The Wireless IP Project

Mikael Sternad[1]

[1]Signals and Systems, Uppsala University, PO Box 528,SE-751 20 Uppsala, Sweden.

Abstract

The optimization of resources in wireless packet data systems is challenging when users are mobile with time-varying link quality. Within the SSF PCC program, we have since year 2000 formed the Wireless IP project, which studies such issues. We perform research towards a flexible packet data system with wide area coverage for mobile users. This system should have performance equivalent to a 100Mbit/s Ethernet connection, with support for Quality of Service and fairness between wireless users.

This will require an optimization that involves many levels in the OSI stack. In the project, we develop and integrate a set of key technologies, consisting of prediction of radio channels, fast link adaptation, scheduling of several packet data streams over time-varying channels, fast resource allocation using antenna arrays and the use of information from lower layers in higher layers, in particular the transport layer. With these methods, the transmission of packet data to/from mobile users can be radically improved, without expensive use of additional spectral bandwidth.

1 Introduction

Wireless systems are evolving rapidly and most traffic to mobile terminals will be IP-based end-to-end in a not too distant future. This gives rise to many performance trade-offs and design issues, and we need to reexamine our approach to the design of wireless systems.

Wideband wireless links are used today to transport packet data to stationary users. A main challenge is to improve the economy, spectral efficiency and bitrates provided in wide-area coverage for mobile (vehicular) users. Potential markets exists, as indicated e.g. by the increased interest in "telematics" and "infotainment" in the automotive industry, but severe problems remain, as illustrated by the economic and technical difficulties accompanying the birth of 3G systems all over the world. The spectral efficiency has to improve to decrease the cost per bit in any proposed novel system beyond 3G.

Within PCC, the Wireless IP project [1][1] performs research with the aim of proposing a flexible and affordable general packet data system, with wide area coverage for mobile users. It should have *performance equivalent to a 100Mbit/s Ethernet connection, with support for Quality of Service (QoS) and fairness between wireless users.*

This goes far beyond what is attainable today with e.g wireless LAN systems such as Hiperlan II, which are appropriate only for short range and slow users, or GPRS/WCDMA 3G systems, that offer lower capacity at rather high cost. The time-varying radio propagation conditions encountered by vehicular users represent a major challenge. However, we believe our goal to be attainable at reasonable cost. Long-standing basic design principles for data communication systems and wireless systems have conspired to create inefficiencies in mixed fixed and wireless mobile environments. By reducing these inefficiencies, packet transmission to mobile users may be radically improved without the use of additional and expensive spectral bandwidth.

Systems for data communication are conceptually designed in multiple layers, from applications down to the physical layer. Design and standardization is simplified when layers are handled separately, but this may lead to inefficient resource utilization.

In lower layers, the design of wireless systems traditionally has the goal of hiding the effect of time-varying channel conditions by averaging: variations in channel quality are counteracted by coding and interleaving. Spread spectrum techniques are used partly to average out and reduce variations in the interference environment. The resource allocation is designed to guarantee a modest level of performance for all users, rather than maximizing the spectral efficiency. This leads to conservative designs: the received power and channel quality in general becomes higher than required by the services, which wastes resources.

The Wireless IP project develops methods that depart radically from the principles outlined above. We investigate intelligent resource utilization for wireless packet data systems, with the following characteristics:

1. Wherever possible, resources should be adjusted to the instantaneous channel quality, to prevent waste. The use of channel coding should be minimized. We systematically explore methods that use channel

[1]The Wireless IP project is a collaboration between researchers from Uppsala University, Chalmers University of Technology, Karlstad University and Politechnico di Bari, Italy, with Ericsson Research, Ericsson Mobile Data Design and Nera, Norway as industrial partners.

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quality feedback and optimize resources, instead of using averaging.

2. We develop and use methods that *take advantage of the varying channel properties*, to obtain “trunking gains”, or multiuser selection diversity, for multiple users who share the radio bandwidth.

3. Multiple antennas, at receivers as well as transmitters, reduce interference, increase the range and limit the required transmitted power. Their use and design is integrated in the proposed schemes.

4. Finally, we strive to make congestion control more efficient by using information from lower layers.

A careful application and combination of these methods lead to accumulated gains in efficiency: improved spectral efficiency as well as increased efficiency at higher layers.

Sections 2-4 below provide an overview of the research conducted within the project and of our present results. The most recent results are presented in more detail in the papers [2, 3, 4, 5, 6] at this conference. See also our webpage [1] and the Licentiate Theses [7], [8] and [9].

2 Prediction of Fading Channels

A main difficulty in data transmission over wireless links to mobile users is the fading, which introduces variations in the channel quality on all time-scales. At the lowest layer, we therefore develop predictors of the time-varying impulse responses of fading channels to mobile users, and of the signal-to-interference and noise ratio (SINR). We have so far focused on prediction of short-term fading, which is crucial for link-level adaptive modulation and scheduling. Predictions of 2-5 ms ahead are required, and will at vehicular speeds correspond to a considerable fraction of the radio wavelength.

Channel prediction over such horizons is difficult, and has only recently begun to be investigated. We have developed predictors that use channel tap estimates as regressors to predict the power of all significant channel taps. The predictors have been validated on an extensive set of broadband channel measurements [10, 11], see Figure 1 for an illustration. A recently developed unbiased quadratic predictor [3] provides the so far best performance, see Figure 2. We have also obtained a good theoretical understanding of the limits of attainable performance in different propagation environments.

3 The Link- and MAC Levels

Channel prediction can be used to adapt the data rate to the channel properties, via *adaptive modulation and coding* (link adaptation). With our recent results [4], the channel prediction error can be taken into account when optimizing the adaptive modulation.

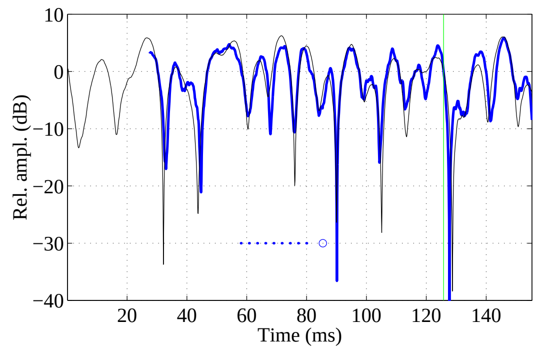

Figure 1: Typical prediction result for the fast fading of one channel tap in a channel of bandwidth 5MHz at 1880MHz. The prediction horizon is 5.5ms. The prediction (solid) is overlaid on a least squares estimate of a true tap (thin line). Measured channel sounding data is used. Note that it is possible to predict beyond a fading dip, so that the transmission can be planned accordingly. For details, see [3], [10],[11].

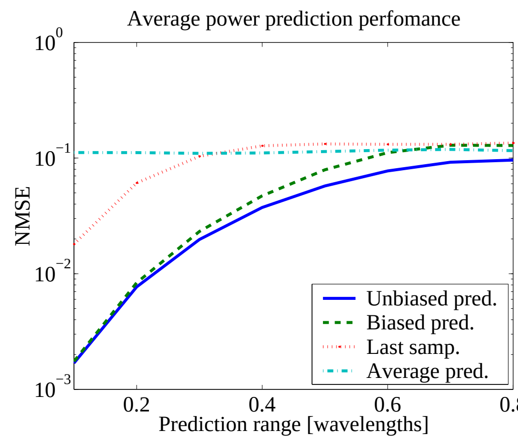

Figure 2: Power prediction on 5 MHz channels at 1880MHz. The normalized MSE is evaluated as a function of the prediction range, averaged over 37 measurement locations. The average predictor extrapolates an estimated average power level, while the last sample predictor extrapolates the last measurement [3].

Prediction is also of crucial importance for improving the MAC (Media Access Control) layer. It can there enable the *scheduling* of several data streams to/from mobile users whose channels fade independently: instead of counteracting the fast fading with coding and spreading, one should instead, if possible, delay transmission of a particular user’s data until the channel is good. This principle, which has been denoted multiuser diversity, represents a powerful tool for improving the system capacity.

We have studied and developed schemes for using multiuser diversity by combining adaptive modulation and predictive scheduling [7, 16, 17, 20]. An important aspect of our work is that packets with different payloads should reliably be provided with different Quality of Service (delay and error probability), despite channel variations.

3.1 Link Adaptation and Scheduling

We have so far primarily considered downlink (base to mobile) transmission from a single base station over a shared bandwidth to several mobile users. Per-flow buffering of data streams is assumed at the interface between the wired system and the wireless links, see Figure 2. Our proposed solution involves the use of channel power prediction at the mobiles. All active mobiles transmit quantized channel quality prediction reports to the base station.

Based on this information, a scheduler, located at the interface between the fixed network and the radio links, should distribute a set of shared radio resources (time-slots and perhaps also frequencies and base stations, see Section 3.2 below). The task of the scheduler is then to empty the buffers, taking into account the predicted channel capacities for each user several time-slots ahead. The scheduler should also take the buffer contents and the quality of service requirements (packet error probabilities and delays) for each data stream into account.

When the scheduling for a time interval is complete, bits from appropriate queues are formed into link level packets, modulated with a modulation alphabet appropriate for the predicted channel quality and are then transmitted in their appropriate time-slots.

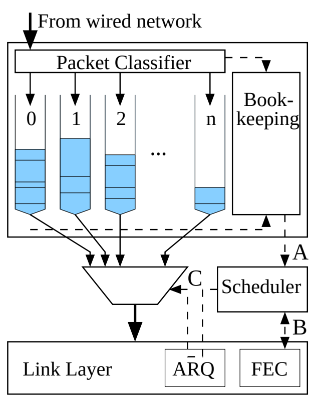

Figure 3: The downlink buffer and the scheduler. Packets arrive at the top and are inserted into their respective queues, restoring order among occasionally arriving out-of-order packets. The buffer regularly submits a status report (A) to the scheduler, containing info about the priorities, the size of the queues, and the required link service, some of which is also passed to the link layer (B). The scheduling decision (C) is updated by the link layer ARQ, and is then used to drain the queues, with a bit-level resolution of the outflows. For details, see [7, 17, 19].

3.2 Scheduling in Multiple Dimensions: An Adaptive OFDM System Proposal

We have until now mainly studied adaptive modulation and scheduling in a TDMA time slot reservation framework. The whole slot is then assigned to one user, as will also mostly be the case in HSDPA for release 5 of WCDMA [12, 13].

Depending on the scattering environment, the fading at different frequencies within a 5 MHz UMTS bandwidth may be almost uncorrelated, as exemplified by Figure 4. This provides another dimension over which to perform optimization and scheduling, and thus another tool for improving the total system capacity. To explore these possibilities we consider a slotted OFDM system in which the scheduler reserves time-frequency slots for multiple users.

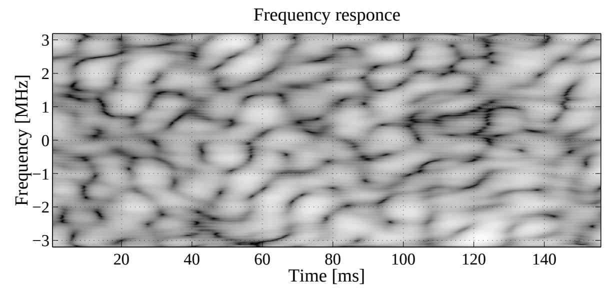

Figure 4: Time-frequency representation of an estimated channel obtained from real measurement data on a 6.4MHz channel. White color denotes high power whereas dark color denotes low power. The dynamic range and the speed of the mobile is approximately 40 dB and 50 km/h, respectively. The coherence bandwidth is 0.6 MHz.

The efficiency is in this system increased further by including the slot allocations within neighboring transmission beams in the scheduling. This limits interference and we may attain a frequency reuse close to a factor of 1.

We are at present performing research into the possible capacity attainable by such a hypothetical 4G system [2, 14, 15]. A preliminary proposal for the downlink, and an estimate of its spectral efficiency is presented at this conference in [2]. Most time-frequency slots can be utilized by mobile terminals with good channels even with rather few active users within an antenna beam/sector. High order modulation is then used in most slots.

For example, Figure 5 considers downlink transmission with ARQ of best effort traffic to K mobile users per sector, to mobiles that each have L antennas with 16dB SINR per antenna and that use maximum ratio combining (MRC). An efficient fast link adaptation scheme is used, which provides a spectral efficiency of 1.8 bits/s/Hz when one user with one antenna uses the channel exclusively. The estimated spectral efficiency improves to 3.6 bits/s per Hz per sector when five active users, each with two receiver antennas, share the channel.

3.3 Scheduling Methodologies

We have proposed to base the scheduling on a criterion that represents the total user satisfaction [18]. We are developing algorithms that optimize this criterion and make efficient use of the available bandwidth, at reasonable computational complexity [7].

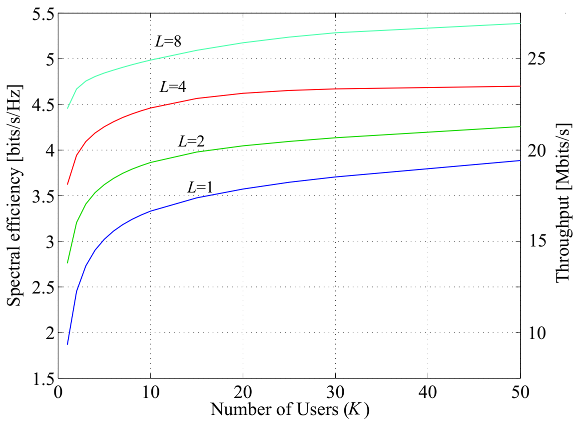

Figure 5: Spectral efficiency using AMS and simple ARQ with Lth order MRC diversity in the mobile and Kth order of selection diversity between the users. The symbol energy to noise ratio per receiver antenna is 16 dB. Right-hand scale: The capacity within one sector or beam in a 5MHz downlink [2].

Furthermore, we combine scheduling with Hybrid type-II ARQ [8], a link level retransmission scheme that uses incremental redundancy. Link-level packets are first transmitted uncoded, with additional coding information transmitted later, if required due to an unsuccessful transmission. This combination attains high throughput, low delay and it makes the performance relatively insensitive to the unavoidable errors in channel predictions [16, 17, 19]. We use rate compatible convolutional codes, that enable soft decoding with acceptable computational complexity.

We also study Turbo codes, of interest in particular in environments with high interference levels [9, 23, 24, 25]. The critical issues of rate compatibility, channel estimation and header encapsulation are treated in [5].

A novel scheduling methodology, that offers high performance and flexibility at the price of higher computational complexity as compared to the methods mentioned above, has recently been derived [21, 22]. In this method, Bayesian probability theory and the maximum entropy principle are used to optimize a throughput criterion in a way that handles fairness constraints as well as different amounts of knowledge about buffer inflow statistics, channel capacities and prediction errors.

4 Transport Protocols over Fading Wireless Links

On a higher level, we study the behavior of transport protocols, in particular TCP. Fading wireless links are often characterized by a sporadic high bit error rate and a rather high and time-varying bandwidth-delay product. TCP performance is then often reduced.

An ingenious end-to-end scheme that requires modification of the bandwidth estimation algorithms only at the sender side of a TCP connection is TCP Westwood [27], recently proposed by Saverio Mascolo, who is engaged as a researcher in our project. Preliminary investigations have shown TCP Westwood to provide a large performance improvement over wireless links. We are evaluating TCP Westwood in a simulation environment with link level retransmissions, realistic fading models and erroneous feedback of ACK's due to wireless return channels. Results are presented in the poster [6].

4.1 Interaction of Link Level Retransmissions with Transport Level Protocols

Link level retransmissions are used in GPRS, and will probably have to be used in all future systems aimed at mobile users with fading channels. They improve the channel quality but may adversely affect higher level transport protocols if many retransmission attempts are allowed.

With mobile users traveling through complicated propagation environments, fading will generate channel quality variations on all time-scales. An important aspect here is how transport level congestion control reacts in such environments when link level retransmissions such as our Hybrid type II ARQ are active.

Split connections, with a separate transport-level protocol over the wireless link, offer potential advantages. They enable the introduction of performance-enhancing algorithms, that use information from lower layers, at a gateway to the wireless part of the system. There are also potential drawbacks with split connections. They break the end-to-end semantics. They may offer only limited improvements when link-level retransmission is already in place. They will also require fast migration of information between nodes at hand-over. A further aspect that may limit the use of split connection schemes would be an increased use of IP-level security and encryption [28].

4.2 A Simulation Environment for Studying Multilevel Optimization and Interlayer Interaction

It is not at all simple to obtain reliable and relevant results when investigating multilayered communication systems working on different time-scales. We are therefore making a major effort to create an appropriate simulation environment [6, 29, 30, 31]. Using real TCP and UDP stacks, it generates packets that propagate in real time over simulated wireless links, so that important aspects and time-scales of lower layers, and inter-layer interactions can be studied. Radio channel properties are obtained from ray-tracing simulations, which are validated against channel sounding measurements provided by industry. This simulator will be a valuable tool in our continued research.

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