CHAPTER 6

CONCLUSIONS AND FUTURE WORK

This chapter sums up the objective, highlights of the major contributions and results of the research work carried out. Followed by few suggestions for future work.

6.1 Summary of the Thesis

In the upcoming era of dynamic spectrum allocation, CR needs to be fully operational. A major task of CR is to find the vacant channels in the spectral space and that too with proper precision. This thesis aims at providing solutions to challenges faced in the spectrum sensing domain. The thesis has started with an overview of the related research in the field of spectrum sensing for cognitive radio. Scarcity in electromagnetic spectrum and the ramifications thereof are highlighted in the context of the present spectrum licensing policy and the spectrum allocation for various applications. As the utilisation of spectrum is very low, dynamic reuse of the spectrum is proposed as the spectrum strategy for tomorrow. Cognitive radio is introduced as the potential device that can perform this dynamic usage of the spectrum. Spectrum sensing is an important task in this regard and CSS is proposed as one of the best method to obtain the right sensing. Decision fusion based on fusion rules is a task to be carried out to finalize the presence of a PU. Therefore, previous work in the area of fusion rules and prediction based spectrum sensing are analysed. The relevance of the proposed work, in light of previous research work in this area is also presented.

This thesis initially proposes decision fusion approaches for distributed spectrum sensing and external sensing. This is followed by a comprehensive prediction based spectrum sensing approach that can improve the throughput of the system.

An effective decision fusion approach for distributed sensing is evolved through various stages of analysis and modifications. Initially, a fuzzy based approach (named as Fuzzy-SNR) was proposed and an analysis thereof was carried out using energy
detection under Rayleigh fading channel. Its performance was compared with classical fusion rules such as ‘AND’ & ‘OR’ rules. Analysis of $P_f$ and $P_d$ with respect to SNR and ‘time consumed’ for a decision fusion were then carried out. Even though the detection performance was very good, time consumption of fuzzy-SNR rule was noted to be quite high. For a fast decision making, a weighted combining approach with SNR as its key component was therefore proposed and analysed using path loss model under shadowing. For the above cases, the assumption was that all the CRs are located within the coverage area of a PU under consideration. A realistic scenario with CRs located at the boundary of PUs is suggested and the SNR-rule is modified to adapt to the situation. It is named as ‘Intelligent rule’ and its performance was analysed using energy detection model under Rayleigh fading as well as path loss model under shadowing. In order to improve its performance further, antenna selection scheme with multiple region encoding for SU reporting was added to the ‘Intelligent rule’. Its performance was compared with other optimal rules and fuzzy rules from the literature. Analysis of $P_f$ versus $P_d$, $P_f$ versus $P_m$, $P_d$ versus ‘N’ (no. of neighbouring nodes) and computational complexity were carried out. On analysing various parameters associated with this evolved approach, it is found that this approach is giving a better performance in all respects.

For the external sensing scenario (which uses wireless sensor networks for spectrum sensing and a centralized node that aggregate the sensor results to form the final decision), CA based approach is proposed for decision fusion and to form the coverage area of PUs. This approach will reduce the task of CR and hence the battery of such mobile SUs may get a longer life. Two fusion rules named ‘CA1’ and ‘CA2’ are proposed under CA scheme and its performance is compared with available distributed sensing algorithms such as DDA (Harrold et al., 2008), Fuzzy2 (Matinmikko et al., 2009) and Fuzzy1 (Taghavi et al., 2011). Performance comparison of all the algorithms were carried out. Coverage area of a transmitter is an important aspect when a CN monitors a large area. CA based approaches are giving a realistic coverage area. ‘CA1’ perform exceptionally well in forming the coverage area. With all the other algorithms, it was very difficult to derive a proper coverage area. False alarm rate of ‘CA1’ is very low compared to other algorithms. Probability of detection is very high for ‘CA1’ algorithm. It is also proved that CA based approach is the most computationally efficient algorithm among the five and hence it is energy efficient. Considering the properties of CA and
its massive parallelism of information processing, CA will be a favourite choice for low power VLSI implementation of decision fusion blocks for an external sensing scenario in cognitive radio.

If the spectrum sensing is limited to only those channels which are having higher probability of being idle, CR can save a lot of time in sensing activity and resultantly more time can be spent on utilising that channel. A prediction based spectrum sensing approach for CR systems is also proposed to improve the throughput of the system. It consists of a predictor that takes the ‘present’ and ‘prior’ information to predict the probability of any channel to be idle. Predictor can generate a rank list of suitable channels for future spectrum sensing. Two approaches based on Bayesian inference are proposed here to predict the future probability. Analysis on the predicted probability by both the methods are carried out. Channel ranking is formed based on these methods and they are compared with other prediction approaches such as EWMA, HMM and Neural Network. On analysis it was found that the amount of data required under ‘prior’ and ‘present’ is relatively less for Bayesian approaches. These analysis and comparisons were done on both synthetic as well as real data. Real data was obtained through spectrum measurement.

In order to analyse the performance of the predictors a spectrum occupancy measurement and its analysis was carried out and presented. Obtained spectrum hole details were used for analysing the predictors. On analysing the measured data it was found that GSM downlink channels are heavily utilised and others are lightly utilised. Analysis of spectrum occupancy, hourly utilisation, received energy levels etc. were carried out. On analysing the spectrum holes, it can be inferred that CRs with different complexity can work at different types of spectrum holes. In other words, a low end CR device can work in slowly varying spectrum holes and a high end device with multiple protocols can adapt to any types of spectrum holes.

### 6.2 Future Work

For decision fusion in the distributed sensing scenario, proposed fuzzy approach in this thesis, has considered all the possible rules for its decision making. It has led to high computational complexity. Since the detection rate is a promising factor, the possibility
of reducing the computational complexity can be explored by restricting the number of rules or by any faster implementation approach. There is a scope in further optimising the membership functions and fuzzy rules.

In the proposed adapted weighted combining for decision fusion, weights for various components were finalized based on various trials carried out with respect to specific scenarios. These weights can be optimized with the help of optimization algorithms.

For decision fusion in the external sensing scenario, CA based fusion rules are proposed in the thesis. These rules were developed based on heuristic approaches. Based on the number of neighbours considered and the state of each neighbours, a large number of rules or its combinations are possible in CA. Possibility of finding better rules from the large rule base can be explored with the help of evolutionary algorithms such as Genetic Algorithm.

Since CA based structure are suitable for low power VLSI integration, implementation of this approach as a low power VLSI core can be explored. This approach may also be extended to distributed sensing where the nodes are randomly distributed.

Outdoor propagation models were considered for the analysis of all the above fusion rules. CR devices are expected to be present in numerous scenarios and to operate in various frequency bands, indoor propagation models and other channel models may also be tried out for the analysis.

For the prediction based spectrum sensing presented in this thesis, Bayesian inference is considered for proposing the predictor. In order to further improve the performance, possibility of modelling this scenario using recursive Bayesian approach can be explored.

All the approaches considered in this thesis were analysed with the help of Matlab simulations. Physical verification of all the approaches can be carried out by setting up a network with the help of a software defined radio platform.