Received July 29, 2020, accepted August 28, 2020, date of publication September 1, 2020, date of current version September 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3020826

An Optimal Power Allocation and Relay Selection Full-Duplex Store-Carry-Forward Scheme for Intermittently Connected Vehicular Networks

ALI A. SIDDIG[1], AHMED S. IBRAHIM[2], (Member, IEEE), AND MAHMOUD H. ISMAIL[1,3], (Senior Member, IEEE)

[1]Department of Electrical Engineering, American University of Sharjah, Sharjah, United Arab Emirates
[2]Electrical and Computer Engineering Department, Florida International University, Miami, FL 33174, USA
[3]Department of Electronics and Electrical Communications Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt

Corresponding author: Mahmoud H. Ismail (mhibrahim@aus.edu)

This work was supported in part by the Smart Cities Research Institute (SCRI), American University of Sharjah, under Grant EN0281:SCRI18-07. The work of Ahmed S. Ibrahim was supported in part by the National Science Foundation under Award CNS-1816112.

ABSTRACT We consider intermittently connected vehicular networks (ICVNs) in which base stations (BSs) are installed along a 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 store-carry-forward (SCF) 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 a full-duplex (FD) SCF scheme that exploits the relay's ability to simultaneously receive and transmit in order to improve the effective communication time (ECT) with the target vehicle and accordingly deliver more data to it in the UA. The optimal power allocation (PA) that maximizes the ergodic capacities of the links is determined and the amount of data that can be buffered inside the BS coverage and can be delivered by each relay candidate to the target vehicle in the UA is found. Since the relay cannot deliver more data in the UA than what can be buffered inside the coverage, the performance of each relay candidate is limited by the minimum of the two amounts and hence is used as a relay selection (RS) criteria. To reduce the computational complexity, an alternative RS scheme that selects the relay candidate that offers the highest ECT is proposed. As compared to half-duplex SCF schemes, simulation results show that the proposed FD schemes are capable of delivering significantly higher amount of data to the target vehicle in the UA.

INDEX TERMS Intermittently connected vehicular networks (ICVNs), full-duplex, store-carry-forward, outage time, relay selection, power allocation.

I. INTRODUCTION

Vehicular communication networks (VCNs) have attracted a lot of attention due to their ability to improve road safety and traffic control as well as support advanced infotainment applications [1]. In certain vehicular environments, such as highways, it maybe hard to provide seamless connectivity due to geographical conditions or deployment cost. VCNs in which the distance between neighboring base stations (BSs) is large such that there are uncovered areas (UAs) between them is known as intermittently connected vehicular networks (ICVNs) [2] or as vehicular delay tolerant networks (VDTNs) [3]. Such lack of connectivity is more common in developing countries than developed ones due to deployment cost. It is reported in the literature that the average distance between adjacent Internet access points in highways might reach 8-16 km [4]. Therefore, vehicles may fail to fulfill the download requirements of large-size content due to the existence of UAs as well as the short duration inside the coverage area as a result of the high mobility. The problem is even aggravated by the fact that resources in terms of time or bandwidth are shared among vehicles inside the coverage. To overcome this limitation, several cooperative store-carry-forward (SCF) schemes are proposed to convert vehicles from being competitors to cooperators [2].

The time duration in which a vehicle stays in the UA without connectivity is known as the outage time. A moving vehicle may request large amounts of data that cannot be fully

The associate editor coordinating the review of this manuscript and approving it for publication was Muhammad Awais Javed.

transferred within the BS coverage. In such case, this vehicle, referred to as the target vehicle henceforth, suffers from outage 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 [2], [3]). To minimize the outage time and provide more persistent services, several SCF relaying schemes have been proposed. In these schemes, based on certain criteria, one or more vehicles are selected to act as relays. While the target vehicle is receiving data from the BS, the selected relay(s) stores part of or the entire remaining data (RD) 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. Consequently, the outage time is reduced by the time duration of the communication between the relay and the target vehicle in the UA. This time duration will be termed as the effective communication time (ECT).

Due to the high mobility of the vehicles, the available time for the relay(s) to buffer the target vehicle's data as well as the available time for the relay(s) to stay within the communication range of the target vehicle in the UA are both limited. The ECT between the relay and the target vehicle is clearly equal to the minimum between the available time for buffering and that available for communication in the UA [3]. Therefore, minimizing the outage time in ICVNs remains a real challenge, and this is the main scope of this paper.

In-band full-duplex (FD) communications, where nodes are able to transmit and receive simultaneously over the same band, can achieve high spectral efficiency as opposed to HD communications. Recently, the impressive improvement in self-interference cancellation (SIC) techniques (e.g., in the order of $70-110$ dB) has attracted a lot of attention to in-band FD communication as a promising technology for future wireless systems [5]. For VCNs, in particular, there is a great potential for using FD communications where requirements such as the need for space for antenna isolation and for an on-board unit with high computational efficiency as well as energy consumption considerations are less challenging to be satisfied in vehicles than in mobile devices [5]. To the best of our knowledge, with the exception of our previous work in [6], all the existing SCF schemes in the literature that have been proposed for ICVNs are using half-duplex (HD) communication, in which once the selected relay(s) start transmission to the target vehicle, they have to stop from storing more data. On the contrary, FD communication offers the ability of transmitting and receiving simultaneously. 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. Therefore, the ECT will be increased, which, in turn, reduces the outage time and allows for delivering larger amounts of information to the target vehicle in the UA.

According to the discussion above, in this paper, we investigate the downlink communication scenario of ICVNs in which a large amount of data may be requested by a target vehicle V_o. We propose an FD SCF scheme that exploits the relay's ability of receiving and transmitting simultaneously to improve the ECT between the relay and the target vehicle. Accordingly, more data can be delivered to the target vehicle in the UA. The proposed scheme exploits the spectral efficiency of FD communication to maximize the ergodic capacities of the links. Since the BS can transmit with higher rate to the target vehicle V_o, either the relay help will not be required or at least less data must be delivered through the selected relay to V_o in the UA. In addition, the relay can buffer more data inside the BS coverage and deliver more data to V_o in the UA. Since the proposed scheme depends on ergodic maximization (EM), we refer to it as the EM-SCF scheme hereafter.

The proposed EM-SCF scheme consists of power allocation (PA) and relay selection (RS) steps. Inside the BS coverage, at each time slot, the optimal PA that maximizes the ergodic capacity of the downlink while satisfying the capacity requirements of the uplink is determined for each of the target vehicle and the relay. The capacity requirements of the uplinks are fulfilled by ensuring the outage probabilities of these links are less than an acceptable threshold. At the relaying stage, in which the target vehicle stays in the UA, at each time slot, the optimal PA that maximizes the ergodic capacity of the link between the relay and the target vehicle is found. Clearly, the maximum amount of information that can be buffered by the relay is equal to the sum of ergodic capacities over the time slots in which the relay stays inside the BS coverage, while the maximum amount of information that can be transferred to V_o in the UA is equal to the sum of ergodic capacities over the time slots in which the relay can communicate with V_o in the UA. Since the relay cannot deliver more information to V_o in the UA than what can be buffered inside the coverage, the performance of each relay candidate can be assessed based on the minimum of the two sums of the ergodic capacities. The proposed EM-SCF scheme thus selects the relay candidate that has the maximum minimum.

Finally, to reduce the computational complexity, we propose a hybrid SCF scheme that merges the simple RS of the special case in [6] with the PA of the proposed EM-SCF scheme. Specifically, the hybrid scheme uses the RS of the scheme in [6], i.e., assuming fixed transmission rate (FTR), to select the relay candidate that offers the highest ECT, and thereby can deliver the largest amount of data to the target vehicle V_o in the UA. Then, at each time slot, the ergodic capacities of the links are maximized as in the proposed EM-SCF scheme. The rest of the paper is organized as follows: the next section surveys the related works in the literature, Section III presents the system model under consideration along with other assumptions, the problem formulation is then introduced in Section IV followed by the proposed EM-SCF scheme in Section V. Simulation results and discussions are then presented in Section VI before the paper is finally concluded in Section VII.

II. RELATED WORK

Minimizing the outage time is of great interest and it has been previously considered in the literature. The outage time can be significantly reduced if multihop SCF relaying is used such as the schemes in [7]–[9]. However, in addition to the high signaling overhead, the throughput will rapidly diminish as the number of relay hops increases [10]. Accordingly, keeping the number of relay hops as low as possible is preferred [2].

In [11], the outage time is reduced by adjusting the speed of the target vehicle to extend the communication time with the selected relay vehicle. A bivious SCF scheme is proposed in [12], which minimizes the outage time by selecting forward and backward relays. In addition, the speed of the target vehicle is adjusted to extend the communication time. The main drawback of the works in [11] and [12] is that the problem of speed adjusting is solved using the interior-point method that inevitably involves large number of iterations [2]. The SCF scheme proposed in [2], on the other hand, minimizes the outage time by selecting two relays one from each traffic direction. When the first relay loses communication with the target vehicle in the UA, the second relay from the opposite direction starts relaying to the target vehicle. The outage time is minimized by the amount of the sum of the ECT of the two relays. In [13], based on the size of the RD, one or more relays are selected from the opposite traffic direction. While V_o receives data directly from the roadside unit (RSU), the selected relays from the opposite traffic direction pre-store part of or the entire RD. When V_o enters the UA, the selected relays start relaying the pre-stored data to V_o. The work in [13] has been extended in [4], where a cluster-based relay selection is proposed. In this scheme, the target vehicle V_o follows the vehicles that have no download requirements and form a cluster together. In addition, one or more relays are selected from the opposite traffic direction in similar criterion as that of [13]. When V_o enters the UA, the selected relays and cluster members start relaying the buffered data inside the RSU coverage to V_o. In [3], the fact that relay candidates give priority to their data transfer over helping the target vehicle is considered. Based on the size of the RD, relay candidates are selected based on their ECT. The relay candidate that offers the highest ECT is selected first. Since FTR is assumed, the relay candidate with highest ECT is the one capable of delivering the largest amount of data to the target vehicle in the UA.

It is very important to note that all the aforementioned SCF schemes use HD communications, in which once the selected relay starts relaying to the target vehicle, it has to stop from storing more data. The FD SCF scheme we proposed in [6] exploits the relay's ability of receiving and transmitting simultaneously to increase the ECT. More specifically, the selected relay can continue in buffering more data as long as it stays within the BS coverage while transmitting to the target vehicle. The FD SCF in [6] represents a special case of the proposed EM-SCF scheme in this work since, for simplicity, FTR was assumed instead of maximizing the ergodic capacities of the links. In each time slot, the scheme in [6] determines the PA that minimizes the transmission cost (i.e., consumed energy/rate). To achieve that, the optimization problem was formulated as an standard geometric program (GP) and solved using the interior-point method.

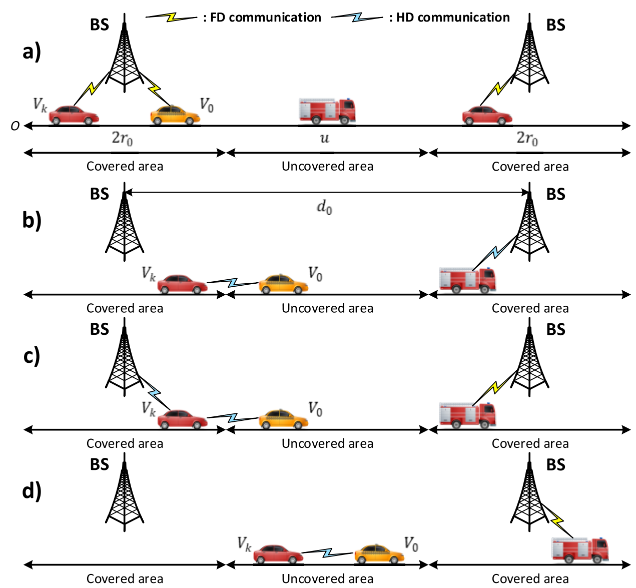

FIGURE 1. Network model of ICVN, where V_o is the target vehicle and V_k is the relay. a) Coverage stage: V_o and V_k are inside the BS coverage. b) The start of the relaying stage in the HD schemes such as [3]. c) The start of the relaying stage in the proposed FD scheme. d) Relaying stage in the UA.

III. SYSTEM MODEL

A. NETWORK MODEL

As mentioned earlier, we consider ICVNs, where BSs are installed linearly (i.e., with equal inter-BS distance d_0) along a highway to connect moving vehicles with the Internet. Without loss of generality, we consider the simple one-way highway model used in [3] as shown in Fig. 1. We assume that all vehicles and BSs have equal transmission ranges, denoted by r_0, i.e., the cell radius is r_0. 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 as illustrated in Fig. 1, i.e., $d_0 > 2r_0$ and the uncovered distance $u = d_0 - 2r_0$.

We also assume that BSs and vehicles are capable of FD communications and are equipped with isolated antennas for transmission and reception. Similar to the works in [2]–[4], [11]–[13], we investigate the downlink communication scenario in which a target vehicle V_o may request a large amount of data that cannot be received entirely inside the BS coverage. To provide a persistent service, one of the vehicles is selected to act as a relay by buffering part of or the entire remaining data that cannot be delivered to V_o inside the BS coverage to be relayed to V_o in the UA. Figure 1 illustrates the coverage stage, relaying stage and what differentiates the proposed FD SCF schemes from the existing

HD ones. More specifically, Fig. 1(a) shows the coverage stage in which both V_o and V_k stay inside the BS coverage. In the HD SCF schemes, once V_o reaches the UA, the relay V_k stops the reception from the BS and starts relaying to V_o as shown in Fig. 1(b). On the contrary, in the proposed FD SCF schemes, the relay V_k can continue buffering data while relaying already buffered data to V_o as demonstrated in Fig. 1(c). Lastly, when both V_o and V_k are located in the UA, there is one active transmission from V_k to V_o in all schemes as illustrated in Fig. 1(d).

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 to V_o, the signal-to-interference plus noise ratio (SINR) at V_o is given by [14]

$$\gamma_o^D = \frac{P^{c,o} h^{c,o}}{\beta P^o h^{o,o} + \sigma^2}, \tag{1}$$

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 [15]

$$h^{c,o} = g^{c,o} u^{c,o}, \tag{2}$$

where $u^{c,o}$ represents the small-scale fading channel power 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 pathloss) 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

$$\gamma_o^U = \frac{P^o h^{o,c}}{\beta P^{c,o} h^{c,c} + \sigma^2}. \tag{3}$$

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

$$\gamma_r^D = \frac{P^{c,r} h^{c,r}}{\beta P^{r,c} h^{r,r} + \sigma^2}, \tag{4}$$

$$\gamma_r^U = \frac{P^{r,c} h^{r,c}}{\beta P^{c,r} h^{c,c} + \sigma^2}, \tag{5}$$

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 [2], [3]. We also assume that the BS has the large-scale information of all links, which depend on the vehicles' locations and that change with a low rate. As the BS only tracks large-scale information, 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 [1].

IV. PROBLEM FORMULATION

The proposed EM-SCF scheme exploits the spectral efficiency of FD communication to maximize the ergodic capacities of the links. Since FD communication is considered, the impact of the uplink transmission on the amounts of data that can be buffered inside the BS coverage and can be delivered to the target vehicle V_o in the UA must be taken into account. The optimal PA that maximizes the ergodic capacities of the links inside the BS coverage and in the UA will be determined as explained in the following subsections.

A. COVERAGE STAGE

In each time slot, for each of the target vehicle V_o and a relay, say the kth vehicle, V_k, the optimal PA that maximizes the ergodic capacity of the downlink while guaranteeing the minimum capacity requirement of the uplink needs to be determined. Since the downlinks are of interest in this work and the usage of the downlinks resources is more intensive as compared to the uplinks [1], the ergodic capacities of the downlinks are maximized while the minimum capacity requirements of the uplinks are fulfilled. For the relay V_k, at the i-th slot time slot, assuming that the maximum allowed transmit powers for the BS and the relay vehicle are given by P^c_{max} and P^r_{max}, respectively, the PA problem can now be formulated as

$$\max_{\{P_i^{c,r}, P_i^{r,c}\}} \quad E_i^{r,u}(V_k) \tag{6a}$$

$$\begin{aligned} \text{subject to } & \text{Prob}\left\{\gamma_r^U \leq \gamma^U\right\} \leq O^U_{max}, \\ & 0 \leq P_i^{c,r} \leq P^c_{max}, \\ & 0 \leq P_i^{r,c} \leq P^r_{max}. \end{aligned} \tag{6b}$$

In (6a), $E_i^{r,u}(V_k)$ is ergodic capacity of the downlink from the BS to V_k while transmission in the uplink is still active, which is given by [16, Appendix C]

$$\begin{aligned} E_i^{r,u}(V_k) &= \mathbb{E}\left[\log_2\left(1 + \frac{P_i^{c,r} g_i^{c,r} u_i^{c,r}}{\beta P_i^{r,c} g_i^{r,r} u_i^{r,r} + \sigma^2}\right)\right] \\ &= \frac{yW\left[e^{\frac{1}{y}} E_1\left(\frac{1}{y}\right) - e^{\frac{1}{z}} E_1\left(\frac{1}{z}\right)\right]}{(y-z)\ln(2)}, \end{aligned} \tag{7}$$

where $\mathbb{E}[\cdot]$ returns the expected value, $E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt$ is the exponential integral function of the first order, which is available as a built-in function in software packages such as MATLAB, W is the channel bandwidth, $y = \frac{P_i^{c,r} g_i^{c,r}}{\sigma^2}$ and $z = \frac{\beta P_i^{r,c} g_i^{r,r}}{\sigma^2}$. The constraint in (6b) fulfills the minimum capacity requirements of the uplink by ensuring that the outage probability of the link is less than an acceptable threshold

O^U_{max} where $\gamma^U = 2^C - 1$ is the SINR threshold and C is the fixed transmission rate, both of the uplink.

The optimization problem in (6) is formulated assuming that transmission in the uplink is active; however, if the relay V_k has finished from transmission in the uplink, there will be no interference to the downlink. The ergodic capacity of the downlink in case of no interference from the uplink is given by [17, Eq. (39)]

$$E^r_i(V_k) = \mathbb{E}\left[\log_2\left(1+\frac{P^{c,r}_i g^{c,r}_i u^{c,r}_i}{\sigma^2}\right)\right] = \frac{W\left[e^{\frac{1}{y}}E_1\left(\frac{1}{y}\right)\right]}{\ln(2)}, \tag{8}$$

It is worth mentioning that the constraints in (6b) and (6b) are constraining the uplink transmission, and will thus be neglected in this case. The ergodic capacity of the downlink is thus maximized considering the power constraint (6b) only.

For the target vehicle V_o, the ergodic capacity of the downlink under the existence or the absence of the uplink transmission can be maximized similar to the relay V_k by replacing r by o in the superscripts of all the variables used.

B. RELAYING STAGE

As mentioned earlier, when the target vehicle V_o enters the UA, the selected relay V_k continues buffering more data while transmitting to V_o as shown in Fig. 1(c). If the relay V_k enters the UA, it stops the reception but continues the transmission to V_o as long as it stays within the communication range of V_o as shown in Fig. 1(d). First, we will tackle the first scenario in which V_k receives from the BS while transmitting to V_o. Clearly, there are two active links; the downlink from the BS to V_k and the link from V_k to V_o. Indeed, maximizing both links is the best choice. However, while the capacity of the second link increases as the transmission power $P^{r,o}_i$ increases, it causes SI to the downlink. Accordingly, it is difficult to maximize the ergodic capacities of both links concurrently. Alternatively, we choose to maximize the ergodic capacity of the link from V_k to V_o while setting a minimum capacity requirement, C, for the downlink. We gave more priority for delivering the buffered data to V_o over buffering more data from the BS to avoid buffering more data than what can actually be delivered. As will be shown in the sequel, this decision has been tested using simulations and actually resulted in more delivered data to V_o in the UA as compared to the choice of maximizing the downlink. Now, the ergodic capacity of the link from V_k to V_o is given by

$$E^{r,o}_i(V_k) = \mathbb{E}\left[\log_2\left(1+\frac{P^{r,o}_i g^{r,o}_i u^{r,o}_i}{\sigma^2}\right)\right] = \frac{W\left[e^{\frac{1}{q}}E_1\left(\frac{1}{q}\right)\right]}{\ln(2)}, \tag{9}$$

where $q = \frac{P^{r,o}_i g^{r,o}_i}{\sigma^2}$. The PA problem that maximizes $E^{r,o}_i(V_k)$ can now be formulated as

$$\max_{\{P^{c,r}_i, P^{r,o}_i\}} \quad E^{r,o}_i(V_k) \tag{10a}$$

$$\text{subject to } \mathrm{Prob}\left\{\gamma^D_r \le \gamma^D\right\} \le O^D_{max}, \tag{10b}$$

$$0 \le P^{c,r}_i \le P^c_{max}, \tag{10c}$$

$$0 \le P^{r,o}_i \le P^r_{max}, \tag{10d}$$

where γ^D_r is the SINR of the downlink from the BS to V_k that is given by (4) and $\gamma^D = 2^C - 1$ is the SINR threshold of the same link. The constraint in (10b) ensures that the outage probability of the link is less than an acceptable threshold O^D_{max}. Now, if the relay has finished its reception from the BS, which occurs either when it has reached the UA or received all the RD, it will not experience any SI. In that case, the ergodic capacity $E^{r,o}_i(V_k)$ is maximized under the power constraint in (10d) only.

Finally, the maximum amount of data that can be buffered by the relay V_k is equal to the sum of the maximized ergodic capacities of the time slots in which it stays inside the BS coverage, while the maximum amount of data that can be transferred to V_o in the UA is equal to the sum of the maximized ergodic capacities of the time slots in which the relay can communicate with V_o in the UA. Since the relay cannot deliver more information to V_o in the UA than what can be buffered inside the BS coverage, the performance of each relay candidate is limited by the minimum of the two sums of the ergodic capacities. Based on this discussion, the proposed EM-SCF scheme in this work selects the relay candidate that has the maximum minimum as will be discussed in details in the next section.

V. THE PROPOSED EM-SCF SCHEME

In this section, we explain the proposed EM-SCF scheme that exploits the spectral efficiency of FD communication to maximize the ergodic capacities of the links. This scheme enables the BS and vehicles to transmit with higher rates as compared to the special case in [6] and the HD schemes such as those in [2] and [3]. Since the BS transmits with higher rate to the target vehicle V_o, either the relay help will not be required or at least less data must be delivered through the selected relay. In addition, the relay will be able to buffer more data inside the BS coverage and deliver more data in the UA.

Since the proposed EM-SCF scheme is not using FTR, it is difficult to find the relay candidate that can help V_o the most at the instant of RS. Specifically, it is difficult to determine the amount of data that can be buffered by each relay candidate inside the BS coverage as well as the amount that can be delivered to V_o in the UA. Consequently, first, the optimal PA that maximizes the ergodic capacities of the links will be found as formulated in the previous section. Then, we introduce the RS step as well as a proposed hybrid scheme that aims to deliver as large amount of information as possible to V_o in the UA. Lastly, we provide a comparison between the RS steps of the proposed schemes and those of previous works in terms of the computational complexity and performance.

A. ERGODIC CAPACITY MAXIMIZATION

As before, let V_k be the selected relay, where the RS will be discussed in Section V-C. The maximization of the ergodic capacities of the links at the BS coverage and the UA is found next.

1) COVERAGE STAGE

The PA problem that maximizes the ergodic capacity of the downlink while guaranteeing the minimum capacity requirement of the uplink is formulated in (6). Using the definition of γ_r^U in (5), the constraint (6b) can be rewritten as

$$\text{Prob}\left\{P_i^{r,c} g_i^{r,c} u_i^{r,c} \le \gamma^U \left(\beta P_i^{c,r} g_i^{c,c} u_i^{c,c} + \sigma^2\right)\right\} \le O_{max}^U. \tag{11}$$

Using the result in [15, Appendix I], which is also restated in Lemma 1 in [1], the constraint in (11) can be expressed as

$$1 - \exp\left(-\frac{\gamma^U \sigma^2}{\mathbb{E}\left[P_i^{r,c} g_i^{r,c} u_i^{r,c}\right]}\right)\left(\frac{1}{1 + \frac{\mathbb{E}[\gamma^U \beta P_i^{c,r} g_i^{c,c} u_i^{c,c}]}{\mathbb{E}[P_i^{r,c} g_i^{r,c} u_i^{r,c}]}}\right) \le O_{max}^U. \tag{12}$$

Since large-scale fading parameters are assumed to be fixed within the time slot and small-scale fading is modelled by exponentially distributed random variables with unit mean as mentioned in Section III, (12) reduces to

$$1 - \exp\left(-\frac{\gamma^U \sigma^2}{P_i^{r,c} g_i^{r,c}}\right)\left(\frac{1}{1 + \frac{\gamma^U \beta P_i^{c,r} g_i^{c,c}}{P_i^{r,c} g_i^{r,c}}}\right) \le O_{max}^U. \tag{13}$$

where $\mathbb{E}\left[P_i^{r,c} g_i^{r,c} u_i^{r,c}\right] = P_i^{r,c} g_i^{r,c}$ [15]. Similarly, the other expected values in (12) can be found as expressed in (13). In [18], upper and lower bounds on the outage probability in the left side of (13) were found. This upper bound is given by

$$1 - \exp\left(-\frac{\gamma^U \left(\beta P_i^{c,r} g_i^{c,c} + \sigma^2\right)}{P_i^{r,c} g_i^{r,c}}\right). \tag{14}$$

In the typical area of interest of the outage probability (i.e., in the order of $O_{max}^U \le 5\%$), the lower and upper bounds are actually so tight and the difference between them almost vanishes [18]. Hence, inspired by [1], the outage probability in the left side of (13) will be replaced by its upper bound in (14) and the problem in (6) can now be expressed as

$$\max_{\{P_i^{c,r}, P_i^{r,c}\}} \quad E_i^{r,u}(V_k) \tag{15a}$$

$$\text{subject to } \frac{\gamma_U' \left(\beta P_i^{c,r} g_i^{c,c} + \sigma^2\right)}{P_i^{r,c} g_i^{r,c}} \le 1, \tag{15b}$$

$$0 \le P_i^{c,r} \le P_{max}^c, \tag{15c}$$

$$0 \le P_i^{r,c} \le P_{max}^r, \tag{15d}$$

where $\gamma_U' = \gamma^U / \ln\left(1 - O_{max}^U\right)^{-1}$. Since the ergodic capacity $E_i^{r,u}(V_k)$ in (7) is monotonically increasing (decreasing) as $P_i^{c,r}$ ($P_i^{r,c}$) increases. The optimal PA problem in (15) necessitates that the outage constraint in (15b) be met with equality. This can be proved by contradiction as follows. Let us assume that at the optimal point, the outage constraint in (15b) does not satisfy the equality, then we have

$$\frac{\gamma_U' \left(\beta P_i^{c,r} g_i^{c,c} + \sigma^2\right)}{P_i^{r,c} g_i^{r,c}} < 1. \tag{16}$$

This means, however, that we still can increase $P_i^{c,r}$ and/or decrease $P_i^{r,c}$ until equality is reached since the objective function in (15) is monotonically increasing (decreasing) with $P_i^{c,r}$ ($P_i^{r,c}$). Therefore, the inequality in the outage constraint contradicts the optimality of the solution. Accordingly, at optimality, the outage constraint in (15b) must be met with equality and $P_i^{r,c}$ can be expressed in terms of $P_i^{c,r}$ as

$$P_i^{r,c} = \frac{\gamma_U' \left(\beta P_i^{c,r} g_i^{c,c} + \sigma^2\right)}{g_i^{r,c}}. \tag{17}$$

After substituting $P_i^{r,c}$ in the objective function (15) with its value in terms of $P_i^{c,r}$ using (17), the objective function becomes monotonically increasing with $P_i^{c,r}$. Meanwhile, $P_i^{c,r}$ increases with the increase of $P_i^{r,c}$ as can be seen in (17). Accordingly, taking into account the equality of the outage constraint in (17) and the power constraints (15c)-(15d), the optimal PA solution of the problem in (15) can be obtained as

$$P_i^{c,r^*} = \min\left\{P_{max}^c, \frac{P_{max}^r g_i^{r,c} - \gamma_U' \sigma^2}{\gamma_U' \beta g_i^{c,c}}\right\}, \tag{18}$$

and

$$P_i^{r,c^*} = \frac{\gamma_U' \left(\beta P_i^{c,r^*} g_i^{c,c} + \sigma^2\right)}{g_i^{r,c}}. \tag{19}$$

Henceforth, we use $\boldsymbol{E}_i^{r,u}(V_k)$ to denote the maximized value of $E_i^{r,u}(V_k)$ that is obtained by replacing $P_i^{c,r}$ and $P_i^{r,c}$ in (7) with their optimal values P_i^{c,r^*} and P_i^{r,c^*}, respectively.

We next consider the next case as mentioned in Section IV-A; that is if the relay V_k has finished transmission in the uplink and there is no interference to the downlink. The ergodic capacity of the downlink in the absence of the SI from the uplink transmission is equal to $E_i^r(V_k)$ that is given by (8). Since $E_i^r(V_k)$ is monotonically increasing with $P_i^{c,r}$, the optimal power P_i^{c,r^*} that maximizes $E_i^r(V_k)$ is simply equal to P_{max}^c. By replacing $P_i^{c,r}$ in (8) with its optimal value P_i^{c,r^*}, we obtain the maximum ergodic capacity $\boldsymbol{E}_i^r(V_k)$.

Now considering the target vehicle V_o, the ergodic capacity of the downlink under the existence of the uplink transmission $E_i^{o,u}(V_o)$ and under the absence of the uplink transmission $E_i^o(V_o)$ can be found similar to $E_i^{r,u}(V_k)$ in (7) and $E_i^r(V_k)$ in (8), respectively, by replacing r by o in the superscripts of all variables in these equations. Similarly, the optimal PA P_i^{c,o^*} and P_i^{o,c^*} that maximizes the ergodic capacity of the downlink while guaranteeing the minimum capacity requirement of the uplink can be found similar to (18) and (19), respectively, by replacing r by o in the superscripts of all variables in these equations. Finally, $\boldsymbol{E}_i^{o,u}(V_o)$ and $\boldsymbol{E}_i^{o}(V_o)$ are used to denote the maximized ergodic capacities of the target vehicle.

2) RELAYING STAGE

First, we tackle the scenario in which the selected relay V_k receives from the BS while transmitting to the target vehicle V_o that stays in the UA. For this scenario, the PA that maximizes the ergodic capacity of the link from V_k to V_o while fulfilling the capacity requirement of the downlink from the BS to the relay is formulated as given in (10). Similar to the simplification of the outage constraint from (6b) to (15b), the outage constraint in (10b) can be simplified, and the problem in (10) can be expressed as

$$\max_{\{P_i^{c,r},P_i^{r,c}\}} \quad E_i^{r,o}(V_k) \tag{20a}$$

$$\text{subject to} \quad \frac{\gamma_D'\left(\beta P_i^{r,o} g_i^{r,r}+\sigma^2\right)}{P_i^{c,r} g_i^{c,r}} \leq 1, \tag{20b}$$

$$0 \leq P_i^{c,r} \leq P_{max}^{c}, \tag{20c}$$

$$0 \leq P_i^{r,o} \leq P_{max}^{r}, \tag{20d}$$

where $\gamma_D' = \gamma^D / \ln\left(1-O_{max}^D\right)^{-1}$. As discussed earlier, the optimal PA problem in (20) necessitates that the outage constraint in (20b) be met with equality. Again, this can be proved by contradiction as shown before. Therefore, taking this into consideration along with the power constraints (20c)-(20d), the optimal PA of the problem in (20) can be obtained as

$$P_i^{r,o^*} = \min\left\{P_{max}^{r}, \frac{P_{max}^{c} g_i^{c,r} - \gamma_D'\sigma^2}{\gamma_D'\beta g_i^{r,r}}\right\}, \tag{21}$$

and

$$P_i^{c,r^*} = \frac{\gamma_D'\left(\beta P_i^{r,o^*} g_i^{r,r}+\sigma^2\right)}{g_i^{c,r}}. \tag{22}$$

By replacing $P_i^{r,o}$ and $P_i^{c,r}$ in (9) with their optimal values P_i^{r,o^*} and P_i^{c,r^*}, we obtain the maximum ergodic capacity $\boldsymbol{E}_i^{r,o}$.

For the last scenario in which the relay V_k has finished reception from the BS, there is no SI at the relay. Therefore, the ergodic capacity of the link from V_k to V_o is equal to $E_i^{r,o}(V_k)$ as given by (9). As mentioned in Section IV-B, $E_i^{r,o}(V_k)$ is maximized under the power constraint in (20d) only. Like earlier, since $E_i^{r,o}(V_k)$ is monotonically increasing with $P_i^{r,o}$, the optimal power P_i^{r,o^*} is simply equal to P_{max}^{r}. In this case, we denote the maximum ergodic capacity by $\boldsymbol{E}_i^{r,o'}$.

B. OVERALL PERFORMANCE OF THE RELAY

As mentioned in Section IV, the performance of each relay candidate is limited by the minimum between the maximum amount of data that can be buffered inside the BS coverage and the maximum amount of data that can be delivered in the UA. In this section, these amounts will be determined based on the optimal PA presented in V-A.

We first start with the amount of RD, R_d, that must be delivered to the target vehicle V_o in the UA through the selected relay is equal to

$$R_d = R_q(V_o) - \boldsymbol{E}^o(V_o), \tag{23}$$

where $R_q(V_o)$ is the size of the requested data by V_o and $\boldsymbol{E}^o$ is the maximum amount of data that V_o can receive inside the BS coverage, which is given by

$$\boldsymbol{E}^o(V_o) = \sum_{i=1}^{t_o} a_i \boldsymbol{E}_i^{o,u}(V_o) + (1-a_i)\boldsymbol{E}_i^{o}(V_o), \tag{24}$$

where the computation of $\boldsymbol{E}_i^{o,u}(V_o)$ and $\boldsymbol{E}_i^{o}(V_o)$ is explained in Section V-A and t_o is the number of time slots in which V_o stays inside the BS coverage. Obviously, $t_o = \lfloor T_r(V_o)/T_s \rfloor$, where T_s is the time slot duration and $T_r(V_o)$ is the remaining time for V_o inside the BS coverage that is given by

$$T_r(V_o) = \frac{2r_0 - d(V_o)}{v_o}, \tag{25}$$

with 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. Also, $\lfloor t \rfloor$ returns the largest integer smaller than or equal to t. The binary variable a_i in (24) is indicating whether the uplink transmission is active ($a_i = 1$) or not ($a_i = 0$), viz.,

$$a_i = \begin{cases} 1, & \text{if } i \leq \lfloor T_n(V_o)/T_s \rfloor \\ 0, & \text{otherwise} \end{cases}, \tag{26}$$

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

$$T_n(V_o) = \min\left\{T_r(V_o), \frac{R_q^{Tx}(V_o)}{C}\right\}, \tag{27}$$

with $R_q^{Tx}(V_o)$ being the size of the requested data by V_o in the uplink.

Similar to [3], 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

$$D(V_k) = 2r_o - \left(T_r(V_o) \times v_k + d(V_k)\right), \tag{28}$$

where $d(V_k)$ 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.

On the other hand, the amount of data, $\boldsymbol{E}^b(V_k)$, that can be buffered by a relay candidate V_k inside the BS coverage is equal to

$$\boldsymbol{E}^b(V_k) = \boldsymbol{E}^r(V_k) - R_q(V_k), \tag{29}$$

where $R_q(V_k)$ is the size of the requested data by the relay candidate V_k in the downlink and $\boldsymbol{E}^r(V_k)$ is the maximum amount of data that can be received by V_k inside the BS coverage. This is given by

$$\boldsymbol{E}^r(V_k) = \sum_{i=1}^{t_r} c_i \boldsymbol{E}_i^{r,u}(V_k) + (1 - c_i)\boldsymbol{E}_i^r(V_k), \quad (30)$$

where $t_r = \lfloor T_r(V_k)/T_s \rfloor$ and the computation of $\boldsymbol{E}_i^{r,u}(V_k)$ and $\boldsymbol{E}_i^r(V_k)$ is given in Section V-A. The binary variable c_i indicates whether the uplink transmission is active ($c_i = 1$) or not ($c_i = 0$) and is given by

$$c_i = \begin{cases} 1, & \text{if } i \leq t_n \\ 0, & \text{otherwise} \end{cases}, \quad (31)$$

where $t_n = \lfloor T_n(V_k)/T_s \rfloor$. In terms of time, the available time for buffering, $T_b(V_k)$, is equal to the time duration in which V_k stays inside the BS coverage minus the required time for V_k to receive its own data, viz.,

$$T_b(V_k) = T_r(V_k) - \frac{R_q(V_k) t_q T_s}{\sum_{i=1}^{t_q} c_i \boldsymbol{E}_i^{r,u}(V_k) + (1 - c_i)\boldsymbol{E}_i^r(V_k)}, \quad (32)$$

where t_q is the smallest integer in the range $[1, t_r]$ that satisfies $\sum_{i=1}^{t_q} \left(c_i \boldsymbol{E}_i^{r,u}(V_k) + (1 - c_i)\boldsymbol{E}_i^r(V_k)\right) \geq R_q(V_k)$.

Since the one-way highway model of [3] is adopted as mentioned in Section III, the parameters that only depend on vehicles' locations and speeds can be computed similar to [3]. Specifically, the time duration $T_m(V_k)$ in which a relay candidate V_k stays within the communication range of the target vehicle V_o depends on the locations and speeds of V_o and V_k (i.e., $d(V_o)$, $d(V_k)$, v_o and v_k) and can be found as given in [3, Eqs. (5)-(7)]. However, the relay gives priority to its uplink transmission over helping V_o, and thus the relay will not be able to help V_o unless the uplink transmission is finished. Therefore, 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

$$T_c(V_k) = \max\left\{0, T_m(V_k) - T'_m(V_k)\right\}, \quad (33)$$

where $T'_m(V_k)$ is the remaining time for V_k to finish transmission in the uplink after V_o has reached the UA, i.e.,

$$T'_m(V_k) = \max\left\{0, T_n(V_k) - T_r(V_o)\right\}, \quad (34)$$

where $T_n(V_k)$ represents the remaining time for V_k to finish transmission in the uplink as given in (27). Based on $T'_m(V_k)$ and $T_m(V_k)$, there are three possible cases for $T_c(V_k)$. First, if V_k has finished transmission in the uplink before V_o reaches the UA (i.e., $T_n(V_k) < T_r(V_o)$), then $T'_m(V_k) = 0$ 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 the uplink transmission after the entire duration $T_m(V_k)$ has passed (i.e., $T_m(V_k) < T'_m(V_k)$), the relay will be removed from the candidate list where $T_c(V_k) = 0$. 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 will be equal to the remaining time $T_m(V_k) - T'_m(V_k)$.

The maximum amount of data that can be delivered by the relay candidate V_k to the target vehicle V_o in the UA is equal to

$$\boldsymbol{E}^d(V_k) = \sum_{i=t_f}^{t_e} b_i \boldsymbol{E}_i^{r,o}(V_k) + (1 - b_i)\boldsymbol{E}_i^{r,o'}(V_k), \quad (35)$$

where t_f and t_e are the first and last time slots of the relaying stage, respectively. This stage starts if V_o reached the UA and the relay has finished its uplink transmission, and accordingly t_f is given by

$$t_f = \left\lceil \frac{T_r(V_o) + T'_m(V_k)}{T_s} \right\rceil, \quad (36)$$

where $\lceil t \rceil$ returns the smallest integer greater than or equal to t. On the other hand, the relaying stage ends when the time duration $T_m(V_k)$ ends. Hence, the last time slot t_e of the relaying stage is equal to

$$t_e = \left\lfloor \frac{T_r(V_o) + T_m(V_k)}{T_s} \right\rfloor. \quad (37)$$

In (35), the binary variable b_i is equal to zero if V_k has finished reception and is thus only relaying to the target vehicle V_o. It can thus be calculated as

$$b_i = \begin{cases} 1, & \text{if } \sum_{j=1}^{i-1} \left(c_j \boldsymbol{E}_j^{r,u}(V_k) + (1 - c_j)\boldsymbol{E}_j^r(V_k)\right) \\ & \geq R_d + R_q(V_k) \text{ OR } i > \lfloor T_r(V_k)/T_s \rfloor \\ 0, & \text{otherwise} \end{cases} \quad (38)$$

The relay reception will stop (i.e., $b_i = 0$) if all data has been received in the previous time slots or the relay has reached the UA. This data comprises both the relay's requested data $R_q(V_k)$ in addition to the RD R_d that will be relayed to V_o in the UA.

Finally, since any relay cannot deliver more information to the target vehicle V_o in the UA than what can be buffered inside the BS coverage, a performance metric for each relay candidate can be defined as the minimum of the amounts $\boldsymbol{E}^b(V_k)$ and $\boldsymbol{E}^d(V_k)$ as

$$M_k = \min\left\{\boldsymbol{E}^b(V_k), \boldsymbol{E}^d(V_k)\right\}. \quad (39)$$

The relay candidate V_k that has the highest metric M_k is the one capable of delivering the maximum amount of data to the target vehicle V_o in the UA.

C. RELAY SELECTION

At the instant of RS, when the target vehicle V_o requests the download of a large file, all the parameters required for the computation of M_k of each relay candidate V_k are available except for the large-scale fading parameters (i.e., $g_i^{c,r}$, $g_i^{r,c}$, $g_i^{c,o}$, $g_i^{r,o}$, $g_i^{r,r}$) of the upcoming time slots. As assumed in Section III, these large-scale parameters model both pathloss and shadowing. The pathloss can be determined based on speeds and locations of the vehicles; however, shadowing cannot be computed at the instant of RS. Therefore, the proposed EM-SCF scheme assumes that large-scale fading parameters model the pathloss only at the RS stage (i.e., it excludes the shadowing effect) in order to find M_k of each relay candidate V_k. It then selects the relay candidate V_k that has the highest M_k. Indeed, by excluding the shadowing effect, the proposed EM-SCF scheme does not fully guarantee that the selected relay V_k will enjoy the highest M_k as this relay may suffer from severe shadowing. The impact of that assumption on the ability of the proposed EM-SCF scheme to select the best relay candidate is assessed in Section VI. After the RS step, at each time slot, the proposed EM-SCF scheme computes the optimal PA for transmission as explained in Section V-A. At this stage, both pathloss and shadowing are considered.

Algorithm 1 Proposed EM-SCF Algorithm

Inputs: vehicles speeds v_k and locations $d(V_k)$.

1: Find the set $\mathcal{K} = \{V_1, V_2, \ldots, V_K\}$ that encompasses the eligible relay candidates for RS such that $|D(V_k)| \leq r_0, \forall\, V_k \in \mathcal{K}$, where $D(V_k)$ is given by (28).

% RS stage

2: **for** $k = 1$ to K **do**

3:     Find M_k as given by (39).

4: **end for**

5: Select the relay candidate V_k that has the highest M_k.

% Transmission stage: at any time slot $i \in [1, t_e]$

6: **if** $i \leq t_f$ **then** % Coverage stage

7:     **if** $c_i = 1$ **then** % For the selected relay V_k

8:         Find $\boldsymbol{E}_i^{r,u}(V_k)$ by computing P_i^{c,r^*} and P_i^{r,c^*} using (18) and (19), respectively.

9:     **else if** $i \leq t_r$ **then**

10:         Find $\boldsymbol{E}_i^{r}(V_k)$ by setting $P_i^{c,r^*} = P_{max}^{c}$.

11:     **end if**

12:     **if** $a_i = 1$ **then** % For the target vehicle V_o

13:         Find $\boldsymbol{E}_i^{o,u}(V_o)$ as explained in Section V-A.

14:     **else if** $i \leq t_o$ **then**

15:         Find $\boldsymbol{E}_i^{o,u}(V_o)$ as explained in Section V-A.

16:     **end if**

17: **else if** $i \leq t_e$ **then** % Relaying stage

18:     **if** $b_i = 1$ **then**

19:         Find $\boldsymbol{E}_i^{r,o}(V_k)$ by computing P_i^{r,o^*} and P_i^{c,r^*} using (21) and (22), respectively.

20:     **else**

21:         Find $\boldsymbol{E}_i^{r,o'}(V_k)$ by setting $P_i^{r,o^*} = P_{max}^{r}$.

22:     **end if**

23: **end if**

To make the implementation of the proposed EM-SCF scheme straightforward, Algorithm 1 is presented. Steps (1)-(5) in the algorithm show the RS stage where it is assumed that large-scale fading parameters model the pathloss only as mentioned earlier. The relay candidate that has the highest M_k as stated in step (5) will be selected, where M_k is given by (39). The remaining steps from (6)-(23) describe the communications based on the location of V_o and V_k. More specifically, steps (6)-(16) demonstrate communications inside the BS coverage between the BS and each of V_o and V_k. This stage starts from the RS instant (i.e., $i = 1$) until the relay V_k starts relaying to V_o, which marks the start of the relaying stage at the instant $i = t_f$ that is given by (36). As mentioned in Section V-A.1, the PA that maximizes the ergodic capacities of the downlinks depends on whether the uplink transmission is active or not. For the target vehicle V_o, the uplink transmission is active if $a_i = 1$, where a_i is given by (26). For the relay V_k, the uplink transmission is active if c_i that is given by (31) equals one. The remaining steps (17)-(23) show the communications in the relaying stage between V_o and V_k in the UA, which starts at the instant $i = t_f$ and ends at $i = t_e$, where t_e is given by (37). As mentioned in Section V-A.2, the PA that maximizes the ergodic capacity of the link from V_k to V_o depends on whether V_k has finished reception from the BS or not, which is determined by the binary variable b_i (38).

D. ALTERNATIVE RELAY SELECTION SCHEME

The proposed EM-SCF scheme consists of RS and PA phases that maximize the ergodic capacities of the links as shown in Algorithm 1. The PA has low complexity as can be seen in (18), (19), (21) and (22). On the other hand, as compared to the RS steps of the FD scheme in [6] and the HD scheme in [3], the RS of the proposed EM-SCF scheme has higher computational complexity. More specifically, the three schemes select the relay candidate that can deliver the largest amount of data to the target vehicle V_o in the UA. While this amount is equal to M_k in the proposed scheme, it is simply equal to ECT$\times C$ in the schemes in [6] and [3]. Clearly, the complexity of computing M_k is indeed higher than that of the ECTs of the schemes in [6] and [3] with the latter requiring fewer number of multiplications and additions as illustrated in Table 1. This is because the computation of M_k necessitates the computation of $\boldsymbol{E}^b(V_k)$ and $\boldsymbol{E}^d(V_k)$, which in turn involves exponential operations as well as the evaluation of the exponential integral function $E_1(\cdot)$. Although the latter might seem complicated, there are very efficient approximations of this function such as in [19] and [20] that offer tradeoff between complexity and accuracy and the complexity of the proposed EM-SCF scheme still remains affordable.

TABLE 1. Complexity Comparison between the RS step of EM-SCF and that in previous works.

Operation	ECT [3]	ECT [6]	M_k
Additions	3	6	$2t_n + 1$
Multiplications	2	4	$5(t_n + t_r + t_e - t_f + 1)$
Exponential	None	None	$t_n + t_r + t_e - t_f + 1$
$E_1(\cdot)$	None	None	$t_n + t_r + t_e - t_f + 1$

In spite of that, in this subsection, we propose a hybrid SCF scheme that merges the RS of the FD scheme in [6] with the PA of the proposed EM-SCF scheme aiming at reducing complexity. First, the proposed hybrid scheme selects the relay candidate V_k with the highest ECT as given in [6, Eq. (9)]. Then, at each time slot, the optimal PA of the proposed EM-SCF scheme that maximizes the ergodic capacities of the links is used. Accordingly, the hybrid scheme can be implemented using Algorithm 1 after replacing the RS stage in steps (1)-(5) with selecting the relay candidate that has the highest ECT instead, where the ECT is given in [6, Eq. (9)]. To make the implementation of the proposed hybrid scheme straightforward, Algorithm 2 is presented.

Algorithm 2 Proposed Hybrid Algorithm

Inputs: vehicles speeds v_k and locations $d(V_k)$.

1: Find the set $\mathcal{K} = \{V_1, V_2, \ldots, V_K\}$ that encompasses the eligible relay candidates for RS such that $|D(V_k)| \leq r_0, \forall\, V_k \in \mathcal{K}$, where $D(V_k)$ is given by (28).
% RS stage
2: **for** $k = 1$ to K **do**
3: Find the ECT of the relay V_k using [6, Eq. (9)].
4: **end for**
5: Select the relay candidate V_k that has the highest ECT.
% Transmission stage
6: At any time slot $i \in [1, t_e]$, the optimal PA that maximizes the ergodic capacities of the links is used exactly as steps (6)-(23) in Algorithm 1.

Since the computation of the ECT in [6, Eq. (9)] depends on the assumption of fixed transmission rate C, the RS step of the hybrid scheme will not be as accurate as that of the EM-SCF scheme. Therefore, the reduction in the computational complexity will be at the expense of the accuracy of selecting the best relay candidate that can deliver the largest amount of data to the target vehicle in the UA. The loss in performance will be quantified in Section VI along with our other results.

E. OPTIMAL HALF-DUPLEX SCF SCHEME

The related HD SCF schemes, e.g., the works in [2]–[4], [11]–[13], are assuming fixed rate for transmission. For fair comparison between the usage of FD and HD transmissions in SCF schemes for ICVNs, the optimal PA that maximizes the ergodic capacities of the downlinks and the link from the relay to the target vehicle are determined in this section.

The ergodic capacity of the downlink from the BS to V_k is equal to $E_{i,\mathrm{HD}}^{r,u}(V_k) = 0.5\, We^{\frac{1}{\nu}} E_1(\frac{1}{\nu})/\ln(2)$, where $\nu = P_i^{c,r} g_i^{c,r}/\sigma^2$ [17]. The factor of 0.5 captures the fact that the uplink and downlink in HD transmission use orthogonal channels in time or frequency, while the channel is used simultaneously by both of the uplink and downlink in the proposed FD SCF schemes. Since $E_{i,\mathrm{HD}}^{r,u}(V_k)$ is monotonically increasing with $P_i^{c,r}$, the optimal power P_i^{c,r^*} that maximizes $E_i^r(V_k)$ is simply equal to P_{max}^c. Likewise, the optimal power P_i^{c,r^*} that maximizes $E_{i,\mathrm{HD}}^{r,u}(V_k)$ is equal to P_{max}^c. By replacing $P_i^{c,r}$ with its optimal value P_{max}^c in $E_{i,\mathrm{HD}}^{r,u}(V_k)$, we obtain the maximum ergodic capacities $\boldsymbol{E}_{i,\mathrm{HD}}^{r,u}(V_k)$.

The performance of each relay candidate can be determined in a similar manner to that of the proposed FD scheme in Section V-B. The amount of data that can be buffered by a relay candidate V_k inside the BS coverage is equal to

$$\boldsymbol{E}_{\mathrm{HD}}^{b}(V_k) = \boldsymbol{E}_{\mathrm{HD}}^{r}(V_k) - R_q(V_k), \tag{40}$$

where $\boldsymbol{E}_{\mathrm{HD}}^{r}(V_k)$ is the maximum amount of data that can be received by V_k inside the BS coverage that is equal to

$$\boldsymbol{E}_{\mathrm{HD}}^{r}(V_k) = \sum_{i=1}^{t_o} \boldsymbol{E}_i^{r,u}(V_k), \tag{41}$$

where $t_o = \lfloor T_r(V_o)/T_s \rfloor$, $T_r(V_o)$ is given by (25) and the ergodic capacity $\boldsymbol{E}_{i,\mathrm{HD}}^{r,u}(V_k)$ is given above. As mentioned in Section II, in the HD SCF schemes, once the target vehicle V_o reaches the UA, the relay V_k must stop from storing more data and start relaying to V_o. On the contrary, in the proposed FD SCF schemes, the relay V_k can continue buffering data while relaying buffered data to V_o. Hence, t_o is used in (41) instead of using t_r as in (30).

In terms of time, the available time for buffering is equal to

$$T_b^{\mathrm{HD}}(V_k) = T_r(V_o) - \frac{R_q(V_k) t_q T_s}{\sum_{i=1}^{\mu} \boldsymbol{E}_i^{r,u}(V_k)}, \tag{42}$$

where μ is the smallest integer in the range $[1, t_o]$ that satisfies $\sum_{i=1}^{\mu} \boldsymbol{E}_i^{r,u}(V_k) \geq R_q(V_k)$. Again, what differentiates the available time for buffering in (42) from that in (32) is the relay's ability of simultaneous transmission and reception, which allows the relay to store more data while relaying buffered data to V_o.

On the other hand, the amount of data that can be delivered by the relay candidate V_k to the target vehicle V_o in the UA is equal to

$$\boldsymbol{E}_{\mathrm{HD}}^{d}(V_k) = \sum_{i=t_f}^{t_e} \boldsymbol{E}_{i,\mathrm{HD}}^{r,o}(V_k), \tag{43}$$

where $\boldsymbol{E}_{i,\mathrm{HD}}^{r,o}(V_k) = We^{\frac{1}{\zeta}} E_1(\frac{1}{\zeta})/\ln(2)$, $\zeta = P_i^{r,o^*} g_i^{r,o}/\sigma^2$, t_f and t_e are given by (36) and (37), respectively. Obviously, the optimal power P_i^{r,o^*} that maximizes $\boldsymbol{E}_{i,\mathrm{HD}}^{r,o}(V_k)$ is equal to P_{max}^r.

Lastly, similar to the proposed FD SCF scheme in (39), the performance of each relay candidate is limited by the minimum between the amount of data that can be buffered inside the BS coverage and the amount that can be delivered to the target vehicle V_o in the UA. i.e., $\boldsymbol{E}_{\mathrm{HD}}^{b}(V_k)$ and $\boldsymbol{E}_{\mathrm{HD}}^{d}(V_k)$, respectively. The relay candidate V_k that has the maximum minimum is the one capable of delivering the highest amount of data in the UA, and accordingly will be selected.

VI. SIMULATION RESULTS

In this section, the performance of the proposed SCF schemes are assessed based on simulations of the system model described in Section III. The performance, in terms of the amount of delivered data to the target vehicle V_o in the UA,

TABLE 2. Simulation parameters.

Parameter	Value
Cell radius r_0	300 m
Inter-BS distance d_0	1500 m
Channel bandwidth W	10 MHz
The fixed transmission rate C	6 Mbps
P^c_{max} and P^v_{max}	23 dBm
σ^2	-114 dBm
O^D_{max}	0.001

is compared with that of the special case in [6], the optimal HD SCF scheme in Section V-E and the HD scheme proposed in [3]. All the simulation results presented in this section are obtained from 100,000 realizations, where vehicles are distributed randomly in the highway in each realization. The fixed parameters of the simulations are detailed in Table 2.

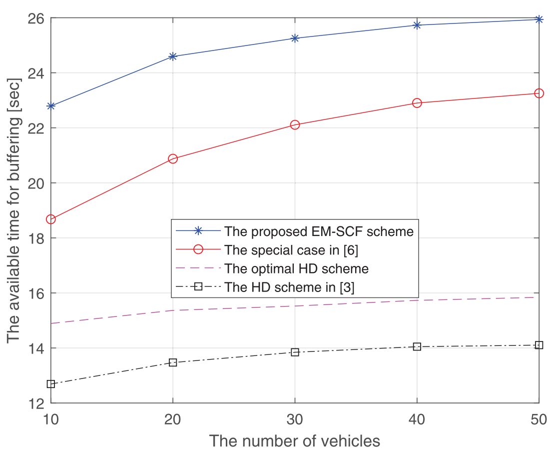

FIGURE 2. A comparison between the available buffering times of the proposed EM-SCF scheme, the special case in [6] the optimal HD SCF scheme in Section V-E and the HD scheme proposed in [3].

Figure 2 shows the available time for buffering the RD of the target vehicle V_o versus the increase in the number of vehicles. The available time for buffering of the proposed scheme is compared with those of the benchmark schemes mentioned earlier. Simulations with $R_q(V_k) \in [20, 50]$ Mbits, $R_q^{Tx}(V_k) \in [20, 50]$ Mbits, $\beta = -90$ dB and vehicles speeds randomly assigned in the range [50, 90] km/h are performed. Intuitively, when the number of vehicles decreases, the number of relay candidates decreases as well, which decreases the probability of having a relay candidate with a high buffering time. Therefore, the four schemes offer higher buffering time as the number of vehicles increases as seen in the figure. As mentioned earlier, in the HD scheme in [3] and the optimal HD SCF scheme in Section V-E, once the target vehicle V_o reaches the UA, the selected relay stops from buffering more data and starts transmitting the buffered data to V_o. On the contrary, in the proposed EM-SCF scheme and the special case in [6], by virtue of the relay's ability of receiving and transmitting simultaneously, the relay can continue buffering data while transmitting to V_o. Accordingly, these FD schemes offer significantly higher buffering times. As given in (32) and (42), the available time for buffering is equal to the entire available time for reception inside the BS coverage minus the required time for V_k to receive its own data. Since the ergodic capacities of the downlinks are maximized in each of the proposed EM-SCF scheme and the optimal HD SCF scheme in Section V-E, the BS can transmit with higher transmission rates, and consequently, the selected relay can receive its requested data $R_q(V_k)$ in a shorter time. Hence, as shown in Fig. 2, the proposed EM-SCF scheme and the optimal HD SCF scheme in Section V-E offer higher buffering time as compared to the special case in [6] and HD scheme in [3], respectively.

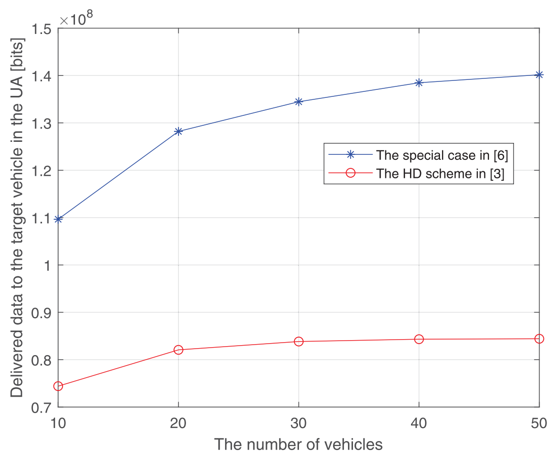

FIGURE 3. The impact of the number of vehicles on the performance of the special case in [6] and the HD scheme proposed in [3].

Figures 3 and 4 show the impact of the number of vehicles on the performance in terms of the amount of delivered data to the target vehicle V_o in the UA. The aforementioned simulation parameters of Fig. 2 are adopted. For the clarity of the presentation, the performance of the special case in [6] and the HD scheme in [3] and those of the proposed schemes are presented in separate figures. Since the special case in [6] offers higher buffering time as shown in Fig. 2, it consequently offers higher ECT, and accordingly delivers higher amount of data as shown in Fig. 3. In agreement with the discussion on Fig. 2, the performance of both schemes improves as the number of vehicle increases.

As for the proposed schemes and the optimal HD SCF scheme in Section V-E, Fig. 4 shows the impact of the number of vehicles on their performance. Beside having higher buffering time, by virtue of the ergodic capacity maximization of the links, the proposed schemes and the optimal HD SCF scheme in Section V-E can buffer higher amount of data inside the BS coverage as well as deliver more data to V_o in the UA. Comparing Figs. 3 and 4, it can be readily noticed

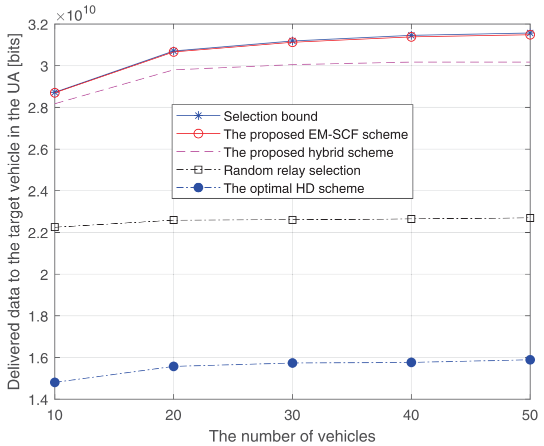

FIGURE 4. **The impact of the number of vehicles on the performance of the proposed EM-SCF scheme, the proposed hybrid scheme and the optimal HD SCF scheme presented in Section V-E.**

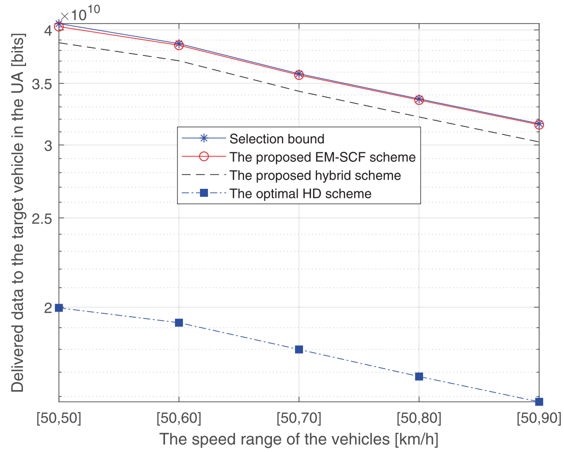

FIGURE 5. **The impact of the speed range of the vehicles on the performance in terms of the amount of delivered data to the target vehicle V_o in the UA.**

that these schemes outperform the special case in [6] and the HD scheme in [3].

In addition to the above, Fig. 4 shows the accuracy of the RS steps of the proposed EM-SCF and hybrid schemes. To achieve that, in each simulation realization, we scanned through all the potential relay candidates and saved the performance metric of the candidate that can deliver the largest amount of data to the target vehicle V_o in the UA. By the end of all the realizations, we obtained the performance of the case in which the best relay candidate is selected in each realization. We refer to this performance as the selection bound. As shown in the figure, the proposed EM-SCF scheme offers comparable performance to the selection bound. In agreement with the discussion in Section V-D, the proposed hybrid scheme offers reduction in the computational complexity at the expense of the RS accuracy. Also, to show the importance of the RS step, we show the performance of the case in which one of the relay candidates is randomly selected in each realization. In both the selection bound and random RS, after selecting one of the relay candidates, the ergodic capacities of the links are still optimally maximized as in the proposed EM-SCF scheme. As illustrated in Fig. 4, the performance of the random RS is much lower than that of the proposed schemes, which proves the importance of accuracy of the RS step.

To study the impact of the speed range of the vehicles on the performance, simulations with $R_q(V_k) \in [20, 50]$ Mbits, $R_q^{Tx}(V_k) \in [20, 50]$ Mbits, $\beta = -90$ dB and a number of vehicles equals 50 are performed. When the speed v_k of the relay is close to the speed v_o of the target vehicle, the relay stays within the communication range of the target vehicle for a longer time, i.e., higher T_m and the amount of data that can be delivered to V_o in the UA increases as can be seen in (33), (43), [3, Eq. (8)] and [6, Eq. (12)]. Accordingly, all schemes offer better performance as the speed range of the vehicles decreases as shown in Fig. 5. Due to the same reasons mentioned above about the FD capability of the relay and the maximization of the ergodic capacity of the links, the proposed EM-SCF scheme and the hybrid scheme clearly offer improved performance.

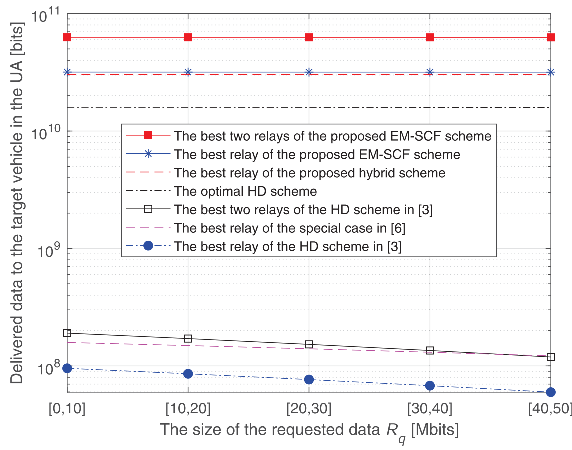

FIGURE 6. **The impact of the size of the requested data by relay candidates $R_q(V_k)$ on the performance in terms of the amount of delivered data to the target vehicle in the UA.**

Figure 6 shows the impact of the size of the requested data by the relay candidates $R_q(V_k)$ on the performance of the SCF schemes. When $R_q(V_k)$ is increased from [0, 10] to [10, 20], [20, 30], [30, 40] and [40, 50] Mbits, all schemes offer less data as the available time for buffering is decreased in agreement with [3, Eq. (3)], [6, Eq. (10)], (30) and (40). Since the considered size of the requested data $R_q(V_k)$ is too small compared to that of the delivered data by the proposed schemes, it is difficult to notice the reduction and the performance appears as a straight line.

It is worth noting that the HD SCF scheme in [3] may select more than one relay if the RD of the target vehicle V_o cannot be delivered by one relay as can be seen in the examples in [3, Fig. 5]. In this work, our goal is to study the potential improvement in the performance of the relay by virtue of using FD instead of HD communications, and accordingly we focused so far on the performance of the best relay only. However, selecting more than one relay allows for delivering even higher amounts of data to V_o in UA, which is equal to the sum of the amounts that can be delivered by each of the selected relays. In Fig. 6, we show the performance of the proposed EM-SCF scheme and the HD SCF scheme in [3] in case the best two relays are selected. As can be clearly seen, the proposed scheme significantly outperforms the HD scheme in [3].

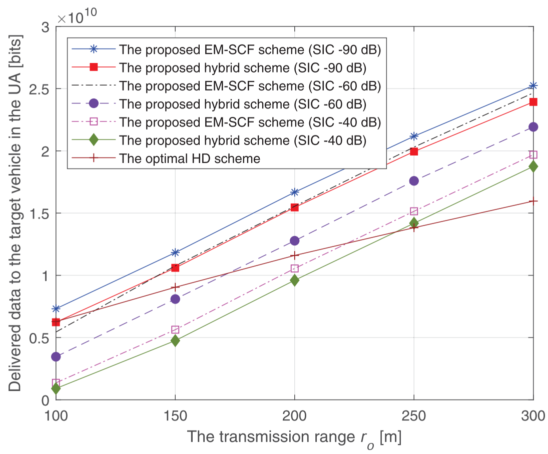

FIGURE 7. The impact of the transmission range r_0 on the performance of the proposed EM-SCF scheme and the proposed hybrid scheme.

The impact of the transmission range r_0 on the performances of the proposed schemes and the optimal HD SCF scheme in Section V-E are assessed in Fig. 7. Simulations with $R_q(V_k) \in [20, 50]$ Mbits, $R_q^{Tx}(V_k) \in [30, 50]$ Mbits, $\beta = -90$, number of vehicles equals 50 and vehicles speeds randomly assigned in the range [50, 90] km/h are performed. When the transmission range r_0 increases, the relay can stay for longer time within the communication range of the target vehicle V_o in the UA, i.e., higher $T_m(V_k)$, which in turns increases t_e that is given by (37). When t_e increases, more data can be delivered through the relay to V_o in the UA as given in (35) and (43), and clearly depicted in Fig. 7. As mentioned earlier, by virtue of the spectral efficiency of FD communications as well as having higher buffering time as shown in Fig. 2, the proposed schemes can deliver more data to V_o in the UA as presented in Fig. 7.

Finally, Fig. 7 shows the impact of SIC on the performance of the proposed EM-SCF and hybrid schemes. As SIC increases (i.e., less residual SI β), the amount of data that can be delivered to V_o in the UA of the two schemes increases as shown in Fig. 7. This is because the relay will be able to buffer more information inside the BS coverage as well as deliver more data in the UA. Inside the BS coverage, the BS can also use higher transmission power P_i^{c,r^*} in the downlink without violating the capacity requirement of the uplink. As can be seen in (18), P_i^{c,r^*} increases as β decreases, which in turns increases the ergodic capacity of the downlink $E_i^{r,u}(V_k)$ that is given by (7). Similarly, in the UA, the relay can use higher P_i^{r,o^*} in the transmission to V_o without violating the capacity requirement of the downlink. As given in (21), P_i^{r,o^*} increases as β decreases. The ergodic capacity of the link from the relay to the target vehicle $E_i^{r,o}(V_k)$, given by (9), is monotonically increasing with P_i^{r,o^*}. On the contrary, as SIC decreases (i.e., larger residual SI, e.g., $\beta = -60$ dB), the performance of the proposed schemes starts to degrade. When $\beta = -40$ dB is used, the optimal HD SCF scheme presented in Section V-E actually outperforms the proposed EM-SCF and hybrid schemes. This result reveals that efficient SIC is required for the proposed EM-SCF and hybrid schemes. Fortunately, as mentioned in Section I, the impressive improvement in SIC techniques (e.g., in the order of $70 - 110$ dB reported in [5]) makes the use of the proposed schemes justifiable.

VII. CONCLUSION

We proposed an FD store-carry-forward scheme for ICVNs. The FD capability of the relay has been exploited to extend the ECT with a target vehicle thus minimizing the outage time and delivering more data to it in the UA. Based on information of speeds, locations and data traffic requirements of the vehicles, the optimal PA that maximizes the ergodic capacities of the links is found. Moreover, the proposed scheme selects the relay candidate that can deliver the highest amount of data to the target vehicle in the UA. To reduce the computational complexity, a hybrid scheme is also proposed assuming a fixed transmission rate. This scheme selects the relay candidate that offers the highest ECT. Then, at each time slot, the optimal PA that maximizes the ergodic capacities of the links is determined as in the first scheme. The reduction in the computational complexity comes at the price of delivering less data to the target vehicle in the UA. As compared to the half-duplex SCF schemes, it has been shown that both proposed FD schemes can deliver significantly more data in the UA.

REFERENCES

[1] L. Liang, S. Xie, G. Y. Li, Z. Ding, and X. Yu, "Graph-based resource sharing in vehicular communication," *IEEE Trans. Wireless Commun.*, vol. 17, no. 7, pp. 4579–4592, Jul. 2018.

[2] Y. Wang, Y. Liu, J. Zhang, H. Ye, and Z. Tan, "Cooperative store–carry–forward scheme for intermittently connected vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 777–784, Jan. 2017.

[3] S. H. Ahmed, D. Mu, and D. Kim, "Improving Bivious relay selection in vehicular delay tolerant networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 3, pp. 987–995, Mar. 2018.

[4] M. Zhang, C. Li, T. Guo, and Y. Fu, "Cluster-based content download and forwarding scheme for highway VANETs," *China Commun.*, vol. 15, no. 4, pp. 110–120, Apr. 2018.

[5] C. Campolo, A. Molinaro, A. O. Berthet, and A. Vinel, "Full-duplex radios for vehicular communications," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 182–189, Jun. 2017.

[6] A. A. Siddig, A. S. Ibrahim, and M. H. Ismail, "Full-duplex store-carry-forward scheme for intermittently connected vehicular networks," in *Proc. IEEE 91st Veh. Technol. Conf. (VTC-Spring)*, May 2020, pp. 1–6.

[7] Y. Ge, S. Wen, Y.-H. Ang, and Y.-C. Liang, "Optimal relay selection in IEEE 802.16j multihop relay vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 5, pp. 2198–2206, Jun. 2010.

[8] S. H. Ahmed, H. Kang, and D. Kim, "Vehicular delay tolerant network (VDTN): Routing perspectives," in *Proc. 12th Annu. IEEE Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2015, pp. 898–903.
[9] M. F. Feteiha, H. S. Hassanein, and O. Kubbar, "Opportunistic cooperation for infrastructure-to-relaying-vehicles over LTE—A networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 6376–6380.
[10] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.
[11] D. Wu, G. Zhu, and D. Zhao, "Adaptive carry-store forward scheme in two-hop vehicular delay tolerant networks," *IEEE Commun. Lett.*, vol. 17, no. 4, pp. 721–724, Apr. 2013.
[12] S. H. Bouk, S. H. Ahmed, B. Omoniwa, and D. Kim, "Outage minimization using bivious relaying scheme in vehicular delay tolerant networks," *Wireless Pers. Commun.*, vol. 84, no. 4, pp. 2679–2692, Oct. 2015.
[13] T. Guo, C. Li, Z. Miao, W. Dong, and X. Su, "Prefetching-based content download for highway vehicular ad hoc networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Oct. 2017, pp. 1–6.
[14] S. Li, Q. Ni, Y. Sun, and G. Min, "Resource allocation for weighted sum-rate maximization in multi-user full-duplex device-to-device communications: Approaches for perfect and statistical CSIs," *IEEE Access*, vol. 5, pp. 27229–27241, 2017.
[15] S. Kandukuri and S. Boyd, "Optimal power control in interference-limited fading wireless channels with outage-probability specifications," *IEEE Trans. Wireless Commun.*, vol. 1, no. 1, pp. 46–55, Jan. 2002.
[16] L. Liang, G. Y. Li, and W. Xu, "Resource allocation for D2D-enabled vehicular communications," *IEEE Trans. Commun.*, vol. 65, no. 7, pp. 3186–3197, Jul. 2017.
[17] C. Guo, L. Liang, and G. Y. Li, "Resource allocation for vehicular communications with low latency and high reliability," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 3887–3902, Aug. 2019.
[18] J. Papandriopoulos, J. Evans, and S. Dey, "Optimal power control for Rayleigh-faded multiuser systems with outage constraints," *IEEE Trans. Wireless Commun.*, vol. 4, no. 6, pp. 2705–2715, Nov. 2005.
[19] A. A. Alkheir and M. Ibnkahla, "An accurate approximation of the exponential integral function using a sum of exponentials," *IEEE Commun. Lett.*, vol. 17, no. 7, pp. 1364–1367, Jul. 2013.
[20] D. A. Barry, J.-Y. Parlange, and L. Li, "Approximation for the exponential integral (Theis well function)," *J. Hydrol.*, vol. 227, nos. 1–4, pp. 287–291, Jan. 2000.

ALI A. SIDDIG received the B.S. and M.S. degrees in electronics engineering (communications) from the Sudan University of Science and Technology, Sudan, in 2006 and 2012, respectively, and the Ph.D. degree in wireless and mobile systems from Universiti Sains Malaysia (USM), Pinang, Malaysia, in 2018. He is currently working as Research Associate with the American University of Sharjah, Sharjah, United Arab Emirates. His research interests include cooperative communications, vehicular communications, and signal processing for wireless communication networks.

AHMED S. IBRAHIM (Member, IEEE) received the B.S. degree (Hons.) and the M.S. degree in electronics and electrical communications engineering from Cairo University, Cairo, Egypt, in 2002 and 2004, respectively, and the Ph.D. degree in electrical engineering from the University of Maryland, College Park, MD, USA, in 2009. He was an Assistant Professor with Cairo University, a Wireless Research Scientist with Intel Corporation, and a Senior Engineer with Inter digital Communications Inc. He is currently an Assistant Professor with the Electrical and Computer Engineering Department, Florida International University, Miami, FL, USA. His research interests include next-generation mobile communications and the Internet of Things, such as heterogeneous networks, drone-assisted millimeter-wave communications, and vehicular networks.

MAHMOUD H. ISMAIL (Senior Member, IEEE) received the B.Sc. degree (Hons.) in electronics and electrical communications engineering and the M.Sc. degree in communications engineering from Cairo University, Egypt, in 2000 and 2002, respectively, and the Ph.D. degree in electrical engineering from The University of Mississippi, Oxford, MS, USA, in 2006. From August 2000 to August 2002, he was a Researcher and a Teaching Assistant with the Department of Electronics and Electrical Communications Engineering, Cairo University. From 2004 to 2006, he was a Research Assistant with the Center for Wireless Communications (CWC), The University of Mississippi. He was also a Systems Engineering Consultant with Newport Media Inc., (now part of Microchip) Egypt Design Center, Cairo, from 2006 to 2014. He is currently a Full Professor with the American University of Sharjah, Sharjah, United Arab Emirates, and a Full Professor (on leave) with the Department of Electronics and Electrical Communications Engineering, Cairo University. His research is in the general area of wireless communications with emphasis on performance evaluation of next-generation wireless systems and communications over fading channels. He was a recipient of the University of Mississippi Summer Assistantship Award in 2004 and 2005, The University of Mississippi Dissertation Fellowship Award in 2006, The University of Mississippi Graduate Achievement Award in Electrical Engineering in 2006, and the Best Paper Award presented at the Tenth IEEE Symposium on Computers and Communications (ISCC 2005), La Manga del Mar Menor, Spain. He has served as a Reviewer for several refereed journals and conferences. He is a member of Sigma Xi and Phi Kappa Phi.