Pervasive Spectrum Sharing for Public Safety Communications

Murat Yuksel, İsmail Güvenç, Walid Saad, and Naim Kapucu

Next-generation public safety communication systems must sustain high-speed, ultra-reliable wireless data transmissions. Moving toward this next generation of PSCs warrants a new perspective of increased heterogeneity in emerging wireless architectures and increased multiplexing of wireless spectrum.

ABSTRACT

Next-generation public safety communications (PSC) systems must sustain high-speed, ultra reliable wireless data transmissions. Moving toward this next generation of PSCs warrants a new perspective of *increased heterogeneity* in emerging wireless architectures and *increased multiplexing* of wireless spectrum. To realize this vision, models that incentivize users to *opportunistically share* their spectrum as substrates over possibly multiple hops, and *decentralized and open* techniques that seamlessly exploit these substrates for public safety applications are much needed. The value of such *multihop and multi-technology pervasive spectrum sharing (PSS)* is more pronounced for application scenarios in which the need for spectrum access is vital, and infrastructure-less operation is necessary. This article introduces PSS as a new architecture where sharing is the norm, and outlines its vision, principles, and technical challenges.

INTRODUCTION

Public safety communications (PSC) carry critical importance to save lives and property in case of incidents such as fires, terrorist attacks, and natural disasters. The National Broadband Plan (NBP) [1] included the enhancement of the nation's PSC capabilities as one key priority. Three major challenges face our nation's public safety agencies in their use of radio communications [2, 3]:

1. Lack of capacity (radio spectrum allocated for public safety use is highly congested, especially in urban areas and during emergencies)
2. Lack of interoperability (multiple frequency bands, incompatible radio equipment, and a lack of standardization)
3. Lack of functionality (e.g., support for high definition video)

Remarkably, until recently, PSC has been handled via narrowband technologies that fall short on addressing the stringent quality of service (QoS) requirements of critical public safety applications.

To move U.S. PSC capabilities toward the next generation, there is an urgent need for pervasive availability of the spectrum with more open boundaries (Fig. 1). This is particularly critical for scenarios that require little or no infrastructure support and involve disaster response and recovery situations [1]. Emerging wireless standards such as fourth generation (4G) Long Term Evolution (LTE) and relatively shorter-range technologies such as WiFi have the potential to transform the capabilities of next-generation PSC systems. In particular, LTE is emerging as a dominant technology to support PSC, as evidenced by its adoption in the United States, Australia, and other countries. These global decisions triggered the Third Generation Partnership Project (3GPP) standardization group to specify advanced functionalities of 4G LTE technology and its evolution, such as device-to-device (D2D) communications, to support specific requirements of PSC [4].

Several advanced methods have been introduced to increase the efficiency of spectrum sharing, such as auctions [5, 6]. Although these advanced approaches have been successful at increasing the efficiency of spectrum sharing in a confined local neighborhood (a.k.a. one-hop relationships), improving spectrum access and efficiency on a larger horizon, such as within PSC and D2D scenarios, requires a truly interdisciplinary effort solving the technical, economic, and policy problems that are involved.

As recently recognized in the Boston Marathon bombings,[1] in an emergency scenario with limited infrastructure and a large number of users overloading the spectrum, it is of paramount importance to utilize all available substrates such as cellular, WiFi, Bluetooth, and multihop communication capabilities (e.g., via WiFi-Direct[2] and/or LTE-Direct[3]) for efficient usage of the spectrum by victims and first responders.

One promising direction in this regard is the recent introduction of D2D communication over cellular and WiFi bands. Indeed, while resource sharing between wireless devices has been traditionally restricted to short-range technologies such as Bluetooth or Zigbee, enabling D2D over cellular and WiFi presents a high-reward opportunity for realizing a *highly participatory and pervasive sharing* of heterogeneous, multi-purpose wireless spectrum resources, to which we will refer hereinafter as pervasive spectrum sharing (PSS). Providing incentives for such pervasive sharing of a valuable resource involves many techno-economic challenges, such as:

Murat Yuksel is with the University of Nevada, Reno; İsmail Güvenç is with Florida International University; Walid Saad is with Virginia Tech and Kyung Hee University; Naim Kapucu is with the University of Central Florida, Orlando.

This work is supported in part by the U.S. National Science Foundation under Grants AST-1444077, AST-1443999, AST-1506297, and AST-1443946. The authors thank Thomas Quint, Arvind Merwaday, Meryem Simsek, and Brie Haupt for discussions and support.

[1] "Cellphone Networks Overwhelmed after Blasts in Boston," The Boston Globe, April 16, 2013; https://www.bostonglobe.com/business/2013/04/16/cellphone-networks-overwhelmed-blast-aftermath/wq7A-X6AvnEemM35XTH152K/story.html

[2] WiFi Direct, http://www.wi-fi.org/discover-and-learn/wi-fi-direct

[3] LTE Direct, http://www.qualcomm.com/research/projects/lte-direct

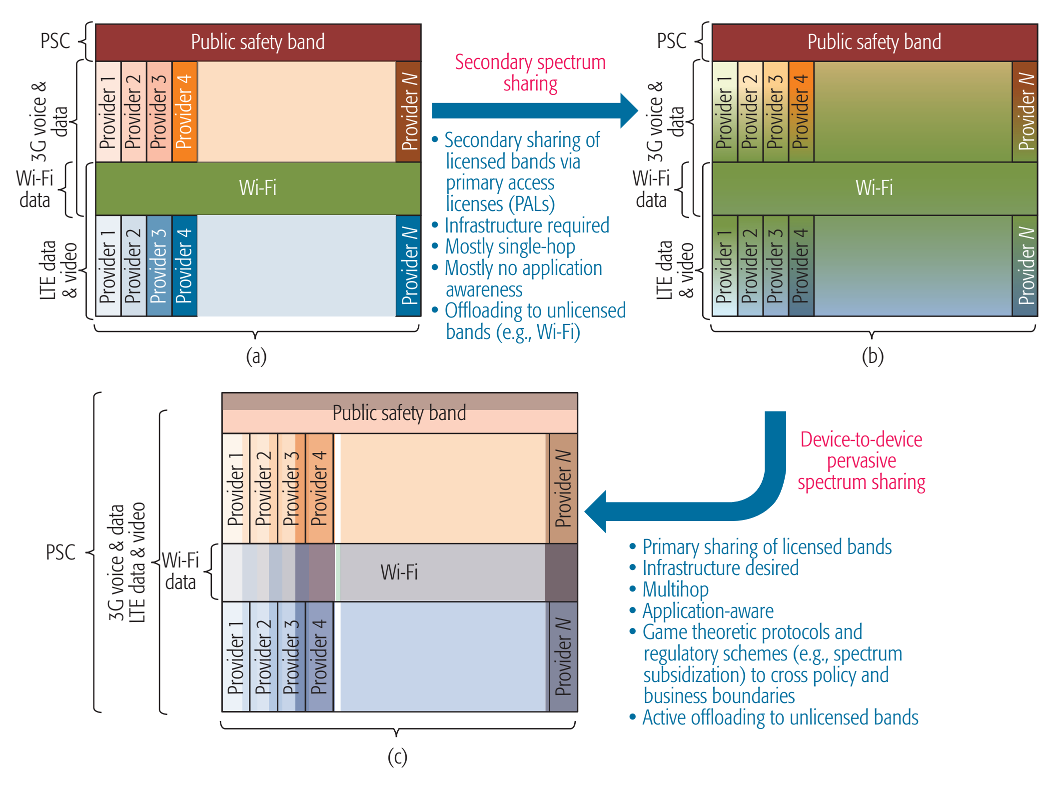

Figure 1. D2D pervasive spectrum sharing. Toward a smoother spectrum usage across licensed, unlicensed, and public safety bands: a) scattered and bordered spectrum with no sharing; b) cross-provider sharing of secondary spectrum when the primary user is idle and offloading 3G and LTE data to WiFi, relieving the spectrum scarcity to some extent; c) cross-provider sharing of primary and secondary spectrum. Coping with critical needs of future services like PSC requires much more active and pervasive sharing at the primary level (e.g., even when the primary user is busy), and across licensed, unlicensed, and restricted bands such as the public safety band.

> PSC for threat prevention and emergency response involves swift usage of available resources. Hallmarks of such a PSC situation are high node density, partial availability of heterogeneous network infrastructure, the urge of surviving against attackers, further/cascading emergency events, and a heavily congested spectrum.

- Incentivization of providers and users to cooperate and share their resources over multiple hops
- Policy decisions and regulations to foster more sharing at all levels from regulatory bodies to the device users
- Seamless D2D negotiation and sharing of wireless connectivity and the spectrum
- Formation and design of multiple, coexisting, and interdependent spectrum sharing groups over large and possibly infrastructure-less areas

The following PSC scenarios illustrate the need for D2D-based PSS.

Scenario I: Scarce Capacity — Trying to Reach Infrastructure Nodes. PSC for threat prevention and emergency response involves swift usage of available resources. Hallmarks of such a PSC situation are *high node density*, partial availability of heterogeneous network infrastructure, and the urgency of surviving against *attackers*, *further/cascading emergency events*, and a *heavily congested spectrum*. As seen in Fig. 2a, each device seeks to reach a close infrastructure node (e.g., access point) to communicate with its destination, for example, to report a scene to an official or contact a loved one. However, the problem of composing usable end-to-end paths is complex, and requires fast and seamless settlement of which device is going to use which resource over a highly dynamic topology. It is further complicated as each device has different capabilities and can only use a certain set of spectrum substrates.

Scenario II: Scarce Power — Trying to Reach Public Safety Officials. In more devastating situations, communicating with a public safety official can make the difference between life or death. Consider devices stranded in rubble after an earthquake. Hallmarks of such a situation include infrastructure-less operation, fast discovery, and, most importantly, using device power wisely. The key metric for PSC in such cases is the outage probability or energy efficiency. The number of devices will likely be sparse; thus, capacity will be less of a concern. But the availability of multiple substrates to contact a nearby public safety official is vital, as seen in Fig. 2b. The devices must resolve among each other how to schedule and use heterogeneous substrates for reliable and low-power communication.

Next, we outline the PSS vision and its architectural principles. Then we discuss challenges in realizing PSS's principles in legacy PSC systems and offer various ideas to tackle them. Finally, we conclude the article.

PSS Vision and Architectural Principles

Given the recent saturation of the licensed radio bands, the adoption of new policies and princi-

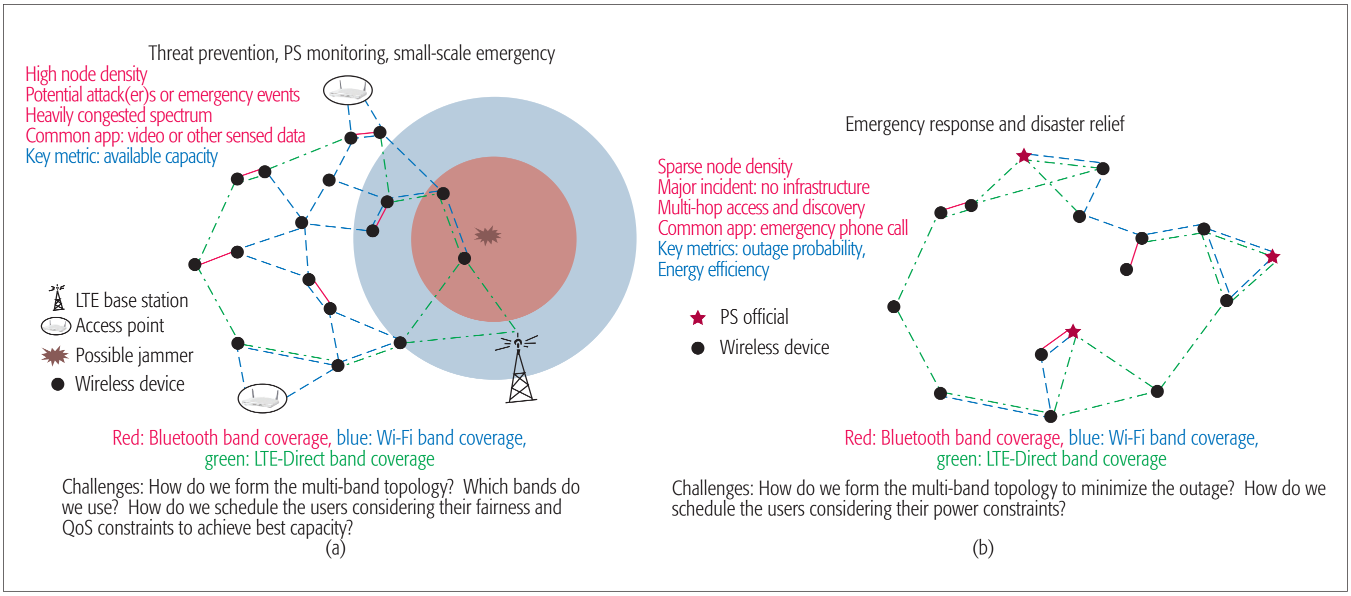

Figure 2. PSC scenarios where D2D PSS will be beneficial: a) scenario I: scarce capacity; b) scenario II: scarce power.

ples is required to address the future needs of PSCs. We envision the following hallmarks of a PSS environment to serve the future PSC applications:

Providers Are Motivated to Share. Currently, spectrum sharing happens at secondary levels, that is, if the primary user is not occupying the channel, another user can use it. Effective utilization of the spectrum is heavily dependent on cross-provider sharing, not just at the secondary level but at the primary one too.

Sharing Is the Norm. Protocol and market designs must be revamped into regimes where sharing is the norm rather than being opportunistic. Wireless protocols and business models sharing spectral resources should retain larger value and generate more revenue.

Government Power Is Wisely Used to Incentivize More Sharing, Particularly for the "Greater Good." Performance-based governmental support and policies should be put in place to foster sharing of the spectrum so that end users can enjoy a better quality service. This is particularly important for PSC applications (e.g., 911 calls and emergency response) that serve the good of the whole society.

These characteristics indicate a spectrum management vision where sharing is pervasive. Attaining such visionary goals requires the following architectural principles for future wireless and PSC systems.

Bottom-Up when Seeking Lower-Level Optimizations. D2D is a great way to discover and exploit spectrum sharing across users and providers. Involving centralized solutions to optimize a local situation may easily become prohibitive due to overhead. Furthermore, PSC scenarios with no or little infrastructure availability force local designs like D2D systems.

Top-Down when Trying to Enforce a Sustainable "Larger Good" Policy. Stakeholders of a multi-owner system like the wireless service provisioning ecosystem rightfully compete for more revenue. Although this competition ensures a healthy market, it can become too aggressive in optimizing the individual benefit at the risk of the larger good. Sharing of a precious resource like spectrum thus requires well designed top-down approaches to policy and regulation. Governments and regulatory agencies must maintain policies for incentivizing operators to share.

Game-Theoretic Designs when Crossing Trust and Administrative Boundaries at Scale. Success of a highly participatory sharing system heavily depends on the incentive (or even urge) of individual device owners. Naturally, most device owners will want to be free riders, unwilling to share their devices' resources. As observed in peer-to-peer systems (e.g., BitTorrent), game-theoretic designs are successful in enforcing sharing at scale. D2D protocols must incorporate simple and effective negotiations to seamlessly form coalitions on the fly so that two conflicting goals can be achieved:

- Fast and efficient wireless downloads/transfers for a device
- Sharing of resources

CHALLENGES AHEAD

HOW TO CONVERGE ON BEST POLICIES AND REGULATIONS

In the current national PSC system, one of the greatest challenges relates to spectrum sharing policies. The U.S. government is seeking to make spectrum more available for mobile use and other services involving wireless broadband technologies [7]. Regulations should allow for growth of wireless and mobile broadband networks to modify and generate new spectrum sharing regulations while also exploring the impact on the effective and efficient utilization of wireless systems. Key assumptions for a model of spectrum sharing include:

- Authority over and responsibility for the PSC system is given to local governments.
- Responsible authorities are limited in the ability to connect and make use of commercial networks for wireless services.
- There are regulations, and spectrum and needed equipment must be dedicated entirely to PSC.

- The principal application is narrowband real-time voice communications [3].

Current practices include authorization by the Federal Communications Commission (FCC) or the President in specific circumstances, and a return to a potential market-based distribution approach. Such a market-based approach was originally developed in the late 1950s with spectrum considered as property. This was efficiently implemented by private users who were considered the best for management purposes since it was assumed that they internalized benefits and costs, and would sell valuable bands to assist the economy. Issues with this exclusive market-based approach soon surfaced regarding license allocation and costs. Although exclusive access eliminated interference, license distribution removed the capability of sharing and limited access. However, tension surfaced between primary and secondary users regarding performance and protections.

According to the President's Council of Advisors on Science and Technology (PCAST), a more constructive management system utilizing allocations and incentives pertaining to spectrum in a market system can use a three-tier interference protection: incumbent, secondary, and general authorized access. The authors in [8] proposed a two-stage pricing combination. The first uses a sound static pricing policy that sets a specific level of commercial traffic. This is followed by an optimal dynamic policy for admission control. The benefits of such a combination include efficient spectrum sharing without requiring additional availability, more stable revenue between commercial networks and users, and an ability to adapt quickly to network conditions [8]. The current management systems of spectrum sharing include the spectrum access system (SAS) and the emergency response interoperability center (ERIC). A SAS allows spectrum allocation between commercial and federal entities, while an ERIC is a committee-based partnership to establish a common technical framework through issues of security, roaming, and priority access. The FCC is responsible for conducting an incentive auction to reallocate spectrum for mobile broadband uses and funded FirstNet,[4] which is the first high-speed nationwide broadband network dedicated to public safety.

Regardless of policy, a pervasive notion of spectrum sharing is dependent on a shift in mindset from the traditional operators [7]. Operators must adapt and utilize cognitive technologies to navigate dynamic spectrum availability. Making decisions regarding spectrum sharing regulations affects a multitude of stakeholders due to band availability along with long-term and short-term needs as well as variations between licensed and unlicensed bands [7]. Acknowledging who is utilizing spectrum is an important aspect for government to be aware of when generating policies for effective spectrum sharing in response to unexpected public safety challenges.

More policy adaptations occurred during the establishment of the Department of Homeland Security (DHS) in 2003, and Title XVIII of the Homeland Security Act of 2002 leading to the establishment of the DHS Office of Emergency Communications. The evolution continued with the National Preparedness Goal promoting *shared responsibility* across all sectors as well as a Quadrennial Homeland Security Review identifying threats with strong implications for national resilience and preparedness. The National Response Framework (NRF) provided a template for agencies to determine appropriate levels for federal involvement regarding domestic incidents. Moreover, this plan supported harmonization and an inter-agency incident management system to handle determined incidents of national significance.

To fund this venture, responsibility was given to the FCC to conduct a two-sided auction for spectrum reallocation and to continue development of their main emergency communications components:

- The 911 call processing and delivery system
- The emergency alert system
- The radio/broadcast or television system

In addition, the NBP [1] was developed to strategize a 10-year implementation plan for a PSC infrastructure. The NBP is a multi-faceted approach to wireless infrastructure through:

- Hardened radio access network infrastructure to enable a higher degree of coverage and resilience
- Priority roaming on commercial networks for additional capacity and increased network resilience
- Mobile technology for coverage during failures or remoteness

The collection of these services influences the broadband ecosystem in four ways:

- Maximizes consumer welfare, investment, and innovation through policies designed for robust competition
- Encourages competitive entry and network upgrades through government influences or controls to ensure management and efficient allocation
- Boosts adoption and utilization and ensures affordability through reform relating to current deployment of universal service mechanisms
- Maximizes benefits for various sectors through policy, standards, incentives, and law reform

Since events like 9/11, emergency and disaster management planning has focused on enhancing and managing collaborations between stakeholders regarding access and operation [9]. In addition, the integration of policies and procedures is challenging and requires a great deal of time. Once strategic plans are in place, policy makers must begin to predict future needs, such as changes due to population and terrain, as gaining access to spectrum and connecting infrastructure will, at some point, compromise public safety objectives. Regardless of the challenges, the development and growth of a national public safety system is not a hopeless cause, as seen through the coordination of response agencies during the Boston Marathon bombings [9].

Once strategic plans are in place, policy makers must begin to predict future needs, such as changes due to population and terrain, as gaining access to spectrum and connecting infrastructure will, at some point, compromise public safety objectives

How to Incentivize Providers

A major impediment for PSS is the providers' tendency to protect the bands they earned with a lot of licensing and operating costs. Adopting new technologies to facilitate D2D spectrum

---

[4] FirstNet: First Responder Network Authority, http://www.firstnet.gov

Beyond incentivizing providers, there is also a need to incentivize the users themselves to share spectrum resources. In particular, the wide-scale use of D2D communication is of paramount importance in public safety scenarios where it is likely that the infrastructure will be damaged.

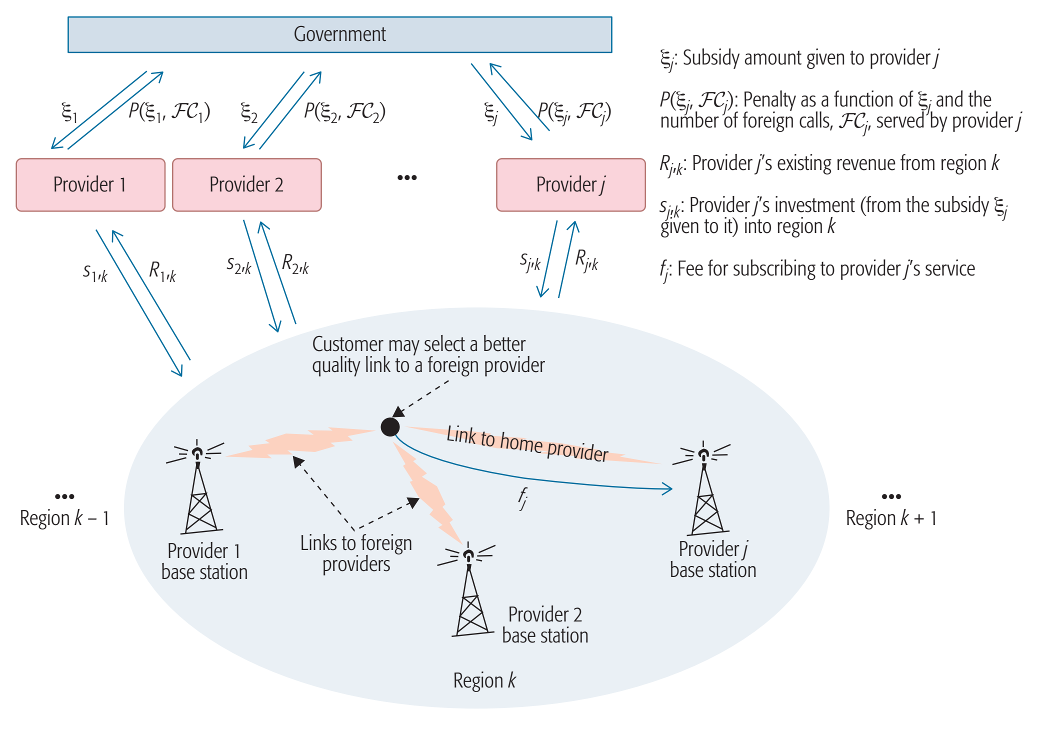

Figure 3. Model for a performance-based spectrum subsidy market.

sharing has become a key policy consideration for spectrum management. Current spectrum usage [10] heavily follows competitive auctions, which can balance standardization trends, Current policies [1] dictate that competitive auctions must remain intact, while simultaneously incorporating new ways to share and manage spectrum usage (e.g., via D2D). In such policies, developing *a governance structure for public safety broadband networks* and *making more spectrum available for PSC* is critical [10] and necessary for enabling heterogeneous spectrum sharing.

To foster more sharing of the spectrum via large-scale D2D, regulatory power can be introduced. In fact, the NBP [1] recommends the widespread development of the concept of "spectrum subsidy," for example, licensing of the D block for commercial use if *public safety partnerships* are considered by the licensee. Here, we leverage this idea of subsidizing the spectrum to the providers with lower costs in return of "proof of sharing." Thus, providers will be offered discounted bands, potentially at different locations, but will be asked to cover users not subscribed to them to maintain their subsidy incentives from the government (i.e., to sustain spectrum sharing via D2D).

Recent studies suggest significant market and user welfare gains under such subsidization (e.g., data subsidy for offering minimal data plans to users for free) [11]. To understand spectrum subsidization, we introduce a game-theoretic market model with three types of players, as shown in Fig. 3: customers, providers, and the government. Customers are end-user devices spread out to regions who engage in localized spectrum sharing markets, as discussed in the next subsection. Customers are subscribed to a "home" provider. In a quest for better experience, they are given the option to dynamically select another provider's base station if the signal quality may be better.

Providers operate in all regions and receive monetary subsidies, which they use for improving their infrastructure in regions where their service quality is weaker. After a subsidy interval (e.g., a month), a provider j may have to return some or all of its subsidy, ξ_j, back to the government if its "sharing performance" was not good. As a proof of sharing to avoid the penalty, provider j keeps track of the number of foreign customers it served, $\mathcal{FC}_j$. The penalty, $P(\xi_j, \mathcal{FC}_j)$ is a monotonically increasing function of the proof of sharing, $\mathcal{FC}_j$. In such markets, provider j solves the following optimization:

$$\max_{\{s_{jk}\}, f_j} \sum_{k=1}^{K} R_{jk} + (\xi_j - P(\xi_j, \mathcal{FC}_j)) - \sum_{k=1}^{K} s_{jk} \qquad (1)$$

where the first term is the total revenue, the second is the leftover subsidy money after the penalty is deducted due to less than required sharing of spectrum, and the last term is the total amount of expenses the provider uses from its subsidy. The provider's controls are the amount of investment it makes into a region k, $\{s_{jk}\}$, and the subscription fee, f_j, that it charges to its customers.

Finally, the government's decision variables are ξ_j and the penalty function $P(.)$. An important feature of this model is that the government motivates the providers to give service to customers who are far away from the base stations of their *home providers*. The government aims to motivate foreign providers by reducing each provider's subsidy if the provider does not service enough "foreign" customers. This penalty motivates the providers to serve foreign customers at the primary level, sometimes instead of their own customers. Hence, the penalty function $P(.)$ makes this subsidization scheme a "performance-based" one, so providers that attained more sharing of their licensed spectrum bands will have to return less of their subsidy to the government.

Our preliminary results show the impact of subsidy on provider revenue for a simple two-provider scenario. We considered two regions with two providers having 10 and 60 users, which corresponds to a weak and a dominant provider, respectively. The government's total subsidy budget is set to $\xi_1 + \xi_2 = 500$. We looked at two scenarios with $\beta = 20$ and $\beta = 40$, where β denotes the average number of calls made by a user via its home provider. Assuming users' calls via providers are proportional to their monetary and hence infrastructural strength [12], we solved Eq. 1 to find the optimal revenue. Figure 4 shows the dependence of the individual and total provider revenue on the government subsidy. Results show that the subsidy monotonically improves the revenue, and the government can control (ξ_1, ξ_2) to facilitate spectrum sharing between providers, while guaranteeing their profit. Our recent work [12] further showed that subsidization will:

- Be more beneficial for smaller providers, allowing them to compete better against large providers
- Motivate providers to invest in regions with weaker coverage

How to Incentivize Users

Beyond incentivizing providers, there is also a need to incentivize the users themselves to share spectrum resources. In particular, the widescale use of D2D communication is of paramount importance in public safety scenarios where it is likely that the infrastructure will be damaged. In such scenarios, the key challenges include:

- Neighbor discovery
- Enabling multiple levels of cooperation between devices ranging from sharing spectrum to performing standard cooperative transmission
- Analyzing how the devices can interact with one another and form D2D groups

For neighbor discovery, traditional D2D typically relies on detecting uplink cellular transmissions. However, in PSC such detection may not be possible due to lack of infrastructure and thus the lack of any uplink transmissions. Here, one can develop new techniques built on some concepts that are routed in ad hoc networks. For example, rendezvous techniques that rely on temporary traffic ad hoc control channels can be used. Alternatively, devices can use historical data from D2D communication or historical encounters to attempt to discover their D2D neighbors.

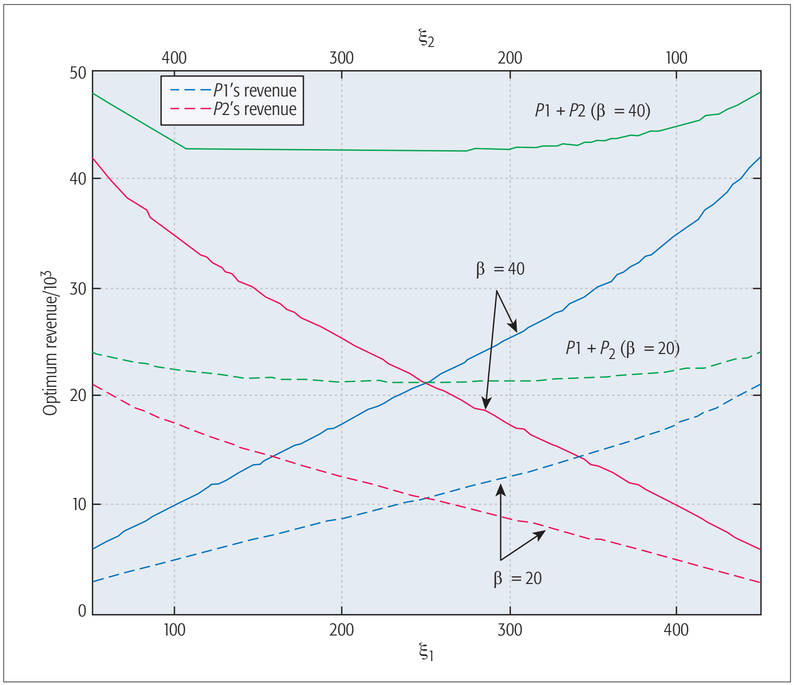

Figure 4. Provider revenue vs. subsidy.

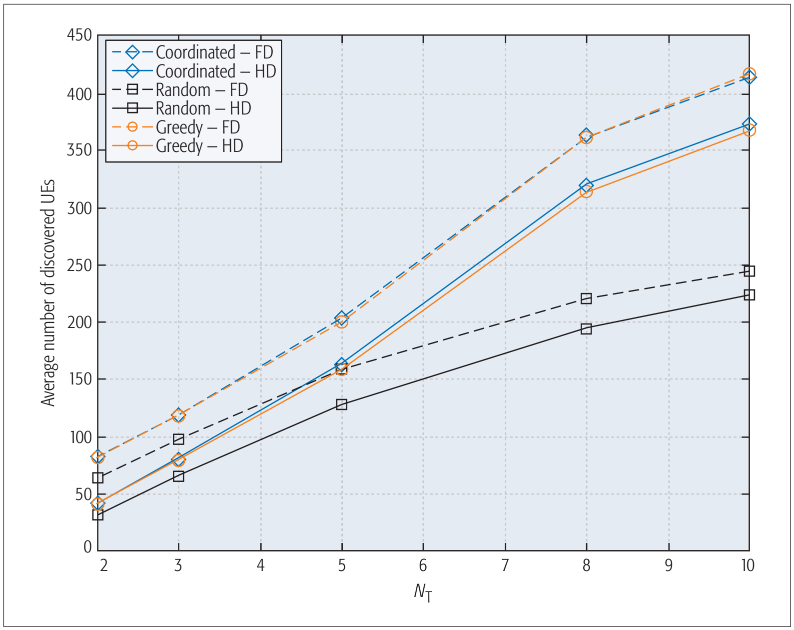

Figure 5. Number of discovered users vs. discovery symbols N_T in 3GPP system-level simulations.

Due to its promise in proximity services (ProSe) and PSC, D2D device discovery has also received significant interest from 3GPP. In 2012, a new study item was created to study LTE ProSe, and its initial focus was D2D user discovery. In particular, in a typical communication environment, users have to select discovery resources and transmit discovery signals so that they can be identified by other nearby users. To this end, in [13], we compared the performance of three different discovery techniques considering 3GPP-compliant simulations: random, greedy, and centralized discovery resource selection. In the random approach, each user randomly selects a discovery resource to transmit its discovery signal, which may result in collisions if the same resources are used by multiple nearby users. The greedy approach, on the other hand, selects resources with minimal interference levels. Finally, the centralized approach centrally assigns discovery resources to users, assuming that locations of all users are known at the centralized scheduler.

In Fig. 5, we show the performance of the

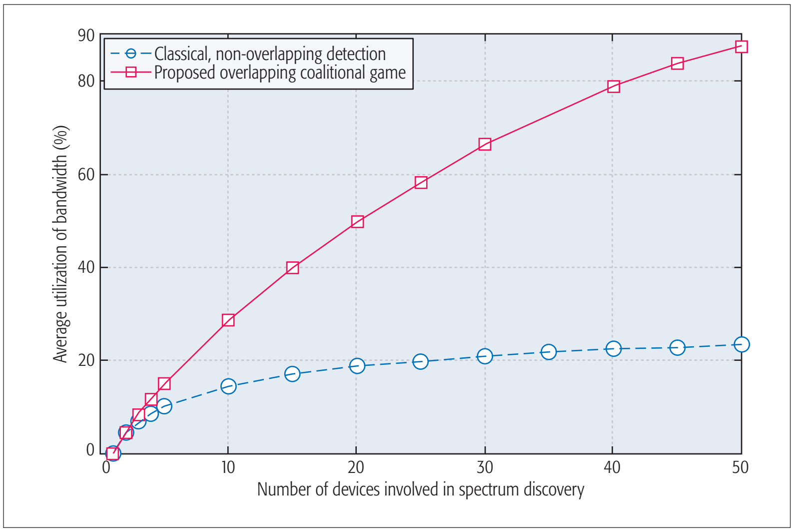

Figure 6. Benefits of overlapping coalition formation for spectrum detection.

D2D discovery algorithms in terms of average number of discovered user equipments (UEs) vs. the number of discovery opportunities, N_T. We consider a macrocell consisting of three sectors with different ISDs for each simulation layout. A hotspot simulation layout that may happen occasionally in public safety scenarios is also considered. Here, based on the simulation assumptions agreed on in 3GPP [13], two-thirds of the UEs are dropped within a circle with radius of 40 m, and the remaining UEs are uniformly distributed. The solid lines in Fig. 5 represent the half-duplex (HD) discovery case and dashed lines the full-duplex (FD) scenario. For each D2D discovery algorithm, it can be observed that the FD case always outperforms the HD case since devices transmitting in the same slot can also be discovered in FD. For small N_T, the algorithms show similar performance. For larger N_T, the random discovery selection method shows the weakest performance due to collisions during random discovery resource selection of UEs. The coordinated discovery resource selection algorithm, which is a centralized algorithm based on path loss estimation using known D2D distances, obtains slightly better performance than the greedy approach, which is a distributed approach based on known received powers.

Once D2D discovery is done, the next step is to effectively share resources and cooperate. Here, cooperation can be at different levels and network layers. For example, the devices can simply cooperate to form a local D2D LAN to share information (e.g., a local D2D LAN between first responders), or they can cooperate to form a spectrum market. Similarly, devices can cooperate to relay each other's data over multiple hops to disseminate certain emergency messages. In some cases, only part of the infrastructure is damaged, so users can cooperate to use spectrum-sensing-like techniques to detect neighbors. However, since only a few neighbors will access the infrastructure, the devices will need to cooperate to improve their detection capabilities in the presence of limited infrastructure access. Clearly, device cooperation for PSC must satisfy key characteristics:

- Lack of infrastructure
- Presence of multiple coexisting and interdependent cooperative groups
- Heterogeneity in terms of resources and node types
- Distributed decision making such that each device can, during an emergency, individually decide on which resource to share and with which neighbors

This, in turn, requires introducing new self-organizing approaches to incentivize users to form cooperative groups, or *coalitions*, to share resources, and cooperate at multiple levels. Here, one suitable framework is that of *coalitional game theory*. Coalitional game theory enables multiple devices to individually weigh in the mutual benefits and costs of cooperation and then decide on whether to cooperate or not. Despite the surge of works on coalitional games for wireless networks, most existing approaches have one limitation: they assume that users can only belong to one coalition. In public safety scenarios, users can share resources with multiple coalitions simultaneously. To this end, one must expand existing models to account for *overlapping coalition formation* cases in which a device can belong to multiple coalitions simultaneously. While the mathematical details of overlapping coalition games are outside the scope of this article (the reader is referred to [14] for one possible approach), it is important to note that such game models can yield a suite of algorithms that can be used by devices to autonomously form cooperative groups, which can include spectrum markets, multihop communication, cooperative sensing, or simply cooperative formation of overlapping D2D LANs.

Using an overlapping coalitional game, one can characterize how a PSC network can autonomously form local D2D communication pairs to share resources and incentivize users to forward each other's packets. Several design questions must be addressed such as how to model mutual benefits and costs that pertain to QoS metrics such as energy, rate, and even neighbor discovery performance; how to handle the interdependence between user-level resource sharing and providers' participation; and how to ensure that cooperation is beneficial not only to individual users, but also to the public safety system as a whole. Moreover, within each formed coalition, devices may be engaged in other optimization or game-theoretic mechanisms. Therefore, one must build multi-level games that include an overlapping coalitional game with underlaid uncooperative or even auction games for resource sharing within each coalition. Last but not least, public safety scenarios may require the deployment of mobile base stations that are integrated in public safety personnel cars or even on unmanned aerial vehicles. The interdependence between such mobile base stations and D2D formation is critical in PSC, as studied in our work in [15].

To illustrate the benefits of overlapping coalition formation, in [14], we adopted this framework to allow neighboring devices to collaboratively detect available spectral bands by sharing spectrum sensing results. These results are then collectively combined within a coalition to get a final decision on whether a certain band is vacant or not. In this model, a device may share its sensing result with multiple coalitions simultaneously. This collaborative detection automatically yields better spectrum usage. Figure 6 shows that additional sharing of spectrum detection results via an overlapping coalitional game formulation can yield significant gains in terms of the percentage of bandwidth (i.e., spectrum) utilization, compared to traditional collaborative approaches with no overlapping coalition.

Clearly, large-scale cooperation between devices of a PSC system is a critical challenge that must be addressed in order to generate a new breed of systems with users who can autonomously form coalitions and cooperate effectively under infrastructure-less scenarios.

> Clearly, large-scale cooperation between devices of a PSC system is a critical challenge that must be addressed in order to generate a new breed of systems whose users can autonomously form coalitions and cooperate effectively under infrastructure-less scenarios.

SUMMARY

In this article, we have studied the potential of PSS for PSC applications. We have outlined three hallmarks for successful PSS: providers are motivated to share; sharing is the norm; and government power is wisely used to incentivize more sharing. We have shown how the realization of PSS requires multiple architectural principles to be adopted: bottom-up approach when seeking lower-level oa ptimizations, a top-down approach when trying to enforce sustainable and "larger good" policies, and game-theoretic designs when crossing trust and administrative boundaries at scale. In a nutshell, we have shown that moving toward a new breed of PSC systems requires overcoming key technical and regulatory challenges that include how to converge on best policies and regulations, how to incentivize providers, and how to incentivize users.

REFERENCES

[1] FCC, "Connecting America: The National Broadband Plan," Mar. 2010; http://download.broadband.gov/plan/national-broadband-plan.pdf.

[2] L. E. Miller, "Wireless Technologies and the SAFECOM SoR for Public Safety Communications," tech. Rep, NIST, Gaithersburg, MA, 2005; http://w3.antd.nist.gov/pubs/WirelessAndSoR060206.pdf.

[3] J. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," *Proc. IEEE*, vol. 97, no. 4, 2009, pp. 708–19.

[4] X. Lin *et al.*, "An Overview of 3GPP Device-to-Device Proximity Services," *IEEE Commun. Mag.*, vol. 52, no. 4, 2014, pp. 40–48.

[5] Y. Zhang *et al.*, "Auction Approaches for Resource Allocation in Wireless Systems: A Survey," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 3, July 2013, pp. 1020–41.

[6] G. S. Kasbekar and S. Sarkar, "Spectrum Pricing Games with Spatial Reuse in Cognitive Radio Networks," *IEEE JSAC*, vol. 30, no. 1, 2012, pp. 153–64.

[7] L. Doyle and T. Forde, "A Regulatory Perspective on Cognitive Radio and Spectrum Sharing," *Cognitive Radio and Networking for Heterogeneous Wireless Networks*, ser. Signals and Communication Technology, Springer Int'l. Publishing, 2015,, pp. 257–89.

[8] Q. Wang and T. Brown, "Public Safety and Commercial Spectrum Sharing Via Network Pricing and Admission Control," *IEEE JSAC*, vol. 25, no. 3, 2007, pp. 622–32.

[9] Q. Hu, C. C. Knox, and N. Kapucu, "What Have We Learned Since September 11, 2001? A Network Study of the Boston Marathon BombingsResponse," *Public Admin. Rev.*, vol. 74, no. 6, 2014, pp. 698–712.

[10] L. K. Moore, "Spectrum Policy in the Age of Broadband: Issues for Congress," CRS Report for Congress, Feb. 2010, pp. 1–28; http://fpc.state.gov/documents/organization/138723.pdf

[11] S. M. Yu and S.-L. Kim, "Guaranteeing User Welfare in Network Service: Comparison of Two Subsidy Schemes," *Perf. Eval. Rev.*, vol. 40, no. 2, Sept. 2012, pp. 22–25.

[12] M. Yuksel *et al.*, "Fostering Wireless Spectrum Sharing Via Subsidization," *Proc. IEEE Annual Allerton Conf. Commun., Control, and Comp.*, Urbana-Champaign, IL, Oct. 2013, pp. 1192–99.

[13] M. Simsek *et al.*, "Device-to-Device Discovery Based on 3GPP System Level Simulations," *Proc. IEEE GLOBECOM Wksps.*, 2013, pp. 555–60.

[14] T. Wang *et al.*, "Cooperative Spectrum Sensing in Cognitive Radio Networks: An Overlapping Coalition Formation Game Approach," *IEEE Trans. Commun.*, vol. 62, no. 9, Sept. 2014, pp. 3144–60.

[15] M. Mozaffari *et al.*, "Drone Small Cells in the Clouds: Design, Deployment and Performance Analysis," *GLOBECOM*, San Diego, CA, Dec. 2015.

BIOGRAPHIES

MURAT YUKSEL [SM'11] (yuksem@unr.edu) received his B.S. degree in computer engineering from Ege University, Izmir, Turkey, in 1996, and his M.S. and Ph.D. degrees in computer science from Rensselaer Polytechnic Institute (RPI), Troy, New York, in 1999 and 2002, respectively. He is an associate professor at the Computer Science and Engineering Department, University of Nevada-Reno (UNR). Prior to UNR, he was with the Electrical and Computer Science Engineering Department, RPI, as a postdoctoral associate and a member of adjunct faculty until 2006. He was a software engineer at Pepperdata (Sunnyvale, California) and a visiting researcher at AT&T Labs and Los Alamos National Laboratory. His research interests are in networked, wireless, and computer systems with a recent focus on big data networking, UAV networks, optical wireless, public safety communications, device-to-device protocols, economics of cyber security and cyber sharing, routing economics, network management, and network architectures. He has been on the Editorial Board of *Computer Networks*, published more than 100 papers in peer-reviewed journals and conferences, and received the IEEE LANMAN 2008 Best Paper Award. He is a Senior Member and Life Member of the ACM, and was a member of Sigma Xi and ASEE.

İSMAIL GÜVENÇ [SM'10] (iguvenc@fiu.edu) received his Ph.D. degree in electrical engineering from the University of South Florida in 2006, with an outstanding dissertation award. He was with Mitsubishi Electric Research Labs during 2005, and with DOCOMO Innovations Inc. between 2006 and 2012, working as a research engineer. Since August 2012, he has been an assistant professor with Florida International University. His recent research interests include heterogeneous wireless networks and 5G wireless systems. He has published more than 100 conference/journal papers and book chapters, and several standardization contributions. He co-authored/co-edited three books for Cambridge University Press, served as an Editor for *IEEE Communications Letters* (2010–2015) and *IEEE Wireless Communications Letters* (2011–present), and as a Guest Editor for several other journals. He is an inventor/coinventor in 23 U.S. patents, and has another 4 pending U.S. patent applications. He was a recipient of the 2014 Ralph E. Powe Junior Faculty Enhancement Award and the 2015 NSF CAREER Award.

WALID SAAD [SM'15] (walids@vt.edu) received his Ph.D degree from the University of Oslo in 2010. Currently, he is an assistant professor and the Steven O. Lane Junior Faculty Fellow at the Department of Electrical and Computer Engineering at Virginia Tech, where he leads the Network Science, Wireless, and Security (NetSciWiS) laboratory within the Wireless@VT research group. His research interests include wireless networks, game theory, cybersecurity, and cyber-physical systems. He was the recipient of the NSF CAREER award in 2013, the AFOSR summer faculty fellowship in 2014, and the Young Investigator Award from the Office of Naval Research (ONR) in 2015. He was the author/co-author of five conference best paper awards at WiOpt 2009, ICIMP 2010, IEEE WCNC 2012, IEEE PIMRC 2015, and IEEE SmartGridComm 2015. He was the recipient of the 2015 Fred W. Ellersick Prize from the IEEE Communications Society. He serves as an Editor for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Communications*, and *IEEE Transactions on Information Forensics and Security*.

NAIM KAPUCU (Kapucu@ucf.edu) is a professor of public policy and administration and director of the School of Public Administration at the University of Central Florida (UCF). He is also the founding director of the Center for Public and Nonprofit Management (CPNM) at UCF. His research interests are collaborative governance, emergency and crisis management, decision making in complex environments, social inquiry and public policy, and scholarship in teaching and learning. He teaches network governance, collaborative public management, emergency and crisis management, methodology, and leadership courses. He received his Ph.D. in public and international affairs from the Graduate School of Public and International Affairs at the University of Pittsburgh, Pennsylvania, in 2003. Prior to that, he earned a Master of Public Policy and Management degree from Heinz College's School of Public Policy and Management, Carnegie Mellon University, Pittsburgh, Pennsylvania, in 1997.