



# TCCN Communications

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## Director's Message

Dear Fellow TCCN Members,

I am very happy to introduce to you the inaugural issue of TCCN Communications. I would like to express my sincere thanks to TCCN Chair, Dr. Ying-Chang Liang, and other TCCN officers for their enthusiastic support for starting this initiative to serve the community.

TCCN Communications is a bi-annual electronic platform dedicated to excel in the following aspects:

- Introducing forward-looking research ideas,
- Updating members on new industry, standard, and policy initiatives,
- Promoting top-quality publications with high potential impacts,
- Increasing the visibility of TCCN within ComSoc and beyond.

This inaugural November 2015 issue includes two special issues on some very hot topics of cognitive communications and networking:

- A special issue on “Cognitive Radio for Heterogeneous Networks” edited by Prof. Walid Saad from Virginia Tech,
- A special issue on “TV White Space Communications and Networking” edited by Prof. Yue Gao from Queen Mary University of London.

These two special issues contain a total of 13 contributions from leading experts in the field, and cover both recent progress and forward-looking insights regarding technology, economics, and regulations of cognitive radio networks. I would like to congratulate Walid and Yue for the excellent work. I also want to thank Prof. Lingjie Duan from Singapore University of Technology and Design for taking care of the formatting and final editing details as the Publication Editor.

Besides publishing the special issues, we plan to further recommend selected top papers and PhD Dissertations in future TCCN Communication issues. We also welcome any suggestions from TCCN members regarding how to make this platform most interesting and useful to the community. Please feel free to contact me at [jwhuang@ie.cuhk.edu.hk](mailto:jwhuang@ie.cuhk.edu.hk) if you have any suggestions.

Thanks and best regards,



IEEE Fellow (Class of 2016)  
Vice Chair, IEEE TCCN  
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**Editorial: Cognitive Radio for Heterogeneous Networks**

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Future wireless networks are expected to be largely heterogeneous, in terms of the available spectrum bands, types of devices and their capabilities, as well as the overall types of traffic and wireless services that must be sustained by such wireless networks. Communications in such *heterogeneous wireless networks* requires significant advances to the way in which networks operate and manage their resources. In particular, concepts from *cognitive radio* systems in which the network can smartly learn and adapt to its environment are crucial for enabling communications in heterogeneous networks.

This special issue brings together a number of contributions that touch upon the challenges and opportunities brought forward by cognitive radio for heterogeneous networks. In the first paper by *Haykin and Setoodeh*, the authors focus on developing new cognitive radio notions for resource sharing among multiple networks, in a heterogeneous environment. This is done via a holistic view that captures both network metrics, such as energy and spectrum, as well as economic drivers. This topic of spectrum sharing and utilization is further emphasized in the next article by *Mandayam and Raychaudhuri* who investigate the challenges of spectrum sharing within a software defined (SDR/SDN) environment. The next article by *Olfat, Reed, and Schaubach* zooms in on transmit power requirements for spectrum sharing within the scope of the citizen broadband radio service (CBRS) framework for 3.5 GHz.

Next, the paper by *Liu, Xiao, and Soong*, delves into the challenges brought forward by the ultra-dense nature of future heterogeneous networks. In particular, this paper discusses the challenges of effective spectrum utilization in ultra-dense heterogeneous networking environments, while providing the industry's perspective on the matter. The subsequent two articles focus on two emerging issues: the use of graph compression techniques for enabling cognition and the role of network virtualization. In particular, the contribution of *Levorato, Mitra, and Ortega*, discusses the application of sparse approximation and graph signal processing to improve the overall learning and estimation

process of next-generation cognitive radio networks. Last but not least, the work of *DaSilva* discusses the role of network virtualization in future wireless networks. In particular, it touches upon the challenges of virtualization at all network levels and layers, ranging from network architecture to resource management.

In a nutshell, this special issue gathers together state-of-the-art contributions that touch upon all aspects of cognitive radio for heterogeneous networks, starting from spectrum sharing all the way to virtualization and large-system analysis. We believe that the techniques and results discussed in these position papers will pave the way towards a plethora of novel research directions pertaining to cognitive heterogeneous networks.



**Walid Saad** (S'07, M'10, SM'15) received his Ph.D degree from the University of Oslo in 2010. Currently, he is an Assistant Professor at the Bradley 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 and social networks, game theory, cybersecurity, and cyber-physical systems. Dr. Saad is the recipient of the NSF

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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 three conference best paper awards at WiOpt in 2009, ICIMP in 2010, IEEE WCNC in 2012, and IEEE PIMRC in 2015. He is the

recipient of the 2015 Fred W. Ellersick Prize from the IEEE Communications Society. Dr. Saad serves as an editor for the IEEE Transactions on Wireless Communications, IEEE Transactions on Communications, and IEEE Transactions on Information Forensics and Security.

## Cognitive Heterogeneous Networks: Economic Provisioning for 5G

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### 1. The Role of Cognition in HetNets

*Heterogeneous networks* (HetNets) provide an innovative and intelligent, yet realistic and pragmatic approach for expanding mobile network capacity in order to cope with the ever-increasing mobile broadband traffic [1]. In this newly-emerged communication network paradigm, low-power nodes such as femtocells and relay nodes are deployed within macrocells [2]. Moreover, a variety of radio access technologies, architectures, and transmission schemes may be employed in the network [1]. The kind of hyper-densification of small cells proposed by the HetNet paradigm can be considered as one of the key enabling technologies for 5G. The 5G must support an extremely wide range of wireless devices and in effect therefore, by moving towards the 5G, the heterogeneity of networks will significantly increase [3].

In HetNets, while macrocells are responsible for broad coverage, femtocells are placed at the coverage holes of the macrocells as well as close to the high-demand locations [4]. In addition to femtocells, relay nodes are deployed close to the cell edge to improve coverage [2]. Interference management (both intracell and intercell) is a critical issue in HetNets and calls for careful resource partitioning [4]. Moreover, in hyper-dense HetNets, challenges such as resource utilization, cell association, fairness, complexity, QoS, self-organization, mobility management, and *green communication* deserve special attention [2], [4].

In addition to energy efficiency, enhancing spectral efficiency through spatio-temporal reuse of spectrum has been a major concern in recent years. It continues to be a key challenge for the 5G as well. Cognitive radio is expected to play a key role in improving the efficiency of spectrum utilization [5]. Spectrum markets can provide a driving force for more efficient spectrum allocations through secondary usage [6]. Such markets and even the whole communication network can be viewed as supply chain networks, in which the spectrum plays the role of a commodity or product [7]. This framework can capture the dynamics of spectrum sharing among

different users in both unlicensed and licensed bands. In the most general scenario, a user's demand can be met by taking a share from unlicensed bands and leasing (i.e., buying the right for temporarily using of) some licensed subbands. Spectrum markets can be managed by brokers, who buy and sell the right of using idle subbands over different time scales [6]. However, two different sets of brokers may be involved in the spectrum supply chain, where one set of brokers negotiate on behalf of the legacy owners and the other set on behalf of the secondary users.

More efficient utilization of the spectrum can be achieved through resource sharing among different networks. In this regard, resource allocation is viewed as a collaborative problem solved by a set of networks, which requires autonomous dynamic *reconfiguration* for the distribution of information and skills as well as adjusting goals [8]. Resource allocation in communication networks is a distributed-constrained optimization problem. Taking a network-centric (i.e., centralized) approach may lead to an optimal solution that is computationally intractable. On the other hand, terminal-centric (i.e., decentralized) radio resource-management schemes may lead to equilibria that are far from optimal solutions, which can be provided by centralized approaches. In other words, in decentralized approaches, phenomena such as *tragedy of the commons* usually lead to inefficient equilibria. In order to improve the quality of the equilibrium in heterogeneous wireless networks, two operations can be employed for finding a middle-way solution between the centralized and decentralized approaches: *merging* and *splitting*, respectively [8]. In the context of communication networks, merging can be interpreted as resource sharing among different networks. A *cognitive dynamic system* (CDS) [9] can play the role of a supervisor that decides when the resource sharing would be beneficial. Thus, the CDS can improve the efficiency through controlled employment of the above-mentioned two operations. It is worth noting that a CDS has five pillars: perception-action cycle, memory, attention, intelligence, and language.

Decoupling of infrastructure and spectrum will provide an additional degree of freedom that leads to a more fluid market and more efficient spectrum utilization [6]. In the economic model, which is built around such a decoupling, network owners, legacy owners, and operators can be separate entities. Mobile *virtual* network operators and *roaming* are also allowed in this framework. Resource (i.e., infrastructure and spectrum) sharing has significant advantages including coverage expansion, smooth handling of spatial and temporal demand fluctuations, improved spectral and energy efficiency as well as revenue benefits [3]. Regarding the fact that HetNets are multi-tier networks in nature, the resource sharing in such networks can be performed at different levels. Hence, integration of spectrum supply chains associated with different networks is quite similar to the *horizontal merger* of corporations [10].

The novelty of the perspective presented here is the conceptualization of telecommunication firms as networks of their economic activities. Within this framework, strategic advantages of spectrum supply chain network integration (i.e., *synergy*) can be evaluated quantitatively based on a system-optimization viewpoint. Strategic importance of controlling the supply chain as a whole calls for a *holistic* viewpoint. The holistic view that comes with formulating the optimization problem at the system level, allows for capturing different criteria such as spectral efficiency, energy efficiency, environmental impacts, and *risk* management. In light of *network science*, mergers or even acquisitions can be formulated by adding a set of appropriate links with their associated costs to join the two networks that were originally separated [10]. Similarly, infrastructure sharing, spectrum sharing or both can be performed through adding proper extra links that joins different spectrum supply chains. The pre- and post-horizontal mergers of spectrum supply chain networks will be discussed next.

## 2. Horizontal Mergers

In this section, we present the supply chain network models before and after the horizontal mergers. Although the presented formulation is quite general and can be applied to any number of networks, for simplicity of representation, two networks denoted by A and B are considered. These two networks are integrated into a single network after the merger. Four different cases are considered [10]:

- *Case 0*: This is the baseline case, where networks A and B are considered individually before the merger (Fig. 1).
- *Case 1*: Networks A and B merge and only share the spectrum (Fig. 2).
- *Case 2*: Networks A and B merge and only share the infrastructure (Fig. 3).
- *Case 3*: Networks A and B merge and share both the spectrum and infrastructure (Fig. 4).

The system-optimization problem associated with each case is derived in the following.

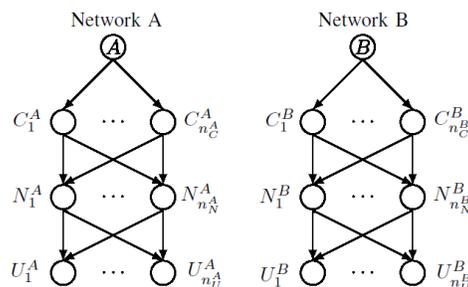


Fig. 1. Case 0) Networks A and B prior to horizontal merger.

### A. Pre-Merger Case

As shown in Fig. 1, before the merger, each network  $i$  ( $i = A, B$ ) has  $n_N^i$  network nodes (i.e., infrastructure components),  $n_C^i$  channels, and provides service to  $n_U^i$  users. Symbols  $N$ ,  $C$ , and  $U$  refer to nodes, channels, and users, respectively. The graph that represents network  $i$  is denoted by  $G_i = [N_i, L_i]$ , where  $N_i$  refers to nodes and  $L_i$  refers to directed links associated with economic activities. In this case, the graph  $G^0 = [N^0, L^0] = \bigcup_{i=A,B} [N_i, L_i]$  represents the super network composed of the two networks, where the superscript 0 refers to the case 0. A link from a channel to a node shows that the channel can be accessed through that node by a set of users. Also, a link from a node to a user shows that the user can potentially access all the channels that are accessible via that node. Depending on the geographical location of a user, cell association and spectrum allocation determine the set of paths  $P_{U_k^i}^0$  that connect the origin node  $i$  ( $i = A, B$ ) to the destination node (i.e., user)  $U_k^i$  in the network. We define an indicator  $\delta_{ap}$  such that  $\delta_{ap} = 1$  if path  $p$  includes link  $a$  and  $\delta_{ap} = 0$ , otherwise. Let  $P^0$  denote the set of all paths  $P^0 = \bigcup_{i=A,B; k=1, \dots, n_U^i} P_{U_k^i}^0$ . The flow  $f_a$  on link  $a$  corresponds to the amount of accessed

resource units (i.e., bits/s/Hz/node), which comes at the estimated cost of  $\hat{c}(f_a)$ . Similarly, path flows are denoted by  $x_p$ . Also, the capacity on link  $a$  is denoted by  $u_a$ . The objective is to minimize the total cost while meeting all the users' demands denoted by  $d_{U_i}$ :

$$\min_{f_a} \sum_{a \in L^0} \hat{c}(f_a) \quad (1)$$

Subject to:  $d_{U_i} = \sum_{p \in P^0_{U_i}} x_p, \quad i = A, B; k = 1, \dots, n_U^i$

$$f_a = \sum_{p \in P^0} \delta_{ap} x_p, \quad \forall p \in P^0$$

$$x_p \geq 0, \quad \forall p \in P^0$$

$$f_a \leq u_a, \quad \forall a \in L^0$$

The first set of constraints guarantees that all users' demands will be met. The second set represents the conservation of flow and states that the flow on a link must be equal to the sum of path flows for all paths, which include that link. The third set states that the path flows must be nonnegative, and the fourth set guarantees some specified level of QoS by considering a capacity for each link flow. The optimal set of flows,  $f_a^*, \forall a \in L^0$ , is obtained by solving the optimization problem (1). Then, the total minimal cost will be  $TC^0 = \sum_{a \in L^0} \hat{c}(f_a^*)$ . Before the

merger, there is no common link between the paths, which are associated with different networks. However, after the merger, the number of paths, the sets of paths, the number of links, and the sets of links will all change [10].

**B. Post-Merger Cases**

In Figs 2 to 4, the super node 0 and the corresponding links to nodes A and B symbolically represent the merger of the two networks. The corresponding graph for spectrum sharing (Fig. 2) is  $G^1 = [N^1, L^1]$ , where  $N^1 = N^0 \cup \text{node } 0$  and  $L^1 = L^0 \cup \text{additional links due to spectrum sharing}$ . For infrastructure sharing (Fig. 3),  $G^2 = [N^2, L^2]$ , where  $N^2 = N^1$  and  $L^2 = L^0 \cup \text{additional links due to infrastructure sharing}$ . For spectrum and infrastructure sharing (Fig. 4),  $G^3 = [N^3, L^3]$ , where  $N^3 = N^2 = N^1$  and  $L^3 = L^1 \cup L^2$ . In all three post-merger cases, the system-optimization problem is formulated in a manner similar to that in (1) for the corresponding graph  $G^j (j=1,2,3)$ . The *synergy measure* is defined as [10]:

$$S^j = 100 \times (TC^j - TC^0) / TC^0 \quad (2)$$

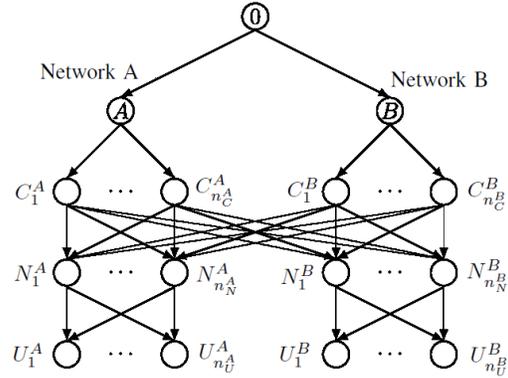


Fig. 2. Case 1) Networks A and B merge: users associated with either network A or network B can now access each network's spectrum but infrastructure of each original network deals with its original users.

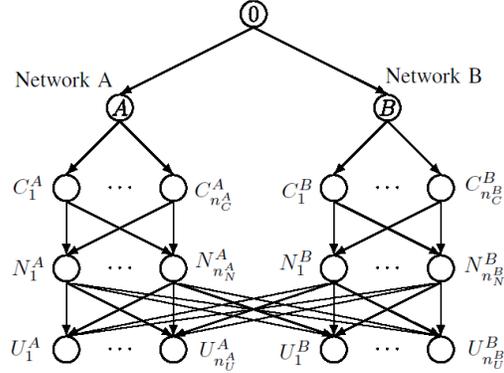


Fig. 3. Case 2) Networks A and B merge: users associated with either network A or network B can now access any network's infrastructure but each user is supplied by each network's original spectrum.

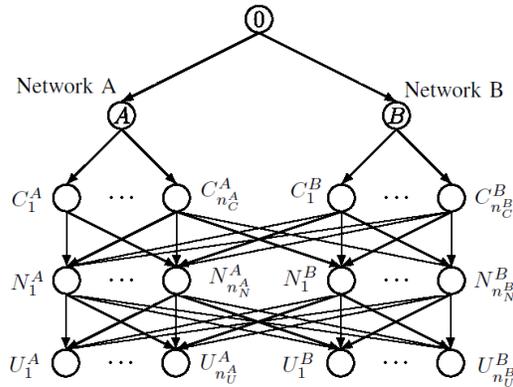


Fig. 4. Case 3) Networks A and B merge: users associated with either network A or network B can now access any network's infrastructure and spectrum.

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**Simon Haykin** received the B.Sc. (first class honors), Ph.D., and D.Sc. degrees in electrical engineering from the University of Birmingham, U.K. He is a Distinguished University Professor with the Faculty of Engineering, McMaster University, Hamilton, ON, Canada. For much of the past 15 years, he has focused his entire research program on learning from the human brain and applying it to a new generation of cognitive dynamic systems, exemplified by cognitive radar, cognitive control, and cognitive radio. He is the author/coauthor of over 50 books on communication systems (analog and digital), adaptive filter theory, neural networks and learning machines, and cognitive dynamic systems. Professor Haykin is a fellow of the Royal Society of Canada. He was the recipient of the Honorary Doctor of Technical Sciences (ETH, Zurich, Switzerland), the Booker Gold Medal from URSI for his outstanding contributions to radar and wireless communications, as well as many other medals and awards.



**Peyman Setoodeh** received the B.Sc. and M.Sc. degrees (Honors) in electrical engineering from Shiraz University, Iran, and the Ph.D. degree in Computational Engineering and Science from McMaster University, Canada. He is currently an Assistant Professor with the School of Electrical and Computer Engineering, Shiraz University. Previously, he was a Lecturer with the Department of Electrical and Computer Engineering, McMaster University. He has coauthored the paper entitled “Cognitive Control”, which was featured as a cover story in the December 2012 issue of Proceedings of the IEEE. His research interests include cognitive systems, machine learning, and complex networks. Dr. Setoodeh was the recipient of the Monbukagakusho Scholarship from the Ministry of Education, Culture, Sports, Science and Technology in Japan.

**The Virtualization of Wireless Networks**

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This year, *Time* magazine proclaimed that virtual reality is about to change the world. And, if reality can go virtual, why shouldn't wireless networks follow suit? Far from being just a fad, there are some compelling reasons to believe in the virtualization of the wireless access. In our vision, it is a step towards the end-to-end network becoming virtual and specifically orchestrated for the delivery of a particular class of service.

Virtualization is, at its heart, an illusion: for example, a virtual storage system feels to its user like a hard disk, but may comprise pieces of multiple storage devices scattered throughout the globe. Similarly, a virtual wireless network is one that seems to its subscribers just like a traditional network operated by a single entity, but it is orchestrated from a diverse pool of real resources with different ownership models, including multiple radio access technologies (RATs) and spectrum under different licensing regimes. The ability to slice resources, such as spectrum or cell capacity, among multiple virtual wireless network operators, and to dynamically manage these resources, if necessary reshaping the network on the fly, are key aspects of the virtualization of future wireless networks [1][2].

There are already indications that the world is moving in that direction. In some European countries, such as Poland and Denmark, traditional mobile operators are entering into joint ventures that control the combined network infrastructure, with operators competing only at the service level. In the US, Google is starting to act as a mobile virtual network operator, relying on Sprint and T-Mobile for 4G radio access technology and supplementing it with WiFi coverage. And globally, some service and network providers are entering into agreements that allow customers to access a particular service without paying data charges to the mobile operator, as is the case with Facebook Zero, Wikipedia Zero, and Google Free Zone. All of these examples require from the wireless network at least some rudimentary virtualization capabilities, such as policies that define how to slice and share some of the network resources among different populations of subscribers (e.g., Google Project Fi and native T-Mobile

subscribers).

The push for virtualization is intimately related to the efficiency gains that come from resource sharing. Passive sharing of physical infrastructure such as base station masts has been common practice among operators for a long time. And the dynamic sharing of spectrum has been extensively studied for the past decade, to combat inefficiencies that have developed from legacy spectrum allocation regimes. Virtualization may enable the active sharing of RAT infrastructure and spectrum under different usage modes, as well as backhaul and core network, processing power, and storage, to form bespoke networks that are driven by the specific needs of a service provider.

Sophisticated dynamic sharing can bring cost efficiencies in providing coverage and capacity to a variety of user needs, from high data rates (e.g., HD video) to low (e.g., metering applications envisioned as part of the Internet of Things). The virtualization and dynamic composition of virtual wireless networks will also lower the barriers to entry for small operators that specialize in a particular RAT or coverage of a particular geographic area (e.g., a university campus, or an airport).

The virtualization of wireless networks also opens new research questions, including the need for intelligent ways to select and combine heterogeneous network resources to deliver a desired quality of experience to users. The cognitive radio and networks research community has been applying machine learning techniques to the development of cognitive engines for dynamic spectrum access for a while. There is the opportunity to expand the scope of this work beyond spectrum, to consider all network assets that can be shared, sliced, and combined.

As usual, advances on this topic will require significant work on mathematical models, simulation, and prototype/experimentation. We advocate the use of real data from operators, or crowdsourced from mobile users, to validate these models and performance studies.

We are starting to apply stochastic geometry to these problems, for instance studying the point processes that best characterize the combined networks of multiple mobile operators [3] and quantifying the networks' resulting performance when sharing licensed spectrum, sharing base stations, or both [4]. We show, for example, that the spatial distributions of the networks of the sharing operators have a significant impact on the performance of a combined network, and how the respective density of the networks of the two operators influences how each accrues coverage and capacity gains from sharing.

Game theory is another tool that can play an important role in understanding the incentive structures from resource sharing and for the interactions between infrastructure and service providers. Although there is rich literature in game theory applied to spectrum sharing, there is little that models the more complex interactions between virtual network providers and the holders of the physical resources. The network management, security and privacy issues that ensue from the virtualization of wireless networks are also fertile ground for research.

Virtualization will ultimately affect how the architecture of future wireless networks will evolve [5]. For instance, it will require new programming interfaces and resource description languages that allow service providers to describe service needs and virtual network architects to combine resources from several providers.

Of course, the technical aspects of and potential performance gains in resource sharing and network virtualization don't tell the whole story. We must have the right economic models and public policies to make the whole thing work. Here, the bridges that have been built between telecommunications engineering researchers and business and public policy experts on the topic of spectrum sharing (e.g., [6]) can hopefully be leveraged for multi-disciplinary work on virtual wireless networks.

Finally, new models of resource management in virtual wireless networks must be tested and prototyped in the lab. In addition to sophisticated but technology-specific capabilities that are typically found in some of the leading telecommunications research groups, initiatives such as Future Internet Research and Experimentation (FIRE) in Europe and GENI in

the US are starting to create large testbed federations that will enable researchers to test an end-to-end, large-scale network comprising both wireless access and optical networks.

I believe that wireless networks of the future will be characterized by heterogeneity (of spectrum usage regimes, of ownership models, of radio access technologies), where resources are shared and orchestrated to form virtual, bespoke networks designed for specific services. To get there will require diverse expertise from within the telecommunications community, as well as business, economics, public policy, and even the social sciences. This vision may lead to a world in which providers furnish us with highly customized and ubiquitous service, while having even more access to information about our daily lives. How to reap the benefits of this evolution while curtailing its unintended consequences is a challenge that society constantly faces.

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### **A Software Defined (SDR/SDN) Framework for Heterogeneous Spectrum Sharing** *Narayan B. Mandayam (IEEE Fellow), Dipankar Raychaudhuri (IEEE Fellow) and Ivan Seskar (IEEE Senior Member), WINLAB, Rutgers University, USA* *{narayan, ray, seskar}@winlab.rutgers.edu*

#### **1. SDR/SDN Framework**

Opportunistic transmission using noncontiguous chunks of spectrum is of emerging interest due to the increasing push towards coexistence and spectrum sharing between different commercial systems in heterogeneous networks (HetNets) but also between DoD and commercial systems. The last decade has seen the advent of software defined radio (SDR) based cognitive radios that have the ability to recognize signals received by them and adjust their own transmission frequencies, waveforms and protocols. More recently, the paradigm of software defined networking (SDN) has emerged as a means to flexibly engineer networks by decoupling the functionality of the control plane and the data plane. We envision combining SDR and SDN technologies to develop a comprehensive software defined framework for opportunistic networking and spectrum management. Such a framework will allow heterogeneous systems (and radios) to dynamically and opportunistically transmit in noncontiguous portions of spectrum, provide robustness against radio channel variations due to both electromagnetic propagation and interference, as well as adversarial conditions such as attacks.

The mechanisms developed under the above framework will fundamentally rely on the ability of SDR based cognitive radios (and multiradio radio platforms) in the network to execute noncontiguous multicarrier modulation and use noncontiguous Orthogonal Frequency Division Multiple Access (NC-OFDMA)[1,2] where by noncontiguous subcarriers can be flexibly assigned across nodes. An accompanying SDN based control plane architecture will be necessary for implementing such opportunistic spectrum sharing mechanisms in heterogeneous networks.

#### **2. SAVANT: An Exemplary Architecture**

As an example of a SDN based control framework, the SAVANT architecture [3] enables the sharing of spectrum usage information between collocated wireless networks, such as transmitter and receiver locations, transmit power, bandwidth of operation, channels being used, radio sensitivity,

SNR vs. bit-rate, MAC schemes being employed, antenna properties, etc. This distributed sharing of spectrum information goes beyond the centralized spectrum database [4] approach mandated for white space systems [5], and may also be applied to emerging dynamic spectrum scenarios such as the 3.5 GHz Citizens Broadband Radio Service band in the FCC's recent NPRM [6]. Each network can use these parameters in autonomous distributed algorithms for spectrum sharing.

In SAVANT, the sharing of spectrum use information, however, is just the first part of the solution – that of increasing the visibility of each transceiver much beyond what it can sense on its own. The second part comes from the ability to instantiate a higher-layer negotiation protocol between neighboring networks to support joint assignment/management of spectrum resources, negotiations between heterogeneous entities, and controller delegation. While the above two parts enable assessment and management of spectrum resources, the glue that fundamentally holds the entire solution is the ability to execute noncontiguous spectrum transmissions such as NC-OFDMA at the PHY layer.

Fig. 1 shows a physical world view of the proposed SAVANT system as described in [3]. Each wireless network has a local controller which collects radio device parameters as summarized in Fig 1, along with an RRM control interface for setting parameters for operation. The local controllers communicate with each other over the control plane designed to have two specific services – the first is a geographic multicast (“geocast”) service which delivers the aggregate radio map to all networks in the region of interest (as calculated from the radio coverage parameters). This ensures that networks have information about spectrum use by other networks in the region, thus enabling each RRM controller to execute an appropriate distributed spectrum coordination algorithm to avoid excessive interference and achieve good spectrum use efficiency. With increasing spectrum packing, it may also be desirable for interfering networks to negotiate directly with each other using the management control



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## Maximum Transmit Power and GAA Channel Assignments on CBRS 3.5 GHz Spectrum sharing Framework

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### 1. Abstract

This paper describes the Citizen Broadband Radio Service (CBRS) framework for 3.5 GHz spectrum sharing and some of the concerns that industry has raised about the FCC Report and Order that defines this service [1]. Specifically, the transmit power limits proposed by FCC unnecessarily limits the efficient coverage in 3.5 GHz band and hence new power limits have been proposed by WInn Forum members to address this issues [2]. Moreover, the FCC report and order has not defined an efficient channel allocation mechanism for General Authorized Access (GAA) assignment. The problem is described and a high level problem statement is proposed to address the concern. User Generated Content is starting to dominate the Internet. The public now have access to the killer combination of smart devices capable of capturing digital photographs, video and audio, and the ability to upload these to cloud service providers, and share them via social networks and tagging and recommendation systems.

### 2. Introduction

United States Federal Communications Commission (FCC) issued a Report and Order (R&O) [1], adopting rules for commercial use of 150 MHz of spectrum in the 3550-3700 MHz band (3.5 GHz Band). The R&O establishes a roadmap for making the whole 150 MHz available for commercial under the Citizen Broadband Radio Service (CBRS). The 3550-3650 MHz band segment is currently allocated for use by US Department of Defense (DoD) radar systems. In 2010, the National Telecommunications and Information Administration (NTIA) proposed making the band available for shared use with commercial systems though large exclusion zone to protect DoD radar systems. In 2015, however, NTIA recommended the reduction of the geographic area of the zones by approximately 77 percent, and by using sensor technologies they permitted commercial use inside the zones.

FCC suggested three-tiered sharing framework enabled by a Spectrum Access System (SAS), a centralized management system for spectrum that leverages sensor technologies. The DoD radar system along with FSS at 3625-3650 MHz, and, for a finite period, grandfathered terrestrial wireless operations in the 3650-3700 MHz portion compose the highest tier of the sharing framework entitled “Incumbent” users. The second and third tiers encompass commercial services, and are titled Priority Access Licenses (PAL) and General Authorized Access (GAA), respectively. The incumbents must be protected from anybody else using the band. The SAS authorizes certain frequencies in any given location by the PAL or GAA. PALs are authorized (through an auction) to use a 10 MHz channel in a single census tract for three years. PAL users must protect the incumbent system, and other PAL users, while being protected from General Access Authority (GAA) users. GAA users must protect both PAL and incumbent users, but will receive no interference protection from other users in the band.

PAL users may be assigned in up to 70 MHz of the first 100 MHz portion of the band (3550-3650 MHz). However, the rule allows the GAA use over the entire 150 megahertz band. Figure 1 depicts the 3.5 GHz spectrum structure, and allowed spectrum location for PAL and GAA.

FCC has envisioned a central spectrum management entity called Spectrum Access System (SAS), augmented by a network of Environment Sensing Capability (ESC) components to sense every channel in the range 3.55-3.7 GHz for incumbent users, and manage the spectrum allocation and assignment of PAL and GAA users.

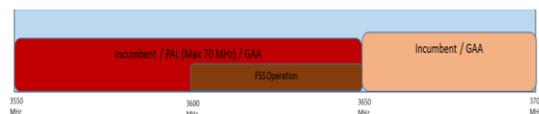


Figure 1: CBRS Spectrum

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### 3. CBRS System Architecture

The heart of CBRS system architecture is the central spectrum manager and scheduler called the Spectrum Access System (SAS). The architecture includes an incumbent detection capabilities provided by ESCs. The information from ESCs and FCC channel databases enable the SAS to effectively provide dynamic channel allocation to different users, and ensure the Quality of Service (QoS) for different tiers, and enforce the protection requirements set by FCC R&O. The Citizen Broadband Radio Service Devices (CBSDs) can use the spectrum in this band, only if they are authorized by SAS to operate. Each CBSD has to register and authenticate with the SAS before being able to operate in this band. CBSDs could either communicate with the SAS directly, or through a Domain Proxy. A Domain Proxy is a managing intermediary, which could perform bulk registration, authentication, and directive processing on behalf of all CBSDs in a certain operator network, or enterprise. It can perform bidirectional information processing, reporting, and routing such as interference reporting, power configuration, etc. Domain Proxy could directly communicate with the CBSDs or optionally through the operators existing Element Management Systems (EMS).

The SAS-SAS interface allows sharing the databases, allocated channels, load balancing, and interference management of CBSDs to enable each SAS to perform its management functionalities more efficiently.

band. Some of those concerns are listed below:

- The reconfiguration response time specified in Part 96.15(b)(4) in [1] for relocation is defined to be 60 seconds. This value is very small and a larger value is encouraged.
- The conducted and EIRP power levels for indoor and outdoor uses would not necessarily meet the requirement of acceptable services and coverage in this band, and therefore it is recommended that FCC increases those values.
- Part 96.39(a) in [1] mandates CBSDs to report their geographic coordinates to an accuracy of +/-50 meters horizontal and +/-3 meters of elevation. Unlike the CBSD horizontal accuracy requirements, the elevation accuracy requirement significantly exceeds the capability of standard GPS equipment. So, it is recommended that SAS estimates the elevation/ground level based on location and detailed terrain databases.
- The FCC order does not clarify the GAA spectrum allocation process. It is not clear whether GAA allocation is managed or unmanaged by SAS.
- The FCC rules does not enable the PAL secondary market.
- The FCC PAL protection criteria incurs a large burden on SAS, lacks clear protection to PAL CBSDs, and introduces unnecessarily blocking co-channel devices.
- The FCC needs to adopt an efficient criterion for protecting Fixed Satellite Services to avoid further conflicts.

Device	Geographic Area	Max Conducted Output Power in 10 MHz Channel (dBm/10MHz)	Max EIRP in 10 MHz Channel (dBm/10MHz)	Max Conducted PSD in 10 MHz Channel (dBm/10MHz)
End User	All	N/A	23	N/A
Category A CBSD	All	24	30	14
Category B CBSD	Non-Rural	24	40	14
Category B CBSD	Rural	30	47	20

### 4. Concerns on FCC CBRS Rule & Order

Even though FCC's plan on defining the three-tier spectrum sharing model is a major step forward to facilitate dynamic spectrum sharing, there are some concerns that certain elements of the order could potentially discourage the development of innovative services in 3.5 GHz

- The FCC should define mechanisms by which the "use" of a PAL by a PAL licensee is determined, so that the SAS could allocate the channel to GA users temporarily.

Majority of these concerns are filed as

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reconsideration requests or reply comments to FCC through [2]. However, in this paper only two of those concerns are elaborated, namely the EIRP and conducted power limits, and the GAA spectrum allocation criterion.

### a. CBSD Maximum Power Considerations

FCC Order [1] in part 96.41 has defined the maximum allowable conducted output power and EIRP used by CBSDs and End User Devices (EUD). The limits are defined for EUDs, Category A CBSDs, Category B Non-rural CBSDs, and Category B Rural CBSDs, and are summarized in Table 1. The rules allow a maximum of 6 dBi antenna gain for indoor Category A, a maximum of 16 dBi antenna gain for Category B Non-rural outdoor, and a maximum of 17 dBi antenna gain for category B Rural outdoor.

However, there are a number of concerns with the power limits defined by FCC. First, it is not clear whether the conducted power and EIRP limits are applied to each antenna port in a multiple antenna CBSD, or the limits are the total conducted or total EIRP emanated from the CBSD. This would impact the coverage and capacity achieved by the CBSD. Using the power limits, and the antenna configuration reported by the CBSDs to the SAS, the environment interference map could be calculated.

Second, it is recommended that the fixed limits are applied to EIRP, regardless of antenna gain levels. The limits on the conducted powers are accordingly determined, using the antenna gains.

Third, the EIRP limits for both Category A CBSDs for indoor operation, and Category B CBSDs for outdoor operation are generally too low for appreciable indoor and outdoor coverages, so that for category B CBSDs the use of high gain, sectorized, and directional antennas are required to achieve acceptable outdoor coverage. These conducted power levels are even less than the unlicensed power levels used by WiFi access points. Therefore, it is recommended to raise all CBSD EIRP limits by 6 dB to match unlicensed power levels for indoor and outdoor applications.

Fourth, the conducted power and EIRP limits are

determined for 10 MHz channel, and the PSDs are calculated accordingly. It is not clear from FCC rules whether the maximum output power (conducted and EIRP) can be scaled by actual transmission channel bandwidths. It is also not clear that if EUDs use only a portion of assigned channel bandwidth (say 1.8 MHz out of 10 MHz channel bandwidth), they need to scale their transmission power.

### b. GAA Spectrum Allocation

FCC Rules [1] are not explicit about how GAA operating channels are assigned to CBSDs. In Part 96.35.(e) of [1], FCC rule mandates GAA Category B CBSDs to make every effort to cooperate in the selection and use of available frequencies provided by an SAS to minimize the potential for interference and make the most effective use of the authorized facilities. Therefore, the role of SAS for GAA is to facilitate coordination between users operating Category B CBSDs, and to resolve conflicting uses of the band, while maintaining the required quality of services provided to end users.

The two extreme approaches to deal with GAA spectrum assignment are 1) fully managed GAAs, and 2) fully unmanaged GAAs. Obviously, the fully managed GAA spectrum assignment is more favorable to SAS providers. In this case, spectrum assignment to every GAA CBSD, and management and mitigation of interference in the GAA tier is provided by SAS. However, this requires the industry to define a standardized mechanism for SASs to co-operate in managing and minimizing interference among GAA users, while maintaining a fair and non-discriminatory treatment of all GAAs.

In the second extreme approach, SAS has no role in providing spectrum assignment to GAA CBSDs, except to protect the incumbents, and PAL users. In this case, a set of available channels are specified (channels that are not used by incumbents or any PAL user) by the SAS, and the actual channel assignment are left for GAA CBSDs decided by their sensing and contention-based mechanisms. A given CBSD could then perform its own interference sensing and do frequency/channel hopping autonomously, without assistance from the SAS. This approach is very similar to an unlicensed operation, which does not guarantee the quality of services for end user devices. Since no

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sensing mechanism is mandated for CBSDs in 3.5 GHz, if fully unmanaged operation is adopted for GAAs, its performance is even worse than the performance that is expected from LTE LAA or WiFi.

One of the mid-way solutions between fully managed, and fully unmanaged approaches, the SAS could define a time period over which a certain number of GAAs may contend for a certain number of available channels. Let's consider a time period of  $T$  seconds, and assume  $N$  channels are available for GAA use in a certain area. The number of GAA users requesting to access 3.5 channels is  $L$  assuming that  $L > N$ . The SAS could divide the available channels into  $M$  groups, with  $N_1, N_2, \dots, N_M$  available channel in each group, and  $N = \sum_{i=1}^M N_i$ . The GAA users requesting channel access in an area could also be divided into  $S$  groups, with  $L_1, L_2, \dots, L_S$  users in each group contending for some available channels, and  $L = \sum_{i=1}^S L_i$ , where only the GAA users within each group contend against each other. The possible scenarios are

1.  $M = 1$  and  $S = 1$  means all GAA users contend against each other for all available channels. This is equivalent to fully unmanaged and unlicensed operation.
2.  $M = 1$  and  $S > 1$  means all available channels could be used and contended by some or all GAA users, as decided by SAS.
3.  $M > 1$  and  $S > 1$  is the general case.

An objective function must be defined, in order to compare different approaches. This function takes fairness and overall network performance of the network into account.

The factors used to determine fairness could be number of users supported, service priority, channel quality, or the level of interference they cause to the environment. These factors, or a combination of these factors could be taken into account to define the fairness factor for a user, and assign weightings to each GAA, when calculating the objective function. The network performance could be defined in terms of overall throughput, aggregate interference to PAL users, sum of aggregate interferences from all GAAs averaged over the service area, aggregate SINR from all GAAs averaged over the service area, or overall network capacity in terms of number of users

supported, etc. Now we can devise the problem statement as follows:

*"Assuming a fairness mechanism is defined, we would like to find  $T, M$  and  $S$ , and group GAA users into  $S$  groups, where GAA users within a group contend for one or more of  $M$  available channel groups, such that that the pre-defined objective function, defined using the weight factors for GAA users is optimized."*

The detail procedure for choosing fairness criteria and the objective function and ultimately devising the solution that SAS takes to optimize the objective function is a subject for future research.

### 5. Conclusion

In this paper, the CBRS framework for 3.5 GHz spectrum sharing defined by FCC is explained. The industry has several concerns regarding the FCC rules and has requested FCC to modify some those rules to achieve more efficient deployment at 3.5 GHz and two of those concerns discussed, 1) maximum CBSD and end user transmit powers and 2) the criteria by which channels are assigned to GAA users. A high level problem formulation is proposed to address the second concern, and the details solution is a subject for future research.

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## Efficient Spectrum Utilization in Ultra-Dense Heterogeneous Networks

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### 1. Introduction

The wide spread adoption of the smart phone has transformed human society. Each day, more and more applications are developed that enables new and novel ways for users to use mobile computing to enrich our lives. In the near future, as the wireless communication industry moves towards 5G, it is anticipated that the amount of data moving through the network would increase by up to a factor of 100 in order to support traffic generated by the high speed mobile broadband traffic and internet of things (IoT) connected via machine-to-machine (M2M) communications.

The wireless industry has considered many different technologies to solve this challenge. Considerable research has been done in the last few years on advance antenna systems, multi-tier communication systems and new and novel ways to use the wireless spectrum [see the review in 1]. Among the most promising is densification of the network with heterogeneous networks. Indeed, the commercial wireless networks are already becoming denser. The nominal cell to cell distances are smaller through each generation of the network. This trend is expected to continue for the foreseeable future. The rest of the paper will detail methodologies needed for the fulfillment of ultra-dense networks.

### 2. Ultra-dense Networks with Massive Spectrum Resources

To deal with the capacity crunch in wireless networks, several major research directions have been identified, such as further densifying the networks leading to dense heterogeneous networks, utilizing all possible spectrum available, and further improving spectral efficiency using advanced technologies (e.g., massive MIMO, advanced transmitters / receivers). Densification and incorporating as much available spectrum as possible have been shown to be very effective in providing multi-fold capacity gains and are considered as key technologies for future wireless communications. Densification of network nodes and incorporating more spectrum resources are

closely related. For example, though generally densification is not limited to small cell layers (i.e., macro layers are also being densified), it is the small cell layers that normally are deployed with significantly more spectrum resources (such as in higher frequency bands which have smaller coverage). As the trends continue, it is expected that wireless networks will evolve into ultra-dense networks with massive spectrum resources. In another word, the density of the networks may be defined as the amount of radio communication resources including transmission nodes and spectrum resources within a spatial area. We define the ultra dense network as a network that is so dense that network capacity growth rate is no longer invariant to additional densification [see 2 for a formal discussion]. In the next section we discuss efficient spectrum utilization with ultra dense networks.

### 3. Efficient Spectrum Utilization Approaches

Dense heterogeneous networks with wide spectrum resources are already being deployed, where different cells types may operate on the same and/or different (and hence, generally partially overlapped) frequency layers with careful consideration of network interference. For example, practical implementations may consider orthogonalization of spectrum resources that could cause serious interference damage within neighboring cells, or coordinate transmission patterns between neighboring cells. However, as the network becomes ultra-dense and localized to handle the traffic demand, it is shown that conventional interference management techniques are becoming less and less effective, such as static frequency reuses [2].

In essence, there is a fundamental tradeoff between spectrum/node resource orthogonalization and reuse. Orthogonalization of resources may significantly reduce interference, but it also reduces the amount of usable resources in the network. On the other hand, reusing resources may increase interference, but it also increases the amount of usable resources. Which resources should be used for which traffic loads is a key issue to be

addressed.

Cognitive and coordinated network adaptation, which is an “unconventional” interference coordination technique, seems essential to dense networks with wide spectrum resources. A dense network with many carriers is deployed in an over-provisioning way, but some of the resources are not needed (or maybe even harmful) to stay on all the time; rather, they should be adaptively put into use only if computations based on information about interference and loads justify so.

To be more specific, in a dense network, turning off certain cells and carriers can significantly reduce interference experienced by other cells. Which cells and carriers should be on or off may be determined by the cell/carrier itself (e.g., turning off when the cell serves no users or detects significant interference), a cell cluster, or by a central controller. This may be used in conjunction with suitable UE-cell association and carrier selection techniques.

Load shifting consists of two (seemingly conflicting) aspects—namely, load balancing and load aggregation. In load balancing, the network attempts to distribute traffic loads as evenly as possible to different cells/carriers, whereas in load aggregation, certain traffic loads are aggregated to a subset of cells/carriers so that others may be turned off, which may improve overall performance by reducing interference. When and how to perform load balancing and load aggregation may be determined by a centralized or distributed algorithm which optimizes a chosen utility [3].

In a network with a massive number of carriers, the cell on/off, load balancing/shifting, interference coordination and avoidance as described above can be manifested as carrier selection/switching. Carrier selection is performed by the network nodes (e.g., cellular eNBs) to determine which carriers of which network nodes should be utilized and serve which traffic loads. Per network instruction, the user devices (e.g., cellular UEs) switch to receive/transmit on designated carriers. Carrier selection/switching can be done in semi-static time scales and dynamic time scales.

#### 4. Unlicensed Access

Generally, the cellular networks operate on licensed spectrum for its quality of service (QoS)

guarantee. However, the licensed spectrum generally may be limited and can be costly to acquire. The unlicensed spectrum (sub-6 GHz or above), on the other hand, is rather abundant. Therefore, recently the unlicensed spectrum has attracted significant attention. In addition, since LTE can offer superior spectrum efficiency, enhanced system capacity and coverage, flexible bandwidth operation, it is desirable to incorporate the unlicensed band into the LTE systems in a seamlessly integrated way.

This leads to the consideration of LTE on unlicensed or Licensed-Assisted Access with LTE (LAA-LTE) in 3GPP [4]. The licensed spectrum with LTE can be used as the primary carrier for cellular services, including coverage support, system information and control information transmissions, etc.; and the unlicensed spectrum with U-LTE can be used as the secondary (complementary) carrier for offloading and best-effort transmissions. However, on the unlicensed spectrum, other radio access technologies (RATs) may exist, such as WiFi. The coexistence among different RATs operating on the same frequency band can be a complex issue, and some unlicensed spectrum regulations are imposed. Therefore, it is envisioned further research and evaluations are needed in the next few years regarding integrating the unlicensed spectrum into cellular systems.

#### 5. Efficient Spectrum Utilization with Wireless Inband backhauling

A key enabler of ultra dense network is wireless inband backhauling. This is motivated as wireline backhaul may not be always feasible for a dense network and the spectrum resources may be vast. For this method, wireless backhaul will share the same pool of spectrum resources as the data transmissions. This may not only reduce the amount of frequency resources for data transmission, but also introduce co-channel interference between backhaul transmissions and data transmissions. Once again, this can be formulated as a problem of cognitive and coordinated network adaptation, but a dedicated study may be needed given the specialty of the problem.

#### 6. Cognitive Heterogeneous Networks

Cognitive radio is another intriguing method to improve the performance of heterogeneous networks [5] that has not yet been fully explored in the literature. Cognitive radio was first

envisioned to take advantage of the results from spectrum occupancy measurements which demonstrated that much of the spectrum seems to be unused most of the time [see 6]. As a consequence, dynamic spectrum sharing was proposed as a method to fully realize the potential of US government-held spectrum [7]. The FCC released the rules for spectrum sharing in the 3550-3650 MHz band on April 2015 [8] and commercialization is expected within the next few years. It should be noted, however, that the system envisioned in [8] is based upon the notion that there exist some priority usage of the spectrum by a primary user. In contrast, for a cognitive heterogeneous network, since all tiers are licensed to use the network, there is no such notion of priority. Consequently, the design tradeoffs between primary and cognitive users can be re-optimized such that it optimizes the overall performance of the cellular network [9]. Recent work has shown that cognitive radio can be used to improve the outage probability [10] but in the case of dense network, the performance gain in SNR is wasted because the transmission opportunities are very rare [11]. Thus, even though spectrum access schemes are investigated in [11, 12], we are still in the early stages of the research. Nevertheless, cognition has shown that it has the promise to provide a dynamic spectrum allocation which will adapt to the network states.

### 6. Conclusions

Ultra-dense heterogeneous network will undoubtedly be part of the next generation wireless communication networks. This discourse has shown that much work is still needed before it can be fully understood. The work ranges from fundamental mathematical modeling to cognitive algorithms [2]. It should be noted that a recent theoretical extension of the stochastic geometry method to multi-slope path loss has been made [13]. The results have shown that, at least theoretically, under certain channel conditions and system traffic load, densification has a limit. Where (and whether) the limit exists in the commercial network is still unclear. Furthermore, research into the understanding of the impact to the mobile core network is still in its infancy [14]. Nevertheless, commercial densification will continue and work to achieve its fundamental understand will be key to an industry currently serving over 5 billion users worldwide.

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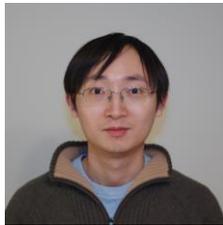
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## Graph Compression Techniques for Next Generation Cognitive Networks

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### 1. Realizing Large Scale Cognitive Networks

The cognitive radio concept was introduced in [1], where the insertion of additional intelligence in wireless terminals was proposed. Since [1], there has been significant research effort developing techniques for the coexistence of cognitive (unlicensed) terminals with licensed terminals operating in the same frequency bands [2]. *We assert that modern signal processing methods based on sparse approximation and graph signal processing can significantly contribute to the realization of truly cognitive radio networks at a large scale.*

In much of the early work on cognitive networks, the objective of the smart terminals was to identify and exploit channel resources left unused by the licensed terminals in the time and frequency dimensions, *i.e.*, the *white space* approach. The focus on the avoidance of interference to licensed users led to solutions primarily based on channel sensing, where cognition is used to acquire sufficient information to make transmission decisions with constrained sampling capabilities [2]. A challenge with most white space approaches is that they are local in nature, confined to directly observable network features, and with limited degrees of freedom in terms of control structures.

While cognition is central to next generation wireless networks, future networks will be highly complex due to heterogeneous sub-networks. Thus, traditional network protocols will be insufficient. Future protocols will require adaption and the ability to learn network behavior that is more global. Introducing this high-degree of cognition into future wireless networks is non-trivial. A key technical challenge is enabling individual wireless nodes with the capability of inferring global network properties from local network. The duality between local and global information interests both the topological and temporal dimensions. To achieve this goal, estimators need to be built that encode structural information about the network operations. Cross-layer techniques will be needed to achieve this goal and will require a diversity of tools from information theory, signal processing and estimation theory, and network

optimization.

In our proposed approach, network operations and the environment are mapped to a directed graph, which we refer to as the *logical graph*, where vertices are network states and edges are probabilistic state transitions. The application of sparse approximation and graph signal processing is natural with such a model. Based on this representation, we have developed algorithms [3-6] for the estimation of fundamental control functions from a small number of network observations. The proposed algorithms exploit the unique structure of this class of graphs to obtain concise representations of these functions, which enable a considerable acceleration of the learning/estimation process. Furthermore, the model enables inference of long-term network dynamics versus just local, instantaneous, state. We contend that this approach suggests a new networking paradigm, where cognition is used to distill information from observation data based on structural knowledge of fundamental properties of the network dynamics.

### 2. Reactive Cognitive Networks

Our recent work [7-10] extends the cognitive radio framework beyond the white space, enabling simultaneous coexistence of licensed and unlicensed users in shared spectrum (or other network resources). In this approach, which we name *reactive cognition*, the cognitive terminals evaluate and control the impact of their transmission strategy on the long-term statistics of the network. Intuitively, the “reaction” of the network to interference is a function of the entire network state, and the acquisition of information and optimization of the interference strategy is a much more challenging task compared to the white space approach, where the network is typically modeled as a binary idle-busy random process whose statistics are independent with respect to interference.

In the reactive cognitive network framework, network operations are modeled as a Finite State Machine (FSM), whose states track channel state, packet buffering, packet service, and other relevant networking mechanisms. Markov

Decision Process (MDP) theory [11] can be used to find the optimal action distribution over the state space. Typically, estimation, learning, and optimization are confined to simplistic and idealized scenarios due to the high complexity and learning time of MDP-based algorithms. Thus, fundamentally new strategies are needed to address the technical challenges posed by the reactive cognitive network paradigm. Techniques based on a Markovian representation of the stochastic processes generating the observations, and associated cost functions, although useful to analyze structural properties of protocols and optimal strategies [3,7], are not a viable solution for real-world networks due to their complexity.

### 3. Compressed Sensing and Graphs

The power of graph-based abstractions has long been recognized for a variety of problems (e.g., community detection, clustering, etc.) and spectral graph theory has provided a particularly fruitful avenue for solving problems in areas such as network analysis, sensor networks, security or social networks. While spectral graph theory has close links to tools used in signal processing (i.e., it provides a frequency interpretation), a more sustained effort to bring a signal processing perspective to these graph problems has emerged only recently [12].

Our approach explicitly brings this signal processing perspective into the network control problem. We observe that the overall network FSM results from the concatenation of sub-FSMs (*sub-chains* [3]), which model network mechanisms, e.g., packet retransmission, and the temporal evolution of individual state variables, such as the channel state. The simplicity of these structures enabled the analytical derivation of optimal control policies in specific scenarios [7,9]. Importantly, this observation led to a novel class of network estimation and optimization techniques based on the representation of the dynamics of networks as a directed graph. Furthermore, the underlying sparsity of graph signals with respect to a key basis is also exploited.

Network tomography uses graph representations of the physical links composing communication networks, i.e., *physical graphs*, to infer the topological structure of the network and link properties (e.g., average delay) from a small number of aggregate measurements [13,14]. These techniques implement Expectation

Maximization estimation based on pseudo-likelihood function.

In the problem at hand, the vertices of the graph are network states and the edges correspond to state transitions. We refer to this class of graphs as the *logical graphs* to emphasize the difference with the *physical graphs*: the physical graphs capture physical connections between terminals, whereas the logical graphs model the temporal evolution of the network's state. In this representation, the sub-chains correspond to sub-graphs with a relatively simple connectivity structure, that is, a small number of connections between states exist, and many states have analogous connections to their one-hop neighbors [3]. Logical graphs, which are generated as the composition of multiple sub-graph structures associated with the sub-chains, inherit their structural regularity. In particular, the connectivity structure presents typical multi-hop trajectories, which are shifted and replicated along the dimensions defined by the sub-graphs. Note that hops on the graph correspond to temporal units on the stochastic process associated with the FSM. Additionally, relevant performance measures for wireless networks cluster high cost/reward states in precise regions along these dimensions [14]. The graph connectivity and cost function structure induce regularity on the graph of control functions such as the value function [11]. We developed two classes of algorithms that exploit these characteristics of the network logical graphs and performance metrics to build non-Markovian concise representations of long-term cost functions. These compressed representations enable fast online learning and optimization.

*Compressive Sensing*: In [15], the authors proposed a representation technique based on the projection of cost functions defined on general Markov processes onto Diffusion Wavelets (DW) kernel. In [3], we analytically proved that Compressive Sensing can be used to define online algorithms for the estimation of cost functions measuring the performance of wireless networks. Furthermore, we proved that due to the properties of cost function sampling in wireless networks, these algorithms suffer instability. This issue can be alleviated using techniques correlating the output of the estimator. Numerical results show that 15 wavelets coefficient can accurately represent a cost function defined on a state space of 2000 states. The estimation algorithm produces accurate

estimation of cost functions with a number of observations orders of magnitude smaller compared to traditional temporal-difference learning algorithm.

*Graph Filtering* For the problem at hand, we explored graph sampling and simplification ideas in [4-6]. In [4], we used the graph-Quadrature Mirror Filters proposed in [16] to generate smooth approximations of value functions measuring the performance of wireless networks. The state space was regularly downsampled along the dimensions defined by the sub-graphs to capture the regularity of the transition probability matrix. In [5], we proposed reconstruction based on low-complexity multi-scale, lifting graph operators. In this case, the information learned by observation was projected on the Minimum Connected Dominating Set of the graph to ensure full reconstruction. In [4-5] the logical graph is used to analyze and compress the graph signal. In [6], the value function is processed based on an auxiliary graph that connects states with similar cost/reward multi-hop trajectories. A Tikhonov regularization framework is used to recover smooth signals that are not strictly band limited. Projection on the auxiliary graph rather than directly on the transition graph is shown to improve performance. Furthermore, developing the node coloring and downsampling strategies needed to implement the technique in [4] without causing a significant loss of information might be difficult in complex networks.

In recent work [17], we build on our prior approach [5] by approximating the original Markov chain by a simplified one whose state transition graph contains an independent set of a pre-specified size, and such that the Kullback-Leibler distance is minimized. As a result, value iteration needs to be performed only on the vertex cover of the network, from which the value function on the independent set can be obtained in a one-step process. The approximately independent set is found via greedy methods and numerical results show that for a class of random networks, the Markov chain approximation is accurate, even with large independent sets. In fact, the size of the independent set is a design parameter that enables the tradeoff between complexity and accuracy.

#### 4. Conclusions

A fundamentally new approach in the design of networking technologies is needed to address the

challenges posed by the modern network scenario. Implementing cognitive capabilities at the terminal and network level can empower the network with the ability to effectively operate in a wide spectrum of scenarios and environments. Based on our recent results, we contend that graph signal processing and compressive sensing can provide fundamental tools to concisely represent the global network dynamics and enable practical online learning and adaptation.

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**Editorial: TV White Space Communications and Networking**

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TV White Spaces (TVWS) are frequencies made available for secondary use at locations where primary users, such as television broadcasting, are not using the spectrum. TVWS technology has been moved forward initially by regulatory steps and deployments of White Space Devices (WSDs) by FCC in the US, further white space trials and developments in Africa. Europe is proceeding with the finalization of rules and testing of TVWS technology on a large scale. The European progress is particularly driven by the UK regulator Ofcom's work and instantiation of a large pilot of WSDs and the underlying enabling technology. Owing to UHF operating frequency, wireless networks and services are working at TVWS spectrum benefit from large communication range and good in-building penetration, which enable its applications to rural broadband, indoor communications and long range Machine-to-Machine communications via geo-location database or spectrum sensing.

In this Special Issue, we bring to our readers a collection of 7 invited articles that address various aspects of TV white space communications and networking. Authors from different regions share their individual perspectives regarding the opportunities and challenges brought forth by the recent regulatory development of TVWS technology, economics outlook for the database-assisted long range wireless connectivity, as well as ongoing research efforts in leveraging TVWS for current and future wireless applications and services.

The first article, "*TV White Space Networking: A (U.S. Centric) Retrospective*" by Roy, presents broad view of cognitive approach for wireless networks. The future of wireless broadband access with cognitive rules is emphasized with the U.S. National Broadband Plan. A recap of TVWS in US is discussed in line with an assessment of FCC TVWS rules. Finally, the outlook of TVWS is concluded.

From the UK Ofcom perspective, the second article, "*White Space, White Space, Wherefore Art Thou White Space?*" by Holland, presents the white space device pilot under Ofcom

framework, harmonized at the European level through ETSI EN 301 598 standard, which has been carried out in London and at a number of other locations across the UK. A number of key observations in terms of TVWS deployment have been discussed. The outcome of the large-scale pilot with qualified geo-location database providers results in that Ofcom gives green light for 'TV white space' wireless technology.

Taking a market perspective, authors of the third article, "*Economics of Database-Assisted TV White Space Networks*" by Luo et al., shows critical economic challenges in the large-scale commercial implementation of a database-assisted TV white space network. The economic roles of each involved TVWS network entity are defined. The information definition and evaluation as well as market evolution and optimization are modeled as a framework to derive the optimal information price for geo-location databases. The hybrid spectrum and information market approach is analyzed.

Apart from conventional spectrum database, Fujii et al. contributing to the fourth article, "*Smart Spectrum Utilization Based on Spectrum Measurement and Statistical Modeling*", present a smart spectrum management system based on hierarchical spectrum database. The smart spectrum map is updated with distributed spectrum measurements. The smart spectrum access extending dynamic spectrum access utilizes useful prior information, such as statistical information in terms of spectrum utilization by the primary system. Finally, two-layer smart spectrum access with spectrum awareness system is presented.

With aforementioned regulatory and technical challenges, TVWS spectrum and technology as a promising practical implementation of cognitive radio system, has found itself a number of popular applications, such as vehicular networks, cellular and WiFi networks.

Aygun et al. presenting the fifth article in this Special Issue, entitled "*Adaptive Behavioral Responses for Dynamic Spectrum Access-Based*

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*Connected Vehicle Networks*”, propose a bio-inspired bumblebee model for an efficient channel sensing and selection system in rapidly and adaptively changing multi-channel environments. Unlike ants and honeybees, bumblebees socially share information with others but they do not depend on others when performing their individual optimizations within the distributed network. The proposed architecture based on flower selection process employed by foraging bumblebees provides spectrally efficient wireless access in time varying vehicular networking environments.

The sixth article, “*A Cognitive TD-LTE System Operating in TV White Space: Test-bed and Performance Evaluation*” by Feng et al., presented a Cognitive Radio (CR) enabled TD-LTE test-bed in TVWS spectrum. The test-bed based on spectrum sensing has been evaluated in China, which achieves 99.9% detection probability and 1% false alarm probability. To reduce the interference between the TD-LTE system and the TV broadcasting system, appropriate guard bands between two systems are used. The width of the guard bands is explored. Moreover, the protocol stack and frame structure are redesigned with the minimum modification to the existing TD-LTE standard to support CR functions.

The final article, “*TVWS as a valuable spectrum offloading opportunity for Wi-Fi like connectivity*” by Bedogni et al., compares the channel capacities between WiFi and TVWS. In the range of 300 to 700 meters, TVWS clearly provide the benefits, especially in an indoor environment with multiple walls and floors. The TVWS availabilities and trails are discussed for different use cases. In the scenarios of poor coverage or data rate, TVWS can bring additional valuable spectrum to offload part or all the data of the device.

This Special Issue has, by no means, presented a complete picture on the TV white space

communications and networking. In fact, given the highly active involvement of both regulator, industry and academia practitioners in this field, we expect that more exciting results from expanded explorations will appear soon on the horizon. We nevertheless hope that our readers will enjoy sampling through the list of invited articles and get a flavor of the interesting possibilities offered by TV white space.

Our special thanks go to all authors for contributing their interesting research work to this Special Issue and sharing with us their individual perspectives. We would also like to acknowledge the gracious support from the TCCN Communications Board.



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## TV White Space Networking: A (U.S. Centric) Retrospective

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### 1. The Future of (Wireless) Broadband Access: Cognitive Rules

“Broadband is the great infrastructure challenge of the early 21st century” declares the U.S. National Broadband Plan [1] which also lays down clear definitions for ‘broadband’ (e.g., access speeds in excess of 100 Mbps download etc.) and enabling mandates (500 MHz of new RF spectrum to be made available for this purpose to alleviate the so-called Spectrum Crunch, along with incentives/mechanisms for their efficient use) as part of a visionary push to enable the next generation of wireless access networks. Pursuant to this agenda, the Federal Communications Commission (the U.S. regulatory authority with rulemaking jurisdiction over the ‘civilian’ spectrum) has opened portions of terrestrial TV broadcast bands (400-700 MHz in the U.S, nominally corresponding to channels 1-51) resulting from the spectrum freed up due to the transition from analog to digital broadcasting under a new class of ‘white space access’ rules. Briefly, the structure of these rules is built on the following precepts: secondary users at any location may use white (temporarily unused by the licensed users) channels [2] subject to acceptable (additional) interference conditions constraints at incumbent receivers. Such ‘cognitive’ approaches to spectrum sharing, enabled by software defined radio technologies, represent a welcome new policy approach towards spectrum sharing, as a component of encouraging more efficient spectrum utilization. However, the difficulty of formulating effective spectrum sharing policies that translate to working spectrum sharing systems, lies in achieving the reasonable ‘median’ in terms of rulemaking – balancing the incentives for newcomers seeking to develop viable new networks based for secondary TV band devices (TVBDs) while ensuring adequate protection for the licensed or primary services (notably TV broadcasters and wireless microphones).

### 2. TV White Spaces in U.S.: A Brief Recap

In Dec. 2010, the FCC adopted the Final Rules for Unlicensed Operation in TV White Spaces whereby the Commission defined the conditions under which an unused TV channel may be accessed by unlicensed users by ensuring that no harmful interference occurs to TV receivers and

other authorized users such as wireless microphones. In principle, feasible solution architectures to this problem revolve around three core primitives – i. Geo-location of secondary users, ii (distributed) client-side sensing of channel state and iii. (centralized) database access.

Initially, there was considerable support for including client-side spectrum sensing as a key component of the solution, but subsequently the difficulty of reliably sensing wireless microphones to desired degree relegated this to an optional component, leaving the other two as the core pillars of the solution architecture. Fundamentally, all TVBDs *must* consult a database which contains current information about available white space channels at the secondary’s location. Accordingly the unlicensed TV band devices were classified into two functional categories – a) lower power “personal/portable” devices, such as Wi-Fi-like cards in laptops and smartphones and b) higher power “fixed” devices such as 802.22 Base station/CPEs providing a backhaul for broadband Internet access at customer premises. The portable devices are further classified into Mode I (do not need to geolocate and/or connect to a TVWS database and obtain their channel allocation from a Mode II device) and Mode II (must geolocate and be able to connect to a TVWS database). All higher power fixed devices must also be able to geolocate and connect to the database.

TVBDs are required to be ‘intelligent’ by way of requiring transmit power control and dynamic channel selection capabilities. Fixed TVBDs are allowed a higher transmitter power of 1 watt or up to 4 watts EIRP with a 6 dBi gain antenna and can use any available WS frequency but may not operate above 512 MHz (above TV channel 20) if those available channels are adjacent to occupied TV channels. Personal/portable device transmissions are restricted to available channels in the frequency bands 512 - 608 MHz (TV channels 21-36) and 614-698 MHz (TV channels 38-51). These devices are limited to a maximum EIRP of 100 mW (20 dBm) or 40 mW (16 dBm) if the device is operating on a channel adjacent to an occupied TV channel.

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The role of geolocation is to a) set up protection contours for incumbent receivers and b) constrain transmit power/channel use of secondary devices with the explicit purpose of meeting the ‘no harmful interference to primary’ constraint. For example, fixed (portable) TVBDs are not permitted to operate within 1 km (400 m) of low power auxiliary TV transmitters as well radio astronomy reception sites; also see above restrictions on transmit EIRP for portable TVBDs based on proximity to active TV channels.

TV Bands Database: This is a queryable database that responds to TVBD requests with a list of available white space channels at its location. This is obtained based on internal records for all primary services (that contain following detailed information: transmitter coordinates, effective isotropic radiated power (EIRP), antenna height above terrain (HAAT), antenna pattern, beam tilt, channel number etc.) and an approved propagation or path loss model for TV spectrum by the FCC, notably the F-curves [9] for predictive computation of the received signal E-field to determine protection regions (i.e. area surrounding the primary transmitters that may not be used by any secondary device) and the list of white space channels outside the protection region that are available.

### 3. An Assessment of FCC TVWS Rules

Since FCC’s rulemaking in 2010, there has been a noticeable lack of consumer TVBDs in the marketplace, and no significant commercial deployment of TVWS networks to date. We thus review some of the policy implications of the FCC ruling as plausible contributors to this current state-of-affairs.

Accuracy of TVWS Database Predictions: The empirical propagation model imposed by the FCC (F-curves [6]) on DBAs has very significant shortcomings. The frequency dependence of the predicted path loss is not specific to a U.S. 6 MHz TV channel (instead, an average value is used) and does not incorporate any local terrain data in the path loss prediction. Further, the model does not account for built environments and large, singular obstructions and thus its best case is for outdoor environments with clear line-of-sight (LOS). Hence, the quality of predicted WS spectrum availability as predicted by DBAs is suspect, particularly for urban metro areas where the interests in WS is potentially the greatest. Several recent work

demonstrate significant Type I (that needlessly restrict spectrum availability by not correctly identifying available free channels) and Type II (that fundamentally violate the principle of white space use by failing to protect primary receivers from harmful interference) errors. In summary, incorrect and conservative predictions have significantly limited the business case for using TVWS by operators.

### Inadequate Flexibility in TVWS System Parameters Setting:

Several TVWS parameter settings were specified without due finer-grained analysis of application scenarios, which in turn have impacted the maturation and ultimate deployment of TVWS networks. We only mention one among a host of factors due to space limitations: the transmit mask adopted by the FCC for TVBDs sets extremely stringent limits on out-of-band emissions (35 dB more stringent than the industry standards for Wi-Fi). As a result, expensive and complex analog filtering must be added, essentially ruling out a low-cost solution. The FCC also did not consider making the average transmit power and in-band power spectral density of TVBDs flexible which along with appropriate choice of separation distances between the secondary source and primary (victim) receiver could have provided a feasible solution to the above problem of device cost. The point is that overtly rigid parameter specifications have negatively impact the potential of secondary networks in terms of its ability to offer desired services and features.

### 4. TVWS Position Statement/Look Ahead

As mentioned at the start, protecting incumbents while introducing new services requires current FCC TVWS rules, and some recommendations for future amendments are outlined below.

Identify improved path loss models such as the Longley-Rice Point-to-Point Mode or Irregular Terrain Model (ITM) that incorporate fine-grained local terrain information, resulting in more accurate (outdoor) WS predictions.

### Augment Propagation Modeling with Empirical Client-side Sensing.

Even the best-in-class propagation models are fundamentally unable to meet desired predictive WS accuracy levels under all conditions. Thus the current database only approach must be supplemented by client-side/local spectrum sensing to generate more accurate, real-time spectrum usage maps [3,4]. In turn, these will result in better allocation of

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resources to secondary nodes (i.e. channels, power, time etc.) in terms of optimizing aggregate secondary network throughput. In particular, the variation of WS spectrum availability over space is a largely under-explored domain that invites the use of spatial statistics for optimal mapping and allocation.

Adopt rule differentiation tuned to different use cases – i.e. separate indoor use from outdoors, consider different deployment scenarios (e.g. local access using a star network) versus point-to-point links for backhaul and allow different (if appropriate) WS control/management architecture for each.

Amend current TVBD regulations for more flexible secondary use – allow greater flexibility in setting secondary network parameters (transmit power, channel etc.) for scenario based specific operational conditions that enhance secondary network capacity [7].

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## White Space, White Space, Wherefore Art Thou White Space?

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### 1. Prologue

In the sleepy medieval village of London, on the Southern bank of the River Thames a few steps from Shakespeare's spiritual home The Globe Theatre, resides a regulator that is currently creating a well-crafted play out of the TV spectrum. The lead characters in this play are incumbent spectrum users (e.g., TV services, wireless microphones), and opportunistic spectrum users (white space devices—WSDs). The stage on which the play is performed is of course spectrum, and the spoken language of the play is interference. The storyline is that the opportunistic spectrum users must be allowed to use the TV spectrum that is not used by the incumbent spectrum users (i.e., the TV “white space”—TVWS), without causing harmful interference to the incumbent spectrum users. The Artistic Director is a geolocation database that is run by Ofcom, which (among other tasks) calculates which TV channels can be used with which Equivalent Isotropically Radiated Powers (EIRPs) at the given location, without causing a harmful level of interference to the TV receivers that are operating within interference range of that location. There are many Artistic Sub-Directors. These are other geolocation databases run by private companies and “qualified” by Ofcom as performing correctly. These Artistic Sub-Directors take the direction from the Artistic Director, and on top of that calculate which additional EIRP restrictions have to be applied to not cause a harmful level of interference to the licensed Programme Making and Special Events (PMSE) services, such as wireless microphones. More detail can be obtained in [1], [2].

### 2. Scene 1: “The Ofcom TV White Spaces Pilot”

A major pilot of this aforementioned TVWS framework [3], harmonized at the European level through ETSI EN 301 598 standard [4], is being carried out in London and at a number of other locations across the UK. The pilot aims to serve purposes and objectives such as:

- Provision of a proof of concept of the TVWS framework.
- Verification before commercial TVWS operations start.
- Involvement of the regulator, industry, and end users in the process, such that

their individual roles and interactions between the relevant stakeholders can be verified.

The pilot also aims to test several aspects, such as:

- WSD operation and conformance.
- Geolocation database (GLDB) contract qualification.
- GLDB operation and calculations.
- Ofcom's provision of the qualifying GLDB listing.
- Ofcom's Digital Terrestrial Television (DTT) calculation results and provision of Programme Making and Special Events (PMSE) data.
- Interference management.
- Coexistence.

The pilot started, in effect, with the qualification by Ofcom of the first GLDBs in May-June 2014. It is continuing until late 2015.

### 3. Scene 2: “Our Trial, and Summary of Some Current Observations”

King's College London is leading a major trial within the Ofcom TV White Spaces Pilot [5], [6], prominently also involving Queen Mary University of London, the Joint Research Centre of the European Commission, Eurecom, and many others. The trial has many purposes, including testing of WSDs, assessment of deployment scenarios and performance of TVWS deployments (including aggregation options), assessment of the correctness of the Ofcom framework and ETSI EN 301 598, among others. Some of the observations that have been derived based on a subset of the work that has been done so far in the trial include:

- i. In the UK, it seems likely that TVWS has most performance/benefit potential in below-rooftop receiver and indoor/underground deployments. Much of our work has particularly defined and assessed TVWS scenarios where the receiver is below rooftop given such observations. We have further demonstrated the strengths of TVWS for indoor wireless communications through a range of challenging indoor experiments with WSDs.
- ii. There is good TVWS availability in much of the UK and particularly in the

- London area, although this is affected greatly by the scenario that is considered and spectrum mask class, and can be highly variable. Impressive capacities can be achieved by optimal aggregation in TVWS. Achievable area capacity in TVWS is high.
- iii. In a number of cases, and particularly under some aggregation scenarios, subsets or indeed all WSD spectrum mask classes give similar performance.
  - iv. A worst case 700 MHz spectrum reassignment for ITU Region 1 in WRC 2015 could significantly affect availability/capacity in some TVWS usage scenarios, for lower quality spectrum mask class WSDs.

In this article, we provide some background on these observations, particularly studying where white space is available in London and a larger area of England, what can be achieved with that white space, in terms of capacity, through aggregating the available resource.

**4. Scene 3: “Wherefore<sup>1</sup> Art Thou Whitespace?”**

One aspect of our trial has been an analysis of the availability and performance of TVWS across London and England, particularly focusing on potential to aggregate TVWS. Here we report on some of that work. First, based on an implementation of the logical aspects (e.g., communication with the GLDB) of a WSD created at King’s College London, Figure 1 presents the number of TV channels available for a WSD operating at 30 m above ground level and with at least 30 dBm allowed EIRP, in an area approximately equivalent to the London “M25” area; Figure 2 expands this to a larger area of England ranging from the South Coast in the South to Birmingham in the North, and 20 km West of Bristol in the West to the beginnings of the Thames Estuary (near Tilbury) in the East. Figure 1 covers an area of 52 km by 41 km (2,132 km<sup>2</sup>), and Figure 2 and area of 225 km by 188 km (42,300 km<sup>2</sup>). In both cases, a Class 5 spectrum mask device is assumed [4].

Table I reports statistics on available channels for all Classes in the London “M25” area with a transmitter height of 30m and at least 30 dBm allowed maximum EIRP, and Table II reports the

<sup>1</sup> “Wherefore” is commonly misinterpreted as meaning “where”. We use that same misinterpretation here.

statistics on capacity that can be achieved by optimally aggregating all channels at maximum allowed EIRP on a per-channel basis, again for the London “M25” area. Tables I and II are the matching results for the wider area of England. Capacity analyses assume a transmitter height of 30 m, receiver height of 1.5 m, transmission distance of 2 km, the Hata urban loss model for large cities, and a Shannon efficiency of 0.5.

Results show a good availability and capacity of TVWS *on average*, with exceptional availability and capacity in some particular areas. However, for lower performance classes of devices (Classes 4 and 5), availability is spatially unpredictable with Class 5 having no available channels with at least 30 dBm maximum EIRP in over 32% of locations in the wider England example. Availability and capacity both increase very significantly if the spectrum mask class is improved, to only around 2% of locations with no such availability for Class 3, and less than 1% of locations for Class 1. It is noted that the areas of exceptional availability and capacity overlap with the coverage areas of major high-power TV transmitters, since in these areas only one set of (typically 8) multiplexes is blocked by TV transmissions by those transmitters. In other areas (e.g., in strong overlaps between TV transmitter areas) multiple sets of multiplexes are blocked, thereby significantly reducing the TVWS availability/capacity. It is noted that the shielding of incumbents from interference by buildings in built-up areas can also assist the interference situation (although, the particular scenario considered here doesn’t so much reflect that due to the large WSD height above ground).

A further observation is the “blotches” of reduced availability in Figure 1; these are due to PMSE (typically wireless microphone) usage.

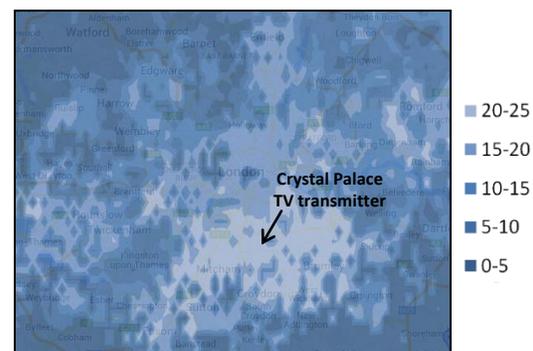


Figure 1: Map of available TV channels with at least 30 dBm maximum EIRP, for a WSD at 30m height in the London “M25” area.

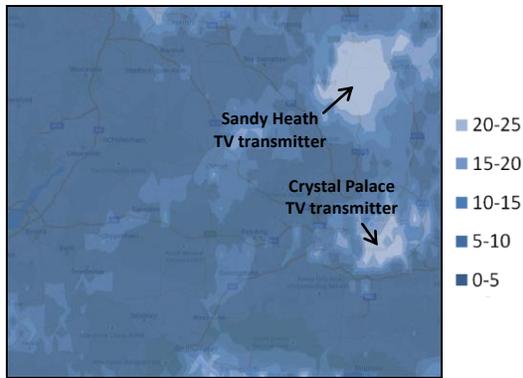


Figure 1: Map of available TV channels with at least 30 dBm maximum EIRP, for a WSD at 30m height in a wider area of England.

TABLE I: STATISTICS ON CHANNEL AVAILABILITY FOR A WSD AT 30 m HEIGHT WITH AT LEAST 30 dBm MAXIMUM EIRP, FOR ALL SPECTRUM MASK CLASSES, LONDON “M25” AREA

	Number of channels				
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	15.6	15.4	15.2	12.6	10.2
STD	8.4	8.4	8.5	8.1	7.1
CoV	0.54	0.55	0.56	0.64	0.70

TABLE II: STATISTICS ON AVAILABLE CAPACITY AGGREGATING ALL CHANNELS AT MAXIMUM ALLOWED EIRP ON A PER-CHANNEL BASIS, TRANSMITTER HEIGHT 30 m, RECEIVER HEIGHT 1.5 m, TRANSMISSION DISTANCE 2 km, HATA URBAN LARGE CITY, SHANNON EFFICIENCY 0.5, LONDON “M25” AREA

	Achieved Rate (Mbps)				
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	167.0	165.1	155.4	130.9	104.7
STD	84.2	84.4	82.5	77.4	66.8
CoV	0.50	0.51	0.53	0.59	0.64

TABLE III: STATISTICS ON CHANNEL AVAILABILITY FOR A WSD AT 30 m HEIGHT WITH AT LEAST 30 dBm MAXIMUM EIRP, FOR ALL SPECTRUM MASK CLASSES, WIDER AREA OF ENGLAND

	Number of channels				
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	8.9	8.8	8.5	6.6	4.4
STD	7.2	7.2	7.2	6.6	5.7
CoV	0.81	0.82	0.84	0.99	1.29

TABLE IV: STATISTICS ON AVAILABLE CAPACITY AGGREGATING ALL CHANNELS AT MAXIMUM ALLOWED EIRP ON A PER-CHANNEL BASIS, TRANSMITTER HEIGHT 30 m, RECEIVER HEIGHT 1.5 m, TRANSMISSION DISTANCE 2 km, HATA URBAN LARGE CITY, SHANNON EFFICIENCY 0.5, WIDER AREA OF ENGLAND

	Achieved Rate (Mbps)				
	Class 1	Class 2	Class 3	Class 4	Class 5
Average	106.4	103.4	98.5	78.9	57.0
STD	74.6	72.0	71.5	66.0	58.1
CoV	0.70	0.70	0.73	0.84	1.02

5. Scene 4: “Some Other Interesting Results”

An additional observation from our trial has been that there is a high interference in some locations caused by TV transmissions that aren’t meant to

be covering the area. For example, in much of London, there is exceptional TVWS availability at maximum allowed EIRP on a per-channel basis, but almost all the channels have some degree of interference from systems that are not meant to be covering the area, which is in many cases significant interference reducing the SINR seen by the WSD receive radio by some 10 dB or more. This leads to the observation that it is often better to scan for the best channel to use before using it. Indeed, during the trials we found that using a channel with lower than absolute maximum allowed power (31 dBm in our case, 5 dB lower than the absolute maximum) was better than all channels with the absolute maximum of 36 dBm allowed due to the interference being a lot more than 5 dB lower in the 31 dBm channel. Another observation is that we believe this interference situation will get far worse when many WSDs are being deployed, many operating with different radio interface standards or some with no standard at all (i.e., proprietary). A key inference we make based on these observations is that below rooftop receiver or indoor/underground deployment scenarios may be most beneficial for TVWS in much of the UK (definitely in the areas of London/England that are covered in this article), also taking into account the better ability to penetrate obstacles of TV frequencies. Further, we have carried out experiments at King’s College, and shown the indoor performance of the WSDs to be good—even over indoor distances of some 80-90 m in the robust stone building (depending on the antenna and scenario configuration – e.g., number of people in the building).

An additional observation we have found is that spectrum mask classes 1-3 perform relatively similarly; spectrum mask classes 1 and 2 are often identical. Classes 4 and 5 generally incur big hits to availability and performance. Moreover, if channels are contiguously aggregated by the WSDs with a spectrally flat transmission waveform (as would commonly be the case), then very often all classes perform similarly or even identically. This is because the distance to victim receivers quickly becomes the constraint—rather than out of channel leakage—as more contiguous channels are being aggregated.

Although results are not included here due to space limitations, the situation in a worst case scenario after WRC 2015 (in November 2015)

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has been assessed, noting that 694 MHz – 790 MHz will be assigned to mobile broadband on a co-primary basis after WRC 2015 in ITU Region 1. TV channels 49 (lower edge 694 MHz) and above have been banned from WSD usage entirely to reflect the case if all of these were taken by mobile broadband and other co-primary services (i.e., not available for WSD usage). It has been found that such a reduction in available possible white space could have a severe effect on some TVWS deployment scenarios, for poor classes of WSD spectrum masks such as classes 4 and 5 [4]. In such cases, e.g., for the scenario presented here where the WSD antenna is 30m above ground level with at least 30 dBm maximum power, there is a very significant increase in the proportion of locations that have no white space available.

### 6. Scene 5: “Conclusions: Important Future Proofing Observations”

We have discussed some results from our TV white spaces trials, presenting observations on scenarios for white space deployments, and other factors. It is essential to note that Ofcom has, in its statement approving of the use of white space devices based on the pilot [7], also announced changes to the framework—for the most part (directly or indirectly) leading to significant additional restrictions on acceptable interference to incumbent services. This implies some very significant changes in availability and capacity. However, our understanding is that Ofcom will consider relaxing such restrictions if it is proven that interference is not being caused in the roll-out of WSDs, and also are looking at using other methods (e.g., more appropriate propagation modelling) that will likely allow the WSDs to operate with far higher powers. So, it is anticipated that the tougher restrictions that Ofcom will impose, or the severity of their effects, will relax closer back to the current situation in the medium term.

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**Economics of Database-Assisted TV White Space Networks**

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**1. Database-Assisted TV White Space Network**

Driven by the explosive growth of smartphones and bandwidth-hungry applications, radio spectrum is becoming increasingly congested. *TV White Space (TVWS)* has been recently recognized as a promising new spectrum opportunity for wireless broadband services, due to its low utilization (in most time and many areas) and excellent propagation and obstacle penetration characteristics [1]. Specifically, TV white spaces refer to those underutilized frequencies in the VHF (e.g., 54-216 MHz in the US) and UHF (e.g., 470-698 MHz in the US) frequencies, which are currently licensed to TV broadcast services. By allowing unlicensed wireless broadband devices (called white space devices, WSDs) to reuse the TV white spaces in a license-exempt and opportunistic manner, we can effectively improve the spectrum efficiency and alleviate the global spectrum scarcity.

To effectively reuse the TV white space spectrum without harming the interests of licensed TV devices, spectrum regulators of many countries (such as FCC in the US and Ofcom in the UK) have advocated a *database-assisted* TV white space network architecture [1-2]. In this architecture, a certified *geo-location* database houses a global repository of TV licensees, and updates the licensees' channel occupations periodically. To access any TV white space, WSDs first report their locations to a database, and then the database computes and returns the available TV channels that WSDs can use in a certain time period (e.g., typically 15 minutes). The communication between the WSD and database is through existing communication networks such as cellular and Wi-Fi network. The WSDs hence do not need to directly sense the local spectrum environments for spectrum opportunities.

**2. Challenge**

The database-assisted TV white space network has received wide and enthusiastic supports, not only from spectrum regulators, but also from standards bodies (e.g., IEEE 802.22 WRAN) and industrial organizations (e.g., Google, Spectrum

Bridge, and Microsoft).

To develop a database-assisted TV white space network, we need to solve several technical challenges, such as (i) How to design and manage a geo-location database? (ii) How should the database accurately compute the available TV channels in a particular location? (iii) How to efficiently deploy and optimize a database-assisted TV white space network? Due to the great effort of both academia and industry, most of the above technical issues have been adequately addressed solved (e.g. [3-8]). As a result, in the US, several authorized database administrators (including Spectrum Bridge, Iconectiv, Google, and Key Bridge Global) have developed databases to provide service for WSDs [9].

In addition to the technical challenges mentioned above, there are several critical economic challenges in the large-scale commercial implementation of a database-assisted TV white space network. In particular, there is a lack of a systematic economics analysis for such a network, and the key challenges include (i) Who will be involved in a TV white space business model, and how to properly define the economic role of each involved network entity? (ii) What kind of services will be supported in a TV white space network, and how the services exploit the unique characteristics of TV channels? (iii) How to design efficient mechanisms to guarantee the economics performance of such a network with low implementation complexity?

Tackling the above questions is challenging due to the following reasons. First, TV channels are heterogeneous in term of their properties. There are two types of TV channels in such a network: *licensed* and *unlicensed* TV channels. The licensed TV channels are those registered to some TV licensees but under-utilized by the licensees. Hence, the licensees can temporarily lease the under-utilized (licensed) channels to WSDs for the exclusive usage during a short time period. The unlicensed TV channels are those *not* registered to any TV licensee at a particular location, hence are the public

resources. The spectrum regulators can assign the unlicensed TV channels for the public and shared usage among unlicensed WSDs, and usually do not allow directly trading of such channels in a spectrum market. Due to the heterogeneity of these two kinds of TV channels, the business model related to the licensed TV channels must involve their licensees, while the business model related to the unlicensed TV channels does not necessarily involve any licensee. Second, the database operators are also heterogeneous in term of their interests and operational costs, which lead to different economics strategic decisions. Moreover, to balance the secondary spectrum utilization and primary licensee protection, spectrum regulators have specified strict technical restrictions on the secondary usage of TV channels. This brings additional challenges in the economics analysis for such a network.

Considering the heterogeneity of TV channels, researchers have proposed several models to analyze and tackle the economics issues in a database-assisted TV white space network. These models can be mainly categorized into two classes: *Spectrum Market* and *Information Market*.

### 3. Spectrum Market

The spectrum market model is motivated by the Spectrum Bridge's current business practice: *SpecEx*, where TV licensees temporarily lease their licensed TV channels to unlicensed WSDs. During this process, the database acts as a spectrum broker, purchasing licensed TV channels from TV licensees in advance and reselling the purchased licensed TV channels to WSDs. WSDs further serve their subscribed end-users by using the purchased TV channels.

In such a market, the database needs to purchase (reserve) licensed TV channels from the licensees in advance, before knowing the actual demands from WSDs. This is because the database needs to guarantee the exclusive usage of licensed TV channels by WSDs. The WSDs have a better understanding of their demands (which come from their own end-users), which leads to the information asymmetry between the database and WSDs. The database needs to negotiate with the TV licensees in advance, in terms of when and which licensed TV channels can be used by WSDs. Therefore, a key problem is: *how much channels should the database reserve for each WSD, under demand*

*uncertainty and information asymmetry?*

One way to address this is to design a contract between the database and WSDs regarding the amount of TV channels to be reserved [10]. The key idea is as follows. Before reserving TV channels, the database announces a reservation contract, which consists of a menu of contract items, each specifying a particular reservation amount and the corresponding reservation fee. The WSD selects the contract item (i.e., the reservation amount and the corresponding reservation fee) that maximizes its expected profit, based on its private demand information.

In addition to the reservation problem, another challenging problem in such a spectrum market is to study the competitive behavior of multiple WSDs, who compete for the same pool of end-users. We formulated the WSDs' competition as a non-cooperative game, and characterized the game equilibrium analytically by using tools from supermodular game theory [11].

### 4. Information Market

In the information market model, the database sells the advanced information regarding the quality of unlicensed TV channels to unlicensed WSDs. This model is motivated by the fact that the geo-location database knows more information regarding the quality of unlicensed TV channels than unlicensed WSDs. Such information can be potentially used by WSDs to improve their communication performances. A commercial example of information market is *White Space Plus*, operated by Spectrum Bridge.

There are several challenging issues in the formulation and analysis of an information market, including: (i) *Information Definition*: What kind of information can be traded in the information market? How to define the quality of information? (ii) *Information Evaluation*: How will WSDs evaluate the information? Will the same information have different values for different WSDs? (iii) *Market Evolution*: How would the information market dynamically evolve based on the WSDs' purchasing behaviors? What type of network externality (i.e., positive or negative) will the market appear? (iv) *Market Optimization*: How will the database make the best pricing decision for the information?

To tackle the above issues, we proposed a

general framework, where the (advanced) information provided by the database is the interference level on each unlicensed TV channels. We analytically showed that such an information market processes the unique feature of *positive externality*: more WSDs purchasing the information from the database leads to a higher value of the information for each WSD [12,13]. Based on the market evolution analysis, the database operator can derive the optimal information price that maximizes the database's revenue.

#### 4. Hybrid Spectrum and Information Market

Most existing studies related to the economics study of TV white space network considered the spectrum market and information market separately. In practice, however, the licensed TV channels and unlicensed TV channels often co-exist at a particular location. Some WSDs may prefer to lease the licensed TV channels for the exclusive usage, while other WSDs may prefer to share the free unlicensed TV channels with others (and purchase the information if needed). We formulated and optimized a hybrid spectrum and information market, which considers the tradeoff between positive and negative network externalities [14].

#### 5. Conclusions

Economics analysis is important for the large-scale commercialization of database-assisted TV white space networks. In this article, we discuss three promising business models: spectrum market, information market, and hybrid spectrum and information market. These models allow the geo-location databases to exploit the unique characteristics of licensed and unlicensed TV channels. The results in these models can provide important insights into the practical impact of TV white space markets.

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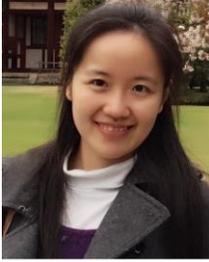
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## Smart Spectrum Utilization Based on Spectrum Measurement and Statistical Modeling

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### 1. Introduction

A spectrum database stores spectrum information for allocating the available frequency to wireless systems. Currently, a specific spectrum database has attracted attention to aid in protection of primary systems in TV white space based cognitive radio in the US [1]. The TV white space spectrum database stores the available frequency channels for each location where secondary systems can transmit without harmful interference. The availability of the spectrum is calculated using the propagation model called F-curb defined by the Federal Communications Commission (FCC). This kind of database is also considered for TV white space communications in other countries. However, the utilized spectrum band is limited to TV band.

In a future wireless world, more flexible and dynamic spectrum allocation is required, considering both the spectrum environment and user demands, such as dynamic spectrum access (DSA) [2]. To accomplish this, several advanced techniques and approaches are currently being investigated such as hierarchical spectrum database, smart spectrum map, two layer smart spectrum access with spectrum awareness system, etc. One important aspect of the above approaches is to utilize useful information, such as statistical information in terms of spectrum utilization in time, frequency and space dimensions, propagation, etc, in an efficient and flexible manner.

The spectrum management with measurement is receiving significant attention and the authors have organized a workshop, "International Workshop on Smart Spectrum (IWSS)" at IEEE WCNC 2015 in New Orleans, US. In addition, we are planning to organize IWSS 2016 at IEEE WCNC 2016.

### 2. Smart Spectrum Management Based on Hierarchical Spectrum Database

In order to realize smart spectrum management, we have considered an advanced hierarchical spectrum database supporting dynamic spectrum

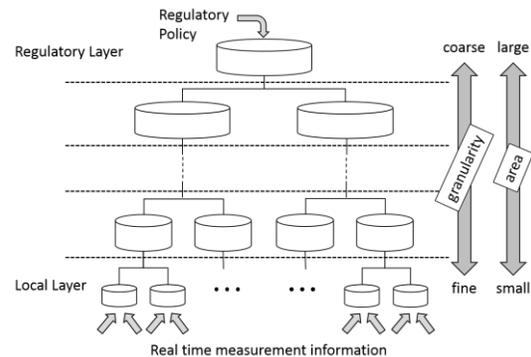


Fig.1 Hierarchical Smart Spectrum Database.

allocation [3]. The architecture of the hierarchical spectrum database is summarized in Fig.1. The key point of this database is multiple layered structure and the database of different layer supports the area with different size. The higher layer database manages spectrum policy defined by the spectrum regulator, such as FCC. This allows the realization of more flexible spectrum use coordinated by the spectrum regulator. Illegal wireless systems and terminals can be controlled by the database of this layer. The spectrum regulatory policy database can also allocate the spectrum with priority to specific systems like public safety in emergency situation. Spectrum reforming can be also controlled by this layer. One or few policy databases are expected to be prepared in each country. On the other hand, a lower layer database can be used for storing spectrum information in small area. For example, a base station in a cellular system can be used for a lower layer spectrum database. In a lower layer spectrum database, real time spectrum state and spectrum demand are stored. The lowest layer spectrum database contains each user or each connected unit, such as a basic service set of wireless LAN or a set of mobile terminals within a cell in a cellular system. The lowest layer local database can gather the measured real time spectrum information from users. Therefore, several kinds of spectrum information such as the average received power, the spectrum occupancy, and the active user

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information can be obtained. Finally, a smart spectrum map shown in Section 3 can be obtained using the information from this domain.

Since the hierarchical layers of the spectrum database can be connected each other, not only coordinated but also dynamic spectrum allocation can be realized. The fine granularity measurement based spectrum data gathered in the lower layer database is converted into statistical information with degrading granularity to be stored in the higher layer spectrum database. The higher layer database supports wider area with spectrum information of more coarse. On the other hand, the highest layer spectrum database informs spectrum policy defined by regulator. Therefore, the spectrum policy is informed from the higher layer to the lower layer. Finally, coordinated and dynamic spectrum utilization can be realized by using such hierarchical spectrum database concept.

### 3. Smart Spectrum Map via Distributed Spectrum Measurement

Currently, the spectrum map stored in the spectrum database for TV white space is generated according to the radio propagation model. However, the actual spectrum environment cannot be calculated by using simple propagation models because of the geographical impact and the influence of surrounding buildings. In order to improve the accuracy of the estimated spectrum environment, measurement results at distributed nodes can be utilized. In these days, people all around the world have mobile terminals with high functionality, such as smart phones, which can potentially be used to measure the spectrum at each location. The measured results are gathered at the local spectrum database and the information can be statistically processed to generate a highly accurate spectrum map for the spectrum database [4]. The system model of the smart spectrum map generated by the distributed terminals is shown in Fig.2. Several papers have been published discussing a spectrum map based on distributed measurement devices. The spectrum map generated by using the measurement devices installed on vehicles are discussed in [5][6]. Measurement campaign on Japanese TV broadcasting band has been reported in [7] and the performance is compared to the current propagation based model. The simple spectrum measurement device setting with smart phones has been introduced in [8].

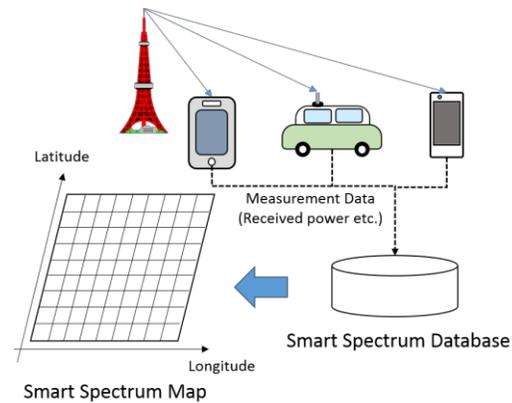


Fig.2 Smart Spectrum Map.

While the measurement based spectrum map has potential to improve the accuracy, it requires special attention to maintain measurement reliability. The measurement reliability of each device depends on sensitivity, location of antenna, and surrounding environment. In particular, the spectrum measurement using smart phones requires careful calibration to improve the reliability of the spectrum map.

### 4. Two Layer Smart Spectrum Access with Spectrum Awareness System

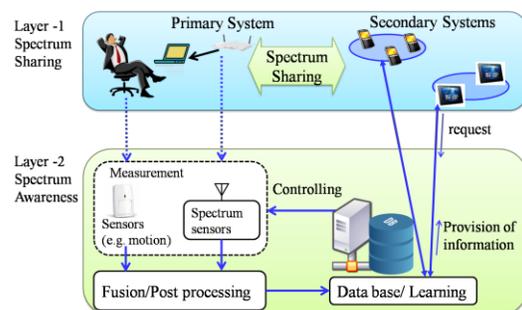


Fig. 3 Two Layer Smart Spectrum

One of challenges of DSA where primary system and secondary system share the spectrum owned by the primary system is spectrum sensing which requires high accuracy, low latency and low cost. One potential approach to solve the issue of spectrum sensing is smart spectrum access (SSA) which is an extended DSA that utilizes useful prior information, such as statistical information in terms of spectrum utilization by the primary system [9]. It has been shown that using statistical information can enhance the spectrum sensing performance [10]. In addition, it can also enhance other techniques employing vacant spectrum utilization, such as spectrum management, channel selection and MAC protocol design [11].

Still cost of the functionality responsible for obtaining the prior information, especially at wireless terminals is not negligible. For this issue, we have proposed a system architecture which consists of two layers in [9]: the first layer corresponds to a DSA system and the second layer is a spectrum awareness system (SAS). The concept of the two-layer SSA is shown diagrammatically in Fig. 3. In the two-layer SSA, the SAS is dedicated for measurement to obtain the proper information and to provide it to the secondary system. Therefore, DSA terminals no longer suffer from the implementation cost, but the useful information is provided by the SAS. The prior information can consist of spectrum utilization statistics such as channel occupancy rate (COR), statistics (e.g., mean and variance) of COR, statistics of busy (idle) period length [12], as well as other information such as number of people in office room, for example. The former information can be obtained based on the spectrum measurement carried out by spectrum sensors and the later information can be obtained by a motion sensor. This means that the SAS attempts to utilize any possibly useful information to achieve much more efficient spectrum utilization.

In fact, the measurement part in the SAS may consume significant amount of computational and spectrum resources, as well as electricity. To efficiently be aware of the environment, the SAS can utilize the obtained information to control the measurement part. For example, during night, or if the number of people in the office is low, the measurement cycle can be longer since the COR has to be low.

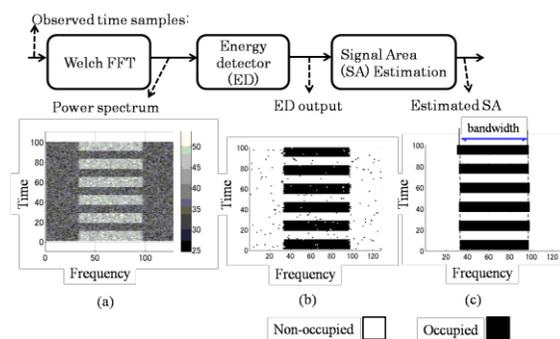


Fig. 4 Functional block diagram of spectrum measurement

It is also necessary to investigate signal processing in spectrum measurement such as spectrum usage detection including noise floor

estimation, statistics estimation (COR estimation) [13], [14], design of discrete Fourier transformation [15], etc. Unlike in spectrum sensing, the required latency of spectrum measurement is larger. Therefore, post-processing after signal detection, such as energy detector, is available. One example of functional block diagram of the spectrum measurement signal processing is shown in Fig. 4.

**5. Conclusion**

In the letter, we have introduced the latest approaches and techniques for future spectrum management/utilization based on spectrum measurements/observations.

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**Adaptive Behavioral Responses for Dynamic Spectrum Access-Based Connected Vehicle Networks**

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**1. Introduction**

One technological solution of reliable intelligent transportation systems is the concept of vehicular ad hoc networks (VANETs), which has been actively studied over the past several decades. The U.S. Department of Transportation National Highway Traffic Safety Administration (NHTSA) [1] reported that VANET systems would help drivers avoid 41-55% of intersection crashes and 36-62% of left turn crashes. Although the 5.9 GHz band is allocated to vehicular applications in the US, these dedicated channels will potentially not be sufficient to handle all connected vehicle traffic in the future. One solution to this spectrum scarcity issue is to leverage underutilized wireless spectrum elsewhere, such as digital television spectrum (DTV) band, and perform Dynamic Spectrum Access (DSA) [2, 3].

In order to enable effective real time, we will examine in this paper a DSA framework for distributed Vehicle-to-Vehicle (V2V) networks based on adaptive behavioral responses of animals exposed to similar sensory conditions in their natural habitat (Figure 1). Specifically, we focus on bumblebee foragers since they have evolved cognitive abilities that enable them to make adaptive behavioral decisions based on both individually and socially acquired

information. Using the bumblebee model, we show how an efficient channel sensing and selection system can be performed rapidly and adaptively in order to respond to changes in multi-channel environments.

**2. The Bumblebee Model**

There have been several practical approaches proposed in the open literature that leverage distributed optimization techniques employed in nature, such as ant colonies, honeybees, and other insects, that perform swarm optimization of available resources. However, these techniques require that each node within the network is dependent on the social interaction with all other nodes within the network, which is not the case in applications such as VANETs. As a result, more suitable social insect is needed. Consequently, unlike ants and honeybees, bumblebees socially share information with others but they do not depend on others when performing their individual optimizations within the distributed network.

Bumblebees are social insects that form colonies comprised of a single queen and up to several hundred workers. A small subset of workers called “foragers” has the sole task of finding and collecting food for the colony in the form of floral nectar and pollen rewards. Foragers

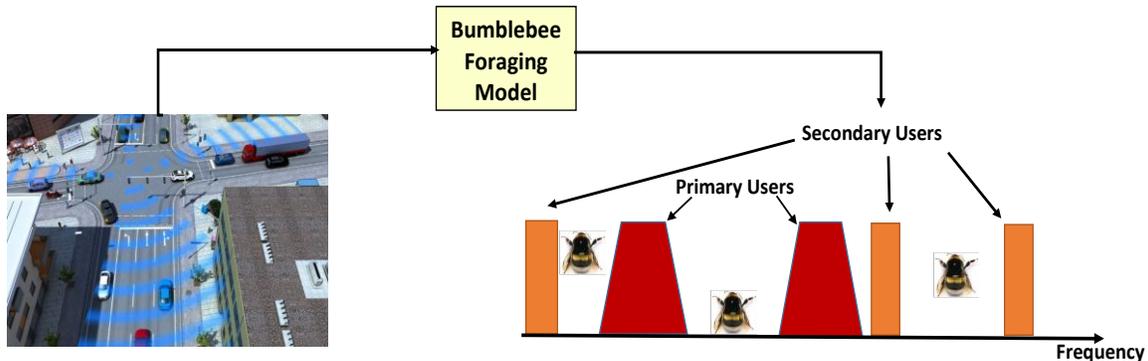


Figure 1 Concept diagram of bumblebee foraging model for vehicular dynamic spectrum access (VDSA) (adapted from [4]).

routinely encounter a wide array of flowers with reward levels that rapidly change over time and space. Foragers are not pre-programmed with information on the reward level associated with different flowers. Rather, they learn and remember the reward level and sensory cues (color, odor, shape) associated with each flower types and then decide which ones to visit. Importantly, bumblebee foragers do not depend on “scout” bees such as honeybees or pheromone trails left by others such as ants. Consequently, each individual has the capacity to learn, remember and track changes in floral rewards on its own. This system has evolved to enable maximal reward intake to the colony under complex and highly variable floral conditions.

While searching for flowers containing the greatest reward, foragers implement a number of adaptive behavioral processes that are comparable to those processes needed for vehicles to function independently and effectively in a connected network environment. First, foragers (vehicles) evaluate available flower types (channels) and then select the type that yields the greatest reward (channel quality). Second, foragers track and respond to changes in floral reward levels. Finally, foragers make floral decisions that maximize the rate of nectar delivery to the colony (constant utilization of a high quality channel by the vehicle). For example, the decision whether or not to switch to a new flower type is based on a trade-off between the rewards gained by visiting a new type types and the time costs incurred when switching to that type (channel; also referred to as a “switching cost”) [5]. Although they primarily use their personal experiences to make floral decisions, they can also enhance their knowledge of floral environments by gaining information from other foragers.

### 3. Adaptive Channel Switching Decision

Leveraging this Bumblebee model, we can now devise a connected vehicle networking architecture based on a distributed network organization. Vehicles use periodic message exchanges (also referred to as “beaconing”) in order to exchange available channel information, position, speed, heading, and other vital information that helps the vehicles adapted to their surroundings. The vehicles within the vicinity of other vehicles individually detect the available channels for secondary users. Each vehicle intercepts the periodic control messages as well as the available channel list from one-hop

neighbors. The shared information is used for the cooperative sensing mechanism.

Once secondary user (SU) vehicles occupy the channel, they need to periodically check whether they may switch to a better channel. The key parameter of the channel switching decision is the switching threshold that decides whether the users should go on at the same channel or search for another. However, the fixed switching threshold does not work for highly dynamic VANET environments. To overcome this issue, we borrow the control mechanism employed in optimal foraging theory [7]:

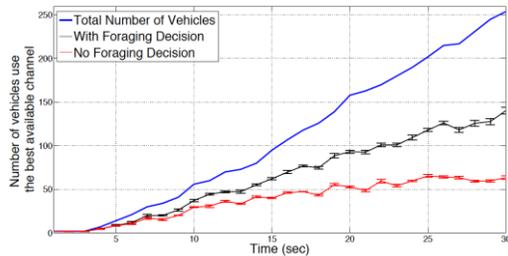
$$\text{Decision} = \begin{cases} \text{Switch} & \frac{\max_j(E_j) - E_i}{h_i} \leq \frac{\sum_{k \neq i} I_k (\max_j(E_j) - E_k)}{1 + \sum_{k \neq i} I_k h_k} \\ \text{Stay} & \text{otherwise} \end{cases} \quad (1)$$

where the subscript  $i$  refers to the channel which is currently used, while  $k$  refers to the other channels, and  $j$  refers to the channel which has the highest energy level. The duration of searching for and switching to channel  $k$  is defined as  $\lambda_k$  and the other cost to switch channel  $k$  such as energy consumption and computation is defined as the parameter of  $h_k$ . Without loss of generality, we assume the switching time and cost are the same for all channels since the network devices and capabilities are considered to be the same for all vehicles.

The fraction defined in Eq. (1) formalizes the **Benefit/Cost Rate** of the switching operation. The benefit is defined as the lowest energy level since SUs are searching for the available channels with least interference. Therefore, the benefit is the difference between the energy level of the channel, which has the highest one, and the energy level of the current channel. A more significant difference implies a more beneficial channel. In case the current benefit/cost rate is less than the others, it implies there is a channel less noisy channel worth switching to despite the switching cost.

### 4. Numerical Result

The performance of a DSA-based VANET has been analyzed using the adaptive behavioral response mechanism in the *GEMV<sup>2</sup>* Vehicle-to-Vehicle (V2V) propagation simulator via *MATLAB* [110]. The experimental traffic data is generated in SUMO for a  $1\text{km}^2$  region around

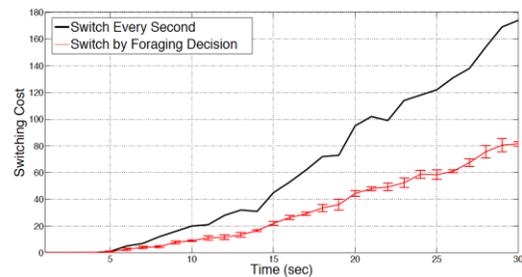


**Figure 2** The adaptive behavioral response decides whether there is a better channel worth to switch.

the Worcester Polytechnic Institute, Worcester, MA campus in downtown. The channel sensing algorithm is performed for DTV frequency band at 700MHz.

In Figure 2, the utilization of the best available channel is compared for two cases. Note that the best available channel is defined as an available channel with the least noise such that it has the lowest energy level. In this experiment, the number of vehicles in the chosen region increases each second. The total number of vehicles (blue line) would provide the upper bound of the performance if all the vehicles are capable of using the best available channels. In the first case (black line), the switching mechanism based on the adaptive behavioral response is employed. In the second case (red line), the vehicles stay in the current channel until they loose the connectivity. The results show that the proposed approach can handle energy level changes of the channels approximately 150% more than the second case. Although the second case has less switching cost, the performance increase of the adaptive behavioral response is observed.

In Figure 3, the total switching cost in the experiment region as a function of time is shown. Since the number of vehicles increase each second in the experiment scenario, the spectrum utilization is increased. Therefore, the changes of energy levels of the channels are becoming more dynamic, as well the number of switching operations being increased at each time step. In this experiment, the proposed approach is compared with the case that switching operation is applied every time step without considering if it is worth to switch. As shown in this figure, approximately 50% decreases the switching cost. Although switching every second can give a better performance result, the switching cost and process time can cause excessive overhead.



**Figure 3** The behavioral response adapts the switching operation to changing environment.

**4. Conclusion**

In this letter, an architecture capable of spectrally efficient wireless access in time varying vehicular networking environments that is inspired by the optimal flower selection process employed by foraging bumblebees is presented. Numerical results show that the proposed solution 150% increase on channel selection performance and 200% decrease on switching cost.

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# A COGNITIVE TD-LTE SYSTEM OPERATING IN TV WHITE SPACE: TEST-BED DESIGN

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## I. Introduction

The available licensed frequency bands for 4G cellular networks using Long Term Evolution (LTE) technology in Asia are around 2 GHz and above, which increases the network cost for large area deployments. According to spectrum occupancy measurements in Beijing, significant white space opportunities exist among the Television (TV) broadcasting system bands around 700 MHz [1] and allow the operation of 4G cellular networks in TV White Space (TVWS). Such opportunistic operation will require dynamic spectrum access (DSA), which is based on effective Cognitive Radio (CR) principles. Compared to the strict requirements of the paired downlink and uplink spectrum bands with appropriate spectrum separation for FDD LTE, the TD-LTE system with multiplexed downlink and uplink in the same spectrum band can fully utilize the fragmented TV white space (TVWS). Besides, to meet the service demands in hot spots, multi-tier heterogeneous radio access networks are deployed extensively with overlapped coverage areas, which will lead to the spectrum allocation and interference among multi-tier heterogeneous networks big challenges. Therefore, DSA and efficient spectrum management technologies should be applied in heterogeneous radio access networks with various coverage types, such as macro cells and small cells.

Standardization activities targeting TVWS utilization include IEEE 802.22 [2] for Wireless Regional Area Networks (WRAN), European Computer Manufacturers Association (ECMA) 392 [3] for Wireless Personal Area Network (WPAN), and, most recently, the IEEE 802.11af Task Group [4] for Wireless Local Area Network (WLAN). Collectively, the above standards espouse mechanisms for co-existence between secondary and primary networks (via mechanisms such as node geo-location, spectrum sensing and dynamic channel selection) for a variety of use case scenarios, such as fixed, long-range outdoor services for 802.22 and short range, indoor services for ECMA-392 and 802.11. With regards to spectrum sensing, these standards mostly advocate a quiet period for spectrum sensing by interrupting an existing communication session. This is not appropriate for TD-LTE system which has strict QoS

requirements for latency in the voice service, which precludes interrupting a communication session [5]. Therefore, other new and simple modifications to the existing TD-LTE protocol stack are needed to support cognitive users in TVWS.

In this article, a CR enabled TD-LTE test-bed that operates in TVWS is proposed that supports the multi-tier heterogeneous radio access networks. Specifically, an efficient feature detection based spectrum sensing method is proposed for TD-LTE nodes which can achieve 99.9% detection probability and 1% false alarm probability. The proposed CR enabled TD-LTE frame structure utilizes the guard period and adjacent vacant uplink subframe for spectrum sensing by the Cognitive eNodeB (CeNB), which requires minimum protocol stack modifications. In particular, Cognitive Control Channel (CogCCH) is proposed in Medium Access Control (MAC) layer to transmit CR-related Radio Resource Control (RRC) information and Physical Cognitive Channel (PCogCH) is proposed in Physical (PHY) layer to broadcast the spectrum decision information to CR user. To mitigate any potential adjacent channel interference between the TD-LTE system and the TV broadcasting system, appropriate guard bands between these two systems are needed. The width of the guard bands is determined through simulations and field experiments. To the best of our knowledge, the proposed test-bed is the first CR enabled TD-LTE system operating in TVWS.

## II. CR Enabled TD-LTE Test-bed Utilizing TVWS

To solve the challenges of deploying CR enabled TD-LTE system operating in TVWS, both solutions and analyses are proposed, including an efficient spectrum sensing method for TV signal detection, interference analysis and the CR enabled TD-LTE protocol stack.

### A. Spectrum Sensing in TVWS

The CeNB based spectrum sensing method is proposed for spectrum sensing in TVWS. Unlike the US where White Spaces exist among digital TV signals, analog TV signals will be the dominant primary users in China for many years. Therefore, a feature detection based spectrum

sensing method exploring the specific characteristic of the analog TV signals is proposed. According to the spectrum characteristics of analog TV signals (PAL-D) in China [6], the energy of the baseband TV signals is mostly concentrated on 1.25 MHz, chroma vice carrier on 5.68 MHz and audio FM carrier on 7.75 MHz as illustrated in Fig. 1.

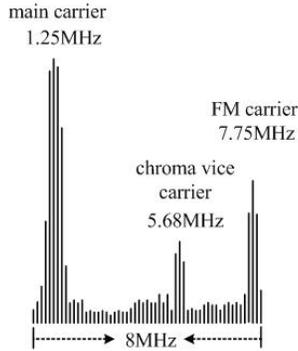


Figure 1 Spectrum characteristics of analog TV signals

B. Interference Analysis

One approach to reduce the adjacent channel interference (ACI) between TD-LTE system and TV broadcasting system is reconfiguring the central frequency of the TD-LTE system and setting appropriate guard bands between two systems, which will reduce available spectrum resources. Another approach is to use power control scheme to transmit with lower power on adjacent channels closed to the active TV channels. Based on the geo-database, if the TD-LTE system is close to TV receivers, it can use the spectrum bands far from the active TV channels to reduce the interference. Based on the mapping relationship between ACIR and the

width of guard bands [6], the frequency separation bandwidth of 7 MHz is appropriate to enable the coexistence of two systems.

C. The CR Enabled TD-LTE Protocol Stack

In this section, modifications to the TD-LTE protocol stack for both the CeNB and the CR user are designed to support CR functions, as illustrated in Fig. 2.

In the RRC layer, we introduce the spectrum decision management module in CeNB to make spectrum decision according to the spectrum sensing information received from the spectrum sensing module. Two main spectrum management functions are proposed for RRC. The first one is called the long-term spectrum management among different CeNBs for the efficient allocation and utilization of TVWS. The second one is called the short-term spectrum management within CeNB. The MAC layer provides different types of data transmission on different types of logic channels, so the types of logic channels are determined by data types. To accomplish the interaction of CR-related information, a new logic channel called CogCCH is proposed both in CeNB and CR users to transmit CR-related RRC messages. In the PHY layer, a physical channel called PCogCH is proposed both in CeNB and CR user to carry the spectrum decision information on the transport channel called Cognitive Channel (CogCH) and broadcast the spectrum decision information to CR users through the special subframe. The CR user executes the spectrum decision after receiving the broadcast information. To reduce the power consumption and signaling overhead for the CR user, the

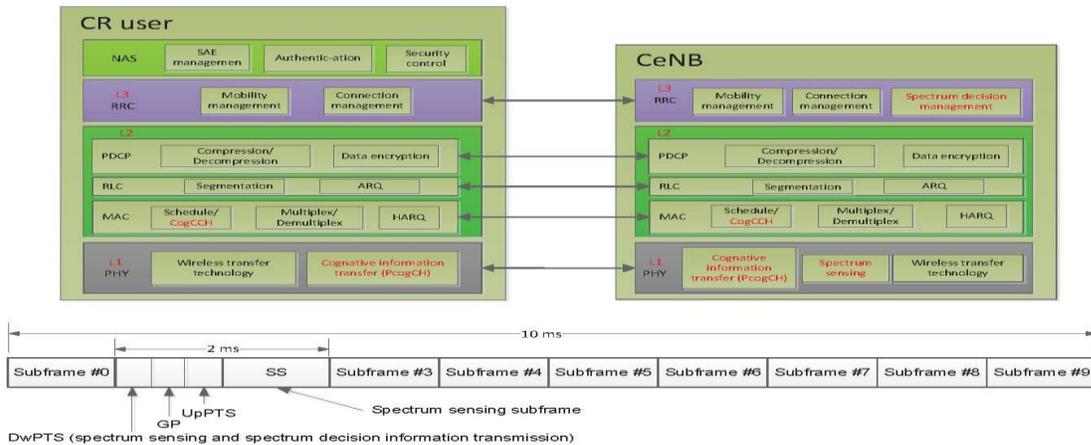


Figure 2 Proposed CR enabled TD-LTE protocol stack and frame structure

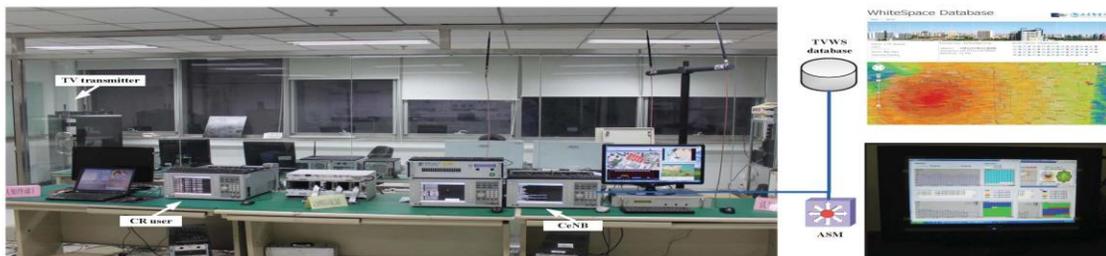


Figure 3 CR enabled TD-LTE Test-bed

spectrum sensing module is only added in CeNB to perform the spectrum sensing and report the spectrum sensing results to RRC layer. Meanwhile, through the X2 interface among CeNBs, cooperative spectrum sensing can be performed accordingly, which will be used between the adjacent CeNBs for spectrum sensing information exchange and long term spectrum management.

Furthermore, the TD-LTE frame structure is modified to enable CR functions as illustrated in the lower part of Fig. 2. Within 10 ms TD-LTE frame, the Guard Period (GP) in the special subframe #1 is used for spectrum sensing which will not disrupt the communication between CeNBs and CR users. Moreover, the adjacent vacant uplink subframe #2 is also used for spectrum sensing when the candidate TVWS is too wide. Thus, the TD-LTE system performs spectrum sensing within 2 ms in each 10 ms frame period. Meanwhile, the spectrum sensing module will perform spectrum sensing and deliver the results to the RRC layer. The DwPTS in the special subframe is chosen to transfer both spectrum sensing and spectrum decision information of the previous frame.

### III. Test-bed

A CR enabled TD-LTE test-bed has been designed and developed with two CeNBs and eight CR users. Both CeNBs and CR users are implemented with a unified hardware platform [7], where the baseband signal processing functions are implemented on TI C6487 DSP. In the three-core DSP, one of the DSP core is used for downlink signal processing, the second one is used for uplink signal processing and the third one is for scheduling. AD/DA operation is implemented in Xilinx FPGA, with the AURORA interface to DSP. Besides, the platform can also download different protocols from DSP dynamically, which is capable of reconfiguring its work mode and parameters intelligently to efficiently utilize TVWS.

Each TV channel occupies a frequency of 8 MHz in China, thus the TD-LTE system can be

implemented with 20 MHz system bandwidth when three continuous TV channels (24 MHz) are vacant. After the CeNB detects the TV signal, the CeNB will execute spectrum handover and switch to another vacant spectrum band accordingly. Furthermore, the spectrum sensing results will also be sent to the TVWS database for vacant spectrum information update, which is used for vacant spectrum information coordination and synchronization among CeNBs. In addition, considering the scenario that continuous TV channels are less than three, the test-bed can apply the dynamic system bandwidth adjustment technology, which means that 15 MHz bandwidth is used when two continuous TV channels are vacant and 5 MHz bandwidth is used if only one TV channel is available. Therefore, the test-bed can dynamically change its system bandwidth in order to adapt to different vacant spectrum conditions in practical scenarios.

The test-bed is illustrated in Fig. 3 with three analog TV signal transmitters deployed as the primary TV broadcasting system. The CeNB and CR users are placed inside the room with a Light-of-Sight (LoS) propagation. The antennas for both CeNB and the CR users are 6 dBi rod-antenna. The transmit power of the CeNB is 20 dBm. In addition, the CeNBs are connected to the TVWS database and advanced spectrum management (ASM) subsystem. The TVWS database will collect and update the crude data of spectrum sensing results from different CeNBs, the database of mobile network, TV broadcasting operators and the database of state spectrum regulators, in order to draw the global spectrum occupancy graph. Moreover, based on the global spectrum occupancy graph from the TVWS database, the ASM subsystem is responsible for an efficient spectrum management and coordination among different CeNBs by making decisions for the efficient vacant spectrum allocation.

### IV. Conclusion

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This paper discusses the challenges and solutions for the CR enabled TD-LTE system using TVWS. To solve the challenges of employing CR in the TD-LTE system, an integrated solution framework has been conceived, which meets the demands for a large coverage in low frequency bands. The proposed CR enabled TD-LTE frame structure utilizes the guard period and adjacent vacant uplink subframe for spectrum sensing in CeNBs. Besides, a feature detection based spectrum sensing method is designed to improve the TV signal detection probability. In order to reduce the interference between the TD-LTE system and the TV broadcasting system, appropriate guard bands between two systems are used and the width of the guard bands is determined. Moreover, the protocol stack and frame structure are redesigned with the minimum modification to the existing TD-LTE standard to support CR functions. Finally, CR enabled TD-LTE test-bed is presented.

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**TVWS as A Valuable Spectrum Offloading Opportunity for Wi-Fi like Connectivity**

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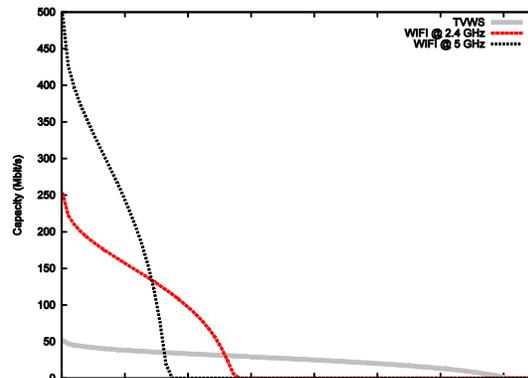
**1. TVWS**

New application and services are demanding a constantly increasing amount of spectrum. People often carry smartphones and other devices in their pocket, browsing the Internet, watching videos, and listening to audio on demand. In this scenario, finding new spectrum is mandatory but challenging, since almost all frequencies are statically allocated.

Recently, national regulators worldwide like the FCC in the U.S. [2] and Ofcom in the U.K. [3] started to issue regulations on the opportunistic usage of the so-called TV White Space (TVWS) spectrum. What is particularly interesting about these frequencies is the fact that they have good transmitting range, since they are considerably lower than mostly frequency bands used for WiFi Like connectivity like the 2.4 GHz and the 5GHz. Thus, building networks on TVWS could be cheaper, since less access points are needed, and can also provide a better coverage in indoor locations, thanks to the superior propagation characteristics of the sub-1GHz spectrum band. This can be easily seen in Figure 1, where we plot the channel capacity for TVWS networks (with a channel bandwidth of 8 MHz), WIFI in the 2.4 GHz band (with a channel bandwidth of 40 MHz), and WIFI in the 5 GHz band (with a bandwidth of 80 MHz) [5].

To access TVWS, a device must obtain information about the available channels on its location, by querying a remote spectrum database asking for the channels not in use by a DVB-T broadcaster. The database will reply with a list of the possible channels to use, and the device will eventually tune to one of them.

Two problem arise: at first, by forcing TVWS enable devices to ask for the list of channels each time they want to transmit, an additional wireless technology is needed to route their traffic to a the remote database, otherwise device cooperation should take place [6]. Secondly, TVWS are abundant in rural areas, but scarce in highly populated areas. For instance, cities like New York City, NY, Los Angeles, CA, and many other metropolitan areas in the U.S. offer less than 2 channels for opportunistic use [4] [10]. Thinking at the TVWS as a sole wireless



**Figure 4: Channel capacity for TVWS and WIFI networks.**

technology for a given device is thus hard, but TVWS can bring valuable spectrum when available, and can be used as an offload technology for a multitude of devices [5].

**2. Use-Cases**

TVWS can provide different interesting use-cases for the end user. They were initially studied to bring high speed Internet to rural communities, with poor or no cellular coverage and no high speed fixed connections [10]. However, more recently they have also been studied to provide shorter-range communications, in a Wi-Fi like connectivity, mainly to reach possible poorly covered spots in buildings [8]. The IEEE published the 802.11af standard, which is the amendment to IEEE 802.11 to use TVWS [9], providing a standard suitable for communication indoor like with the widely adopted IEEE 802.11 standard.

Another interesting use-case is about sensor networks, in which TVWS can bring long-range communication and also lower energy usage, thanks to a reduced power needed to transmit [7].

In [1] [11] there is a detailed list of deployed networks in Scotland that benefits from TVWS. They range from maritime connection for sea ferries, to healthcare assistance, to video monitoring in the city of Glasgow, Scotland. TVWS are extremely flexible, and can thus

accommodate a wide range of services.

### 3. TVWS availability

TVWS certainly face a problem, that is, their scarcity in densely populated areas. This is slowing their adoption for a wider use beyond rural Internet access. For a device operating in these scenario, mainly two different approaches exist: *i*) Cognitive Underlay Access (or TV Gray Space) [8], *ii*) Relaying on a licensed technology thus using TVWS only for offloading data when available [5].

It is important to note that the regulators do currently not envision the first approach, because it might disrupt the service of the DVB-T broadcaster by transmitting on a channel currently used. The second approach is instead always available, which thus envisions devices with TVWS as backup technology, with another possible one like Wi-Fi or LTE.

The latter approach work as follows: when the first technology can provide the desired QoS, it should be used for transmission. When it starts to experience difficulties, maybe because of lack of coverage, the device should offload part of the data to TVWS, if available, to provide a better transmission coverage [5].

### 4. Trials

TVWS networks have attracted a huge audience also from the industry, with top firms like Google, Microsoft, and Qualcomm, to name few. Through the world, a series of trails took place, and more are carried out now or will be held in the future, to assess the viability of TVWS operated networks.

Among all, it is important to cite the Ofcom trials and pilots [1] [11] which assessed several use cases, ranging from sea ferries connections to the mainland, to ambulances and hospitals wireless coverage, to video surveillance in downtown Glasgow, Scotland.

Another important trial is currently undergoing in Africa, split into Kenya, Botswana, and Ghana, among the others, where Microsoft is the lead investigator and is mainly focused on connecting rural villages [12], and South Africa, carried out, among the others, by Google, aiming at connecting schools [13]. Both trials confirmed that TVWS was an ideal technology for such use-cases, combining a large transmitting range

with a sufficient data rate.

### 5. Conclusions

TVWS are appealing for a multitude of reasons. Longer transmitting range compared to other technologies, superior propagation through obstacles, and a possibly large set of channels to be used. TVWS however lack of availability in densely populated areas, where more customers live, and thus where more people might adopt them. In addition, they also present slightly lower throughput compared to other technology, which can however be maintained also in shadowed scenarios. Hence, TVWS can be seen as a valuable offloading solution, where another wireless technology might not provide satisfactory performance, due to lack of coverage or poor data rate. In those scenario TVWS can bring additional valuable spectrum to offload part or all the data of the device. Several standards have already been proposed, and test pilots and trails spread worldwide, confirming the goodness of TVWS operated networks. It is hard to see TVWS as a substitute for other wireless technologies in indoor scenarios, due to a lower data rate and to the possible lack of available channels. Still, they present valuable characteristics that make them ideal for a multitude of use-cases and services, hence confirming their attractiveness.

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