EVALUATION OF FUNCTIONAL ARCHITECTURES FOR COGNITIVE RADIO SYSTEMS

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ABSTRACT

This paper proposes and compares two new physical layer architectures for cognitive radio. The idea of cognitive radio has been proposed for a while, but little research has been done on detailed architectural design and complexity analysis of physical layer functions and systems. Two cognitive radio functional architectures are proposed: one is based on the traditional communication components and the other is based on blind signal separation. Complexities of critical cognitive radio functions are evaluated and the two proposed architectures are compared.

Index Terms— Cognitive radio, blind signal separation, multiuser detection, software radio, computational theory

1. INTRODUCTION

Recently, software radio and cognitive radio have become very active research areas. These promising technologies provide opportunities to allow a single transceiver to communicate using different modulations and multiple frequency bands for more efficient use of radio spectrum. Cognitive radios are rooted on software radios. Other than reconfigurability and compatibility to different protocols and modulation schemes, cognitive radios perform some extra functions to achieve the goal of spectrum efficiency. Although quite a few cognitive radio functions and schemes have been proposed and discussed [1], there lacks design proposals of physical layer functional architecture from the system point of view. Existing quantitative analysis of computational complexity for cognitive radios is also insufficient. Therefore, it is our contributions to propose two architectural designs of cognitive radio systems and to compare their computational complexities.

2. COGNITIVE RADIO ARCHITECTURES

The goal of cognitive radios is to efficiently use the radio spectrum. A cognitive radio system must be able to detect spectrum activities and plan transmission schemes according to the spectrum usage. To be more specific, a cognitive radio device or user must know other users' activities so that it can use the best strategy to access the spectrum and then transmit with little or even no interference to other users. A cognitive radio system should also have the capability to receive several kinds of signals or separate mixed signals. Therefore, a cognitive radio system must have dedicated functions and system architecture compared to conventional radios. In this section, we will introduce two new physical layer architectural implementations of cognitive radio systems.

2.1. Traditional component-based implementation

Fig. 1 shows the first implementation. This implementation is adapted from the traditional design but some cognitive radio functions have been incorporated. Received signals are input to two blocks: spectrum sensing and packet processing. If users are not communicating with others, only the spectrum sensing function is active. Spectrum sensing function uses the signal feature information generated offline to monitor spectrum activities. Once a communication is setup, packet processing function extracts channel and location information from the training sequences of packets. This information is used for multiuser separation, precoding, and beamforming. In cognitive radio, several transmissions with possibly different modulated and multiple-accessed signals can happen at the same time. It is thus required to extract the signals of interests using multiuser separation. Possible multiuser separation implementations include channelization for different frequencies and multiuser detection for CDMA signals. Several methods have been developed for multiser detection with complexity and performance tradeoffs. To avoid interfering with other users, signals to be transmitted are pre-coded such that they are invisible and cause no interference to other users. A possible precoding scheme is dirty paper coding, which requires the knowledge of channel condition and other users' messages. Interference to other users can be largely mitigated using beamforming, which has also been proved to provide energy-efficient transmissions. At the mean time of signal transmissions, the spectrum sensing function keeps tracking spectrum activities. This implementation is called traditional because most of the functions can be found in a traditional communication system but with different configurations.

2.2. Blind signal separation (BSS)-based system

The second implementation of cognitive radio, shown in Fig. 2, utilizes the blind signal separation (BSS) method. The advantage of this implementation is that it replaces several functional blocks with one single function. Instead of having different blocks for specific functions, blind

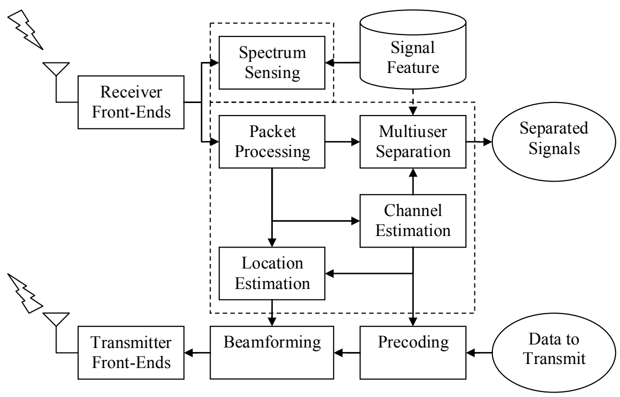

FIG. 1. COGNITIVE RADIO WITH TRADITIONAL IMPLEMENTATION

signal separation can serve for many purposes, including spectrum sensing, channel estimation, location estimation, and most important of all, signal separation. Information generated from BSS can then be used for precoding and beamforming. Since input signals of BSS-based implementation come from different antennas, multiple-antenna is required.

2.3. Comparison of two implementations

In the first implementation, spectrum sensing is always active but packet processing, multiuser separation, channel estimation, and location estimation are only required during signal transmissions. In BSS-based system, BSS function is always active. As a result, BSS-based architecture is more suitable for systems with intensive transmissions. Compared to the traditional design, BSS-based implementation is easier to implement since a single function deals with many things. However, blind signal separation introduces two major challenges, namely convergence rate (many iterations to find receiver parameters) and the quality of the signal separation (robustness to noises). In addition, BSS-based implementation also needs the support of multiple antennas.

3. COGNITIVE RADIO FUNCTIONS

Cognitive radio functions include spectrum sensing and precoding at transmitter and multiuser detection or separation at receiver. Beamforming can be at either side.

3.1. Spectrum sensing

The first function of cognitive radio to be performed is spectrum sensing. Three main spectrum sensing techniques are matched filter, energy detection, and cyclostationary detection, and the last two are probably the most popular ones. Energy detection is a simple method although it suffers some near-far problems. It is realized as

$$d = \sum_{q=0}^{Q-1} \left| \hat{y}_q \right|^2 . \quad (1)$$

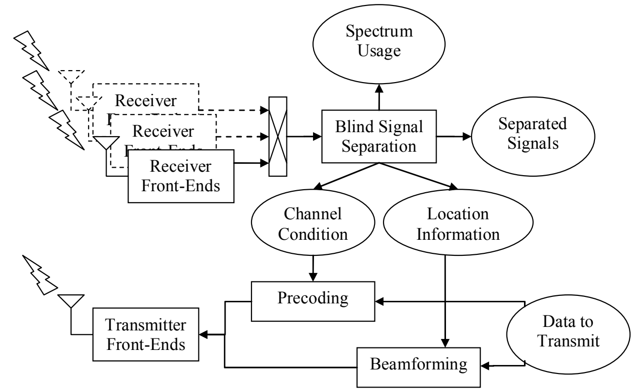

FIG. 2. BLIND SIGNAL SEPARATION-BASED COGNITIVE RADIO SYSTEM

$\hat{y}$ is bandpassed version of received signals y, d is detection metric, and Q is training sequence length. Comparing d with a threshold then decides the spectrum activity. Cyclostationary detection utilizes the fact that communication signals are mostly cyclostationary but noises are not. To further distinguish the signals, information such as signal features is required. To perform cyclostationary detection, the spectral correlation function is firstly calculated using equation (2) [1]

$$S(f,\alpha) = \frac{1}{U(Z+1)} \sum_{m=-Z/2}^{Z/2} Y\left(f + \frac{m}{UT_s} + \alpha/2 \right) Y^*\left(f + \frac{m}{UT_s} - \alpha/2 \right)$$

, where $Y(f)$ is the frequency transform of $y(n)$. This is then compared to signal features to decide spectrum activities. Cyclostationary detection is more complicated but more robust than energy detectors.

3.2. Precoding

Precoding is a signal processing technique performed at the transmitter. Traditionally it is used to remove ISI caused by the channel, so it needs the channel information in advance, usually through a feedback channel. After the spectrum is detected, a cognitive radio transmitter can decide whether to transmit on top of other users. If the messages of a primary user are non-causally known (or known in advance) to the secondary user, precoding can be applied. A practical precoding scheme performing dirty paper coding has been proposed [1]. With the following pre-processing, the primary user will not notice any interference from the secondary user:

$$x = \left[\sqrt{E_2} w_2 - w_1 \sqrt{E_2} \frac{\langle h_1^*, w_2 \rangle}{\langle h_1^*, w_1 \rangle} \right] s , \quad (3)$$

where s and x are original and transmitted signals by the secondary user, h_1 is channel vectors of the primary user, and w_1 and w_2 are beamforming vectors.

3.3. Beamforming

Beamforming can be implemented either at the transmitter or at the receiver. Trasmitter beamforming concentrates the transmission signal at a certain direction so it causes less interference to other users. Receiver beamforming is usually used for signal localization or to take advantage of spatial diversity. Multiple-antenna is necessary for transmitter to generate beam pattern and for receiver to make use of the phase difference. Let $\hat{w}$ be the optimal weighting vector of the beamformer, an example of receiver beamforming is [3]

$$\hat{w}_i = \Phi_i^{-1} p_i , \tag{4}$$

$$\Phi_i = \frac{1}{Q}\sum_{q=1}^{Q} Y_i(q)Y_i^H(q) , \; p_i = \frac{1}{Q}\sum_{q=1}^{Q} Y_i(q)d_i , \tag{5}$$

where Φ_i is estimated correlation matrix, p_i is cross correlation between the received vector X and the training sequence d, and Q is the length of training sequence. The complexity of this direct matrix inversion is $O(Q^3)$. Adaptive methods, such as least mean-square (LMS), fast transversal filter (FTF), and least square lattice (LSL), can highly reduce the computational complexity [3].

3.4. Multiuser detection (MUD)

A cognitive radio system can be viewed as a multiuser system since many users are transmitting at the same time. Performing multiuser detection at the receiver is thus critical. The optimal multiuser detector is the maximum-likelihood sequence estimator (MLSE) detector, but its complexity grows exponentially with the number of users. Some linear-complexity sub-optimal detectors have been proposed, such as decorrelator, minimum mean-square error (MMSE) estimator, multistage parallel architecture, and successive interference cancellation [4].

3.5. Blind signal separation

The function of spectrum sensing, multiuser separation (or detection), and channel estimation can be done through blind signal separation. BSS-based multiuser detector has been proposed and discussed recently. During the process of signal separation, channel matrix is also estimated. If the signals can be separated and the channel can be estimated, knowing the spectrum activities is straightforward. That means while we do the blind signal separation, we actually perform different functions at the same time. The object of blind signal separation is to separate signals x from mixed signals y by estimating the demixing matrix W.

$$\hat{x} = Wy \tag{6}$$

Several blind signal separation algorithms are available for different cases: linear mixture versus convolutive mixture, determined versus underdetermined. In the natural gradient algorithm [5], the adaptation of W follows the following rule

$$\Delta W = \eta[I - f(y)y^T]W . \tag{7}$$

$f(y)$, for example, is $\alpha y + y\,|\,y\,|^2$ for sub-Gaussian signals. η is learning constant.

TABLE I
COMPLEXITY OF COGNITIVE FUNCTIONS

Functions	Complex MAC	Division
Energy detector	Q	-
Cyclostationary detection	$(U\log U+ Z)*(D/U)$	-
Precoding	$(K^2+4K+1)*(D/K)$	$1*D/K$
Beamforming weight (LMS)	$(2Q+1)*M$	-
Beamforming weight (FTF)	$(7Q+12)*M$	$4*M$
Beamforming weight (LSL)	$(10Q+3)*M$	$(6Q+2)*M$
Beamforming	M^2*D	-
MUD (Multistage parallel)	$\{ML[S(6FN_s+7)-4FN_s-1]\}*D$	
MUD (Successive)	$\left\{\begin{matrix} L[M(8FN_s+12)-6FN_s-7] \\ +\frac{M}{D}(2D+\log_2 M+1) \end{matrix}\right\}*D$	
BSS update W (Sub-Gaussian)	$(M^3+2M^2+3M)*Itr$	-
Blind signal separation	M^2*D	-

*Some functions have already included division.

4. COMPLEXITY

The complexities of cognitive radio functions and architectures are compared to show how much computation is needed for processing one frame or packet. It is easy to derive the complexity of energy detector from equation (1) and the complexity of precoding from equation (3). For cyclostationary feature detection, we only consider the complexity of generating spectral correlation function (equation (2)). It is expected that FFT operations, which complexity is at the order of $U\log U$, will dominate the complexity. Besides, feature comparison can be done using simple comparison schemes so the complexity is negligible. The process of beamforming contains two parts: finding weight vector and the actual beamforming processing. The complexity of finding optimal weighting factor of a beamformer has previously been derived [3], and the actual processing depends on data length. Complexities of multiuser detectors have also been derived previously [4], and we only consider linear MUD detectors here. Since these complexities are for obtaining one bit, they need to be multiplied by data length to get the complexity of one frame. Like beamforming, blind signal separation also contains two steps: demixing matrix update and the actual signal separation. Table I summarizes the complexity and Table II lists meanings of the symbols. Complexities are compared in the number of complex operations. We assume that the multiply-accumulate (MAC) instruction is available in the processor or platform such that the computation of additions following multiplications does not take extra cycles. We also assume that division is roughly twice complex as multiplication and MAC [6]. The complexities

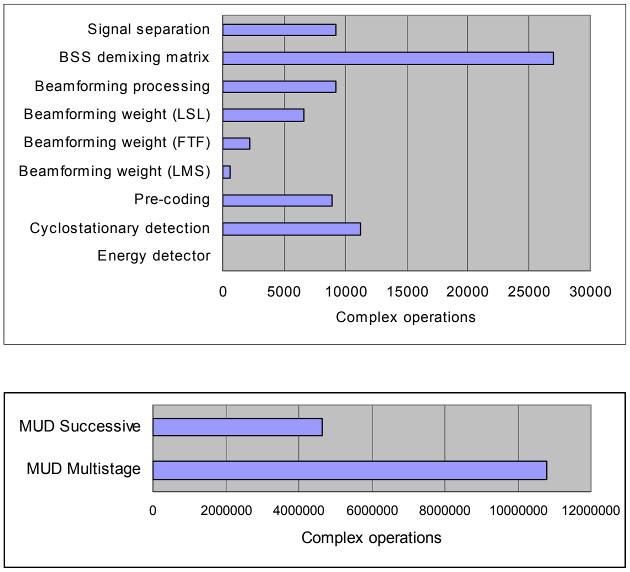

FIG. 3. COMPLEXITY OF COGNITIVE RADIO FUNCTIONS

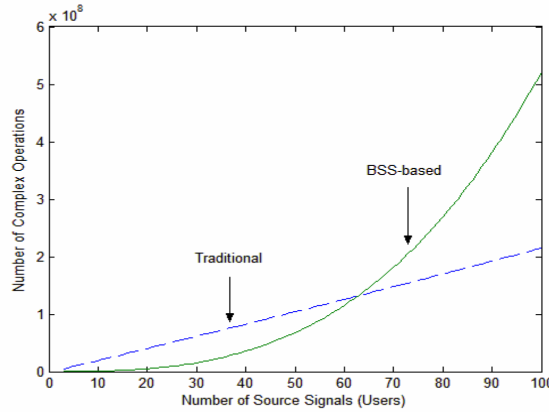

FIG. 4. COMPARISON OF PROPOSED COGNITIVE RADIO ARCHITECTURES

of energy detector and beamforming weight vector update only depend on training sequence length because they are only active during the training sequence stage. Other functions depend on the length of the frame.

TABLE II
SUMMARY OF SYMBOLS

Symbol	Meaning	Value
Q	Training sequence length	100
D	Data length per packet or frame	1024
U	Number of FFT points	1024
Z	Frequency resolution	1024
K	Size of channel vector	4
L	Number of resolvable paths (RAKE fingers)	2
M	Number of source signals, users, or antennas	3
F	Spreading factor	31
Ns	Number of samples per chip	4
Itr	Number of iterations	500

Using the values shown in Table II, Fig. 3 shows the complexity comparison. For spectrum sensing, energy detector is much simpler than cyclostationary detection. For beamforming, complexities of different adaptive algorithms are quite different. Among multiuser detectors, successive interference cancellation is the least complex. We also compared the two proposed cognitive radio system architectures. We chose the most compact implementations of each component in the traditional design except choosing cyclostationary detection for its superiority. Apparently, multiuser detection is the most computationally intensive component and much more complex than other components in the traditional implementation. Consequently, multiuser detection almost decides the overall complexity alone. Calculations showed that the blind signal separation-based architecture needs far fewer operations than the architecture based on traditional components, as shown in Fig. 4. Only when the number of users or source signals is large, for example, over 60 users, traditional architecture starts to take advantage. This is because the complexity of BSS-based architecture grows exponentially with the number of source signals. The above results compared the complexity when multiple-transmission happens. If there is no transmission, cyclostationary detection is the only active function in the traditional implementation. However BSS, which is more complex compared to cyclostationary detection as shown in Fig. 3, is always active. BSS-based system, therefore, is most efficient when transmission happens all the time.

5. CONCLUSIONS

We have proposed two architectural designs of cognitive radio systems and evaluated their components and complexities. Numerical experiments showed that the BSS-based system is more computationally efficient. However, the performance of these two approaches is still unclear. Our future work is thus to conduct the comparison of signal separation quality of these two architectures.

6. REFERENCES

[1] D. Cabric, I.D. O'Donnell, M.S.-W. Chen, and R.W. Brodersen, "Spectrum Sharing Radios," *IEEE Circuits and Systems Magazine*, Vol. 6, No. 2, pp.30-45, 2006.

[2] M. Airy, A. Forenza, R.W. Heath, Jr., and S. Shakkottai, "Practical Costa Precoding for the Multiple Antenna Broadcast Channel," *GLOBECOM*, 2004, pp.3942-3946.

[3] J. Razavilar, F. Rashid-Farrokhi, K.J.R. Liu, "Software Radio Architecture with Smart Antennas: A Tutorial on Algorithms and Complexity," *IEEE Journal on Selected Areas in Comm.*, Vol. 17, No. 4, pp.662-676, April 1999.

[4] R.M. Buehrer, N.S. Correal-Mendoza, and B.D. Woerner, "A Simulation Comparison of Multiuser Receivers for Cellular CDMA," *IEEE Transactions on Vehicular Technology*, Vol. 49, No. 4, pp.1065-1085, July 2000.

[5] S. Amari and A. Cichocki, "Adaptive Blind Signal Processing-Neural Network Approaches," *Proceedings of the IEEE*, Vol. 86, No. 10, pp.2026-2048, Oct. 1998.

[6] K. Venkat, "Efficient Modulation and Division Using MSP430," http://focus.ti.com/lit/an/slaa329/slaa329.pdf.