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Communications Group

Overview of the Research Activity in Digital Transmission Systems

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Current Research Projects

The research activity of the Communications Group in the area of Digital Transmission Systems spans a wide range of subjects. It has been historically focused on detection theory, but it has also expanded towards coding theory and wireless networks analysis. The principal research projects can be summarized as follows.

- Third and fourth generation wireless networks (EDGE, UMTS, 4G)
- Iterative detection and decoding techniques
- Ad-hoc wireless networks
- Detection techniques for CDMA systems (multiuser detection, interference mitigation, iterative detection)
- Multiple-antenna transmission systems and space-time codes
- Multi-carrier (OFDM) transmission techniques (equalization in the frequency domain, synchronization)
- Detection techniques for magnetic and optical storage systems
- Adaptive demodulation and decoding techniques for channels with unknown parameters (phase and frequency uncertainty, fading, Doppler shift, nonlinearities)
- High-speed transmission techniques for twisted pairs (xDSL)
- Graph-based detection

General Overview of Research Results

The research activity of the Communications Group in the area of Digital Transmission Systems produced extensive work regarding adaptive detection for linear and nonlinear modulations. In the following, a brief overview of the main research results is presented. Each area of interest is shortly described and the main publications are cited.

1 Iterative Detection

It is possible to prove that most of the adaptive maximum likelihood sequence detection strategies can be extended to iterative detection schemes. In particular, in

G. Colavolpe, G. Ferrari and R. Raheli, "Noncoherent Iterative (Turbo) Decoding," *IEEE Trans. Commun.*, vol. 48, pp. 1488-1498, September 2000

a class of soft-output algorithms for linear modulations transmitted through phase-uncertain channels is proposed. This work is extended to the case of spectrally efficient coded modulations in

G. Ferrari, G. Colavolpe and R. Raheli, "Noncoherent iterative decoding of spectrally efficient coded modulations," *Annales des Telecommunications*, vol. 4, pp. 409-421, July-August 2001 (invited paper).

The above paper was also selected in the form of book chapter (no. 4) in

"Turbo Codes: Error Correcting Codes of Widening Applications," Edited by M. Jézéquel and R. Pyndiah, *Hermes Penton Science*, London, 2002.

A general analysis of the important role of the extrinsic information in the iterative detection process is carried out in

G. Colavolpe, G. Ferrari and R. Raheli, "Extrinsic information in iterative decoding: a unified view," *IEEE Trans. Commun.*, vol. 49, pp. 2088-2094, December 2001.

In this paper it is shown that using suboptimal soft-output algorithms, significant gains are possible by properly scaling (through a multiplicative constant) the generated soft-output information.

2 Complexity Reduction in Detection Algorithms

The complexity of a detection algorithm is fundamental for its practical implementation. This aspect has been a major concern in the research activity pertaining the receiver design. A seminal paper, where the concept of "per-survivor processing" (PSP) for sequence detection in uncertain environments was first clearly formalized, is

R. Raheli, A. Polydoros and C. K. Tzou, "Per-survivor processing: a general approach to MLSE in uncertain environments," *IEEE Trans. Commun.*, vol. 43, Part I, pp. 354-364, Feb.-Apr. 1995.

The PSP concept can be also interpreted as a generalization of reduced-state sequence detection techniques for adaptive processing.

A simple approach to perform reduced-complexity phase synchronization and data detection, based on a Viterbi algorithm (VA), of continuous phase modulation (CPM) signals is proposed in

G. Colavolpe and R. Raheli, "Reduced-complexity detection and phase synchronization of CPM signals," *IEEE Trans. Commun.*, vol. 45, pp. 1070-1079, September 1997.

This work effectively exploits the powerful Laurent decomposition of CPM signals.

A general approach to perform state reduction for trellis-based forward-backward algorithms is proposed in

G. Colavolpe, G. Ferrari and R. Raheli, "Reduced-state BCJR-type algorithms," *IEEE J. on Selected Areas Commun.*, vol. 19, pp. 848-859, May 2001.

An extension to the case of graph-based detection is presented in

P. Thiennvibon, G. Ferrari and K. M. Chugg, "An overstructured graph for reduced-state forward-backward algorithms," in *Proc. IEEE Intern. Symp. Inform. Theory*, (ISIT'02), Lausanne, Switzerland, July 2002, p. 367.

3 Sequence Detection for Channels with Phase and Frequency Uncertainty

This research activity led to the design of trellis-based detection schemes for transmission through channels affected by phase and frequency instabilities. In particular, a class of VA-based detection algorithms for linear modulations is proposed in

G. Colavolpe and R. Raheli, "Noncoherent sequence detection," *IEEE Trans. Commun.*, vol. 47, pp. 1376-1385, September 1999.

This work is extended to the case of CPM signals in

G. Colavolpe and R. Raheli, "Noncoherent sequence detection of continuous phase modulations," *IEEE Trans. Commun.*, vol. 47, pp. 1303-1307, September 1999.

In all cases, the branch metrics are defined in terms of a short window of signal observations, based on the assumption of truncating the overall channel memory. The resulting receivers are totally invariant to the channel phase rotation. Due to these properties, the proposed schemes feature a very high robustness to phase instabilities and a gracefully improving performance for increasing complexity and a sufficiently stable channel phase. This work is further expanded in

G. Colavolpe and R. Raheli, "Detection of linear modulations in the presence of strong phase and frequency instabilities," *IEEE Trans. Commun.*, vol. 50, pp. 1617-1626, October 2002 obtaining robust detection schemes capable of tolerating uncompensated frequency offsets up to about 10% of the signaling frequency.

A theoretical performance analysis of noncoherent sequence detection schemes for the special case of phase shift keying (PSK) is presented in

> G. Colavolpe and R. Raheli, "Theoretical analysis and performance limits of noncoherent sequence detection of coded PSK," *IEEE Trans. Inform. Theory*, vol. 46, pp. 1483-1494, July 2000.

It is theoretically shown that for increasing truncation length, i.e., for increasing length of the window of observation samples, the performance of a general coded system employing this class of noncoherent detection schemes approaches that of coherent detectors with ideal phase reference. This result is substantiated, from an information theoretical point of view, in

> G. Colavolpe and R. Raheli, "The capacity of the noncoherent channel," *European Transactions on Telecommunications*, vol. 12, n. 4, pp. 289-296, July-August 2001

where it is shown that the capacity of a channel affected by a time-invariant phase rotation rapidly converges to that of an additive white Gaussian noise (AWGN) channel for a sufficiently long transmission length.

4 Sequence Detection for Fading Channels

The problem of optimal sequence detection of linear modulations transmitted through a fading channel is considered in

> P. Castoldi and R. Raheli, "On recursive optimal detection of linear modulations in the presence of random fading," *European Trans. Telecommun.*, vol. 9, No. 2, pp. 209-220, March-April 1998

where it is shown that increasing the complexity in a VA-based detection algorithms allows to reduce the receiver front-end complexity without incurring in any loss of optimality.

An extension of the noncoherent sequence detection schemes considered for a phase-uncertain channel, mentioned in Section 3, to the case of slowly varying frequency non-selective fading channels is presented in

> G. Colavolpe and R. Raheli, "Noncoherent sequence detection in frequency nonselective slowly fading channels," *IEEE J. on Selected Areas Commun.-Wireless Series*, vol. 18, pp. 2302-2311, November 2000.

In particular, the proposed branch metrics are very effective for any type of slow fading channels, with Rice factors over the entire range (from Rayleigh to AWGN channels). No knowledge of channel statistics is required. The schemes cover the general case of coded linear modulations, including multi-level quadrature amplitude modulations (QAM).

5 Spread Spectrum Systems

The detection algorithms developed for narrowband transmission systems can be extended to the case of spread spectrum communications systems. In particular, a possible approach to perform robust noncoherent detection of direct-sequence spread spectrum signals is proposed in

> G. Colavolpe and R. Raheli, "Improved differential detection of chip-level differentially encoded direct-sequence spread-spectrum signals," *IEEE Trans. Wireless Commun.*, vol. 1, pp. 125-133, January 2002.

6 Sequence Detection for Nonlinear Channels

Satellite communications are characterized by the use of nonlinear amplifiers (for example, traveling wave tube amplifiers), which introduce significant distortions in the transmitted signal. Nonlinear effects also occur in magnetic and optical storage systems. At the receiver side care has to be taken to recover this distortion. In particular, it is possible to show that near-optimal VA-based detection is appreciably more efficient than other ad-hoc less effective solutions, such as analog pre-distortion, preserving the receiver complexity to an affordable level. Details can be found in

> A. Vannucci and R. Raheli, "Sequence detection in nonlinear channels: a convenient alternative to analog pre-distortion," *IEEE Trans. Commun.*, vol. 50, pp. 1515-1524, September 2002.

Industrial Patents

The research activity of the Communications Group in the area of Digital Transmission Systems has lead to a few industrial patents, including the following:

- R. Raheli and G. Colavolpe, "Noncoherent sequence estimation receiver for digital modulations," assigned to Siemens ICN, Milan, Italy, United States Patent Application n. 09/437,668, November 1999, Publication n. 20010017898, August 2001, United States Patent n. 6,389,079 B2, May 2002.

- R. Raheli and G. Colavolpe, "Noncoherent sequence estimation receiver for digital modulations," assigned to Siemens ICN, Milan, Italy, International Patent Application n. PCT/EP98/03486, June 1998, International Publication n. WO 98/56119, December 1998.

- G. Colavolpe and R. Raheli, "Ricevitore non coerente a stima di sequenza per modulazioni numeriche lineari," assigned to Siemens ICN, Milan, Italy, Italian Patent n. MI97A 001301, June 1997.

- R. Raheli and A. Vannucci, "Ricevitore a stima di sequenza a massima verosimiglianza per la ricezione di dati seriali trasmessi su canali di comunicazione comprendenti una non linearità polinomiale," assigned to Siemens ICN, Milan, Italy, Italian Patent n. MI97A 001299, June 1997.

- R. Raheli and A. Vannucci, "Ricevitore a stima di sequenza a massima verosimiglianza in configurazione sub-ottima per la ricezione di dati seriali trasmessi su canali di comunicazione comprendenti una non linearità polinomiale," assigned to Siemens ICN, Milan, Italy, Italian Patent n. MI97A 001298, June 1997.

- A. Polydoros and R. Raheli, "System and method for estimating data sequences in digital transmission," assigned to the University of Southern California, Los Angeles, U.S.A., licensed to ViaSat Inc., CA, U.S.A., United States Patent n. 5,432,821, July 1995.