Final report for CENIIT project 05.03 (2005-10)

Spectrum sensing techniques with cognitive radio applications

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The project has been divided into two parts with different topics of the research. During the first three years $(2005-2007)$ the main direction has been towards investigation of efficient methods for modulation and decoding in digital transmission systems. The research spectrum sensing techniques for cognitive radio has been performed during the second three year period $(2008-2010)$ of the project.

1 Summary of Results

1.1 Results for the Period $2005-2007$

Our main objectives have been to investigate existing combinations of modulation and decoding for wireless as well as wire-bound communication schemes and finding ways for improving upon them.

We have performed some work on developing of efficient decoding algorithms for the so called Low-Density-Parity-Check (LDPC) codes. The results have been presented at the IEEE International Symposium on Information Theory [1]. We have investigated reduced complexity decoders for LDPC codes over M-PSK modulation. Capacity calculations show only minor losses if only phase information is considered in the decoder. A decoder based on phase angle summation has also been devised. For codes over Galois fields we have constructed table-based decoders which give performance close to belief propagation decoders at substantially reduced complexity.

The other direction of our research during this period has been towards decoding algorithms for use with majority logic decoders. Our modifications enhance the message error performance, and in some cases outperform maximum-likelihood (ML) decoding. For some codes they also offer a quality measure of different message parts. It means that different parts of the information message have variable protection levels. Because of this inconstant sensitivity to channel errors, it is possible to use the coding and decoding scheme as a self-adaptive variable rate scheme.

We have also provided some basic analytical tools to analyze the problem of message-to-codeword mapping. For the special case of binary Reed-Muller codes we have proposed novel decoding schemes based on the structural properties of these codes [2]. A novel hybrid ARQ scheme based on the developed decoding algorithms has been suggested as well. The detailed description of these results can be found in the licenciate thesis [3].

1.2 Results for the Period $2008 - 2010$

Signals used in practical communication systems contain distinct features that can be exploited to improve the detection performance, and to estimate unknown parameters. One main focus of the work in the project has been on the design of detectors that are able to exploit such known features of the transmitted signal. For example, an orthogonal frequency division multiplexed (OFDM) signal with a cyclic prefix is non-stationary (in fact even cyclostationary) by construction. If the size of the cyclic prefix and the size of the effective data (size of the IFFT) are known, it is possible to estimate the time-varying (and periodic) autocorrelation of the received signal. We have proposed and evaluated detectors that exploits the autocorrelation of such an OFDM signal [4, 5, 6].

We have also studied detection of signals that have covariance matrices with some specific structure. Communication signals contains redundancy that incurs that the signal covariance matrix has low-rank. Moreover, if the signal is of some specific kind, the eigenvalues of the covariance matrix may have some known structure. For example, detection of one single transmitted signal, using multiple antennas, incurs a covariance matrix with a rank-one-plus-identity structure. We have studied, and proposed spectrum sensing algorithms that exploits knowledge of the structure of the eigenvalues of the covariance matrix introduced by an orthogonal space-time block code [7, 8] or by the fact that the receiver has multiple antennas [9, 8]. Recently, we also proposed detectors exploiting a more general knowledge of the multiplicities of the eigenvalues [8]. The generalization of [8] includes detection using multiple antennas [7, 9] and a particular case of OFDM signal detection [4], as special cases.

Another important issue in spectrum sensing is that any parameter uncertainties lead to fundamental limits on the detection performance (cf. [10]). For example, an imperfect noise power estimate impacts the decision threshold and causes a severe degradation of the detection performance. In all of the above work, we also considered unknown noise power, and proposed detectors that do not require any knowledge of the noise power.

In practice, it is desirable to be able to detect multiple channels simultaneously. This problem was considered in [11], in a Bayesian framework. In particular, we dealt with the problem of unknown noise power in a Bayesian framework, by asserting a non-informative a priori distribution to it. Assuming that the noise power is correlated (or even equal) for all channels, the detection problem becomes a composite hypothesis test. The complexity of this composite hypothesis test grows exponentially with the number of channels. Hence, we have also studied and proposed approximations to the optimal detector to reduce the complexity [11, 12].

Our gathered knowledge during the project, in the area of spectrum sensing, have also been summarized in two tutorial papers [10, 13] and a licentiate thesis [14].

At an early stage, we also made some analysis of system aspects of cognitive radio, and in particular on the achievable rate of a cognitive radio system [15]. Our motivation has been that the investigated sensing methods are aimed to be applied in cognitive radio systems.

Another direction of our research has been the design and evaluation of sensing techniques for the signals defined by the ETSI's DVB-T standard since the television broadcasting frequency band is a good candidate for deployment of a cognitive radio networks. The performance of the novel techniques as well as the previously known methods for detecting of DVB-T signals have been thoroughly investigated. The evaluation has involved more sophisticated statistical channel models and thus a more realistic comparison has been obtained. Our investigations show that pilot detection techniques are to be preferred in this case. The results are summarized in [5, 16]

2 Exams and Promotions

Two doctoral students, Daniel Puaca [3] and Erik Axell [14], have received their Lic. Eng. degrees within the project. Danyo Danev has received his docent degree within the duration of the project.

3 Masters' Thesis

None

4 Personnel

The researchers that have been financed by this project are Danyo Danev, Daniel Puaca and Erik Axell.

5 Industrial Contacts

Our industrial partners in this project have been Telenor, Norway and THALES communications, France. The main cooperation contacts have been through the EU's FP7 financed project SENDORA. Together with our industrial partners we have discussed integration of our results in a complex network allowing cognitive spectrum access.

6 CENIIT Colaboration

None

7 Research Group

The persons involved in the project are, or have been, part of the newly established Communication system group within the department of Electrical engineering. Currently there are 1 full professor, 3 associate professors, 2 research associates, 4 Post Docs and 7 PhD students in the group.

List of Publications

[1] M. Tjader, M. Grimnell, D. Danev, and H. Tullberg, "Efficient message-passing decoding of LDPC codes using vector-based messages," in *Information Theory, 2006 IEEE International Symposium on*, July 2006, pp. 1713–1717.

[2] D. Danev and D. Puaca, "New majority logic decoding algorithm for reed-muller codes," in *Fifth International Workshop on Optimal Codes and Related Topics*, Balchik, Bulgaria, June 2007, pp. 203–208.

[3] D. Puaca, "Topics on majority logic decoding," Licentiate thesis, Linköping University, 2008.

[4] E. Axell and E. G. Larsson, "Optimal and sub-optimal spectrum sensing of OFDM signals in known and unknown noise variance," *IEEE J. Sel. Areas Commun.*, vol. 29, Feb 2011.

[5] D. Danev, E. Axell, and E. G. Larsson, "Spectrum sensing methods for detection of DVB-T signals in AWGN and fading channels," in *Proc. IEEE Int. Symp. on Personal, Indoor, Mobile Radio Commun. (PIMRC)*, Istanbul, Turkey, Sep 2010.

[6] E. Axell and E. G. Larsson, "Optimal and near-optimal spectrum sensing of OFDM signals in AWGN channels," ELba Island, Italy, June 2010, pp. 128–133.

[7] ——, "Spectrum sensing of orthogonal space-time block coded signals with multiple receive antennas," in *Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Process. (ICASSP)*, Dallas, Texas, USA, Mar. 2010, pp. 3110–3113.

[8] ——, "A unified framework for GLRT-based spectrum sensing of signals with covariance matrices with known eigenvalue multiplicities," in *Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Process. (ICASSP)*, Prague, Czech Republic, 2011.

[9] ——, "Comments on "multiple antenna spectrum sensing in cognitive radios"," submitted.

[10] E. Axell, G. Leus, E. G. Larsson, and H. V. Poor, "Spectrum sensing for cognitive radio: State-of-the-art and recent advances," *IEEE Signal Process. Mag.*, submitted.

[11] E. Axell and E. G. Larsson, "A Bayesian approach to spectrum sensing, denoising and anomaly detection," in *Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Process. (ICASSP)*, Taipei, Taiwan, Apr. 2009, pp. 2333–2336.

[12] E. Axell, E. G. Larsson, and J.-Å. Larsson, "On the optimal K-term approximation of a sparse parameter vector MMSE estimate," in *Proc. IEEE Workshop on Statistical Signal Proces. (SSP)*, Cardiff, Wales, UK, Aug-Sep 2009, pp. 245–248.

[13] E. Axell, G. Leus, and E. G. Larsson, "Overview of spectrum sensing for cognitive radio," June 2010, pp. 322–327.

[14] E. Axell, "Topics in spectrum sensing for cognitive radio," Licentiate thesis, Linköping University, Dec 2009.

[15] E. Axell, E. G. Larsson, and D. Danev, "Capacity considerations for uncoordinated communication in geographical spectrum holes," *Physical Communication*, vol. 2, pp. 3–9, 2009.

[16] D. Danev, "On signal detection techniques for the dvb-t standard," in *Proceedings of the International Symposium on Communications, Control and Signal Processing (ISCCSP)*, 2010, pp. 1–5.