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| 13. ABSTRACT (Maximum 200 words)<br><br>Feasibility of <i>adaptive transmission</i> enabled by the <i>Long Range Fading Prediction (LRP)</i> was investigated for rapidly varying fading channels encountered in peer-to-peer mobile communication systems. The LRP algorithms were tested using the standard Jakes model and <i>the realistic physical model</i> developed by the PIs. <i>This research was an interdisciplinary effort in communication theory, physics, and signal processing.</i><br>Correlated fading was exploited in the development of the LRP algorithm to enable adaptive modulation for <i>Frequency Hopping Spread Spectrum (FH/SS)</i> mobile radio channel. Adaptive frequency diversity transmission for FH systems with partial band interference was also explored. <i>Significant performance gains were demonstrated relative to non-adaptive methods.</i><br>Efficient channel loading for wireless <i>Adaptive Orthogonal Frequency Division Multiplexing (AOFDM)</i> systems aided by robust <i>LRP</i> was investigated. <i>Reduced feedback techniques</i> were also developed. The bit rates approaching those of <i>AOFDM with perfect knowledge of fading conditions were achieved.</i><br>Several linear and nonlinear Multi-Access Interference (MAI) mitigation and frequency diversity combining transmitter precoding methods aided by the LRP were developed for the <i>downlink of the Direct Sequence Spread Spectrum (DS/SS)</i> systems. <i>The proposed techniques were shown to improve upon previously proposed precoding and detection methods while providing the desired performance/complexity trade-off.</i> |                                                             |                                                            |                                                                        |                                                                          |
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1. J. Liu and A. Duel-Hallen, "Transmitter-based Joint Nonlinear Multiuser Interference Cancellation and Multipath Diversity Combining for DS/CDMA Systems," submitted to *IEEE Transactions on Communications*.
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3. A. Duel-Hallen, H. Hallen, T. S. Yang, "Long Range Prediction and Reduced Feedback for Mobile Radio Adaptive OFDM Systems," *IEEE Transactions on Wireless Communications*, under second revision.
4. H. Hallen, S. Hu, A. Duel-Hallen, "Physical Model for Understanding and Testing Long Range Prediction of Multipath Fading in Wireless Communications," *IEEE Transactions on Vehicular Technology*, under second review.
5. S. Guncavdi, A. Duel-Hallen, "Performance Analysis of Space-Time Transmitter Diversity Techniques for W-CDMA Using Long Range Prediction," *IEEE Transactions on Wireless Communications*, Vol. 4, No. 1, Jan. 2005, pp. 40-45.
6. T. S. Yang, A. Duel-Hallen, H. Hallen, "Reliable Adaptive Modulation Aided by Observations of Another Fading Channel," *IEEE Transactions on Communications*, Vol. 52, No. 4, Apr. 2004, pp. 605-611.
7. A. El-Ezabi, A. Duel-Hallen, "Improved Viterbi Decoder Metrics for Two-Stage Detectors in DS-CDMA," *IEEE Transactions on Wireless Communications*, Vol. 3, No. 5, Sept. 2004, pp. 1399-1404.
8. ARO interim reports filed annually.
9. A. Duel-Hallen, "Fading Channels," *the Wiley Encyclopedia of Telecommunications*, John Wiley&Sons, Inc., J. G. Proakis, editor, 2003, pp. 781-789 (invited paper).
10. J. Liu and A. Duel-Hallen, "Performance Analysis of Tomlinson-Harashima Multiuser Precoding in Multipath CDMA Channels," Proc. *4GMF'05*, July 07-08, 2005.
11. L. Ming, A. Duel-Hallen, H. Hallen, "Enabling Adaptive Modulation and Interference Mitigation for Slow Frequency Hoppin Communications," Proc. *SPAWC'05*, June 5-8, 2005.
12. J. Liu and A. Duel-Hallen, "Nonlinear Multiuser Precoding for Downlink DS-CDMA Systems over Multipath Fading Channels," Proc. *GLOBECOM'04*, Nov. 29-Dec. 3, 2004.
13. T. S. Yang, A. Duel-Hallen, H. Hallen, "Enabling Adaptive OFDM for Mobile Radio Channels," Proc. *MILCOM'04*, Oct. 31-Nov. 3, 2004.

14. T. S. Yang, A. Duel-Hallen, H. Hallen, "Validation of Adaptive Transmission for Realistic Single- and Multi-Carrier Mobile Radio Channels," Proceedings of *URSI'04, Special Session on Propagation Effects in Wireless Communications Channels*, Boulder, CO, Jan. 2004, p. 75 (invited).
15. S. Guncavdi and A. Duel-Hallen, "Space-Time Pre-RAKE Multiuser Transmitter Precoding for DS/CDMA System," Proceedings of *VTC'03, MUD and Signal Proc. Issues Session*, pp. 1-5, Orlando, FL, Oct. 03 (invited).
16. L. Ming and A. Duel-Hallen, "Long Range Channel Prediction and Adaptive Transmission for Frequency Hopping Communications," Proceedings of *41<sup>st</sup> Annual Allerton Conference on Communication, Control and Computing, Session V.C*, pp. 1-10, Monticello, Illinois, Oct. 03.
17. T.-S. Yang, A. Duel-Hallen and H. Hallen, "Long Range Fading Prediction to Enable Adaptive Transmission at Another Carrier," Proceedings of *SPAWC'03*, Paper #522, pp. 1-5, Rome, Italy, June 2003.
18. J. Liu and A. Duel-Hallen, "Tomlinson – Harashima Transmitter Precoding for Synchronous Multiuser Communications," Proceedings of *37<sup>th</sup> Annual Conference on Information Sciences and Systems, CISS'03*, Paper # 60, pp. 1-6, Baltimore, MD, March 2003.
19. S. Guncavdi and A. Duel-Hallen, "Pre-RAKE Multiuser Transmitter Precoding for DS/CDMA Systems," Proceedings of *37<sup>th</sup> Annual Conference on Information Sciences and Systems, CISS'03*, Paper #169, pp. 1-6, Baltimore, MD, March 2003.
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21. T.-S. Yang, A. Duel-Hallen and H. Hallen, "Reliable Adaptive Modulation Using Long-Range Prediction at a Different Carrier Frequency," Proceedings of *ISIT'02*, Lausanne, Switzerland, June 30 – July 5, 2002, p.359.
22. S. Hu, A. Duel-Hallen and H. Hallen, "Adaptive Modulation for Transmitter Antenna Diversity Mobile Radio Systems," Proceedings of *ISIT'02*, Lausanne, Switzerland, June 30 – July 5, 2002, p.105.
23. T. S. Yang, A. Duel-Hallen, "Adaptive Modulation Using Outdated Samples of Another Fading Channel," Proceedings of *WCNC'02*, Orlando, FL, March 17-21, 2002, vol. 1, pp. 477-481.
24. S. Hu, A. Duel-Hallen, "Combined Adaptive Modulation and Transmitter Diversity Using Long Range Prediction for Flat Fading Mobile Radio Channels," Proceedings of *Globecom'01*, San Antonio, Texas, Nov. 25-29, vol. 1, pp. 1256-1261.

#### **Scientific personnel in addition to PIs:**

Research assistants partially supported by the grant: M. Lei (PhD, Dec. 2004), L. Ma, T. S. Yang (PhD, Dec. 2004), J. Liu (PhD expected Aug. 2005).

Others: Dr. S.Hu, Dr. A. El-Ezabi, Dr. S. Guncavdi.

#### **Scientific progress and accomplishments:**

Research has focused on *realistic channel modeling, long range channel prediction, adaptive transmission and interference mitigation for fading OFDM, FH and DS spread spectrum channels*.

- Due to correlated fading in FH spread spectrum wireless communication systems, it is possible to *predict the future channel state information (CSI) for one frequency based on the channel observations of other frequencies*. As a result, *the performance of FH systems can be improved by utilizing adaptive*

*transmission techniques*. In [16], we proposed the optimal Minimum Mean Square Error (MMSE) long-range channel prediction method for slow FH systems that employ coherent detection. A low complexity recursive filter update method was developed for this prediction technique. Statistical model of the prediction accuracy was used in the design of the reliable adaptive transmission systems. We then investigated the performance of adaptive transmission for high-speed data transmission in SFH systems based on the proposed long-range channel prediction algorithm in [2, 11, 16]. In addition, for communications in the presence of *partial-band interference*, we have investigated adaptive frequency diversity transmission combined with adaptive modulation [2,11]. Standard Jakes model and a *realistic physical model* [4, 14, 20] were used to validate our algorithms. Analysis and simulation results show that *significant performance gains can be achieved relative to non-adaptive methods*.

- In [3, 13], *adaptive orthogonal frequency division multiplexing (AOFD)* was investigated. AOFDM is a promising technique for achieving high data rates required for wireless multimedia services. To accomplish efficient adaptive channel loading, the channel state information (CSI) needs to be fed back to the transmitter. Since the fading channel varies rapidly for fast vehicle speeds, *long range fading prediction (LRP)* is required for mobile radio AOFDM to insure reliable adaptation. We used past channel observations to predict future CSI and perform adaptive bit and power allocation for the OFDM system. We have first derived the minimum mean-square-error (MMSE) long-range channel prediction that utilized the time and frequency domain correlation functions of the Rayleigh fading channel. Since the channel statistics are usually unknown, *robust adaptive prediction methods* that do not require the knowledge of the correlation functions were also developed. Statistical model of the prediction error was created and used in the design of reliable adaptive modulation. In addition, several methods that significantly *reduce the feedback load* for mobile radio AOFDM systems were developed and compared. We used a sum-of-sinusoids (modified Jakes) model *and our novel physical model* [4, 14, 20] to test our algorithm. Feasibility of AOFDM for rapidly varying mobile radio channels was demonstrated, with *bit rates approaching those for channels with the ideal knowledge of the CSI*.
- Research on *adaptive modulation aided by observations of another carrier* for realistic fading conditions was carried out in [6, 21, 23]. *Significant gains relative to non-adaptive techniques were demonstrated for sufficiently correlated channels and realistic prediction ranges*. Results of this research are applicable to correlated uplink and downlink channels as in Frequency Division Duplex (FDD). This work also provided the foundation for our research on adaptive FH and OFDM signaling.
- Feasibility of several *transmitter diversity techniques and precoding methods for Wideband CDMA (W-CDMA)* systems was investigated in [5]. It is demonstrated that the proposed Space-Time Pre-RAKE (STPR) technique is the optimal method to combine antenna diversity and temporal precoding. This method achieves the gain of maximum ratio combining of all space and frequency diversity branches when perfect channel state information (CSI) is available at the transmitter. We employ the long range fading prediction algorithm to enable transmitter diversity techniques for rapidly time varying multipath fading channels. In addition, *a combined adaptive modulation and selective transmitter diversity system made feasible by the LRP* was investigated in [24].
- *A linear transmitter-based precoding* method that combines Multiuser Interference (MAI) cancellation with frequency and transmitter antenna diversity was investigated for the *downlink of the Direct Sequence Code Division Multiple Access (DS/CDMA) channel* in [15,19]. Since diversity combining and MAI cancellation are employed in the transmitter, the mobile user receivers remain as simple as in single-path single user channels. It was demonstrated that this method has *better performance than single user* space-time methods [5] and maintains *lower complexity* while providing comparable performance relative to other linear MAI-mitigation techniques suitable for the downlink. *Long range prediction* is employed to enable performance of transmitter precoding for rapidly time varying fading CDMA channels.

- ***A transmitter-based nonlinear decorrelating interference cancellation*** method, Tomlinson-Harashima precoding (THP), to combat MAI for the downlink of DS/CDMA systems in multipath fading channels was explored in [1,10,12,18]. Two THP designs, PreRakeTHP and Multipath Decorrelating THP (MDTHP), were derived and compared with previously investigated decorrelating techniques. It was shown that the ***proposed methods improve upon linear precoding and detection techniques and on the decision-feedback detectors for multipath DS/CDMA channels, while retaining low complexity.*** Moreover, the MDTHP precoder is attractive for rapidly varying mobile radio channels since its filters do not need to be updated as fading coefficients vary. It was shown that ***accurate LRP is required*** to maintain reliable performance for these closed-loop methods in mobile radio channels. Finally, an ***improved metric calculation method for combined two-stage multiuser detection and decoding in DS/CDMA*** systems was developed in [7]. (A U.S. patent was also filed for this invention.)