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Design and Implementation of a Cognitive Radio Based Emergency Sensor Network in Disaster Area

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Abstract Emergency communication systems are set to perform efficient rescue operations after disasters. Wireless communications is the only choice for these networks. After a natural disaster like earthquake in a metropolitan area, rescue operations must be quick and collaborative. Rescue teams setup their own emergency networks urgently. Checking the availability of the wireless channels in the disaster area is a time consuming and inconvenient solution. A spectrum sensing network that can detect the location and frequency of active emergency radio emitters in the disaster area can be helpful to avoid the interference among the rescue teams. This study discusses about the technologies and framework of such a spectrum sensing system for emergency communications.

Key words Emergency communications, Spectrum Sensing, Geolocation, Database, Multipath

1. Introduction

Wireless communication systems have been evolving for decades to make life easier and more convenient. The wide range of applications and possibilities has made wireless communications one of the most popular research topics nowadays. Human civilization has always been devastated by natural disasters like earthquakes, tsunamis, hurricanes etc. Most obvious outcomes of such natural disasters are loss of human lives and collapse of infrastructure. Although these natural hazards can not be avoided, valuable human lives can be saved by quick and efficient rescue efforts. Telecommunication infrastructure falls apart during most of the disasters. Telecommunication has become the part and parcel of almost all of the national and international rescue teams. Wireless technologies are most perfect for post disaster rescue operations.

After a big disaster generally emergency rescue teams from all over the world come to the scene and try to participate in the rescue activities. Usually each agency set their own wireless networks to coordinate among the mobile teams. As the number of wireless channels for emergency communications are limited, it is quite possible that two teams are using the same wireless standards with same physical specifications. The result is severe interference between the two networks that hinders the rescue efforts. A well informed wireless environment may help the systems to avoid interferences and perform rescue operations smoothly.

Geolocation based spectrum usage information may help the rescue teams to avoid the unwanted interferences. A well planned spectrum sensing network may scan the geolocation based channel information and form a central database to inform the rescue teams beforehand. The database may contain some PHY/MAC layer parameters as well as the geolocation of each of the radio emitters active on the scene with different standards. Sensing the spectrum and extracting the PHY/MAC parameters as well as geolocation estimation of an active radio emitter is a very big challenge. Spectrum sensors may not have any pre-knowledge about the radio emitters and the radio channels. Blind channel estimation techniques are very useful to identify them.

The concept of software defined radio (SDR) has been generating a lot interest from various quarters, from the pure hobbyist through to academics and business minded people. The benefits to SDR include reconfigurability and possibility of rapid prototyping among others. The GNU Radio project has emerged as one the most exciting SDR development project. The GNU Radio technology provides an opensource software platform which together with low cost hardware called USRP (Universal Software Radio Periph-

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eral) can be used to develop and implement various software radio applications. GNU radio and USRP can be used to design and implement a wireles spectrum sensor to develop and maintain the geolocation based channel database.
Remaining part of this study includes some introductory discussions about the related technologies. Framework of the spectrum sensing system has been presented in the next section followed by the implementation issues. Subsequently conclusions and future works finishes the study.

2. Technical Overview

To develop a spectrum sensing system for emergency communications a number of technologies are needed to be studied. Spectrum sensing techniques like energy detection and cyclostationarity with cooperative sensing algorithms are needed to be investigated. TDOA based geolocation technique is suitable to estimate the geolocation of the unknown emitters. Design and development of the database algorithm is another important task for the system. Prediction of propagation channel in the post-disaster and emergency environment should have some special attention also.

2.1 Spectrum Sensing Techniques

Energy Detection

In the energy detection approach, the energy of a received signal is compared to a predetermined threshold to determine whether the channel is active or not. This is called energy detection based on the χ^2 hypothesis test. One of the advantages of energy detection is that it has low complexity and can be simple to implement. It is also suitable when the CR user does not have any prior information about the received signal.

In the time domain, the energy detection is based on the following hypothesis:-

$$\begin{cases} \mathcal{H}_0 : r(n) = v(n) \\ \mathcal{H}_1 : r(n) = h(n) \cdot s(n) + v(n) \end{cases}$$

where $r(n)$ denotes the received signal, $s(m)$ and $v(n)$ denote a transmitted signal and the band limited additive white Gaussian noise (AWGN). The linear time varying characteristics $h(n)$ of the propagation channel is herein assumed to be constant without loss of generality.

The test statistics are given by

$$\mathcal{T} = \sum_N |r(n)|^2$$

and the detection rule with threshold γ is as

$$\begin{cases} \mathcal{T} \geqq \gamma & \Rightarrow \text{ signal present} \\ \mathcal{T} < \gamma & \Rightarrow \text{ signal absent} \end{cases}$$

We assume that $x(n)$ is Gaussian random process with variance ${\sigma_n}^2$ and zero mean under the $\mathcal{H}_0$ hypothesis. When the signal is absent, the test statistic follows the central χ^2 distribution with N degrees of freedom [1]. According to the central limit theorem, as the number of samples N increases, the test statistics $\mathcal{T}$ can be approximated by the normal distribution

$$\mathcal{T} \approx \mathcal{N}\left(N{\sigma_n}^2, 2N{\sigma_n}^4\right) \text{ under } \mathcal{H}_0$$

The probability of false alarm P_{FA} can be calculated by :

$$P_{fa} = Q\left(\frac{\gamma - N{\sigma_n}^2}{\sqrt{2N}{\sigma_n}^2}\right)$$

where the detection threshold γ is usually obtained by predetermined P_{FA} as

$$\gamma = \left[Q^{-1}(P_{FA})\sqrt{2N} + N\right]{\sigma_n}^2$$

The probability of detection P_D can be calculated in the same way as P_{FA}. When the signal is present ($\mathcal{H}_1$), the only difference from $\mathcal{H}_0$ is the variance of the total input signal if the signal can also be treated as independent random process to the noise with zero mean. The signal variance can be written as ${\sigma_n}^2 + {\sigma_s}^2$. From this fact, the probability of detection can be calculated by

$$\begin{aligned} P_d &= Q\left(\frac{\gamma - N({\sigma_n}^2 + {\sigma_s}^2)}{\sqrt{2N}({\sigma_n}^2 + {\sigma_s}^2)}\right) \\ &= Q\left(\frac{Q^{-1}(P_{FA})\sqrt{2N}{\sigma_n}^2 - N{\sigma_s}^2}{\sqrt{2N}({\sigma_n}^2 + {\sigma_s}^2)}\right) \end{aligned}$$

Cyclostationary Detection

Although spectrum sensing using energy detection is relatively simple to implement, a more sophisticated method is required in order to obtain more information about the received signal. Cyclostationary detection is able to provide information such as the modulation type and data rate by exploiting the cyclostationarity features of the received signal [2].

Generally, most signals are cyclostationary, which means that their statistics exhibit periodicity. This periodicity is usually caused by modulation and coding, and can be exploited by calculating its cyclic autocorrelation function [2]:

$$R_x^\alpha(\tau) = \lim_{T\to\infty}\frac{1}{T}\int_{T/2}^{T/2} x(t+\tau/2)x^*(t-\tau/2)e^{-j2\pi\alpha t}dt$$

where α is called the cyclic frequency. Then, we compute the discrete Fourier transform of the cyclic autocorrelation function to obtain the cyclic spectral correlation density (CSCD) function, which is a function of two variables, frequency f and cyclic frequency α.

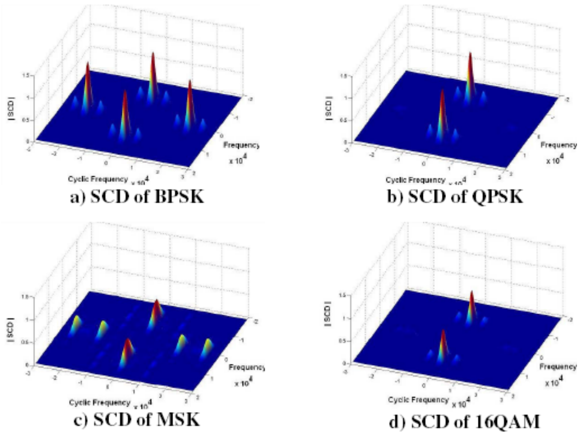

Figure 1 Cyclostationarity [2]

$$S_x^\alpha(f) = \sum_{-\infty}^{\infty} R_x^\alpha(\tau) e^{j2\pi f t}$$

By substituting $\alpha = 0$ in R_x^α, we can see that R_x^0 is similar to the autocorrelation function, and therefore S_x^0 is just the power spectral density (PSD) of the signal. However, for non-zero α values, the CSCD is the cross-spectral density of the signal and its frequency shifted version.

In [2] the CSCD method for signal signature detection has been practically implemented. By investigating the CSCD function plots at various values of f and α, it can be seen that there is a unique pattern for different modulation types. The surface plots for BPSK, QPSK, MSK and 16QAM modulated signals are as shown in the Figure 1. Therefore we can use the CSCD function to recognize the modulation of an unknown digital transmission.

Cooperative Sensing

The information sensed by single sensor might be heavily affected by the fundamental characteristics of the wireless channel like multipath fading and shadowing. If the signal emitted by the emitter is deeply faded by channel or blocked by the large obstacles in the environment then the sensor might not be able to detect that signal when it is actually present and also shadowing causes the severe problem called the hidden terminal problem.

To mitigate these kind of effect multiple sensor can be designed collaborate in spectrum sensing. This can be termed as the collaborative spectrum sensing or cooperative spectrum sensing. [3], [4], [5] and [6] demonstrate that the cooperation between the sensors or secondary user improves the detection performance, reduce the sensitivity requirement and decrease the detection time. The cooperation among the sensors can be implemented in two fashion, (1)Centralized and (2)Distributed. In centralized sensing, the sensor will send the sensed information to the central unit where the necessary information were extracted on the basis of the information send by the sensors. Where as in case of distributed Cooperative sensing, the sensors will share the information to each other but finally the sensor will make its own decision by combining the information send by the other sensors. Combining techniques in centralized sensing can be categorized by soft combination and hard combination. The former is also called the data combination and the later is decision combination. In soft combination the sensor will forward the information sensed by them to central processing unit without quantization and where the data were combined together using various signal processing techniques. Soft combination requires the high bandwidth among the sensor network but will show the high performance. Whereas in hard combination the sensor will forward the quantized data to the central processor. The quantized data can be one bit data like 1 for presence of emitter and 0 for absence of emitter in the sensed area. [4] shows that the performance of data combination can be increased by increasing the number of sensor. Data combination can be done by using AND, OR or M-Out-of-N combination method. The sensor can cooperate with each other and with the central unit by using different strategy. The first one is partial cooperation in which sensor will share only few information to other. The second one in total cooperation in which the sensor will share all its information. And the third one is adaptive cooperation in which the sensor can switch between cooperative sensing and non cooperative sensing depending upon the situation. To fulfill the requirement of the emergency sensor network which will sense the emitters in the emergency area and maintain the data base containing various information of the emitters, centralized cooperative sensing with data fusion in the central processing unit would be applicable.

2.2 Geolocation

In an environment where multipath effects could be promi-

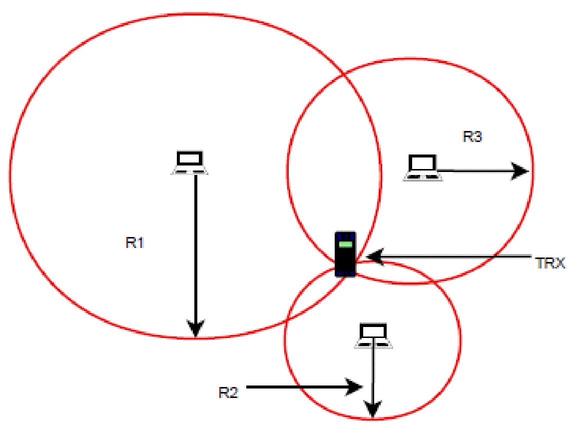

Figure 2 Range-based localization

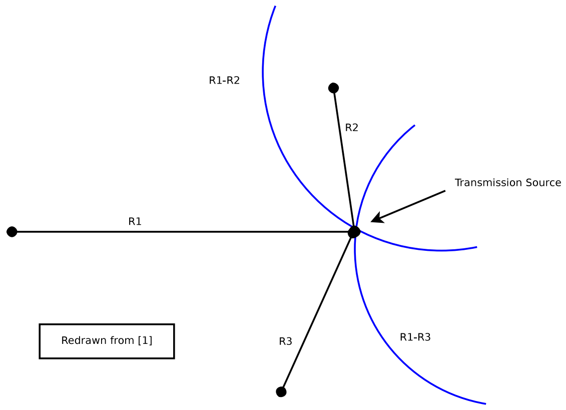

Figure 3 TDOA Estimation Technique

nent the challenge is to be able to passively locate the RF emitters on the scene. In the considered scenario there is no communication with or control of the RF emitters whatsoever. It is therefore inherent that network baased localization methods are to be pursued, as opposed to mobile based ones. The network based localization methods may generally be devided into two stages namely, *signal parameter measurement* and *data fusion* [7]. In the measurement phase the sensors extract a signal parameter like time of arrival (TOA), time difference of arrival (TDOA) or received signal strength (RSS). The measured parameters are then sent to a central processing system which will combine the measurements from many different sensors and apply an appropriate algorithm to determine the position of the RF emitter. There are many methods that have either been proposed or are actually being used to realize RF emmiter localization [8], [9]. Each one of them has its merits and demerits, with accuracy and implementation complexity being some of the issues to be considered. For *range-based systems* like TOA and TDOA, the localization scenario is as depicted in Figure 2 [10]. The time measurements are converted into distance or range and then the goal is to locate intersection of three ranges. One of the possible localization methods being considered for this scenario is the TDOA method. One of its main advantages is the fact that there is no need to have perfect knowledge of the emitter timing but the sensors need to be synchronized amongst themselves. Figure 3 shows that by obtaining the intersection of the parabola formed by range differences from TDOAs observed at two sensors, it is possible to calculate the position of the emitter. In [8] and [9] several methods on how to obtain accurate TDOAs measurements and the suitable algorithms that may be used to do the data fusion in oder to finally estimate the emitter position were extensively examined. The challenge is to choose the best of these methods.

It has to be said however that sensor synchronization is at the core of TDOA usability. Synchronization using network protocol based methods like IEEE1588 and that using GPS is being considered.

2.3 Channel Model

Proposed emergency system will be simulated in Matlab software by employing a specific channel model to show the system performance. The channel model should be sufficient to cover all aspects of the system such as geolocation, spectrum sensing, nodes and emitters mobility, etc. The environment effects also should be intensively incorporated such as multipath and shadowing, and also scattering effect due to collapse buildings as the earthquake aftermaths.

Regarding the number of system components (emitters, sensors, and base station) that have to simulate simultaneously to investigate the system capabilities to handle the network expansion, the chosen channel model should be as simple as possible to prevent the limitation of computation time. However, some aspects of the system can not be solved by either of the deterministic or stochastic channel models. The first aspect is geolocation calculation, as mentioned the previous section that the geolocation of each emitter will be calculated cooperatively by some sensors. The existence of any obstacles in the scene produces a different effect (multipath or shadowing) for the links for each emitter to each sensor relative to its actual position. Therefore, an area specific channel model such as ray tracing should be chosen. In the other hand, the multipath and shadowing that must be incorporated in the work tend to produce propagation effects in stochastic instead of deterministic manner. Therefore, the semi-deterministic channel modelling should be chosen for this specific system.

There are some researches that proposed the semi-deterministic channel models to work on geolocation propagation model as listed in [11] and [12]. Both model used the same combined tracing and stochastic model using Nakagami-m distribution function, but in the different manner. [11] took into account the stochastic characteristics to consider the diffusive propagation. The diffusion rays calculated by Nakagami-m distribution function arrived at receiver, so the parameters on distribution function were set based on the environment characteristics. While the [12] used it to describe the scattered signal due to the random surface of the building walls, so the parameters of the distribution function were derived from the roughness parameters of building walls.

This work will propose to simulate a semi-deterministic channel models described above. But the stochastic model will be aimed to consider the environment effect and the existence of the collapsed buildings on the working scene.

3. Framework

A number of spectrum sensors are placed in the disaster area. Sensors will start scanning the spectrum sequentially and forward the information toward the head node. A wifi based Mobile Ad Hoc Network (MANET) will be used to share data among the sensor nodes. IEEE 802.11s standard (enhanced version of IEEE802.11 for advanced mesh networks) is most suitable in this context. Assumptions for the framework designs are as follows:

- Earthquake in a major city (10.0 Richter Scale)
- Telecommunication Infrastructure collapsed
- Rescue teams from all over the world are coming and setting their own networks
- Area under consideration is within 5Km.
- Each emergency rescue team will be responsible to maintain their own networks.
- Sensors will not communicate with any of the emitters in operation.
- Sensor network will try to find the frequency and bandwidth used by the emitters.
- WiFi and MANET based sensor network will be used to form the sensor networks.
- Sensors will try to adapt the MAC and PHY parameters of the emitters to find the source and destination addresses for identifications. (Assumed no encryption on lower layers)

Framework of the proposed system is shown in Figure 4. An emitter can be detected by multiple sensors. Channel model for emergency environment will be employed on the sensors to predict the possible channel characteristics. Each sensor will extract the PHY parameters from the received signal and forward to the head node through the wifi link. Cooperative algorithm discussed earlier will be used to update database accordingly. TDOA based geolocation mentioned above will be used to estimate the location of the emitters.

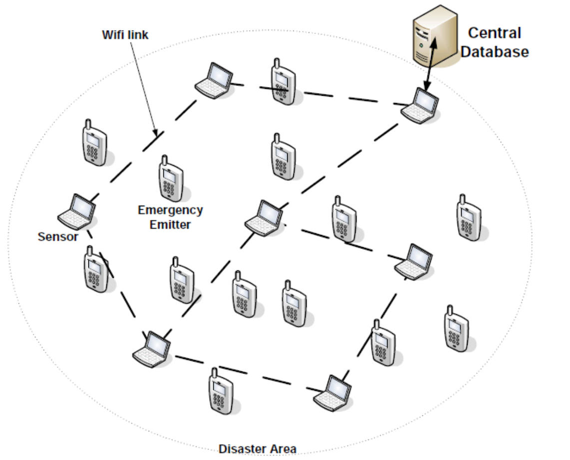

Figure 4 Spectrum Sensing Framework

4. Implementation Issues

4.1 Sensor Implementation

Spectrum sensing is divided into two steps. Identifying the presence of signals in a channel and extracting the required parameters for that signal. Sensors will be implemented on the GNU radio platform. One of the most relevant tools for spectrum sensing is the GNU Radio spectrum analyzer (usrp_fft.py). The analyzer can detect frequency, peaks, average for a multiple frequency range. Central frequency of the spectrum can also be detected by adjusting the decimation and Low Noise Amplifier (LNA) gain. This tool is most suitable for narrowband measurements. To analyze a wide range of frequencies at a time "usrp_rx_cfile.py" module can be used. This module allows to collect samples taken from the USRP and store them in a data (.dat) file. A number of parameters like central frequencies, LNA gain, decimation value, number of samples etc. can be adjusted as necessity. In the proposed system sensor nodes will be responsible to scan the spectrum from 150MHz to 900MHz and analyze them onto a big picture. A shell script can easily be prepared to scan and store the spectrum information to a data file. Finally MATLAB FFT toolboxes can be used to perform the necessary signal processing and detect the presence of signal on a specific frequency. Threshold value for the energy detection will be determined by the channel models employed on the sensors. Setting up the frequency resolution is another important task in this step. Afterwards, each sensor will create a list of central frequencies that are occupied by different emitters. Cyclostationary sensing technique will be employed to these signals to extract modulation and bandwidth information. This information about each emitter will be delivered to the head node where they will be matched with a reference table to identify the association of the emitter. A glimpse of the protocols used for sensors can be found in the Figure 5.

4.2 Database Design

Head node is responsible to develop and maintain the cen-

App.	Emitter info, Geolocation etc.
Transport	VITA 49
Network	MANET
MAC	WIFI, MAC1...MACn
PHY	WIFI, PHY1.....PHYn

Figure 5 Sensor Architecture

tral database. Database will contain the following information.

- Emitter ID (Set randomly)
- Geolocation (TDOA based estimations)
- Center Frequency
- Modulation
- Bandwidth
- Association info
- Other PHY/MAC parameters

As shown in Entity-Relationship diagram in Figure 6 the database has three classes: Network, Sensor and Emitter. An emitter is a member of a network of the network class. An emitter can be detected my multiple sensors and multiple emitters can be detected by one sensor also. Information on the sensor class will be used to estimate the geolocation of the emitter and as well as the cooperative sensing decision. The geolocation information is put in the emitter class. Network class is assumed to be created by pre collected information about the possible emergency networks that may work on the disaster area.

5. Conclusions

Framework to collect and distrubute the information of emergency emitters in terms of architecture and technology has been discussed in this study. The system will be developed by April 2010 to take part in the SDR forumś smart radio challenge [?] final. Deliverables includes algorithm to develop a cooperative database of emergency emitters, algorithm of Cooperative sensing, Geolocation algorithm with multipath and shadowing effect of the simulated channel on MATLAB and implemented sensor on GNU radio platform.

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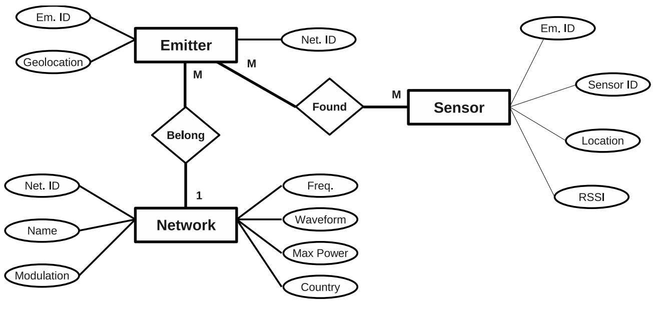

Figure 6 E-R diagram