Virtual Infrastructure at Traffic Lights: Vehicular Temporary Storage Assisted Data Transportation at Signalized Intersections

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***Abstract*—In this correspondence, we propose to exploit vehicles waiting at red lights as virtual network infrastructure, for communication, computing, and storage, based on the observation that there always exists a direction getting red lights at signalized intersections. To illustrate our idea, we study how those vehicles stopping at red lights can be utilized as vehicular temporary storage (VTS) to create more contact opportunities between vehicles at signalized intersections and facilitate timely data transportation. We design a VTS-assisted data transportation scheme through Markov decision processes and demonstrate its effectiveness via simulations.**

***Index Terms*—Vehicular networks, data transportation, signalized intersections, computing, Markov decision processes**

I. Introduction

With the impetus from both governments and industries, vehicles are expected to be equipped with communication devices in the near future [1]–[3]. Unlike traditional mobile devices, vehicles are less constrained in size and power supply and their mobility is more regular. With proper management, we can exploit the mobility of vehicles and the store-carry-forward mechanism to offload delay-tolerant traffic from existing telecommunication networks, which not only relieves network congestion but also supports newly emerging smart-city applications [3], [4]. For example, this vehicle-aided data delivery is particularly useful for supporting vehicle-based urban sensing services in smart cities. To support self-driving, vehicles will be equipped with various sensing devices for environment perception. Besides self-driving, the data sensed by these sensing devices can also be used to support different smart-city applications, such as traffic monitoring, environmental monitoring, and distributed surveillance [5]. Considering the large numbers of vehicles in the cities and the large amount of sensing data generated per vehicle, the data traffic generated from sensing data collection could potentially overwhelm existing telecommunication networks [5], [6]. In this case, the vehicle-aided data delivery offers us an alternative way to complement exiting telecommunication networks in sensing data collection. In the subsequent development, we call the procedure where vehicles store and carry data to intended locations as data transportation.

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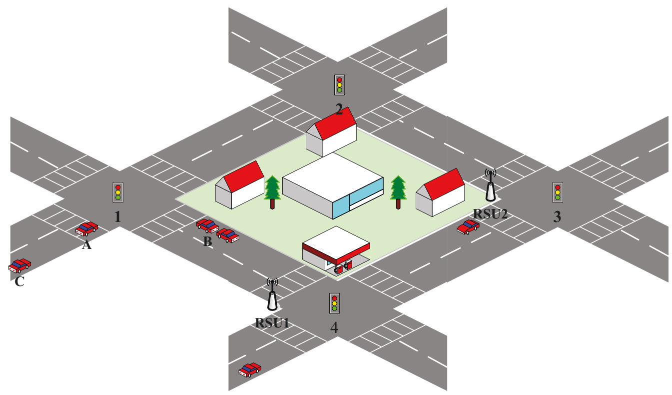

Fig. 1. An illustrative example.

One of the key challenges to utilize vehicles for data transportation is their uncertain mobility at intersections. If not properly handled, data can be delivered to a direction which leads to unsuccessful delivery due to the violation of delay constraints [7]. For illustrative purpose, let us consider the scenario shown in Fig. 1 where a data-carrying vehicle, vehicle A, approaches intersection 1. The data carried on vehicle A needs to be uploaded to data networks via a roadside unit (RSU). Due to delay constraints, RSU1 located at intersection 4 is the only RSU through which the data block can be timely uploaded. Namely, if vehicle A does not turn right at intersection 1, either uploading via another RSU, such as RSU2 at intersection 3, or replanning the path for data transportation will result in unsuccessful delivery because of the violation of delay constraints. In this case, an effective way to enable timely data uploading is to transfer the carried data block to another vehicle which moves towards RSU1. In the subsequent development, such a vehicle will be called a connecting vehicle. Due to mobility, vehicle A stays at intersection 1 for a limited duration and the contact opportunities between vehicle A and other vehicles are limited. Thus, the probability that vehicle A encounters a connecting vehicle is limited. In the literature, this challenge is usually addressed by deploying a storage device, called dropbox or throwbox, at the corresponding intersection, which creates more contact opportunities between data-carrying vehicles and other vehicles [8]. Unfortunately, as pointed out in [8], [9], the number of intersections with dropboxes/throwboxes deployed is limited by the deployment cost. Thus, we still need to

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find ways to create more contact opportunities between data-carrying vehicles and other vehicles at intersections where dropboxes/throwboxes are not deployed.

In this correspondence, we propose to exploit the vehicles waiting at red lights to our advantage by noticing that there is always one direction with red light at a signalized intersection. According to current industrial initiatives, vehicles will support services far beyond safety related services and thus are expected to be equipped with powerful communication devices with sufficient computing and storage capabilities [10], [11]. With proper management, the vehicles stopping at red lights can potentially serve as a virtual infrastructure for either edge computing or short-term data storage. Above observations motivate us to employ vehicles stopping at red lights as vehicular temporary storage (VTS) for carried data blocks so that more contact opportunities between data-carrying vehicles and other vehicles are created. For the example shown in Fig. 1, if vehicle A caches the carried data block in vehicle B which is waiting at the red light at intersection 1, this data block can be transferred to vehicle C which possibly turns right at intersection 1 but is outside the transmission range of vehicle A, through vehicle B. In this way, we can create more contact opportunities between data-carrying vehicles and other vehicles at intersections and thus facilitate timely data transportation without excessive deployment of infrastructure, such as dropboxes/throwboxes. It should be noted that how vehicles waiting at red lights are used in this paper is different from that in [12]–[14]. In [12]–[14], the authors exploit the communication capability of vehicles waiting at red lights to relay data towards red light segments and investigate how to select the most appropriate route for each data block at signalized intersections. In contrast, in this paper, we exploit the onboard storage of vehicles waiting at red lights as temporary storage at signalized intersections to increase the probability that the data block is routed along certain directions.

In the following, we will study how to utilize such VTS for data transportation at intersections under our recently proposed vehicular cognitive capability harvesting network (V-CCHN) [3]. Particularly, we design a VTS-assisted data transportation (VADT) scheme through Markov decision processes and demonstrate its effectiveness via simulations. To facilitate easy reading, the important concepts/abbreviations used in this paper are summarized in Table I.

II. Network Model

The V-CCHN is designed to opportunistically exploit vehicles traveling in cities as a "transmission medium" (i.e., an opportunistic data carrier), besides wireless spectrum, to transport massive volume of data from the location where it is collected to the place where it is consumed or utilized in a smart city environment. The V-CCHN consists of a secondary service provider (SSP), cognitive radio router enabled vehicles (CRVs), and cognitive radio capable roadside units (CRSUs) [3], [15], [16]. The SSP is the operator of the V-CCHN and coordinates CRVs to either offload delay-tolerant traffic from existing telecommunication networks or transport a large amount of data for smart-city applications. For example, the city government can assume the role of SSP or designate a telecommunications operator to provide the information and communications technology (ICT) support for smart city operations. CRSUs are roadside infrastructure nodes deployed by the SSP and provide access to data networks. Interested readers are referred to [3] for detailed introduction to the V-CCHN.

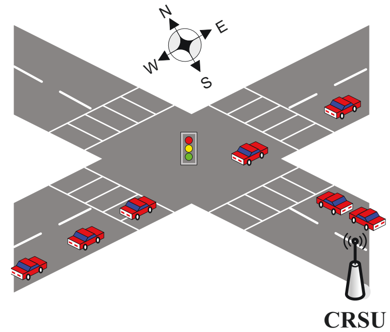

Fig. 2. The considered scenario.

In this correspondence, we are interested in the data transportation at a specific intersection as shown in Fig. 2. The east/westbound road has the green light and the south/northbound road has the red light. For simplicity, we only consider the data-carrying CRVs moving from west to east and assume all the carried data needs to be delivered to the CRSU shown in Fig. 2 for timely uploading. Since the SSP might have different amount of information on data-carrying CRVs and other CRVs, the probability that a data-carrying CRV turns right at the intersection is set as q, whereas, other CRVs turn right at the intersection with probability[1] p. In the subsequent development, we will study how the SSP utilizes the CRVs stopping at the red light as the VTS for efficient data transportation within the duration of a green interval where the east/westbound road gets the green light. To perform the evaluation of the proposed scheme, we consider a time slotted system where a slot corresponds to the control granularity of the SSP, i.e., the control interval, determined by the data block design (or burst transmission mechanism). Data-carrying CRVs arrive at the intersection at the beginning of each time slot and the considered green interval consists of K slots. Noticing that the mobility of CRVs before reaching the intersection is constrained by road topology, the SSP is assumed to exactly know when each CRV arrives at the intersection. Data-carrying CRVs arrive at the intersection at the beginning of each time slot, and there is at most one data-

[1] Although sometimes we could learn the turning directions of vehicles through their lanes, this is not always the case. For example, when there is no right turn only lane, the vehicles in the rightmost lane can either turn right or go straight. Moreover, as mentioned in [17], lane information might not be available when making data routing decisions. In view of this, we characterize the mobility of vehicles through turning probabilities instead of the turning direction.

TABLE I
THE LIST OF IMPORTANT CONCEPTS/ABBREVIATIONS AND DEFINITIONS.

Concept/Notation	Definition
VTS	The temporary storage offered by vehicles stopping at red lights
VADT	VTS-assisted data transportation
V-CCHN	A network utilizes the "free" resource, opportunistic presence of vehicles and their mobility, to carry data closer to the location where data is consumed
SSP	The service provider which manages the operation of the V-CCHN
CRV	Vehicles opportunistically utilized in the V-CCHN to carry and forward data
CRSU	Roadside infrastructures where the access to data networks is provided

TABLE II
THE LIST OF IMPORTANT MATHEMATICAL NOTATIONS AND DEFINITIONS.

Notation	Definition
K	The number of time slots in the considered green interval
$\mathcal{K}$	The set which collects the indices of the time slots with data-carrying CRVs arriving
$e(k)$	$=1$ if a data-carrying CRV arrives at the considered intersection at the kth slot and is 0 otherwise
$n(k)$	$=1$ if at least a candidate connecting CRV is available at the kth slot and is 0 otherwise
$\eta(k)$	$=1$ if the VTS is able to cache a data block at the kth slot and is 0 otherwise
$\beta(k)$	the number of data blocks being successfully directed towards the CRSU after the $(k-1)$th slot
$a(k)$	The data transportation decision made by the SSP at the beginning of the kth slot
$N(k)$	The number of CRVs which could potentially serve as connecting CRVs in the kth time slot

carrying CRV arriving at each time slot[2]. The indices of the time slots with data-carrying CRV arriving are collected in a set $\mathcal{K}$. Upon the arrival of a data-carrying CRV, the SSP determines if the data-carrying CRV should cache a copy of the carried data in the VTS or transfer it to another CRV moving towards the CRSU, if possible. For the time slot without data-carrying CRVs arriving, if there happens to be a CRV moving towards the CRSU at the intersection, the SSP can choose to deliver the data block cached in the VTS to this vehicle for uploading. In the next section, we formulate this VADT process as a Markov decision process, which facilitates the derivation of the optimal VADT scheme yielding the optimal strategy for the SSP at each time slot. For readers' convenience, the important mathematical notations used in this paper is summarized in Table II.

III. PROBLEM FORMULATION

A. State Space and Actions

At the beginning of each slot, the SSP learns the arrivals of data-carrying CRVs, the availability of candidate connecting CRVs[3], the status of the VTS, and the number of data blocks being successfully directed towards the CRSU in the last time slot. Then, the state of the considered system at the kth slot is

$$s(k) = (e(k), n(k), \eta(k), \beta(k)), \tag{1}$$

where $e(k)$ equals 1 when a data-carrying CRV arrives at the considered intersection at the kth slot and equals 0 otherwise. $n(k)$ represents if there exist candidate connecting CRVs at the intersection at the kth slot. $n(k) = 1$ implies that at least a candidate connecting CRV is available, and $n(k) = 0$, otherwise. Considering the large size of the data carried on each vehicle and the availability of communication resources, when $n(k) = 1$, at most a data block, be it carried by the data-carrying CRV or cached at the VTS, can be transferred to candidate connecting CRVs during the kth slot. For simplicity, we assume that only one data block can be cached at the VTS. Thus, $\eta(k)$ is used to indicate if the VTS is able to cache a data block at the kth slot and can take value either 0 or 1. When $\eta(k) = 1$, the VTS is available to cache the data carried by the data-carrying CRV at the kth slot, and $\eta(k) = 0$, otherwise. $\beta(k)$ is the number of data blocks being successfully directed towards the CRSU after the $(k-1)$th slot. Noticing that, at most two data blocks, the one cached at the VTS and the one carried by the data-carrying CRV, are handled during each time slot, $\beta(k)$ can potentially be 0, 1, and 2.

The SSP makes data transportation decisions, denoted as $a(k)$, based on $s(k)$ at the beginning of the kth slot. For the considered scenario, there are generally 4 possible choices for $a(k)$,

$$a(k) = \begin{cases} 0 & \text{take no action} \\ 1 & \text{transfer the carried data to } \nu \\ 2 & \text{transfer the cached data to } \nu \\ 3 & \text{cache the carried data at the intersection,} \end{cases} \tag{2}$$

where the carried data is the data carried by the data-carrying CRV, the cached data is the data cached at the VTS at the considered intersection, and ν represents the candidate connecting CRVs. Clearly, action 1 and action 2 are available at the kth slot only when $n(k) = 1$, and action 3 is available at the kth slot only when $\eta(k) = 1$. Through this Markov decision process, the SSP can obtain a policy g which specifies the actions to be selected at each state of each stage, i.e., $a(k) = g(s(k))$ [18]. To proceed further, the state transition probabilities will be derived in the next subsection.

[2]Given large numbers of vehicles traveling in the city, not all of them will serve as data carriers. Noticing that this paper serves as the proof-of-concept study of our idea, we assume at most one data-carrying vehicle arrives at the intersection during each time slot just for the illustrative purposes.

[3]Candidate connecting CRVs refer to the CRVs moving towards the CRSU at the considered intersection and are able to receive the data blocks from the data-carrying CRVs or the VTS.

B. State Transition Probabilities

Noticing that state transitions depend on both $s(k)$'s and $a(k)$'s, we have the following state transition probability

$$\begin{aligned}&\mathrm{P}\left(s\left(k+1\right)=\left(e',n',\eta',\beta'\right)|s\left(k\right)=\left(e,n,\eta,\beta\right),a(k)=a\right)\\=&\mathrm{P}(e\left(k+1\right)=e',n(k+1)=n',\eta\left(k+1\right)=\eta',\beta\left(k+1\right)=\\&\beta'|e\left(k\right)=e,n(k)=n,\eta\left(k\right)=\eta,\beta\left(k\right)=\beta,a(k)=a).\end{aligned} \tag{3}$$

Since the SSP knows when each data-carrying CRV arrives at the considered intersection, $e(k+1)$ is independent of $s(k)$ and $a(k)$. Given each CRV turns right at the considered intersection with probability p, $n(k+1)$ is closely related to the number of CRVs which could potentially serve as connecting CRVs in the $(k+1)$th time slot, denoted as $N(k+1)$. As mentioned in Section II, the SSP accurately knows when each CRV arrives at the intersection. Thus, $N(k)$'s are known to the SSP, which implies that $n(k+1)$ is independent of $s(k)$ and $a(k)$. In view of this, the state transition probability in (3) can be reformulated as

$$\begin{aligned}&\mathrm{P}\left(s\left(k+1\right)=\left(e',n',\eta',\beta'\right)|s\left(k\right)=\left(e,n,\eta,\beta\right),a(k)=a\right)\\=&\mathrm{P}\left(e\left(k+1\right)=e'\right)\mathrm{P}\left(n\left(k+1\right)=n'\right)\\&\times\underbrace{\mathrm{P}\left(\begin{array}{c}\eta\left(k+1\right)=\eta',\beta\left(k+1\right)=\beta'|e\left(k\right)=e,\\n(k)=n,\eta\left(k\right)=\eta,\beta\left(k\right)=\beta,a(k)=a\end{array}\right)}_{\phi}.\end{aligned} \tag{4}$$

Given $e\left(k\right)=e$, $n(k)=n$, $\eta\left(k\right)=\eta$, $\beta\left(k\right)=\beta$, and $a(k)=a$, $\eta\left(k+1\right)$ is independent of $\beta\left(k+1\right)$. Thus, ϕ in (4) can be further obtained as

$$\begin{aligned}\phi=&\underbrace{\mathrm{P}\left(\begin{array}{c}\eta\left(k+1\right)=\eta'|e\left(k\right)=e,n(k)=n,\\\eta\left(k\right)=\eta,\beta\left(k\right)=\beta,a(k)=a\end{array}\right)}_{\phi_1}\\&\times\underbrace{\mathrm{P}\left(\begin{array}{c}\beta\left(k+1\right)=\beta'|e\left(k\right)=e,n(k)=n,\\\eta\left(k\right)=\eta,\beta\left(k\right)=\beta,a(k)=a\end{array}\right)}_{\phi_2}.\end{aligned} \tag{5}$$

By definition, $\mathrm{P}\left(e\left(k+1\right)=e'\right)$ can be expressed as

$$\begin{aligned}&\mathrm{P}\left(e\left(k+1\right)=e'\right)\\=&\begin{cases}0 & \{e'=1,k+1\notin\mathcal{K}\}\cup\{e'=0,k+1\in\mathcal{K}\}\\1 & \{e'=0,k+1\notin\mathcal{K}\}\cup\{e'=1,k+1\in\mathcal{K}\}.\end{cases}\end{aligned} \tag{6}$$

As aforementioned, given $N(k+1)$, $n(k+1)$ follows a binomial distribution with parameters $N(k+1)$ and p. Then, $\mathrm{P}\left(n\left(k+1\right)=n'\right)$ can be derived as

$$\mathrm{P}\left(n\left(k+1\right)=n'\right)=\begin{cases}\left(1-p\right)^{N(k+1)} & n'=0\\1-\left(1-p\right)^{N(k+1)} & n'=1.\end{cases} \tag{7}$$

From (4) and (5), we still need to find the expressions for ϕ_1 and ϕ_2. Clearly, both $\eta\left(k+1\right)$ and $\beta\left(k+1\right)$ depend on the values of e, n, η, and a. To facilitate the derivation of ϕ_1 and ϕ_2, we need to consider the following cases.

1) $e=0$, $n=0$, $\eta=0$: In this case, the only available action for the SSP is $a=0$, and thus we have

$$\begin{aligned}\phi_1&=\begin{cases}0 & \eta'=1,a=0\\1 & \eta'=0,a=0,\end{cases}\\\phi_2&=\begin{cases}1 & \beta'=0,a=0\\0 & \text{otherwise}.\end{cases}\end{aligned} \tag{8}$$

2) $e=0$, $n=0$, $\eta=1$: Similar to the first case, only $a=0$ is available to the SSP. ϕ_1 can be expressed as

$$\phi_1=\begin{cases}1 & \eta'=1,a=0\\0 & \eta'=0,a=0.\end{cases} \tag{9}$$

The expression for ϕ_2 is the same as that in (8).

3) $e=0$, $n=1$, $\eta=0$: In this case, action 0 and action 2 are available to the SSP. Then, it follows

$$\begin{aligned}\phi_1&=\begin{cases}1 & \{\eta'=0,a=0\}\cup\{\eta'=1,a=2\}\\0 & \text{otherwise},\end{cases}\\\phi_2&=\begin{cases}1 & \{\beta'=0,a=0\}\cup\{\beta'=1,a=2\}\\0 & \text{otherwise}.\end{cases}\end{aligned} \tag{10}$$

4) $e=0$, $n=1$, $\eta=1$: In this case, only action 0 is available to the SSP. Thus, the expression of ϕ_1 is the same as (9) and that of ϕ_2 is the same as that in (8).

5) $e=1$, $n=0$, $\eta=0$: The SSP can only choose action 0 in this case. The expression of ϕ_1 is the same as that in (8). $e=1$ implies that a data-carrying CRVs arrives at the intersection for the considered time slot. Noticing that the data-carrying CRV can potentially turn right at the intersection, ϕ_2 can be derived as

$$\phi_2=\begin{cases}1-q & \beta'=0,a=0\\q & \beta'=1,a=0\\0 & \text{otherwise},\end{cases} \tag{11}$$

where q is the probability that the data-carrying CRV turns right at the intersection.

6) $e=1$, $n=0$, $\eta=1$: The SSP can choose either action 0 or action 3 in this case. When action 3 is selected, the SSP directs the data-carrying CRV to cache a copy of the carried data block to the VTS. If the data-carrying CRV turns right during the considered time slot, the copy cached at the VTS will be removed. Then, ϕ_1 and ϕ_2 can be derived as

$$\begin{aligned}\phi_1&=\begin{cases}1-q & \eta'=0,a=3\\q & \eta'=1,a=3\\1 & \eta'=1,a=0\\0 & \text{otherwise},\end{cases}\\\phi_2&=\begin{cases}1-q & \{\beta'=0,a=0\}\cup\{\beta'=0,a=3\}\\q & \{\beta'=1,a=0\}\cup\{\beta'=1,a=3\}\\0 & \text{otherwise}.\end{cases}\end{aligned} \tag{12}$$

7) $e=1$, $n=1$, $\eta=0$: In this case, action 0, action 1, and action 2 are available to the SSP. By definition, ϕ_1 and ϕ_2 can be derived as

$$\begin{aligned}\phi_1&=\begin{cases}1 & \{\eta'=0,a=0\text{ or }1\}\cup\{\eta'=1,a=2\}\\0 & \text{otherwise},\end{cases}\\\phi_2&=\begin{cases}1-q & \{\beta'=0,a=0\}\cup\{\beta'=1,a=2\}\\q & \{\beta'=1,a=0\}\cup\{\beta'=2,a=2\}\\1 & \beta'=1,a=1\\0 & \text{otherwise}.\end{cases}\end{aligned} \tag{13}$$

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8) $e = 1$, $n = 1$, $\eta = 1$: In this case, action 0, action 1, and action 3 are available to the SSP. Then, ϕ_1 and ϕ_2 can be obtained as

$$\phi_1 = \begin{cases} 1-q & \eta' = 0, a = 3 \\ q & \eta' = 1, a = 3 \\ 1 & \{\eta' = 1, a = 0\} \cup \{\eta' = 1, a = 1\} \\ 0 & \text{otherwise,} \end{cases}$$
$$\phi_2 = \begin{cases} 1-q & \{\beta' = 0, a = 0\} \cup \{\beta' = 0, a = 3\} \\ q & \{\beta' = 1, a = 0\} \cup \{\beta' = 1, a = 3\} \\ 1 & \beta' = 1, a = 1 \\ 0 & \text{otherwise.} \end{cases} \tag{14}$$

With (6), (7), and the results for ϕ_1 and ϕ_2, the state transition probabilities can be derived based on (4) and (5).

C. Objective and Reward

The SSP attempts to deliver as many data blocks towards the CRSU as possible during the K time slots. This implies that the SSP needs to find a policy g^* to maximize $\vartheta = \mathcal{R}(g) = \mathrm{E}\left[\sum_{k=1}^{K} \mathcal{R}(s(k), s(k+1), a(k))\right]$, where $\mathcal{R}(s(k), s(k+1), a(k))$ is the reward received during the kth time slot and can be expressed as

$$R(s(k), s(k+1), a(k)) = \beta(k+1) R, \tag{15}$$

where R is the reward received by directing a data block towards the CRSU. With the state transition probability obtained in Section III.B, the SSP can obtain the optimal policy g^*, i.e., the optimal VADT scheme, via dynamic programming [18].

IV. Performance Evaluation

In this section, simulations are conducted to evaluate the effectiveness of the proposed VADT and the performance of the obtained VADT scheme. We consider the scenario shown in Fig. 2 where the east/westbound road gets the green light and the data-carrying CRVs arrive at the intersection from the west. The green interval consists of $K = 10$ time slots. Once a data block is successfully directed towards the CRSU, a reward of $R = 1$ is obtained. Thus, the total reward received during the K time slots, ϑ, is the average number of data blocks which have been successfully directed towards the CRSU. In the simulations, $\mathcal{K} = \{1, 2, 3, 5, 7, 9\}$ and the values of $N(k)$'s, $k = 2, \cdots, K$, are set according to the vector [2 0 1 0 2 0 1 0 2]. At the beginning of the first time slot, there is a candidate connecting CRV at the intersection and the VTS is able to cache a data block. $\beta(1)$ is set to 1.

In Fig. 3, we evaluate the performance of the obtained VADT scheme by comparing it with a benchmark scheme where the VTS is not utilized. In the benchmark scheme, the data-carrying CRV does not utilize the VTS to cache a copy of the carried data but attempts to transfer the carried data to a candidate connecting CRV when possible. The parameter settings are the same as introduced at the beginning of this section except $p = 0.5$. From Fig. 3, the VADT scheme achieves significant performance gain over the benchmark scheme, particularly when q is small. Since q is the probability that the data-carrying CRVs turn to the desired direction, a smaller q means the data-carrying CRVs will deviate from the intended direction with higher probability. Noticing that the VTS is introduced to timely adjust the carried data block towards the desired direction when data-carrying vehicles divert from the desired direction, it is not surprising that a more significant performance gain can be observed when q is smaller. These results implies that, with proper management, exploiting the vehicles stopping at red lights as the VTS at intersections can effectively improve the efficiency for data transportation.

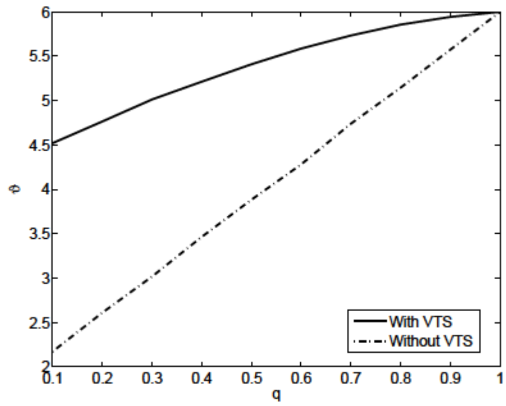

Fig. 3. The average number of data blocks being successfully directed towards the CRSU, ϑ, v.s. the probability that the data-carrying CRVs turn to the desired direction, q. The curve labeled "With VTS" corresponds to the VADT scheme and that labeled "Without VTS" corresponds to the benchmark scheme.

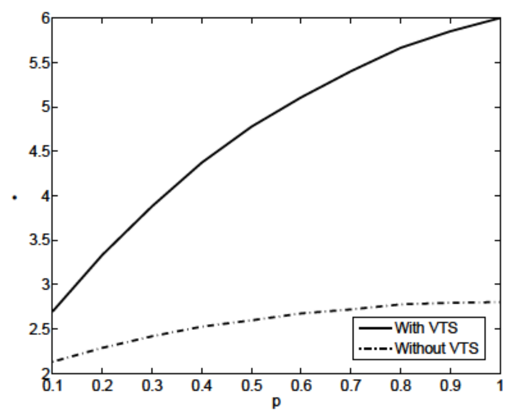

Fig. 4. The average number of data blocks being successfully directed towards the CRSU, ϑ, v.s. the probability that non-data-carrying CRVs turn to the desired direction, p.

In Fig. 4, we further compare the performance of the VADT scheme with that of the benchmark scheme under different values of p. The parameter settings are the same as those in Fig. 3 except $q = 0.2$. From Fig. 4, the performance gain of the VADT scheme over the benchmark scheme increases with p increasing, which demonstrates the effectiveness of the VADT scheme. The results in Fig. 4 implies that, through the VADT scheme, non-data-carrying vehicles can be more effectively

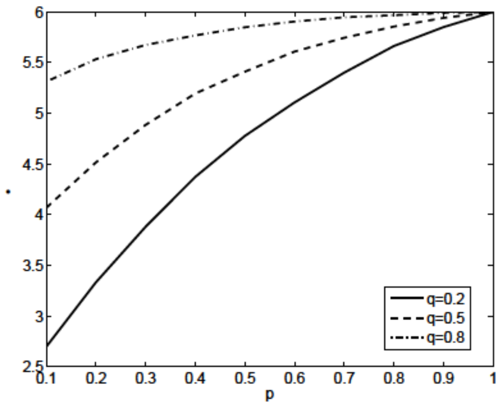

Fig. 5. The average number of data blocks being successfully directed towards the CRSU, ϑ, v.s. the probability that non-data-carrying CRVs turn to the desired direction, p.

utilized to route data towards desired directions.

In Fig. 5, the relationship between the average number of data blocks being successfully directed towards the CRSU, ϑ, and the probability that non-data-carrying CRVs turn to the desired direction, p, is investigated. Clearly from Fig. 5, ϑ increases with p. With a larger p, each non-data-carrying CRV turns to the desired direction with higher probability. In this case, the SSP is more likely to find a candidate connecting CRV for each data block and thus more data blocks are expected to be directed to the desired directions. This explains why a larger ϑ is observed when p increases. Since connecting CRVs are needed only when the data-carrying CRVs deviate from the desired direction, p has more significant impacts on ϑ when q is small, which matches the results in Fig. 5.

V. Conclusion

In this correspondence, we propose to exploit the vehicles stopping at red lights as the VTS to create more contact opportunities between data-carrying vehicles and other vehicles and facilitate efficient data transportation despite the uncertain mobility of vehicles at intersections. We develop a VADT scheme based on Markov decision processes and demonstrate the effectiveness of utilizing the VTS for efficient data transportation at intersections. In the future, we will further explore the potentials of the vehicles stopping at red lights since they offer us not only temporary storage but also virtual infrastructure at intersections for communication and computing service provisioning.

References

[1] N. Cheng, N. Lu, N. Zhang, T. Yang, X. S. Shen, and J. W. Mark, "Vehicle-assisted device-to-device data delivery for smart grid," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2325–2340, Apr. 2016.

[2] N. Lu, N. Cheng, N. Zhang, X. S. Shen, J. W. Mark, and F. Bai, "Wi-fi hotspot at signalized intersection: Cost-effectiveness for vehicular internet access," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3506–3518, May 2016.

[3] H. Ding, C. Zhang, Y. Cai, and Y. Fang, "Smart cities on wheels: a newly emerging vehicular cognitive capability harvesting network for data transportation," *IEEE Wireless Commun. Mag.*, vol. 25, no. 2, pp. 160–169, Apr. 2017.

[4] J. Feng, S. Yang, and Z. Feng, "Vehicle-assisted offloading on metropolitan streets: Enhancing geographical fluidity of wireless resources," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 622–625, 2017.

[5] U. Lee, E. Magistretti, M. Gerla, P. Bellavista, and A. Corradi, "Dissemination and harvesting of urban data using vehicular sensing platforms," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 882–901, Feb. 2009.

[6] W. Xu, H. Zhou, N. Cheng, F. Lyu, W. Shi, J. Chen, and X. Shen, "Internet of vehicles in big data era," *IEEE/CAA J. Autom. Sinica*, vol. 5, no. 1, pp. 19–35, Jan. 2018.

[7] H. Ding, X. Li, Y. Cai, B. Lorenzo, and Y. Fang, "Intelligent data transportation in smart cities: a spectrum-aware approach," *IEEE/ACM Trans. Netw.*, accepted for publication 2018.

[8] J. He, Y. Ni, L. Cai, J. Pan, and C. Chen, "Optimal dropbox deployment algorithm for data dissemination in vehicular networks," *IEEE Trans. Mobile Comput.*, vol. 17, no. 3, pp. 632–645, Mar. 2018.

[9] T. H. Luan, L. X. Cai, J. Chen, X. S. Shen, and F. Bai, "Engineering a distributed infrastructure for large-scale cost-effective content dissemination over urban vehicular networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 3, pp. 1419–1435, Mar. 2014.

[10] Intel, "Intel predicts autonomous driving will spur new 'passenger economy' worth $7 trillion," 2017, available at:https://newsroom.intel.com/news-releases/intel-predicts-autonomous-driving-will-spur-new-passenger-economy-worth-7-trillion/.

[11] N. Banks, "Ces 2018: Meet toyota's flexible, electric, automated e-palette," 2018, available at:https://www.forbes.com/sites/nargessbanks/2018/01/10/toyota-e-palette-ces2018/#64deed0e5368.

[12] J.-J. Chang, Y.-H. Li, W. Liao, and C. Chang, "Intersection-based routing for urban vehicular communications with traffic-light considerations," *IEEE Wireless Commun. Mag.*, vol. 19, no. 1, pp. 82C–88, Feb. 2012.

[13] Q. Ding, B. Sun, and X. Zhang, "A traffic-light-aware routing protocol based on street connectivity for urban vehicular ad hoc networks," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1635–1638, Aug. 2016.

[14] O. S. Oubbati, A. Lakas, N. Lagraa, and M. B. Yagoubi, "Etar: efficient traffic light aware routing protocol for vehicular networks," in *2015 International Wireless Communications and Mobile Computing Conference (IWCMC)*, 2015, pp. 297–301.

[15] H. Ding, Y. Fang, X. Huang, M. Pan, P. Li, and S. Glisic, "Cognitive capacity harvesting networks: Architectural evolution toward future cognitive radio networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1902–1923, Thirdquarter 2017.

[16] H. Ding, C. Zhang, B. Lorenzo, and Y. Fang, "Access point recruitment in a vehicular cognitive capability harvesting network: How much data can be uploaded?" *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 6438–6445, Jul. 2018.

[17] S. Demetriou, P. Jain, and K.-H. Kim, "Codrive: improving automobile positioning via collaborative driving," in *2018 Proceedings IEEE INFOCOM*, Apr. 2018.

[18] D. P. Bertsekas, *Dynamic Programming and Optimal Control (Third Edition), Vol. I.* Athena Scientific, 2005.