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Modulated Coding for Digital Communication Systems Under ISI/Multipath Fading and Jamming

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13. ABSTRACT *(Maximum 200 words)*

This report describes the main research achievements during the time period cited above on the research project in the area of telecommunications. The main achievements include the systematic study of modulated codes that are convolutional codes defined on real/complex field over intersymbol interference, multipath, jamming channels. We obtained the joint maximum-likelihood decoding, and the MMSE-DFE decoding algorithms. We proved the existence of the coding gain compared to the uncoded AWGN chanel. We also obtained space-time modulated codes for multiple transmit and multiple receive antenna systems. A new precoded OFDM system was also obtained, which is robust to spectral-nulls.

14. SUBJECT TERMS

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Final Report

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A. Objective: The goal of this research is to systematically develop modulated coding as a new coding scheme for dispersive channels, where modulated coding is naturally combined with a channel.

B. Main Research Accomplishments: We have made several research accomplishments as follows.

(i). *Modulated codes for ISI channels.* Modulated codes (MC) were proposed by the PI for mitigating ISI, which are defined on the complex field and encoded after the binary-to-complex symbol mapping. The main advantage of MC is that their encoding arithmetic operations and the ISI channel arithmetic operations are all defined on the complex field and therefore can be naturally combined together, which is not possible for any current error correction coding schemes. The combination provides the convenience of the optimal study of the coding. We have systematically studied MC, such as encoding/decoding, performance analysis, efficient distance spectrum calculation algorithms. We have proved that, for any finite tap ISI there always exist MC with coding gain compared to the ideal channel, i.e., the AWGN channel, and the coding gain is upper bounded by the number of the ISI taps. As an example, for the ISI channel $[0.7071, 0.7071]$, we have found simple rate $1/2$ and $2/3$ MC of memory size less than 3 that have coding gain about 2.5dB compared to the uncoded AWGN channel. We have also proved that the MC coded ISI channels may have larger information rates than the uncoded ISI channels do when the channel SNR is relatively low, where the information rates are the achieveable rates using the standard random coding techniques.

(ii). *Modulated code assisted zero-forcing decision feedback equalizer (ZF-DFE) and minimum mean square error Decision Feedback Equalizer (MMSE-DFE)* . Due to the different arithmetic operations of the ISI channel and the current error correction codes (ECC), it is hard to incorporate the ECC with any equalization techniques, such as the decision feedback equalizer (DFE). Since MC are defined over the complex field, they can be used to assist equalization techniques. A new MC coded zero-forcing DFE (ZF-DFE) was proposed and it turns out that this new method outperforms all the existing ECC assisted equalizers significantly at low signal-to-noise (SNR) ratios. Furthermore, the performance and the optimal MC design for the ZF-DFE were also obtained. Furthermore, we also developed the MC coded MMSE-DFE that improves the ZF-DFE for severe ISI channels.

(iii). *Space-time modulated codes.* Space-time coding for multiple transmit and receive antenna channels has recently attracted considerable attentions in wideband communi-

cation systems due to the potential capacity gain. Most current studies on space-time coding are for memoryless channels. In the last year, we studied space-time MC for memory channels, such as multiple transmit and receive antenna systems with ISI. Similar to MC for single antenna systems, the space-time MC can be also naturally combined with a multiple antenna system with ISI. We derived some lower bounds on the capacities and the information rates of the MC coded systems. As a property of space-time MC, it is shown that, for an N transmit and N receive antenna channel with memory and AWGN, there exist MC with arbitrary rates r, $0 < r < 1$, such that the MC coded systems have larger information rates than the original system does at relatively low channel SNR. We also proposed an MC coded zero-forcing decision feedback equalizer (ZF-DFE) and presented its performance analysis, where the channel was assumed known at both the transmitter and the receiver. We then presented the optimal MC design based on the ZF-DFE.

(iv). *Precoded and vector OFDM systems.* Orthogonal frequency division multiplexing (OFDM) systems have been widely used in high speed digital wireline communication systems, such as VHDSL and ADSL. Recently, the applications of OFDM systems to high speed digital wireless communication systems have become an active research area. In high speed digital wireless applications, however, the ISI channel may have spectral nulls, which may degrade the performance of the existing OFDM systems. Another problem with the existing OFDM systems is that, when the ISI channel has many taps, the data rate overhead of the cyclic prefix insertion is high. In the last year, we proposed a precoded OFDM system that may improve the performance of the OFDM systems for spectral null channels. We also proposed size $K \times 1$ vector OFDM systems that reduce the cyclic prefix length by K times comparing to the conventional OFDM systems. The precoding scheme is simply to insert one or more zeros between each two sets of K consecutive information symbols. This precoding scheme may be able to remove the spectral nulls of an ISI channel without knowing the ISI channel.

(v). *Other Main Results in Theory and Applications in Radar and Communications of Wavelets, Filterbanks, and Joint Time-Frequency Analysis and Synthesis*

A new prefiltering for discrete multiwavelet transforms, which has better energy compaction than other prefiltering, was obtained.

A new synthetic aperture radar (SAR) imaging method, non-uniform speed SAR imaging, of ground moving targets was proposed, where the radar platform moves with a nonuniform speed. This method is able to accurately locate slowly and

fast moving targets.

We quantitatively studied the sidelobes of the discrete chirp-Fourier transform for estimating the chirp parameters analogous to the discrete Fourier transform for estimating the frequencies.

A noncoherent coded modulation for 16QAM was obtained with noncoherent detection.

A block coded modulation for the reduction of the peak-to-average power ratio (PAPR) in OFDM systems was proposed, where the PAPR gain, the coding gain and overall gain were introduced.

A quantatitive SNR analysis for joint time-frequency analysis by introducing 3dB SNR in the joint time-frequency plane was presented. A quantitative SNR analysis for the pseudo Wigner-Ville distribution was obtained.

An image compression scheme using discrete multiwavelet transform was proposed.

A characterization of analytic signals with nonnegative instantaneous frequency was obtained.

We obtained an iterative algorithm for direction of arrival (DOA) estimation with wideband chirp signals, which is a generalization of the time-frequency MUSIC algorithm from a narrow band model to a wideband model.

C. Significance: Modulated coding and precoded and vector OFDM systems provide new ISI mitigation techniques for broad band wireline and wireless digital communications. These techniques are particularly important for ISI channels with spectral nulls.

D. Publications, Abstracts, Technical Reports, and Patent Disclosures or Applications

Published and Accepted (Refereed) Journal Publications

1. X.-G. Xia, An efficient frequency estimation algorithm from multiple undersampled waveforms, *IEEE Signal Processing Letters*, Feb. 2000.
2. P. Y. Fan and X.-G. Xia, Block coded modulation for the reduction of the peak to average power ratio in OFDM systems, *IEEE Trans. on Consumer Electronics*, vol.45, pp.1025-1029, Nov. 1999.

3 X.-G. Xia and H. Liu, Polynomial resistant precoders: theory and applications in ISI/multipath cancellation, *Circuits, Systems and Signal Processing*, to appear.

4 H. Liu and X.-G. Xia, Precoding techniques for undersampled multi-receiver communication systems, *IEEE Trans. on Signal Processing*, to appear.

5 X.-Q. Gao, Z.-Y. He, and X.-G. Xia , The theory and implementation of arbitrary-length linear-phase cosine-modulated filter bank, *Signal Processing*, to appear.

6 K. Bao and X.-G. Xia, Image compression using a new discrete multiwavelet transform and a new embedded vector quantization, *IEEE Trans. on Circuits and Systems for Video Technology*, to appear.

Submitted (Refereed) Journal Publications

7 Q. Xie and X.-G. Xia, Modulated coding with ISI channels, submitted to *IEEE Trans. on Communication Theory.*

8 X.-G. Xia, Modulated Codes with Coding Gain for ISI Channels and Modulated Code Coded Zero-Forcing Decision Feedback Equalizer, submitted to *IEEE Trans. on Communications.*

9 P. Fan and X.-G. Xia, Some new results on coding gain of modulated codes over ISI channels, submitted to *IEEE Trans. on Information Theory.*

10 P. Fan and X.-G. Xia, A noncoherent coded modulation for 16QAM, submitted to *IEEE Trans. on Communications.*

11 X.-G. Xia, Discrete chirp-Fourier transform, submitted to *IEEE Trans. on Signal Processing.*

12 X.-G. Xia, Precoded OFDM systems robust to spectral-null channels and vector OFDM systems with reduced cyclic prefix length, submitted to *IEEE Trans. on Communications.*

13 P. Fan and X.-G. Xia, Capacity and information rates of the discrete time Gaussian channel with intersymbol interference and modulated code encoding, submitted to *IEEE Trans. on Communications.*

14 X.-G. Xia, G. Wang, and P. Fan, Space-time modulated codes for memory channels: capacity and information rates, zero-forcing decision feedback equalizer, submitted to *IEEE Trans. on Information Theory.*

15 X.-G. Xia and S. Qian, On the rank of the discrete Gabor transform matrix, submitted to *Signal Processing.*

16 G. Wang, X.-G. Xia, and V. C. Chen, Dual-speed SAR imaging of moving targets, submitted to *IEEE Trans. on Aerospace and Electronic Systems.*

17 G. Wang and X.-G. Xia, An iterative algorithm for direction of arrival estimation with wideband chirp signals, submitted to *IEE Proceedings Radar, Sonar and Navigation.*

18 X.-G. Xia, Channel identification with Doppler and time shifts using mixed training signals, submitted to *Signal Processing.*

19 Y.-J. Zhang and X.-G. Xia, A new modulated code design for ISI channels, submitted *IEEE Trans. on Communications.*

20 X.-G. Xia, W. Su, and H. Liu, Polynomial ambiguity resistant precoders for blind ISI mitigation, submitted to *IEEE Trans. on Circuits and Systems I* (invited).

Conference Proceeding Publications

1 X.-G. Xia, Doppler ambiguity resolution using optimal multiple pulse repetition frequencies, Conference on Information Sciences and Systems, Princeton University, March 18-20, 1998.

2 X.-G. Xia, Dynamic range determination of the detectable parameters for polynomial phase signals using multiple lag diversities in high-order ambiguity functions, Conference on Information Sciences and Systems, Princeton University, March 18-20, 1998.

3 X. Gao, Z. He, and X.-G. Xia, A new implementation of arbitrary length cosine modulated filterbanks, Proceedings of IEEE ICASSP'98, Seattle, May 12-15, 1998.

4 X.-G. Xia, Channel identification with Doppler and time shifts using mixed training signals, Proceedings of IEEE ICASSP'98, Seattle, May 12-15, 1998.

5 X.-G. Xia, ISI Mitigation Using Nonmaximally Decimated Multirate Filterbanks as Precoders, Proceedings of The 1998 Symposium on Image, Speech, Signal Processing and Robotics, Sept. 3-4, Hong Kong, 1998.

6 X.-G. Xia, Dynamic range determination of the detectable parameters for polynomial phase signals using multiple lag diversities in high-order ambiguity functions, Proceedings of IEEE-SP Internal. Symposium on Time-Frequency and Time-Scale Analysis, Pittsburgh, PA, Oct. 6-9, 1998.

7 X.-G. Xia and S. Qian, Gabor transforms: some new theory and applications, Proceedings of the 28th Annual Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, California, Nov. 1-4, 1998.

8 X.-G. Xia, P. Fan, and Q. Xie, Modulated codes: A new coding scheme for ISI channels, Proceedings of SPIE, Orlando, April 5-9, 1999.

9 X.-G. Xia, Modulated coded zero-forcing decision feedback equalizer, Proceedings of SPIE, Orlando, April 5-9, 1999.

10 P. Fan and X.-G. Xia, Block coded modulation for the reduction of the peak-to-average power ratio in OFDM systems, Proceedings of SPIE, Orlando, April 5-9, 1999.

11 X.-G. Xia, A New Coded Zero-Forcing Decision Feedback Equalizer Using Modulated Codes, Proceedings of Conference on Information Sciences and Systems, the Johns Hopkins University, March 17-19, 1999.

12 X.-G. Xia, On Discrete Chirp-Fourier Transform, Proceedings of Conference on Information Sciences and Systems, the Johns Hopkins University, March 17-19, 1999.

13 X.-G. Xia and L. Cohen, On analytic signals with nonnegative frequencies, Proc. of ICASSP'99, Phoenix, March 1999.

14 G. Wang, X.-G. Xia, and V. C. Chen, Dual-speed SAR imaging of moving targets, Proceedings of SPIE, Orlando, April 5-9, 1999.

15 X.-G. Xia, P. Fan, and Q. Xie, A new coding scheme for ISI channels: Modulated codes, Proceedings of ICC'99, Vancouver, Canada, June 6-10, 1999.

16 X.-G. Xia, Some filterbank properties for blind equalization, Proceedings of SPIE'99, Denver, July, 1999.

17 X.-G. Xia, Discrete chirp-Fourier transform, Proceedings of SPIE'99, Denver, July, 1999.

18 P. Fan and X.-G. Xia, Block coded modulation for the reduction of the peak-to-average power ratio in OFDM systems, Proc. IEEE Wireless Commun. Networking Conf., New Orleans, Sept., 1999.

19 P. Fan and X.-G. Xia, A noncoherent coded modulation for 16QAM, Proc. IEEE Wireless Commun. Networking Conf., New Orleans, Sept., 1999.

20 X.-G. Xia, Modulated coded zero-forcing decision feedback equalizer, Proceedings of MILCOM1999, Atlantic City, New Jersey, Oct.31-Nov.3. 1999.

21 P. Fan and X.-G. Xia, A noncoherent coded modulation for 16QAM, Proceedings of MILCOM1999, Atlantic City, New Jersey, Oct.31-Nov.3. 1999.

22 G. Wang, X.-G. Xia, and V. C. Chen, Dual-speed SAR imaging of moving targets, Proceedings of IEEE Radar Conference, Boston, April 20-22, 1999.

23 G. Wang, X.-G. Xia, and V. C. Chen, Iterative direction of arrival estimation of wideband chirp signals, Proceedings of SPIE'99, Denver, July, 1999.

24 P. Fan and X.-G. Xia, Block coded modulation for the reduction of the peak-to-average power ratio in OFDM systems, Proc. IEEE Wireless Commun. Networking Conf., New Orleans, Sept., 1999.

25 P. Fan and X.-G. Xia, A noncoherent coded modulation for 16QAM, Proc. IEEE Wireless Commun. Networking Conf., New Orleans, Sept., 1999.

26 X.-G. Xia, Modulated coded zero-forcing decision feedback equalizer, Proceedings of MILCOM1999, Atlantic City, New Jersey, Oct.31-Nov.3. 1999.

27 P. Fan and X.-G. Xia, A noncoherent coded modulation for 16QAM, Proceedings of MILCOM1999, Atlantic City, New Jersey, Oct.31-Nov.3. 1999.

28 Q. Xie and X.-G. Xia, Coded MMSE-DFE using modulated codes, Proceedings of Conference on Information Sciences and Systems, Princeton University, March 15-17, 2000.

F. Collaborators

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G. Post Doctors and Students Supported by the Grant

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H. Appendix: Some Publications