolerant networks (VDTNs) [2]. The time duration in which a vehicle stays in the UA without connectivity is known as outage time. A moving vehicle may request the download of large amount of data that cannot be fully transferred within the BS coverage. In such case, this vehicle, referred to as the target vehicle henceforth, suffers from outage time in the UA before reaching the coverage of the next BS. If the UA is large, the outage may cause intolerable delay for some applications (e.g., file download or video transmission [1], [2]).

To minimize the outage time and provide more persistent services, several cooperative store-carry-forward (CSCF) schemes have been proposed. In these schemes, based on

certain criteria, one of the vehicles is selected to act as a relay. While the target vehicle is receiving data from the BS, the selected relay stores part or the entire remaining data that cannot be delivered to the target vehicle inside the BS coverage. When the target vehicle enters the UA, the relay stops from storing more data and starts relaying the buffered data to the target vehicle. The outage time is reduced by the time duration of the communication between the relay and the target vehicle in the UA which will be termed as *effective communication time* T_e .

Due to the high mobility of the vehicles, the available time for the relay to buffer the target vehicle's data is limited as well as the available time for the relay to stay within the communication range of the target vehicle in the UA. The effective communication time between the relay and the target vehicle is equal to the minimum between the available time for buffering and the available for communication in the UA [2]. Therefore, minimizing the outage time in ICVNs remains a real challenge, and this is the main *scope* of this paper.

Minimizing the outage time is of great interest and it has been previously considered in the literature. In [3], the outage time is reduced by adjusting the speed of the target vehicle to extend the communication time. A bivious CSCF scheme is proposed in [4], which minimizes the outage time by selecting forward and backward relays as well as adjusting the speed. In [1], the outage time is minimized by selecting two relays one from each traffic direction. When the first relay loses communication with the target vehicle, the second relay from the opposite direction starts relaying to the target vehicle. In [2], the fact that relay candidates give priority to their data transfer over helping the target vehicle is considered, where the relay must receive its own data first before starts helping the target vehicle. The relay candidate that offers the highest effective communication time is selected.

All of the previous CSCF schemes consider half-duplex (HD) communication, in which once the selected relay starts transmission to the target vehicle, it has to stop from storing more data. On the contrary, full-duplex (FD) communication in VCNs has a great potential, where requirements such as space for antenna isolation and on-board unit with high computational efficiency are less challenging to be provided in vehicles than mobile devices [5]. Furthermore, the impres-

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sive improvement in the self-interference cancellation (SIC) techniques (e.g., 70 ~ 110 dB) has attracted a lot of attention to in-band FD communication as a promising technology for future wireless systems [5]. In this paper, we propose an FD CSCF scheme that exploits the relay ability of receiving and transmitting simultaneously to improve the effective communication time T_e between the relay and the target vehicle. Simply put, if the relay is capable of FD communication, the relay can continue in buffering more data as long as it stays within the BS coverage while transmitting to the target vehicle. By increasing T_e , the outage time will be reduced.

Unlike previous CSCF schemes such as [2] and [1] that completely neglect the uplinks, we take both of the downlinks and uplinks into consideration while assessing the performance of the downlink. This is because if a vehicle is busy transmitting data to the BS, it cannot communicate with the target vehicle before finishing transmission in the uplink. Thus, considering both of uplinks and downlinks is a more practical scenario. The proposed FD scheme exploits vehicles' speeds and locations as well as their traffic requirements in the uplinks and downlinks to select the relay that offers the highest T_e . Also, the power allocation (PA) that minimizes the transmission cost (TC) under the fixed transmission rates constraints is found. Based on the traffic activity in the uplinks and downlinks of the target vehicle and the relay, eight possible scenarios may occur. For each of these scenarios, minimizing the TC can be formulated as a geometric program (GP) and globally solved using the interior-point method.

II. SYSTEM MODEL

A. Network Model

We consider ICVNs, where BSs are installed linearly (i.e., with equal inter-BS distance) along a highway to connect moving vehicles with the Internet. Without loss of generality, we consider the simple one-way highway model used in [2] as shown in Fig.1.

We assume that BSs and vehicles are capable of FD communications and equipped with isolated antennas for transmission and reception. Similar to the works in [2] and [1], we investigate the downlink communication scenario in which a large amount of data may be requested by a target vehicle V_o .

Let d_0 and r_0 denote the inter-BS distance and cell radius, respectively, as shown in Fig. 1. Due to the installation cost, it is hard to cover the entire highway with BSs coverage. Thus, we assume that the BSs coverage is not seamless and there are UAs, i.e., $d_0 > 2r_0$ as illustrated in Fig. 1. We assume that all vehicles and BSs have equal transmission ranges, denoted by r_0 , and use fixed rate for transmission C .

B. Channel Model

Vehicles and BSs are assumed to use in-band FD communications to exchange information. Henceforth, we use c , r and o in the subscript to denote the BS, the relay and the target vehicle V_o , respectively. In the downlink from the BS

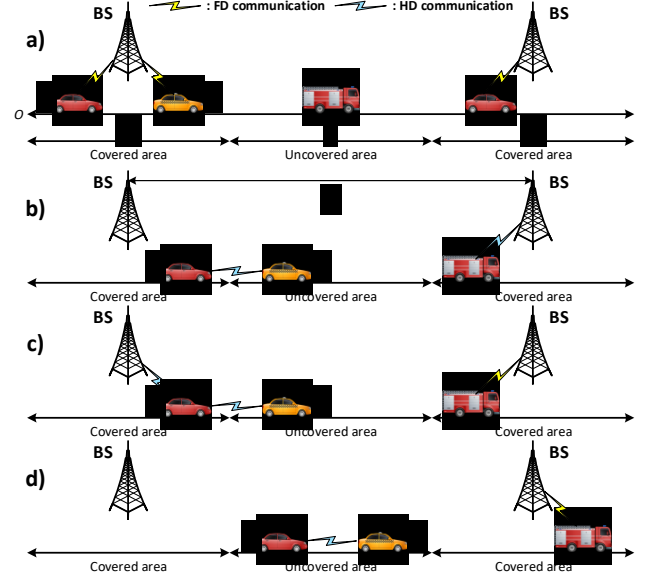


Fig. 1. Network model of ICVN, where V_o is the target vehicle and V_k is the relay. a) Coverage stage: V_o and V_k are inside the BS coverage. b) The start of the relaying stage in the HD schemes such as [2]. c) The start of the relaying stage in the proposed FD scheme. d) Relaying stage in the UA.

to V_o , the signal-to-interference plus noise ratio (SINR) at V_o is given by [6]

$$\gamma_o^D = \frac{P_{c,o} h_{c,o}}{\beta P_o h_{o,o} + \sigma^2}, \quad (1)$$

where $P_{c,o}$ is the transmission power used by the BS in the downlink, while P_o is the transmission power used by V_o in the uplink that causes self-interference (SI) to the downlink. The fact that the SI cannot be removed perfectly is captured using the factor β that represents the residual SI, where $0 \leq \beta \leq 1$. Also, σ^2 is the variance of the zero-mean additive white Gaussian noise (AWGN). Finally, $h_{c,o}$ is the channel power gain of the link from the BS to V_o that is given by [7]

$$h_{c,o} = g_{c,o} u_{c,o}, \quad (2)$$

where $u_{c,o}$ models the small-scale fading channel power. It is modelled by an exponentially distributed random variable with unit mean assuming that channels follow Rayleigh fading. Also, $g_{c,o}$ models the large-scale fading power component (i.e., shadowing and path-loss) and $h_{c,c}$, $h_{r,r}$ and $h_{o,o}$ are the channel power gains of the SI links at the BS, the relay and V_o , respectively. All the remaining channels of the network follow the same modelling as $h_{c,o}$. Similarly, the SINR of the uplink from V_o to the BS is equal to

$$\gamma_o^U = \frac{P_o h_{o,c}}{\beta P_{c,o} h_{c,c} + \sigma^2}. \quad (3)$$

For the FD communications between the BS and the relay, the SINR of the downlink and uplink are, respectively, given by

$$\gamma_r^D = \frac{P_{c,r} h_{c,r}}{\beta P_{r,c} h_{r,r} + \sigma^2}, \quad (4)$$

$$\gamma_r^U = \frac{P_{r,c} h_{r,c}}{\beta P_{c,r} h_{c,c} + \sigma^2}, \quad (5)$$

where $P_{c,r}$ ($P_{r,c}$) is the transmission power used by the BS (the relay) in the downlink (uplink) to the relay (the BS).

We assume that the BS is capable of estimating the instantaneous locations of all vehicles inside its coverage as well as their speeds [1], [2]. We also assume that the BS has the large-scale information of all links, which depend on the vehicles' locations and change with a low rate. Meanwhile, statistical parameters of the small-scale fading of the links can be estimated by the receivers of these links and transmitted periodically to the BS. As the BS only tracks statistical information of the small-scale fading, it avoids the overhead of tracking and transferring instantaneous channel state information (CSI) that is characterized by a fast rate of change due to the vehicles mobility [8].

C. Review of the effective communication time modelling

The effective communication time modelling is slightly differing from one scheme to another based on the network modelling and assumptions [1], [2]. As the HD CSCF scheme in [2] has considered the practical fact that relay candidates give priority to their data transfer over helping the target vehicle V_o , it will be used to represent the HD CSCF schemes. The relay performance depends on how much time the relay can offer for buffering V_o 's data after receiving its own data and how much time is available for delivering this buffered data to V_o in the UA [1], [2]. These times will be denoted by T_b and T_m , respectively. The effective communication time for a relay candidate V_k can thus be defined as [2]

$$T_e^{\text{HD}}(V_k) = \min \{T_b^{\text{HD}}(V_k), T_m(V_k)\}. \quad (6)$$

In the HD CSCF schemes, when V_o reaches the UA, the selected relay has to stop buffering more data and start relaying the buffered data to V_o as illustrated in Fig. 1(b). Thus, the offered buffering time of a relay candidate V_k is given by [2]

$$T_b^{\text{HD}}(V_k) = \max \left\{ 0, T_r(V_o) - \frac{R_q(V_k)}{C} \right\}, \quad (7)$$

where $R_q(V_k)$ is the size of the requested data by V_k in the downlink. $T_r(V_o)$ is the remaining time for V_o inside the BS coverage that is given by

$$T_r(V_o) = \frac{2r_0 - d(V_o)}{v_o}, \quad (8)$$

where v_o and $d(V_o)$ being, respectively, the speed and distance of V_o from the reference point O as shown in Fig. 1. On the other hand, $T_m(V_k)$ is the time duration in which a relay candidate V_k stays within the communication range of V_o in the UA. $T_m(V_k)$ depends on the locations and speeds of V_o and V_k and can be found as given in [2, Eqs. (5)-(7)].

III. THE PROPOSED FD CSCF SCHEME

When a vehicle V_o requests downloading data, the BS exploits its speed and location information to determine whether the remaining coverage time for V_o is enough to deliver the

requested data or relay selection is required. Obviously, relay selection is required if $R_q(V_o) > T_r(V_o) \times C$. Once relay selection is needed, the BS selects the relay candidate that offers the largest effective communication time, and is thus offering the minimum outage time. The considerations of FD communications and uplink transmission impact on the relay ability to communicate with the target vehicle V_o have effects on the available time for buffering V_o 's data and the available time for delivering this buffered data to V_o , respectively. In the proposed scheme, these times will be denoted by T_b^{FD} and T_c^{FD} , respectively. The effective communication time offered by the relay candidate V_k is given by

$$T_e^{\text{FD}}(V_k) = \min \{T_b^{\text{FD}}(V_k), T_c^{\text{FD}}(V_k)\}. \quad (9)$$

Unlike the HD schemes as shown in (8) and Fig. 1(b), when V_o reaches the UA, the selected relay V_k can continue buffering more data as long as it stays inside the BS coverage while transmitting to V_o as illustrated in Fig. 1(c). The offered time for buffering by a relay candidate V_k is thus equal to

$$T_b^{\text{FD}}(V_k) = \max \left\{ 0, T_r(V_k) - \frac{R_q(V_k)}{C} \right\}. \quad (10)$$

In other words, it is all the available time for reception minus the time that V_k uses to receive its own data.

The available time for V_k to deliver the buffered data to V_o in the UA, $T_c^{\text{FD}}(V_k)$, depends on V_k 's location and speed as well as its traffic in the uplink. Among all relay candidates, only candidates that will be within the transmission range r_0 of V_o when it reaches the UA will be considered. When V_o reaches the UA, the distance between V_o and V_k is given by

$$D(V_k) = 2r_0 - (T_r(V_o) \times v_k + X(V_k)), \quad (11)$$

where $X(V_k)$ is the location of V_k at the instant of relay selection. If $|D(V_k)| > r_0$, V_k will be removed from the candidate list. As mentioned earlier since the one-way highway model is adopted, the parameters that only depend on vehicles' locations and speeds can be computed similar to [2]. Specifically, the time duration $T_m(V_k)$ in which a relay candidate V_k stays within the communication range of V_o depends on the locations and speeds of V_o and V_k (i.e., $X(V_o)$, $X(V_k)$, v_o and v_k) and can be found as given in [2, Eqs. (5)-(7)]. However, the relay gives priority to its uplink transmission over helping V_o , and thus the relay may not be able to use the entire $T_m(V_k)$ for relaying. The offered time by a relay candidate V_k for delivering data to V_o in the UA after finishing transmission in the uplink is consequently equal to

$$T_c^{\text{FD}}(V_k) = \max \{0, T_m(V_k) - m(V_k)\}, \quad (12)$$

where $m(V_k)$ is the remaining time for V_k to finish transmission in the uplink after V_o has reached the UA, viz.,

$$m(V_k) = \max \{0, n(V_k) - T_r(V_o)\}, \quad (13)$$

where $n(V_k)$ represents the remaining time for V_k to finish transmission in the uplink, which may take the entire coverage time $T_r(V_k)$. This is given by

$$n(V_k) = \min \left\{ T_r(V_k), \frac{R_q^{Tx}(V_k)}{C} \right\}, \quad (14)$$

with $R_q^{Tx}(V_k)$ being the size of the requested data by V_k in the uplink. Based on $m(V_k)$, $T_m(V_k)$ and $T_r(V_o)$, there are three possible cases for $T_c^{FD}(V_k)$. First, if V_k has finished transmission in the uplink before V_o reaches the UA (i.e., $n(V_k) < T_r(V_o)$), $m(V_k)$ equals zero and the relay can use the entire time $T_m(V_k)$ for relaying the buffered data to V_o . Second, if V_k has finished uplink transmission after the entire duration $T_m(V_k)$ has passed (i.e., $T_m(V_k) < m(V_k)$), the relay will be removed from the candidate list where $T_c^{FD}(V_k) = 0$. Lastly, if the relay has finished transmission in the uplink after V_o has reached the UA but within the duration $T_m(V_k)$, the offered time by V_k for helping V_o in the UA is equal to the remaining time $T_m(V_k) - m(V_k)$. Based on (9), (10) and (12), the effective communication time $T_e^{FD}(V_k)$ of each relay candidate V_k can be found and the proposed scheme selects the relay candidate that offers the highest $T_e^{FD}(V_k)$.

IV. ENERGY EFFICIENCY

The energy efficiency (EE) can be defined as the ratio between the consumed energy and the amount of transmitted information [9]. In other words, it is the transmission cost (TC) that is equal to the consumed energy per transmitted bit [10]. To study the impact of $T_e^{FD}(V_k)$ on the performance in terms of delivered data to V_o , fixed transmission rate is used instead of maximizing the system throughput. Since fixed transmission rate is adopted, in order to do not missing out the potentials of the PA to improve the system performance, the optimal PA that minimizes the TC of the system while ensuring the reliability of the links is found. At any given time slot, in the downlink from the BS to V_o , the BS consumes $T_s P_{c,o}$ Joule in the transmission of $T_s C$ bits, where T_s is the time slot duration. Thus, the TC for this link is equal to $P_{c,o}/C$ Joule/bit. For the uplink, the TC is given by P_o/C . For the relay, the TC of the downlink (uplink) is given by $P_{c,r}/C$ ($P_{r,c}/C$). First, we minimize the TC of the system for the coverage stage in which both of the target vehicle V_o and the relay V_k stay inside the BS coverage as shown in Fig. 1(a). Then, we minimize the TC for the relaying stage in which V_o stays in the UA as illustrated in Fig. 1(c,d).

A. The Coverage Stage

In this stage, the BS is directly communicating with the target vehicle V_o and the relay V_k as shown in Fig. 1(a). At any given time slot, the TC of the system can be minimized while ensuring the reliability of the uplinks and downlinks as follows

$$\min_{\{P_o, P_{r,c}, P_{c,o}, P_{c,r}\}} \frac{P_o + P_{r,c} + P_{c,o} + P_{c,r}}{C} \quad (15a)$$

subject to

$$\text{Prob} \{ \gamma_{c,o} \leq \gamma^D \} \leq O_{max}, \quad (15b)$$

$$\text{Prob} \{ \gamma_{c,r} \leq \gamma^D \} \leq O_{max}, \quad (15c)$$

$$\text{Prob} \{ \gamma_{o,c} \leq \gamma^U \} \leq O_{max}, \quad (15d)$$

$$\text{Prob} \{ \gamma_{r,c} \leq \gamma^U \} \leq O_{max}, \quad (15e)$$

$$P_{min} \leq P \leq P_{max}, \quad \forall P \in \{P_o, P_{r,c}, P_{c,o}, P_{c,r}\} \quad (15f)$$

where the SINRs of the links $\gamma_{c,o}$, $\gamma_{o,c}$, $\gamma_{c,r}$ and $\gamma_{r,c}$ are given by (1), (3), (4) and (5), respectively. As C is a constant, the objective function can be expressed equivalently as the sum of the used transmission powers. The reliability of the links are met by ensuring that the outage probabilities of these links are less than an acceptable small threshold O_{max} as seen in (15b)-(15e) with γ^D and γ^U being the SINR thresholds of the downlinks and uplinks, respectively. As we assumed fixed transmission rate C in all links, $\gamma^D = \gamma^U = \gamma$ where $\gamma = 2^{\frac{C}{B}} - 1$, and B is the channel bandwidth. The constraints in (15f) set the allowed transmission power values.

Using the definition of $\gamma_{c,o}$ in (1), the outage constraint in (15b) can be rewritten as

$$\text{Prob} \{ P_{c,o} h_{c,o} \leq \gamma(\beta P_o h_{o,o} + \sigma^2) \} \leq O_{max}. \quad (16)$$

By exploiting the result in Lemma 1 of [8], the outage constraint in (16) can be expressed as

$$1 - \exp \left(-\frac{\gamma \sigma^2}{P_{c,o} g_{c,o}} \right) \left(\frac{1}{1 + \frac{\beta P_o g_{o,o}}{P_{c,o} g_{c,o}}} \right) \leq O_{max}. \quad (17)$$

Although we assume that the BS can estimate the statistical parameters of the small-scale fading in section II, these parameters do not appear in (17) and the following analysis. This because we assume that channels have unit mean similar to [7] and [8]; otherwise, means of the channels will appear in Lemma 1 of [8] and (17). The upper and lower bounds of the outage probability in the left side of (17) are derived in [7] and [11], where the noise power σ^2 is considered in [7] and neglected in [11] for simplicity. Both works have shown that the upper and lower bounds are very tight in the area of interest (i.e., outage probability less than 5%). Similar to [8], the outage probability in the left side of (17) will be replaced by its upper bound, and (17) can be expressed as

$$1 - \exp \left(-\gamma(\beta P_o g_{o,o} + \sigma^2)/(P_{c,o} g_{c,o}) \right) \leq O_{max}. \quad (18)$$

The problem in (15) can thus be expressed as

$$\min_{\{P_o, P_{r,c}, P_{c,o}, P_{c,r}\}} P_o + P_{r,c} + P_{c,o} + P_{c,r} \quad (19a)$$

subject to

$$\bar{\gamma}(\beta P_o g_{o,o} + \sigma^2)/(P_{c,o} g_{c,o}) \leq 1, \quad (19b)$$

$$\bar{\gamma}(\beta P_{r,c} g_{r,r} + \sigma^2)/(P_{c,r} g_{c,r}) \leq 1, \quad (19c)$$

$$\bar{\gamma}(\beta P_{c,o} g_{c,c} + \sigma^2)/(P_o g_{o,c}) \leq 1, \quad (19d)$$

$$\bar{\gamma}(\beta P_{c,r} g_{c,c} + \sigma^2)/(P_{r,c} g_{r,c}) \leq 1, \quad (19e)$$

$$\frac{P_{min}}{P} \leq 1, \quad \frac{P}{P_{max}} \leq 1, \quad \forall P \in \{P_o, P_{r,c}, P_{c,o}, P_{c,r}\}, \quad (19f)$$

where (19b) is obtained after applying basic mathematical manipulations on (18), and $\bar{\gamma} = \gamma / \ln(1 - O_{max})^{-1}$. The reliability constraints in (15c)-(15e) are similarly simplified to (19c)-(19e). It is noted that the objective function (19a) and the reliability constraints in (19b)-(19e) are posynomial functions, while the power constraints in (19f) are monomials [12]. Accordingly, the problem in (19) is a GP in the variables $P_o, P_{r,c}, P_{c,o}$ and $P_{c,r}$. An efficient global solution of this GP can be obtained by using the interior-point method for GPs as detailed in [12].

While V_o needs the relay help to receive the data that cannot be delivered within the BS coverage (i.e., V_o is in receiving status inside and outside the coverage), it is not necessary that V_o always needs the uplink. There is a probability that V_o does not need or has already finished transmission in the uplink. Thus, we use the binary variable a_i that is equal to one (zero) if V_o needs (does not need) the uplink transmission in the i -th time slot. Similarly, we use the binary variable b_i (c_i) that indicates whether the downlink (uplink) of the relay V_k is active or not in the i -th time slot. Based on a_i, b_i and c_i , eight possible combinations are possible; each of which leads to a different problem formulation and solution. These eight possible formulations can be represented together in a general formulation as follows

$$\min_{\{P_o, P_{r,c}, P_{c,o}, P_{c,r}\}} a_i P_o + c_i P_{r,c} + P_{c,o} + b_i P_{c,r}$$

subject to

$$\begin{aligned} C1 : & \quad \bar{\gamma}(a_i \beta P_o g_{o,o} + \sigma^2) / (P_{c,o} g_{c,o}) \leq 1, \\ C2_{\{b_i=1\}} : & \quad \bar{\gamma}(c_i \beta P_{r,c} g_{r,r} + \sigma^2) / (P_{c,r} g_{c,r}) \leq 1, \\ C3_{\{a_i=1\}} : & \quad \bar{\gamma}(\beta P_{c,o} g_{c,c} + \sigma^2) / (P_o g_{o,c}) \leq 1, \\ C4_{\{c_i=1\}} : & \quad \bar{\gamma}(b_i \beta P_{c,r} g_{c,c} + \sigma^2) / (P_{r,c} g_{r,c}) \leq 1, \\ C5_{\{a_i=1\}} : & \quad \frac{P_{min}}{P_o} \leq 1, \quad \frac{P_o}{P_{max}} \leq 1, \\ C6_{\{c_i=1\}} : & \quad \frac{P_{min}}{P_{r,c}} \leq 1, \quad \frac{P_{r,c}}{P_{max}} \leq 1, \\ C7 : & \quad \frac{P_{min}}{P_{c,o}} \leq 1, \quad \frac{P_{c,o}}{P_{max}} \leq 1, \\ C8_{\{b_i=1\}} : & \quad \frac{P_{min}}{P_{c,r}} \leq 1, \quad \frac{P_{c,r}}{P_{max}} \leq 1, \end{aligned}$$

For instance, if ($a_i = 0, b_i = 1, c_i = 1$), the target vehicle V_o does not need the uplink. Accordingly, there is no SI to the downlink in C1 ($a_i \beta P_o g_{o,o} = 0$) as well as the reliability constraint of the uplink C3 should be removed. It can be readily checked that all the eight possible formulations that may result based on the values of a_i, b_i and c_i are GPs in the standard form and can be solved efficiently using the interior-point-method [12]. The values of the binary variables a_i, b_i and c_i depend on the sizes of the requested data $R_q^{Tx}(V_o)$, $R_q(V_k)$ and $R_q^{Tx}(V_k)$, respectively. At the i -th time slot, the binary variables a_i, b_i and c_i are given by

$$a_i = \begin{cases} 1, & \text{if } i \leq \lfloor n(V_o)/T_s \rfloor, \\ 0, & \text{otherwise,} \end{cases} \quad (21)$$

$$b_i = \begin{cases} 1, & \text{if } i \leq \lfloor \left(\frac{R_q(V_k)}{C} + T_e^{FD}(V_k) \right) / T_s \rfloor, \\ 0, & \text{otherwise,} \end{cases} \quad (22)$$

$$c_i = \begin{cases} 1, & \text{if } i \leq \lfloor n(V_k)/T_s \rfloor, \\ 0, & \text{otherwise.} \end{cases} \quad (23)$$

The transmission in the uplink will stop ($a_i = 0$ or $b_i = 0$ for V_o and V_k , respectively) if all data has been transmitted or the vehicle has left the BS coverage as given in (14). The relay reception will stop (i.e., $b_i = 0$) if all data has been received (22), which consists of the relay's requested data plus the buffered data that will be relayed to V_o in the UA.

B. The Relaying Stage

As mentioned earlier, the selected relay V_k is capable of buffering more data while transmitting to V_o as given in (10). At a given time slot i , two scenarios are possible as shown in Fig. 1(c,d). First, the relay V_k works in FD mode, i.e., receives from the BS and transmits to V_o simultaneously. Second, if the relay reception has ended ($b_i = 0$), the relay only transmits to V_o . The minimization of the TC can thus be expressed as

$$\min_{\{P_{r,o}, P_{c,r}\}} P_{r,o} + b_i P_{c,r}$$

subject to

$$\begin{aligned} C1_{\{b_i=1\}} : & \quad \bar{\gamma}(\beta P_{r,o} g_{r,r} + \sigma^2) / (P_{c,r} g_{c,r}) \leq 1, \\ C2 : & \quad \bar{\gamma} \sigma^2 / (P_{r,o} g_{r,o}) \leq 1, \\ C3 : & \quad \frac{P_{min}}{P_{r,o}} \leq 1, \quad \frac{P_{r,o}}{P_{max}} \leq 1, \\ C4_{\{b_i=1\}} : & \quad \frac{P_{min}}{P_{c,r}} \leq 1, \quad \frac{P_{c,r}}{P_{max}} \leq 1, \end{aligned}$$

where $P_{r,o}$ is the transmission power used by the relay to communicate with the target vehicle V_o . It can be readily checked that the two possible formulations that may result based on the value of b_i are GPs in the standard form. As V_o stays in the UA, the transmitted signal from the BS to V_k will not cause an interference to V_o as given in C2.

V. SIMULATION RESULTS

In this section, the performance of the proposed scheme is assessed based on simulations of the system model described in Section II. The performance, in terms of effective communication time T_e^{FD} , successfully delivered data to the target vehicle V_o as well as the TC is compared with that of the HD scheme proposed in [2]. In all the considered simulations, we used $C = 6$ MHz, $B = 10$ MHz, $U = 900$ m, $r_0 = 300$ m, $P_{max} = 23$ dBm, $P_{min} = 0$ dBm, $\sigma^2 = -114$ dBm, number of vehicles = 50, $R_q^{Tx}(V_k) \in [10, 20]$ MHz and $v_k \in [50, 90]$ km/h. All simulation results presented in this section are obtained from 10,000 realizations, where vehicles are distributed randomly in the highway in each realization.

First, the performances are compared in terms of the effective communication time T_e . As discussed in Section III, by virtue of the relay's ability to continue buffering data while transmitting to V_o , the proposed scheme offers more buffering

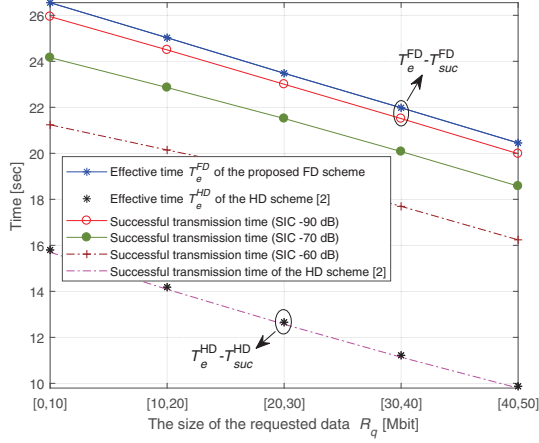


Fig. 2. The impact of the size of the requested data by relay candidates $R_q(V_k)$ on the the performance in terms of the effective communication time and successful transmission time.

time (10), and accordingly more effective time (9) as clearly shown in Fig. 2. When the size of the requested data by the relay candidates $R_q(V_k)$ is increased from 0 ~ 10 Mbit to 10 ~ 20 Mbit, 20 ~ 30 Mbit, 30 ~ 40 Mbit and 40 ~ 50 Mbit, both schemes offer less T_e as the available time for buffering T_b is decreased in agreement with (8) and (10).

In [2], the transmission rate C is assumed to be guaranteed and neither channel fading nor PA is considered. Taking the channel fading into account, outage events may occur and data that can be delivered successfully to V_o is effectively equal to $T_{suc}^{HD}(V_k) \times C$ instead of $T_e^{HD}(V_k) \times C$, where T_{suc}^{HD} is the successful transmission time. The difference $T_e^{HD}(V_k) - T_{suc}^{HD}(V_k)$ represents an outage time during which the requirements of the links could not be fulfilled. The results of [2] in this section have been obtained by assuming vehicles are using fixed transmission power P_{max} . As shown in Fig. 2, the proposed FD scheme is subjected to more outage events (i.e., $T_e^{FD}(V_k) - T_{suc}^{FD}(V_k)$); however, it still offers significantly higher successful transmission time (i.e., delivers more data) due to its much higher effective time $T_e^{FD}(V_k)$. In addition, Fig. 2 shows the impact of the SIC on the performance of the proposed scheme. Higher SIC obviously improves the SINRs of the links as given in (1) and (4), which in turn minimizes the outage probability (i.e., $T_e^{FD}(V_k) - T_{suc}^{FD}(V_k)$). As shown in Fig. 2, the $T_{suc}^{FD}(V_k)$ increases as the SIC factor β decreases.

Figure 3 shows the TC of the systems. As the proposed FD scheme has lower SINR threshold ($\gamma < \gamma_{HD}$, where $\gamma = 2^{C/B} - 1$ and $\gamma_{HD} = 2^{2C/B} - 1$) and its TC has been optimally minimized, it offers lower TC than the HD scheme in [2]. Also, as the SIC factor β increases in the proposed scheme, higher transmission powers must be used to fulfill the required rates. Hence, as shown in Fig. 3, the TC increases as β increases.

VI. CONCLUSION

We proposed an FD store-carry-forward scheme for ICVNs. The FD capability of the relay has been exploited to extend the effective communication time with the target vehicle, and

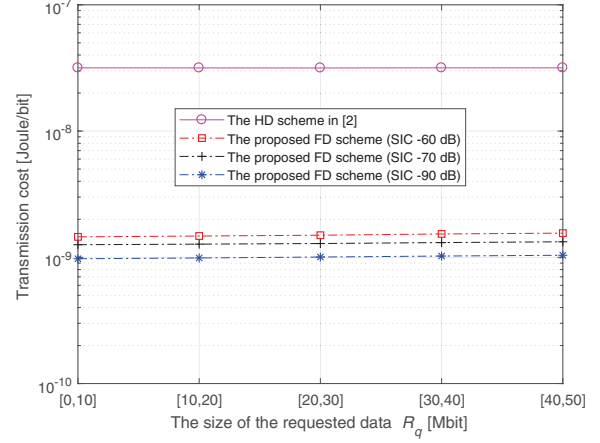


Fig. 3. The performances of the proposed scheme and the HD scheme [2] in terms of the total consumed energy.

accordingly minimizing the outage time. The proposed scheme exploits speeds and locations information of the vehicles as well as traffic requirements information of the uplinks and downlinks to select the relay that offers the highest effective communication time. The transmission cost has been minimized. It has been shown that the proposed FD scheme improves the effective communication time significantly as well as offering lower transmission cost.

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