Smart Cities on Wheels: A Newly Emerging Vehicular Cognitive Capability Harvesting Network for Data Transportation

Haichuan Ding, Chi Zhang, Ying Cai, and Yuguang Fang

Abstract

With the emergence of IoT and smart cities, wireless data traffic is exponentially increasing, motivating telecom operators to search for new solutions. In this article, we propose a solution based on the premise that vehicles are equipped with CR routers, specially designed powerful devices with agile communication interfaces, rich computing resources, and abundant storage space. To fully exploit the capabilities of such vehicles, we propose a V-CCHN architecture where CR router enabled vehicles are employed to connect end devices to the V-CCHN and transport data to intended locations via storage of on-board CR routers and spectrum resources harvested from various systems. Considering the abundant storage of on-board CR routers and a wide range of under-utilized spectrum, the V-CCHN is expected to effectively transport substantial amounts of data between end devices and data networks, which offers an effective solution to handling the explosive wireless data traffic and well complements existing telecommunications networks.

Introduction

Although the capacities of our telecommunications networks have been greatly expanded over the last two decades, they are easily overwhelmed by the constantly exponentially increasing wireless data traffic. This situation will be aggravated in the coming era of the Internet of Things (IoT) and smart cities. Smart cities are expected to involve various kinds of cyber-physical systems (CPSs), such as smart grids, intelligent transportation systems and mobile healthcare systems, where a tremendous number of IoT devices with heterogeneous communication capabilities will be deployed in order to make physical systems smart. In the foreseeable future, these devices will generate substantial amounts of data, including metering data for utilities, sensory data for traffic management, and surveillance data for monitoring, which must be processed at certain locations and shared with various parties, and hence may have to be stored or transported to the appropriate locations [1].

To handle the explosively growing wireless data traffic, telecom operators constantly extend the abilities of their radio access networks (RANs) by reducing the last-hop distance (i.e., cell size), acquiring new licensed spectrum bands, and developing advanced technologies [2]. Unfortunately, these approaches are not the ultimate solutions. On the one hand, telecom operators will soon be trapped into a dilemma where the revenue generated from the increased network capacity may not be able to justify their investments in extra spectrum resources and infrastructure. On the other hand, due to various constraints, such as size and power supplies, those advanced technologies might not be affordable for the massive number of lightweight end devices ([3, 4] and references therein). Thus, the telecom industry is urgently searching for new solutions to deal with the explosion of wireless data traffic. Many solutions, such as WiFi-based offloading and terminal-to-terminal (T2T) communications (machine-to-machine (M2M) communications or device-to-device (D2D) communications), have been introduced to offload wireless data traffic from the RANs of telecom operators [2, 5]. Unfortunately, the effectiveness of these offloading schemes in handling the soaring wireless data traffic is rather limited, as most of them are mainly designed for mobile users' smart devices. In contrast, with the advent of IoT and smart cities, wireless data traffic is generated from devices with various types of potentially incompatible radio interfaces [6]. Even if the radio interface issues can be addressed, the amount of offloaded wireless data traffic will be constrained by available spectrum resources, coverage, and mobility.

In this article, we propose an alternative solution where numerous vehicles on the road are used as complements to telecommunications networks in handling the soaring data traffic and offering end devices another way to access data services. Different from existing works on vehicular communications, our proposed solution goes one step further and envisions future vehicles to be endowed with powerful communication devices, called cognitive radio routers (CR routers), which have cognitive radio (CR) and routing capabilities and are equipped with agile communication interfaces, sufficient computing

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resources, and abundant storage space [3, 7–9]. When compared to existing wireless data offloading schemes, our vehicle-based solution has many advantages. First, our solution does not impose specific requirements on the radio interfaces of end devices. Vehicles can reconfigure their agile communication interfaces to interoperate with devices from heterogeneous systems through the interfaces that these devices normally use.[1] Second, unlike fixed infrastructures, vehicles can move close to infrastructure nodes/end devices and exchange data with them within their proximity, which can significantly reduce the last-hop distance and thus substantially improve spectral efficiency without excessive investment in infrastructure. For example, with appropriate power control, vehicles can more efficiently utilize local spectrum resources to collect (deliver) data from (to) a massive number of devices while moving. Third, since the utilization of communication resources varies in different frequencies, locations, and systems, vehicles can take advantage of storage and communications capabilities built into CR routers to store and carry data while opportunistically harvesting unused resources from different spectrum bands, locations, and systems so that data can be either delivered to the intended end devices or uploaded to the Internet. Fourth, with the built-in computing capability of CR routers, vehicles can serve as edge cloud servers for local data processing and aggregation, useful intelligent information extraction, and user iterations, which further improves the efficiency of data transmissions.

Considering that a huge number of vehicles travel on roads, once they are equipped with CR routers, we will have a massive number of intelligent mobile nodes opportunistically available for data collection, processing, and transportation. If properly managed, those traveling vehicles will offer us an emerging viable *data transportation network*, the vehicular cognitive capability harvesting network (V-CCHN), to complement existing telecommunications systems in adding new services, relieving network traffic congestion, or transporting big data for various cyber-physical systems (CPSs) to implement the vision of smart cities. Considering the mobility of vehicles and the variations in harvested resources, a flexible network architecture is indispensable to fully exploit the above benefits. Although vehicular communications have been extensively studied under cellular networks and vehicular ad hoc networks (VANETs), given the substantial differences between our V-CCHN and existing proposals, network architectures therein cannot be directly applied to the V-CCHN, which motivates us to design this novel V-CCHN architecture. In the following section, we will present why our vehicle-based solution is a good approach to handling the soaring data traffic generated from IoT and smart city applications.

The Move to the V-CCHN

In this section, we elaborate on why it is a good idea to have the V-CCHN to complement telecommunications networks in handling the explosive wireless data traffic. We first review current solutions and identify their limitations which motivate us to search for alternative solutions. Then, we present the rationale behind the V-CCHN and compare it with existing wireless data offloading schemes.

The Limitations of Current Solutions

The most direct way to handle the increasing wireless data traffic is to improve the capacity of RANs. Generally speaking, this can be achieved via reducing the last-hop distance (i.e., cell size), acquiring more licensed spectrum bands, and adopting advanced technologies. By reducing the last-hop distance, the licensed bands can be more aggressively reused. With more spectrum resources, the capacity of telecommunications networks can significantly be increased. Unfortunately, these approaches are no longer cost-effective for telecom operators [2]. Even though the effectiveness of various advanced communications technologies has been widely confirmed, their efficiency in practice might be limited by the capability of end devices. With the advent of IoT and smart cities, future end devices are expected to come with different sizes, storage capacities, and power supplies, and not all of these devices can afford the implementation of those advanced technologies [3].

The aforementioned observations motivate telecom operators to find alternative channels to offload data traffic. According to [2], WiFi-based offloading and T2T-based offloading are the most common approaches for data offloading. The WiFi-based approach allows end devices to obtain wireless data services via fixed WiFi access points (APs) instead of going through the RANs of telecom operators. An experiment conducted in 2010 shows that for smartphone users with high WiFi coverage, 65 percent of the total mobile data traffic can be offloaded through WiFi APs [10]. The results in [10] also imply that the effectiveness of WiFi-based offloading is limited by the availability of WiFi APs and users' moving speed. In view of limited WiFi coverage, WiFi-based offloading cannot fully address the proliferation of wireless data traffic [10]. On the other hand, T2T-based offloading, such as device-to-device (D2D) communications, relies on direct communications between end devices without going through RANs in order to localize wireless data traffic and improve frequency reuse [2]. One premise of T2T-based offloading is that end devices should be within proximity, which depends on devices' mobility patterns. As a result, the uncontrollable mobility of end devices will significantly impair the efficiency of T2T-based offloading. Moreover, T2T-based offloading primarily targets content distribution services, which are only part of the data services envisioned for IoT and smart cities [2]. Apart from the aforementioned issues, the offloading processes of both the WiFi-based approach and the T2T-based approach are carried over specific spectrum bands with limited bandwidth, such as the ISM bands and the cellular bands. In view of the soaring wireless traffic, we will quickly hit the spectrum ceiling according to Shannon's capacity theorem. Additionally, both of these approaches require end devices to be equipped with specific communication interfaces, such as WiFi interfaces and cellular interfaces, which is not always the case for IoT and smart city applications. Clearly, these existing data offloading

Different from existing works on vehicular communications, our proposed solution goes one step further and envisions future vehicles to be endowed with powerful communication devices called cognitive radio routers, which have cognitive radio and routing capabilities and are equipped with agile communications interfaces, sufficient computing resources, and abundant storage space.

[1] Vehicles here refer to their on-board CR routers. For ease of presentation, in the following, we will use vehicles and CR routers interchangeably.

Opportunistic access of data with low time urgency by users creates another opportunity for network providers to more flexibly handle delay-tolerant traffic by using other innovative method for delivery, hence relieving traffic burden from existing telecommunications infrastructure such as cellular systems.

schemes are not enough to handle the soaring wireless traffic, and it is necessary for us to identify alternative approaches.

The Road to the V-CCHN

The U.S. Department of Transportation (U.S. DoT) issued the mandate in 2012 that car makers should equip lightweight vehicles with communication capability so they can communicate for safe driving, leading to the resurgence of VANETs. Recently, we have witnessed various standardization activities for vehicular communications, such as the IEEE Standard for Wireless Access in Vehicular Environments (WAVE), and different types of on-board communication systems, such as BMW's ConnectedDrive [7]. The OnStar Corporation has developed an aftermarket device, the OnStar FMV, to replace vehicles' rearview mirrors so that vehicles can get network connectivity without built-in communication devices [11]. Unfortunately, given various proposals for vehicular communications, we still have not converged on what types of communication devices should be installed and what type of capability the devices should have although some important wireless technologies are suggested to be deployed.

Notice that what all these efforts intended is to mainly instill intelligence into transportation systems and improve drivers' experiences for efficiency and safety. In view of this, an interesting question to ask is what will happen if vehicles are equipped with more powerful communication devices. Imagine if most lightweight vehicles were equipped with more powerful communication facilities such as CR routers; we would have a newly emerging dynamic data transportation network that can be used to transport large volumes of data for congested telecommunications systems and/or for emerging big data systems. For example, we envision a CR router equipped with agile communication interfaces with CR capabilities, relatively large storage space, and sufficient computing power. CR routers are capable of sensing spectrum occupancy in their surrounding environment, collecting traffic and vehicular mobility information, and then using a carefully designed reliable control signaling channel to distribute such intelligent information across the transportation network. Based on such rich information and delay-tolerant network (DTN) technologies [11, 12], we can come up with intelligent store-carry-forward strategies to transport data to the proximity where they can be effectively delivered or consumed, and intelligent decisions can be made. Along this line of thought, the resulting data transportation network could be used to offer various communications services not only to improve the driving experience, safety, and congestion relief, but also in enabling data collections, data storage management, and command and control for future intelligent cyber-physical systems (CPSs) such as smart city operations.

Another motivating observation is the change of traffic composition supported over telecommunications networks. Mobile users tend to use non-real-time services, such as audio, imaging, and video, much more often than ever before, for daily communications, which can be observed through the popularity of Twitter and Wechat. Tremendous monitoring data, such as in mobile health, smart grid, and public safety surveillance, are also relatively delay insensitive, at least insensitive in certain time scales [1]. All resulting data traffic belong to a traffic type, namely, delay-tolerant traffic, which may be needed in the future at different locations. For example, certain video clips of popular news items such as presidential debates may be requested by many users at different locations at unpredictable times. To relieve traffic pressure from their supporting communications networks with their own bandwidth, it may be better to transport such *delay-tolerant traffic* to those locations from which potential users may frequently access it. Opportunistic access of data with low time urgency by users creates another opportunity for network providers to more flexibly handle delay-tolerant traffic by using other innovative methods for delivery, hence relieving the traffic burden from existing telecommunications infrastructure such as cellular systems.

Based on the above considerations, we advocate the utilization of powerful CR routers in lightweight vehicles and develop CV technologies, which eventually leads to a novel data transportation network, the vehicular cognitive capability harvesting network (V-CCHN). There are a few good reasons why we take this position. First, future vehicles, particularly autonomous vehicles, will support various kinds of infotainment services, which will generate tremendous amount of wireless data traffic, and powerful communication devices will facilitate such a type of service provisioning. Besides, the price of a communication device, even for more powerful CR routers, should be relatively insignificant compared to the price of the car, and hence can be easily absorbed by the manufacturers (or customers). Second, energy consumption for CRs expended on spectrum sensing and processing will be rather insignificant, if not negligible, considering the power supply in vehicles, and thus CR technologies may find the right place to show their vast application potential. Third, CR routers allow vehicles to interact with various systems over different bands. On the one hand, on-board CR routers can reconfigure their agile communication interfaces to those that end devices normally use for data exchanges. On the other hand, since the utilization of communication resources varies in space, frequency, and system, on-board CR routers are able to harvest resources from different locations, spectrums, and communication systems for data exchanges. Fourth, thanks to mobility, vehicles can exchange data with end devices and infrastructure nodes within their proximities, which greatly shortens the communication distance and possibly offers high-speed connections. In such a way, we are able to reduce the last-hop distance without excessive investment in infrastructure and push Internet access much closer to end devices. In addition, with properly designed power control, the local spectrum resources can be more efficiently utilized by vehicles to exchange data with a massive number of devices and infrastructure nodes while moving. Fifth, the computing capabilities of on-board CR routers can be exploited to provide edge computing services to end devices, extract useful intelligence, and aggregate data to facilitate data transportation. Sixth, the mobility of vehicles is inherently constrained by road layout and thus offers another dimension of opportunities we can take advantage of for transmissions and traffic delivery. By taking advantage of relatively regular mobility of vehicles and abundant storage built into CR routers, we can employ vehicles to store and carry data while opportunistically harvesting spectrum resources for data exchange. Thus, vehicles can not only enable us to exploit a wide range of under-utilized spectrum resources for data exchange, but also offer us another newly emerging medium, storage, for data transportation. Once provided with judicious resource utilization strategies, vehicles on roads can transport a tremendous amount of delay-tolerant data between different geographical areas and between end devices and the Internet, without imposing constraints on the capability of end devices, and thus offer us an alternative way to complement telecommunications networks and fulfill the vision of IoT and smart cities. Finally, the developed CV technologies, if successful, can be easily deployed to handle emergency situations (e.g., disaster preparation, rescue, and recovery) while providing needed services demanded by the intelligent transportation systems (ITSs).

Obviously, there are more potential applications for this emerging data transportation network by deploying vehicular CR routers. One important observation is that the V-CCHN provides an effective solution to network traffic congestion problems when vehicular traffic is congested. When road traffic is higher, user traffic density will be higher, resulting in more network data traffic from vehicular users' devices or vehicular sensing and communication devices. With deployed CR routers, the dynamically organized V-CCHN becomes more connected, and hence should provide better network capability with proper management. In fact, the V-CCHN starts to emerge and become more powerful whenever users need the network capability the most (during the day more vehicles appear, which is when users demand more network services, while at night, the density of vehicular users is low, which is when not many users need network services). This forms another attractive feature offered by the V-CCHN.

In summary, the aforementioned elaboration provides us strong incentive to design the V-CCHN architecture where vehicles equipped with powerful CR routers collaboratively harvest communications resources, such as idle spectrum bands and infrastructure nodes, and transport aggregated delay-tolerant traffic, for telecommunications networks and various CPSs, to appropriate locations for data service provisioning. The V-CCHN is further compared with existing solutions in Table 1, where "Capacity improvement" refers to those solutions that aim to improve the capacity of telecommunications networks, and "Traditional offloading" refers to those solutions where either WiFi-based offloading or T2T-based offloading is adopted.

	Capacity improvement	Traditional offloading	V-CCHN
Targeted traffic types	Delay-sensitive Delay-tolerant	Delay-sensitive Delay-tolerant	Delay-tolerant
Specific interfaces on end devices	Required	Required	Not required
Mobility of end devices	Not required	Required	Not required
Transmission medium	Licensed spectrum	Licensed spectrum Unlicensed spectrum Limited storage	Harvested spectrum Abundant storage
Infrastructure	Fully provided	Partially provided	Partially provided
Offloading traffic between different geographical areas	Not support	Opportunistically	Regularly
Service provisioning	Fully managed	Partially managed	Partially managed
Cost	High	Low	Low

TABLE 1. The comparison of the V-CCHN to current solutions to data traffic explosion.

New Features in the V-CCHN

The most significant divergence from traditional VANETs is that in our proposed V-CCHN, vehicles are assumed to be equipped with more powerful communication devices, i.e. CR routers, with higher capability and capacity. The research works on traditional VANETs primarily address how to enable communications among vehicles (the vehicle-to-vehicle or V2V communications) with on-board communication devices, such as DSRC on-board units (OBUs), to improve safety and driving experiences [7]. The OBUs in traditional VANETs are communication devices without specified communications capability, mostly used to exchange safety and traffic control related messages, although some do address other applications such as infotainment. Even though a few recent works have considered OBUs with CR capabilities, these OBUs are primarily used to provide vehicles with more spectrum access opportunities and do not share the same level of communications, computing and storage capabilities as CR routers as we have envisioned in our V-CCHN[2] [9]. For example, these OBUs can only interact with other devices having the same radio interfaces, such as the DSRC radio interface [7]. For the scenario envisioned for the V-CCHN, these OBUs might suffer from interoperability issues since future IoT and smart city applications will involve different kinds of communications devices which might not have the same desired radio interfaces as existing telecommunications systems due to size and battery capacity constraints.

In addition, the V-CCHN and traditional VANETs are targeted to different application scenarios. Traditional VANETs are originally designed to deliver messages for road safety and traffic efficiency, and other data services, such as infotainment services, are viewed as add-on services that are supported by opportunistically utilizing spare on-board communication resources [13]. Thus, research efforts on traditional VANETs mainly focus on how to enable reliable and timely V2V data delivery instead of transporting data for CPSs and big data systems. While the V-CCHN is envisioned to collect and transport massive amounts of delay-tolerant data for not only intelligent transportation systems, particularly for future connected vehicles for autonomous driving, but, more

[2] It should be noted that CR routers can not only harvest spare communication resources from surrounding environment but also can provide network access and edge computing services to end devices.

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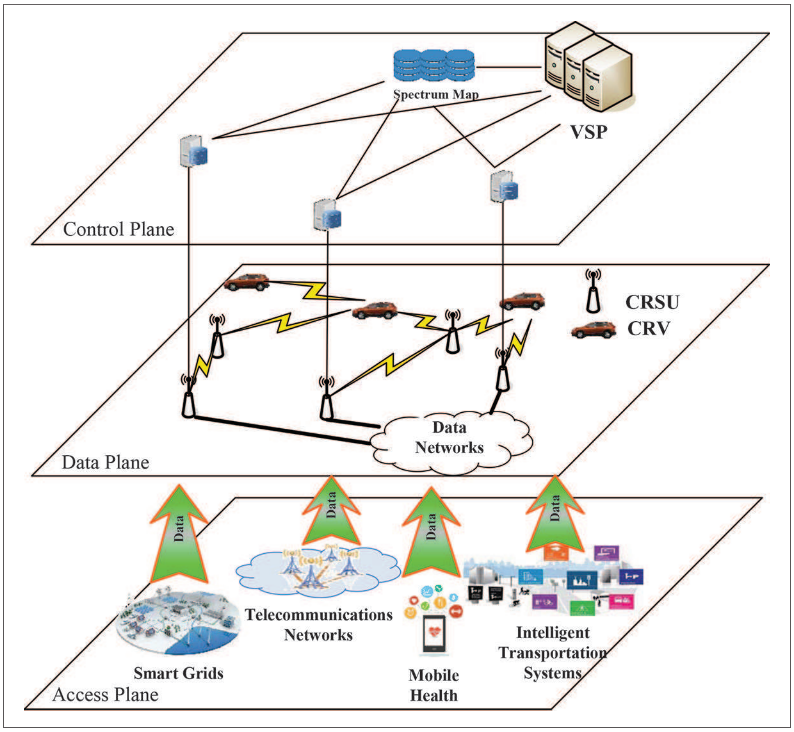

FIGURE 1. The network architecture of the V-CCHN.

importantly, also for IoT, smart cities, and already congested cellular systems. Different from the traditional VANETs, our proposed V-CCHN aims to proactively exploit the node cognitive capabilities and deployment of partial infrastructure to our advantage, changing commonly observed mobility disadvantage into opportunity! Unlike existing works on traditional VANETs, the primary issue concerned with the V-CCHN is how to efficiently utilize CR router enabled vehicles (CRVs), that is, vehicles equipped with CR routers, to deliver massive amounts of delay-tolerant data.

Furthermore, the transmission media typically used for communications in traditional VANETs and the V-CCHN are different. Traditional VANETs mainly support data transmissions, via their own licensed spectrum bands such as DSRC bands or uncontrollable unlicensed bands such as WiFi bands, which can be easily overwhelmed by soaring data traffic generated from IoT and smart city applications. A few works on traditional VANETs also make use of on-board storage as a complement to V2V communications ([7, 11] and references therein). Although cognitive radios and harvested spectrum resources have been proposed to be used in VANETs, each cognitive radio device still accesses these harvested spectrum resources individually and passively without good coordination for effective use [9]. In contrast, harvested spectrum bands will be proactively managed and utilized in the V-CCHN to transport tremendous volumes of data, the so-called big data, for IoT and smart cities applications. To handle such a large volume of data, simply relying on wireless transmissions might not be effective, and thus, in the V-CCHN, the storage built in on-board CR routers will be exploited as an important data transportation medium instead of a complement for wireless transmissions.

Clearly, unlike traditional VANETs, service provisioning in the V-CCHN relies on dynamic resources, i.e., harvested bands and storage of on-board CR routers, whose availability is subject to the activities of primary users (PUs) and the mobility of vehicles. As a result, the network architecture of traditional VANETs is not effectively applicable for the V-CCHN. Due to the lack of coordination, the performance of traditional VANETs is greatly limited by the contentions among vehicles even within their own licensed spectrum, let alone those dynamic resources intended for the V-CCHN [9]. To effectively utilize those dynamic resources for data transportation, it will be a good idea to implement certain network management functions within the V-CCHN. Although a few works on traditional VANETs suggest implementing certain management functions via cellular networks, the effectiveness of their solutions suffers from frequent congestion of cellular networks, which could fail the purpose of the V-CCHN [9]. On the other hand, most resource management and data transportation schemes in traditional VANETs are principally designed for data delivery over the licensed spectrum bands of VANETs, which cannot serve the purpose of the V-CCHN. In view of this, we should redesign the resource management and data transportation for the V-CCHN so that the utilization of communication, computing, and storage capabilities of on-board CR routers could be jointly optimized to support the intended data transportation services.

In the following section, we will elaborate on the designed network architecture and its basic operations, such as resource management, data collection, and data transportation, for the V-CCHN.

The Network Architecture for the V-CCHN

In the V-CCHN, data transportation services are delivered by vehicles using harvested resources. Although the mobility of vehicles is constrained by road layout, it is hardly controllable. In addition, the availability of harvested resources, such as spectrum bands, is subject to the variations in the services supported by the incumbent systems. Namely, the services of the V-CCHN are provided over resources that are uncontrollable and stochastic in nature. How to effectively and efficiently exploit these dynamic resources for data transportation is not an easy task. Our basic idea to address these challenges is to deploy partial fixed infrastructure to manage stochastic network resources by using reliable bands (for common control signaling). In the following, we will first present the V-CCHN architecture by introducing important network entities and their functionalities. Then, we elaborate on spectrum management strategies in the V-CCHN. Finally, we illustrate three basic operations in the V-CCHN, i.e., data collection/delivery at the edge of the V-CCHN, data transportation via CRVs, and data exchange between CRVs and data networks, and discuss the relationship between the V-CCHN and 5G.

Important Network Entities and Functionalities

The V-CCHN architecture consists of a *virtual service provider (VSP)*, *CR capable roadside service units (CRSUs)*, and vehicles. Vehicles are equipped with powerful communication devices, namely *cognitive radio routers (CR routers)*, and will be called *CR router enabled vehicles (CRVs)* in the subsequent development. The V-CCHN architecture is shown in Fig. 1, which illustrates the aforementioned network entities and their interactions with end devices from various telecommunications networks and CPSs.

The VSP can be a newly emerging service provider who deploys partial physical infrastructure, CRSUs, just as the secondary service provider (SSP) in [3], to jointly manage CRVs and harvested spectrum resources to offload delay-tolerant traffic from existing telecommunications networks and provide data transportation services for various kinds of CPSs, future smart cities, and IoT systems. A VSP can be an independent wireless service provider with a certain number of reliable licensed spectrum bands called basic bands, i.e., licensed spectrum bands, such as purchased stable TV bands or DSRC bands, with favorable propagation characteristics, or with leased bandwidth from existing wireless service providers such as cellular service providers, who deploy spartial infrastructure for new emerging service provisioning. A VSP can also be an existing cellular service provider who intends to expand its advanced cellular services to users on the road or pick up new added services for other CPSs or IoT systems. It is envisioned that the reliable spectrum bands (basic bands or capability) are mainly used for common control signaling (CCS) to provide fast information exchange to more effectively manage random variations in dynamic traffic, harvested spectrum resources, and vehicular mobility [3, 14].

In this article, we have made the following premise that both CRSUs and CRVs are equipped with CR routers as their communication devices. We envisage CR routers to be capable of sensing spectrum availability in a wide range, including TV white space and high frequency unlicensed bands such as millimeter waves (mmWaves) bands, where they could tune their air interfaces to a wide range of communications devices for data communications. Moreover, they should own sufficiently large storage space so that data can be aggregated, stored if necessary, and then carried to the needed proximity for offloading. Furthermore, they must have relatively high computing power so they could serve as edge cloud servers to provide needed edge computing to process data and proximity user access, extract useful intelligent information, and help manage data transportation. Finally, depending on where they are installed, they may be customized accordingly with their transmissions, storage, and computing capabilities. With CR routers, CRVs and CRSUs are able to communicate with different devices via various interfaces, such as WiFi, cellular, Bluetooth, and Zigbee interfaces, and so on. Specifically, for low-end IoT devices, CRVs and CRSUs can reconfigure their interfaces to the ones which these devices normally use to enable data exchanges. Whenever necessary, CRVs and CRSUs could also tune to the VSP's reliable bands for control message exchanges.

CRSUs are roadside service infrastructures deployed by the VSP so that CRVs and harvested communication resources can be utilized more efficiently. For example, CRSUs can be placed at pivotal locations, such as major intersections, to aid network resource management, mobility prediction, and traffic management. Some CRSUs can be connected to data networks via wired connections or wireless connections with high reliable bandwidth to allow the V-CCHN to gain access to backbone data networks. With CR routers, some CRSUs can even obtain access to data networks by harvesting idle infrastructure nodes and spectrum bands from existing telecommunications networks, while other CRSUs that do not have wired connections to data networks can be deployed in the V-CCHN to form wireless stationary backhaul networks (SBNs) to help CRVs relay data traffic between data networks and end devices. According to the distribution of data traffic, CRVs and CRSUs, the VSP could select a group of CRSUs as its agents to manage all data transportation and resource allocations under their coverages. These CRSUs exchange control messages with CRVs and other CRSUs over the VSP's reliable spectrum bands (the basic bands), and the coverage of a CRSU's control signaling is called a *cell*. Whenever possible, CRSUs can directly connect nearby end devices to data networks.

Under the supervision of the VSP and CRSUs, CRVs collectively exploit onboard storage and harvested resources to provide network and data transportation services to various devices. On the one hand, CRVs serve as access points for end devices to access the V-CCHN. End devices only need to upload (download) their data to (from) nearby CRVs. CRVs collect data from end devices and submit aggregated traffic requests to the VSP for coordination and resource allocation. On the other hand, CRVs work as intermediate nodes for data delivery in the V-CCHN. Specifically, once the VSP receives requests from CRVs, it could conduct network optimization to determine where to push data with a corresponding data delivery scheme according to data types. After that, these decisions will be sent back to the corresponding CRSUs which manage spectrum resources and CRVs for data delivery based on the decisions received from the VSP. Following the received data transmissions and scheduling decisions, CRVs work collectively to transport data to intended locations closer to end users or for data offloading. Finally, due to potentially powerful computing capability, CRSUs and CRVs could also be configured in an on-demand fashion to form self-organizing edge computing servers in proximity where learning and computing should be conducted.

Spectrum Management Strategies

As aforementioned, the V-CCHN is expected to provide network access to a tremendous number of wireless devices, and the VSP needs to allocate spectrum resources to these devices so they can obtain data services. Considering that the V-CCHN is to harvest potentially uncertain licensed/unlicensed bands (including mmWave) for opportunistic access, together with the existence of a large number of devices with high mobility, fully distributed spectrum access in the traditional approaches may not be effective, particularly when the use period of a spectrum band is relatively short. It is better to evoke a certain kind of (partially) centralized coordination to overcome the spectrum uncertainty for fast opportunistic access. As shown in Fig. 1, the

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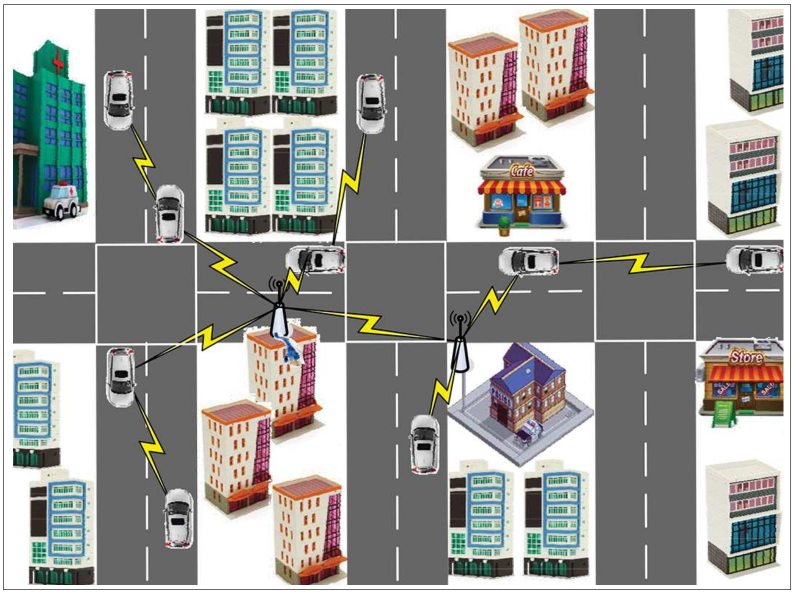

FIGURE 2. Illustration of virtual infrastructure based data transportation.

VSP could delegate the spectrum management functions to a set of CRSUs. Each of these CRSUs gathers spectrum availability information from other CRSUs and CRVs under its coverage and builds a fine-grained spectrum map within its coverage. With the spectrum map and aggregated traffic requests from CRVs, these CRSUs could make spectrum allocation decisions according to the data transportation schemes obtained from the VSP. After that, these CRSUs could effectively coordinate the utilization of spectrum within its cell via the VSP's basic bands by timely delivering resource management information for fast opportunistic access. With properly designed spectrum allocation algorithms, such as those algorithms designed to maximize the end-to-end throughput/delay, together with timely control signaling information delivery, the V-CCHN can be reconfigured automatically based on collected spectrum and traffic information in order to boost the spectral efficiency in the harvested bands with uncertain availability.

Data Collection/Delivery at the Edge of the V-CCHN

Generally speaking, data services in the V-CCHN are offered to end devices upon request. End devices submit their service requests to CRVs or neighboring CRSUs where service requests are aggregated and submitted to the VSP. Then, the VSP employs the CRVs/CRSUs, which can reach the intended end devices via one hop transmissions, for data collection/delivery. In addition, the VSP can take advantage of the storage in CRSUs to create a large number of network connecting points along the road for data storage and buffering. For example, the VSP can proactively cache some popular data content to CRSUs according to a community-based mobility pattern so that potential users can frequently access with convenience, as has been done in information-centric networks (ICNs) [15]. In such a way, the VSP is able to create many network connecting points that can not only provide users with intended data content through high speed connections but also serve as sources for future data transportation. With these network connecting points, upon receiving service requests from end users, instead of coordinating CRVs/CRSUs for data collection/delivery, the VSP can direct users to the CRSUs at their proximity where they can obtain/upload their desired data content with high-speed connections.

Potential Data Transportation Schemes

In this subsection, we discuss potential data transportation schemes for the V-CCHN.

Opportunistic Store-Carry-Forward Data Transportation: Due to the physical constraints of road layouts, the mobility of CRVs tends to be more regular than pedestrians, and thus is easier to predict. In particular, with the popularity of GPS or other navigation systems, we can even accurately track CRVs' potential destinations and trajectories. This predictability in CRV's mobility can enable us to efficiently utilize the CRVs' storage and the spectrum access opportunities while traveling. When the concerned data traffic is delay-tolerant, the VSP can employ CRVs to collect/receive/download data from various CPSs or end users, carry them, and wait for a network connection and spectrum access opportunities to forward/offload data to other CRVs or CRSUs at locations where they could be conveniently handled, resulting in opportunistic store-carry-forward (OSCF) data transportation schemes. In an OSCF scheme, data generated from various IoT and smart city applications can be dumped to CRVs to be transported in the store-carry-forward manner. While traveling, data-carrying CRVs can opportunistically exploit available network connections and spectrum access opportunities to transfer data to other CRVs or CRSUs that can further transport data toward destinations. For example, the VSP could employ CRVs to transport data away from congested areas through store-carry-forward to the areas where there are enough network connection points with spectrum resources for offloading. To further improve the performance of the OSCF scheme, we could borrow the idea of a "throwbox" from delay-tolerant networks and pinpoint multiple locations, such as stores and gas stations, as data transfer stations [16, 17]. In such a way, we can separately address the data transportation between each pair of data transfer stations, which not only improves the efficiency of data transportation but also simplifies the data transportation scheme design. As a remark, the reason we claim that high speed transmissions can be achieved is that data exchanges can be conducted when devices are brought to much closer distances by taking advantage of the mobility of CRVs.

Virtual Infrastructure Based Data Transportation: The future IoT and smart cities will involve applications requiring constant data exchanges with supporting data networks. To enable these kinds of applications, the VSP needs to build up reconfigurable wireless backhaul connections between data networks and those involved end devices to allow fast data exchange. When CRVs stop or move slowly because of traffic jams or speed limits, the VSP can easily achieve this goal by selecting multiple CRVs as virtual infrastructure (VI) nodes for data delivery. Specifically, these VI nodes collectively form a temporary mesh network (TMN) to assist CRSUs in harvesting unused licensed spectrum for service provisioning (Fig. 2). To optimally utilize spectrum resources, each CRSU collects aggregated data requests from the TMN in its coverage and makes spectrum allocation for this TMN. When CRVs are moving at relatively high speed, we can designate certain locations instead of specific CRVs to be VI nodes, and CRVs can assume the responsibility of VI nodes when passing through the designated locations. Then, the VSP can similarly coordinate data transportation within the V-CCHN relying on these location-based VI nodes.

Data Exchange Between CRVs and Data Networks

In the V-CCHN, the data exchange between CRVs and data networks is often achieved via the stationary backhaul network (SBN) formed by CRSUs. For data uploading, CRVs directly dump data to their neighboring CRSUs which will further forward the received data to data networks over the SBN. For data downloading, the VSP can deliver data to CRVs' current locations if there are enough resources, such as harvested spectrum and CRSUs, to do so. If not, the VSP can prepare data for CRVs along their paths based on CRVs' routing information and reserve communication resources for CRVs accordingly so that they can obtain the pushed data content. The most ideal case is that the VSP has some determined information on CRVs' trajectories, such as which locations CRVs will stop by and which CRSUs CRVs will meet in the future. These kinds of information can be obtained via the constraints of road layout or CRVs' navigation systems. In this circumstance, the VSP can directly push data to these locations if there are adequate resources. When determined information is not available, the VSP can take advantage of CRVs' historical routing statistics and efficiently utilized available resources to prepare data for CRVs based on their probabilistic routing information. For example, as shown in Fig. 3, the VSP tries to push data to the CRV1 through CRSU1 or CRSU2, which are one-hop neighbors, but does not know exactly which CRSU CRV1 will meet next. To achieve more efficient resource utilization, the VSP can divide the data for CRV1 into two parts according to the statistical contact information and push them to CRSU1 and CRSU2, respectively. Once CRV1 meets CRSU1, for example, the VSP will inform CRSU2 to deliver the received data content to CRSU1 through local communication links.

Relationship to 5G

Our V-CCHN can complement 5G networks in wireless data service provisioning, and the development of 5G technologies will benefit our V-CCHN. As aforementioned, our V-CCHN makes it possible to pull/push delay-tolerant data from/to end devices without going through 5G networks and thus complement 5G networks in handling a massive number of devices and the soaring wireless data traffic in the era of IoT and smart cities. On the other hand, our V-CCHN architecture can benefit from the development of 5G technologies, particularly those 5G-enabled vehicular communication technologies. For example, the technologies designed for reliable and low latency vehicle-to-infrastructure communications can be applied in the V-CCHN to enable control signaling exchange between CRVs and CRSUs. Since edge computing is one of the key enabling technologies for 5G networks, numerous computing facilities are expected to be deployed at the edge of 5G networks [18]. These computing facilities form another dimension of resources that can be harvested by our V-CCHN to coordinate resource utilization and service provisioning. With these technologies developed for 5G, operators can easily incorporate our V-CCHN architecture into their networks in order to add new services or relieve network congestion, which facilitates the application of our V-CCHN.

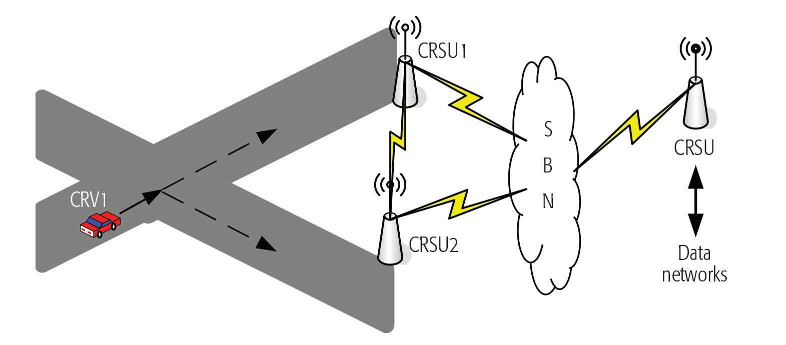

FIGURE 3. An Illustrating example for data exchange between CRVs and data networks.

Performance Evaluation

To show the proof of concept evaluation of the effectiveness of the proposed V-CCHN, we consider the scenario shown in Fig. 4a where the VSP employs CRVs to collect and deliver data from area A, the corresponding road segment labeled A, to the CRSU. The area A has a length of 200m and the distance from the bottom of area A to the CRSU is 2,100m. CRVs heading to the CRSU arrive at area A from the bottom according to a Poisson process with rate λ = 0.1/s. The CRVs are assumed to move at a speed of 8 m/s ($\approx$ 30 km/h). Thus, λ = 0.1/s implies that the average density of CRVs heading to the CRSU is 0.0125/m. Each CRV has one radio and the CRSU has H_r radios. The VSP can potentially exploit M under utilized spectrum bands. Each of these bands can support a data rate of 10 Mb/s. PUs' activities over these bands are modeled as on-off random processes, i.e., the status of spectrum availability updates on the basis of slots. If a spectrum is idle in the last slot, it will remain idle in the considered slot with probability p. If a spectrum is occupied by PUs in the last slot, it will become idle in the considered slot with probability q. While traveling within the area A, each CRV collects data from neighboring IoT and smart city devices at a rate of 3 Mb/s. We assume that CRVs have enough storage to store all collected data. These CRVs will carry the acquired data toward the CRSU. When possible, CRVs will exploit available spectrum resources to forward data to those CRVs that are within the coverage of the CRSU in order to facilitate efficient data delivery. Under the assumption that each CRV has only one radio, when multi-hop transmissions among CRVs are involved, the total time share is equally divided among different hops. We con-

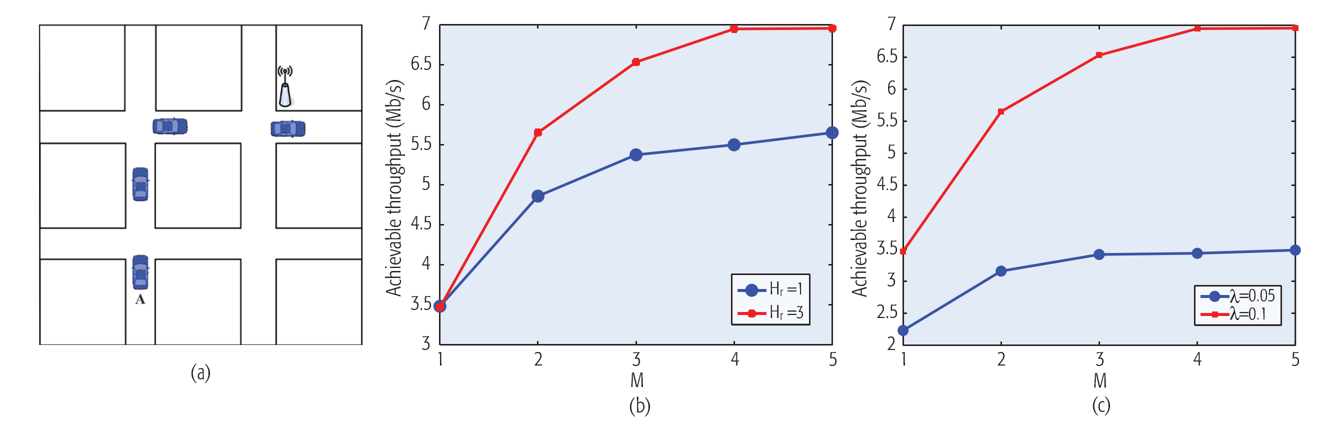

FIGURE 4. The considered V-CCHN and performance evaluation results: a) the considered scenario; b) the achievable throughput vs the number of bands *M* and the number of radios at the CRSU; c) the achievable throughput vs the number of bands *M* and the arrival rate of CRVs.

sider the achievable throughput from area A to the CRSU over a period of 18,000 s (= 5h). The following results are obtained by averaging the results in 10 rounds of simulations. Noticing that our V-CCHN is substantially different from existing works on vehicular communications, such as [19], the effectiveness of our V-CCHN is studied without being compared to other proposals.

Based on the above parameter settings, we investigate how the achievable throughput varies with the number of spectrum bands and the radios at the CRSU in Fig. 4b where both p and q are set as 0.5. As shown in Fig. 4b, considerable throughput between area A and the CRSU can be achieved by following our V-CCHN based solution. The achievable throughput increases with the number of spectrum bands M since the VSP is more likely to observe idle spectrum resources with a larger M. The improvement of achievable throughput becomes negligible when M exceeds certain values, e.g., M = 4 for H_r = 3. This is not surprising since the resources available for data transportation become abundant as M increases and the achievable throughput is limited by the rate of data generated from area A. It also can be observed from Fig. 4b that more radios at the CRSU will result in higher achievable throughput. Clearly, the CRSUs can exploit more spectrum bands with more radios and thus can simultaneously support more connections, which finally leads to higher achievable throughput.

In Fig. 4c, we evaluate the impacts of the number of spectrum bands M and λ, the arrival rate of CRVs, on the achievable throughput. The parameters are the same as those in Fig. 4b other than H_r = 3. According to Fig. 4c, a higher λ will lead to higher achievable throughput, which matches well with our intuition since more CRVs will not only bring about more storage resources but also can more efficiently utilize available spectrum access opportunities for wireless transmissions. These results further demonstrate the effectiveness of the proposed V-CCHN.

Conclusion

Vehicles have been instrumental in our daily life and have transported community and people to mobilize our daily activities. With the premise that vehicles are equipped with more powerful capability in communications, computing and storage, in this article, we have stipulated an emerging data transportation network to realize the grand vision of smart city. Here, we view future communication capability enabled vehicles as important networking resources and propose to employ these vehicles to build up a data transportation network to complement existing telecommunications networks in handling the foreseeable data explosion brought by the emergence of IoT applications. Our proposed network design focuses on a flexible cognitive capability harvesting architecture under which in-network capability can be proactively harvested and opportunistically utilized to boost network service capability without adding too much complexity at the end users' side. It is expected that our proposed approach opens a new research direction in the connected world on the road and puts the workload of smart cities on wheels.

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