Intelligent Data Transportation in Smart Cities: A Spectrum-Aware Approach

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***Abstract*—Communication technologies supply the blood for smart city applications. In view of the ever increasing wireless traffic generated in smart cities and our already congested radio access networks (RANs), we have recently designed a *data transportation* network, the vehicular cognitive capability harvesting network (V-CCHN), which exploits the harvested *spectrum opportunity* and the *mobility opportunity* offered by the massive number of vehicles traveling in the city to not only offload delay-tolerant data from congested RANs but also support delay-tolerant data transportation for various smart-city applications. To make data transportation efficient, in this paper, we develop a *spectrum-aware (SA) data transportation* scheme based on Markov decision process. Through extensive simulations, we demonstrate that the V-CCHN is effective in offering data transportation services despite its dependence on dynamic resources, such as vehicles and harvested spectrum resources. The simulation results also demonstrate the superiority of the SA approach over the spectrum-agnostic approach where the impact of spectrum availability on data transportation is not explicitly considered. We expect the V-CCHN to well complement existing telecommunication networks in handling the exponentially increasing wireless data traffic.**

***Index Terms*—Smart cities, data transportation, data offloading, vehicular networks, cognitive radios**

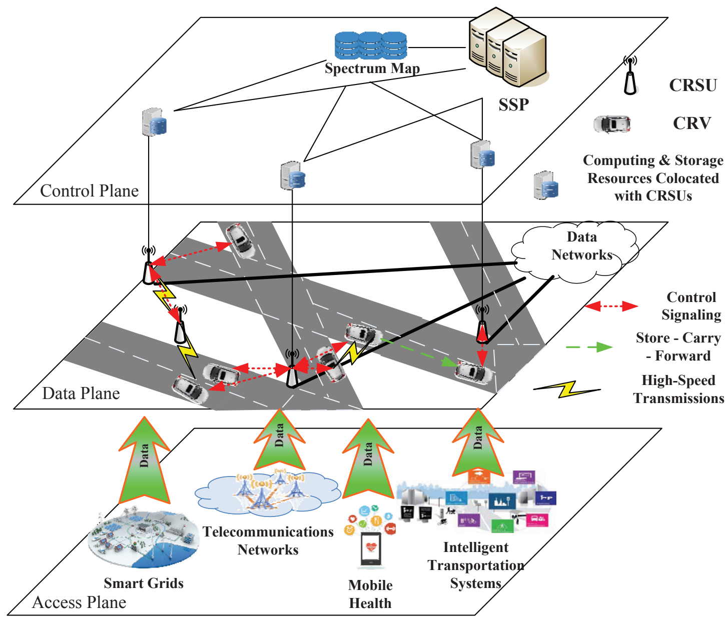

Fig. 1. The V-CCHN architecture.

I. Introduction

The initiatives on smart cities have offered us an informative and smart living environment where we can enjoy better and more convenient daily services, such as transportation, healthcare, and entertainment [1]. To support smart-city applications, numerous devices with different communication capabilities, such as sensors, cameras, and vehicles, are expected to connect and interact with each other for information sharing and delivery, intelligence extraction, and decision making [2], [3]. As a result, tremendous amount of wireless data traffic will be generated, which can easily overwhelm the already congested radio access networks (RANs) [4], [5]. Although people constantly look for innovative solutions, for example, those in 5G, it is still challenging to handle the huge amount of wireless data traffic and facilitate the interconnections between end devices with heterogeneous communications capabilities [6], [7].

To address this challenge, we have recently designed a data transportation network (shown in Fig. 1), called vehicular cognitive capability harvesting network (V-CCHN), to offload delay-tolerant data from congested RANs and support delay-tolerant data transportation for various smart-city applications [8]. The V-CCHN is motivated by the observation that, with the impetus from both governments and industries, such as the mandate from the US Department of Transportation, Intel's vision for "passenger economy", and Toyota's proposal for e-Palette, in the near future, vehicles are expected to be equipped with powerful communications devices with sufficient communications, computing, and storage (CCS) capabilities to support various applications/services [9], [10]. With the CCS capable communications devices onboard, we can not only improve road safety and traffic efficiency but also innovatively exploit the mobility of vehicles, traveling in cities, to transport data besides human beings.

Unlike existing works on vehicular communications, under the V-CCHN, vehicles, be they private or public, are envisioned to be equipped with powerful communication devices, cognitive radio routers (CR routers), with customized CCS

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capabilities. CR routers are intelligent devices with context awareness, cognitive radio (CR) capabilities, and abundant storage space [11]. They can also tune to the corresponding communication interfaces used at end devices, such as cellular and WiFi interfaces, to communicate with them and allow vehicles to pick up data from various end devices and infrastructures, such as surveillance cameras, in their vicinities. In the subsequent development, vehicles installed with CR routers are called CR router enabled vehicles (CRVs). With storage and CR capabilities built in CR routers, CRVs can potentially forward large amount of delay-tolerant data via the store-carry-forward approach and transfer large volumes of carried data to other CRVs by exploiting a wide range of under-utilized licensed/unlicensed spectrum when necessary[1].

In the V-CCHN, the data transferring and spectrum allocation among CRVs are supervised/managed by a service provider, called secondary service provider (SSP), for efficient data transportation. Since CRVs might be recruited private vehicles, the SSP cannot gain full control of their mobility even though their mobility is constrained by road layout[2]. As a result, the SSP often needs to count on a series of CRVs to carry data in succession so that data can be delivered to intended locations. To facilitate efficient data transportation, the SSP collects various kinds of information, such as the availability of licensed/unlicensed bands, and extracts useful statistics. Based on the collected network intelligence, the SSP makes data routing decisions for each data requests and distributes these decisions to data-carrying CRVs in order to help them select data forwarding actions. According to the received decisions, the data-carrying CRVs decide whether to transfer data to another CRVs which can further deliver data towards the intended locations. Once data has been transferred to another CRV, the next data-carrying CRV will be responsible for storing and carrying data towards the destination. In such a way, we expect to have an intelligent data transportation network of large capacity on the road network spreading all over the cities, which offers us an alternative to handle exponentially increasing wireless traffic in smart cities.

Noticing that the data transportation services of the V-CCHN is built on dynamic resources, such as harvested licensed/unlicensed bands, i.e., harvested bands, and recruited CRVs, a primary concern is how effective it could be[3]. Due to the uncertainty in spectrum and CRV availability, the carried data might fail to be transferred to the desired direction. Besides, the uncertain mobility of CRVs could cause the carried data to be routed towards unexpected directions. All these dynamics could lead to unsuccessful data delivery and the SSP needs effective schemes to exploit these dynamic resources for data transportation. Since only the conceptual development of V-CCHN has been presented in [8], in this paper, we attempt to develop an effective data transportation scheme for the V-CCHN. Specifically, we seek for good data routing decisions at road intersections to fully exploit the harvested bands and the mobility of CRVs for data transportation. On the one hand, the data-carrying CRVs have more choices at intersections. On the other hand, the data routing decisions made at intersections determine the moving direction of carried data. If data routing decisions are not properly made, the SSP needs to dedicate extra resources to adjust data delivery and the corresponding data blocks could not even be delivered. Good data routing decisions at intersections will make the data delivery processes in the V-CCHN efficient and effective.

In this paper, under our V-CCHN, we carefully study how the SSP makes data routing decisions to help data-carrying CRVs select their data forwarding actions at intersections so that the considered data block can be efficiently delivered from the source to the destination. To make the data transportation processes effective, we introduce a *spectrum-aware (SA) data transportation* scheme where the effects of spectrum availability, the uncertain activities of licensed/unlicensed spectrum users, contention among different data-carrying CRVs, the mobility of the data-carrying CRV, and the availability of relaying CRVs in each direction are jointly considered during the SSP's decision making process. We model the data delivery process as a Markov decision process by observing that it involves a sequence of data routing decisions made at intersections. The optimal data routing decisions for the SSP are obtained via dynamic programming. Through extensive simulations, we thoroughly discuss the impacts of various parameters on the data delivery process. The results validate the effectiveness of our V-CCHN in handling the envisioned delay-tolerant data transportation services. Moreover, the results also demonstrate that, when compared with the spectrum-agnostic approach where the impact of spectrum availability is not explicitly considered, the SA approach can more efficiently support the data transportation in the V-CCHN.

II. Related Work

Vehicular communications technologies have been extensively studied under the umbrella of vehicular ad hoc networks (VANETs). Due to the lack of continuous end-to-end (E2E) paths between the source and the destination, most data delivery schemes for VANETs are developed based on the store-carry-forward mechanism [12], [13].

In [14], Spyropoulos et al. introduce a multi-copy routing strategy for intermittently connected mobile networks, including VANETs. The proposed scheme sprays a few message copies into the network and independently route these copies towards the destination so that messages can be efficiently delivered. In [15], Zhu et al. propose a utility-based routing scheme by observing the temporal correlation of inter contact times (ICTs) between vehicles. The correlation among ICTs is characterized via a k-order Markov chain, which allows the duration until the next contact between each vehicle and the destination to be estimated. Each vehicle will determine whether to transfer the carried message to another vehicle based on the estimation. Later on, Zhu et al. further develop a scheme called ZOOM, on the basis of [15], to expedite

[1] In this paper, the licensed spectrum, exploited by CRVs for data transportation, refers to the spectrum licensed to other parties rather than the V-CCHN.

[2] In the V-CCHN, we only assume the SSP can supervise the operation of CR routers installed on vehicles. In the following, we will use CRVs and their installed CR routers interchangeably.

[3] Since this work is a preliminary study on the effectiveness of the V-CCHN, we assume enough CRVs participate, and leave the incentive-related issues for future works.

data delivery in VANETs by considering the contacts made by each vehicle [16]. Similar ideas have been explored in [17], [18] where utility-based routing schemes are designed by exploiting the patterns in the trajectories of vehicles. For example, in [17], the mobility patterns of vehicles are modeled as a k-order Markov chain. Based on this Markov chain, Wu et al. derive the delivery probability of each message through each vehicle at each stage and develop a data routing scheme where messages are routed based on the increments in their delivery probability. Generally speaking, all above schemes are developed with our experiences from dealing with delay tolerant networks. As the mobility of vehicles is constrained by road layout, we could come up with more efficient data delivery schemes by taking advantage of the restricted mobility of vehicles [12].

Along this line of thought, various message routing schemes have been developed for VANETs under the assumption that the trajectories of vehicles are exactly known from the on-board GPS-based navigation systems. In [19], the content downloading process in VANETs is studied under the assumption that the mobility of vehicles can be accurately predicted. With such information, Malandrino et al. summarize the mobility of vehicles within a dynamic network topology graph and the message routing is designed through a flow optimization problem. A similar problem has been addressed in [20] where vehicular communications are employed to assist cellular networks in content dissemination. Based on the predicted future contacts, Yao et al. describe the contact events via a deadline timing contact graph and formulate the data dissemination schematic design as a linear programming. Different from these works where the mobility of vehicle is assumed to be accurately predicated, Xu et al. introduce a Shared-Trajectory-based Data Forwarding Scheme (STDFS) in [21] by considering the randomness in the mobility of vehicles. In STDFS, by utilizing shared trajectory information among vehicles, each vehicle constructs a predicted contact graph based on the obtained trajectory information and deliver carried messages to other vehicles accordingly so that the expected delivery delay is minimized and the expected delivery ratio is guaranteed.

Noticing that the trajectories of vehicles cannot always be known in advance, many works attempt to address data forwarding in VANETs without knowing the trajectories of vehicles [22], [23]. Considering the constraints of road topology, these works generally focus on how messages are routed at intersections, which is important and complicated. In [22], Zhao et al. introduce a few vehicle-assisted data delivery (VADD) protocols to facilitate data forwarding in VANETs, with particular emphasis on decision making at intersections. In [23], He et al. further consider employing vehicles moving along the opposite direction to expedite data delivery and develop a minimum delay routing algorithm accordingly. Similar to these works, in the V-CCHN, the SSP cannot gain full control of the trajectories of CRVs even though their mobility is constrained by road topology. According to the same observation as in these works, we focus on how messages or data blocks can be routed at intersections in order to facilitate the data transportation services envisioned for the V-CCHN. However, the routing decision making in the V-CCHN is more complicated than that in existing works. It should be noted that an underlying assumption in these works is that there are always enough resources to support the data transmissions between vehicles as they are primarily targeted at traditional services in VANETs over their own bands. In these works, at intersections, the data-carrying vehicles always route data along the direction leading to the minimum possible data delivery delay, without considering possible deviation from the selected path due to the data transmission failures at intersections and the mobility of vehicles. While, in the V-CCHN, the SSP employs CRVs to collectively deliver large amount of data generated from smart-city applications by harvesting unused licensed spectrum bands or less congested unlicensed bands. To make efficient routing decisions in the V-CCHN, the SSP should jointly consider the large size of data to be transmitted, uncertain activities of licensed/unlicensed users, and contention among different data blocks. Additionally, the V-CCHN offers delay-tolerant data transportation services to deliver data to destinations with the best effort before corresponding deadline expires. All these features of the V-CCHN make the SSP's routing decision making problem different from those in existing works, which implies that the traditional approach is not efficient for the V-CCHN and routing in the V-CCHN needs further exploration.

III. System Model

In this section, we provide an introduction to the V-CCHN architecture and elaborate on the routing problem as well as the corresponding models considered in this paper. The important notations are listed in Table I.

A. The V-CCHN Architecture

As shown in Fig. 1, the V-CCHN consists of an SSP, CRVs, and CR capable roadside service units (CRSUs). The SSP is an independent wireless service provider and the operator of the V-CCHN with its own reliable bands (called basic bands in the subsequent development)[4], for example, the cellular bands for cellular systems if cellular operators are the SSPs. The SSP recruits or deploys CRVs to provide delay-tolerant data transportation services in smart cities. CRSUs are the partial roadside infrastructures deployed by the SSP to improve the efficiency for data transportation. Generally speaking, there are two types of CRSUs in the V-CCHN. The first kind of CRSU does not have wired connections to data networks and are deployed by the SSP to deal with the uncertainty/dynamics in the V-CCHN and improve the efficiency in data transportation. For ease of presentation, this kind of CRSU will be called W-CRSU. The second kind of CRSU is deployed at strategic locations, such as vital intersections, and have wired connections to data networks, enabling the data exchange between the V-CCHN and data networks. By exploiting built-in computing resources, these CRSUs can act as agents for the SSP to manage CRVs and W-CRSUs for data transportation in certain areas called cells. This type of CRSU is called C-CRSU.

[4] The SSP's reliable bands are mainly used for control message exchange.

TABLE I
THE LIST OF IMPORTANT NOTATIONS AND DEFINITIONS.

Notation	Definition
Δ	The size of the considered data block
K	The number of routing decisions can be made before the considered data block is discarded
$\overline{\Theta}$	A set of intersections which lead to the unsuccessful delivery of the considered data block
Θ	The complement of $\overline{\Theta}$
λ_n^v	The average number of potential relays along direction v at the nth intersection
p_n^v	The probability that a potential relay along direction v at the nth intersection is occupied by another data block
β_n^v	The number of potential relays along direction v at the nth intersection which are occupied by other data blocks
M_n	The total number of frequency bands at the nth intersection
ρ_n	The probability that a frequency band is available at the nth intersection
m_i	The number of bands requested to transfer the ith previously arrived data block
p_1, p_2, p_3,p_4	The probabilities that the data-carrying CRV keep current direction, turn left, turn right, and turn around at a interserction
$\mathcal{I}(k)$	The intersection where the data-carrying CRV locates at the kth decision epoch
$\vartheta(k)$	The moving direction of the the data-carrying CRV at the kth decision epoch
$m(k)$	The number of harvested bands available to transfer the considered data block at the kth decision epoch
$\boldsymbol{\eta}(k)$	The availability of potential relays to receive the considered data block at the kth decision epoch
τ_j	The duration where the jth harvested band available for the considered data block can be used for secondary transmissions
λ_s	The mean of τ_j
T	The contact duration between two CRVs

The management function of the SSP can be implemented in clouds/cloudlets, C-CRSUs, or both. To make management more efficient, spectrum allocation can be implemented at C-CRSUs, whereas, the data routing decision making can be either implemented in clouds/cloudlets or carried out by C-CRSUs. The requests for data transportation are first forwarded to, for example, a cloudlet in charge of a large geographic area. Then, the cloudlet determines whether to make routing decisions for these requests by itself or delegate the decision making tasks to a C-CRSU based on certain metrics, such as the distances to be traveled. After that, these routing decisions will be sent to data-carrying CRVs through C-CRSUs via the SSP's basic bands. The SSP's basic bands are primarily used to facilitate control signaling exchange between C-CRSUs and other network entities, such as CRVs and W-CRSUs, in corresponding cells for management and resource allocation.

All CRVs and CRSUs are equipped with CR routers which are powerful communication devices with agile communication interfaces, abundant computing resource and storage space. The agile communication interfaces of CR routers have cognitive radio (CR) capabilities and reconfigurability. Their CR capabilities allow CR routers to sense idle spectrum and exploit a wide range of under-utilized licensed/unlicensed spectrum for high speed data transmissions. Their reconfigurability allows CR routers to collect/deliver data from/to various types of end devices through the corresponding communication technologies used at these end devices, such as LTE, WiFi, and Bluetooth. With CR routers, CRVs can collect data from end devices when moving to their vicinities and collaboratively transport collected data to intended locations through the store-carry-forward mechanism and the harvested spectrum resources, for delivery or uploading.

In the V-CCHN, the data transportation processes are supervised by the SSP. Specifically, the SSP coordinates CRVs and CRSUs for spectrum sensing in order to build up spectrum map and collect spectrum statistics. The C-CRSUs in charge of corresponding cells perform spectrum allocation based on the spectrum map. With collected statistics, the SSP makes data routing decisions which help CRVs route data at various intersections with various spectrum and CRV availability and diverse levels of contentions. When selecting data forwarding actions at the intersections, the data-carrying CRVs query C-CRSUs about available spectrum bands and determine whether to transfer data to another CRVs based on the data routing decisions received from the SSP. Once data has been transferred to another CRV, the next data-carrying CRV is responsible for carrying data towards the destination[5]. The aforementioned data transportation scheme is said to be spectrum-aware since data transmissions and spectrum availability are explicitly considered when the SSP makes data routing decisions.

B. Problem Setting

The generic data routing problem considered in this paper and its corresponding basic setting can be illustrated by the scenario shown in Fig. 2. A CRV approaches the intersection labeled S after collecting a data block of size Δ, such as a video clip from a surveillance camera, and the SSP makes

[5]Since this paper serves as a preliminary study on the data transportation in the V-CCHN, we assume that the data-carrying CRV discards the carried data once it has been successfully transferred to another CRV, for simplicity. How to exploit the redundancy offered by data duplication will be addressed elsewhere.

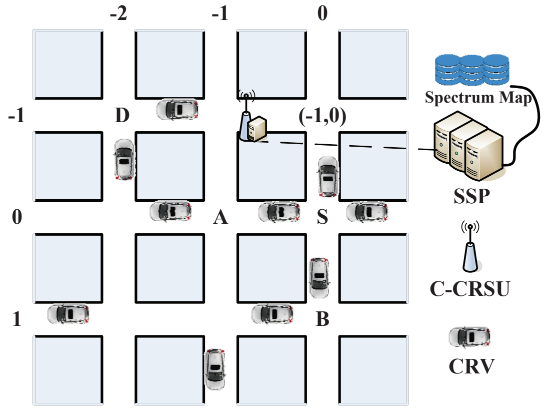

Fig. 2. An illustrative scenario. Intersection S locates at the 0th row and the 0th column. Intersection $(-1, 0)$ is the next intersection to the north of intersection S.

data routing decisions to help CRVs select data forwarding actions at intersections so that this data block can be successfully delivered to the destination, such as a police station for the surveillance camera case, located around intersection D. The C-CRSU shown in Fig. 2 serves as the agent for the SSP to exchange control messages, such as data routing decisions, with CRVs. The roads considered here are either north-southward or east-westward. Thus, CRVs travel along directions $\upsilon \in \{N, S, W, E\}$, where N, S, W, and E represent north, south, west, and east, respectively.

Note that the data block needs to travel through several intersections before arriving at the intersection D. Since the SSP cannot fully control the mobility of CRVs, we assume that, at each intersection, a CRV keeps current direction, turns left, turns right, and turns around with probabilities p_1, p_2, p_3, and p_4, respectively [24]. To facilitate efficient data transportation, the SSP coordinates a series of CRVs to deliver this data block from intersection S to intersection D. At each intersection, the data-carrying CRV either keeps the data block or forwards it to another CRV traveling towards certain directions away from the current intersection. For ease of presentation, the times when the routing decisions are made are called decision epochs. To facilitate efficient resource utilization and data delivery, the data block will be discarded if it is not delivered to intersection D after K decision epochs, with the decision made at intersection S as the first decision. On the basis of K and intersections S and D, we can divide all intersections into two groups, $\overline{\Theta}$ and Θ. If the considered data block is delivered to an intersection in $\overline{\Theta}$, it is impossible for it to be delivered to intersection D right after K decision epochs[6]. An intersection is in Θ if it is not in $\overline{\Theta}$. For example, if we set $K = 3$ for the scenario shown in Fig. 2, the intersection labeled A definitely belongs to Θ, whereas the intersection labeled B could belong to $\overline{\Theta}$. By definition, the data-carrying CRV can directly discard the data block without taking data forwarding actions if it reaches any intersection in $\overline{\Theta}$. Thus, we only need to study how the data-carrying CRV makes data routing decisions at intersections in Θ. For ease of presentation, the north-southward roads are called columns and the east-westward roads are called rows. Since only the north-southward and the east-westward roads are considered, each intersection can be represented by the indices of the row and column where it locates, taking intersection S located at the 0th row and the 0th column as a reference. For example, intersection $(-1, 0)$ is the next intersection to the north of intersection S. Based on this representation, we can index the intersections in Θ as $\Theta_{\mathcal{I}} = \{1, \cdots, N\}$ following the lexicographic order, where N is the cardinality of Θ. The indices of intersection S and intersection D are denoted as n^s and n^d, where $n^s, n^d \in \Theta_{\mathcal{I}}$. In the following development, when referring to the nth intersection, we mean the nth intersection in $\Theta_{\mathcal{I}}$.

When approaching the nth ($n \in \Theta_{\mathcal{I}}$) intersection, the data-carrying CRV will query the C-CRSU about the CRVs, moving towards direction υ away from the current intersection, which are available to relay the considered data block and the available harvested bands utilized to transfer the data block to the relaying CRV. To ensure the contact duration is long enough to perform effective data transmissions, only those CRVs within a certain distance to the nth intersection are considered as potential relays. Denote the number of such CRVs moving towards $\upsilon \in \{N, S, W, E\}$ away from the nth intersection as α_n^υ. These CRVs are called potential relays in the subsequent development. Similar to [22], [23], α_n^υ is assumed to be a Poisson random variable with mean λ_n^υ. The total number of frequency bands at the nth intersection is M_n and each band is found to be available at a decision epoch with probability ρ_n. Noticing that the V-CCHN is designed to provide data transportation services to various smart-city applications, there could be multiple data blocks simultaneously handled at the nth intersection together with the considered one. When the data-carrying CRV requests resources for transferring the considered data block, the SSP could have already allocated certain number of potential relays and available bands to transfer previously arrived data blocks. In view of the random arrivals of data blocks at intersections, we assume that, when the data-carrying CRV arrives at the nth intersection, each potential relay moving towards direction υ is occupied by another data block with probability p_n^υ and m_i harvested bands are requested to transmit the ith of such data blocks. The number of such occupied potential relays along direction υ is denoted as β_n^υ. Then, the number of potential relays, along direction υ, available to receive the considered data block is a Poisson random variable with mean $\lambda_n^\upsilon (1 - p_n^\upsilon)$ and β_n^υ is a Poisson random variable with mean $\lambda_n^\upsilon p_n^\upsilon$. Considering the relatively short contact duration and large data sizes, each potential relay can be designated to relay at most one data block.

IV. The Optimal Data Routing Decisions

Based on above setting, we formulate the delivery process of the considered data block as a Markov decision process, which allows the SSP to obtain the optimal data routing decisions via dynamic programming.

[6]How to find such a $\overline{\Theta}$ will be illustrated in the simulation study.

A. State Space and Actions

Since the routing of the considered data block depends on the specific intersection where the data-carrying CRV stays as well as the spectrum availability and the number of potential relays at the corresponding intersection, the state of the considered system at the kth decision epoch is

$$s(k) = (\mathcal{I}(k), \vartheta(k), m(k), \boldsymbol{\eta}(k)), \tag{1}$$

where $\mathcal{I}(k)$ is the intersection where the data-carrying CRV locates at the kth decision epoch, $\vartheta(k)$ is the current moving directions of the data-carrying CRV, $m(k)$ is the number of harvested bands available for the transferring of the considered data block, $\boldsymbol{\eta}(k) = \left[\begin{array}{cccc} \eta_S(k) & \eta_N(k) & \eta_E(k) & \eta_W(k) \end{array}\right]^{\mathrm{T}}$, T signifies the transpose of a matrix, $\eta_\upsilon(k) = 1$ means at least a potential relay, traveling along the direction υ, is available to receive the considered data block, and $\eta_\upsilon(k) = 0$, otherwise. By definition, the considered data block cannot be delivered to intersection D in K decision epochs once it is delivered to an intersection in $\overline{\Theta}$. Namely, all intersections in $\overline{\Theta}$ correspond to the case where the considered data block cannot be delivered. In view of this, we represent all intersections in $\overline{\Theta}$ as a virtual intersection and index it as the $(N+1)$th intersection. If the considered data block is delivered to an intersection in $\overline{\Theta}$ after a decision epoch, we say it is delivered to the $(N+1)$th intersection, and vice versa. On the other hand, when the considered data block is delivered to the destination, it becomes delivered. In both cases, the data delivery process terminates. When reflecting in the formulation, $s(k)$'s with $\mathcal{I}(k) = N+1$ or $\mathcal{I}(k) = n^d$ will not transfer to any other state. In the subsequent development, we assume that the activities of licensed/unlicensed users on different bands share the same statistical properties for simplicity, which explains why $m(k)$ is used in $s(k)$. Our formulation can cover the case where the activities of licensed/unlicensed users on different bands have different statistical properties by introducing separate state variables to $s(k)$ for different bands. However, this would enlarge the state space. Since we aim to evaluate the effectiveness of the V-CCHN in this paper, we do not consider this diversity in frequency bands and leave it as a future work.

At the kth decision epoch, the SSP makes the data routing decision for the considered data block, denoted as $a(k)$, according to $s(k)$. In general, the SSP has the following choices for $a(k)$

$$a(k) = \left\{ \begin{array}{ll} 0 & \text{Keep the data block in the storage} \\ \delta & \text{Forward the data block to } \delta \end{array} \right., \tag{2}$$

where $\delta = \{N, S, W, E\}$ represents a potential relay moving along the direction indicated by δ. The action δ is available to the SSP at the kth decision epoch only when $\eta_\delta(k) = 1$, $m(k) > 0$. The set of rules used by the SSP in selecting $a(k)$, $k = 1, \cdots, K$ is called a policy, denoted as g. By solving this Markov decision process, the SSP can obtain the data routing policy, denoted as g^*, which is used to assist data-carrying CRVs in selecting data forwarding actions.

B. State Transition Probabilities

By definition, the probability that state $s(k)$ transfers to state $s(k+1)$ under data routing decision $a(k)$ can be formulated as shown in (3), where $\vartheta \in \{N, S, W, E\}$. $n' \in \{n_N, n_S, n_W, n_E\}$, n_N, n_S, n_W, and n_E are the indices of the intersections to the north, south, west, and east of the nth intersection, respectively. Since the number of potential relays available to receive the considered data block is independent of the spectrum availability at each intersection, the first term to the righthand side of (3), denoted as ϕ, can be reformulated as (4). As mentioned previously, considering spatial variations in the activities of licensed/unlicensed users, the availabilities of a specific band at different intersections are assumed to be independent. Noticing that the data-carrying CRV might meet different sets of potential relays at different decision epochs, $\boldsymbol{\eta}(k)$'s are assumed to be independent for this study. Then, ϕ can be expressed as

$$\begin{aligned} \phi = & \underbrace{\mathrm{P}\left(m(k+1) = m' \,|\mathcal{I}(k+1) = n'\right)}_{\triangleq \phi_1} \\ & \times \underbrace{\mathrm{P}\left(\boldsymbol{\eta}(k+1) = \boldsymbol{\eta}' \,|\mathcal{I}(k+1) = n'\right)}_{\triangleq \phi_2}. \end{aligned} \tag{5}$$

The probabilities on the righthand side of (5) is conditioned on $\mathcal{I}(k+1)$ since the distributions of $m(k+1)$ and $\boldsymbol{\eta}(k+1)$ depend on which intersection the data-carrying CRV stays.

In next few subsections, ϕ and φ in (3) will be derived separately. Since the derivation of state transition probabilities when $\mathcal{I}(k) = n^d$ and $\mathcal{I}(k) = N+1$ is trivial, we will only derive φ for the case when $\mathcal{I}(k) \neq n^d$ and $\mathcal{I}(k) \neq N+1$ in the following analysis.

C. Derivation of ϕ

From (5), to obtain ϕ, we should derive ϕ_1 and ϕ_2. According to (5), ϕ_1 is the conditional distribution of $m(k+1)$ given $\mathcal{I}(k+1) = n'$. By definition, $m(k+1)$ equals the difference between the total number of harvested bands, $M(k+1)$, and the number of harvested bands allocated to transfer the scheduled data blocks, i.e.,

$$m(k+1) = \max\left\{ M(k+1) - \sum_{\upsilon \in V} \sum_{i=1}^{\beta_{n'}^{\upsilon}} m_i, 0 \right\}, \tag{6}$$

where $\beta_{n'}^{\upsilon}$ is the number of potential relays occupied by other data blocks, and m_i is the number of harvested bands requested to transmit the ith of these data blocks. The subscript of $\beta_{n'}^{\upsilon}$ is n' since we focus on the derivation of ϕ_1 which is the conditional distribution of $m(k+1)$ given $\mathcal{I}(k+1) = n'$. The max operation is adopted in (6) to include the case where no harvested band is available to the considered data block. Since different data blocks could have diverse data sizes, the number of harvested bands required to transfer these data blocks could be different. In view of this, we model m_i's as random variables. Notice that both $M(k+1)$ and the summation term in (6), $\theta = \sum\limits_{\upsilon \in V} \sum\limits_{i=1}^{\beta_{n'}^{\upsilon}} m_i$, are random variables. To obtain the conditional distribution of $m(k+1)$, we should derive the conditional distributions of $M(k+1)$ and θ.

$$\begin{aligned}
&\mathrm{P}\left(s\left(k+1\right)=\left(n',\vartheta',m',\boldsymbol{\eta}'\right)\left|s\left(k\right)=\left(n,\vartheta,m,\boldsymbol{\eta}\right),a(k)=a\right.\right)\\
=&\underbrace{\mathrm{P}(m\left(k+1\right)=m',\boldsymbol{\eta}\left(k+1\right)=\boldsymbol{\eta}'\left|\mathcal{I}\left(k\right)=n,\vartheta\left(k\right)=\vartheta,m\left(k\right)=m,\boldsymbol{\eta}\left(k\right)=\boldsymbol{\eta},\mathcal{I}\left(k+1\right)=n',\vartheta\left(k+1\right)=\vartheta',a(k)=a\right.)}_{\triangleq\phi}\\
&\times\underbrace{\mathrm{P}(\mathcal{I}\left(k+1\right)=n',\vartheta\left(k+1\right)=\vartheta'\mid\mathcal{I}\left(k\right)=n,\vartheta\left(k\right)=\vartheta,m\left(k\right)=m,\boldsymbol{\eta}\left(k\right)=\boldsymbol{\eta},a(k)=a)}_{\triangleq\varphi}.
\end{aligned}\tag{3}$$

$$\begin{aligned}
\phi=&\mathrm{P}\left(m\left(k+1\right)=m'\left|\mathcal{I}\left(k\right)=n\right.,\vartheta\left(k\right)=\vartheta,m\left(k\right)=m,\boldsymbol{\eta}\left(k\right)=\boldsymbol{\eta},\mathcal{I}\left(k+1\right)=n',\vartheta\left(k+1\right)=\vartheta',a\left(k\right)=a\right)\\
&\times\mathrm{P}\left(\boldsymbol{\eta}\left(k+1\right)=\boldsymbol{\eta}'\left|\mathcal{I}\left(k\right)=n\right.,\vartheta\left(k\right)=\vartheta,m\left(k\right)=m,\boldsymbol{\eta}\left(k\right)=\boldsymbol{\eta},\mathcal{I}\left(k+1\right)=n',\vartheta\left(k+1\right)=\vartheta',a\left(k\right)=a\right)
\end{aligned}\tag{4}$$

Given $\mathcal{I}\left(k+1\right)=n'$, $M\left(k+1\right)$ follows a binomial distribution with parameters $M_{n'}$ and $\rho_{n'}$, i.e.,

$$\begin{aligned}
&\mathrm{P}\left(M\left(k+1\right)=M\left|\mathcal{I}\left(k+1\right)=n'\right.\right)\\
=&\left(\begin{array}{c}M_{n'}\\M\end{array}\right)\rho_{n'}^{M}\left(1-\rho_{n'}\right)^{M_{n'}-M},\\
&0\le M\le M_{n'}.
\end{aligned}\tag{7}$$

θ is the summation of m_i's. In practice, the SSP can learn the distributions of m_i's by gathering corresponding statistics. Since such distributions are currently not available and the number of bands required to handle a data block is closely related to its size, we assume that m_i follows a truncated Poisson distribution with parameter λ to facilitate the data routing policy design [25], i.e.,

$$\mathrm{P}\left(m_i=m\right)=\left\{\begin{array}{cc}\frac{\lambda^m}{1-e^{-\lambda}}\frac{e^{-\lambda}}{m!} & m\ge 1\\ 0 & m=0\end{array}\right..\tag{8}$$

Then, θ is the summation of $\sum\limits_{\upsilon\in V}\beta_{n'}^{\upsilon}$ random variables with the distribution shown in (8). Since $\beta_{n'}^{\upsilon}$'s are Poisson random variables, $\sum\limits_{\upsilon\in V}\beta_{n'}^{\upsilon}$ is a Poisson random variable with mean $\Lambda=\sum\limits_{\upsilon\in V}\lambda_{n'}^{\upsilon}p_{n'}^{\upsilon}$. Based on the formula of total probability, the distribution of θ can be expressed as

$$\begin{aligned}
&\mathrm{P}\left(\theta=\ell\left|\mathcal{I}\left(k+1\right)=n'\right.\right)\\
=&\left\{\begin{array}{cc}\sum\limits_{l=1}^{\infty}\frac{e^{-\Lambda}\Lambda^l}{l!}\mathrm{P}\left(\sum\limits_{i=1}^{l}m_i=\ell\right) & \ell\ge 1\\ e^{-\Lambda} & \ell=0\end{array}\right..
\end{aligned}\tag{9}$$

To facilitate the derivation of $\mathrm{P}\left(\theta=\ell\left|\mathcal{I}\left(k+1\right)=n'\right.\right)$, the distribution of $\iota=\sum\limits_{i=1}^{l}m_i$, the sum of l independently identically distributed (i.i.d.) random variables with distribution functions shown in (8), is obtained in the following lemma.

Lemma 1 *The distribution of* ι *is*

$$\mathrm{P}\left(\iota=\ell\right)=\frac{\lambda^{\ell}e^{-l\lambda}}{\ell!\left(1-e^{-\lambda}\right)^l}\sum_{i=0}^{l}\left(\begin{array}{c}l\\i\end{array}\right)\left(-1\right)^{l-i}i^{\ell}\tag{10}$$

Proof: Noticing that $\mathrm{P}\left(\iota=\ell\right)$'s are probability mass functions and $0\le\mathrm{P}\left(\iota=\ell\right)\le 1$, the series $\sum\limits_{\ell=-\infty}^{\infty}\mathrm{P}\left(\iota=\ell\right)z^{\ell}$ uniformly converges in the disc $|z|<1$ on the complex plane, where $z\in\mathbb{C}$ is a complex number [26]. Then, with the probability mass function of ι, we can define an analytic function in the disc $\{z\in\mathbb{C}\,||z|<1\}$ as

$$\begin{aligned}
X_{\iota}\left(z\right)=&\sum_{\ell=-\infty}^{\infty}\mathrm{P}\left(\iota=\ell\right)z^{\ell}=\mathrm{E}\left[z^{\iota}\right]\\
=&\mathrm{E}\left[z^{\sum\limits_{i=1}^{l}m_i}\right]=\prod_{i=1}^{l}\mathrm{E}\left[z^{m_i}\right],|z|<1.
\end{aligned}\tag{11}$$

With (8), we have

$$\begin{aligned}
\mathrm{E}\left[z^{m_i}\right]=&\frac{1}{1-e^{-\lambda}}\sum_{\ell=1}^{\infty}\frac{e^{-\lambda}\lambda^{\ell}}{\ell!}z^{\ell}\\
=&\frac{e^{-\lambda+\lambda z}}{1-e^{-\lambda}}\sum_{\ell=1}^{\infty}\frac{\left(\lambda z\right)^{\ell}}{\ell!}e^{-\lambda z}\\
=&\frac{e^{-\lambda}\left(e^{\lambda z}-1\right)}{1-e^{-\lambda}}.
\end{aligned}\tag{12}$$

Plugging (12) into (11), it follows

$$\begin{aligned}
X_{\iota}\left(z\right)=&\frac{e^{-l\lambda}\left(e^{\lambda z}-1\right)^l}{\left(1-e^{-\lambda}\right)^l}\\
=&\frac{e^{-l\lambda}}{\left(1-e^{-\lambda}\right)^l}\sum_{i=0}^{l}\left(\begin{array}{c}l\\i\end{array}\right)\left(-1\right)^{l-i}e^{i\lambda z},|z|<1.
\end{aligned}\tag{13}$$

With Cauchy's Integral Formula for Derivatives, $\mathrm{P}\left(\iota=\ell\right)$ can be rewritten as [26]

$$\begin{aligned}
\mathrm{P}\left(\iota=\ell\right)=&\frac{1}{2\pi\mathrm{i}}\oint\limits_{\Gamma}\frac{X_{\iota}\left(z\right)}{z^{\ell+1}}dz\\
=&\frac{e^{-l\lambda}}{\left(1-e^{-\lambda}\right)^l}\sum_{i=0}^{l}\left(\begin{array}{c}l\\i\end{array}\right)\left(-1\right)^{l-i}\frac{1}{2\pi\mathrm{i}}\oint\limits_{\Gamma}\frac{e^{i\lambda z}}{z^{\ell+1}}dz,
\end{aligned}\tag{14}$$

where $\mathrm{i}=\sqrt{-1}$, Γ is a circle centered at the origin followed the anticlockwise direction with radius less than 1. Clearly, $e^{i\lambda z}$ is analytic in the disc $\{z\in\mathbb{C}\,||z|<1\}$. Thus, $e^{i\lambda z}/z^{\ell+1}$ has a pole of order $\ell+1$ at 0. Following from the Residue

Theorem, (14) can be reformulated as [26]

$$\mathrm{P}(\iota=\ell)=\frac{e^{-l\lambda}}{(1-e^{-\lambda})^l}\sum_{i=0}^{l}\binom{l}{i}(-1)^{l-i}\mathrm{res}\left(\frac{e^{i\lambda z}}{z^{\ell+1}},0\right), \tag{15}$$

where res $\left(e^{i\lambda z}/z^{\ell+1},0\right)$ is the residue of $e^{i\lambda z}/z^{\ell+1}$ at 0. By definition of the residue, we have

$$\mathrm{res}\left(\frac{e^{i\lambda z}}{z^{\ell+1}},0\right)=\frac{1}{\ell!}\lim_{z\to 0}\frac{d^\ell}{dz^\ell}e^{i\lambda z}=\frac{1}{\ell!}(i\lambda)^\ell. \tag{16}$$

With (15) and (16), $\mathrm{P}(\iota=\ell)$ can be derived as shown in (10). ■

Remark: According to 0.154 in [27], we have

$$\begin{aligned}\sum_{i=0}^{l}\binom{l}{i}(-1)^{l-i}i^\ell =&(-1)^l\sum_{i=0}^{l}\binom{l}{i}(-1)^{i}i^\ell\\ =&0, \forall l\geq \ell+1.\end{aligned} \tag{17}$$

This result matches our intuition that $\ell\geq l$, i.e., the simultaneous transmissions of l data blocks require at least l harvested bands. With (17), $\mathrm{P}(\iota=\ell)$ can be reformulated as

$$\begin{aligned}&\mathrm{P}(\iota=\ell)\\ &=\begin{cases}\frac{\lambda^\ell e^{-l\lambda}}{\ell!(1-e^{-\lambda})^l}\sum\limits_{i=0}^{l}\binom{l}{i}(-1)^{l-i}i^\ell & \ell\geq l\\ 0 & Otherwise\end{cases}.\end{aligned} \tag{18}$$

With Lemma 1, $\mathrm{P}(\theta=\ell\,|\mathcal{I}(k+1)=n')$ can be derived in the following theorem.

Theorem 1 *The distribution of θ is*

$$\begin{aligned}&\mathrm{P}(\theta=\ell\,|\mathcal{I}(k+1)=n')\\ &=\begin{cases}\frac{e^{-\Lambda}\lambda^\ell}{\ell!}\sum\limits_{l=1}^{\ell}\sum\limits_{i=0}^{l}\frac{(-1)^{l-i}\Lambda^l i^\ell}{(l-i)!i!(e^\lambda-1)^l} & \ell\geq 1\\ e^{-\Lambda} & \ell=0\end{cases}.\end{aligned} \tag{19}$$

Proof: The distribution of θ directly follows from (9) and (18). ■

From (6), the conditional distribution of $m(k+1)$ given $\mathcal{I}(k+1)=n'$ can be expressed as shown in (20). With (19) and (20), we have (21). When $\{m=0,M=0\}$, $\{m=M,M\geq 1\}$, and $\{m=0,M=1\}$, the conditional probability in (21) equals 1, $e^{-\Lambda}$, and $1-e^{-\Lambda}$, respectively. Plugging (7) and (21) into (20), ϕ_1 can be finally obtained.

By definition, ϕ_2 is the conditional distribution of $\boldsymbol{\eta}'=\begin{bmatrix}\eta_N & \eta_S & \eta_W & \eta_E\end{bmatrix}^{\mathrm{T}}$ given $\mathcal{I}(k+1)=n'$ and thus can be derived as

$$\begin{aligned}\phi_2=\prod_{\upsilon\in\{N,S,W,E\}}&\left\{(1-\eta'_\upsilon)\,e^{-\lambda^\upsilon_{n'}\left(1-p^\upsilon_{n'}\right)}\right.\\ &\left.+\eta'_\upsilon\left(1-e^{-\lambda^\upsilon_{n'}\left(1-p^\upsilon_{n'}\right)}\right)\right\}.\end{aligned} \tag{22}$$

Plugging the expressions for ϕ_1 and ϕ_2 back to (5), ϕ can be finally derived.

D. Derivation of φ

Considering the constraint on road layout, if the data-carrying CRV moves towards the direction of ϑ' at the $(k+1)$th decision epoch, the n'th intersection must lie to the direction of ϑ' of the nth intersection. Namely, given ϑ', it must have $n'=n_{\vartheta'}$, which implies that $\varphi=0$ if $n'\neq n_{\vartheta'}$. Thus, in the following, we only focus on the case where $n'=n_{\vartheta'}$. In this case, φ can be reformulated as

$$\begin{aligned}\varphi=&\mathrm{P}(\mathcal{I}(k+1)=n_{\vartheta'},\vartheta(k+1)=\vartheta'\,|\mathcal{I}(k)=n\;,\\ &\vartheta(k)=\vartheta, m(k)=m, \boldsymbol{\eta}(k)=\boldsymbol{\eta}, a(k)=a).\end{aligned} \tag{23}$$

To obtain the expressions of φ, we need to consider the following cases.

1) $a=0$: In this case, the data-carrying CRV keeps the data block in its own storage and thus the data block moves to the intended intersection only when the data-carrying CRV turns to the corresponding direction. In view of this, φ, for the considered case, can be derived as shown in (24).

2) $a=\delta,\vartheta'\neq\delta$: When $a(k)=\delta$, the data-carrying CRV tries to deliver data to a potential relay traveling along the direction δ. In this case, $\vartheta'\neq\delta$ only when the transmission attempt fails, and ϑ' results from the turn of the data-carrying CRV. Thus, φ is the probability that the data transmission fails and the data-carrying CRV turns to the direction ϑ'. Let $\mathcal{F}$ be the event that the transmission of the considered data block fails, given $\mathcal{I}(k)=n$, $\vartheta(k)=\vartheta$, $m(k)=m$, $\eta(k)=\eta$, $a(k)=\delta$, and $\mathcal{T}_{\vartheta'}$ be the event that the data-carrying CRV turns to the direction ϑ', give $\mathcal{I}(k)=n$, $\vartheta(k)=\vartheta$, $m(k)=m$, $\eta(k)=\eta$, $a(k)=\delta$. Then, the event $\mathcal{I}(k+1)=n_{\vartheta'},\vartheta(k+1)=\vartheta'$ given $\mathcal{I}(k)=n$, $\vartheta(k)=\vartheta$, $m(k)=m$, $\eta(k)=\eta$, $a(k)=\delta$ is equivalent to $\mathcal{F}\cap\mathcal{T}_{\vartheta'}$. In view of this, we can rewrite φ through $\mathcal{F}$ and $\mathcal{T}_{\vartheta'}$ as

$$\varphi=\mathrm{P}(\mathcal{F}\cap\mathcal{T}_{\vartheta'}). \tag{25}$$

Noticing that the moving direction of the data-carrying CRV is independent of the transmission of the considered data block, it follows

$$\varphi=\mathrm{P}(\mathcal{F})\,\mathrm{P}(\mathcal{T}_{\vartheta'}). \tag{26}$$

As aforementioned, $a(k)=\delta$ implies that $\eta_\delta(k)=1$, $m(k)>0$. In this case, the transmission failure is caused by the lack of enough available spectrum resources to support the delivery of the considered data block. Without loss of generality, we assume that each harvested band has a bandwidth of w and transmissions on these harvested bands can achieve a spectral efficiency of c. Due to the uncertain activities of lincensed/unlicensed users, the duration where each harvested band can be utilized for transmissions subject to variations and thus is modeled by a random variable τ_j, where the subscript j represents the jth harvested band available to transfer the considered data block. Then, $\mathrm{P}(\mathcal{F})$ can be expressed as

$$\mathrm{P}(\mathcal{F})=\mathrm{P}\left(\sum_{j=1}^{m(k)}cw\times\min\{\tau_j,T\}<\Delta\right), \tag{27}$$

where $m(k)$ is the number of harvested bands available for transferring the considered data block of size Δ, T is the

$$\mathrm{P}\left(m\left(k+1\right)=m\left|\mathcal{I}\left(k+1\right)=n'\right.\right)=\sum_{M=0}^{M_{n'}}\left\{\mathrm{P}\left(\max\left\{M\left(k+1\right)-\theta,0\right\}=m\left|M\left(k+1\right)=M,\mathcal{I}\left(k+1\right)=n'\right.\right)\right.$$
$$\left.\times\,\mathrm{P}\left(M\left(k+1\right)=M\left|\mathcal{I}\left(k+1\right)=n'\right.\right)\right\}. \tag{20}$$

$$\begin{aligned}&\mathrm{P}\left(\max\left\{M\left(k+1\right)-\theta,0\right\}=m\left|M\left(k+1\right)=M,\mathcal{I}\left(k+1\right)=n'\right.\right)\\&=\left\{\begin{array}{cc}\mathrm{P}\left(\theta=M-m\left|\mathcal{I}\left(k+1\right)=n'\right.\right) & 1\le m<M, M\ge 1\\ \left(1-\sum\limits_{\ell=0}^{M-1}\mathrm{P}\left(\theta=\ell\left|\mathcal{I}\left(k+1\right)=n'\right.\right)\right) & m=0, M>1\end{array}\right.\\&=\left\{\begin{array}{cc}\frac{e^{-\Lambda}\lambda^{(M-m)}}{(M-m)!}\sum\limits_{l=1}^{M-m}\sum\limits_{i=0}^{l}\frac{(-1)^{l-i}\Lambda^{l}i^{M-m}}{(l-i)!i!(e^{\lambda}-1)^{l}} & 1\le m<M, M\ge 1\\ 1-e^{-\Lambda}-\sum\limits_{\ell=1}^{M-1}\frac{e^{-\Lambda}\lambda^{\ell}}{\ell!}\sum\limits_{l=1}^{\ell}\sum\limits_{i=0}^{l}\frac{(-1)^{l-i}\Lambda^{l}i^{\ell}}{(l-i)!i!(e^{\lambda}-1)^{l}} & m=0, M>1\end{array}\right..\end{aligned} \tag{21}$$

$$\varphi=\left\{\begin{array}{cc}p_1 & \{\vartheta=N,\vartheta'=N\}\cup\{\vartheta=S,\vartheta'=S\}\cup\{\vartheta=W,\vartheta'=W\}\cup\{\vartheta=E,\vartheta'=E\}\\ p_2 & \{\vartheta=N,\vartheta'=W\}\cup\{\vartheta=S,\vartheta'=E\}\cup\{\vartheta=W,\vartheta'=S\}\cup\{\vartheta=E,\vartheta'=N\}\\ p_3 & \{\vartheta=N,\vartheta'=E\}\cup\{\vartheta=S,\vartheta'=W\}\cup\{\vartheta=W,\vartheta'=N\}\cup\{\vartheta=E,\vartheta'=S\}\\ p_4 & \{\vartheta=N,\vartheta'=S\}\cup\{\vartheta=S,\vartheta'=N\}\cup\{\vartheta=W,\vartheta'=E\}\cup\{\vartheta=E,\vartheta'=W\}\end{array}\right. \tag{24}$$

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contact duration between two CRVs. The min operation in (27) implies that the data transmissions between two CRVs cannot last longer than the contact duration. Similar to [28], τ_j's are assumed to be i.i.d. exponential random variables with parameter λ_s. Then, $\mathrm{P}\left(\mathcal{F}\right)$ can be derived as shown in the following Theorem.

Theorem 2 *When $\frac{\Delta}{cw}>m\left(k\right)T$, $\mathrm{P}\left(\mathcal{F}\right)=1$. When $\frac{\Delta}{cw}\le m\left(k\right)T$, $\mathrm{P}\left(\mathcal{F}\right)$ can be derived in a closed-form as*

$$\begin{aligned}\mathrm{P}\left(\mathcal{F}\right)=&\sum_{j=0}^{\left\lfloor\frac{\Delta}{cw}/T\right\rfloor}\sum_{h=0}^{m(k)-j}\left\{\left(\begin{array}{c}m\left(k\right)\\ j\end{array}\right)\frac{m\left(k\right)-j}{\left(m\left(k\right)-j-h\right)!h!}\right.\\&\times\left(-1\right)^{h}e^{-j\lambda_sT-h\lambda_sT}\\&\left.\times\,\gamma\left(m\left(k\right)-j,\lambda_s\left(\frac{\Delta}{cw}-jT-hT\right)\right)\right\},\end{aligned} \tag{28}$$

where $\gamma\left(b,x\right)=\int\limits_0^x u^{b-1}e^{-u}du$ is the incomplete Gamma function defined in [27].

Proof: From (27), we have

$$\mathrm{P}\left(\mathcal{F}\right)=\mathrm{P}\left(\sum_{j=1}^{m(k)}\min\left\{\tau_j,T\right\}<\frac{\Delta}{cw}\right). \tag{29}$$

If $\frac{\Delta}{cw}>m\left(k\right)T$, $\mathrm{P}\left(\mathcal{F}\right)=1$. As a result, we will focus on the case where $\frac{\Delta}{cw}\le m\left(k\right)T$. Since τ_j's are i.i.d. exponential random variables, $\min\left\{\tau_j,T\right\}$ are i.i.d. with distribution

$$\mathrm{P}\left(\min\left\{\tau_j,T\right\}<t\right)=\left\{\begin{array}{cc}1-e^{-\lambda_st} & t<T\\ 1 & t\ge T\end{array}\right.. \tag{30}$$

$\mathrm{P}\left(\mathcal{F}\right)$ can be expressed based on (29) as

$$\begin{aligned}\mathrm{P}\left(\mathcal{F}\right)=&\sum_{j=0}^{\left\lfloor\frac{\Delta}{cw}/T\right\rfloor}\left\{\left(\begin{array}{c}m\left(k\right)\\ j\end{array}\right)e^{-j\lambda_sT}\left(1-e^{-\lambda_sT}\right)^{m(k)-j}\right.\\&\left.\times\underbrace{\mathrm{P}\left(\widehat{\tau}\left(m\left(k\right)-j\right)<\frac{\Delta}{cw}-jT\right)}_{\triangleq\psi}\right\},\end{aligned} \tag{31}$$

where $\lfloor.\rfloor$ is the floor function, $\widehat{\tau}\left(m\left(k\right)-j\right)$ is the sum of $m\left(k\right)-j$ i.i.d random variables with distribution shown in (30) given each of these variables is less than T. Since $\frac{\Delta}{cw}\le m\left(k\right)T$, $\left(\frac{\Delta}{cw}-jT\right)/T\le m\left(k\right)-j$. From [29], ψ can be derived as

$$\begin{aligned}\psi=&\left(\frac{1}{1-e^{-\lambda_sT}}\right)^{m(k)-j}\sum_{h=0}^{\left\lfloor\left(\frac{\Delta}{cw}-jT\right)/T\right\rfloor}\left\{\frac{m\left(k\right)-j}{\left(m\left(k\right)-j-h\right)!h!}\right.\\&\left.\times\left(-1\right)^{h}e^{-h\lambda_sT}\gamma\left(m\left(k\right)-j,\lambda_s\left(\frac{\Delta}{cw}-jT-hT\right)\right)\right\}.\end{aligned} \tag{32}$$

Plugging (32) into (31), $\mathrm{P}\left(\mathcal{F}\right)$ can be obtained as shown in Theorem 2. ■

By definition, $\mathrm{P}\left(\mathcal{T}_{\vartheta'}\right)$ is the same as in (24). Plugging (24) and (28) into (26), φ can finally be derived.

3) $a=\delta$, $\vartheta'=\delta$: There are two possible ways for the data block to be transferred to the intended direction δ. The first one is that the considered data block is successfully delivered to a potential relay traveling along δ. The other one is that the data transmission fails, but the data-carrying CRV turns to the right direction. The two events corresponding to these two possibilities are denoted as $\overline{\mathcal{F}}$ and $\mathcal{T}_{\mathcal{F},\delta}$, respectively. By definition, $\overline{\mathcal{F}}$ and $\mathcal{T}_{\mathcal{F},\delta}$ will not simultaneously happen. Then, it follows

$$\varphi = \mathrm{P}\left(\overline{\mathcal{F}} \cup \mathcal{T}_{\mathcal{F},\delta}\right) = \mathrm{P}\left(\overline{\mathcal{F}}\right) + \mathrm{P}\left(\mathcal{T}_{\mathcal{F},\delta}\right). \quad (33)$$

Since $a(k) = \delta$, we only need to focus on the case where $\eta_\delta(k) = 1$ and $m(k) > 0$. According to the definition of $\overline{\mathcal{F}}$, we have

$$\mathrm{P}\left(\overline{\mathcal{F}}\right) = \mathrm{P}\left(\sum_{j=1}^{m(k)} cw \times \min\{\tau_j, T\} \geq \Delta\right). \quad (34)$$

Clearly from (34), $\mathrm{P}\left(\overline{\mathcal{F}}\right) = 1 - \mathrm{P}(\mathcal{F})$ and thus can be obtained from Theorem 2.

By definition, $\mathcal{T}_{\mathcal{F},\delta} = \mathcal{F} \cap \mathcal{T}_\delta$, where $\mathcal{F}$ and $\mathcal{T}_\delta$ share the same definition as in (26). With the independence between $\mathcal{F}$ and $\mathcal{T}_\delta$, $\mathrm{P}(\mathcal{T}_{\mathcal{F},\delta})$ can be expressed as

$$\mathrm{P}(\mathcal{T}_{\mathcal{F},\delta}) = \mathrm{P}(\mathcal{F})\,\mathrm{P}(\mathcal{T}_\delta). \quad (35)$$

The expression for $\mathrm{P}(\mathcal{F})$ is the same as that derived in the case with $a(k) = \delta$ and $\vartheta' \neq \delta$. $\mathrm{P}(\mathcal{T}_\delta)$ is the same as φ shown in (24) with $\vartheta' = \delta$. Together with (33), (34), and (35), φ can be obtained accordingly.

With the results in IV.C and IV.D, the state transition probabilities can finally be obtained by plugging the expressions of ϕ and φ into (3).

E. Objective and Reward

As aforementioned, the SSP tries its best to deliver the considered data block to the intended destination in K decision epochs. To put in a mathematical way, the SSP should find a policy $g*$ which maximizes $\mathcal{R}(g) = \mathrm{E}\left[\sum_{k=1}^{K} R(s(k), s(k+1), a(k))\right]$, where $a(k)$'s are actions selected according to the policy g, $R(s(k), s(k+1), a(k))$ is the reward received from the kth decision epoch with

$$\begin{aligned} &R(s(k), s(k+1), a(k)) \\ &= \begin{cases} R & \mathcal{I}(k) \neq n^d, \mathcal{I}(k+1) = n^d, 1 \leq k \leq K \\ 0 & \quad\quad\quad Otherwise \end{cases}, \end{aligned} \quad (36)$$

where R is the reward obtained by successfully delivering the considered data block to the destination. From (36), obtaining $g* = \arg\max_g \{\mathcal{R}(g)\}$ is equivalent to finding a policy such that the probability that the considered data block is successfully delivered to the destination is maximized.

With the state transition probabilities and the reward function presented above, the SSP can obtain the data routing decisions to help CRVs select data forwarding actions by solving the formulated Markov decision process with dynamic programming [30].

V. Performance Evaluation

In this section, extensive simulation results are presented to evaluate the performance of the obtained data routing decisions and the effectiveness of the V-CCHN in data transportation.

A. Considered Scenarios & Parameter Settings

In this section, we consider a road network similar to that in Fig. 2, but, with 21 rows, the east-westward roads, and 21 columns, the north-southward roads. Intersection D locates at the same column as intersection S and is κ rows above intersection S. CRVs traverse each road segment in a time unit and the considered data block needs to be delivered in K times units. Since the first data routing decision will be made at intersection S, $\kappa \leq K$. Otherwise, it is impossible for the SSP to deliver the considered data block to intersection D after K decision epochs. If the considered data block is delivered to intersection D through K decision epochs or less, a reward of $R = 500$ will be received. The set $\overline{\Theta}$ is identified by the following procedure

1) Construct a graph with intersections as vertices and there is an edge between two vertices if the corresponding intersections are adjacent.
2) Calculate the length of the shortest paths from the vertex associated with intersection S to other vertices. $\mathcal{L}_v^S$ is the length of the shortest path to vertex v.
3) Calculate the length of the shortest paths from the vertex associated with intersection D to other vertices. $\mathcal{L}_v^D$ is the length of the shortest path to vertex v.
4) Include the intersection corresponding to vertex v to $\overline{\Theta}$ if $\mathcal{L}_v^S + \mathcal{L}_v^D > K$.

The set Θ consists of intersections other than those in $\overline{\Theta}$. The average numbers of potential relays at different intersections along different directions are 2, i.e., $\lambda_n^N = \lambda_n^S = \lambda_n^W = \lambda_n^E = 2$, $\forall n \in \Theta_{\mathcal{I}}$. Potential relays traveling along the different directions are occupied with the same probability p, i.e., $p_n^N = p_n^S = p_n^W = p_n^E = p$. At intersections, the data-carrying CRV will keep current direction, turn left, turn right, and turn around with probability, $p_1 = 0.36$, $p_2 = 0.3$, $p_3 = 0.3$, and $p_4 = 0.04$, respectively. λ in (8) is set to 0.5. At each decision epoch, each band is found to be available with probability ρ, i.e., $\rho_n = \rho$, $\forall n \in \Theta_{\mathcal{I}}$. If found available, a band will remain available for $7s$ on average, i.e., $\lambda_s = 7$. Each band has a bandwidth of $10MHz$. The links between the data-carrying CRVs and the relaying CRVs can achieve a spectral efficiency of $2bit/s/Hz$ and can last for $T = 10s$ at different intersections. When the considered data block arrives at intersection S, 3 harvested bands are available, and potential relays traveling along south, west, and east are available to receive this considered data block. The data-carrying CRV approaches intersection S from south. The following results are obtained from 10000 rounds of simulations.

B. Simulation Results and Discussions

In Fig. 3, we examine the impacts of Δ, the size of the considered data block, and the level of contention at intersections on the probability of successful delivery, i.e., the probability that the considered data block is delivered to the destination after $K = 9$ decision epochs. Intersection D is $\kappa = 5$ rows above intersection S. The level of contention at the intersections is represented by p, the probability that a potential relay is involved with the transmissions of previously arrived data blocks. The total number of bands

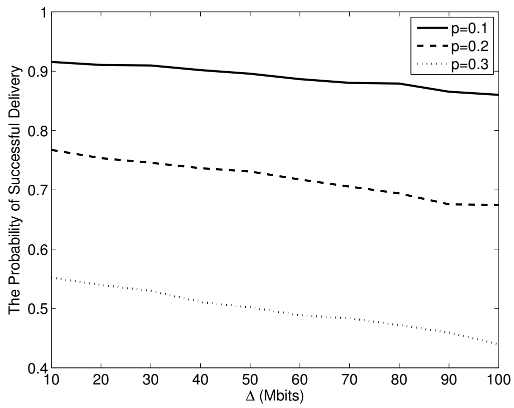

Fig. 3. The probability of successful delivery v.s. the size of the considered data block and the level of contention at each intersection.

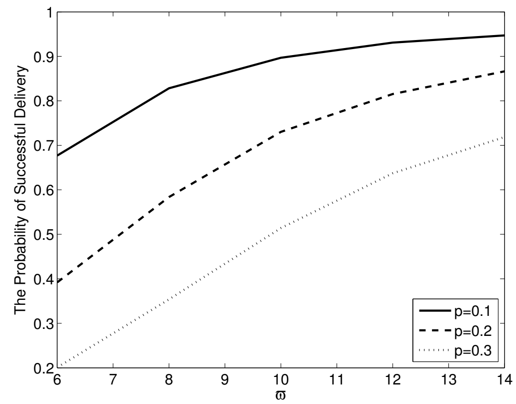

Fig. 4. The probability of successful delivery v.s. the number of frequency bands, ϖ.

is $M_n = 10$, $\forall n \in \Theta_{\mathcal{I}}$ and each band is available with probability $\rho = 0.5$. As shown in Fig. 3, the probability of successful delivery decreases with Δ. Under the same level of resource provisioning, it becomes more difficult for the data-carrying CRV to transfer the considered data block to a relaying CRV when the size of this data block increases. Due to the increase in Δ, the considered data block often cannot be routed to the designated directions, which leads to a decrease in the probability of successful delivery. Similarly, the probability of successful delivery decreases with p increasing, as shown in Fig. 3, since transferring the considered data block from the data-carrying CRV to the relaying CRV will get harder due to the higher level of contention at each intersection. Besides, it can be observed from Fig. 3 that considerable probability of successful delivery can be achieved if the SSP can provide enough resources to facilitate the transportation of the considered data block (the case when $p = 0.1$). This is just the reason why we propose to employ CR technologies in our V-CCHN to harvest the wide range of under-utilized spectrum resources. With enough resources acquired, our V-CCHN is certainly capable of providing the envisioned data transportation services. This observation can be further strengthened by the results as shown in Fig. 4.

In Fig. 4, we investigate how the probability of successful delivery varies with the number of frequency bands in the system. For illustration purpose, we set $M_n = \varpi$, $\forall n \in \Theta_{\mathcal{I}}$. The parameter settings are the same as those in Fig. 3, other than $\Delta = 50Mbits$. The results show that the SSP can achieve a higher probability of successful delivery if there are more frequency bands for it to employ. By comparing the results with different p, i.e., different levels of contention, it is clear that the SSP can effectively overcome the contention at intersections by utilizing under-utilized licensed/unlicensed bands via CR technologies. With enough spectrum resources, the considered data block is more likely to be transferred to desired directions. Thus, the SSP can more efficiently address the uncertainty in the mobility of CRVs and facilitate the envisioned data transportation services, which further validates our V-CCHN.

Fig. 5 presents how the activities of licensed/unlicensed users, signified by ρ, and the delay tolerance of the considered data block, represented by K, affect the probability of successful delivery. The parameter settings are the same as those in Fig. 4 and the only differences are $p = 0.1$ and $M_n = 10$, $\forall n \in \Theta_{\mathcal{I}}$. From Fig. 5, a higher value of ρ improves the probability of successful delivery. Since the bands will be found available with higher probability under a higher value of ρ, the SSP could acquire more available bands to enable the transferring of the considered data block to relaying CRVs. With more spectrum resources, the considered data block could be successfully delivered to the destination with a higher probability, as demonstrated in Fig. 4. Fig. 5 also indicates that the delay tolerance of the considered data block, K, has significant impacts on the probability of successful delivery. As shown in Fig. 3 and Fig. 4, the data delivery in the V-CCHN is subject to the impacts of the activities of licensed/unlicensed users and the mobility of CRVs, which introduces uncertainty to data routing at intersections. Because of these dynamics in the V-CCHN, the considered data block might not be delivered to the desired directions at some intersections. If the data block can tolerate longer delay, the SSP will have more opportunities to make corrections on the routing of this data block and be more capable of handling the dynamics inherent in the V-CCHN, which improves the probability of successful delivery. This is also the reason why the V-CCHN is targeted to handle delay-tolerant data traffic.

A similar conclusion can be drawn from Fig. 6 where the relationship between the probability of successful delivery and the distance between the source, intersection S, and the destination, intersection D, is presented. For ease of illustration, intersection D stays in the same column as intersection S, but, locates κ rows above intersection S. The parameter settings are the same as Fig. 3 other than $\rho = 0.5$ and $p = 0.1$. The results show that the probability of successful delivery decreases with κ increasing. Intuitively, the considered data block will travel a longer distance when κ increases. Once such distance gets longer, as aforementioned, more randomness will be introduced to the data delivery process due to the dynamics

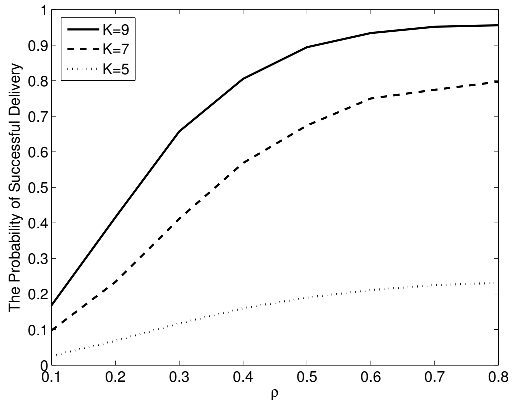

Fig. 5. The probability of successful delivery v.s. the activities of licensed/unlicensed users and the delay tolerance of the considered data block.

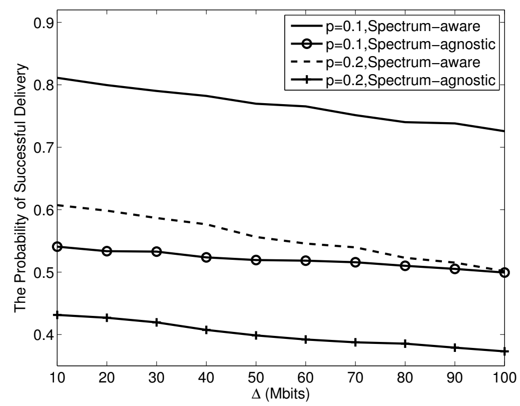

Fig. 7. The probability of successful delivery under the proposed scheme, labeled "Spectrum-aware", and the spectrum-agnostic approach, labeled "Spectrum-agnostic".

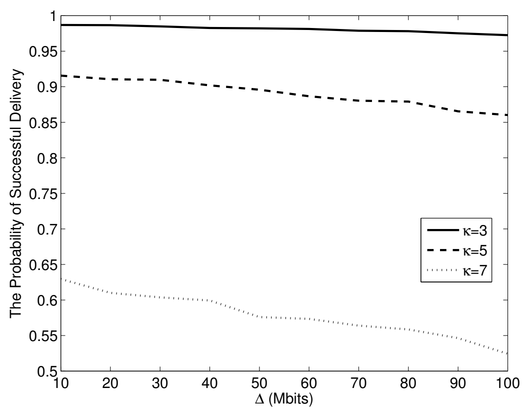

Fig. 6. The probability of successful delivery v.s. the distance between the source and the destination.

inherent in the V-CCHN. In this case, the SSP needs more rooms to deal with these dynamics/randomness and ensure successful delivery, as shown in Fig. 5. This explains why, in Fig. 6, the probability of successful delivery decreases as κ increases since the curves are obtained under the same level of delay tolerance. Combining the results in Fig. 5 and Fig. 6, we can conclude that the V-CCHN can effectively handle the transportation of delay-tolerant data traffic once the delivered data can tolerate long enough delays.

Finally, to evaluate the effectiveness of the proposed SA approach, we compare its data delivery performance with that of the spectrum-agnostic approach in Fig. 7. By the spectrum-agnostic approach, we refer to those data routing schemes where data is routed towards the directions along which the expected delivery delay is minimized without explicitly considering the impacts of spectrum availability and contention in data transmissions. From the discussions in Section II, the spectrum-agnostic approach encompasses the basic principle of how data routing decisions at intersections are made in existing works. To fit the spectrum-agnostic approach into the considered scenario, it is used for data routing decision making at intersections. Specifically, at each intersection, the data-carrying CRV chooses to transfer the considered block towards the direction which has potential relays and leads to the most significant improvement in the delivery delay when wireless communications are assumed to be perfect. Additionally, we consider the case where the transferring of the considered data block at intersections (x, y) ($x \in \{-1, -2\}$ and $y \in \{0, 1, 2\}$) always fails due to either the lack of available bands or severe contentions, where intersection $(-1, 1)$ is one row above the 0th row and one column to the right of the 0th column. The other parameters are the same as those in Fig. 3. It can be observed from Fig. 7 that our SA approach can significantly improve the probability of successful delivery when compared with the spectrum-agnostic approach. The superiority of our scheme is inherent in its spectrum-aware design which judiciously exploits information on contentions and the activities of licensed/unlicensed users to route data blocks in order to circumvent intersections lacking spectrum resources and facilitate efficiently data delivery. Thus, in contrast to the spectrum-agnostic approach, the proposed SA approach can more efficiently support the data transportation in the V-CCHN.

VI. Conclusion

In this paper, we design a spectrum-aware data transportation scheme for our recently proposed V-CCHN architecture by formulating the data delivery process as a Markov decision process. Through extensive simulations, we demonstrate that the obtained data transportation scheme can effectively utilize the spectrum opportunity and mobility opportunity in the V-CCHN for data transportation. This implies that, with properly designed data transportation schemes, our V-CCHN offers us a very promising alternative to handling the soaring wireless data traffic in the incoming era of smart cities. Thus, we hope this work will trigger more research activities and efforts to explore and further develop such an intelligent data transportation network.

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