EVALUATION OF ENERGY-BASED SPECTRUM SENSING ALGORITHM FOR VEHICULAR NETWORKS

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ABSTRACT

Software Defined Radio and Dynamic Spectrum Access technologies have significant potential to enable emerging vehicular network technologies. Capability to sense and manage spectrum in real time is one of the most important requirements for vehicular dynamic spectrum access technologies. In this paper we propose a simple multi-resolution energy detection algorithm for sensing wideband channels. Through extensive experiments with GNU radio software and The Universal Software Radio Peripheral, we evaluate the performance of an energy-based spectrum sensing algorithm depending on sensor location, channel diversity and interference with transmitters and sensors placed in multiple locations. To further validate the results we provide comparisons between the information extracted by the proposed sensing algorithm and by spectrum data collected from a spectrum analyzer. The experiments are performed in the unlicensed ISM band between 2400MHz to 2500MHz over the newly developed cognitive radio testbed platform at Rutgers University.

1. INTRODUCTION

Vehicular networking is a research topic of growing interest. Specifically, vehicle-to-vehicle (V2V) communications, vehicle-to-roadside (V2R) communications and vehicle-to-infrastructure (V2I) communications are envisioned to enable numerous applications associated with vehicles, drivers, passengers, pedestrians, and vehicle traffic. These applications have significant potential to increase safety and convenience of transportation systems in addition to improving road traffic efficiency. For example, messages related to road hazards, obstacles such as stopped vehicles ahead, and other emergencies can be relayed by vehicles using appropriate combinations of V2R, V2I and V2V communications. Likewise, messages carrying non-safety related information such as convenience applications are expected to exploit V2R, V2I and V2V communications to deliver packets to and from vehicles [1].

On the other hand, although spectrum requirements of future vehicular networking applications are yet to be understood, one can expect that, with the proliferation of vehicular applications such as 360 degree real-time situational awareness and many others waiting to be developed, spectrum scarcity will soon be a reality for vehicular networks. With this speculation, we advocate the use of dynamic spectrum access (DSA) techniques in vehicular networks. DSA techniques, or cognitive radio networks in a narrowly defined way, enable detecting spatial and temporal ”holes” in spectrum and allocating those unused portions of the spectrum to communicating entities dynamically on a secondary usage basis.

In previous work [2], we have developed a distributed dynamic spectrum coordination method tailored for vehicular environments where two nodes coordinate to agree on a control channel to subsequently setup data channels and from there to further exchange information on spatial and temporal spectrum changes. In this paper, we look into the problem of detecting those spatial and temporal spectrum holes, also known as spectrum sensing. Spectrum sensing is the main information source of any dynamic spectrum access scheme [3].

Although, in the literature, matched filtering and cyclostationary feature detection are identified as efficient sensing approaches for low SNR environments [4], here we focus our attention on energy detection since energy detection is a non-coherent technique that has the ability to quickly find interference level in the bands of interest. Moreover, its implementation complexity is low.

In this work we address spectrum sensing of wideband from the software defined radio (SDR) perspective. The spectrum sensor is built from the radio frequency (RF) front-end receiver developed by Ettus Research LLC [10] and the GNU Radio [5] SDR that is implemented on a Linux host platform. We envision that DSA for vehicular environments will require radio interfaces that can sense over a wide range of spectrum and adapt its transmission to the available spectrum. Different from narrowband sensing, wideband spectrum sensing becomes a more interesting subject for DSA research not only because the wideband OFDM technology is implemented in many unlicensed systems, but also because the wideband transmitter provides a better spectrum adaptability. The wideband spectrum analysis can be implemented based on narrowband filtering, frequency transforms or wavelets transforms. Of these, the conventional method that employs FFT for multi-resolution analysis is presented in [6]. Wavelet approach for wideband sensing was proposed in [7], where the authors derive wavelet-based techniques for detecting irregular edges in the signal PSD as opposed to irregularities in time series. These sensing techniques provide effective ways of identifying and locating spectrum holes in the signal spectrum.

The reference work of the spectrum sensing implementation on GNU Radio platform is the code *usrp_spectrum_sense.py* that can be found in the GNU Radio software [5]. Wideband spectrum sensing estimates the energy of the narrow bands that compose the wideband in frequency domain. This implementation is developed for sensing narrowband and wideband signals. We mention that the wideband sensing (more than 6MHz) is not performed in real time because it requires time adjustments for switching from a sub-band to another one. The same sensing algorithm for 4MHz band is implemented in [8] to experiment with the co-existence of primary users and secondary opportunistic spectrum users, while an over-the-air interoperability is assumed. As of this writing, we haven't found any analysis regarding the efficiency of GNU Radio implementations over wideband sensing.

In this paper, we propose an implementation method of multi-resolution spectrum sensing algorithm for wideband sensing. Our approach intends to provide input for the upper layer spectrum management/assignment scheme where the primary users are known a priori by employing a separate mechanism (details of such a mechanism is out of scope of current paper). Hence, our sensing algorithm based on energy detector is tested in ISM 2.4 GHz band.

Different from previous approaches, the FFT will be used only for zooming in the band of interest, while the sensing of wideband will be performed in time domain. Approaches for estimating the noise threshold in frequency and time domains will be discussed. Comparisons between the information extracted by our sensing algorithm and the spectrum information collected by a spectrum analyzer will be provided.

The rest of the paper is organized as follows: Section 2 introduces system configuration and describes main components of the spectrum sensor. Section 3 presents the software defined radio (SDR) system implementation. The spectrum sensing algorithm protocol is discussed in Section 4. Section 5 presents numerical examples for different scenarios, and Section 6 presents concluding remarks.

2. SYSTEM CONFIGURATION

System configuration used in the experiments which is developed on the ORBIT platform [9] is shown in Fig. 1. The configuration includes four spectrum sensors, USRP1, USRP2, USRP3 and USRP4, each developed on USRP mother board [10] and a host computer. In our setups the motherboard accommodates a daughterboard, RFX 2400, for sensing the spectrum between 2.4-2.5GHz. The level of the interference is controlled by five WiFi 802.11b transmitters. The ORBIT platform consists of 400 nodes, each containing WiFi 802.11a/b/g cards and few nodes among these 400 containing USRPs. The nodes are hanging from the ceiling at a distance of three feet from each other in a 20-by-20 rectangular grid. More information about this platform can be found in [9]. We use 4 USRP sensors in our experiments, three of them located in the corners and one in the middle of the ORBIT platform. In order to validate our measurements we will transmit wideband signals generated by 802.11b Atheros cards that are installed on the ORBIT platform nodes and are distributed as shown in Fig. 1. The visualization of spectrum is performed by a non-real-time spectrum monitoring interface which is used as an auxiliary development tool for spectrum plotting. The scenarios presented in this paper are for testing the ability of each individual sensor to find the spectrum holes and to propose future approaches for spectrum sensing in vehicular networks.

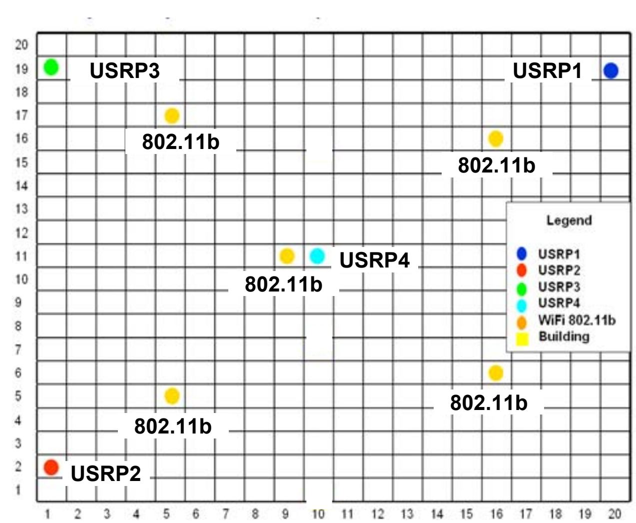

Fig.1. Sensor and transmitter distribution on ORBIT platform

We use the ORBIT platform as a management tool in our experiments, while the spectrum sensors are developed using the Universal Software Radio Peripheral (USRP) from Ettus Research and host computers that are installed in each node located as in Fig. 1.

2.1. GNU Radio Front-End

In this paper, the GNU Radio front-end is developed on the USRP, comprising of a motherboard and a multiple of daughterboards. Mainly, the motherboard is responsible for AD/DA conversion, decimation/interpolation and interfacing. The daughterboard used in our sensor design is the RFX 2400 that covers the spectrum range from 2400MHz to 2500MHz. The USRP is connected to the host computer through an USB 2.0 interface, where the SDR is developed and run on a standard PC with the Linux Operating System.

2.2. SDR Modules

The GNU software radio provides a basic library of digital signal processing (DSP) blocks and routines for easily developing new DSP entities. The signal processing blocks are developed in C++ and they accept data streams on single or multiple inputs and provide processed data streams on single or multiple outputs. In order to form a digital signal processing graph, the individual DSP blocks are interconnected by using the script language Python. This approach allows for easily processing graph modification and data extraction from intermediary blocks.

2.3. Visualization

The Visualization module is a graphical interface developed in Matlab that plots the analyzed spectrum of the received signal. This graphical interface helped us to develop the algorithm, to visualize the spectrum holes and to plot the spectrum sensed by USRP sensors.

3. SDR IMPLEMENTATION

The conventional energy detector (ED) essentially computes a running average of the signal power over a window of pre-specified spectrum length. This is the simplest non-coherent sensing technique that requires no a priori knowledge about the transmitted signals. The conventional ED is an efficient method for narrowband signals, while a wideband sensing based on ED requires a more complex implementation and threshold optimization. The wideband sensing performs the energy estimation of the narrow bands that compose the wideband. This analysis can be implemented based on narrow band filtering, frequency transform or wavelets transforms.

In order to find the spectrum holes in wideband where a cognitive radio system can transmit reliable information, we focus our attention to the multi-resolution techniques. The conventional approach implements a scalable FFT on the band of interest followed by a detector. We argue that this kind of sensor is appropriate for finding the interference levels (temperature) that are essential in defining the transmission strategy of the cognitive system, but it is not recommended for sensing primary users that are working in low SNR. Our wideband sensing block diagram is presented in Fig. 2. Details of sensing protocol will be presented later.

The analog signal received from antenna is passed through GNU Radio Front End providing discrete samples as input to the SDR blocks. The time samples are passed through a delay block for compensating the receiver block delays. Following that, the serial samples from output of delay block are passed through a serial/parallel converter that provides blocks of samples that matches with the FFT dimension. Depending on the sensing mode the sample data is passed through the FFT block for frequency analysis or directly fed to the dot product block. In our case the FFT is used as a zooming technique with the granularity defined as the ratio of sub-band width over FFT dimension. Each block of FFT output is averaged using an accumulator with run-time controllable number of averages. The spectrum rebuilding block is needed for removing the mirror effect introduced by the FFT block. The complex data from spectrum rebuilding block is passed in real domain by using a dot product operation. Finally, the real data is compared with the optimal threshold for the decision of spectrum availability. The digital signal processing blocks are implemented by using GNU radio software on a general computer in C++.

Our scheme is developed in such a way to have the possibility to vary the following parameters:

– *Decimation rate:* Adapting the decimation rate we decrease the amount of information sent by USRP on USB link and also decrease the computational load of the host computer.
– *Gain control:* This parameter mainly defines the receiver gain, which is important for the optimization of the detection threshold.
– *Delay control:* This function allows compensating the delays related to sub-band switching.
– *FFT size control:* This parameter is mainly used for decreasing the computational complexity and zooming in with different resolutions.
– *Accumulator size control:* This block provides the sum of different sensed sample groups with different correlation properties.

Note that in our case the detector will in fact be a multilevel comparator, unlike the conventional detector that makes the decision of present or absent signal. The reason for this implementation comes from [11] which proves that a multilevel sensing algorithm can significantly increase the spectral efficiency of the cognitive radio system. On the other hand, our detector can be considered a quantizer of the interference level sensed on the band of interest.

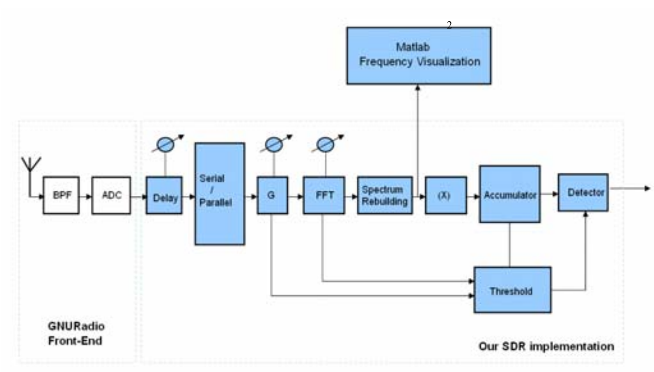

Fig.2. Block diagram of wideband sensing implementation.

One of the most important components in deciding the presence or absence of signal is the threshold block that has to accurately estimate the level of the noise called as noise frequency threshold in our design. Based on this threshold we will decide if we have a spectrum hole and how efficient the transmission can be on that unoccupied band. For an accurate estimation the threshold optimization has to take into considerations the fixed and variable parameters employed in the DSP graph such as:

- Noise power spectral density;
- Deceiver gain;
- Decimation factor;
- Spectral granularity including the bandwidth and FFT size;
- Probability of detection;
- Number of observed samples, N, to estimate the energy.

For the first implementation, this threshold will be empirically established during the calibration mode as presented below.

4. ALGORITHM WORKING MODES

The limitations of the USRP processing power and of the USB link between USRP and host computer do not allow us to process more than 8 MHz of spectrum at a time. Additionally, in order to remove the non-linearity of the USRP digital down converter (DDC) we have to overlap the FFT from successive sub-bands. It seems that 25% band overlapping is enough to compensate the DDC non-linearity as recommended by the manufacturer in *usrp_spectrum_sense.py* example. Thus, using USRP, it is recommended to process less than 6 MHz band at a time to get accurate information about the levels of signal and noise. Choosing a band that is not perturbed by non-linear filtering processes is essential in estimating the right noise threshold employed in our wideband sensing algorithm. Further, to sense a band of 100MHz between 2.4GHz and 2.5GHz the algorithm needs to scan the band with a frequency step less than 6MHz. In order to assure band linearity and to easily process and analyze the data, we preferred to scan the band with steps of 3MHz.

One of the major disadvantages of using USRP for sensing a wideband is that the sensing procedure is not a real time process. That is because the change of the central frequency requires time for tuning the RF on the new frequency and acquisitioning new samples. For USRP, we do not have any documentation regarding the exact delays as in the case of conventional digital signal processors. Here in order to correctly receive information, we have to set propagation delay high enough to assure the stability of the output. On the other hand, GNU Radio allows us to use an inexpensive RF front-end, while the frequency sweeping method decreases the computational complexity on the host computer. This is the real advantage compared to using a DSP board. An example of the computational saving of sweeping method is for sensing the 2.4-2.5GHz band with a frequency granularity of 190KHz. Assuming that we can perform sensing on entire band at a time, we have to implement a 512-FFT requiring around 270,000 floating point multiplications and additions, while sweeping the 2.4-2.5GHz band with 3MHz steps requires just 8,500 floating point multiplications and additions. Thus, scanning the band in real time is a challenging idea because of the computational challenges associated with the FFT process. Next, we discuss the algorithm working modes.

4.1. Calibration Mode

This mode is intended only for estimating the noise threshold for the time and frequency analysis domains. Additionally, this scanning process will provide a general overview about the radio frequency activity in the band of interest. The noise power threshold in frequency domain will be considered the minimum value of the squared output of the FFT block found after scanning the entire band, Th_f. The size of FFT, N, would be chosen as small as possible. In our case we preferred to scan with a precision smaller than 300KHz, that is specific for OFDM systems. Choosing N=16, the space between FFT bins is 3MHz/16=187.5KHz. The noise threshold can be found at the band boundaries if we choose the spectrum band a little bit larger than that of ISM at 2.4 GHZ. Based on Th_f we compute the noise threshold in time domain, $Th\_t=Th\_f/A$ where, A is the amplification gain introduced by the linear FFT process. Note that Th_t has to be computed for the same number of samples, N, found at the input of the FFT block. In our case, A is the ratio of the output over input sample powers of the FFT block.

4.2. Time domain scanning mode

This is the fastest scanning procedure that allows the MAC layer to have an idea about available sub-bands. In this mode parallel samples are passed directly to the dot product block avoiding the use of FFT that has a computational complexity of N^2 complex multiplications and additions. The FFT will not provide any additional information about the sub-band availability, while the time domain sensing is enough for determining the presence or absence of signals in this band based on the estimated *Th_t*. However, when the cognitive radio user wants to transmit information on a free sub-band it is recommended to employ frequency analysis based on FFT zooming procedure.

4.3. Zooming mode

This multi-resolution technique would be employed just for small portions of the sensed band, where the cognitive radio user finds an unused sub-band or where the output of the time domain scanning senses noise or a low level of signal. Additionally, when the user decides to transmit on these sub-bands we recommend the implementation of zooming procedure. In this way we can avoid transmissions on sub-carriers which are already in use, increasing the power efficiency of the user. By employing a variable size FFT we can adjust the scanning resolution according to the access technique that is proper for the user application, while we decrease the computational complexity significantly. For example, in order to scan a band of 99MHz, instead of performing FFT for 33 times, we will perform it just once if we intend to use a specific 3 MHz band. Finally, the advantage of this technique is evident for low traffic when scanning with steps of 3MHz is enough to find spectrum holes.

5. SENSING PERFORMANCE EVALUATION

In this section we present different spectrum sensing experiments that provide practical insights for designing spectrum sensing algorithms for vehicular cognitive radio systems. The experiments will be performed in the unlicensed ISM band between 2400MHz to 2500MHz using the ORBIT platform. The wideband is sensed by using 4 USRP sensors that are located in the three corners and one in the middle of the platform. In order to validate our conclusions we will transmit wideband signals generated by 802.11b Atheros cards that are installed on the ORBIT platform nodes and are distributed as in Fig. 1. In these experiments we did not perform USRP calibration to dBm scale but used magnitude squared of the FFT as power comparison for different experiments.

5.1. Experiment 1 – No transmission

In order to find the noise threshold level and eventually other perturbing interference in 2.4-2.5GHz band, we scan and zoom in the entire band. This experiment can be assimilated with a calibration process that is necessary any time when we have to find the optimal noise threshold. As a general rule, the noise threshold can be considered the smallest value found during this scanning process. As mentioned before, zooming entire band is a time consuming and computationally complex process that has to be run just for calibration purpose. In Fig. 3 we plotted data from all four sensors. Some transmission on Ch6 can be seen where there is one existing access point of experimental WiFi network. Depending on the position, each sensor sees different levels of interference depending on the propagation channel. For both band boundaries, each sensor senses almost the same level of signal, meaning that the propagation channels between each sensor and interference sources is almost the same. The level of noise measured on Ch 6 where we found transmission activity can be easily ignored (note that the y-axis magnitude levels are 1/100th or less than those in latter graphs).

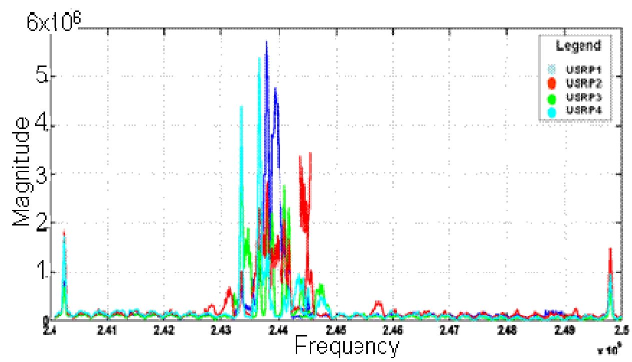

Fig.3. Wideband sensing - no transmissions on ORBIT platform.

5.2. Experiment 2 – Channel 1 Transmissions

In this experiment, once again, we sense the band between 2400MHz to 2500MHz using 4 USRP sensors that are located in the three corners and one in the middle of the platform. The level of interference from the platform is controlled by 5 WiFi 802.11b transmitters that simultaneously broadcast data on channel 1 and are located as shown in the inset in Fig 4. Interference levels sensed by each sensor are shown in Fig.4. Not only the interference sensed by each USRP is very different from sensor to sensor but also, each sensor sees different spectrum holes in the same transmission band of the Ch1 (2401MHz-2423MHz). This raises the issue of stand-alone versus collaborative decisions in finding the right spectrum holes.

In a collaborative scheme, a feedback channel would be necessary to share the sensing information. Besides, collaboration would require the calibration of all front-ends which in turn would require expensive hardware.

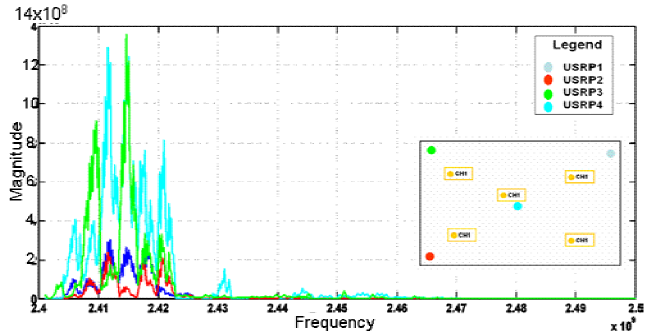

Fig.4. Wideband sensing –WiFi transmission on channel 1.

5.3. Experiment 3 – Channel 1, 6 and 11 Transmissions

In this experiment we consider a more complex scenario, where we transmit simultaneously on the non-overlapping channels 1, 6 and 11, covering almost the entire observed band. We set for broadcasting 2 cards on Ch1, 1 card on Ch6 and 2 cards on Ch11, expecting that the entire band will be covered by the WiFi broadcasts. Employing the same 4 USRP sensors we sense the entire band 2.4GHz-2.5GHz. Fig. 5 shows that there are many spectrum holes in our band even if we set the transmissions on channels that cover the entire band. In Fig.5, not only the interference sensed by each USRP is very different from sensor to sensor but also, each sensor sees different spectrum holes in the 2.4GHz ISM band.

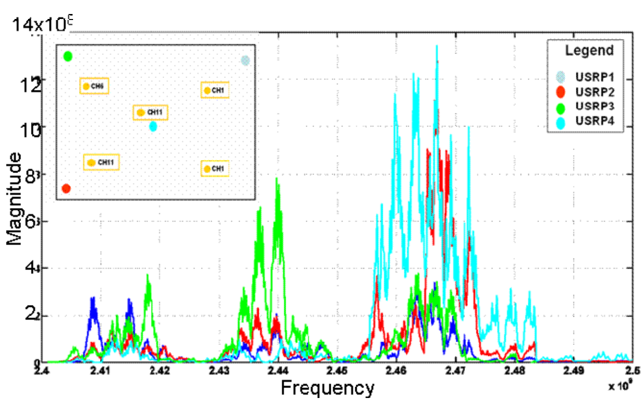

Fig.5. Wideband sensing – WiFi transmissions on channels 1, 6 and 11.

In order to cross-check the validity of the data sensed by our sensors we scanned the same spectrum using a Tektronix SA2600 spectrum analyzer for the same scenario. The same antenna used with USRP2 was connected to the spectrum analyzer input and the spectrum was sensed with the same granularity of 187.5KHz (RBW) as in the case of each USRP sensor. Comparing Fig. 5 with 6 we observe the consistency of the sensor and spectrum analyzer measurements.

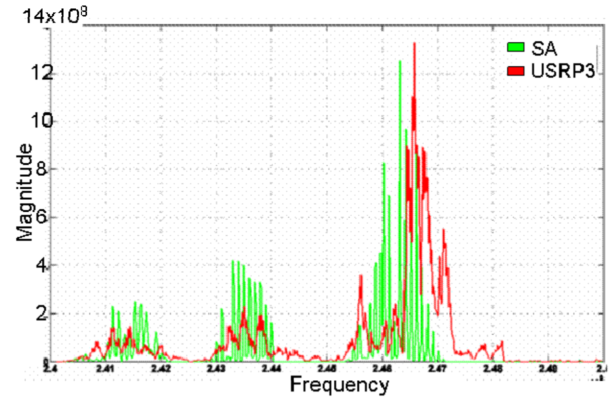

Fig.6. Comparison of sensing results with spectrum analyzer and one USRP sensor – WiFi transmissions on channels 1, 6 and 11

5.4. Experiment 4 – Channel 1, 2, 3, 4 and 5 Transmissions

In this experiment we broadcast on Ch1, Ch2, Ch3, Ch4, and Ch5, expecting that the band 2401MHz-2445MHz to be populated by the WiFi broadcasts. Employing the same 4 USRP sensors we sense the entire band 2.4GHz-2.5GHz. Fig.7 shows the interference levels sensed by each sensor. Once again, the energy sensed by each USRP is very different from sensor to sensor.

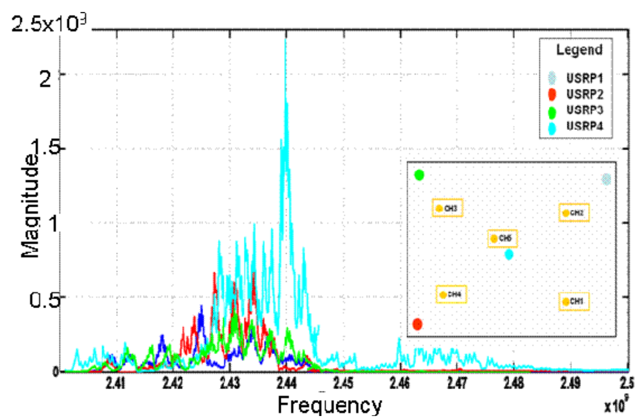

Fig.7. Wide band sensing – WiFi transmissions on channels 1, 2, 3, 4 and 5

6. CONCLUSIONS

We have proposed and implemented a multi-resolution energy detection algorithm for sensing wideband channels where FFT is used only for zooming in the sub-bands of interest and not for scanning the entire band. This approach can reduce the amount of computation and sensing time significantly. Through extensive experiments with GNU radio software and USRP, we evaluated the performance of the energy-based spectrum sensing algorithm depending on sensor location, channel diversity and interference with transmitters and sensors placed in multiple locations. We conducted the experiments in the unlicensed ISM band between 2400MHz to 2500MHz over the newly developed cognitive radio testbed platform at Rutgers University. While experiments are performed using static transmitters and USRP sensors, we varied transmitter and sensor locations, as well as the number of transmitters to reflect vehicular environments in each experiment.

To validate the results we provided comparisons between the information extracted by proposed sensing algorithm and by scanning data from a spectrum analyzer. The experiments we have performed revealed practical aspects that are essential for the development of spectrum sensing methods for vehicular dynamic spectrum access systems. First, we found that although the same interference pattern is seen by each sensor for far transmitters, different levels of energy is seen when the transmitters are close to the sensors. This would be typical for vehicular networks where, location of transmitters, receivers and sensing nodes will be continuously changing due to vehicular mobility. Our subsequent work will include developing methods of collaboration for spectrum sensing, while also trying to find the balance (trade-off) point between overhead that collaboration brings and the level of collaboration that is needed for accurate sensing. Furthermore, we will consider the mobility factor in spectrum sensing algorithm development to match realistic vehicular communication environments.

7. ACKNOWLEDGEMENTS

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