Resource Allocation in Next-Generation Broadband Wireless Access Networks

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Chapter 2

Radio Environment Maps and Its Utility in Resource Management for Dynamic Spectrum Access Networks

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ABSTRACT

Recent measurements on radio spectrum usage have revealed the abundance of under-utilized bands of spectrum that belong to licensed users. This necessitated the paradigm shift from static to dynamic spectrum access (DSA). Researchers argue that prior knowledge about occupancy of such bands, such as, Radio Environment Maps (REM) can potentially help secondary networks to devise effective strategies to improve utilization. In the chapter, we discuss how different interpolation and statistical techniques are applied to create REMs of a region, i.e., an estimate of primary spectrum usage at any arbitrary location in a secondary DSA network. We demonstrate how such REMs can help in predicting channel performance metrics like channel capacity, spectral efficiency, and secondary network throughput. We show how REMs can help to attain near perfect channel allocation in a centralized secondary network. Finally, we show how the REM can be used to perform multi-channel multi-hop routing in a distributed DSA network.

INTRODUCTION

Radio spectrum allocation and management have traditionally followed a 'command-and-control' approach where chunks of spectrum are allocated for specific services under restrictive licenses. The restrictions specify the technologies to be used and the services to be provided, thereby constraining the ability to make use of new technologies and the ability to redistribute the spectrum to higher valued users. Over

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the past years, traditional approaches to spectrum management have been challenged by new insights into the actual use of spectrum. In most countries, all frequencies have been completely allocated to specific uses and spectrum appears to be a scarce resource within the current regulatory framework. Moreover, recent experimental studies have revealed that spectrum utilization is time and space dependent and that most parts of radio spectrum are highly underutilized (Shared Spectrum Company, 2007; Buddhikot, M., 2005; F. communications commission, 2004).

Such limitations have motivated a paradigm shift from static spectrum allocation towards a notion of dynamic spectrum management where secondary networks/users (non-license holders) can 'borrow' idle spectrum from those who primary networks/users (license holders) without causing harmful interference to the latter. Dynamic Spectrum Access (DSA) networks that utilize such unused spectrum holes within the licensed band have been proposed as a possible solution to the spectrum crisis. The idea is to detect times when a particular licensed band is unused and use it for transmission without causing interference to the licensed user. Secondary users equipped with cognitive radio enabled devices will facilitate such DSA where the cognitive radios continuously monitor the presence of primary users and opportunistically access the unused or under-utilized licensed bands (Akyildiz, I. F, 2006). However, the most important regulatory aspect of these networks is that the secondary nodes must not interfere with primary transmissions. Thus, when secondary nodes detect transmissions from primaries, they are mandated to relinquish those interfering channels immediately and switch to other non-interfering channels.

Due to the temporal and spatial fleetingness of spectrum occupancy, such reactive nature of secondary networks is insufficient for desired utilization of under-used licensed spectrum. Researchers have argued that a prior knowledge of the possible transmission activities of the primaries can allow the secondary nodes to effectively access the available resource and predict the expected radio and network performances for quality of service (QoS) provisioning in secondary networks. Such prior knowledge would also help the secondary networks in finding better routes from a source to a destination where route existence and quality are ever changing with primary activity. Thus, there is a need to proactively estimate the spectrum usage at any arbitrary location and then extend that for predicting the nature of spectrum utilization in a region of interest. The recent ruling by FCC (FCC, 2007) also necessitates the need for secondary networks to create, manage and refer to spectrum usage databases for secondary access opening new discussions on design, implementation techniques, and capabilities of such spectrum usage databases.

Spectrum databases are usually manifested either through mandating primary transmitters to report their transmission activities to a central authority, or through building spectrum usage or radio environment maps (REMs), e.g., TV whitespace database (Google, 2015), often called spectrum cartography. Such REMs provide signal strength values from primary transmitters on different channels in a particular geographical region, i.e., multiple 3D plots with one for each channel. The stringent policy enforcement of reporting spectrum activities has had some roadblocks in terms of the underlying legal and policy issues, which are suspected to pose a barrier for wide-adoption of dynamic spectrum access technologies. Thus, primary usage prediction schemes and models have garnered much traction in recent times. Such schemes vary from modeling spectrum utilization using statistical models (Riihijarvi, J., 2008) to real-world measurement data based prediction models (Li, Y., 2009). Some of these techniques are specific to primary network types (such as, TV, cellular etc.) and some are more extensible for any generic primary networks.

This book chapter seeks to introduce concepts of Radio Environment Maps and its utility in efficient resource provisioning in DSA networks. First Section II presents the approaches and consideration for effective and accurate REM construction. Section III discusses how such REMs can be used to predict secondary channel performance metrics that can ensure optimal resource allocation. Subsequently, Section IV discusses how such REM-aided performance metrics prediction can be used for effective and near-optimal resource allocation in terms of channel allocation in a centralized secondary network and multi-channel multi-hop route selection in a distributed secondary network. Finally, conclusions are drawn in the last section.

RADIO ENVIRONMENT MAPS: APPROACHES AND CONSIDERATIONS

In this section, we describe the most popular REM construction approaches and the key considerations needed to make them accurate, i.e., representative of real life primary usage scenario.

Radio Environment Map Construction Approaches

Direct Interpolation Based Methods

The direct method based on the interpolation approaches estimate the primary spectrum usage at any arbitrary location. Such REMs are most often constructed by first fusing measurements from different sensor locations at a centralized or distributed node(s) using cooperative (Ganesan, G., 2007) or collaborative sensing (Ghasemi, A., 2005; Visotsky, E., 2005); and then by applying geostatistical and variational interpolation methods to predict spectrum usage at different location on a geographic plane. The most widely adopted direct interpolation methods for REM construction are: inverse distance weighted (IDW) methods (Denkovski, D., 2012), nearest neighbor (NN) methods (Alaya-Feki 2012), spline methods (Mateos, G., 2009), Kriging methods (Phillips, C., 2012), and modified Shepard's (MS) methods (Debroy, S., 2016). Among these, IDW, NN methods consider mostly local spatial data for interpolation, whereas spline, and Kriging methods use global measurements for primary usage estimation. In IDW based methods, it is assumed that signal spatial samples which are close to each other, are more alike than those which are farther apart. Thus more weightage are given to sensor measurement data close to the interpolating point than further. In NN methods, the sensor measurement with the minimum Euclidean distance from the interpolating point is adopted for the estimated usage at the interpolating point. Spline methods use thin-plate splines based on radial basis functions for interpolation and performs well even in the absence of precise channel frequency and bandwidth information; however suffer from computational complexity issues. The Kriging methods apply a weighted average interpolation technique that takes into account both the distances and the degree of influence between the sensor measurements when estimating the signal level at any arbitrary point.

In one of our earlier works (Debroy, S., 2016)., we presented a modified version of well known Shepard's interpolation function that takes into consideration the locations, number, and relative orientation of the sensor measurement points that constructs a continuously differentiable distribution function. The function estimates the spectrum utilization at any arbitrary location. Our proposed scheme borrows the essence of cooperative spectrum sensing by allowing participating secondary sensor nodes to share their measured spectrum data periodically with a fusion node. However, unlike conventional cooperative spectrum sensing where the devices share decision vectors (representing occupancy of channels), the sensors share their raw spectrum data which are later fused to estimate spectrum usage at unknown points. The proposed scheme is independent of the outdoor fading and shadowing environment; only the sampling and reporting frequencies may vary depending on the environment. Figure 1(a) and Figure1(b) show the power spectral density of primary channel usage for a channel of bandwidth 100 KHz using modified Shepard's interpolation method and with 40 and 80 sensor measurement points respectively. The experiment was performed for a 100x100 sq. km. region with real-world spectrum data archive of 2.4 GHz ISM band in Germany from RWTH Mobnets (Riihijarvi, J., 2008). Locations of the sensor measurement points are shown explicitly. The surface plots become increasingly accurate as the number of data points increases. However, there is a trade-off between the accuracy of estimation and computation complexity with is dependent on other physical and environmental factors such as type of primary network (threshold signal strength to operate, probability of primary activity), accuracy of sensors involved in detecting signals, location of the sensors, physical environment in terms of terrain affecting fading and shadowing (Faint, S., 2010; Wei, Z., 2013).

Indirect Location Based Methods

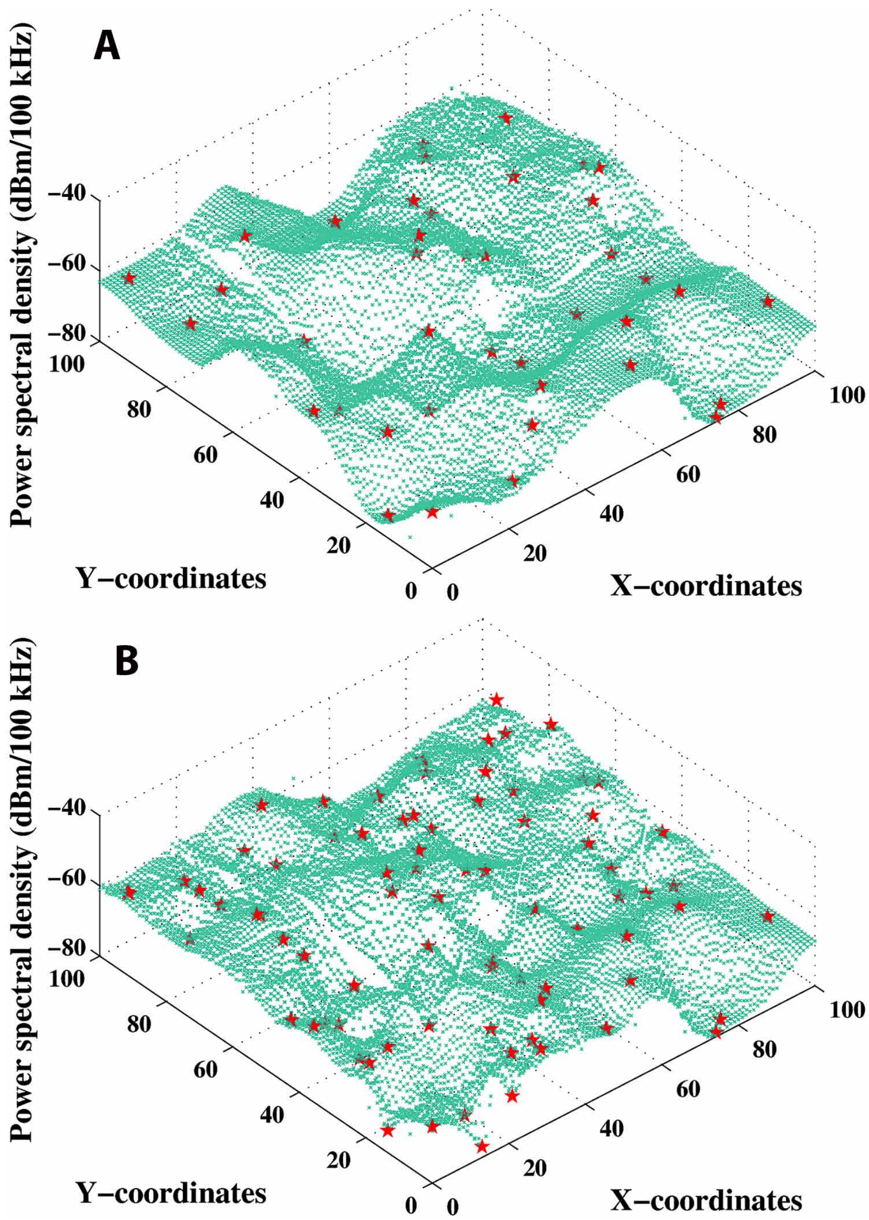
The indirect REM construction methods make use of known parameters of the transmitter and radio propagation modeling to estimate primary occupancy. One of the notable works (Yilmaz, H. B., 2015) in this area proposes a transmitter location estimation based REM construction where the location and transmission power of the primary transmitter is estimated and subsequently REM is constructed taking into account the propagation channel properties. In a similar SNR-aided method (Sun, G., 2010), a low-cost, high-precision localization method for REM construction technique is proposed without any prior knowledge of the interference source other than the transmitter power. Finally in (Meshkova, E., 2011), an indoor REM is constructed by studying the characterization and modeling of the radio indoor environment based on spectrum measurements from heterogeneous spectrum sensors.

Considerations for Radio Environment Map Construction Accuracy

Selection of Spectrum Sensing Locations

The accuracy of REM construction is dependent on the gathered spectrum usage data, and thus such accuracy can be greatly improved by fusing sensed data from strategic locations. Be it centralized or distributed secondary networks, and either with a central repository or multiple fusion centers, strategically placing the sensing locations (pre-deployment) or relying more on data from strategic locations (post-deployment) that in turn depends on the primary transmitter locations have been found to profoundly impact the accuracy of the constructed REM. Research has shown (Debroy, S., 2016) that *iterative clustering* technique using tree structured vector quantization (TSVQ) is one such intelligent strategy for sensing location selection. *Vector quantization* (VQ) is a powerful data compression technique where an ordered set of real numbers is quantized. The idea of such quantization is to find $|\Delta|$ representation points (distinct vectors) from a large set of vectors so that the average distortion is minimized. With iterative clustering, the size of the representation points grows from 1 to the desired value, $|\Delta|$. Thus, for DSA networks, given a set of primary transmitter locations, their centroid (say S_1) is the ideal representation point when $|\Delta|=1$, as the sum of the Euclidean distances to all the primary transmitters is minimum at the centroid.

Figure 1. Radio environment map construction example with different number of sensor measurements used for interpolation: (a) REM with 40 sensor measurements; (b) REM with 80 sensor measurements

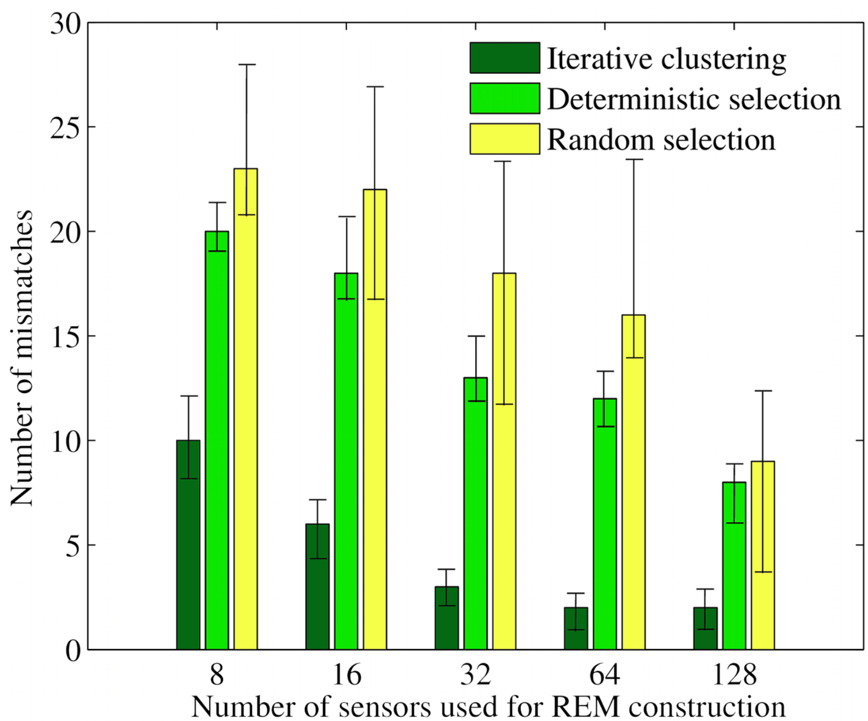


With further iterations, can be split into two points, S_1 and $S_1 + \varepsilon$, where ε is a small Euclidean distance. Each of the primary transmitter locations is grouped on to the closer of the two representation points thereby creating two clusters with two representation points. Again, the new centroids of these two newly formed clusters are determined and the old representation points, S_1 and $S_1 + \varepsilon$, are updated with the new centroids' position creating new representation points S_1 and S_2. Similar iterative clustering is performed until the desired size of |Δ| is achieved. The utility of iterative clustering based sensing location selection over random and deterministic sensing location selection is demonstrated in Figure 2 in a simulated environment representing a centralized DSA network. The utility is measurement in terms of mismatches in estimating primary occupancy using REM constructed through measurement interpolation using the sensing locations selected by three completing techniques. In deterministic selection, locations are chosen uniformly in a grid-like orientation to cover the entire region without considering the locations of the primaries with random selection choosing locations randomly. The performance comparison is made for low primary activity of value 0.3. The figure illustrates that iterative clustering performs better than random and deterministic selections in terms of average mismatches for any number of selected sensing locations for interpolation.

Spectrum Data Falsification in Cooperative Sensing and Sharing

Cooperative spectrum sensing and sharing for REM construction can be vulnerable when multiple malicious nodes share false local sensing reports. As a result, the fused decision may be altered, hence jeopardizing the reliability of REM. Such phenomenon where local sensing result is manipulated is known as Spectrum Sensing Data Falsification (SSDF) or Byzantine attack (Bhattacharjee, S., 2013). A malicious node can either advertise ‘occupied’ channels as ‘available’ and vice versa inducing errors or can alter primary spectrum usage data enough to impact interpolation outcome, and such attacks can be collaborative when attackers plan and attack together, or non-collaborative. Hence researchers proposed methods for secondary node-centric trust/reputation evaluation techniques in DSA networks and trust-aware spectrum usage information fusion schemes to preserve the correctness of primary oc-

Figure 2. Utility of iterative clustering based sensing location selection technique in terms of mismatches in estimating primary occupancy using REM constructed through measurement interpolation



cupancy estimation. Among them, works such as (] Chen, R., 2008; Rawat, A. S., 2011) are notable for centralized DSA networks. In (] Chen, R., 2008), the authors propose a reputation aware malicious node isolation scheme in a centralized DSA network and argue that for any practical scenario majority of the nodes cannot be malicious. Hence, the fusion center uses a majority voting rule to arrive at a global inference on primary occupancy. In (Rawat, A. S., 2011), the authors propose a Kullback-Leibler (KL) divergence based method for cooperative spectrum sensing and sharing under low density collaborative SSDF attacks in a centralized DSA network. The authors observe that below a certain fraction of malicious nodes (50% of all secondary nodes in the networks), their method is able to accurately predict primary occupancy and thus proving to be useful for REM generation.

In our previous works (Bhattacharjee, S., 2011; Bhattacharjee, S., 2013), we proposed trust based fusion techniques for distributed DSA networks under SSDF attacks to improve the integrity of cooperative spectrum sensing and sharing for more accurate REM construction. The proposed monitoring technique gathers trust evidences that could indicate the presence of anomalies in spectrum sensed data for multiple channels shared by other nodes. The anomaly monitoring technique takes into account the relative spatio-spectral orientation of the nodes and isolates potentially malicious nodes using either:

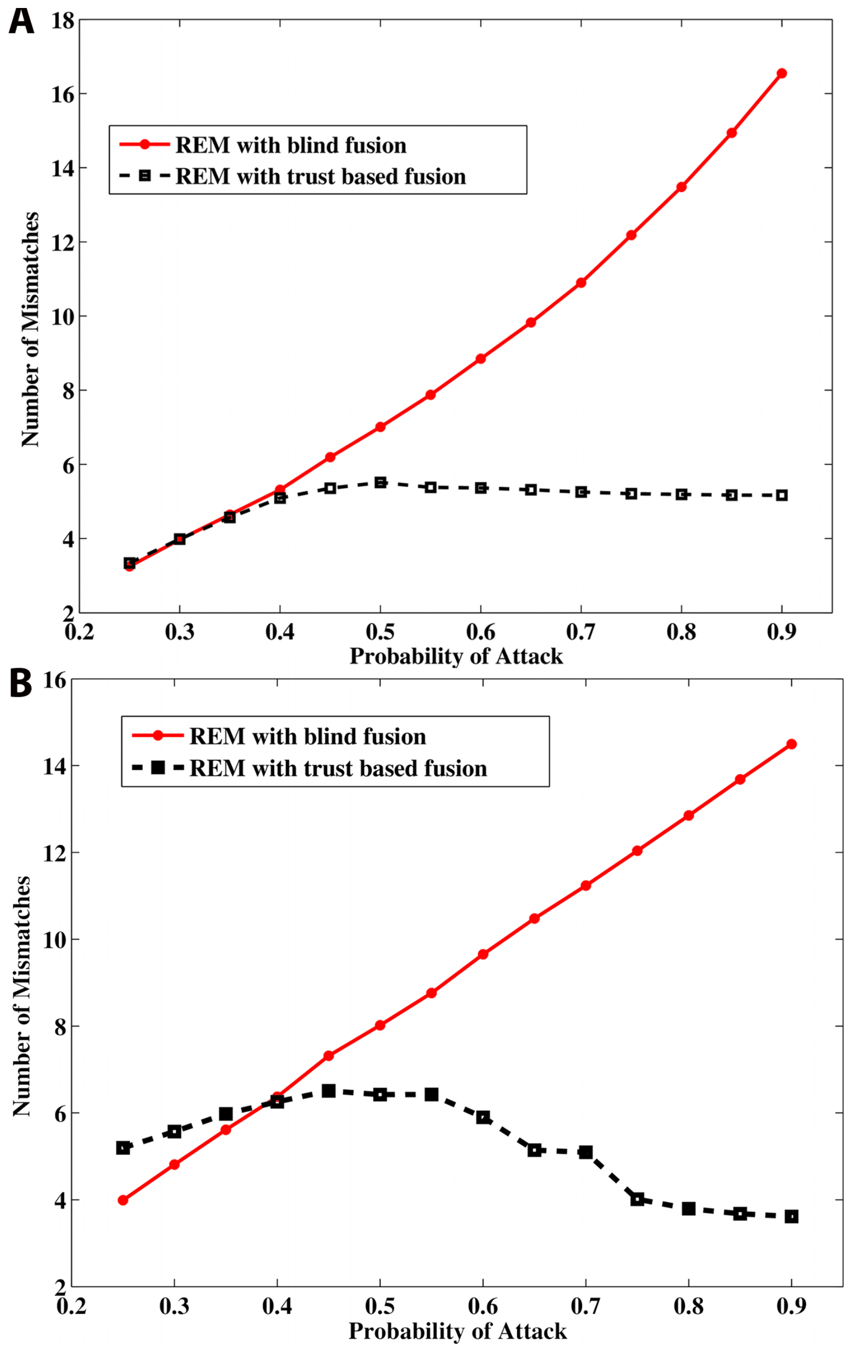
- An optimistic Beta expectation based trust model for low intensity of attacks.
- A conservative Dirichlet distribution inspired trust model for aggressive attacks.

Based on the secondary nodes' trust values, a trust based fusion is adopted that excludes the spectrum sensed data of an untrustworthy node from participating the fusion to generate REM. Figure 3(a) and Figure 3(b) demonstrate the utility of such trust based fusion for REM generation for a simulated distributed DSA network environment. The utility is measured in terms of number of mismatches between estimated and actual number of primary occupied channels. The figures show that for any probability and type (collaborative and non-collaborative) of attacks, the total number of mismatches for a trust based fusion is much less than that for blind fusion, thus proving to be more useful for accurate REM construction.

SECONDARY CHANNEL PERFORMANCE METRICS PREDICTION USING REMS

The REM of a geographical region helps the secondary network to not only estimate or predict the primary spectrum usage of that region, but such usage estimate can be effectively used to predict channel performance metrics, such as, available channel capacity, network throughput, and spectral efficiency for any secondary communication between a secondary transmitter-receiver pair and also the secondary network as a whole. Below we will show how primary spectrum usage information from REMs can be used to predict secondary channel performance metrics. For this, we assume a scenario where *K* secondary nodes are exposed to *M* primary transmitters. And to complicate matters, we also assume secondary channel reuse, i.e., a secondary receiver is interfered by potentially all primary and secondary transmitters on all possible channels. Thus, the interference experienced by a secondary receiver at (x_t, y_t) is due to the primary transmitters as well as other secondary communication using the same channel. Let us suppose that the interference experienced receiver at (x_t, y_t) from all primary transmitters is which is available from the latest REM.

Figure 3. Comparison in terms of number of mismatches between the estimated and actual primary occupancy between trust based and blind fusion techniques of sensed data for REM construction: (a) non-collaborative attack; b) collaborative attack



Now the secondary network (i.e., a base station for centralized networks, and a stand-alone node for distributed networks) can easily predict received signal strength at (x_t, y_t) as $P\left|h_q^t\right|^2$, where *P* is the transmit power of the corresponding secondary transmitter and h_q^t is the channel gain between the secondary transmitter-receiver pair. Thus, if I_q^t is the estimated co-channel interference at receiver (x_t, y_t) experienced from another secondary communication using same channel ch_q, then:

$$I_q^t = \sum_{\forall j \in \mathrm{K}^q} P\left|h_q^t\right|^2 \tag{1}$$

where K^q is the set of all other secondary pairs using channel ch_q, a parameter known by the secondary network. Now, with the above parameters, the secondary network can easily calculate critical channel performance metrics, such as, channel capacity, spectral efficiency, and secondary throughput in order to optimize the overall secondary communication before or during the channel resource allocation process to secondary nodes.

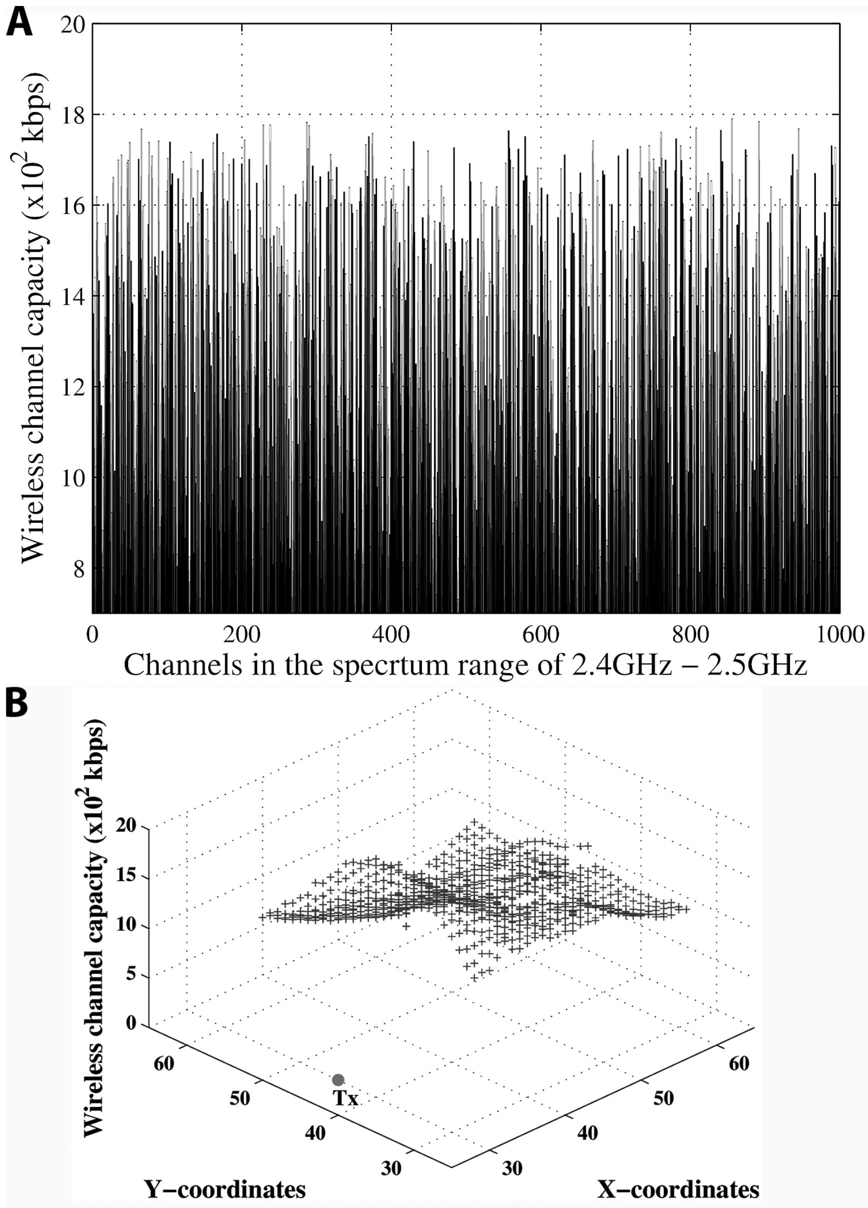
Channel Capacity

Using Shannon-Hartley's capacity model for a band-limited channel with additive white Gaussian noise (AWGN) (Shannon, C. E., 2001), the theoretical maximum secondary channel capacity C_q^t for the channel ch_q used by K^q set of secondary pairs can be estimated as:

$$C_q^t = B\log_2\left(1 + \frac{P\left|h_q^t\right|^2}{\varphi_q^t + I_q^t}\right) \tag{2}$$

where *B* is the channel bandwidth. In Figure 4(a), we show the predicted secondary channel capacity characteristics for an arbitrary secondary receiver location calculated using Equation 2. The figure shows different channel capacity values for 1000 channels of 100KHz each in the primary spectrum of 2.4 GHz ISM band. Such representation of channel capacity can be exploited by a particular transmitter-receiver pair for selecting best channel/s in terms of maximum achievable capacity when multiple such free channels are available for communication. Through another 3D representation shown in Figure 4(b), we present the estimated channel capacity values (calculated using Equation 2) of a particular channel for multiple potential receiver locations to a particular transmitter. Such representation can be further exploited for: a) optimal allocation of a particular channel to the best contending secondary nodes, and b) optimal location selection of a secondary node (in cases where secondary node installation is pre-planned) for statistically empty channels. Both approaches shown in Figure 4(a) and Figure 4(b) are highly effective for better overall secondary utilization.

Figure 4. Predicted channel capacity characteristics with REM: (a) channel capacity for different channels; (b) channel capacity of a region for same channel



Secondary Network Throughput

The secondary network throughput depends on the number of secondary pairs in a network using the same channel. When a secondary transmitter transmits with power *P* to a receiver at (x_t, y_t) on a channel ch_q, then the predicted transmission rate considering all other secondary communication using the same channel is given by:

$$\pi_q^t = \log\left(1 + \frac{P\left|h_q^t\right|^2}{\varphi_q^t + I_q^t + \sigma^2}\right) \tag{3}$$

where the received signals are corrupted by zero-mean additive white Gaussian noise of power σ^2. To predict the network throughput for channel ch_q, summation of the transmission rates of all the secondary pairs using ch_q is taken (Jeon, S.-W., 2011):

$$\Pi_q = \sum_{\forall j \in \mathrm{K}^q} \pi_q^t = \sum_{\forall j \in \mathrm{K}^q} \log\left(1 + \frac{P\left|h_q^t\right|^2}{\varphi_q^t + I_q^t + \sigma^2}\right) \tag{4}$$

In Figure 5(a) and Figure 5(b), we show the system throughput and per-pair throughput in kbps for the simulation scenario discussed previously. The nature of system throughput is similar to a conventional wireless network saturating after a certain point. Per-pair throughput characteristic shows convexity where there exists a optimal number of secondary pairs using a particular channel that yields maximum per-pair throughput.

Spectral Efficiency

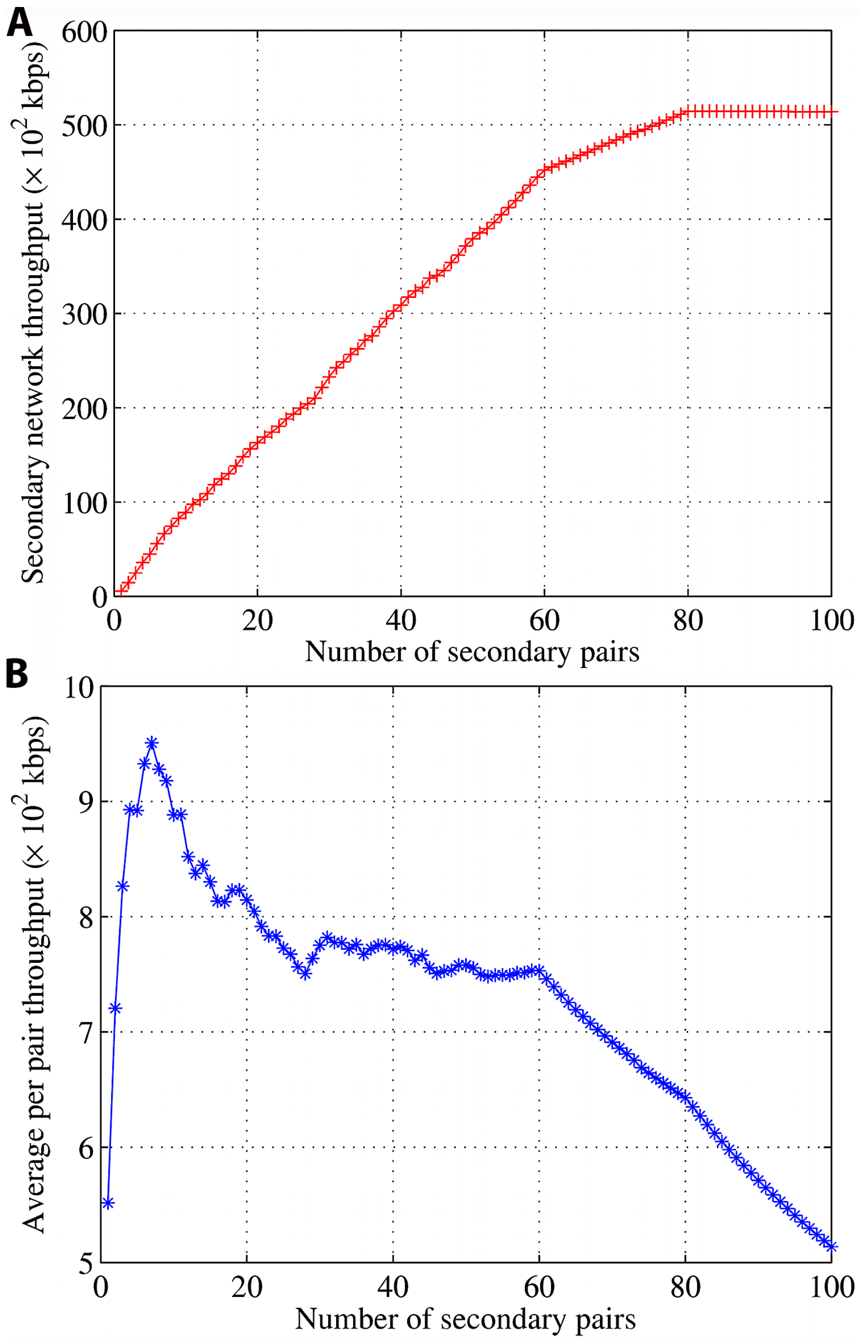
Secondary spectral efficiency provides an indication of how efficiently a bandwidth-limited frequency spectrum can be used. Spectral efficiency measured in bits/sec/Hz can be represented in two ways: link spectral efficiency and system spectral efficiency. The former is defined as the net bit-rate that can be achieved by a link per channel bandwidth (Hz). Similarly, system spectral efficiency is defined as the maximum throughput, summed over all nodes, divided by the channel bandwidth. It quantifies the number of secondary nodes that can be simultaneously supported by the available spectrum in a geographic area. Thus, link spectral efficiency for ch_q between a secondary transmitter-receiver pair can be predicted as:

$$\xi_q^t = \frac{1}{B}\log\left(1 + \frac{P\left|h_q^t\right|^2}{\varphi_q^t + I_q^t} + \sigma^2\right) \tag{5}$$

Similarly, the system spectral efficiency is obtained as:

$$\Xi_q = \sum_{\forall j \in \mathrm{K}^q} \xi_q^t = \sum_{\forall j \in \mathrm{K}^q} \frac{1}{B}\log\left(1 + \frac{P\left|h_q^t\right|^2}{\varphi_q^t + I_q^t} + \sigma^2\right) \tag{6}$$

Figure 5. Predicted throughput characteristics with REMs: (a) system throughput; (b) per-pair throughput



Thus, we see that just by estimating the primary signal strength φ_q^t on a channel ch_q from the REM, multiple key secondary channel performance metrics can be predicted for better utilization of the available spectrum and sustainable and effective secondary communication.

RESOURCE ALLOCATION USING REMS

In this section, we demonstrate how REM-aided performance metrics prediction can be used for effective and near-optimal resource allocation for:

1. Channel allocation in a centralized secondary network.
2. Multi-channel multi-hop route selection in a distributed secondary network.

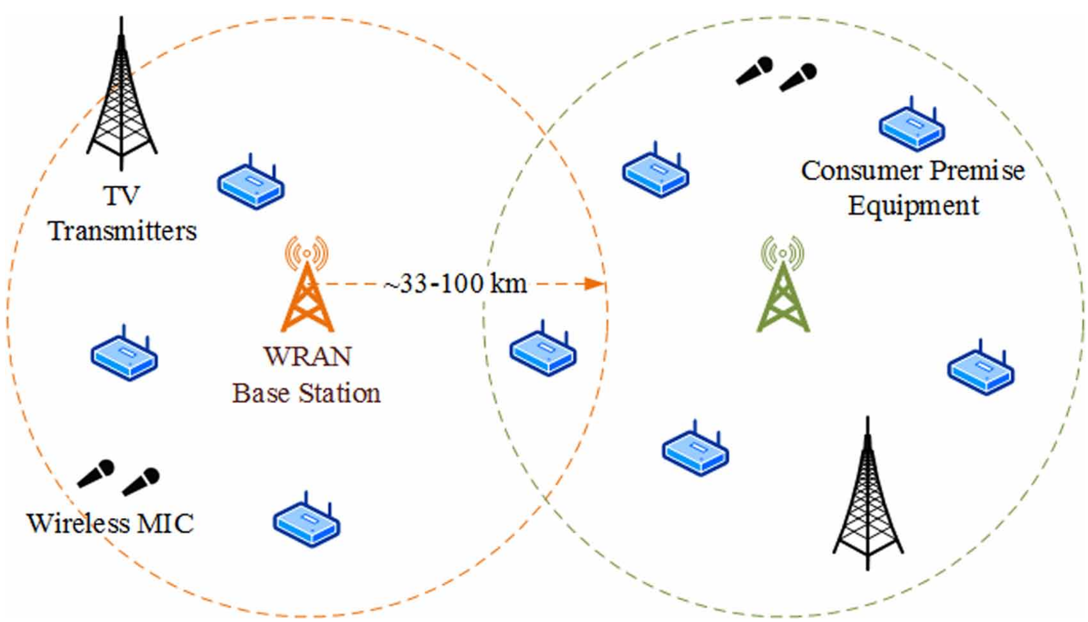
Channel Allocation in Centralized DSA Networks

The utility of REMs for channel resource allocation can be easily understood for a secondary network within TV white space (TVWS) primary environment. The TVWS (sub-900 MHz TV band) is one of the first primary networks to be mandated by FCC for secondary communication and IEEE has already proposed an initial draft standard (IEEE 802.22 WRAN) (IEEE 802.22, 2011) for secondary communication to exploit such unused bands. The core components of an IEEE 802.22 WRAN are base stations (BS) and consumer premise equipments (CPE) as shown in Figure 6. Secondary nodes (BSs and CPEs) opportunistically access unused or underutilized TV bands when not in use.

Primary and Secondary Networks in IEEE 802.22 WRAN

The primary network consists of TV transmitters, TV receivers and wireless microphones with the latter taking only a small amount of band space. The TV transmitters are deployed depending on population density in a geographic region with an urban area having denser transmitters than rural regions. The secondary IEEE 802.22 WRANs are centralized networks divided into cells, each having one BS. The

Figure 6. Architecture of an IEEE 802.22 Wireless Regional Area Network



BS communicates with the CPEs in its cell as well as with neighboring BSs. The BS is aware of the location of all the CPEs under it. The existence of pre-defined control channels are not mandated, i.e., BS and the CPEs may need to communicate with only the free channels that are currently not being used by the primary users.

Resource Allocation Problem

The two major challenges in allocating channels to the CPEs are: a) the absence of pre-defined control channels between the BS and the CPEs, and b) inability of the BS to view a global spectrum availability of its cell using traditional spectrum sensing approaches. The ability of the BS to assign the optimal channels to the CPEs depends on not only how well the BS is able to capture the availability of all channels at a particular CPE location, but also finding out the occupancy of a particular channel at all CPE locations. Since the BS cannot perform sensing at locations other than itself, it has to rely upon the sensed spectrum reports shared by the CPEs. If all the CPEs were to continuously share their spectrum usage reports, the BS would have the most accurate information. However, the communication overhead becomes a bottleneck as sharing of data has to be done on the same channels that the BS is supposed to allocate. Thus, channel assignment to CPEs becomes a challenge which can be address using REMs.

In our earlier paper (Debroy, S., 2016), we designed an on-demand channel allocation scheme for IEEE 802.22 WRANs using REMs. In our scheme, the CPEs work as data points and feed their spectrum usage data to the BS for it to create the map. The map enables the WRAN to achieve an efficient channel resource allocation in two aspects. First, the map is used for quicker communication with a candidate CPE and increases the probability of rendezvous between the CPE and the BS. Such communication allows the BS to acquire the actual spectrum usage at the CPE and evaluate different performance metrics. Secondly, such proactive performance analysis not only identifies the best candidate channel for a CPE but also indicates the best possible CPE among candidate CPEs for a particular channel. Channel allocation scheme thus adopted increases the overall network throughput and achieves close to optimal secondary spectrum usage.

Improving Rendezvous Probability Using Maps

The means of initial communication between the BS and a CPE looking for channels is the beacons sent by the BS and subsequent handshaking process. The latest IEEE 802.22 based WRAN specifications (IEEE P802.22a/D2, 2013) mandate the MAC layer to be able to adapt dynamically to changes in the environment by sensing the spectrum. Although the MAC layer is mandated to consist of specific data structures, details about the mechanism and involved channels (i.e., dedicated common control channel or dynamic channel rendezvous) for such rendezvous are not specified. However, in the absence of any control channel, this communication is probabilistic, i.e., the BS can send beacons with the specific data structures on the available channels and hope that the CPEs respond. Although viable, this traditional technique is ineffective and probability of rendezvous between the BS and a CPE is low. With the help of a REM, the beacon broadcast scheme can be made intelligent that can minimize the number of channels where beacons are sent and thus increasing the probability of dynamic rendezvous with the CPEs. This obviates the need for any control channel between the BS and the CPEs making the secondary communication completely opportunistic.

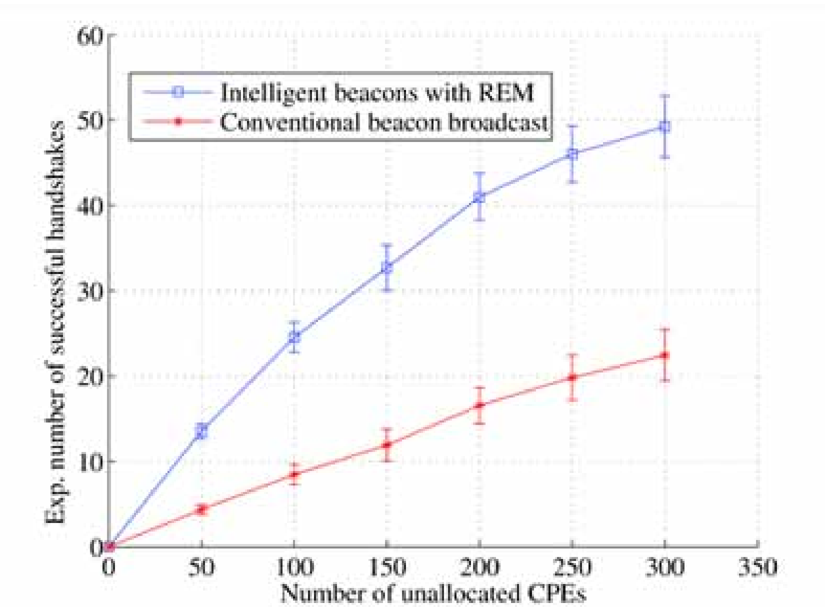
For the REM-aided intelligent beacon broadcasting scheme, the beacons are sent only on selected channels depending on the requirement of idle CPEs. These selected channels are those that belong to the common set of the available channels at the BS and the set of channels which are estimated to be available for the idle CPEs (from the map). The BS sends beacons in each of this common pool of channels and waits for channel allocation request from any node and after a stipulated time moves to the next channel. In case of successful reception of a channel allocation request, the BS logs the request before moving to next channel. At the end of the beacon cycle, the BS proceeds to allocate channels to the nodes whose channel allocation requests were successfully received during the beacon broadcast cycle. Such prediction of channel usage at CPE and sending beacons only on the potential free channels also reduces harmful interference to primaries.

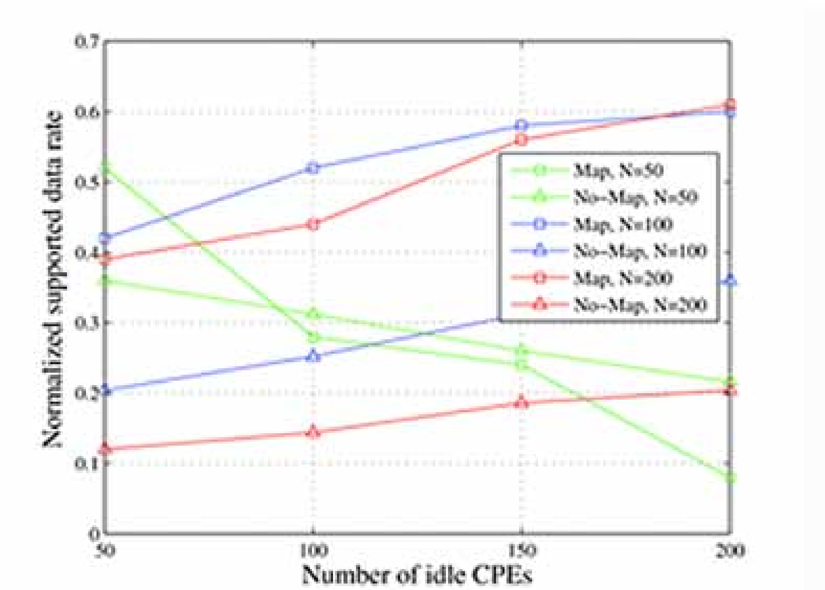
Intelligent Channel Allocation

The allocation process by the BS is initiated by the reception of a channel allocation request from any CPE (as a reply to BS beacon) on any of the free channels. Such allocation reply is accompanied with raw spectrum usage at the CPE location which in turn helps the BS to create the REM. The BS predicts the set of available channels at the CPE locations. In order to ensure no co-channel interference, the BS can estimate from the map all channels that can be allocated to a CPE without causing secondary co-channel interference to other CPEs, and also estimate all the CPEs that can be allocated the same channels without interference. Enabled by such predictions, the BS can also estimate the expected channel performance metrics (as discussed in Section III) for all the allocable (without causing interference to other CPEs) free channels at a CPE location. Such REM-aided greedy channel allocation ensures close to optimal overall secondary utilization. Although more optimized channel allocation schemes can be designed using the primary usage information from REMs, the utility of such maps in achieving near optimal allocation cannot be denied.

We demonstrated the utility of REM in improving the rendezvous probability and in ensuring close to optimal channel allocation by designing an experimental set-up with locations of TV stations being simulated in a 500×500 sq. miles grid using TV station location distribution (Riihijarvi, J., 2008) The total number of channels is varied from 50-400 with corresponding bandwidth of 6 MHz-750 kHz. The power-profile of the TV stations ranges between 10kW-1MW. We identified different regions with dense and sparse primary densities (mimicking big cities and small towns) and deployed IEEE 802.22 WRAN cells. Locations of different types of nodes and transmission patterns are kept different for different scenarios while total number of CPEs, and density are kept the same. Figure 7(a) compares the performance of the map-aided intelligent beacon broadcast against conventional probabilistic rendezvous technique in terms of expected number of successful handshakes in a beacon period. It is evident that for any number of unallocated CPEs, the map assisted beacon broadcast technique performs better than conventional beacon broadcast. In Figure 7(b), we compare the performances of channel allocation with and without using REM for different number of free channels in terms of normalized supported data rate. We define normalized aggregate data rate as the aggregate bit rate supported by the allocated channels to the total achievable capacity of the free channels. We see that except for very low number of free channels, the REM-assisted allocation overall achieves better utilization. For very low number of available channels, if there are more idle CPEs, it creates more collision during beacon broadcast phase resulting less utilization.

Figure 7. REM-aided resource allocation performance in terms of intelligent beacon broadcast and near-optimal channel allocation among candidate CPEs: (a) benefits of intelligent beacon broadcast with REM in terms of expected number of successful handshakes; (b) normalized supported data rate improvement for different number of idle CPEs using REM





Multichannel Multihop Routing in Distributed DSA Networks

Since in a DSA network, the spectrum availability is space and time variant, selection of the best channel between a given pair of transmitter and receiver is very crucial. When some information has to be routed over multiple hops, sophisticated routing algorithms are needed that can not only find the best route but also find the best channel to use at every hop.

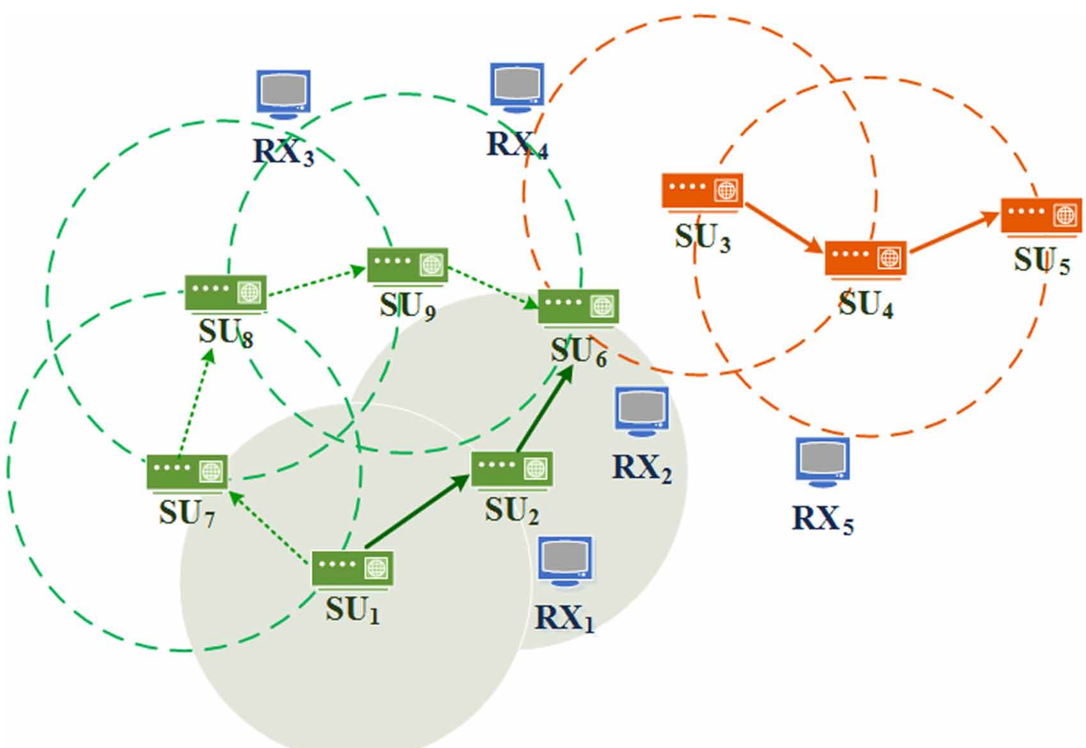
Routing Challenges in DSA Networks

The main challenges for multi-hop routing in a distributed DSA network over conventional ad-hoc networks are:

1. Spatio-temporal spectrum-awareness in terms of finding unoccupied channels in a region and at a particular time.
2. Protecting licensed primary receivers and other ongoing secondary communication from harmful interference.

Figure 8 shows one such scenario where a suboptimal route from source (SU_1) to destination (SU_6) yields harmful interference to primary receivers (RX_1 and RX_2) with an alternate route ($SU_1 \rightarrow SU_7 \rightarrow SU_8 \rightarrow SU_9 \rightarrow SU_6$) being available, assuming all the users are using the same channel. The figure also shows that such suboptimal routing leading to interference to other existing secondary communication (SU_3) due to hidden/exposed terminal problem. It is interesting to note that such interference could have been avoided by intelligently choosing different channels for communication for different hops. Thus, designing efficient routing solutions for multi-hop DSA networks requires a tight coupling between the routing module and the component responsible for managing spectrum availability such that the routing module can be continuously aware of the surrounding physical environment.

Figure 8. Inefficient routing interfering primary receivers and other hidden/exposed secondary nodes



Traditionally, there are two different ways to achieve such competence:

1. Spectrum database or REMs.
2. Distributed sensing mechanisms at secondary locations.

The recent trend is more towards ‘query and use’ which is especially facilitated through REMs (Li, Y., 2009; Debroy, S., 2016; Harrold, T., 2011), that effectively ensures:

- Low cost secondary nodes with sensing capability de-coupled from devices can use the map to find vacant channels, and
- The primary receivers are protected from any kind of harmful interference caused by such secondary communications.

Reference from a map helps building a routing scheme which can couple the legacy ways of assessing the route quality with novel measures on path stability, spectrum availability. A REM aided routing also helps in finding the alternate routes in case of unpredictable route failures due to sudden appearance of primary transmissions. The sudden appearance of primary renders a given channel unusable in a given area, thus resulting in unpredictable route failures, which requires frequent path re-routing either in terms of users or used channels. In such scenarios, effective signaling procedures aided by REMs are useful to restore broken paths with minimal effect on the perceived quality. Furthermore, protecting such primary transmission from secondary communications is made more effective by the use of maps since the spectrum usage scenario of a region is made known to the routing entities.

Notable REM Aided Secondary Routing

Notable works on routing protocols with spectrum knowledge or map include (Cheng, G., 2007; Chowdhury, K. R., 2011; Lin, S. C., 2014). Distributed algorithms are presented in (Cheng, G., 2007; Chowdhury, K. R., 2011) performs multi-hop multi-channel routing DSA networks with partial or complete spectrum knowledge and being aware of channel properties. As one of first comprehensive REM-aided secondary routing techniques, authors in (Lin, S. C., 2014) propose a opportunistic routing protocol for regular and large-scale DSA networks with wireless fading channels, employing a cooperative networking scheme to enable multipath transmissions. In our earlier work (Debroy, S. 2014), we proposed a multi-hop multi-channel secondary routing using our interpolation based REM (Debroy, S., 2016). In our scheme, the secondary network has two components: intelligent sensors in the control plane and unintelligent secondary nodes in the data plane. The sensors are deployed in the area of interest either at strategic locations or randomly depending on the technique used for the construction of the map. The sensors’ responsibilities are broadly two-fold: spectrum map creation and route discovery. These secondary nodes have no sensing capability and are instructed by the sensors to use a particular channel intended for a particular destination. Secondary nodes under the purview of a single sensor are called non-edge nodes while nodes lying in the overlapping regions are called edge nodes as shown in Figure 9(a) and Figure 9(b).

Intra-Domain Routing

Discovery of a route is initiated when a secondary node sends a route request (RREQ) to its associated sensor on the control channel. A route from source to destination can be of two kinds depending on their relative locations: intra-domain and inter-domain. When the source and destination are under the purview of the same sensor then it is called intra-domain and for such routing, a sensor upon receiving the RREQ checks whether the destination is associated with it. If so, then for each source node, the sensor consults the most recent map and eliminates all the channels which are occupied. For all the available channels in the spectrum, using the current map the sensor calculates a power value which is the upper bound on secondary transmission power for a particular channel so that no primary receivers are interfered on that channel. Such upper bound generates connected edges among secondary nodes that can sustain communication (with sustainable capacity values as weights). Thus, all such edges eventually create a connectivity graph within a domain for the most current map. Finally, by employing any well-known shortest path algorithm, the sensor determines the shortest path between the source and destination within its domain.

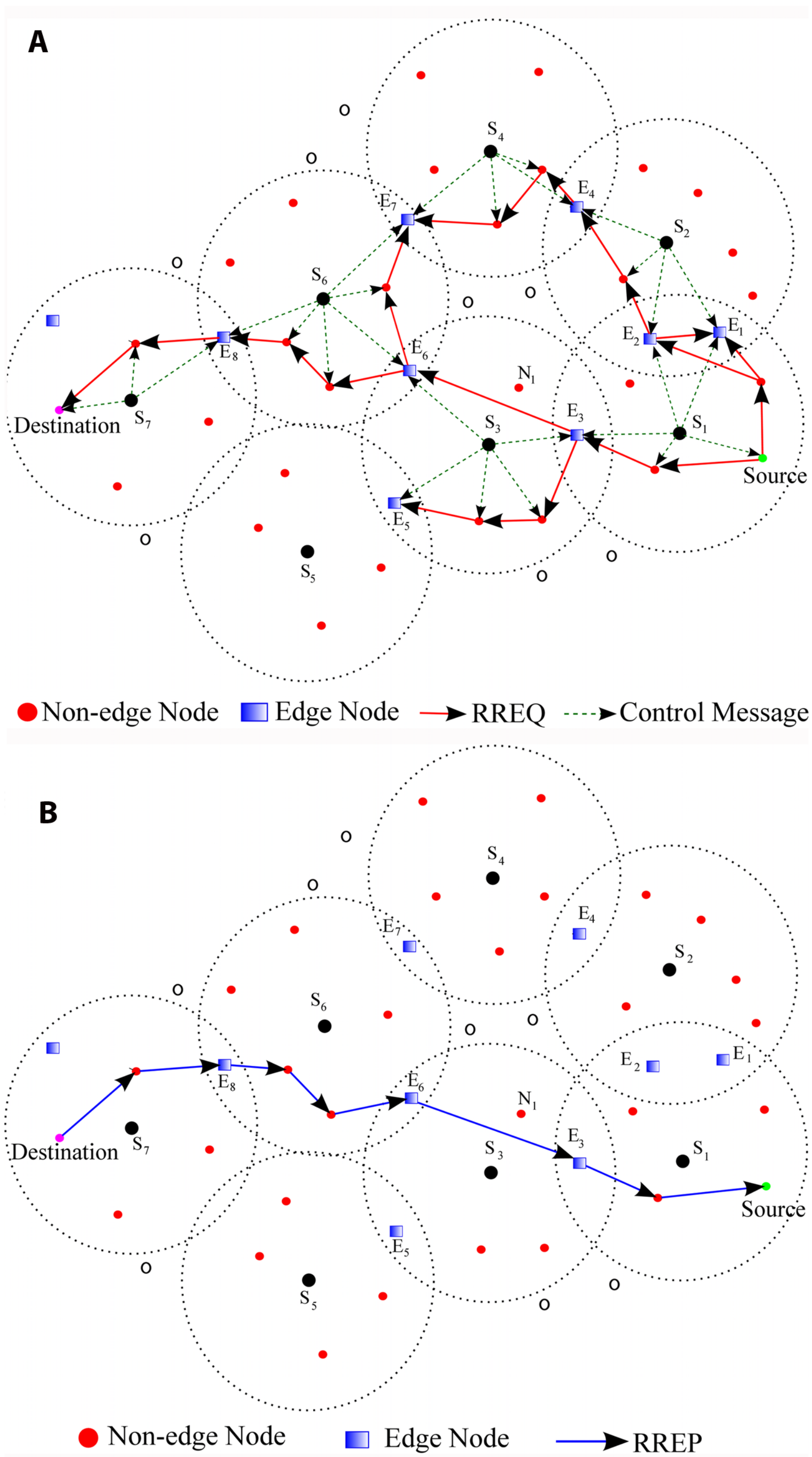
Inter-Domain Routing

For inter-domain routing, RREQ is flooded to the neighboring domains. Therefore once the sensor determines the need of inter-domain routing, it finds the shortest route from the source to each of the edge nodes currently covered under it. The edge nodes, upon the reception of a RREQ where the edge node itself is not the final destination, try to connect to the other sensor/s and initiate a RREQ. Once the neighboring sensor receives the RREQ, it follows the same recursive process of finding a route to the destination or to the edge nodes until the final destination is found. The route discovery scheme employs a selective flooding mechanism where a sensor does not cater to the same RREQ request through its domain as shown in Figure 9(a). When RREQ reaches the intended receiver, route reply (RREP) packet is sent from the destination to the source along the same path which does not involve any sensors, but only the secondary nodes as shown in Figure 9(b).

CONCLUSION

The chapter discussed how different interpolation and statistical techniques are applied to create Radio Environment Maps of a region, i.e., an estimate of primary spectrum usage at any arbitrary location in a secondary DSA network. We demonstrated how such REMs can help in predicting channel performance metrics like channel capacity, spectral efficiency, and secondary network throughput. We showed how REMs can help to attain near perfect channel allocation in a centralized secondary network (i.e., IEEE 802.22 WRAN) by improving the channel rendezvous probability and guaranteeing allocation of best candidate channel. Finally, we showed how the REM can be used to perform multi-channel multi-hop routing in a distributed DSA network. We demonstrated how REMs in such act as reference to find the best channels along a route that not only maximize channel capacity but also protects primary receivers through secondary power control.

Figure 9. Efficient inter-domain route discovery mechanism with the help of local REMs construction: (a) RREQ forwarding through selective flooding; (b) Unicast RREP propagation



Overall, the chapter seeks to introduce the readership towards a new direction of resource allocation in next generation networks where the secondary access is proactive rather than legacy reactive 'sense and use' techniques. The chapter also tries to shed light on the possible implications of such paradigm shift by introducing cross-layer channel allocation techniques that use REMs.

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