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13. ABSTRACT (Maximum 200 words)
In this project we have investigated differential modulation for broadband wireless communication systems equipped with multiple transmit antennas operating in frequency-selective channels. The objective has been to provide full spatio-spectral diversity and coding gain at affordable decoding complexity and without the burden to estimate the underlying space-time frequency-selective channel. Our main results include the following: (1) We have developed two differential space-time modulation schemes tailored to frequency-selective channels. These schemes offer different trade-offs in dealing with time-selective versus frequency-selective fading channels. When applied along with a full-diversity spectral code, these schemes achieve full spatio-spectral diversity and significant coding gain. (2) We have examined the code design problem for the system under consideration, and obtained optimum code design criteria. (3) For practical spectral encoding, we have developed a class of minimum-length full-diversity codes, referred to as linear constellation decimation (LCD) codes, which offer significant coding gain at modest decoding complexity. (4) We have also developed a differential space-time modulation scheme using amplitude-phase shift keying (APSK) symbols, which are more efficient than conventional PSK-based differential space-time techniques.

14. SUBJECT TERMS
Space-time-frequency coding, differential modulation, frequency-selective fading, linear constellation decimation codes, maximum spatio-spectral diversity, OFDM.

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Differential Space-Time Modulation for Wideband Wireless Networks

FINAL PROGRESS REPORT

Hongbin Li

Statement of the Problem Studied

The primary problem addressed in this project is differential modulation for broadband wireless communication systems equipped with multiple transmit antennas operating in frequency-selective channels. The research goal is to obviate the burden to estimate the space-time-frequency channel, while providing full spatio-spectral diversity gain and coding gain at reasonable decoding complexity. Toward this goal, the following two sub-tasks have been investigated in this project: (1) design of differential space-time modulation techniques that offer full spatial diversity; (2) error probability analysis and design criteria for code construction for such systems; and (3) design of short-length spectral codes that offer full spectral diversity and admit efficient decoding.

Summary of Most Important Results

Our main results pertaining to differential space-time modulation include the following:

- **PSK based differential space-time modulation [J7, J13, J19, C6,]:** We have proposed two different differential space-time modulation schemes that utilize phase-shift keying (PSK) signaling. In both cases, orthogonal space-time block codes are used to encode across space and time, which provide full spatial diversity and efficient decoding, and separate spectral encoding across frequency, which offer full spectral diversity. The major difference is that one scheme [J13] differentially encode across time, by differential encoding across two space-time code matrices, whereas the other scheme [J7] differential encode across frequency. Used along with a full-diversity spectral code, both offer full spatio-spectral diversity. The frequency-domain based scheme has been shown to be more robust to time-selective channel fading, but more sensitive to frequency-selective fading than the time-domain based scheme. Based on extensive simulation, we have concluded that for broadband high-speed systems where the channel typically experiences slow fading, the time-domain based scheme should be preferred; meanwhile, for lower-rate applications when fast fading is prevalent, the frequency-domain based scheme should be preferred.
- **APSK based differential space-time modulation [J2, C13, C17]:** We have proposed a generalized multichannel amplitude-and-phase coded modulation scheme for differential space-time communications. Our scheme utilizes code matrices consisting of an amplitude and a phase component, which can be thought of as a space-time multichannel generalization of the scalar amplitude and phase

shift keying (APSK) constellation. The amplitude component takes a scalar coefficient that controls the total transmission power, while the phase component is a unitary matrix formed from PSK symbols. Both the amplitude and phase components are differentially encoded and admit efficient differential decoding. We have shown that the maximum likelihood (ML) decoding of the amplitude coefficient and phase matrix is decoupled. Moreover, the phase matrix, when constructed from orthogonal designs, is amenable to decoupled differential decoding of the phase entries, which further simplifies the decoding complexity significantly. Simulation results have shown that the proposed amplitude-phase differential space-time coded modulation scheme achieves a performance close to its phase-only counterpart, while providing higher spectral efficiency offered by amplitude modulation.

- **Error probability analysis and design criteria for code construction [J13]:** We have derived the performance criteria for code construction based on pairwise error probability (PEP) analysis. We have shown that for an Lth-order frequency-selective multipath channel with rich scattering, the maximum spatio-temporal diversity order is N_t (L+1) with N_t transmit antennas and 1 receive antenna; if N_r receive antennas are in place, the diversity order can be further increased N_r-fold. Based on our analysis, we have developed design criteria that can used to construct codes with full spatio-spectral diversity and optimum coding gain. The resulting codes, in general, require encoding across all frequency bins, which would result in codes with prohibitive decoding complexity.
- **LCD codes [J13, J19]:** To overcome the decoding difficulty of the optimum codes, we have examined minimum-length full diversity codes. We have shown that such codes are essentially permutation codes. To facilitate the search for good minimum-length full-diversity codes, we have introduced a linear structure in such permutation codes by constellation decimation. The resulting permutation codes are referred to as the linear constellation decimation (LCD) codes, and optimum LCD codes with the largest coding gain have been obtained through computer searches.

In addition to the above results which were primarily funded by this project, we have obtained results in the following areas that are partially supported by this grant: blind channel estimation for CDMA with transmit diversity [J4], code-timing synchronization for short-code [J9, J15, C16] and long-code [J12, J16, C14, C18] DS-CDMA with bandlimited chip waveform, joint code-timing and carrier offset estimation [J10], robust estimation and detection for MC-CDMA [J6, J8, C4, C12], joint channel estimation and interference suppression for single- and multi-carrier systems with block transmission [J3, J11, J20, C2, C10], space-time equalization [J18], and distributed estimation with bandlimted constraint [C1], and distributed differential modulation and performance analysis for cooperative relays [J1, J5, J14, C3, C5, C7, C8, C9, C11,C15].

Listing of Publications and Technical Reports Supported Under This Grant

(a) Papers published in peer-reviewed journals

[J1] Qiang Zhao and Hongbin Li, "Differential modulation for cooperative wireless systems," *IEEE Transactions on Signal Processing*, to appear, 2007.

[J2] Hongbin Li and Tao Li, “Generalized multi-channel amplitude-and-phase coded modulation for differential space-time communications,” *Digital Signal Processing* (Elsevier), to appear, 2007.

[J3] Khaled Amleh, Hongbin Li, and Rensheng Wang, “Blind channel estimation, equalization, and CRB for OFDM with unmodeled interference,” *IEE Proceedings – Communications*, to appear.

[J4] Wei Sun and Hongbin Li, "Blind channel estimation and detection for space-time coded CDMA in ISI channels," *Digital Signal Processing* (Elsevier), to appear.

[J5] Hongbin Li and Qiang Zhao, "Distributed modulation for cooperative wireless communications," *IEEE Signal Processing Magazine*, vol. 23, no. 5, pp. 30-36, September 2006.

[J6] Rensheng Wang and Hongbin Li, "A robust approach to channel estimation and detection for multi-carrier CDMA", *IEEE Communications Letters*, vol. 10, no. 9, pp. 652-654, September 2006.

[J7] Hongbin Li and Tao Li, "A new differential modulation for coded OFDM with multiple transmit antennas," *IEEE Signal Processing Letters*, vol. 13, no. 6, pp. 317-320, June 2006.

[J8] Rensheng Wang, Hongbin Li, and Tao Li, "Robust multiuser detection for multi-carrier CDMA systems,"*IEEE Journal on Selected Areas in Communications*, Special Issues on 4G Wireless Systems, vol. 24, no.3, pp. 673-683, March 2006.

[J9] Hongbin Li, Rensheng Wang, and Khaled Amleh, "Blind code-timing estimation for CDMA systems with bandlimited chip waveforms in multipath fading channels," *IEEE Transactions on Communications*, vol. 54, no.1, pp. 141-149, January 2006.

[J10] Khaled Amleh and Hongbin Li, "Joint estimation of carrier offset and code timing for DS-CDMA with performance analysis," *IEEE Transactions on Wireless Communications*, vol. 4, no. 5, pp. 1980-1987, September 2005.

[J11] Khaled Amleh, Hongbin Li, and Rensheng Wang, "Joint blind channel estimation and interference suppression with efficient implementation for OFDM systems," *Electronics Letters*, vol. 41, no. 16, pp. 45-46, 4th August 2005.

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[J13] Hongbin Li, "Differential space-time modulation over frequency-selective channels," *IEEE Transactions on Signal Processing*, vol. 53, no. 6, pp.2228-2242, June 2005.

[J14] Qiang Zhao and Hongbin Li, "Performance of differential modulation with wireless relays in Rayleigh fading channels," *IEEE Communications Letters*, vol. 9, no. 4, pp. 343-345, April 2005.

[J15] Khaled Amleh, Hongbin Li, and Tao Li, "Blind and training-assisted subspace code-timing estimation for CDMA with bandlimited chip waveforms,"*IEEE Transactions on Vehicular Technology*, vol. 53, no. 6, pp. 1735-1745, November, 2004.

[J16] Rensheng Wang and Hongbin Li, "A deterministic multiuser code-timing estimator for long-code bandlimited CDMA systems,"*IEEE Communications Letters*, vol. 8, no. 8, pp. 535-537, August 2004.

[J17] Rensheng Wang, Hongbin Li, and Tao Li, "Code-timing estimation for CDMA systems with bandlimited chip waveforms," *IEEE Transactions on Wireless Communications*, vol. 3, no. 4, pp. 1338-1349, July 2004.

[J18] Ling Li, Yu-Dong Yao, and Hongbin Li, "Transmit diversity and linear and decision feedback equalizations for frequency selective channels,"*IEEE Transactions on Vehicular Technology*, vol. 52, no. 5, pp. 1217-1231, September, 2003.

[J19] Hongbin Li, "Differential space-time-frequency modulation over frequency-selective fading channels," *IEEE Communications Letters*, vol. 7, no. 8, pp. 349-351, August 2003.

[J20] Hongbin Li, "Blind channel estimation for multicarrier systems with narrowband interference suppression," *IEEE Communications Letters*, vol. 7, no. 7, pp. 326-328, July 2003.

(b) Papers published in non-peer-reviewed journals or in conference proceedings

[C1] Wei Wang and Hongbin Li "Distributed maximum likelihood estimation for bandwidth-constrained wireless sensor networks," in Proceedings of the 12th IEEE Digital Signal Processing Workshop (DSP'06), Grand Teton National Park, WY, September 24-27, 2006.

[C2] Khaled Amleh and Hongbin Li, "Blind channel estimation for single carrier and multicarrier systems," in *Proceedings of the 10th World Multi-Conference on Systemics, Cybernetics and Informatics (WMSCI'06),"* Orlando, USA, on July 16-19, 2006.

[C3] Qiang Zhao and Hongbin Li, "Performance of decode-based differential modulation for wireless relay networks in Nakagami-m channels," in *Proceedings of the 2006 IEEE International Conference on Acoustic, Speech, and Signal Processing (ICASSP'06)*, Toulouse, France, May 14-19, 2006.

[C4] Rensheng Wang and Hongbin Li, "Robust multiuser detection for multi-carrier CDMA," in Proceedings of the 2006 IEEE International Conference on Networking, Sensing and Control, Ft. Lauderdale, FL, April 23-25, 2006.

[C5] Qiang Zhao and Hongbin Li, "Distributed modulation for cooperative wireless communications," in Proceedings of the 40th Annual Conference on Information Sciences and Systems (CISS'06), Princeton University, Princeton, NJ, March 22-24, 2006.

[C6] Hongbin Li, "A new differential modulation for coded OFDM with multiple transmit antennas," in *Proceedings of 39th Asilomar Conference on Signals, Systems, and Computers*, pp. 961-964, Pacific Grove, CA, October 30 - November 2, 2005.

[C7] Nilay Shah and Hongbin Li, "Distribution of quadratic form in Gaussian mixture variables and an application in relay networks," in *Proceedings of the 6th IEEE International Workshop on Signal Processing Advances for Wireless Communications (SPAWC'05)*, New York, NY, June 5-8, 2005.

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[C11] Qiang Zhao and Hongbin Li, "Performance of a differential modulation scheme with wirelessrelays in Rayleigh fading channels," in *Proceedings of 38th Asilomar Conference on Signals, Systems, and Computers*, vol.1, pp.1198-1202, Pacific Grove, CA, November 7-10, 2004.

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[C14] Rensheng Wang and Hongbin Li, "A deterministic multiuser code-timing estimator for long-code bandlimited CDMA systems," in *Proceedings of the 2004 IEEE International Conference on Acoustic, Speech, and Signal Processing (ICASSP'04)*, vol.4, pp.825-828, Montreal, Canada, May 17-21, 2004.

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[C16] Khaled Amleh and Hongbin Li, "Blind and Training-Assisted Subspace Code-Timing Estimation for CDMA with Bandlimited Chip Waveforms," in *Proceedings of the 38th Annual Conference on Information Sciences and Systems (CISS'04)*, Princeton University, Princeton, NJ, March 17-19, 2004.

[C17] Hongbin Li and Qiang Zhao, "Differential space-time modulation with LCD codes and APSK constellation," in *Proceedings of 37th Asilomar Conference on Signals, Systems, and Computers*, vol.1, pp.1012-1016, Pacific Grove, CA, November 9-12, 2003.

[C18] Rensheng Wang and Hongbin Li, " Decorrelating code-timing estimation for CDMA systems with long codes and bandlimited chip waveforms," in *Proceedings of 37th Asilomar Conference on Signals, Systems, and Computers*, vol.1, pp.438-442, Pacific Grove, CA, November 9-12, 2003.

(c) Papers presented at meetings, but not published in conference proceedings

N/A

(d) Manuscripts submitted, but not published

N/A

(e) Technical reports submitted to ARO

N/A

List of All Participating Scientific Personnel Showing Any Advanced Degrees Earned by Them While Employed on the Project

- Ling Li, Ph.D. (2004)
- Rensheng Wang, Ph.D. (2005)
- Joseph Dorleus, Ph.D. (2006)
- Qiang Zhao, Ph.D. (2006)

Report of Inventions (by title only)

No patents filed.