Access Point Recruitment in a Vehicular Cognitive Capability Harvesting Network: How Much Data Can Be Uploaded?

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***Abstract*—To effectively deal with exploding traffic from emerging Internet of Things (IoT) and smart cities applications, we have recently designed a vehicular cognitive capability harvesting network (V-CCHN) architecture where a virtual service provider (VSP) coordinates vehicles equipped with powerful communication devices, namely cognitive radio routers, to help various end devices upload their data to data networks via deployed or recruited roadside access points (APs). To make the AP recruitment cost-effective, it is necessary for the VSP to learn what each AP can offer. Thus, in this paper, by modeling the vehicle arrival process as a Poisson process, we analyze the maximum long term upload throughput achieved with an AP. Due to the contention inside the coverage of the AP, the amount of data uploaded by each vehicle is correlated, which makes our analysis difficult. To address this challenge, we reformulate the considered problem as a renewal reward process which allows us to derive the closed-form expression for the maximum long term upload throughput. We validate our analytical results via extensive simulations, which can offer us useful insights on AP recruitment.**

***Index Terms*—Offloading, Internet of things (IoT), smart cities, vehicular networks, performance analysis.**

I. Introduction

Vehicular communications technologies have received a great impetus from both governments and industries, which leads to another research hype in vehicular networking [1], [2]. Existing works on vehicular networking primarily focus on the provisioning of safety, traffic efficiency, and infotaiment services within the framework of vehicular ad hoc networks (VANETs) or cellular networks [3]–[6]. To enable such service provisioning, these works address vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications under the assumption that vehicles are equipped with legacy interfaces, such as DSRC interfaces and cellular interfaces [3]–[5], [7]. Although some services can be supported to some extent, the existing spectrum bandwidth may not be enough to effectively address envisioned emerging intelligent services for future smart driving.

In our recent work, we take one step further and explore the possibility of offering services beyond the ones traditionally envisioned for vehicular networking by assuming that vehicles are equipped with powerful communication devices, called cognitive radio routers (CR routers), together with more powerful computing capability and large storage, and developing vehicular communications technologies accordingly [8], [9]. With these new capabilities, termed Communications, Computing, and Storage capabilities (or CCS capabilities), CR routers enable vehicles to opportunistically exploit a wide range of underutilized spectrum for high speed data exchange, which allows us to efficiently utilize the mobility of vehicles and the storage built in CR routers for data delivery. On the basis of the CR router enabled vehicles (CRVs)[1], we have developed a vehicular cognitive capability harvesting network (V-CCHN) architecture which complements current existing telecommunication networks in handling the exponentially increasing wireless traffic resulting from the development of the Internet of Things (IoT) and smart cities. In the V-CCHN, a virtual service provider (VSP) partially deploys infrastructure nodes, called CR capable roadside service units (CRSUs), to opportunistically utilize the traveling CRVs for resource harvesting and data collection/transportation. CR routers enable CRVs to collect data from IoT devices, such as sensors and surveillance cameras, using different types of radio interfaces, particularly when moving to their vicinities [10], [11]. Under the coordination of the VSP, a network of CRVs collectively transport the gathered data to intended places, exploiting delay-tolerant-networking (DTN) technologies, for data upload or data delivery. In such a way, our V-CCHN helps relieve congestion in cellular networks and transport high volume of delay-tolerant data traffic for cyber-physical systems (CPSs), which facilitates the development of applications for IoT and smart cities.

In the V-CCHN, data uploading from CRVs to data networks is primarily achieved through roadside infrastructure, such as CRSUs. Due to the variations in traffic distributions, the amount of data to be uploaded is also time-varying [12]. To flexibly and efficiently handle these varying uploading traffic, the VSP can deploy a certain number of CRSUs,

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[1]The CR router enabled vehicles refer to vehicles equipped with CR routers as their communication devices.

according to historical statistics and projections, for basic service provisioning, and take advantage of widely available roadside access points (APs) to deal with the variations in uploading traffic [13]–[15]. In this case, the VSP needs to facilitate service provisioning by recruiting APs from, for example, roadside restaurants and grocery stores which may trade their spare bandwidth for some kind of compensation and directing CRVs to upload data via these recruited APs [16], [17]. To make the AP recruitment process cost-effective, it is necessary for the VSP to know what each AP can offer. Since the total amount of data uploaded via an AP not only depends on the capabilities of the AP, but also relies on the number of CRVs on road and resource allocation at the corresponding AP, how to determine it is very challenging. To proceed, in this paper, we endeavor to analyze the maximum long term average upload throughput achieved with an AP, considering the recruitment of an AP can last for a certain period of time, which allows the total amount of uploaded data to be determined. Unlike existing works, we are interested in the aggregated upload throughput from a series of CRVs to an AP under the coordination of the VSP/CRSU. As a result, the steady state analysis developed in existing works are not directly applicable [18], [19]. Due to the limited capability of the AP as well as the scheduling of the VSP/CRSU, the amount of data uploaded by individual CRVs are correlated, which causes difficulties in our analysis. To address this challenge, we reformulate the considered problem as a renewal reward process and derive the maximum long term average upload throughput by obtaining the average values of the inter-renewal time and the associated reward. The effectiveness of our analysis is validated by simulation results and thus the presented analytical results offer us useful guidance on AP recruitment. Through extensive performance evaluation, we thoroughly investigate the impacts of the arrivals of CRVs and the capabilities of the AP on the maximum long term average upload throughput. The results demonstrate that considerable amount of data can be uploaded from CRVs to roadside APs, which further exemplifies our idea on the use of the V-CCHN.

The rest of this paper is organised as follows. Related works are reviewed in Section II. Our V-CCHN architecture is introduced in Section III together with discussions on AP recruitment. The system model and the derivation of the maximum long term average upload throughput is presented in Section IV and the performance evaluation are conducted in Section V. Finally, conclusions are drawn in Section VI.

II. Related Work

Data exchange between vehicles and roadside infrastructures is usually investigated under the drive-thru Internet. In [20], Zhuang et al. study the data uploading process from vehicles to roadside APs, employing IEEE 802.11 DCF as the MAC protocol. Under the assumption that the channel access processes of individual vehicles are regenerative, the average per-vehicle throughput and network throughput are derived. In [18], Luan et al. further consider the case where vehicles upload data to a series of APs located along the road. To facilitate the analysis, the mobility and the transmission status of vehicles are modeled as a three dimensional Markov chain. With the steady state probabilities of this Markov chain, the average per-vehicle and system throughput are obtained. Noticing that, in the V-CCHN, the channel access processes of CRVs are coordinated by the VSP/CRSUs, the regenerative and the steady-state assumption on frame transmissions might not be valid and thus these results cannot be directly applied to the scenario considered in this paper. Although a few works consider the coordinated data exchange between vehicles and roadside APs, they primarily focus on the average amount of data exchanged between an AP and a tagged vehicle [19], [21]. Noticing that, in this paper, we try to figure out the maximum achievable long term average upload throughput from a series of CRVs to an AP instead of the average amount of data exchanged between an AP and a tagged vehicle, new analysis should be developed, particularly considering the correlation among the amounts of data uploaded by individual CRVs.

III. The V-CCHN and AP Recruitment

As described in [8], the V-CCHN under consideration here consists of a VSP, CRVs, and CRSUs. The VSP is a wireless service provider, such as a cellular operator, who is willing to offer data services to IoT devices and various CPSs on the basis of newly emerging networking resources, traveling CRVs. The VSP has certain amount of its own reliable spectrum, called basic bands, to exchange control signaling with CRSUs and CRVs and gather necessary networking intelligence. Those basic bands can either be purchased or leased from spectrum owners. The CRSUs are partial infrastructure deployed by the VSP to help manage CRVs for service provisioning. Those CRSUs with wired connections to data networks not only offer CRVs access to data networks but also serve as agents for the VSP to coordinate the activities of CRVs and other CRSUs for capability harvesting and data transportation. The area covered by the control signaling of such a CRSU is called a cell. The CRSUs without wired connections to data networks are used to assist CRVs in data transportation by serving as, for example, temporary storage [17]. Both CRSUs and CRVs are equipped with CR routers, a powerful communication device integrated with agile communication interfaces, sufficient computing resources, and abundant storage space, which are more capable than the on-board units (OBUs) normally considered in existing VANETs [3], [6], [22]. CR routers can learn from the interactions of their surrounding environments and reconfigure their agile communication interfaces to interact with other devices using various wireless technologies and implement the functions of cognitive radios. With CR routers, CRVs can collect/deliver data from/to IoT devices when traveling in their vicinities without imposing excessive power consumption as well as constraints on their communication interfaces. By exploiting the storage built in CR routers, CRVs can carry the received data to intended places for delivery or upload.

A key design issue for the V-CCHN is how CRVs deliver their collected data to data networks. Generally, this is achieved through roadside infrastructure, such as CRSUs, with connections to data networks. Considering the spatial and temporal variations in uploading traffic distributions, simply relying on CRSU deployment might not be a cost-effective solution to supporting data uploading in the V-CCHN and may lead to inefficient resource utilization [23], [24]. Noticing that CR routers allow CRVs to interact with other devices using different communication interfaces, in view of the wide deployment of APs, the VSP can harvest available bandwidth from roadside APs to assist CRSUs in handling the varying uploading traffic with properly provisioned compensation. Specifically, the VSP can deploy CRSUs, based on historical statistics and projections, to provide basic services and recruit roadside APs from, for example, shops and restaurants, to deal with the variations in uploading traffic. To determine which APs to recruit, it is necessary for the VSP to know what each AP can offer, which motivates our analysis on the maximum long term average upload throughput achieved with an AP [25], [26].

IV. The Maximum Long Term Average Upload Throughput Offered by An AP

To facilitate analysis, we consider the scenario shown in Fig. 1 where CRVs arrive at the considered system from the left following a Poisson process with rate λ and move along the considered road segment at a constant speed v [27], [28][2]. From [31], for the simplicity of analysis, we can assume that the CRVs traveling along the road form a Poisson process with rate $\widetilde{\lambda} = \frac{\lambda}{v}$ and the inter-vehicle distances are independently identically exponentially distributed random variables with mean $\frac{1}{\widetilde{\lambda}} = \frac{v}{\lambda}$. We also assume that each CRV is equipped with one radio. The AP is able to simultaneously communicate with n CRVs. As mentioned in Section III, the data uploading from CRVs to the AP is coordinated by the CRSU which is in charge of the resource allocation within the corresponding cell, on behalf of the VSP. Thus, in the following, the uploading processes of CRVs are said to be coordinated by the VSP. Due to the coordination of the VSP, when scheduled, a CRV can upload data to the AP without interference from other CRVs. The AP has a circular coverage with radius $d/2$ within which a CRV can upload data to the AP at the rate of r when scheduled to transmit[3]. With this model, we evaluate the maximum long term average upload throughput achieved with the considered AP[4], denoted as Γ. Denoting the maximum amount of data uploaded through this AP during a period of T as $\Phi(T)$, it follows

$$\Gamma = \lim_{T\to\infty} \frac{\Phi(T)}{T}, \tag{1}$$

where $\Phi(T) = \sum_{k=1}^{N(T)} \tau_k$, $N(T)$ represents the number of CRVs which meet the AP during T, and τ_k is the amount of data

[2]Similar to [18], [21], we consider a scenario where the density of vehicles is relatively low. In this case, Poisson process is a reasonable model for the considered scenario and will not degrade the accuracy of our analytical results [29], [30].

[3]Similar to [19], [32], the coverage of the AP refers to the area where CRVs enjoy a high upload speed.

[4]In this paper, we employ the maximum long term average throughput to approximate the average upload throughput achieved during a specific period. Namely, we assume the vehicle arrival process is stationary during the considered period [27], [28]. The effectiveness of the adopted approximation will be evaluated in the simulation part.

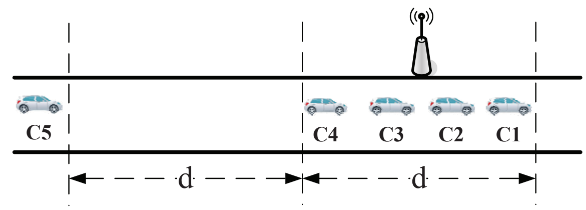

Fig. 1. The considered scenario.

uploaded from the kth CRV to the AP, which can be obtained as

$$\tau_k = r t_k, \tag{2}$$

where t_k is the duration of the transmission of the kth CRV and is determined by the scheduling strategy of the VSP. Clearly from (1), to derive Γ, we need to identify a scheduling strategy for the VSP so that the contacts between the AP and CRVs are fully exploited for data uploading and $\Phi(T)$ is achieved. In our analysis, we assume that the VSP schedules the CRVs which enter the coverage of the AP first until they leave the coverage. Clearly, for every scheduling resulting in $\Phi(T)$, the VSP can always recover the aforementioned scheduling by allocating as many channel access opportunities as possible to those CRVs that enter the coverage of the AP first. Since the purpose of our analysis is to find Γ, i.e., $\Phi(T)$, the aforementioned scheduling will be adopted in the following analysis.

Unfortunately, given the scheduling strategy of the VSP, it is still difficult to obtain Γ since t_k's are correlated random variables. According to the scheduling strategy of the VSP, t_k not only depends on the duration where the kth CRV stays under the coverage of the AP, but also relies on the inter-CRV distances. Consider the example shown in Fig. 1 where 5 CRVs move along the road and the AP can simultaneously communicate with 2 CRVs. Obviously, the VSP will schedule C4 only when C1 and C2 have moved out the coverage of the AP. Noticing that CRVs move at a speed of v, t_{C4} is closely related to the inter-vehicle distances between C1 and C2. Since inter-vehicle distances are random variables determined by the arrival process, t_{C4} is a random variable. On the other hand, t_{C3} and t_{C4} are correlated as both of them depends on the inter-vehicle distances between C2 and C3.

In this paper, we address the correlation among t_k's by observing that t_k will be independent of t_{k+i}, $i = 1, \cdots$, when the distance between the kth and the $(k+1)$th CRVs is larger than d, as shown in Fig. 1. This observation motivates us to model the considered data uploading process as a renewal reward process. Specifically, the arrival process of CRVs are considered as a renewal process where renewals occur when the inter-vehicle distance is larger than d, the coverage of the AP. The amount of data uploaded between a renewal and the next renewal is considered as the reward received from the corresponding renewal. From Theorem 3.6.1 in [33], we have

$$\Gamma = \frac{\mathrm{E}[\Phi(X)]}{\mathrm{E}[X]}, \tag{3}$$

where X is a random variable which represents the time between two consecutive renewals, and $\mathrm{E}[X]$ is the expectation

TABLE I
THE LIST OF IMPORTANT NOTATIONS AND DEFINITIONS.

Notation	Definition
λ	The arrival rate of CRVs
v	The speed of CRVs
d	The diameter of the AP coverage
r	The upload data rate of a CRV when scheduled
Γ	The maximum long term average upload throughput
τ_k	The amount of data uploaded from the kth CRV
$\Phi(T)$	The maximum amount of data uploaded through the considered AP during a period of T
t_k	The duration of the transmission of the kth CRV
y_k	The inter-vehicle distance between the $(k-1)$th and the kth CRVs

of X. In view of (3), $\mathrm{E}\left[\Phi\left(X\right)\right]$ and $\mathrm{E}\left[X\right]$ will be derived in the following analysis. The important notations used in this paper are summarized in Table I.

A. Derivation of $\mathrm{E}\left[\Phi\left(X\right)\right]$

By definition, we have

$$\mathrm{E}\left[\Phi\left(X\right)\right] = \sum_{j=1}^{\infty} \mathrm{P}\left(\delta_j\right) \mathrm{E}\left[\Phi\left(X\right)|\delta_j\right], \tag{4}$$

where δ_j is the event that $j+1$ CRVs, including the two at the renewals, arrives during the considered period X, $\mathrm{E}\left[\Phi\left(X\right)|\delta_j\right]$ is the amount of data uploaded during the period X given δ_j. For ease of presentation, these $j+1$ CRVs are indexed as $1,\cdots,j+1$ in the order of arrivals. Denote the inter-vehicle distances between the $(k-1)$th and the kth CRVs as y_k, $k\in\{2,\cdots,j+1\}$. Then, δ_j corresponds to the event where $y_2<d,\cdots,y_j<d, y_{j+1}\geq d$ and $\mathrm{P}\left(\delta_j\right)$ can be expressed as

$$\begin{aligned}\mathrm{P}\left(\delta_j\right) =& \mathrm{P}\left(y_2<d,\cdots,y_j<d,y_{j+1}\geq d\right)\\ \overset{(a)}{=}& \prod_{k=2}^{j} \mathrm{P}\left(y_k<d\right)\mathrm{P}\left(y_{j+1}\geq d\right)\\ \overset{(b)}{=}& \left(1-e^{-\widetilde{\lambda}d}\right)^{j-1} e^{-\widetilde{\lambda}d},\end{aligned} \tag{5}$$

where (a) and (b) follow from the fact that y_k's are independently identically exponentially distributed random variables. (5) implies that

$$\begin{aligned}\mathrm{P}\left(\delta_j\right) &= \left(1-e^{-\widetilde{\lambda}d}\right)\left(1-e^{-\widetilde{\lambda}d}\right)^{j-2} e^{-\widetilde{\lambda}d}\\ &= \left(1-e^{-\widetilde{\lambda}d}\right)\mathrm{P}\left(\delta_{j-1}\right), \forall j\geq 2.\end{aligned} \tag{6}$$

By definition, $\mathrm{E}\left[\Phi\left(X\right)|\delta_j\right]$ can be expressed as

$$\mathrm{E}\left[\Phi\left(X\right)|\delta_j\right] = \mathrm{E}\left[\sum_{k=1}^{j}\tau_k|\delta_j\right] = \sum_{k=1}^{j}\mathrm{E}\left[\tau_k|\delta_j\right], \tag{7}$$

For the first k ($k\leq n$) CRVs, they can upload data to the AP as long as they stay in the coverage. While, for other CRVs, they will be scheduled by the VSP only when the $(k-n)$th CRV moves out the coverage. For illustration purpose, consider the example in Fig. 1 which is redrawn in

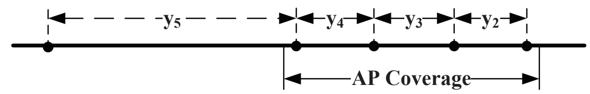

Fig. 2. The abstraction of Fig. 1.

Fig. 2 with CRVs represented by black spots and inter-vehicle distances labeled. Clearly, C1 and C2 can upload data to the AP as long as they stay in the coverage, whereas, C4 can upload data to the AP only when C1 and C2 moves out the coverage. As a result, t_{C1} and t_{C2} equal the durations where the corresponding CRVs stay in the coverage, and t_{C4} equals the duration between the time where C2 moves out of the coverage and that where C4 moves out of the coverage. In view of this observation, we have

$$\begin{aligned}&\mathrm{E}\left[\tau_k|\delta_j\right] = \mathrm{E}\left[rt_k|\delta_j\right]\\ &= \begin{cases} \frac{rd}{v} & k\leq n\\ \mathrm{E}\left[\frac{r\min\{y_k+y_{k-1}+\cdots+y_{k-n+1},d\}}{v}|\delta_j\right] & n<k\leq j\end{cases},\end{aligned} \tag{8}$$

where the min operation is applied since t_k's cannot be longer than the duration where CRVs stay in the coverage.

Notice that $y_2,\cdots,y_j$ are independently identically distributed (i.i.d.) random variables and δ_j corresponds to the event where $y_2<d,\cdots,y_j<d,y_{j+1}\geq d$. Given δ_j, y_k's ($k=2,\cdots,j$) are still independent of each other and follow a truncated exponential distribution with the probability density function (PDF) as

$$f_{y_k|\delta_j}\left(y\right) = \widetilde{f}\left(y\right) = \begin{cases}\frac{\widetilde{\lambda}e^{-\widetilde{\lambda}y}}{1-e^{-\widetilde{\lambda}d}} & 0\leq y<d\\ 0 & \text{Otherwise}\end{cases}. \tag{9}$$

Together with (8), we have

$$\mathrm{E}\left[\tau_k|\delta_j\right] = \overline{\tau} = \mathrm{E}\left[\frac{r\min\left\{Y_n,d\right\}}{v}\right], n<k\leq j, \tag{10}$$

where Y_n is the sum of n i.i.d. random variable with the PDF shown in (9).

From (5), (7), (8), and (10), (4) can be reformulated as

$$\begin{aligned}\mathrm{E}\left[\Phi\left(X\right)\right] =& \underbrace{\sum_{j=n+1}^{\infty}\mathrm{P}\left(\delta_j\right)\left(n\frac{rd}{v}+(j-n)\overline{\tau}\right)}_{\triangleq\mathcal{K}}\\ &+\sum_{j=1}^{n}\mathrm{P}\left(\delta_j\right)j\frac{rd}{v}.\end{aligned} \tag{11}$$

From (11), $\mathcal{K}$ can be rewritten as

$$\begin{aligned}\mathcal{K} =& \sum_{j=n+2}^{\infty}\mathrm{P}\left(\delta_j\right)\left(n\frac{rd}{v}+(j-n)\overline{\tau}\right)\\ &+\mathrm{P}\left(\delta_{n+1}\right)\left(n\frac{rd}{v}+\overline{\tau}\right).\end{aligned} \tag{12}$$

With (6), it follows

$$\begin{aligned}\mathcal{K} =&\mathrm{P}\left(\delta_{n+1}\right)\left(n\frac{rd}{v}+\overline{\tau}\right)+\left(1-e^{-\widetilde{\lambda}d}\right)\\&\times\sum_{j=n+2}^{\infty}\mathrm{P}\left(\delta_{j-1}\right)\left(n\frac{rd}{v}+(j-n)\overline{\tau}\right)\\=&\mathrm{P}\left(\delta_{n+1}\right)\left(n\frac{rd}{v}+\overline{\tau}\right)+\left(1-e^{-\widetilde{\lambda}d}\right)\sum_{i=n+1}^{\infty}\mathrm{P}\left(\delta_{i}\right)\overline{\tau}\\&+\left(1-e^{-\widetilde{\lambda}d}\right)\sum_{i=n+1}^{\infty}\mathrm{P}\left(\delta_{i}\right)\left(n\frac{rd}{v}+(i-n)\overline{\tau}\right)\\=&\mathrm{P}\left(\delta_{n+1}\right)\left(n\frac{rd}{v}+\overline{\tau}\right)+\left(1-e^{-\widetilde{\lambda}d}\right)\sum_{i=n+1}^{\infty}\mathrm{P}\left(\delta_{i}\right)\overline{\tau}\\&+\left(1-e^{-\widetilde{\lambda}d}\right)\mathcal{K}.\end{aligned}\tag{13}$$

Then, $\mathcal{K}$ can be derived as

$$\begin{aligned}\mathcal{K} =&e^{\widetilde{\lambda}d}\mathrm{P}\left(\delta_{n+1}\right)\left(n\frac{rd}{v}+\overline{\tau}\right)+\left(e^{\widetilde{\lambda}d}-1\right)\overline{\tau}\sum_{i=n+1}^{\infty}\mathrm{P}\left(\delta_{i}\right)\\=&e^{\widetilde{\lambda}d}\mathrm{P}\left(\delta_{n+1}\right)\left(n\frac{rd}{v}+\overline{\tau}\right)+\left(1-e^{-\widetilde{\lambda}d}\right)\overline{\tau}\\&\times\sum_{i=n+1}^{\infty}\left(1-e^{-\widetilde{\lambda}d}\right)^{i-1}\\=&\left(1-e^{-\widetilde{\lambda}d}\right)^{n}\left(n\frac{rd}{v}+\overline{\tau}\right)+\overline{\tau}e^{\widetilde{\lambda}d}\left(1-e^{-\widetilde{\lambda}d}\right)^{n+1}\\=&\left(1-e^{-\widetilde{\lambda}d}\right)^{n}\left(n\frac{rd}{v}+e^{\widetilde{\lambda}d}\overline{\tau}\right).\end{aligned}\tag{14}$$

Clearly from (14), we can obtain $\mathcal{K}$ and thus $\mathrm{E}\left[\Phi\left(X\right)\right]$ once $\overline{\tau}$ is derived. To facilitate the derivation of $\overline{\tau}$, we need to identify the distribution of Y_n. According to [33], Y_n has a PDF which can be expressed as

$$f_{Y_n}\left(y\right)=\underbrace{\widetilde{f}*\cdots*\widetilde{f}}_{n}\left(y\right),\tag{15}$$

where $*$ denotes the convolution operation and $\widetilde{f}\left(y\right)$ is defined in (10). With (15) and (10), it can be proved that $f_{Y_n}\left(y\right)$ satisfy the Dirichlet condition and thus has a Fourier transform, which allows $f_{Y_n}\left(y\right)$ to be derived as shown in the following lemma [34].

Lemma 1 *The PDF of* Y_n *is*

$$\begin{aligned}f_{Y_n}\left(y\right)=&e^{-\widetilde{\lambda}y}\left(\frac{\widetilde{\lambda}}{1-e^{-\widetilde{\lambda}d}}\right)^{n}\sum_{i=0}^{n}\left\{\frac{n}{(n-i)!i!}(-1)^{i}\right.\\&\left.\times\left(y-id\right)^{n-1}u\left(y-id\right)\right\},\end{aligned}\tag{16}$$

where $u\left(y\right)$ *is the unit step function defined in [34].*

Proof: With (15), the Fourier transform of $f_{Y_n}\left(y\right)$ can be derived via the convolution property of the Fourier transform as

$$\mathcal{F}_{f_{Y_n}}\left(\omega\right)=\mathcal{F}_{\widetilde{f}}^{n}\left(\omega\right),\tag{17}$$

where $\mathcal{F}_{\widetilde{f}}\left(\omega\right)$ is the Fourier transform of $\widetilde{f}\left(y\right)$. From (9), $\mathcal{F}_{\widetilde{f}}\left(\omega\right)$ can be obtained as

$$\begin{aligned}\mathcal{F}_{\widetilde{f}}\left(\omega\right)=&\int_{-\infty}^{\infty}\widetilde{f}\left(y\right)e^{-\mathrm{j}\omega y}dy=\int_{0}^{d}\frac{\widetilde{\lambda}e^{-\widetilde{\lambda}y}}{1-e^{-\widetilde{\lambda}d}}e^{-\mathrm{j}\omega y}dy\\=&\frac{\widetilde{\lambda}}{\widetilde{\lambda}+\mathrm{j}\omega}\frac{\left(1-e^{-\left(\widetilde{\lambda}+\mathrm{j}\omega\right)d}\right)}{1-e^{-\widetilde{\lambda}d}},\end{aligned}\tag{18}$$

where $\mathrm{j}=\sqrt{-1}$. Then, $\mathcal{F}_{f_{Y_n}}\left(\omega\right)$ can be expressed as

$$\begin{aligned}\mathcal{F}_{f_{Y_n}}\left(\omega\right)=&\left(\frac{\widetilde{\lambda}}{\widetilde{\lambda}+\mathrm{j}\omega}\right)^{n}\left(\frac{1-e^{-\left(\widetilde{\lambda}+\mathrm{j}\omega\right)d}}{1-e^{-\widetilde{\lambda}d}}\right)^{n}\\=&\sum_{i=0}^{n}\left(\begin{array}{c}n\\i\end{array}\right)(-1)^{i}\left(\frac{\widetilde{\lambda}}{\widetilde{\lambda}+\mathrm{j}\omega}\right)^{n}\frac{e^{-i\left(\widetilde{\lambda}+\mathrm{j}\omega\right)d}}{\left(1-e^{-\widetilde{\lambda}d}\right)^{n}}.\end{aligned}\tag{19}$$

Following from [34], we can recover $f_{Y_n}\left(y\right)$ from $\mathcal{F}_{f_{Y_n}}\left(\omega\right)$ through the inverse Fourier transform. The result is shown in (16). This completes the proof .

With 0.154 in [35], it can be proved that $f_{Y_n}\left(y\right)$ equals 0 when $y>nd$, which matches our intuition. As shown in Appendix A, $\overline{\tau}$ can be derived from (10) as

$$\begin{aligned}\overline{\tau}=&\frac{r}{v\widetilde{\lambda}}\left(\frac{1}{1-e^{-\widetilde{\lambda}d}}\right)^{n}\frac{1}{(n-1)!}\gamma\left(n+1,\widetilde{\lambda}d\right)\\&+\frac{rd}{v}\left(\frac{1}{1-e^{-\widetilde{\lambda}d}}\right)^{n}\frac{1}{(n-1)!}\Gamma\left(n,\widetilde{\lambda}d\right)\\&+\frac{rd}{v}\left(\frac{1}{1-e^{-\widetilde{\lambda}d}}\right)^{n}\sum_{i=1}^{n}\frac{n}{(n-i)!i!}(-1)^{i}e^{-\widetilde{\lambda}id}\Gamma\left(n\right),\end{aligned}\tag{20}$$

where $\gamma\left(.,.\right)$ and $\Gamma\left(.,.\right)$ are the incomplete Gamma functions defined in [35], and $\Gamma\left(.\right)$ is the Gamma function defined in [35]. With (11), (14), and (20), $\mathrm{E}\left[\Phi\left(X\right)\right]$ can be derived accordingly.

B. Derivation of $\mathrm{E}\left[X\right]$

By definition, X is the time elapsed between two consecutive renewals. Similarly to (4), we have

$$\mathrm{E}\left[X\right]=\sum_{j=1}^{\infty}\mathrm{P}\left(\delta_{j}\right)\mathrm{E}\left[X\left|\delta_{j}\right.\right],\tag{21}$$

where $\mathrm{E}\left[X\left|\delta_{j}\right.\right]$ is the average inter-renewal time given $j+1$ CRVs, including the two at the renewals, arriving during X. Denote the inter-arrival time between the $(k-1)$th and kth CRV as η_k, $k=2,\cdots,j+1$. Then, $\mathrm{E}\left[X\left|\delta_{j}\right.\right]$ can be expressed as

$$\mathrm{E}\left[X\left|\delta_{j}\right.\right]=\sum_{k=2}^{j+1}\mathrm{E}\left[\eta_{k}\left|\delta_{j}\right.\right].\tag{22}$$

As aforementioned, for the considered renewal process, a renewal occurs when the distance between two consecutive CRVs is larger than d. Namely, a renewal occurs when the inter-arrival time between two consecutive CRVs is longer than

$\frac{d}{v}$. Thus, δ_j also represents the event where $\eta_2 < \frac{d}{v}, \cdots, \eta_j < \frac{d}{v}, \eta_{j+1} \geq \frac{d}{v}$. Following the same argument for (9), $\eta_2, \cdots, \eta_j$ are i.i.d. with the PDF

$$f_{\eta_k|\delta_j}(\eta) = \begin{cases} \frac{\lambda e^{-\lambda\eta}}{1-e^{-\lambda d/v}} & 0 \leq \eta < d/v \\ 0 & \text{Otherwise} \end{cases}, k = 2, \cdots, j. \quad (23)$$

While η_{j+1} has the PDF

$$f_{\eta_{j+1}|\delta_j}(\eta) = \begin{cases} \lambda e^{-\lambda(\eta - d/v)} & \eta \geq d/v \\ 0 & \text{Otherwise} \end{cases}. \quad (24)$$

From (23) and (24), it follows

$$\mathrm{E}[\eta_k |\delta_j] = \begin{cases} \frac{1/\lambda - e^{-\lambda d/v}/\lambda - de^{-\lambda d/v}/v}{1-e^{-\lambda d/v}} & k = 2, \cdots, j \\ \frac{1}{\lambda} + \frac{d}{v} & k = j+1 \end{cases}. \quad (25)$$

Then, $\mathrm{E}[X|\delta_j]$ can be derived as

$$\mathrm{E}[X|\delta_j] = (j-1)\frac{1/\lambda - e^{-\lambda d/v}/\lambda - de^{-\lambda d/v}/v}{1-e^{-\lambda d/v}} + \frac{1}{\lambda} + \frac{d}{v}. \quad (26)$$

By plugging (26) into (21) and applying the same technique as in Section IV.A, $\mathrm{E}[X]$ can be finally derived as

$$\mathrm{E}[X] = \frac{1}{\lambda} e^{\frac{\lambda d}{v}}. \quad (27)$$

With the expressions for $\mathrm{E}[\Phi(X)]$ and $\mathrm{E}[X]$, Γ can be derived through (3).

V. Performance Evaluation

In this section, we will verify the effectiveness of our analytical results by comparing it with simulation results. Then, the impacts of the arrivals of CRVs and the capabilities of the AP on the long term average upload throughput are thoroughly discussed.

The relationship between the maximum long term average upload throughput, Γ, and the data rate offered by the AP, r, is shown in Fig. 3. The AP has a circular coverage with radius $d/2 = 50m$ and can simultaneously communicate with $n = 2$ CRVs [32]. The speed of CRVs v is set to $10m/s$ [30]. For simulation, we consider a duration of 2 hours during which CRVs, traveling at speed $10m/s$, arrive at our system according to a Poisson process with rate shown in Fig. 3. The simulation results shown in Fig. 3 are obtained by calculating the average throughput achieved during these 2 hours. As shown in Fig. 3, the simulation results match well with the analytical results, which not only validates our analytical results, but also demonstrates the effectiveness of our analysis for the long term average upload throughput. It can be observed from Fig. 3 that the value of Γ can be significantly improved with r increasing. Likewise, a larger λ can also lead to a higher Γ. Notice that Γ is the achievable upload throughput from CRVs to the AP. A larger λ implies that more CRVs pass by the coverage of the AP, which creates more opportunities for data uploading and thus results in an improvement in Γ.

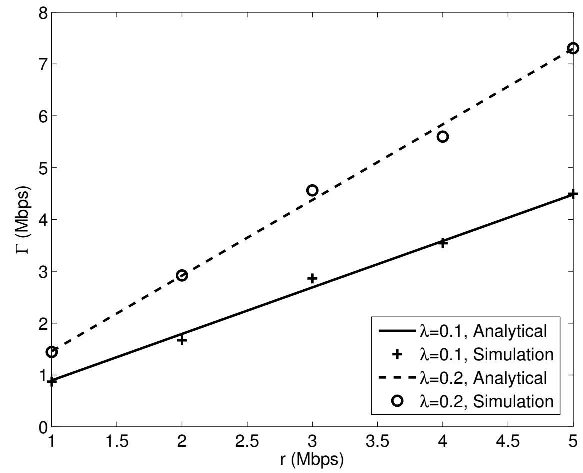

Fig. 3. The relationship between the maximum long term average upload throughput, Γ, and the data rate offered by the AP, r.

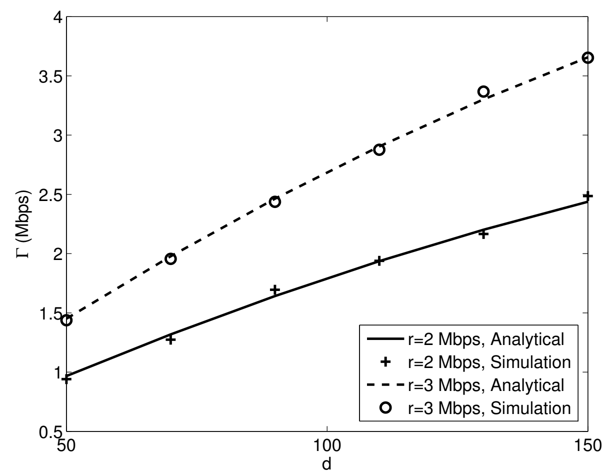

Fig. 4. The relationship between the maximum long term average upload throughput, Γ, and the coverage of the AP with radius $\frac{d}{2}$.

In Fig. 4, we investigate the impacts of the coverage of the AP, represented by d, on Γ. The parameters settings are the same as Fig. 3. The only difference is that λ is set to be 0.1. Clearly from Fig. 4, a larger coverage will lead to a higher Γ, which is due to the increased contact period between CRVs and the AP. This also explains why the gap between the two curves shown in Fig. 4 enlarges as d increasing.

How Γ varies with n, the number of CRVs simultaneously handled at the AP, is studied in Fig. 5. The parameter settings are the same as those in Fig. 3. The only difference is r is set to $3Mbps$. From Fig. 5, Γ first increases with n and approaches a plateau once n reaches a certain value. As the AP gets more powerful, more CRVs can be simultaneously handled, which explains the initial improvement of Γ. Once the AP becomes powerful enough, Γ is limited by the contact opportunities between CRVs and the AP. This can be observed from Fig. 5 where Γ almost stops increasing after $n = 3$ when $\lambda =$

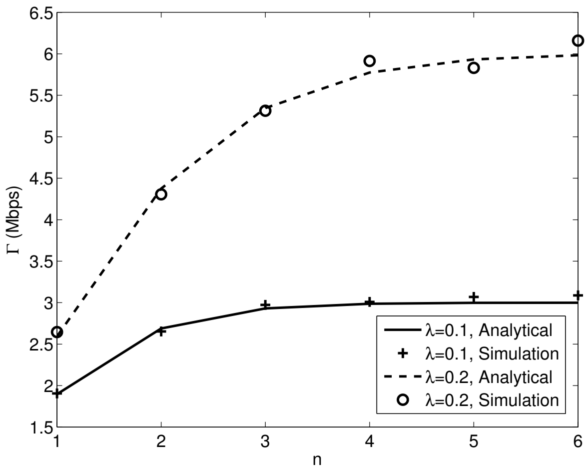

Fig. 5. The relationship between the maximum long term average upload throughput, Γ, and the number of CRVs simultaneously handled at the AP, n.

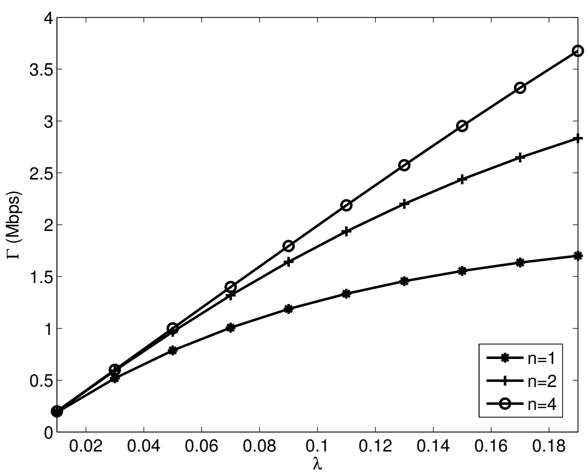

Fig. 6. The relationship between the maximum long term average upload throughput, Γ, and the arrival rate of CRVs, λ.

0.1 , whereas, it continuously improves when n reaches 3 for $\lambda = 0.2$. The results corroborate that whether to recruit an AP depends on not only the capability of this AP but also the number of CRVs passing by this AP. For example, when $\lambda = 0.1$, an AP which can simultaneously communicate with more than 3 CRVs will not result in a significant improvement in Γ and thus it is enough for the VSP to recruit an AP with $n = 3$. While compared with an AP with $n = 3$, an AP with $n = 4$ will be more beneficial to the VSP when $\lambda = 0.2$. To more clearly exhibit the impacts of n and λ on AP recruitment, how n and λ affect Γ is further studied in Fig. 6 with the same parameter settings. The results confirm that, given APs with different n, which AP to recruit relies on λ, the number of CRVs passing by. For the case considered in Fig. 6, an AP with $n = 1$ is enough when $\lambda < 0.02$ and an AP with $n = 4$ will be preferred when $\lambda > 0.18$.

VI. Conclusion

In this paper, we consider the data uploading processes from CRVs to an AP and analyze the maximum long term upload throughput archived with the AP in order to assist the VSP in recruiting APs for service provisioning. By reformulating the problem as a renewal reward process, we obtain the closed-form expression for the maximum long term upload throughput. The analytical results are validated by simulations. Our results confirm that whether the VSP should recruit an AP not only depends on the capabilities of this AP, but also relies on the number of CRVs passing by. In the future, we will extend our analysis to a more general network settings by considering, for example, uncertain spectrum availability.

Appendix A
The Derivation of $\overline{\tau}$

Based on (10), $\overline{\tau}$ can be expressed as

$$\overline{\tau} = \frac{r}{v}\left(\underbrace{\int_{-\infty}^{d} y f_{Y_n}(y)\,dy}_{\triangleq \vartheta_1} + d\underbrace{\int_{d}^{\infty} f_{Y_n}(y)\,dy}_{\triangleq \vartheta_2}\right). \tag{28}$$

According to Lemma 1, ϑ_1 can be derived as

$$\begin{aligned}\vartheta_1 =& \left(\frac{\widetilde{\lambda}}{1-e^{-\widetilde{\lambda}d}}\right)^n \sum_{i=0}^{n}\left\{\frac{n}{(n-i)!i!}(-1)^i\right.\\ &\left.\times\int_{-\infty}^{d} y e^{-\widetilde{\lambda}y}(y-id)^{n-1}u(y-id)\,dy\right\}\\ =& \left(\frac{\widetilde{\lambda}}{1-e^{-\widetilde{\lambda}d}}\right)^n \frac{1}{(n-1)!}\int_{0}^{d} y^n e^{-\widetilde{\lambda}y}dy\\ =& \left(\frac{1}{1-e^{-\widetilde{\lambda}d}}\right)^n \frac{1}{\widetilde{\lambda}}\frac{1}{(n-1)!}\gamma\left(n+1,\widetilde{\lambda}d\right).\end{aligned} \tag{29}$$

Similarly, ϑ_2 can be obtained as

$$\begin{aligned}\vartheta_2 =& \left(\frac{\widetilde{\lambda}}{1-e^{-\widetilde{\lambda}d}}\right)^n \sum_{i=0}^{n}\left\{\frac{n}{(n-i)!i!}(-1)^i\right.\\ &\left.\times\int_d^\infty e^{-\widetilde{\lambda}y}(y-id)^{n-1}u\left(y-id\right)dy\right\}\\ =&\left(\frac{\widetilde{\lambda}}{1-e^{-\widetilde{\lambda}d}}\right)^n \frac{1}{(n-1)!}\int_d^\infty e^{-\widetilde{\lambda}y}(y)^{n-1}dy\\ &+\left(\frac{\widetilde{\lambda}}{1-e^{-\widetilde{\lambda}d}}\right)^n \sum_{i=1}^{n}\left\{\frac{n}{(n-i)!i!}(-1)^i\right.\\ &\left.\times\int_{id}^\infty e^{-\widetilde{\lambda}y}(y-id)^{n-1}dy\right\}\\ =&\left(\frac{1}{1-e^{-\widetilde{\lambda}d}}\right)^n \frac{1}{(n-1)!}\Gamma\left(n,\widetilde{\lambda}d\right)\\ &+\left(\frac{1}{1-e^{-\widetilde{\lambda}d}}\right)^n \sum_{i=1}^{n}\frac{n}{(n-i)!i!}(-1)^i e^{-\widetilde{\lambda}id}\Gamma\left(n\right). \end{aligned} \quad (30)$$

Plugging (29) and (30) to (28), $\overline{\tau}$ can be derived as shown in (20).

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