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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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Enclosure 1
DAAD19-03-1-0184
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 subtasks 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 \( L \)-th-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 bandlimited 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


[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.


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


(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)
- Qiang Zhao, Ph.D. (2006)

**Report of Inventions (by title only)**

No patents filed.