Enabling Emergency Communication through a Cognitive Radio Vehicular Network

Yifan Sun and Kaushik R. Chowdhury

ABSTRACT

Unexpected disasters, both naturally occurring and those caused through human actions, result in severe damage to communication infrastructure. Additionally, such events are accompanied by sharp spikes in the usage of commercially licensed spectrum, when affected victims of the tragedy attempt to transmit information about themselves and capture high bandwidth data in the form of pictures and videos. We envisage cognitive radio as a candidate solution in such situations, where the devices can identify alternate frequency bands, and opportunistically use them. In this article, we describe a network architecture called EC-CRVN composed of CR enabled vehicles that provide critical wireless connectivity to both the general public and emergency responders. We discuss the application scenarios and salient features of the EC-CRVN. We describe the existing state of the art, the research challenges involved in realizing them, and a new approach of spectrum sensing using moving vehicles that reduces errors without adding to communication overhead.

INTRODUCTION

Events like earthquakes, tsunamis, and large-scale man-made disasters pose unforeseen challenges through serious spectrum and traffic jamming, which is caused not only by lack of network devices but also by sharp increases in bandwidth usage that overwhelm the transmission capabilities of the network. For example, after the devastation caused in the United States during Hurricane Katrina in 2005, and the Earthquake in the Sichuan Province of China in 2008, mobile phone calls shot up by as much as 80 times the expected number. Due to the lack of spectrum availability caused by the dramatic spike in traffic load, no communications could be established at all in both the above cases for a large extent of time [1].

We envision *emergency communication through a cognitive radio vehicular network* (EC-CRVN), which will serve as the backbone for essential communications following a disaster. In the scenario shown in Fig. 1, the emergency response network senses the wireless spectrum, possibly licensed by other operators (to whom we refer as primary users, PUs), and identify portions of frequencies that are currently unused. This spectrum can enable high bandwidth communication outside of the regular cellular service bands. The cognitive radio enabled vehicles (CRVs) that form this network can forward data among themselves, forming a mobile backhaul network, or they may connect with roadside base stations (BSs) for offloading the traffic. Roadside BSs may also help obtain spectrum usage information in the neighborhood by accessing centralized Federal Communications Commission (FCC) mandated spectrum databases. The CRVs perform the role of relays for the general public, forwarding their data to the Internet by using the spectrum bands that are identified to be free, as shown in Fig. 1 as *forwarded traffic*. When disasters occur, emergency personnel rush to the scene, and require an accurate assessment of the extent of the damage. The vehicles and BSs may serve as information repositories in these cases. Users can flag data that is permitted for use by emergency responders, which may include short video clips, images, and texts. This flagged information can be transmitted as high priority, allowing the emergency responders to anticipate the damage and prepare for assistance before arriving at the scene.

Motivation for using vehicles: In post-disaster scenarios, compared to buildings and BS towers, vehicles can be quickly driven into the affected areas. Most disaster response agencies already have a fleet of vehicles that can be leveraged for building such a mobile communication backbone. The U.S. National Highway Traffic Safety Administration (NHTSA) is currently working on regulations that will enforce all new cars to have the capability of vehicle-to-vehicle communication. The use of localized radios on vehicles does not require that infrastructural changes be made to the handsets of the general public. In addition, vehicular networks provide bypasses

Yifan Sun and Kaushik R. Chowdhury are with Northeastern University.

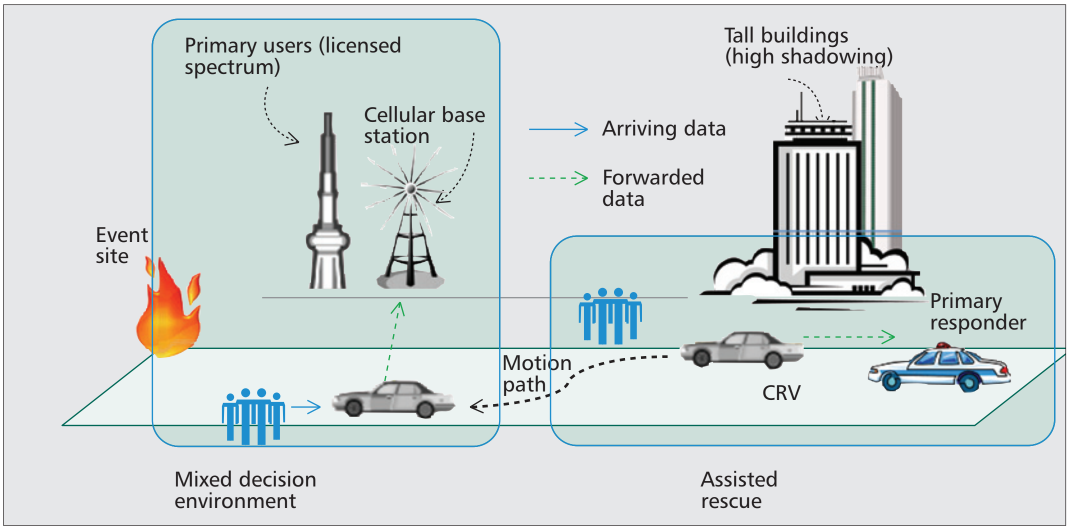

Figure 1. Architecture of EC-CRVN.

When spectrum sensing is undertaken during motion, the number of samples used to make inferences must be carefully decided. Non-intuitively, fewer samples may give better results in an area surrounded by structures as they capture a minimal amount of multi-path reflections that distort the signal.

for the infrastructure-based network and hence relieve network congestion.

Motivation for cognitive radio: CR allows unused spectrum in diverse bands to be identified, including TV bands in ultra high frequency (UHF) that have better propagation characteristics. For this, the radio must periodically undertake accurate spectrum sensing, as the PUs have priority to transmit in the licensed spectrum bands. CR enables various spectrum sensing approaches, including cooperative and spectrum-database-assisted sensing that involves sharing information with external devices. This helps in reducing the possibility of errors but introduces additional overhead for transmitting control messages over the air. Moreover, CR radios can dynamically configure themselves such that they can interoperate with consumer mobile devices as needed.

The EC-CRVN architecture must operate under the following features:

Dynamic network formation: Networks should be formed quickly and dynamically in a large area. The locations of CRVs must be chosen such that they form a connected backbone, but are also able to sense the spectrum availability in the region.

QoS support: To provide real-time video and audio communication for the rescue team, the network should provide high levels of uninterrupted channel access time and meet QoS requirements through optimal bandwidth allocation. Moreover, since the network supports both emergency personnel and the public, appropriate levels of priority must be accorded.

Licensed user protection: Leveraging licensed frequencies requires precise spectrum sensing. The CRVs must select channels such that high-priority users remain unaffected.

Infrastructure reliance: Network formation and spectrum sensing must rely on limited support from external nodes and existing infrastructure. The control overhead of interacting with the external infrastructure must be quantified.

Energy efficiency: Although vehicles are not typically energy constrained, disaster scenarios introduce challenges of extended refueling intervals. Thus ,devices (and hence car battery and fuel) must be used sparingly as far as possible.

The remainder of this article is organized as follows. First, we present the features of the proposed EC-CRVN and survey the current state of the art. Next, we describe a novel approach of sensing. We then describe the research challenges of the area, and finally, we conclude.

Characteristics of EC-CRVN

In this section, we discuss key features of the EC-CRVN that make it suitable for emergency response.

Mobility

The mobility of the CRVs that form the network helps quickly reinstate wireless connectivity. However, this feature also gives rise to time variant channels. When the path of movement involves high-rise buildings (downtown areas) and open stretches (bridges), the channel changes are hard to predict. Routing becomes a concern at the higher layer of the protocol stack as forwarding nodes themselves may be in motion, giving rise to highly dynamic topologies. When spectrum sensing is undertaken during motion, the number of samples used to make inferences must be carefully decided. Non-intuitively, fewer samples may give better results in an area surrounded by structures as they capture a minimal amount of multi-path reflections that distort the signal.

Mobility enables extreme functionalities, where the vehicles may serve as data mules. Such CRVs collect data from user devices and must physically be driven to the nearest BS, shown by the motion path in Fig. 1. However, if the infrastructure damage is so severe that none of the BSs exist or no vacant spectrum is available for long-range transmission, the data mule functionality reduces multihop routing overhead. Also, emergency vehicles need not continuously move throughout the region, but only arrive at critical junctions for picking up the data from the mules.

The responding personnel and rescue activities demand delivery guarantees, bandwidth reservation, delay constraints, or other forms of QoS support, while public communication places less stringent demands on resources. Thus, the network needs to differentiate between these two types of services.

Mixed Decision Environment

The EC-CRVN operates in an environment that combines human input (in terms of feedback from users and decisions of operators) with device capabilities (sensing accuracy, battery level, etc.). This cross-platform framework involves close interplay between decisions made at two different human and cyber levels. Thus, any optimization undertaken in isolation at either end may not yield the globally preferred solution. For example, large user clusters may be concentrated in areas of completely occupied spectrum. In such a case, it may be better for the CRV to move toward more open spectrum areas and gather less data, which can potentially be transmitted with minimal delays, as shown in Fig. 1.

We believe that the EC-CRVN must establish:

- Functionalities that may be fully operated by the devices themselves
- Functionalities that can be totally left to the discretion of the human operators/users
- Functionalities that need to interplay with each other

Devices may themselves raise alerts that propagate back to the user level for timely intervention and high-level policy guidance. For example, the responding personnel can chart out broad areas of traversal and identify a minimum subset of points that must be covered by the EC-CRVN. However, the order of traversal of these critical points, the specific path chosen, the velocity, and so forth can be left to the algorithms within the CRV based on the spectrum availability changes with time.

Post-Disaster Stages and Compatibility with Infrastructures

After a major catastrophe like an earthquake or tsunami, rescue work can be divided into three stages. The first stage that immediately follows the catastrophe is *self-rescue*, where victims escape from immediate life threatening danger, and communicate their state with family and friends. In this stage, CRVs must support the spike in bandwidth usage originating from the affected public users. The transition from communications support from users to emergency response personnel follows in the second stage, called *assisted rescue*, shown in Fig. 1. Here, the information may need to be transmitted over multihop networks to the responding personnel, wherein high-priority data is identified and sent before private communication. In the last stage, called *re-building*, the CRVs may perform other tasks such as serving as stationary cellular towers, assisting physical rescue operations, and directing the flow of traffic through the affected areas.

Review of CRVs in Disaster Recovery

In this section, we review the published results and major advances in the area of using CRVs for disaster recovery. We identify the major thrusts targeted in these works, and list the corresponding solutions in Table 1.

Network Formation

In the first stage of a major disaster, the most important task of the EC-CRVN is to create a wireless network in seconds. In this broad thrust, we focus on data forwarding protocols that allow data packets to be transmitted within strict latency bounds and other quality of service (QoS) requirements to the end destination. This is especially complex, due to the mobility of the vehicles and the rapidly changing channel conditions.

Channel Condition — Inspired by traditional wireless routing protocols, a method is proposed in [2] for a node to select the next hop as a relay with the best channel condition, called CoRoute. In this approach, each vehicle estimates the expected transmission time (ETT) between other adjacent vehicles. It then chooses to forward the packet to the specific next hop that has the minimum ETT. Instead of end-to-end ETTs, vehicles use the ETT of a two-hop path, which suits high mobility scenarios better. This approach also ensures that a globally optimal result is achieved. However, CoRoute cannot provide long-distance multihop routing due to the limitations of the two-hop estimation and the possibility of high mobility within the vehicular network.

Mobility Awareness — A different approach that focuses on the highly mobile nature of the CRV network is proposed in [3], called expected path duration maximized routing (EPDM-R). The authors assume that the quality of every link is perfect; thus, network topology is influenced only as a result of vehicular mobility and the available channels. This approach estimates the relative distance, relative speed, path duration by a freeway mobility model, and PU behavior model. Finally, the work focuses on finding a route that maximizes end-to-end path duration to provide reliable routing even in scenarios of high mobility. A possible limitation of EPDM-R is that it neglects channel conditions, which influences the ability of the channel to deliver packets reliably.

Although routing protocols considering vehicular network and cognitive radio network architectures are well developed separately, the research on data forwarding strategies especially devised for CRVs are limited.

Quality of Service

Post-disaster communication involves providing communication service for public users and emergency responders. The responding personnel and rescue activities demand delivery guarantees, bandwidth reservation, delay constraints, or other forms of QoS support, while public communication places less stringent demands on resources. Thus, the network needs to differentiate between these two types of services. Moreover, the level of QoS must be carefully decided such that the network can realistically support these needs.

Throughput Maximization — The burst of user bandwidth requirement necessitates an immediate focus on throughput maximization.

	Network formation		Quality of service			Licensed user protection	
Challenge	Channel condition	Mobility awareness	Throughput maximization	Support flexibility	Fairness	Sensing accuracy	Stationary sensors
CoRoute [2]	✓	✓					
EPDM-R [3]		✓					
CALS-CVN [4]			✓				
DCV [5]			✓				
OCAM-CVN [6]			✓	✓			
EQ-MAC [7]				✓	✓		
OSA-CVN [8]					✓		
CRA-MC [9]					✓		
BP-on-HW [10]						✓	
Cog-V2V [11]						✓	
SDA-CVN [12]						✓	
SD+CS [13]						✓	
IASC [14]							✓

Table 1. State of the art for post-disaster CRV communication networks.

This can be undertaken at each layer of the protocol stack, from the physical layer up to the transport layer. Cooperative relaying for CRVs is proposed in [4] as a candidate solution. This scheme relies on an overhearing node to repeat the transmission, thereby reducing the bit error rate significantly. The scheduling is done in such a way that multiple nodes transmit simultaneously within the network. The approach creates a 3D cooperative conflict graph, formulates an optimization problem for identifying the best subset of links that may be active at a given time for maximum throughput, and then solves the resulting relaxed optimization problem. This approach demonstrates that CR provides more opportunities for nodes to cooperate and schedule links across a wide spectrum range. However, how to achieve a high level of coordination among relays in mobile scenarios remains an open problem.

QoS Support — Vehicular networks can inherently provide some degree of QoS by using a separate spectrum band that is not impacted by congestion in the regular WiFi and cellular channels. A block of 75 MHz of dedicated short-range communications (DSRC) spectrum in the 5.9 GHz band is allocated by the FCC for vehicle-to-vehicle and infrastructure-to-vehicle communication. This allocated bandwidth is further divided into seven channels, one control channel (CCH) and six service channels (SCHs). This allows safety messages to propagate on the CCH, thereby avoiding congestion if the SCHs are overwhelmed with user data. However, this simple provision may soon become inadequate in high-density regions. Recent research indicates that QoS cannot be satisfied by merely reserving existing channels in CRVs [7].

An approach called DCV is proposed in [5], which allows data delivery guarantees within CRVs. To provide such a guarantee, DCV not only reserves a dedicated channel for safety messages, but also dynamically identifies and allocates external spectrum (so-called whitespace) for them. This approach is further extended in [6] by including thresholds such as packet loss probability and average delay. Three components, queue-aware opportunistic access to shared-use channels, reservation of bandwidth in the exclusive-use channel, and cluster size control, are implemented here to achieve these objectives.

QoS Flexibility — The concept of QoS needs to be appropriately defined for various levels of emergency communications. For example, communication involving life-threatening rescue work deserves the highest bandwidth, and that involving coordination among vehicles enabling distribution of disaster relief material needs reduced QoS support. To fulfill this requirement, a dynamic channel allocation algorithm and a set of special control messages are formulated in [7].

Fairness — The general public, who also require EC-CRVN assistance for establishing connections, must be able to communicate, although at much reduced requirements. These users may be

The success of the EC-CRVN relies on identifying alternate spectrum, which may belong in licensed channels. While opportunistic use of the spectrum can assist in emergency operations, barring any prior permissions, the use of such licensed frequencies should not degrade PU reception.

accommodated in a contention-based access method that allows the support of a large number of requests per channel. However, CRVs that participate in the data forwarding process should guarantee an acceptable level of fairness that prohibits a single user from grabbing all the channel resources.

Methods involving max-min approaches rely on maximizing the minimum throughput among nodes. Such methods may provide the highest level of fairness, but severely impact the overall efficiency of the network. A cooperative resource allocation with QoS support based on Nash-bargaining is developed in [9]. This method achieves a trade-off between the overall throughput and fairness between cells by allocating resources in a weighted fair manner. The approach is to favor cells with severe traffic jams or high incidences of emergency requests. Reference [8] conducted an investigation on the fairness problem by proving the existence of a Nash equilibrium of the CRV network engaged in distributed opportunistic spectrum access. The Nash equilibrium is an key concept in classical game theory, and describes a scenario where all players in a noncooperative game achieve their best possible result by choosing the equilibrium condition, and there is no incentive for unilateral deviation from this optimal point. By achieving the Nash-equilibrium, the CRV network can work with the highest possible efficiency and guarantee fairness.

Licensed User Protection

The success of the EC-CRVN relies on identifying alternate spectrum, which may belong in licensed channels. While opportunistic use of the spectrum can assist in emergency operations, barring any prior permissions, the use of such licensed frequencies should not degrade PU reception. To ensure an accurate understanding when a licensed channel is being used, current approaches can be classified into three categories: sensing-based, database-based [12], and mixed use [13].

Sensing Accuracy — The most straightforward approach is to perform spectrum sensing locally within each CRV. Various techniques have been studied for local sensing, such as energy detection (using the level of the detected signal strength) and feature detection (using recurring patterns to detect the presence of a specific type of signal). However, simple local sensing can be severely impacted in high mobility scenarios, especially if the route passes amid tall structures. A different approach based on commercially maintained spectrum databases has been proposed by the FCC for the TV whitespace, which stores spatio-temporal spectrum information. A CR node queries the spectrum database to acquire a list of available channels before transmitting on them. However, the database-based solutions may not be most suitable in disaster scenarios for the following reasons:

- The destroyed PU infrastructure may create additional spectrum holes, which are not updated within the database.
- In post-disaster scenarios, CRVs may experience difficulty in accessing the database. Moreover, even if vehicles can access the database, the multiple queries (e.g., once every 60 s) add overhead to the existing spectrum congestion.

One way to enhance the spectrum sensing results is to undertake cooperative sensing, which collects more spectrum signal samples from multiple viewpoints. The concern here is the extent of information that must be shared between vehicles, and the best way to aggregate the information that comes in. A solution based on belief propagation in collaborative spectrum sensing is given in [10]. Here, each vehicle shares information about the belief of the existence of PUs with its neighbors. Following this step, each of the vehicles that receive the information combine the others' belief with its local sensing result to enhance the correctness of the sensing decision. A more comprehensive solution is proposed in [11]. In this work, first, a local spectrum availability database is created in each vehicle. The spectrum availability for each channel, including the sensing samples, is shared among neighbors. Finally, the information aggregation is done by a weighted majority decision process. This work also stresses the importance of predicting the traveling path and acquiring future spectrum information in advance.

Stationary Sensors — Classical wireless sensors may be deployed around the path or dropped after a disaster event. These sensors can gather spectrum usage data to create spectrum maps that give the geographical hot spots where the highest data transfer rates may be possible. This spectrum map can be used to design the movement paths of the CRVs. Energy efficiency for sensor operation is a key concern, and one way to solve this problem is to create portions of the map on demand. Thus, based on the movement choices of the CRV, sensors in the predicted area of motion can be activated, leading to step-by-step formation of the spectrum map.

The work described in [14] combined cooperative sensing and standalone sensing through wireless sensor networks. The resulting approach, which we describe as the information-adaptive sensing coordination (IASC) framework, moves away from traditional centralized sensing. Here, CRVs can use channels without a centralized decision maker, and can choose to appropriately weight the sensing results from multiple sources.

Enhancing Spectrum Sensing

Spectrum sensing via cooperative information sharing or accessing spectrum databases contributes to overhead on an already stressed communication infrastructure. Moreover, reaching the database through backhaul connectivity may become impossible in areas suffering extensive traffic jams. For example, in [10] vehicles use spatial correlation, which requires the PU locations to be consistent in space.

Instead of spatial and temporal correlation, we explore signal correlation across different bands to improve the estimation of channel occupancy. The central idea is that if the PUs are co-located with other transmitters, such as cellular BSs that issue regular beacons, portions of the road in which the CRVs move may exhibit similar signal propagation characteristics. Both sets of transmitted signals (from the PUs and the cellular BS) experience a common set of reflections from the structures in their path, up to the reception point on the road. A vehicle in Fig. 2 travels in the North–South direction. It detects similar fluctuation of signals from PU 1, say a TV transmitter, and signals from the 2G tower, which transmit in completely different spectrum bands. This is because the dominant paths of the 2G and TV signals experience similar attenuation and multipath effects. When the vehicle moves out of the solid circle into the dashed circle, it will detect different patterns from 2G and the signals in the TV band from PU 2 due to different paths these signals have traversed. When signal correlation appears, the vehicle can rely on local sensing data. Otherwise, the vehicle has to query the database to guarantee accuracy. Note that we utilize the beacons from the 2G towers, which are sent regularly from the BS and remain unaffected by heavy traffic load in post-disaster scenarios.

Sensing errors can be caused by false alarm or missed detection. Both cases arise when the received signal strength exhibits sudden fluctuations that can be misinterpreted by the CRV. For example, if the net received signal strength indication (RSSI) of the PU falls below a threshold due to destructive interference of multiple reflected copies of the signal, the CRV may mistakenly interpret the spectrum as available. We propose a two-stage sensing mechanism, where a second verification may be undertaken at those locations that exhibit a high level of correlation between the PU spectrum and the 2G bands. If the spectrum sensing result indicates the absence of a PU, at these specific locations the CRV also checks for the beacon signals in the 2G spectrum bands. If these beacons are also not correctly detected, it implies that the same multipath-induced effects that impact the expected beacons may also be a cause of sensing errors.

In post-disaster scenarios, the amount of signal correlation is expected in more spots since structures tend to survive together. In an experimental study conducted in the urban Boston area, we examined the number of points in which the 2G signal showed strong correlations with TV channels. Results revealed in some certain spots, correlation can be as high as 80–95 percent [15], which indicates the viability of this approach.

We conducted simulation trials to identify how much benefit is attained by utilizing signal correlation. We consider the case where a PU may stochastically start and end its transmission. CRVs travel through a PU's coverage region and sense the spectrum to determine whether the channel is occupied. We consider three basic sensing methods: energy detection (in which the PU is identified to be present when the RSSI is above a threshold), belief propagation (through exchange of belief information among 15 vehicles next to each other), and a signal-correlation-based approach. The 2G channel (with always on beacons) and TV channel (PU present occasionally) exhibit varying levels of correlation from 40 to 85 percent. Vehicles sense the channel for 22 μs and make decisions based on the samples taken.

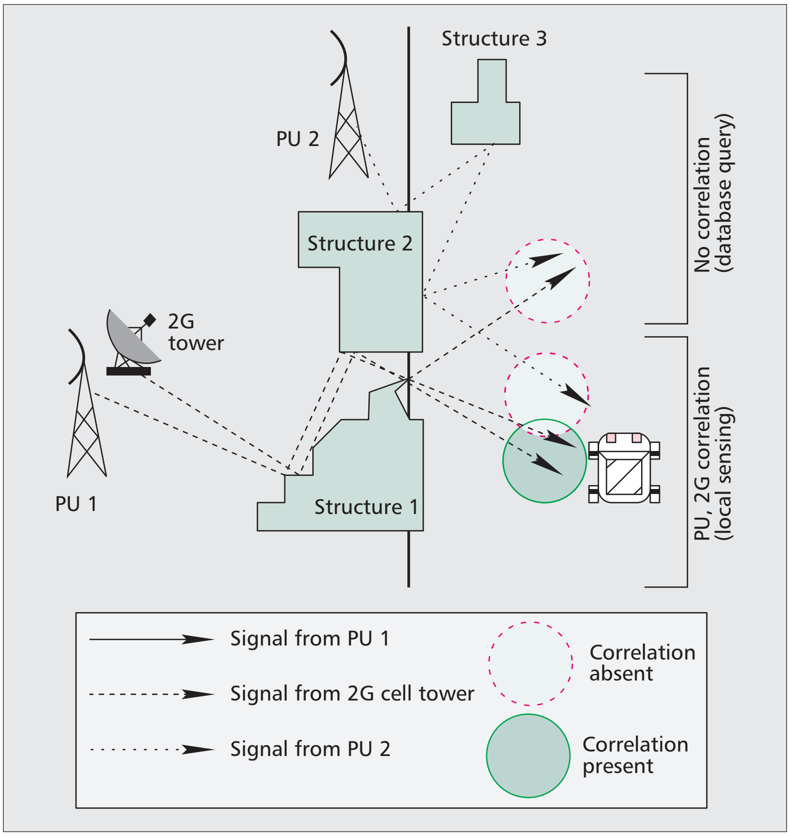

Figure 2. Illustration of the PU and 2G signal correlation that occurs at selected locations in the CRV's path.

Figure 3 presents the simulation results. All spectrum sensing experiences high sensing error rates when vehicles move fast, as vehicles can take only a few samples at a given place. When speed goes up to 20 m/s, the energy detection method suffers from very high sensing error rate and is not much better than random estimation. The belief propagation approach leverages sensing data from other vehicles, through which the effect of noise and stochastic fading can be mitigated. However, in high-speed cases, the improvements remain limited. On the other side, the signal-correlation-based approach described above is able to cut the sensing error rate in half.

Thus, exploiting spectrum measurements from different frequency bands to improve sensing accuracy in a given licensed band without overheads of communicating with other network devices is a viable approach in emergency events.

Research Challenges

The EC-CRVN mitigates congestion and reduces information access delay for affected users by providing them with a means to communicate right after a disaster that wipes out most of the conventional modes of connectivity. However, significant challenges remain in this domain.

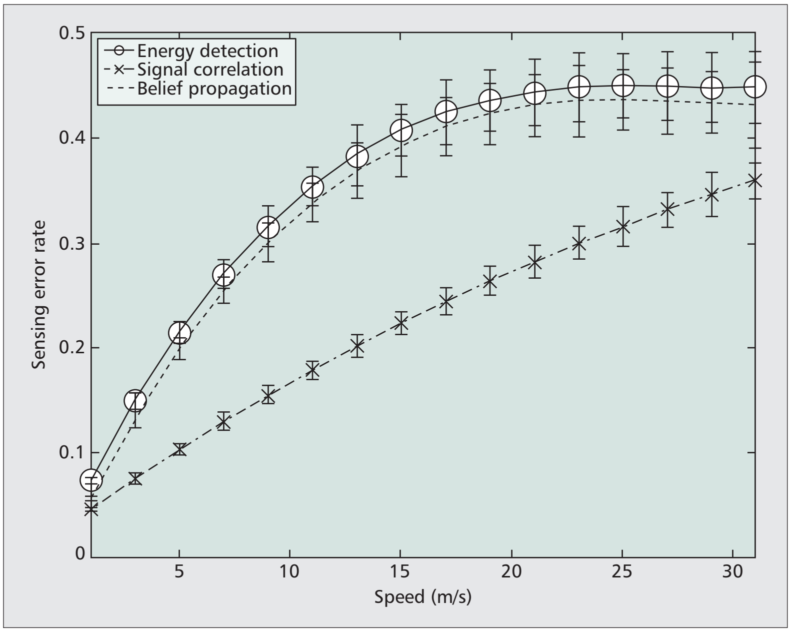

Figure 3. Performance enhancement with the signal correlation approach.

Impact of Latency

There are multiple points of latency that can impact the CRV operation, as described below.

Congestion at the BS: The BS serves as the entry/exit point of communications between the affected area (via the CRV) and the external world. Thus, the BS may become a bottleneck if multiple CRVs attempt to communicate within a narrow window of time.

Number of hops: When CRVs create a multihop forwarding network to emergency providers, each hop contributes to a finite delay. The length of the chain must be carefully controlled with respect to QoS requirements. On the other hand, fewer CRVs may result in large gaps, causing disconnection.

Data mules: Data mules gather data from users and carry it through CRVs' motion toward the desination when communication cannot be established with a roadside BS. However, the physical movement of data mules, especially over damaged roads, can be impaired, leading to large time gaps between successive data downloads.

There can be various approaches to mitigate delay. There must be a distributed priority mechanism among the CRVs for accessing the BS based on the information content, location, and spectrum usage capability, among others. A joint cyber-physical network paradigm may be explored that combines the physical limits of transportation with the cyber aspect of processing and communication. Content-aware communication is a potential way to determine the velocity and routes of data mules.

Need for Routing

Although several routing protocols have been proposed separately for CR networks and vehicular networks, CRV network research is still in its infancy. Typically, in routing protocols for CR networks, the impact of mobility is generally underestimated. Similarly, solutions that work well for vehicular networks do not incorporate the effects of spectrum unavailability. Thus, the EC-CRVN requires robust routing protocols that jointly incorporate mobility and spectrum sensing/switching functions.

Control Channel Saturation

While the TV white space is often leveraged in CR, existing vehicular networks use the DSRC band centered at 5.9 GHz, which also allows a common control channel. This channel is heavily used for supporting tasks of spectrum sharing, frequency switching, and passing safety messages. However, this common control channel can easily be saturated in situations where vehicle densities are high, or when there is a sudden burst of control messages. With a heavily congested control channel, QoS becomes difficult as essential packets can no longer be communicated.

Current research efforts have explored eliminating an exclusive common channel, instead mixing the controlling and data signaling on multiple different channels. However, how to ensure that vehicles are able to listen on different channels at the same time with a limited number of radio interfaces is an open challenge.

Cooperative Sensing Overhead

Cooperative sensing improves over standalone sensing in accuracy. However, this introduces large communication overhead that can adversely impact the spectrum scarcity problem.

In the belief propagation scheme in [10], the authors provide reasoning on how separate belief information exchanging causes lower latency and results in lower channel utilization.

Whether all samples must be exchanged or just the binary results is an open area of research [11]. Improved local spectrum sensing, compared to cooperative sensing, may be needed to achieve higher channel efficiency in emergency events.

Conclusions and Future Directions

In this article, we have described a network architecture for disaster scenarios using CRVs that serve both the general public as well as emergency personnel. We have explored ways to improve local spectrum sensing without contributing to additional overhead. Going beyond the discussions in this article, we envision a future with a prediction-actuation loop that will make intelligent use of spectrum by:

1. Mining data from various different feeds and sources to predict locations prone to large-scale disasters and allocating spectrum in advance in those areas
2. Using CRV technology as a reactive approach once such a tragic event occurs

While existing solutions are largely focused on 2, further investigations through joint considerations of communication needs, economics, and policy are needed to devise viable methods for the predictive approach in 1.

An interesting aspect is developing a *spectrum sense* akin to *civic sense*, where the general public would be encouraged to conserve spectrum through cooperative transmissions, or proactively move to pre-identified locations for their personal communication during emergency events. Thus, personal responsibility in spectrum utilization will ensure that the critical communication needs of the first responders remain unaffected. We believe that only through a synergistic approach that couples social behavior and technology can a suitable framework for disaster-resilient communications be created.

Acknowledgments

This work was supported in part by the U.S. National Science Foundation under research grant CNS-1265166 and the Office of Naval Research under grant number N000141410192.

References

[1] Y. Ran, "Considerations and Suggestions on Improvement of Communication Network Disaster Countermeasures after the Wenchuan Earthquake," *IEEE Commun. Mag.*, vol. 49, no. 1, 2011, pp. 44–47.

[2] W. Kim *et al.*, "CoRoute: A New Cognitive Anypath Vehicular Routing Protocol," *Wireless Commun. and Mobile Computing*, vol. 11, no. 12, 2011, pp. 1588–1602.

[3] J. Liu *et al.*, "Expected Path Duration Maximized Routing Algorithm in CR-VANETs," *IEEE Int'l. Conf. Commun. in China*, Aug. 2012.

[4] M. Pan, P. Li, and Y. Fang, "Cooperative Communication Aware Link Scheduling for Cognitive Vehicular Networks," *IEEE JSAC*, vol. 30, no. 4, 2012, pp. 760–68.

[5] A. J. Ghandour, K. Fawaz, and H. Artail, "Data Delivery Guarantees in Congested Vehicular Ad Hoc Networks Using Cognitive Networks," *IEEE Int'l. Wireless Commun. and Mobile Computing Conf.*, July 2011.

[6] D. Niyato, E. Hossain, and P. Wang, "Optimal Channel Access Management with QoS Support for Cognitive Vehicular Networks," *IEEE Trans. Mobile Computing*, vol. 10, no. 4, 2011, pp. 573–91.

[7] H. E. Ajaltouni, R. W. Pazzi, and A. Boukerche, "An Efficient QoS MAC for IEEE 802.11p over Cognitive Multichannel Vehicular Networks," *IEEE ICC*, June 2012.

[8] N. Cheng *et al.*, "Opportunistic Spectrum Access for CR-VANETs: A Game Theoretic Approach," *IEEE Trans. Vehic. Tech.*, no. 1, 2014, pp. 237–51.

[9] L. Zhang *et al.*, "Cooperative Resource Allocation with QOS Support in Multi-Cell Cognitive Vehicular Networks," *IET Int'l. Conf. Commun. Tech. and Application*, Oct. 2011.

[10] H. Li and D. K. Irick, "Collaborative Spectrum Sensing in Cognitive Radio Vehicular Ad Hoc Networks: Belief Propagation on Highway," *IEEE VTC-Spring*, May 2010.

[11] M. Di Felice, K. R. Chowdhury, and L. Bononi, "Cooperative Spectrum Management in Cognitive Vehicular Ad Hoc Networks," *IEEE Vehic. Net. Conf.*, Nov. 2011.

[12] R. Doost-Mohammady and K. R. Chowdhury, "Design of Spectrum Database Assisted Cognitive Radio Vehicular Networks," *Int'l. Cognitive Radio Oriented Wireless Networks and Commun. Conf.*, June 2012.

[13] M. Di Felice *et al.*, "Integrating Spectrum Database and Cooperative Sensing for Cognitive Vehicular Networks," *IEEE VTC-Fall*, Sept. 2013.

[14] X. Y. Wang and P.-H. Ho, "A Novel Sensing Coordination Framework for CR-VANETs," *IEEE Trans. Vehic. Tech.*, vol. 59, no. 4, 2010, pp. 1936–48.

[15] A. Al-Ali *et al.*, "Querying Spectrum Databases and Improved Sensing for Vehicular Cognitive Radio Networks," *IEEE ICC*, June 2014.

Biographies

Yifan Sun is a Ph.D. student in the Department of Electrical and Computer Engineering of Northeastern University, Boston, Massachusetts. He received his B.S. degree from the Department of Electronic Science and Technology of Huazhong University of Science and Technology in 2011 and his M.S. degree from the Department of Electrical Engineering of the State University of New York at Buffalo. His research interests include network protocol design and optimization, cognitive radio, and full duplex radio.

Kaushik R. Chowdhury [M'09] received his B.E. degree in electronics engineering with distinction from VJTI, Mumbai University, India, in 2003, his M.S. degree in computer science from the University of Cincinnati, Ohio, in 2006, and his Ph.D. degree from the Georgia Institute of Technology, Atlanta, in 2009. His M.S. thesis was given the outstanding thesis award jointly by the Electrical and Computer Engineering and Computer Science Departments at the University of Cincinnati. He is an assistant professor in the Electrical and Computer Engineering Department at Northeastern University. He currently serves on the editorial board of the *Elsevier Ad Hoc Networks* and *Elsevier Computer Communications* journals. His expertise and research interests lie in wireless cognitive radio ad hoc networks, energy harvesting, and intra-body communication. He is the recipient of multiple best paper awards at IEEE ICC.

Personal responsibility in spectrum utilization will ensure that the critical communication needs of the first responders remain unaffected. We believe that only through a synergistic approach that couples social behavior and technology can a suitable framework for disaster-resilient communications be created.