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3D Spectrum hole detector using Support Vector Machine to enable D2D overlay on heterogeneous CR networks

Nagendra Nagaraja, Govind Kadambi MSRUAS India, Vasile Palade Coventry University UK, Yuri Vershinin Coventry University UK

Abstract -- This paper presents a novel architecture of a Cognitive Radio (CR) enabled heterogeneous network to obtain maximum spectrum efficiency by minimizing the interference to the Primary User (PU). In a wideband frequency co-operative spectrum sensing, different CR nodes can be assigned to different frequency bands to detect the spectrum hole. Spectrum hole is a 3-dimensional concept, where space, time and frequency are involved. By estimating the probable distance, time and frequency of primary user and applying transmit power control to the CR node, we can maximize the spectrum efficiency. Since in D2D (Device to Device) communication, the distance of communication is shorter and the propagation delays can be estimated, we can perform very accurate transmit power control. Using a 3-dimensional spectrum detector to detect spectrum holes in space, time and frequency will yield higher spectrum efficiency because it enhances the degrees of freedom from 1 to 3 and, hence, provides flexibility to use resources with lowest probability of interference.

***Index Terms*— Cognitive Radio, Co-operative spectrum sensing, Regression, Heterogeneous network, EDBRA (Estimated Distance Based Resource Allocation), EDBPC (Estimated Distance based Power control), WCSS (Wideband co-operative spectrum sensing), 3-D spectrum detector, Macro spectrum hole detector, Support Vector Machine (SVM), 3D RBF (Radial Basis Function)**

I. Introduction

THIS paper puts forward a novel architecture and implementation of CR based heterogeneous networks. Spatial resource exploitation has given way to a number of ground breaking wireless architectures, like cell based mobile communication using frequency reuse. Similarly, a novel way of using time, frequency and codes has provided various 2G technologies. Further exploiting the orthogonal property of code and frequency has given rise to 3G and 4G networks. Cognitive Radio technologies are expected to be very agile in structure and resource usage. Interference is the key concern in the cognitive radio based networks. If network is heterogeneous (which means many types of air interfaces and networks trying to access the same radio resources), then demand type for resources is also heterogeneous. This requires very nimble resource allocation. Agility of resources also requires robust margin for error. Distance vector based association of sensing frequency and CR communication resources (time, space, and frequency) would provide this margin of error in cognitive radio systems that can enable practical deployments. However, challenge exists at infrastructure and devices interface, where infrastructure must provision the D2D setup based on statistical models in space, time and frequency domains, such that there is almost zero interference probability to the primary user. This paper defines the interfaces between infrastructure and device which acts as both PU on one interface and D2D device on other interface, using controls from the base station of the infrastructure network. This is possible because the infrastructure will be aware of the possible interferences early and more precisely, since infrastructure will be used to setup both D2D as well as primary user networks. Furthermore, this provides practical deployments because it supports the business model of operators, who can discount D2D communication in 700 MHz or cellular band using CR technologies.

II. Brief Survey on CR enabled networks

There is a substantial progress in Cognitive Radio technology literature in recent times. [1] suggests overlaying the D2D network on 4G networks and limiting interference temperature in order to limit interference to primary user. [2] suggests a way of using distance vector to assign frequency of sensing in co-operative spectrum sensing, and further enhances it to derive a 3D spectrum sensing. [3] narrates the spatial statistics of spectrum usage, however time and frequency part was not explored to the fullest. [4] and [5] suggest a basic definition of the spectrum hole. We use the definition for the spectrum hole suggested in [5].

III. System model for heterogeneous CR enabled networks

The system model used in this research is shown in Figure 1. This figure describes a heterogeneous network with a two-level CR detection. The D2D communication is overlaid on the infra based network. The spatial parameters come with two ranges, one is the cell range and the other is the CR D2D communication range. The control plane is divided into CR control plane containing the CR control channels, the CR sensing channel and the infrastructure control channels. The data plane of the network is again divided into the CR data channels and the infrastructure data channel. The communication resources are defined for the CR network in terms of distance, time and frequency (d, t, f). Defining the CR communication resource in 3 dimensions provides greater degrees of freedom in order to allow a good spectrum agility for CR communication. Also switching to newer resources can be very granular, when the differential of agility (Δd, Δt, Δf) is very fine tuned and optimizable as per the CR communication requirement with minimalizing interference to the infrastructure network.

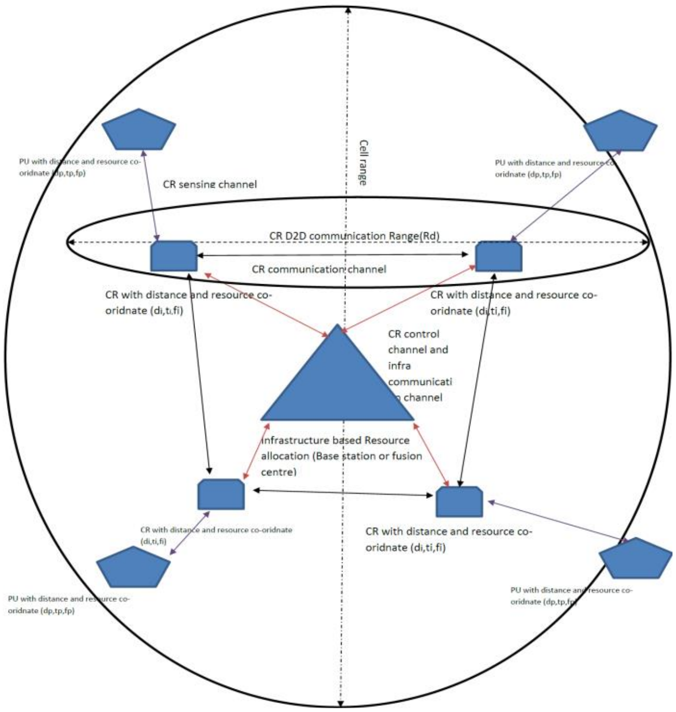

Figure 1. CR Enabled Heterogeneous Network with D2D overlaid on simple cellular network

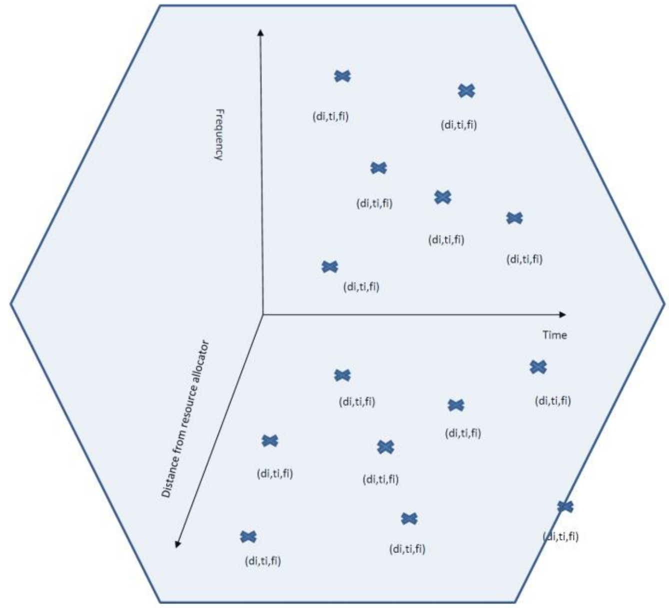

Figure 2. Resource map at the Cognitive Radio Resource Allocator

IV. Spectrum Resource Assignment for CR Usage

The spectrum resource is defined with distance, time and frequency (d, t, f,) co-ordinates. It is important to have this view of spectrum resource rather than a simplistic frequency view to obtain maximum efficiency from spectrum agility. The spatial presence of the primary user is estimated by the primary user detection decision regression on pathloss models. Temporal estimation is obtained by the statistical data of PU usage in a location and a frequency band. The frequency of CR communication is determined by the CR requirement as well as the spatial and temporal PU presence estimation. The central resource allocator will have information about different resources available for CR communication. A typical resource map of the CR communication resource is as indicated in Figure 2??? follows:

Where, t_i is the time slot of the resource availability. f_i is the frequency band or individual frequency resource that is available. d_i is the distance from resource allocator. There can be two types of resources in this heterogeneous network:

1. $R_{is}(d_i, t_i, f_i)$ used by cognitive radio to use infrastructure based network through the base station
2. $R_{d2d}(d_d, t_d, f_d)$ used by cognitive radio for device to device (or P2P) communication without relying on the infrastructure for data channel, but setup or control is provided by the infrastructure initially.

The very nature of classification of the resource types describes the heterogeneity in the network topology. [1] describes the D2D overlay on a cellular network. But it is still more of two network architectures and does not act as a single heterogeneous network with a central resource allocator. Single heterogeneous networks will have more appeal to infra service providers to enable free CR based D2D communication and charge for base station to device communication in case multi-hop communication is required. This makes the proposed CR enabled heterogeneous network architecture to be practically implementable and acceptable to service providers, rather than two-network architectures, where the network service provider is in constant conflict with CR interference possibilities. Also, same device being PU for device to base station communication and CR for D2D communication is an appealing application of cognitive radio.

V. 3D Spectrum hole Detection Algorithm

Prior art shows many ways of detection of frequency occupancy of the Primary User (PU). In this research, strategy is to find the spectrum holes in terms of the distance, time, and frequency (d, t, f) using networked infrastructure and use them for cognitive radio usage for D2D communication as well as protecting PU from any CR interference. Spectrum hole is estimated by deploying spectrum hole detectors across, space, time and frequencies. The time factor can be statistically estimated and we can assign the probability of occupancy through the expected usage model. The spatial spectrum hole detection and power control are derived from EDBRA (Estimated Distance Based Resource Allocation) and EDBPC (Estimated Distance based Power control). Frequency spectrum hole detection is performed by obtaining the frequency bands which has no PU occupancy.

The frequency band is divided into lower frequency bands and higher frequency bands to form WCSS (Wideband co-operative spectrum sensing). Different sensing frequencies are allocated according to distance from base station, the devices to detect high frequency spectrum are allocated at the longest distance from base station and devices to detect lower frequency are allocated nearer to base station. With these temporal, spatial and frequency spectrum hole detection combined and along with D2D power control, the overall chance of obtaining the spectrum for CR D2D communication increases and the probability of interference to PU usage decreases.

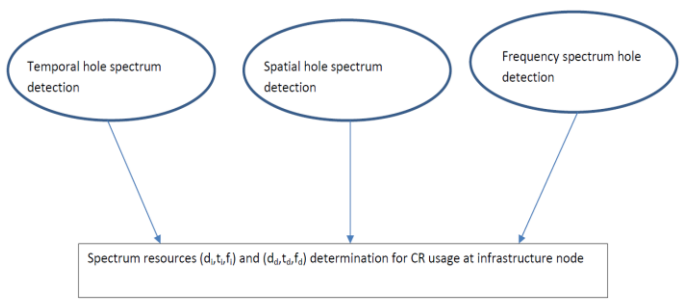

Figure 3. 3D Spectrum Hole Detector

Further, each of these detectors can be classified into dynamic and macro detectors. The dynamic detectors are used to detect the spectrum hole in space, time and frequency as they occur. Macro detectors are used to obtain a large scale spectrum hole depending on the network macros like area of spectrum idle, time of spectrum idle and a frequency of spectrum which is idle for long duration of time and in an area. The dynamic detectors are within D2D module or D2D chip of the mobile device and macro detectors are typically a network element within the infrastructure based network. Macro detectors are information processing elements which extract network statistics and identify spectrum holes with high probability.

A typical communication module architecture of the D2D chip is given as given in Figure 4. In addition to usual receive and transmit chains, the communication module contains spectrum sensors. A spectrum sensor can be energy based or more advanced cyclostationary based.

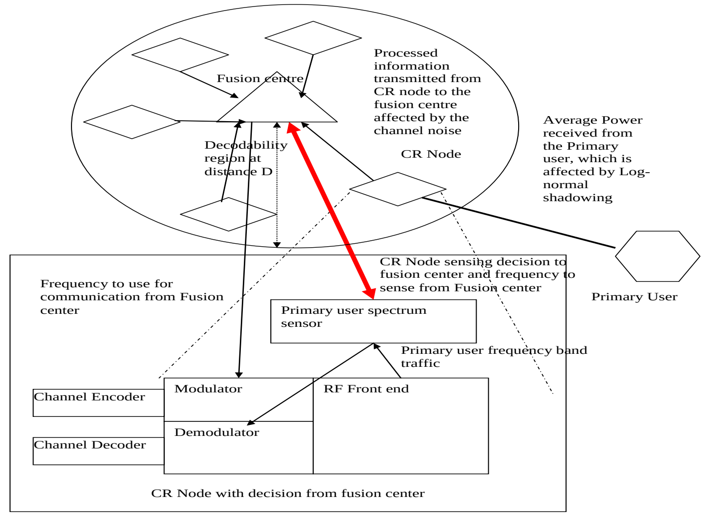

Figure 4. D2D communication module in the D2D integrated circuit

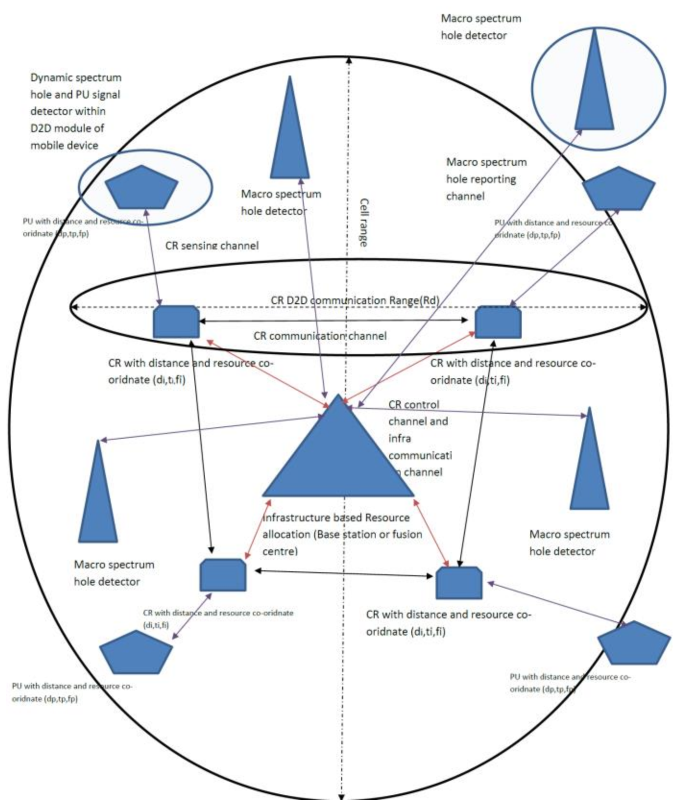

Figure 5, Typical wide area heterogeneous network with two level of 3D spectrum hole detection, with macro spectrum hole detection using a network element and dynamic spectrum hole detection using the D2D spectrum hole detector module

A. *Dual layer of spectrum hole detection in 3 dimensions*

The generic setup for 5he 2-level spectrum hole detection using macro and dynamic spectrum hole detection is given in Figure 5. The same model is applied in all 3 domains of 3D spectrum hole detector. A Support Vector Machine (SVM) with 3D RBF kernels is used to estimate the spectrum holes.

3D RBF is used to transform the data samples collected from space, time and frequency and convert it to the feature space.

Macro statistical model can be based on decision taken by the D2D spectrum hole detector and transmitted to the network element with R_{d2d} (d_i, t_i, f_i) indexing. Each of this detected holes in the 3 dimensions are stored in the database. By mining the database, we can retrieve few of these resource chunks with high probability. Apart from this, the specific model pertaining to space, time and frequency can be deployed, which provides D2D resource map with high probability. So basically, we can define a macro statistical model based on training of decision from the D2D spectrum detector or based on the domain specific models such as HMM (for time), Semivariogram (Space) and regression on path loss model (distance and hence Frequency).

Each statistical model is described in detail and the probability of false alarm and missed detection is arrived are based on the statistical nature of these models considering the effect of feedback from D2D dynamic hole detection and primary user detection.

Table 1. Output of dual layer 3D spectrum detector

Resource name Rd(d,t,f)	Expected operating range of CR D2D device, ΔRd (Δd, Δt, Δf)	Probabilities of primary user usage within the band(P_{pri})
Rd1	$\Delta Rd1^3$	$P_{pri}1$
Rd2	$\Delta Rd2^3$	$P_{pri}2$
Rd3	$\Delta Rd3^3$	$P_{pri}3$
.	.	.
.	.	.
.	.	.
Rdn	ΔRdn^3	$P_{pri}n$

The output of the spectrum detector is given in the Table 1. Output contains Resource co-ordinates in terms of Rd, resource range in-terms of ΔRd^3 and probability of primary user occupying the Resource Rd in terms of range ΔRd^3. We can have a mean value of probability if ΔRd^3 is small or the distribution of probability if ΔRd^3 is large. For a CR device being used for D2D communication, we can use mean value of the probability rather than the probability distribution across the spear of range.

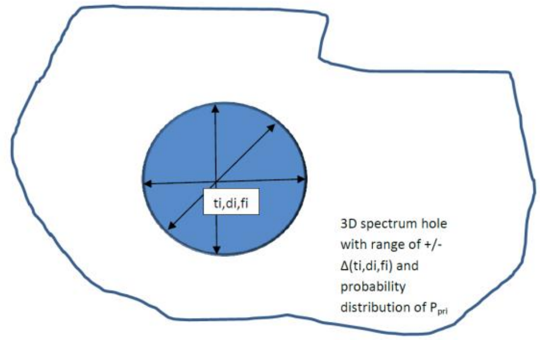

Figure 6. Example 3D Spectrum Hole with defined probability of PU usage within the range of operation of D2D device in terms of distance, frequency and time.

The range of operation of the D2D device ΔRd (Δd, Δt, Δf) is estimated using know transmit power of primary user and estimated required transmit power of secondary user. The estimated range is assigned to be outside no-talk zone of infrastructure network. In [5], no-talk is chalked, depending on the primary user knowledge. This is over simplification of problem with elimination of most important function of network management. We can flip the problem to find out resource which are outside no-talk zone currently and just use it. This can be possible if we maintain the hashes of resources in one coordinate with mapping to other two co-ordinates. For example, we can search resources at current location or duration of time or in a frequency band. Once this scanning is done, Resource can be scheduled for usage by D2D device. The algorithm for the resource allocation by base station for D2D request is as follows:
We define the mapping
Φ () :(Δd, Δt, Δf) → H, where H is a feature space. As we can see, there is a 3 dimensional data space, Δd is the distance vector and (Δt, Δf) denotes time and frequency bands at which the spectrum is not used by the primary user.
We can choose Φ () as a 3D RBF Kernel. Applying this,

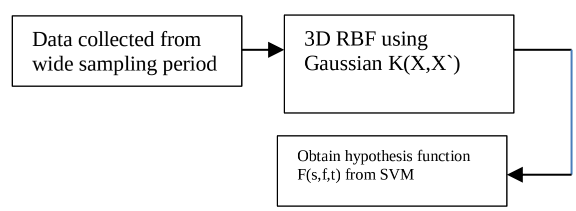

Figure 7. Generic spectrum hole detection in all 3 domains (Space, Time and Frequency) using SVM.

We use simple RBF kernels for the 3 dimensions,

$$\emptyset(X) = \exp(-\gamma|x - \grave{x}|^2) \qquad (1)$$

Where γ is a non-zero constant. In (1), We apply these in time, space and frequency. We combine the prediction results from SVM in these dimensions to obtain the resource map for D2D. The generator for each data is 3 dimensional, for each (x, y, z) in space we will have corresponding (Δd, Δt, Δf). Thus, by applying directly on Δd, Δt, Δf, we reduce our analysis from 3 dimensions to 1-dimension data. Since, space, time and frequency resource availability are independent of each other, this analysis method is valid. Furthermore, SVM provides the probability for each expected hypothesis in each domain. So, for a given sphere of radius Δd, we have probability triplets (P_d, Pt, P_f). So, the problem of increasing throughput (spectral efficiency of combined network) and minimizing d2d interference to primary user, will be maximizing these probability triplets (P_d, P_t, P_f).

When we apply a 3D RBF kernel, we try to identify a 3D vector which provides the resource map described earlier. The algorithm for identifying the primary user is as follows:

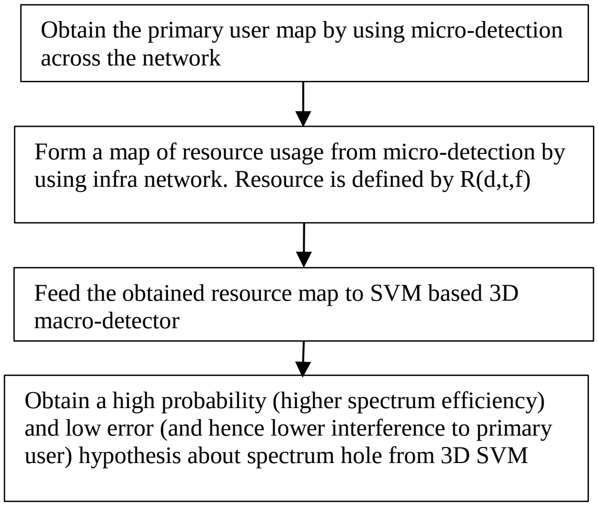

Figure 8. Data collection and macro hypothesis detection using SVM in actual D2D overlaid on the heterogeneous network

The macro hypothesis obtained is a function in the 3D macro detector over (Δd, Δt, Δf), which can be written as f (Δd, Δt, Δf). Hypothesis can change in space, frequency band and time. But assumption is that it will stationary enough to exploit the hypothesis, which are given by Δ over each dimension.

However, for simulation, we model micro detection separately for time, space and frequency using Hidden Markov Model (for time), Semivariogram (space) and Gaussian (for frequency). These three source generators are combined to form a vector of (Δd, Δt, Δf) in Python simulation setup. With these 3 separate sources, the spectrum usage can be accurately modeled.

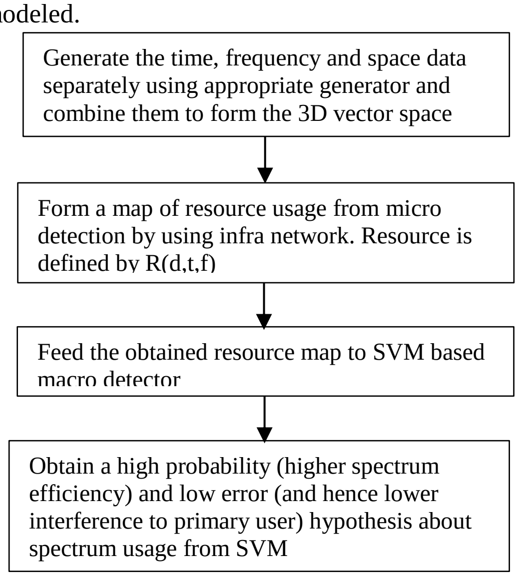

Figure 9. Simulation setup for SVM based macro hypothesis for spectrum usage.

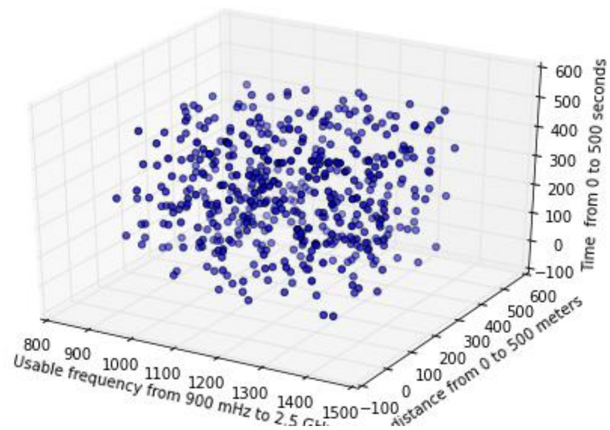

Figure 10. Spectrum holes considering random distribution in all 3 dimensions.

Considering the random distribution of vacant space, time and frequency resources, The distribution is as in Figure-10. But however as measured in real scenario of wireless spectrum utilization, we find that spectrum holes are distributed across time, frequency and space as close to HMM, Gaussian and semivariogram as given in [2] and [3]. So, we train the 3D SVMs according to these distributions, individually and apply models in 3D detection to get cumulative detection.

Data generation for the simulation is obtained from 3 sources, time, frequency and distance vector. For time based spectrum hole, we use Hidden Markov Model (HMM) based duty cycling. For distance/space vector we use Semivariogram as indicated in [5] and for frequency we use Simple Gaussian across the space. Overall setup for simulation is as in Figure 11.

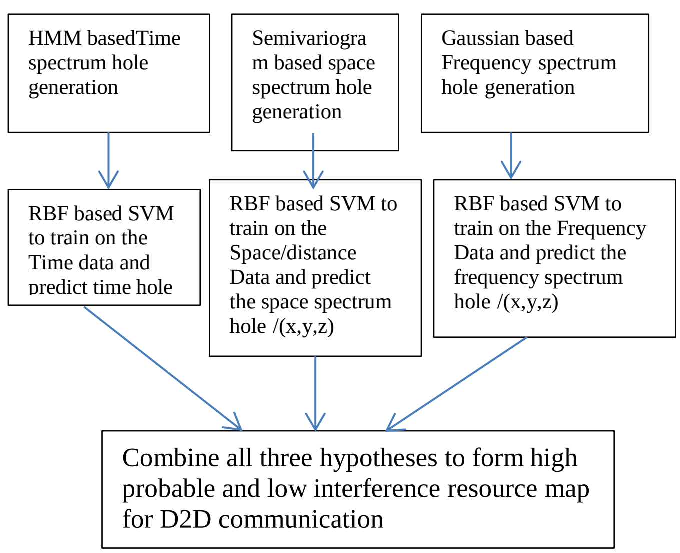

Figure 11. Python based simulation setup for obtaining highly probable hypothesis for 3D spectrum hole detection.

B. Temporal spectrum hole detection

1) Macro temporal spectrum hole detection

In real deployment, temporal spectrum hole sample is obtained using big data server located in NMS. No distribution is assumed. Distributed temporal spectrum sensors provide their inputs to NMS. This is combined at NMS using majority rule and forms temporal resource map, across space and frequency band.

As denoted in [3], we can use Hidden Markov Model to model the duty cycle of the spectrum occupancy. For lack of field data, we model time duty cycle using first order HMM.

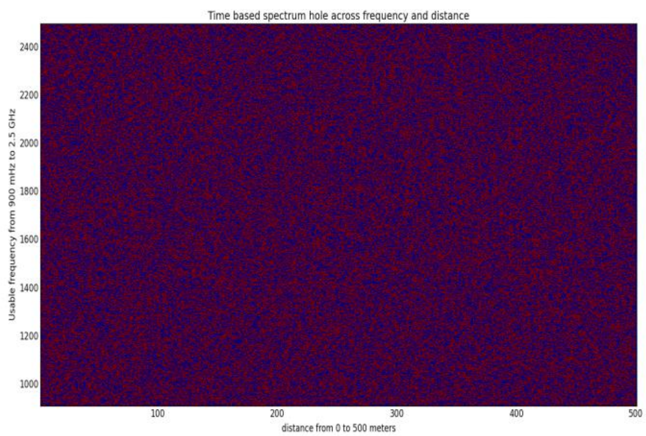

Figure 12. Time based spectrum hole (red -> occupied, blue -> empty)

C. Spatial spectrum hole detection

1) Macro spatial spectrum hole detection

In real deployment setup, spatial spectrum hole information is obtained using distributed spectrum sensors, which would send the spatial hole information to NMS, through cooperative spectrum sensing.

For simulation, we use semivariogram model to simulate spectrum hole generation. Semivariogram is defined by the function in (2):

$$\acute{\gamma} = \frac{1}{2N(h)} \sum_{N(h)} \left(Z_i - Z_j\right)^2 \qquad (2)$$

h is the assumed distance of separation; Z_i and Z_j are two points in the space and N(h) is number of points separating Z_i and Z_j.

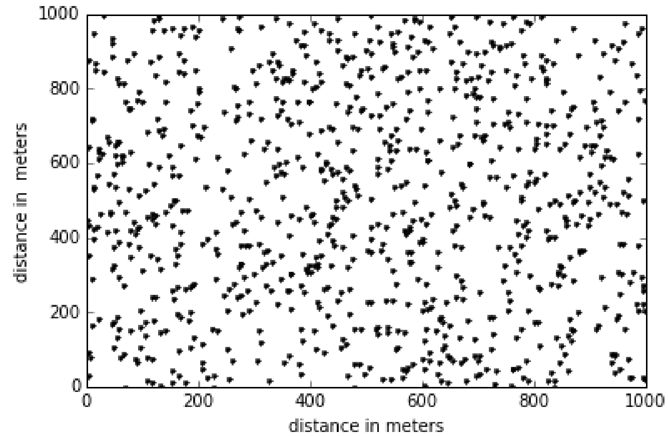

Figure 13 . Distribution of holes in space, when considering semivariogram distribution

It is widely known that there are huge geographical regions where spectrum utilization is very low among some frequency at some time, as well as most of the frequencies and most of the time. In [3] various semivariogram based correlation models are introduced. Many empirical results are derived for UMTS, WLAN and DVB-T wireless networks. These results can be applied to find out point where correlation becomes zero. This also marks "Spatial spectrum hole" for a frequency band. In this research, we use this detection technique to sweep space with frequency band of interest and check for zero correlation to flag spatial spectrum hole. Detection of the spatial Macro spectrum hole must be done with Macro spectrum hole detector, which is a part of networked infrastructure.

D. Frequency spectrum hole detection

1) Macro Frequency spectrum hole detection based on idle frequency

Frequency distribution is assumed to be Gaussian as given in [3] as given below

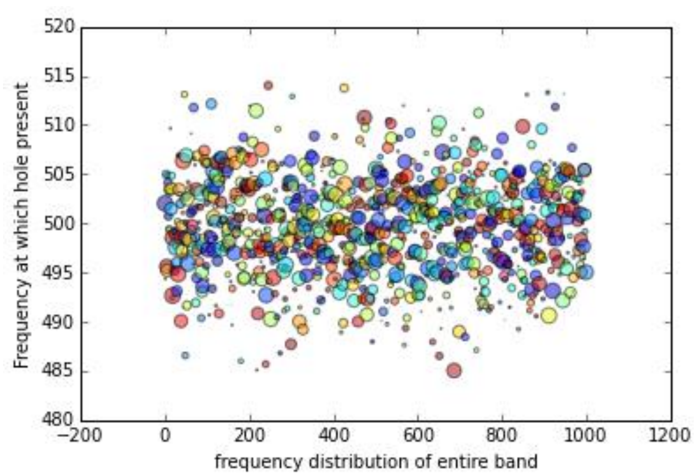

Figure 14. Frequency holes distribution assuming mean as 500 MHz and variation of 5 MHz

Assume Gaussian distribution and with mean of 500 MHz and variation of 5 MHz Typical vacant spectrum with random bandwidth is shown in Figure-13.

So, with this simulation setup we train 3D SVM spectrum detector.

VI. Error in detecting the spectrum hole using 3D detector

Total error in detecting spectrum hole is union bound of errors in detection in all 3 domains. As analyzed in [17], the SVM error has two parts, sampling error and regularization error. As also indicated by [18], the SVM error is given by generalization error. [18] goes into details of SVM error in terms of loss function and Risk associated with loss function. [18] also suggests using relative loss function w.r.t target function *f*. The error in misclassification of spectrum hole is misclassification error of SVM classifier after training. If X is the input data and Y is the classifier output, we get misclassification error from SVM defined in (3):

$$e(s) = P[s(X) \neq Y] \quad (3)$$

Where s(x) is given by as in [18]:

$$s(x) = 2X1\{P(Y = 1|X = x) > \tfrac{1}{2}\} - 1 \quad (4)$$

Where s(x) in (4) is misclassification error minimizer. However, for simulations, we use *python* package *sklearn and accuracy* function to obtain estimate error rate (error rate = 1 – accuracy). For different parameters of gaussian, semivariogram and HMM duty cycle, we insert confusion matrix to obtain error bounds of the SVM classifiers. Since we are dealing with binary classification problem of detecting the spectrum hole, we can use confusion matrix to obtain, true position (t_p), false positive (f_p), true negative (t_n), false negative (f_n) using confusion matrix we obtained. After many trails, we obtain average values of these measures.

For each svm classifier we can define following equations (5) and (6):

Probability of missed detection, $P_m = \frac{fn}{tn+fn}$ (5)

Probability of false alarm, $P_f = \frac{fp}{tp+fp}$ (6)

Assuming the total system probabilities are union bound of 3D detectors, which are independent of each other. We obtain the overall detection probabilities as:

System level missed detection probability is given by (7):

$$P_{msys} = 1 - (1 - P_{md})(1 - P_{mt})(1 - P_{mf}) \quad (7)$$

Where,
P_{md}: Probability of missed detection in space
P_{mt}: Probability of missed detection in time
P_{mf}: Probability of missed detection in frequency

System level false alarm probability is given by (8):

$$P_{fsys} = 1 - (1 - P_{fd})(1 - P_{ft})(1 - P_{ff}) \quad (8)$$

Where,
P_{fd}: Probability of false alarm in space
P_{ft}: Probability of false alarm in time
P_{ff}: Probability of false alarm in frequency

With these news metrics for measuring effective detection of spectrum holes, we obtain following heuristics for interference and spectrum efficiency of the overall network.

Interference to PU is directly result of missed detection, hence depends on P_{msys}. It also depends on the speed of actions after detecting, we can this *switching time*. In this research, we just correlate Interference to PU to accuracy of 3D SVM spectrum hole detector. considering detection is a continuous process after spectrum being occupied. Assuming that interference directly depends on probability of missed detection of PU, we can say

$$I_{pu} = KP_{msys}$$

Where I_{pu} is the Interference to PU and K is proportionality function. This can be written as:

$$I_{pu} = K(d,t,f)(1 - (1 - Pmd)(1 - Pmt)(1 - Pmf))$$

$$I_{pu} = K(d,t,f)(1 - \left(1 - \frac{f_{nd}}{t_{nd} + f_{nd}}\right)\left(1 - \frac{f_{nt}}{t_{nt} + f_{nt}}\right)\left(1 - \frac{f_{nf}}{t_{nf} + f_{nf}}\right))$$

Where *K(d,t,f)* is an interference proportionality function dependent on space, time and frequency, it can be further divided into components in space, time and frequency. But separability of the function into subcomponents may depend on model we select for this function, which is beyond scope of this paper. We assume *K(d,t,f)* partially differentiable w.r.t to d, f and t independently and is completely separable in time, space and frequency.

For a minimal interference to PU, we need to meet the necessary condition

$$\nabla I_{pu}(d,t,f) = 0$$

Taking partial derivative in each domain we get.

$$\frac{\partial(I_{pu}(d,t,f))}{\partial d} = 0$$

$$\frac{\partial(I_{pu}(d,t,f))}{\partial t} = 0$$

$$\frac{\partial(I_{pu}(d,t,f))}{\partial f} = 0$$

Where we assume this gives us extremum and all partial derivative exist at a point (d_0, t_0, f_0). So most optimal value for the resource block that minimizes the interference to PU is given by (d_0, t_0, f_0). Following this optimization technique, the infrastructure can assign the resource blocks to CR communication. Apart from this we can use multivariable stochastic gradient descent algorithm to find most optimal values of resource blocks to be assigned for CR communications.

Substituting the four probability components (t_p, f_p, t_n, f_n) in all 3 dimensions into equation, we get

Highest missed detection probability that can be allowed is

$$Pmys = \left(1 - \left(1 - \frac{f_{nd0}}{t_{nd0}+f_{nd0}}\right)\left(1 - \frac{f_{nt0}}{t_{nt0}+f_{nt0}}\right)\left(1 - \frac{f_{nf0}}{t_{nf0}+f_{nf0}}\right)\right) \quad \text{--(8)}$$

Corresponding to resource block (d_0, t_0, f_0)

Apart from interference, we need to also obtain the optimal throughput of CR network with $I_{pu} = I_{pu(Qspec)}$ as a constraint

Throughput of the CR network can be defined in equation (9):

$$T_{CR} = \frac{N(d,t,f)}{(1-(1-P_{ft})*(1-P_{fd})*(1-P_{ff}))} \qquad (9)$$

Where *N(d,t,f)* is the throughput proportionality function. Again here we assume that *N(d,t,f)* partially differentiable w.r.t to d, f and t independently as below:

$$T_{CR\rightarrow T_{CR}(optimal)} = \frac{N(d,t,f)}{(1-(1-P_{ft})*(1-P_{fd})*(1-P_{ff}))} \Bigg|_{I_{pu} = I_{pu(Qspec)}}$$

With constraints from Qspec as $I_{pu} = I_{pu(Qspec)}$, best throughput for CR can be obtained by assign resource block (d_0, t_0, f_0). Throughput at this point is given by (10)

$$T_{CR} = \frac{N(d_0,t_0,f_0)}{(1-(1-P_{ft0})*(1-P_{fd0})*(1-P_{ff0}))} \qquad (10)$$

As we see throughput of the CR network will be constrained by Q_{spec} requirement of primary user network. The specification of tolerable interference to primary user will determine throughput achievement of the CR network. We limit our scope of the work to formulation of optimization problem and obtaining the bounds of throughputs of CR network as a function of probabilities of misclassifications. Further work can be carried out w.r.t to transmit power and interference reduction through better 3D classifiers.

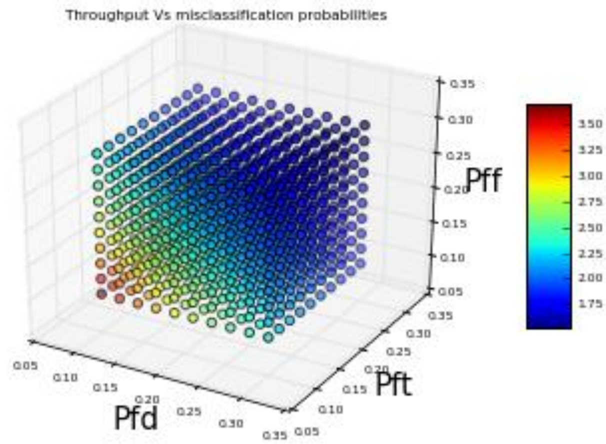

Figure 15. Throughput mapped to 3D false alarm probabilities for a given Qspec

As we can see from the Figure-15, Throughput almost doubles by reducing the false alarm probabilities in space, time and frequency. So, constraining for lower interference to PU and improving false alarm can provide higher throughput to Cr based D2D networks. As shown in the color map of 3D simulation results, the throughput is maximum at lowest false alarm probabilities. It almost halves when false alarm probabilities go close to 0.3. Throughput here is measured in bits/sec/Hz/unit area.

VII. Algorithm for Spectrum Allocation Using 3D Spectrum Hole Detector

Further algorithm for the spectrum resource formation at the central infrastructure node is given by as shown in Fig-4. Central part of algorithm is Quality of spectrum requirement for infrastructure network, which we define as Qspec. Key innovation in this research is to dynamically know required Quality specification (Qspec) of Primary user spectrum. Once the quality requirement is known to both infrastructure monitoring the CR network and the CR nodes, the interference can be mitigated as shown in the above equations. So, the problem of minimizing PU interference is problem of solving the classifier whose error probability or RoC characteristic satisfies the Qspec constraints.

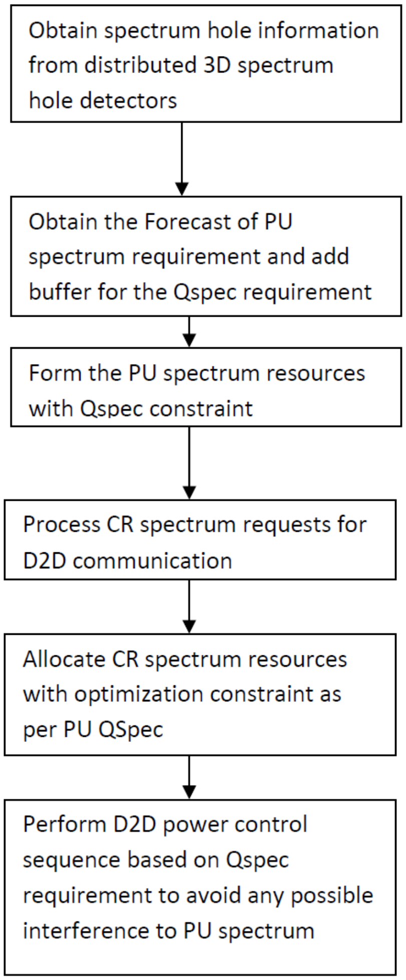

Figure 16. Algorithm for Qspec Optimization

VIII. Optimization of Qspec

Typically, the optimization problem in Cognitive Radio technologies are derived based on the time and probability of missed detection and the probability of false alarm, which in turn need to determine the secondary user data rate and protection to primary user. [5] advocates metrics which are the measurement of uncertainty and area recovered. However, it is difficult to compare two network topologies with these metrics. Absolute measurement of improvements obtained using Cognitive in terms of bits/sec/Hz. This would provide spectral efficiency improvements. When we normalize spectrum efficiency w.r.t existing spectrum efficiency of a network without CR and after deploying CR, we obtain improvements in spectral efficiency. We define CR gain as

$$CR_{gain} = \frac{SpecEff_{CR+prim}}{SpecEff_{prim}}$$

$SpecEff_{CR+prim}$ is the spectrum efficiency of network with CR deployment

$SpecEff_{Prim}$ is the spectrum efficiency without CR deployment

CR technologies comprise of network topology, sensing technique and protocol definition. So, to capture all these to prove merits of CR deployments, we need to provide a metric to prove the improvements in spectrum efficiency.

But since improvement in spectrum efficiency has to be constrained by the quality of spectrum usage by primary user, we constraint CR_{gain} with Q_{spec} , thus we can define the optimization problem as

$$CR_{gain} = \frac{SpecEff_{CR+prim}}{SpecEff_{prim}} \left\{ \quad Q_{spec} = Q_{spec}(opt) \right.$$

where, Qspec(opt) is the quality of interference free spectrum required by the primary user.

IX. Future Work and Enhancement Currently Being Carried Out

Obtaining the tradeoff of spectrum efficiency and quality of spectrum using Qspec will be a ground breaking research in spectrum agile networks. Also using D2D transmit power control can make this research deployment ready. Both are currently being researched in a broader set of experiments. Apart from the single hop network assumed in this paper, multihop D2D network with dynamic CR resource allocation, along with mobility will result in interesting scenarios. Better machine learning algorithms, like deep reinforcement learning and hierarchical reinforcement learning are also explored. Most of the optimization problems we formulated in this paper will be solved in the our future experiments.

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Nagendra Nagaraja Author: Currently Nagendra is student at Coventry university. He worked at Nvidia as SoC designer. He was with ST-Ericsson as a Senior specialist. He was a Technical Director in a Startup. Prior to this he worked at Qualcomm as a lead engineer Sr, Agere and Transwitch as an IC designer. He completed his Bachelor's degree in Electronics and communications engineering from Bangalore University, Karnataka, India in 2000 and Master's degree in Network Engineering in 2008 from Illinois Institute of Technology, Chicago, USA. He also underwent management program focused on entrepreneurship at Indian Institute of Management, Bangalore (IIM-B). He is also currently pursuing his PhD in Cognitive Radio applications on P2P networks from Coventry University, UK. Nagendra has 30 plus patent applications filed in areas of security, air interfaces and multimedia, Artificial Intelligence, and many internal publications and 21 granted patents from USPTO. His active research areas are Machine learning, Artificial Intelligence, Cognitive Radio, 5G air interfaces, Low power mobile computing, Biometry, security and Low power multimedia

Dr Govind Kadambi is a Pro Vice Chancellor - Research of M.S. Ramaiah University of Applied Sciences. Prior to this, he was the Dean (Academics) of M.S. Ramaiah School of Advanced Studies, which is now a part of M.S. Ramaiah University of Applied Sciences. He graduated from University of Mysore with B.E. degree in Electronics and Communication Engineering. He pursued the research for his M.S. and Ph.D. degrees with specialization in Antenna Engineering at the Indian Institute of Technology, Madras. Govind R. Kadambi has been granted 24 U.S. patents and has filed several more patent applications. He has authored/coauthored more than 50 research publications in peer reviewed International Journals and Conferences. He also served as a reviewer for IEEE Transactions on Antennas and Propagation. He was Session Chair and invited speaker at several international conferences abroad. He has over 30 years of experience involving Research/ Technology Development and Academics. He has been associated with various Academic Institutions, R&D Labs in India and Abroad. He has been the Principal Investigator and Co – Principal Investigator for many Sponsored Research projects. His current Research interests are focused on Antennas, Computational Electromagnetics, Digital Beamforming and Signal Processing for Wireless Communication, Mobile AdHoc Networks, Adaptive Techniques in Communication Engineering, Optic Flow Techniques and Cognitive Radio Technology. Govind R. Kadambi is listed in: Marquis Who is Who in the World, Marquis Who is Who in Science and Engineering, Marquis Who is Who in Asia and Dictionary of International Biography, Cambridge, England.

Dr. Vasile Palade is a Reader in Pervasive Computing in the Faculty of Engineering and Computing at Coventry University. He previously had academic and research positions at the University of Oxford - UK, University of Hull – UK, and the University of Galati - Romania.

His research interests lie in the area of machine learning/computational intelligence, and encompass mainly neuro-fuzzy systems, various nature inspired algorithms such as swarm optimization algorithms, hybrid intelligent systems, ensemble of classifiers, class imbalance learning.

Dr. Palade is author and co-author of more than 100 papers in journals and conference proceedings as well as books on computational intelligence and applications. He has also co-edited several books including conference proceedings. He is an Associate Editor for several journals, such as Knowledge and Information Systems (Elsevier), International Journal on Artificial Intelligence Tools (World Scientific), International Journal of Hybrid Intelligent Systems (IOS Press), Neurocomputing (Elsevier). He has delivered keynote talks to international conferences on machine learning and applications.

Dr. Vasile Palade is an IEEE Senior Member and a member of the IEEE Computational Intelligence Society.

Dr. Yuri Vershinin is the Senior Lecturer at Coventry University, UK. He joined Coventry University, as Senior Lecturer in late 2000 after his research at Aston University, following on from his industrial career. His industrial work experience included digital and analog systems design, design and implementation of electronic systems for automation and control, and microprocessor control systems. His recent research has been carried out in the area of adaptive control systems, identification, decentralized control, Kalman filtering and optimal control. He has worked in machine vision, image processing and computer graphics.

Yuri Vershinin organized the Special Edition "Advanced Control Systems in Automotive Applications" of the International Journal "Modelling, Identification and Control", IJMIC, (Guest Editors: Y.A. Vershinin, (Coventry University, UK), Professor V. Utkin (The Ohio State University, USA), and Professor G. Rizzoni (The Ohio State University, USA). Yuri Vershinin was the Co- Chair of ICEEE and the Invited Speaker on ICME of the World Congress on Engineering (WCE2012), Imperial College, London, UK. Also, he has provided the

Keynote Speech on the International Multi-Conference of Engineers and Computer Scientists (IMECS-2013), International Conference on Electrical Engineering (ICEE) in Hong Kong, March 2013, and on "The World Congress on Engineering and Computer Science 2014" (WCECS-2014), the University of California at Berkeley, San Francisco, USA. He is the Associate Editor and Member of the International Program Committee for the IEEE Intelligent Transport Systems Conference ITSC-2013 (Hague, the Netherlands), ITSC-2014 (Qingdao, China), and ITSC-2015 (Spain). He has published as the author and co-author around 80 journal and conference papers and contributed the Book Chapter "Adaptive Control System for Solution of Fault Tolerance Problem" (Springer Publication, 2014). He was invited to give the Keynote Speech at the international conference in the University of California at Berkeley (UC Berkeley), 2014. He organized the Special Session on Application of Intelligent Systems for the IEEE ITSC 2014 (Quindío, China). He is the member of the International Program Committee for the IEEE ITSC-2015 (Spain), IEEE ITSC-2016 (Brazil), IEEE Intelligent Vehicle Symposium (Sweden, 2016) and IEEE ITSC-2017 (Japan). At Coventry University he has formed the Intelligent Transport Systems and Telematics (ITS&T) Applied Research Group in order to work on practical tasks related to advanced automotive systems. He participated in the preparation of joint project proposals for the European Union Frame Work Programme, FP-7, and was the Principal Investigator in several practical projects financed by the EPSRC and external companies. He has prepared with his colleagues from the Applied Mathematics Research Centre the project proposal to the European Union Commission FP-7 Marie Curie "DIONICOS", which includes 19 partner organizations around the world. The project proposal has been successful and has been awarded the grant. Also, Yuri Vershinin is working on specific research and consultancy projects with industrial organizations. He successfully completed the research and consultancy contract from an external organization to work on the project following to the given tasks by the General Motors Company (GM Co.). He is the IEEE Member and member of the IEEE Intelligent Transportation Systems Society.