Wideband Sensing for Cognitive Radio Systems in Heterogeneous Next Generation Networks

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Abstract

Mobile Next Generation Network (MNGN) is characterized as heterogeneous network where varieties of access technologies are meant to coexist. Decisions on choosing an air interface that meets a particular need at a particular time will be shifted from the network's side to (a more intelligent) user's side. On top of that network operators and regularities have come to the realization that assigned spectrum bands are not utilized as they should be. Cognitive radio stands out as a candidate technology to address many emerging issues in MNGN such as capacity, quality of service and spectral efficiency. As a transmission strategy, cognitive radio systems depend greatly on sensing the radio environment. In this paper, we present a novel approach for interference characterization in cognitive radio networks based on wideband chirp signal. The results presented show that improved sensing accuracy is maintained at tolerable system complexity. Remittance

Keywords: Cognitive Radio, Spectrum Sensing, MNGN, Interference Characterization.

1. INTRODUCTION

Mobile Next Generation Network is perceived as a collection of unconventional concepts for network management rather than a universally standardized technology. It is widely accepted by all players that no single mobile wireless technology will prevail on the expense of the others in the foreseen future. Thus the novelty in future networks is in facilitating the coexistence of different technologies not in waging competition between them.

For many years to come we will have 2nd, 3rd and 4th mobile generations along with WIMAX, WIFI and Bluetooth in operation. The heterogeneous nature of next generation networks have pushed the technology frontiers toward decentralization

For network operators, the distributed and localized decision making which will feature in next generation networks will bring dramatic reduction in operational cost (OPEX) and improve the performance [1]. A key technology to bring this into realization is cognitive radio systems.

Cognitive Radio (CR) is defined as a system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets [2]. Hence, one main aspect of cognitive radio is related to autonomously exploiting locally unused spectrum to provide new paths to spectrum access [3].

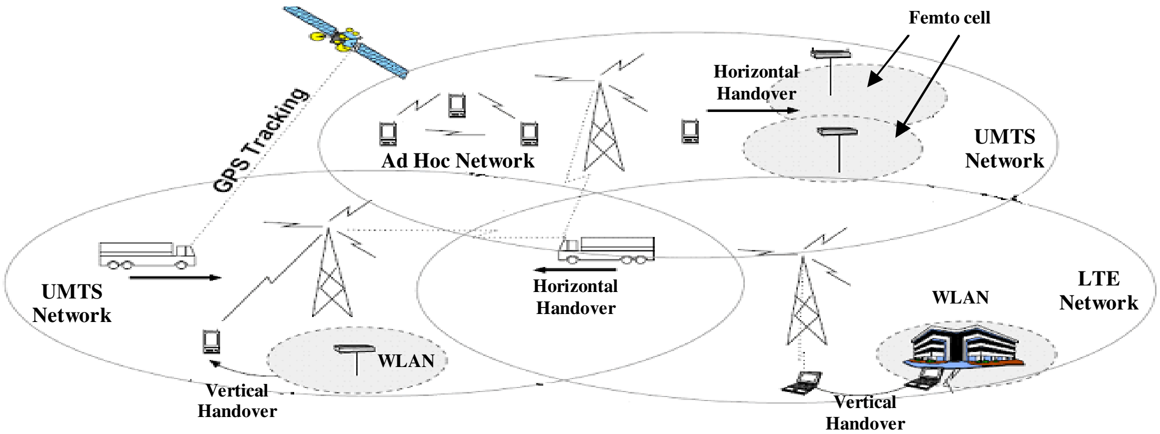

FIGURE 1: Mobile Next Generation Heterogeneous Network

The success of this transmission strategy relays on the quality and quantity of cognition possessed by CR user. This cognition is obtained through rigorous sensing of the radio channel and ability to characterize the interference. Based on the sensing functionality, CR users are ought to adapt their transmission accordingly in a manner not to harm the transmission of primary (incumbent) users of the channel.

The problem of spectrum sensing is a typical tradeoff problem where the accuracy and system simplicity are inversely related. The most known sensing techniques used are match filtering, energy detection, and cyclostationary features detection [4][5]. Match filtering is the technique with optimal detection, however due to system requirements it is practically difficult to implement [4]. Though at a lower level of implementation difficulty the performance of cyclostationary features detection is near optimal, system complexity is not trivial [4]. Energy detection is the least complex and most inaccurate among the three methods [5].

Wideband spectral sensing is a challenging aspect in cognitive radio sensing [3][7][8][9]. In [10][11][12], sequential sensing was introduced where a wideband radio channel is sensed using tunable narrowband bandpss filter at the RF front-end to sense one narrow frequency band at a time. In [8][9], multiband joint detection approach for wideband spectrum sensing was proposed where a bank of narrowband subchannels is used to concurrently sense a wideband rather than considering a single band at a time. The complexity of the two techniques (sequential or concurrent) is considered none travail especially as the bandwidth sensed grows. The accuracy is also compromised as they suboptimal detection is utilized.

In this paper we address the issues of wideband sensing. We introduce novel sensing techniques to be used for interference characterization for cognitive radios in heterogeneous networks. These techniques use of the chirp signal in an infrastructural cognitive radio networks.

Chirp signal is a wideband signal that has “interesting” cross correlation characteristics in time and frequency domains. The use of chirp signal is shown to ease system complexity and improve quality of sensing and therefore offer enhanced cognition at cognitive radio user in heterogeneous networks.

This paper is organized as follows: In II, we set up the scene for heterogeneous next generation network. In III, we discuss how cognitive radio can be utilized in heterogeneous environment. In V, we explain and analyze our sensing methodology. In VI, we present the simulation models. In VII, the results are presented and discussed. In VIII, we conclude.

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2. MOBILE NEXT GENERATION NETWORK

Mobile Next Generation Network (MNGN) is a heterogeneous network. Figure 1 demonstrates the “operational theater” for heterogeneous network in which different access technologies are arranged in different topologies. And being accessed by a range of user’ devices that enable variety of applications. The management of such scene constitutes a challenge for both operators and regulators as resources being depleted. To overcome those challenges innovative solutions are coming into place.

Some of challenges related to our work in heterogeneous network could be summarized as follows [1];

1. Increased demand on capacity and bandwidth
2. Offering differentiated services and application
3. Controlling operational cost

As for the capacity question, increasing spectral efficiency is more viable solution than boosting operators’ spectrum that is a result of scarcity of available frequency bands [13]. Classical solutions to improve spectral efficiency include; (1) the usage of Multi Input Multi Output systems (MIMO), (2) adaptive Modulation and Coding (AMC) and (3) Deployment of smaller cells (Macro/Micro cells). Even though the overall spectral efficiency improves dramatically, system complexity and hence the operational cost increases significantly.

2.1 Innovative Solutions

Innovative solutions are designed to be effective in terms of cost and operational management. We will be focusing in here on four of them, i.e. (1) the use of femto cells, (2) vertical handoff, (3)self organization, and (4) Direct Spectrum Access (DSA)

2.1.1 Femto Cells

The deployment of smaller cell i.e. femto cells is becoming an attractive solution. Network operators are projecting that deployment of smaller cells in indoor spaces such as houses, enterprise building and public spaces will dramatically improve special coverage and off-load traffic from macro/micro-cells. The operational cost for this strategy is also minimized having the mini cells getting connected to the backhaul network wirelessly [19].

2.1.2 Vertical handoff

In a heterogeneous network where different access technologies overlap with one another, vertical handoff (handover) become a necessity to guarantee certain level of quality of service for mobile users. Vertical handoff will become a feature of MNGN especially in scenarios where connectivity is established on bases of content awareness. Thus for example a mobile user with urge to download a multimedia file will have to handoff from 3.5G connection to WiFi connection. The overall outcome of such technique is offloading traffic from bandwidth limited network [14].

2.1.3 Dynamic Spectrum Access

Dynamic spectrum access is a technology aimed at enabling cellular networks to exploit gaps and opportunities for accessing the radio channel when no activities are monitored. This technology can dramatically increase the spectral efficiency at low level of complicity as it won't impose any further requirement on existing networks operating using the current regulations of spectrum licensing, this in turn will boost current infrastructure and investments.

2.1.4 Self Organization

In this innovative solution, the problem of network capacity is addressed from the prospective of the mobile part of the system rather than the fixed part. In another word, group of users will organize their transmissions (among themselves) in an ad hoc fashion of communication. They would probably also use each other as intelligent relays to take their messages to farther destinations. Capitalizing on improved network coverage at low complexity, self organization is one important candidate to overcome the capacity demands for MNGN [15].

3. COGNITIVE RADIO NETWORKS

Cognitive technology is the underlying technology behind the solutions proposed to address capacity and performance improvement in MNGN. A network that enables self organization, DSA, handoffs between access technologies or handovers between micro/macro/femto cells will defiantly require this technology [1]. In such a system, possession of local cognition (via rigorous sensing) determines the vital decisions to be made by users in heterogeneous wireless networks.

3.1 Cognitive Network Architecture

Cognitive Radio Network can be deployed in different methods such as infrastructural and distributed architectures, to serve licensed and unlicensed applications. In this work we are concerned with infrastructural architecture. Figure 2 shows the system architecture. The system is hybrid and contains two networks; a primary radio network and a cognitive "adaptive" radio network [16]. The two networks are not physically connected however they meant to coexist.

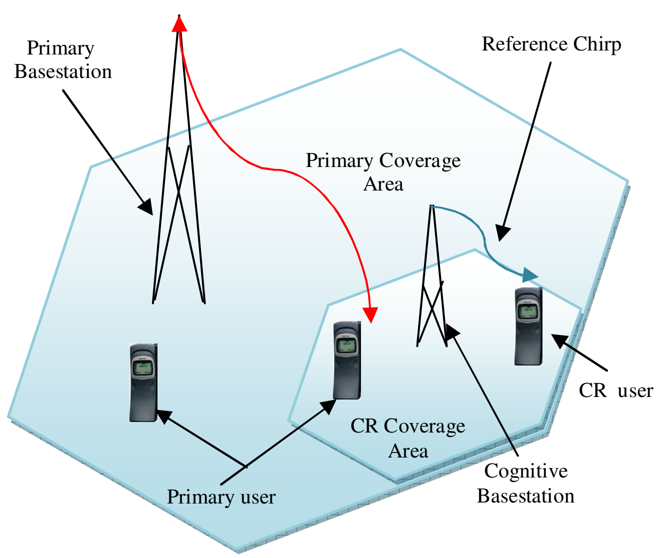

FIGURE 2: System Architecture

3.1.1 Primary Radio network

Primary radio network is the essential part of the system. It consists of a primary base station serving primary “licensed” users over the primary coverage area. The primary base station performs normal functions of a cellular base station.

3.1.2 Cognitive Radio network

The cognitive radio network is the adaptive part of the system. It consists of cognitive radio base station (CR-BS) serving cognitive radio users (CR-user). The cognitive radio coverage area overlaps with primary coverage area. A CR-user is ought to behave in opportunistic manner where it only can transmit after sensing the availability of the radio resources thus guarantee no excessive interference occurs at a primary user’s receiver.

4. Wideband Sensing Methodology

The proposed wideband cognitive radio sensing techniques is designed for infrastructural cognitive radio networks. A reference chirp signal that is transmitted over the coverage area of cognitive radio “femto” cell is used in this process [19]. The idea is to utilize resolution characteristics of chirp signal (in time and frequency) while removing excessive noise interference in the reception process.

4.1 Chirp Signal [17]

Wideband chirp signal is a result of linear frequency modulation of digital signal. The instantaneous frequency of the chirp signal increases or decreases linearly with time, Figure 3a shows a chirp signal. The bandwidth of a chirp signal, F, extends from the starting frequency sweep, f1, to the final frequency sweep f2. With proper choice for processing gain i.e. FT product, where T is the bit period, the spectrum of chirp signal has a distinctive near square shape, Figure 3b.

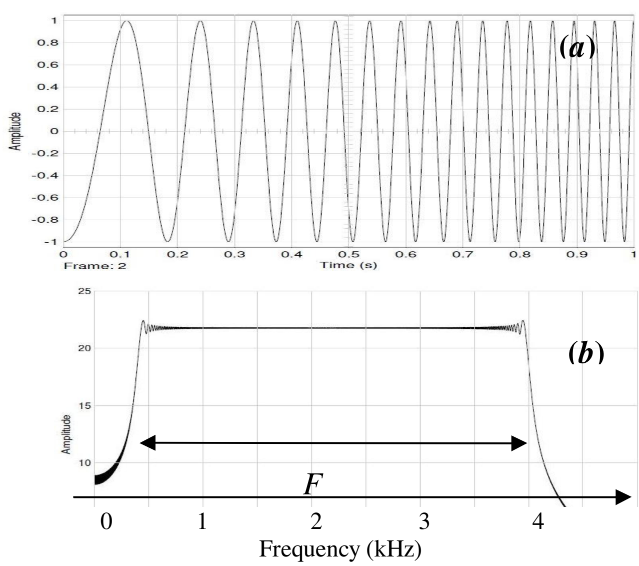

FIGURE 3: (a) Chirp signal, (b) Chirp spectrum

Chirp signal has very interesting correlation characteristics that gave it multi use in different applications [20]. In our methodology we are interested in two characteristics which will be helpful for sensing both frequency and time related behavior of primary user.

As for frequency sensing, spectral resolution in the presence of white noise is sought. The spectral resolution is obtained by cross-correlating the chirp signal with locally generated copy of itself (i.e. matched filtering). The result of this is optimal reception of chirp signal where excessive noise components are removed, Figure 7b.

As for temporal (time related) sensing the resolution sought is in the time domain. This resolution is obtained by correlating the received chirp with a locally generated conjugate of itself. The result of this operation is removal of noise components and resolution in time domain, Figure 13a.

4.2 Frequency Sensing Methodology

The novel frequency sensing methodology can be summarized as follows:
CR-BS broadcast low powered reference chirp signal with a bandwidth covering the sensed frequency spectrum.
After traveling over the radio channel and interfering with primary users' transmissions and noise, the reference chirp signal is then received at the CR-user using a chirp signal matched filter.
Fast Fourier Transform (FFT) is then applied to the output of the match filter. Figure 7a shows the spectrum of the received reference signal. As it is shown, the utilized (interfering) frequencies appears as spikes (peaks) rising above the flat floor of the received chirp signal spectrum.
The output from the previous step is fed into a decision circuit stage where a threshold value is set to decide the minimum amplitude of utilized frequencies.

4.2.1 Decision Circuit

Decision circuit is an algorithm implemented in software to detect the peaks representing primary users' frequencies. This algorithm belongs to search algorithms family and could be implemented either using sequential or binary search. The sequential search algorithm will sweep across the magnitude values of FFT samples and sequentially comparing them to a threshold value (which determines the existence of the tone.) However, the binary search algorithm will first sort the values of the FFT samples then it will discard the samples below the threshold value. Either algorithm should return the frequency values at which the FTT magnitude values exceed the threshold.

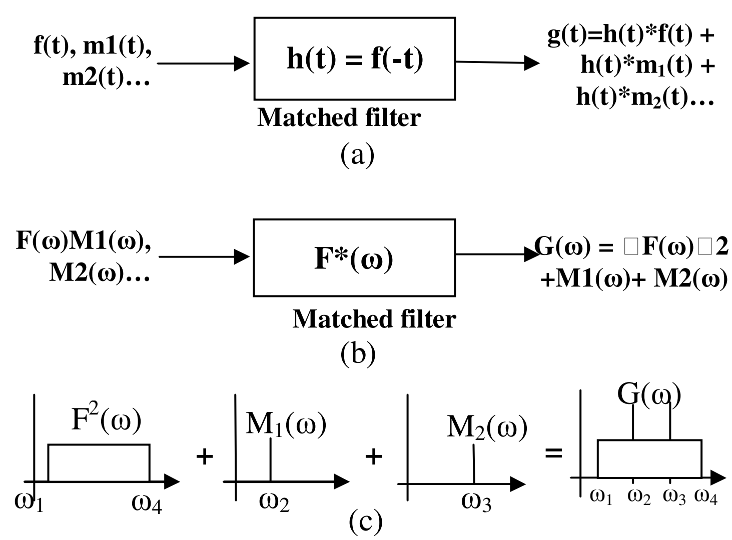

FIGURE 4: Analysis

4.2.2 Mathematical Modeling

Mathematical modeling can show a proof the concept for our methodology. Figure 4a shows the block diagram of the system. The inputs to the chirp signal matched filter is the reference chirp signal f(t), and the interfering carrier signals (tones) of primary users m1(t), m2(t)…
For simplicity, we will address the problem in the frequency domain as time convolution is transferred into frequency multiplication, Figure 4b. Therefore:

$$G(\omega) = F2(\omega)+ F(\omega)\, M1(\omega) + F(\omega)M2(\omega) \qquad (1)$$

Since the frequency representation of a sine wave is the unit impulse function in the frequency domain shifted to its corresponding frequency, (2) can be further simplified as:

$G(\omega) = F2(\omega) + M1(\omega) + M2(\omega)$ (2)

Assuming that the spectrum of chirp signal is a square wave function, Figure 3c visualizes $G(\omega)$.

4.2.3 Temporal (time related) Sensing Methodology
Temporal sensing for primary user's time related behavior could be summarized as follows:
CR-BS broadcasts a low power reference chirp signal with a bandwidth covering the sensed spectrum.
After traveling over the radio channel and interfering with primary users' transmissions and noise, the reference chirp signal is correlated with a locally generated conjugate of the reference chirp signal. Figure 13b shows the received signal. As it is shown, the presence of the tone is sensed as soon as the flat top starts to change.
Finally, the output of chirp signal correlation is fed to delay estimation circuit to estimate the delay referenced to the starting moment of tone's reception.

4.2.4 Delay Estimation Circuit
Delay estimation circuit is simply a timer that starts counting the tone delay referenced to the starting time of the chirp signal reception. The timer is re-set as soon as the flat top of received chirp signal has begun to deform. The deformation corresponds to the moment a primary user starts to transmit. To sense this moment, received samples must be compared against a threshold value. The threshold value should be set just above the flat top of the received waveform.

5. Simulation Model
Simulations models using Matlab are constructed to draw initial conclusions on the sensing methodology.

5.2 Frequency Sensing Simulation Model
Figure 5 shows a block diagram for the proposed algorithm implemented using Matlab™. The reference chirp signal is received at the CR-receiver after interfering with primary user's signals in AWGN channel. The Chirp signal is firstly received by chirp signal matched filter. Then FFT is applied and the output of the FFT passes to the decision circuit to decide whether primary users interfering with the referenced chirp signal.

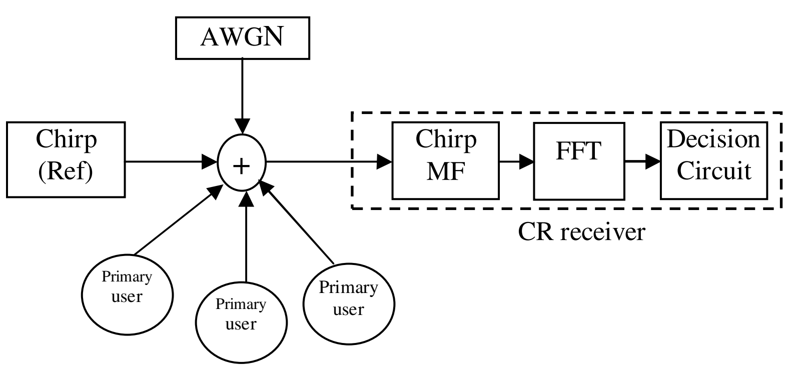

FIGURE 5: simulation model

5.3 Temporal Sensing Simulation Model
Figure 6 shows a block diagram for the simulation model that was implemented using Matlab™. The reference chirp signal is received at the CR-receiver after interfering with primary user's signals in AWGN channel. The Chirp signal is firstly received and cross-correlated with a locally

generated conjugate of the reference chirp signal. Then the output passes to a delay estimation circuit to estimate the moment when primary user's transmission took place.

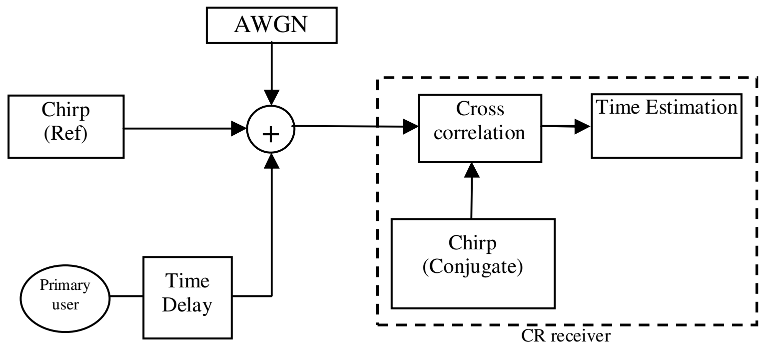

FIGURE 6: simulation model

6. RESULTS AND DISCUSSIONS

6.1 Frequency Sensing Performance Evaluation

Figure 7 shows spectrum of received chirp signal. The "interesting" characteristic or received chirp signal is obvious where a near flat floor extends over the bandwidth i.e. 3600 Hz. For chirp signal period of 1 s, the processing gain is 3600. It is shown that two distinctive peaks occur at frequencies corresponding to primary users' carrier frequencies at 500 Hz and 1800 Hz. Figure 7a shows the scenario where Signal to Interference plus Noise Ratio (SINR) for the interfering (primary users) carriers is 20 dB. Figure 7b shows the scenario where SINR is -5 dB. It is obvious that as SINR decreases, noise floor rises toward the peak value.

In order to quantify the performance of the system we define d which measures the distance (in dB) between the peak of the carrier's spike and the flat floor of chirp signal spectrum. In Figure 8, we plot the carrier's SINR versus d, normalized to value of d at SINR = 10 dB. The value of d = 0 dB signifies that the spike is no longer distinguishable from the noise and therefore probability of false alarm is very likely. The level of the noisy floor should determine the threshold value for the decision circuit. It is obvious that as SINR decreases d decrees. For our setup, it is shown that d = 0 at SINR= -25 dB which is extremely a low SINR value.

From above discussion it is becoming very important for a cognitive user to be able to set the threshold value for its decision circuit. This process, which depends on the level of Signal to Noise Ratio (SNR) of received reference chip signal, should be dynamic as the value of SNR changes upon many factors in the mobile environment. In order to address this problem, CR-user must be capable of estimating the SNR of received reference signal. This estimation could be further fine tuned by CR-user to minimize probability of false detection.

The results in Figure 8 assume that primary users' transmissions are in synch with the reference chirp signal. The performance is expected to degrade as this assumption is getting relaxed which is probably more a realistic assumption. Figure 9 illustrates the delay scenario between reference chirp signal and primary user's carrier.

To investigate the effect of a more realistic scenario where both networks (primary and cognitive) are not synchronized, Figure 10 shows how d changes with respect to the delay between primary user's signal and reference chirp signal. The results shows SINR in two cases, SINR = 10 dB and -10dB. As expected, system performance degrades as delay increases. For example, if the user's signal is delayed by 0.5Tc s, Tc is the chirp signal bit period, d drops by 25% in both SINR scenarios. Nonetheless, the system is showing tolerant to delay up to 0.25Tc s in both SINR cases. Also from Figure 10, we can deduce that below -10 dB the performance will greatly degrades especially if synchronization is not maintained.

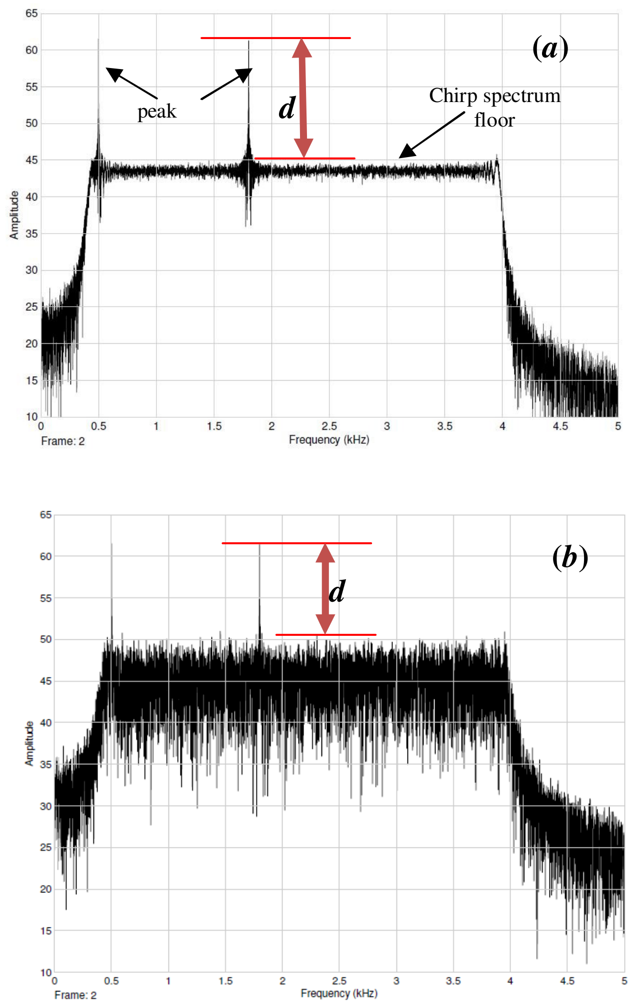

FIGURE 7: received chirp spectrum (a) SINR = 20 dB, (b) SINR = -5dB

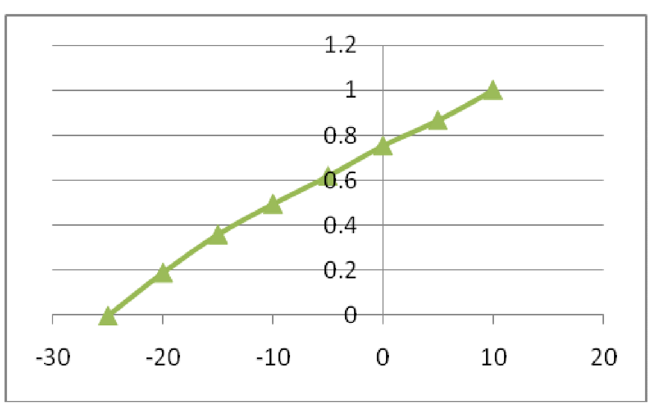

FIGURE 8: SINR versus normalized ***d***.

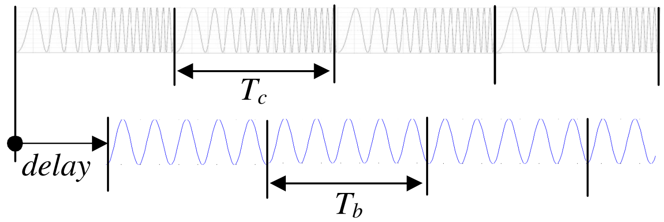

FIGURE 9: delay between reference chirp signal and received primary signal

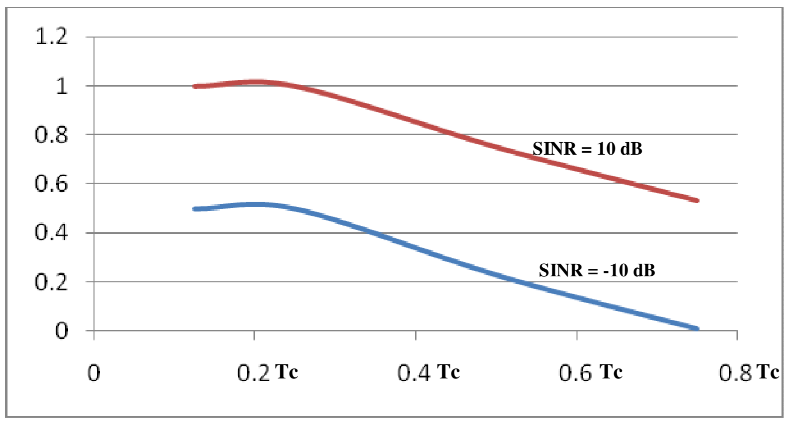

FIGURE 10: delay versus normalized d.

It must be noted that the results shown in Figure 10 simulate the scenario of one chirp signal with bit period Tc and a delayed carrier with bit duration of Tb. Also it must be noted that in this simulation Tb = Tc. The obvious conclusion to be drawn from this is that d is dependent on the overlapping duration between the chirp duration (Tc) and the bit duration (Tb). Therefore, even in worst case scenarios when the overlapping between the first chirp duration and the carrier bit is not enough, the consecutive overlapping should be enough to make a better decision. This may lead to the conclusion that observation interval must be at least twice as much as chirp signal period to avoid this drawback.

From this discussion, we can determine other important criteria necessary for the success of the sensing strategy which is the relation between Tb and Tc since it is evident that if Tb is not long enough to produce enough overlapping duration, the sensing strategy will fail. To drive the relation between Tb and Tc, we need to observe the relationship between the delay and d. in Figure 10, it is shown that in worst case scenario i.e. SINR = -10 dB, d has values greater than 0 if the delay is less than 0.75Tc. This is interpreted as that the minimum overlapping duration should be greater than one forth the chirp signal duration. On the other hand, if we want to estimate the duration of overlapping which is just enough to give optimal performance, we need to observe the performance between delays equal to 0 to 0.25Tc. It is shown that between delays equal to 0 to 0.25Tc, d remains unchanged regardless to the SINR. This is interpreted as that it is enough for Tb to last 0.75Tc and still being received optimally. To summarize this point, we imply that 0.25Tc <Tb< 0.75Tb or 1.33Tb < Tc < 4Tb.

Another important suggestion to be concluded from observing the relationship between Tb and Tc is possibility for sensing signals with spread spectrum and frequency hopping. However this point is out of scope in this paper, we argue that since we are capable of sensing tones with signaling rate higher than the signaling rate of the reference signal, spread spectrum sensing seems possible.

6.1.1 Compassion Between Spectrum Sensing Techniques

It is always difficult to compare results of different systems tested on different simulation testbeds. Therefore in this subsection we are concerned with subjective comparison. Future work should investigate this point thoroughly. And hence, the above discussion entitles us to highlight how our strategy addresses the main shortcoming of other known sensing strategies i.e. energy detection, matched filtering and cyclostationary feature detection.

As for energy detection technique, the main problem is setting the threshold value in presence of background noise. This problem is alleviated by the virtue of flat floor of chirp signal matched filter output which maintains good resolution. Here our sensing technique outperforms energy detection in two ways; firstly setting the threshold will be easier as it depends on estimating the SNR of received reference signal, and secondary, wideband resolution is very important as in case we are dealing with the 4G modulation OFDMA where subcarriers frequencies are set adjacent to one another. Figure 11a shows the spectrum of a tone received using our strategy of sensing and Figure 11b shows a tone received based on energy detection. It is obvious that the resolution in frequency domain is maintained better in the latter case. As a result of, improved measurement accuracy is insured. This should be obvious in dispersive mobile channel where frequency dispersion become a problem, in [18] this issue has been addressed for OFDMA.

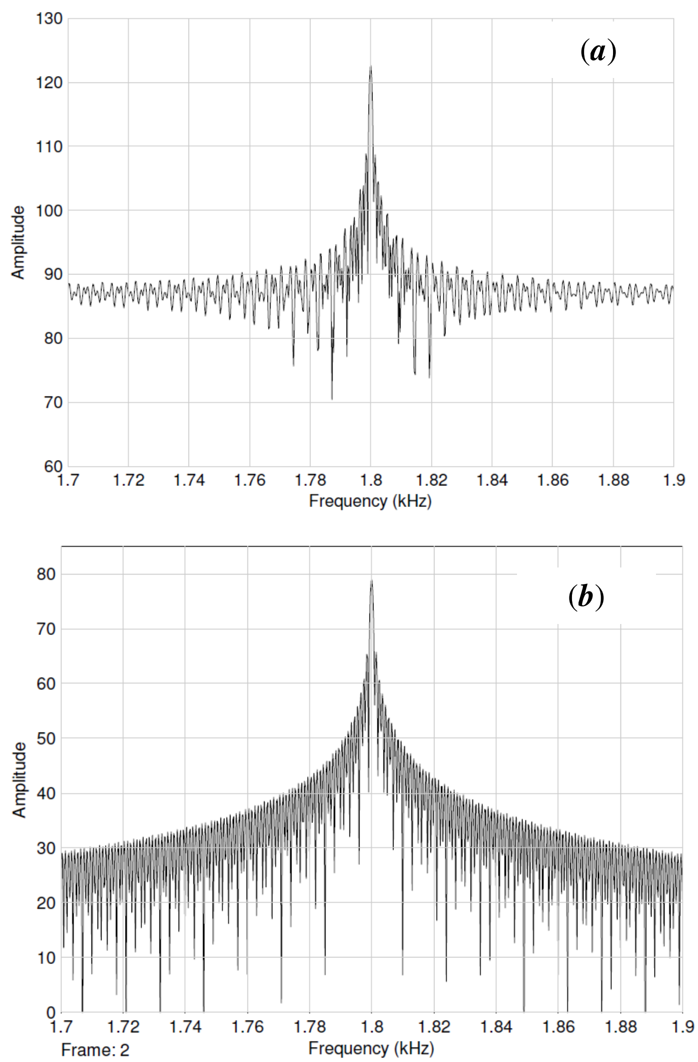

FIGURE 11: A simulation shown a tone received using (a) chip sensing and (b) energy detection

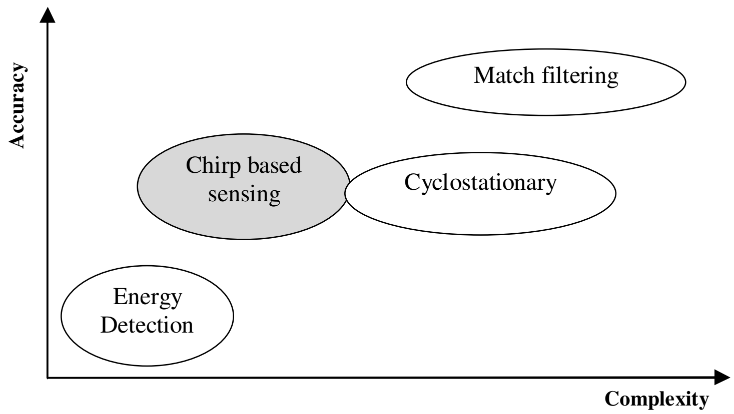

FIGURE 12: Sensing methods compression

As for match filtering, the main problem is that this method requires priori knowledge of primary user signal for optimal detection, in our strategy this is not the case. Although the accuracy of our strategy is not expected to match the optimal solution, the relief of complexity to sense wideband spectrum is considered an advantage. Finally, in cyclostationary feature detection, the main problem is increasing complexity however it is shown that the complexity of our system is moderated. Figure 12 shows a schematic of how we compare our sensing technique to the other techniques.

6.2 Temporal Sensing Performance Evaluation

Figure 13a and 3b show the output of received signal after cross-correlation with the conjugate of referenced chirp signal in time domain without and with an interfering tone respectively. As it is shown in Figure 13b, the presence of the tone is sensed as soon as the flat top of the cross-correlation's output starts to change. We denote Td as the time at which primary user started to transmit. Td is referenced to the beginning of chirp signal's reception.

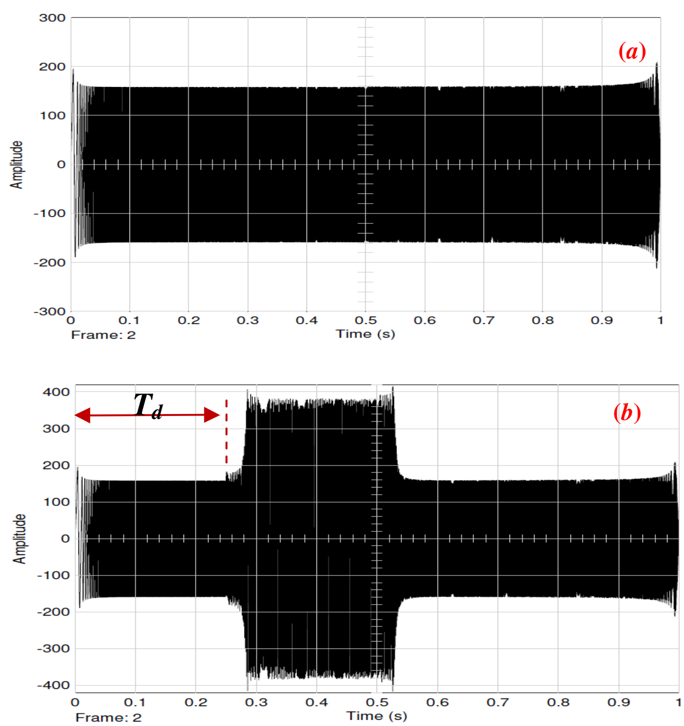

FIGURE 13: Output after correlation (a) without the presence of primary tone and (b) with the presence of primary tone.

In order to evaluate the performance, Figure 14 shows the delay estimation error probability Pd versus SNIR. It is shown that as SNIR decreases, error probability increases as the marking of the tone presence become difficult to recognize from background noise.
Further performance improvement is possible have we applied coherent “optimal” detection of the tone. The requirement for such improvement is a prior knowledge of the carrier frequency. This knowledge can easily be obtained from spectrum sensing based on chirp signal as we have shown above. Figure 14 shows the improvement using optimal detection.

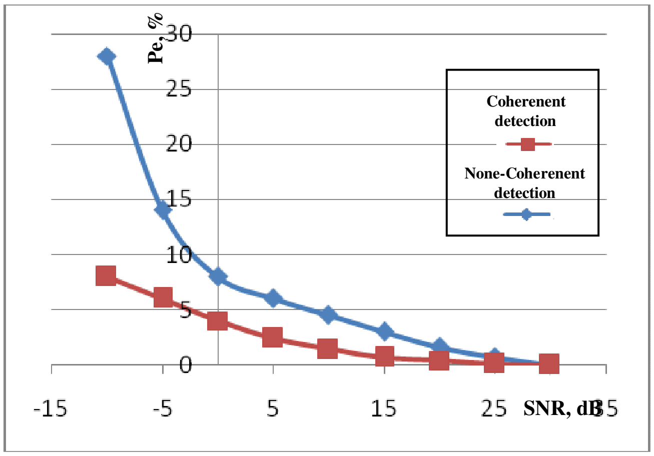

FIGURE 14: SNR vs probability of error

Another aspect to be investigated is the case of multi carrier reception. An example of the superposition of carriers resulted from this scenario is shown in Figure 15. To resolve this ambiguity, interference suppression technique should be used. This technique can be accomplished using band pass filtering to filter out the tones of interest (one at a time) having had knowledge of their frequencies.

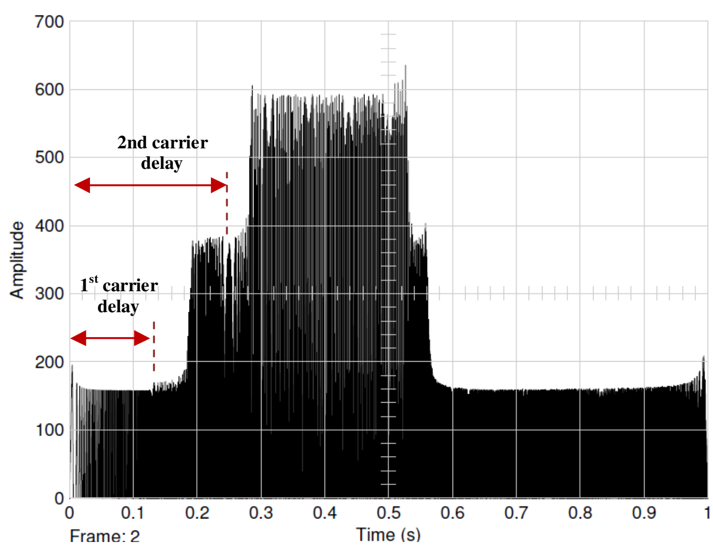

FIGURE 15: Superposition of two received tones

6.3 Sensing Based on Chirp Signal System Overview

Based on above discussion we can put together a design for intelligent sensing strategy. Figure 16 shows a block diagram of the system. Both modules for time and frequency sensing will interact to resolve ambiguity either in time or frequency estimation. Information from both modules is used to map interfering carriers along with the time it accesses the channel and their relative power measurements. Addition algorithms will be developed to obtain further "value added" information such as the set of subcarriers for OFDMA air interface, temporal behavior of users or unutilized timeslots for CDMA/TDD. In future work, hardware implementation based on Software Defined Radio (SDR) platform will be developed and tested.

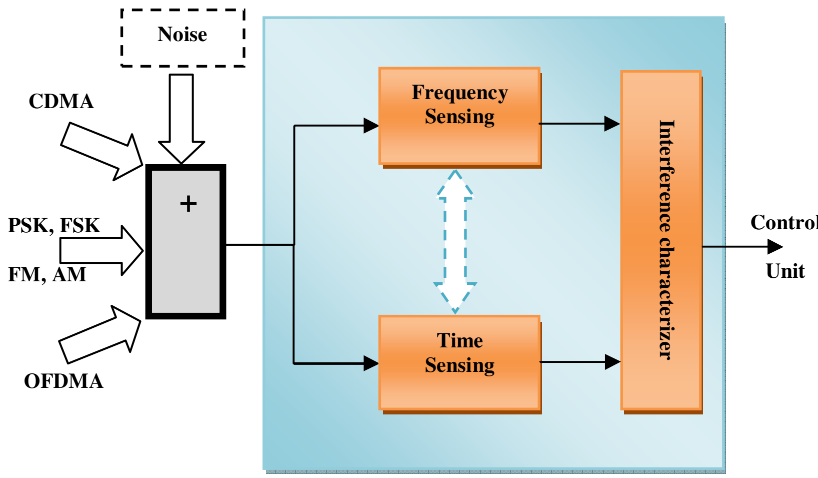

FIGURE 16: System block diagram

7. CONCLUSIONS

Our novel methods for sensing in cognitive radio environment significantly enhance spectral and temporal sensing at moderate complexity. We have evaluated the performance against different parameters and created different related arguments. Future work aiming to design an SDR-based system for interference characterization in heterogeneous future networks will benefit from these findings.

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