Key Issues in Radio Interface Design

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INTRODUCTION

This project aims at investigating key issues in radio interface design for practical frequency-selective fading channels. It is focused on the new opportunities and challenges that arise when considering broadband radio systems, with an emphasis on packet data transmission.

The purpose of such a radio interface is to carry packets to or from wireless users. The destination of packets may be one single user but especially in the downlink it may also be several users (broadcasting). The most important aspects related to the radio interface are

- high spectrum efficiency (as high number of bps/Hz as possible),
- high power efficiency (low transmitter power is important at least in wireless terminals),
- low delay (some packets are likely to have a maximum transmission delay of 10 ms),
- low complexity of algorithms (again, especially in wireless terminals) and
- adaptivity, for different requirements and channel conditions.

Some of the particular issues we investigate are:

- Efficient codes for data transmission (Turbo codes),
- new ways of optimizing the downlink transmission in CDMA systems,
- synchronization at low SNR's,
- channel modelling for improved antenna array receivers,
- multiuser detectors for CDMA and array receivers and
- adaptive methods for modulation, coding and protocols in packet radio systems.

Our aim is to master these key issues, and thereby provide input to a discussion of possible future system designs which we expect to emerge within PCC in the coming years. Our input takes the form of both possibilities and constraints. Possibilities, in the form of novel transmission schemes, receiver algorithms and novel ways of modelling and understanding the radio interface. Constraints, in the form of limits of performance in various situations.

There are presently seven workpackages (WP's) within this project. Their purpose, motivation and present status are outlined briefly below. The project has been running since 1997, with Uppsala University joining in 1998. Thus, much of the work is still at a preliminary stage, and the results presented at this conference describe our pilot studies and initial research results. Details can be found in the subsequent papers presenting the individual WP's.

To coordinate the project as a whole, we held a kickoff meeting in November 1997 and organized a workshop on April 7-8 1998. This workshop was organized jointly with participants in the NUTEK Telecommunications program. Several main advisors and researchers have been active in helping and supporting the work of all the graduate students, in a process of cross-reviewing the work packages. A joint graduate course on Digital Communications was held by Arne Svensson (CTH), Göran Lindell (LTH) and Tommy Öberg (UU).

THE WORKPACKAGES

WP1: Low-rate Turbo Codes

Carl-Fredrik Leanderson, Ove Edfors and Torleiv Maseng

Industrial cooperation: FFI, Norway, and Ericsson Radio Systems, Kista.

Turbo coding is known to be the latest and most powerful error correcting coding technique at least for AWGN channels (non-fading channels with additive white Gaussian noise). The error correcting performance of turbo codes approach the Shannon limit. Since this field is new (the original publication [1] appeared in 1993), practical compromises and improvements are continuously being published. The main objective here is to design turbo codes suitable for wireless radio channels and to develop implementable decoding algorithms. Practical turbo coding would constitute an important tool for reducing transmitted power in a personal communication system.

This workpackage focuses on different low-rate turbo coding schemes for very noisy channels. The characteristics of these codes in spread spectrum- and packet radio systems is investigated, adressing in particular power limited satellite communication links and interference-limited systems, such as direct sequence code-division multiple access (DS-CDMA).

The work within the WP has during 1998 been focused on the performance of low rate turbo codes on AWGN channels. The main question is how to attain the best performance improvement for a given bandwidth expansion. At present, our work is focused on puncturing strategies to achieve rate-compatible turbo codes, rate compatability being a desirable property in CDMA systems. (Please refer to our Workshop paper on this topic for more details.) We also investigate ARQ systems with partial retransmission.

While turbo encoding is simple, turbo decoding is a time-consuming iterative process [2]. The development of decoders which provide a good compromise between performance, computational complexity and time delay is a crucial issue for the application on real systems, in particular DS-CDMA systems where the decoder may have to work at the chip rate. Another important issue is the sensitivity of the decoding procedure to timing and phase synchronization errors in the receiver. This issue is investigated in WP3, and preliminary results are presented at this conference. Finally, the possibility to utilize these codes in systems using adaptive coding, to be studied in WP7, should be investigated.

WP2: Communication over Multiple Band-limited Rayleigh Fading Continuous-time Channels

Anders Hansson and Tor Aulin

Industrial cooperation: Ericsson Mobile Data Design AB, Göteborg.

Within this work package, we study communication through a continuous-time fading channel when the receiver has multiple antenna elements. The aim is to develop detectors which perform very efficient space-time processing in rapidly time-varying environments.

The work [3] of Dr. Ulf Hansson constitutes a starting point for the investigation. It deals with the design and analysis of coding and detection strategies for transmission to a single antenna via a Rayleigh fading rapidly time-varying continuous-time channel. We are now generalizing this approach to multiple antennas. As a preliminary step, we study the optimal detection of a single symbol, which forms a basis for subsequent studies. For more details, please see the corresponding paper this conference.

WP3: Synchronization Techniques

Bartosz Mielczarek and Arne Svensson

Industrial cooperation: Ericsson Radio Systems, Kista, Ericsson Microwave Systems, Mölndal, Ericsson Mobile Communications, Lund.

Future systems will be required to work well at very low signal to noise ratios (SNRs). The overall design of such systems is usually focused on providing good algorithms for channel coding, modulation and decoding, under the assuption of perfect channel knowledge and synchronization of signal phase and symbol timing.

In reality, however, imperfect channel estimation and synchronization can lead to severe deterioration of the performance of a system. Existing algorithms solve the synchronization problem for relatively large SNRs but their performance for bad conditions is usually unacceptable, due to very long acquisition times and large errors.

It is not clear how synchronization should be performed in practice on radio channels with low SNR's. It may be necessary to transmit known information in the form of pilot symbols or pilot CDMA channels. The objective of this work package is to develop robust synchronization techniques capable of operating at low SNRs and evaluate their impact on the overall performance of systems and on the complexity of implementations.

During 1998, the investigation has focused on joint timing synchronization and decoding of turbo codes [4]. Turbo decoding, also studied in WP1, is sensitive to synchronization errors. An algorithm for timing synchronization has been presented and its performance has been compared to that of the more complex maximum likelihood syncronization, and to the Cramer-Rao bound, which is the theoretical bound on the synchronization accuracy. It turns out that synchronization can be achieved by using soft bit outputs of the turbo decoder, without the need for using a complex separate synchronizer prior to feeding the signal to the turbo decoder. For additional details, please see the presentation at the present conference.

In the coming years, this WP will interact with WP5 on synchronization for CDMA receivers and with WP6 on multi-user detectors, many of which require good synchronization.

WP4: Adaptive Strategies for High Efficiency Transmission in CDMA Systems

Ola Wintzell and Kamil Sh. Zigangirov

Industrial cooperation: Ericsson Radio Systems, Kista, Ericsson Mobile Communications, Lund, Ericsson RTP, Raleigh, USA.

The purpose of this WP is to investigate novel ways to increase the capacity in CDMA systems, mainly in the downlink. In modern CDMA systems, the uplink and downlink transmissions are organized according to the same scenario. This is in spite of the fact that the downlink transmission, which is a one-to-many transmission, has some advantages in comparison to the uplink transmission, which is many-to-one transmission. Since the transmitter in the base station knows the transmitted information of all users, it can use this information in the encoding process and improve significantly the performance of the overall system.

As a first approach, we have within this WP developed a way of frequently pre-adjusting the powers of the transmissions to different users in the downlink. This improves the performance when using non-orthogonal spreading sequences [5], [6] by limiting the mutual interference between the downlink transmissions. The use of non-orhtogonal spreading sequences can increase the total system capacity[1].

This type of approach opens up a new dimension in which we may optimize our CDMA systems: The transmitter (base station) estimates the mutual interference of the individual signals, and adjusts the transmitted signal in order to yield minimum average error probability. This adjustment is performed by a special block in the transmitter in the base station, called *coordinator* (this procedure is also called *precoding*). The coordinator coordinates the encoded and spreaded information sequences of the individual users before modulation. Our initial investigations indicate that using coordination, the number of users can be increased by up to three times, both for the AWGN channel and the Rayleigh fading channel [5], [6].

Up until now, we have used conventional convolutional coding and pseudo-random spreading. In our coming research (starting from the year 2000), we intend to study the performance of a coordinated downlink CDMA system and its dependence on the choice of coding and spreading. In particular we intend to use orthogonal convolutional codes, low-density parity-check convolutional codes and Gold spreading sequences. We expect that the use of these codes and spreading methods can increase the radio channel capacity. We are also planning to study the performance for more realistic channel models, like frequency selective fading channels.

As synchronization is an important task in the communication process, we intend, in the coming years, to interact with WP3 on synchronization for downlink CDMA. Another possible extension is to work with WP5 on space-time coding, which is possible when more than one antenna is used.

[1] In voice or packet data systems, each user is active for only a small fraction of the total time. If we can minimize their mutual interference, a large number of users could utilize the same channel. However, if the system is designed to require orthogonality of the received signals, the number of simultaneous users will be limited by the number of orthogonal spreading sequences which can co-exist.

WP5: Adaptive Antennas and Channel Modelling

Thomas Svantesson and Mats Viberg

Industrial cooperation: Ericsson Radio Systems, Kista, Ericsson Microwave Systems, Mölndal, Telia Research, Lund.

This work package studies the use of adaptive antennas in communication. The adaptive antenna, which is considered to be an array of elements, is studied jointly with the channel.

Unlike most existing "practical models", we start the analysis of the antenna and the channel from the fundamental electromagnetic principles that govern the propagation of radio wawes. With the resulting insight into the electromagnetic properties, the existing signal processing models are analyzed, with the aim of finding new and more adequate models.

For example, the multipath propagation is an important phenomenon in mobile communications. The energy is received from several paths via reflections from buildings and other objects. Existing signal processing methods are based on purely "optical models" of the reflections. However, not all objects can be considered to be large (the optical region) for a given bandwidth and wavelength. Hence, it is interesting to study effects described by the Rayleigh and resonance (Mie) regions on the the channel properties. This is one example of an interesting connection to the field of electromagnetics.

Another closely related topic is the wider concept of electromagnetic scattering, which is analyzed using integral equations and the moment method. Finally, it is interesting to investigate the relation of the optical models used in signal processing applications to the geometrical theory of diffraction and physical optics.

To initiate the work within this WP, an array of dipole elements is studied. A derivation of the properties of this array, starting from the basic electromagnetic principles, has been carried out. The radiation properties of the array were studied and the conventional data model, mainly used in array processing, was derived. However, it was found that this model could easily be extended to include the effects of mutual coupling between the array elements [7, 8, 9]. This extended model was analyzed and the possibilities of estimating the mutual coupling will be investigated.

WP6: Multi-User Detection

Anders Ahlén and Mikael Sternad (grad. student: vacant)

Industrial cooperation: Ericsson Radio Systems, Kista.

The performance of a high capacity digital radio system depends critically on its ability to handle co-channel interference. The dominating technique for interference rejection is to regard the interference as noise, and to design single user detectors which reject this noise.

As an alternative, we could model the strongest disturbances as digital signals, propagating through transmission channels. If these signals and channels can be estimated by the receiver, then the interference rejection problem becomes a multiuser detection problem.

Due to several theoretical reasons which are supported by experimental results, multi-user detection provides superior performance in many situations [10]. The price to be paid is an increased computational complexity. Multiuser detectors can be utilized in CDMA receivers as well as in TDMA receivers with multiple antenna elements. The aim of the work package is to investigate and develop practical and efficient multi-user detectors for packet radio systems, in TDMA as well as CDMA systems.

As in the other WP's, the algorithmic complexity is again a crucial issue; Multi-user detectors are inherently more complex than single-user detectors. Synchronization of the receiver is also an important aspect. Another key aspect to investigate is the synergy between the use of multi-user detection and the use of adaptive methods for modulation, coding and protocols, investigated in WP7 described below. Downlink performance and the use of antenna diversity in mobile terminals will also be studied.

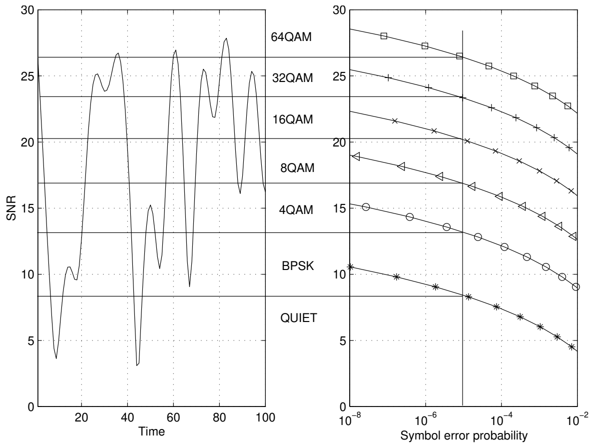

Figure 1: SNR profile and modulation level related to the error probability. For a predicted value of the signal to noise ratio (SNR) of the channel, the modulation level is maximized under the constraint of a certain probability P_M of symbol error, for example, $P_M \leq 10^{-5}$. If no modulation level attains the required probability of symbol error, then transmission is deferred until later when the SNR is higher, thus avoiding retransmissions.

WP7: Adaptive Methods for Modulation, Coding and Protocols in Packet Radio

Nilo Ericsson, Anders Ahlén and Mikael Sternad

Industrial cooperation: Ericsson Radio Systems, Kista.

Adaptivity has for a long time been used in detectors for mobile radio systems to alleviate the effect of fading. In some systems, such as IS-136, adaptivity is crucial: Without tracking of the rapidly time varying channel, the detector would fail completely and the bit error rate would reach unacceptable levels. Unfortunately, adaptivity is not yet used on higher system levels. At present, neither the modulation nor the coding has been designed to take advantage of the current channel condition. They are designed for a typical signal to interference-and-noise ratio and to be on the safe side, the design might even reflect a worst case thinking.

By introducing adaptation also for the modulation and coding schemes, the effective bit rate can be increased substantially. For a scenario where data traffic dominates also on the mobile network, the channel must be used efficiently to maximize throughput at an acceptable rate of requests for retransmission.

The aim of this work package is to investigate and develop efficient strategies for adaptation of modulation and coding schemes. Although all systems are of interest, a primary goal is to investigate the benefits of adaptive techniques in packet switched TDD systems. The design of adjustable protocols should also be considered, since joint optimization, taking several hierarchical levels within the communications system into account, holds large promises. While adaptive modulation has been studied previously [11], this is still a novel and very exciting field.

In our initial study, we have investigated adaptive modulation for fading channels, in TDD as well as FDD systems [12]. See Figure 1, where the left hand part illustrates the SNR-variation of a typical channel, while the right hand part illustrates how the level of modulation can be selected for a pre-specified symbol error probability. For further details, see the corresponding paper at this PCC workshop. In a parallel study outside of PCC, we are also investigating and developing high-performance nonlinear predictors for signal-to-noise ratios and channel coefficients. Such predictors, with high accuracy, are crucial building blocks in adaptive schemes, since required changes in modulation, coding, spreading and protocol properties cannot be implemented instantaneously. The required latencies increase as we try to adapt properties higher up in the system hiearchy.

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