The SSF Wireless IP Project: Final Report

Summary

The Wireless IP project within the SSF IT program 2002-2005 has been a collaborative research effort involving researchers from Uppsala University, Chalmers University of Technology and Karlstad University. Industrial partners were Ericsson Research and Ericsson in Göteborg. Uppsala University acted as lead partner. The objectives were to develop and to study algorithms and system design for future wireless packet data transmission beyond 3G. In particular, the objective of the program has been to develop and explore a new type of radio system based on adaptive transmission.

Wireless IP was initiated as a multi-university research project within the SSF PCC program in 2000. It became a SSF IT program funded by 10 MSEK from mid-2002 to mid-2005, after which the program received a 2.5 -year extension funded by 5 MSEK from mid 2006 to the end of 2008.

During 2002-2003, the WIP program performed an intense design effort, which resulted in the design and evaluation of a downlink for an adaptive OFDM system. The work discussed and offered answers to the following questions:

- Can a balanced adaptive OFDM-based downlink be designed without too much overhead due to guard-bands and control signaling? What multiuser scheduling gains may be attained in such systems?
- What spectral efficiency may be expected by using adaptive OFDM-based downlinks in a multicellular system?
- What are the most promising ways to integrate multi-antenna transmission with adaptive transmission, so that reinforcing advantages are created?
- What are the effects of realistic prediction errors on the attainable performance if the terminals move at vehicular velocities, and the link adaptation design takes the prediction uncertainty into account?

In mid-2004, the results obtained were very promising. The Wireless IP constellation was at this point invited to continue the system design effort in collaboration with the main European effort aiming at new radio systems beyond 3G, the EU 6FP project WINNER. Ideas, algorithms and concepts developed within the Wireless IP project, spanning channel adaptive predictive scheduling, advanced link adaptation, the use of orthogonal OFDM signaling for adaptive transmission and the use of interference avoidance between base stations were well received. They were integrated into the WINNER system concept. The WINNER concept lead, in its turn, to standardization in the form of the 3GPP LTE standard and its ongoing development "LTE-advanced". Adaptive OFDM systems are now destined to become the dominant wireless broadband technology of the future.

Our work has been published in two book chapters and 17 Journal papers, of which three are in a Special Issue on adaptive transmission by the Proceedings of the IEEE. It has led to 48 conference publications, many of which are jointly co-authored with industrial and academic partners, as well as contributions in numerous WINNER project reports. The project has resulted in five Ph.D. Thesis and five Licentiate Theses, with two additional Ph.D. Theses to be defended in the spring of 2010.

The objectives of the project

The Wireless IP program[1] has been a collaborative research effort involving researchers from Uppsala University, Chalmers University of Technology and Karlstad University. Industrial partners were Ericsson Research and Ericsson in Göteborg. Uppsala University acted as lead partner. The objectives were to develop and to study algorithms and system design for future wireless packet data transmission beyond 3G.

In particular, the objective of the program has been to develop and explore a new type of radio system based on *adaptive transmission*. This represented a reversal of the so far used design principles. A completely packet-based system was envisioned, with no fixed channels. The transmission would here be varied on a fast time scale to adapt to the changing transmission resources. More data are transmitted in good channels, less data in bad channels. Users share transmission resources in the form of time, frequency and antennas at the base stations in an optimized way. The resources are allocated to the user who at the moment needs them most and can use them best.

Furthermore, adaptation over multiple cells is used to avoid interference from being created, instead of trying to suppress it at the receiver after it has occurred.

Combined, these tools and principles have the potential to enable a large gain in the data throughput in novel wireless systems, both within cells and for individual users. This is important because radio bandwidth is a relatively expensive resource. The aim of the project was to reach data throughputs in the range of 100 Mbit/s/cell-1000 Mbit/s/cell.

For this purpose,

- We aimed at developing channel-adaptive transmission and packet scheduling methods as well as methods for interference avoidance. The goal was to obtain extreme spectral efficiency for stationary as well as vehicular users.
- We also focused on investigating the gains and problems encountered in cross-layer cooperation in wireless packet data systems.
- We then intended to develop and combine the ideas and algorithms into concrete proposed 4G radio transmission systems.

The last point, the systems aspect, was important. While we strive to push the limits of each technology, it was crucial to study the interactions of different algorithms, to avoid situations where their properties cancel rather than providing mutually reinforcing advantages.

1 History of the project

Our combined research effort originated within the SSF Graduate School PCC, Personal Computing and Communication in 1999. At that time, the so-called WCDMA (Wideband Code Division Multiple Access) systems were being designed as the third generation (3G) wireless systems. The Wireless IP project originated from a strong belief by the involved researchers that future wireless transmission would be IP (Internet Protocol)-based packet switched and that the 3G CDMA design was far from optimal

[1] www.signal.uu.se/Research/PCCwirelessIP.html

for such transmission. WCDMA for 3G was originally essentially designed and motivated as a better circuit-switched system for speech, rather than optimized for packet switched data. Based on preliminary studies within PCC, we in 2001 formulated the separate Wireless IP project. Starting from mid-2002, it was to focus on a new type of broadband wireless system, designed to provide radically improved data throughput for fixed as well as mobile users. For that purpose, adaptive transmission, with fast allocation and re-allocation of transmission resources when requirements and channel properties change, needed to be investigated and evaluated. We focused on a promising type of transmission, Orthogonal Frequency Division Multiplexing (OFDM), that at that time had not yet been introduced into wireless mobile systems. We also focused on cross-layer aspects to improve the efficiency and perceived quality of service of the data transmission.

A research program was formulated, containing the specific research problems summarized in Section 2.

In 2001, only a few research groups pursued the kind of radically new adaptive OFDM-based system that we envisioned. In the years thereafter, the interest in adaptive transmission has increased steadily, from a trickle to a flood. We have now reached the point where adaptive transmission has been introduced, first in modifications of the 3G standard (HSPA, High Speed Packet Access), then as a cornerstone of the presently developed wireless broadband systems 3GPP LTE (Third Generation Partnership Project Long-Term Evolution) and IEEE 802.16 (mobile WiMAX) and now the “true 4G” systems that are now (mid 2009) in a pre-standardization study phase, under the name IMT-Advanced.

Foremost of the long-term research efforts for beyond 3G systems during the period 2004-2007 has been the EU WINNER project, where we were involved and had an influential position since the start, as a direct consequence of our SSF-funded work within Wireless IP. This collaborative effort provided a unique avenue for our SSF-funded research, via the WINNER projects, to influence the essential features of systems that will follow beyond 3G, primarily 3GPP LTE and its ongoing development “LTE-Advanced”. The interaction of the research within the Wireless IP Programme and the WINNER project will be discussed in more detail in the next section. This collaborative effort within WINNER culminated in a complete 4G system proposal for a flexible new air interface.

Funding

Wireless IP was initiated as a multi-university research project within the SSF PCC program in 2000. It became a SSF IT program funded by 10 MSEK from mid-2002 to mid-2005, after which the program received a 2.5 -year extension funded by 5 MSEK from mid 2006 to the end of 2008.

The involved PhD students and researchers (see Appendix 3) were funded by SSF on the level 50-80% for PhD students, 100 % for postdocs and 10-30 % for senior researchers. The level of funding and the number of funded researchers was reduced during the extension phase, where a larger part of the total funding for our research efforts instead came from the WINNER II EU project.

Organization

The Wireless IP program was not organized into distinct isolated sub-projects. Instead, the system design effort was a common organizing theme. Research groups that all contained members from several of the partners investigated subproblems motivated by the system design work. A total of 20 project meetings were held during the period 2002-2008, and three workshops were organized together with external collaborators, see Appendix A5.

For budgetary reasons, the project is subdivided into three parts:

Project 1, Uppsala University, Leader: Mikael Sternad
Project 2, Karlstad University, Leader: Anna Brunström
Project 3, Chalmers. Leaders: Tony Ottosson 2002-2004 and Tommy Svensson 2005-2008.

The Wireless IP program steering group consisted of

Professor Anders Ahlén, Uppsala University
Professor Mikael Sternad, Uppsala University
Professor Arne Svensson,Chalmers
Professor Mats Viberg, Chalmers
Professor Tony Ottosson, Chalmers
Professor Anna Brunström, Karlstad University.

Mikael Sternad acted as program director, while Ylva Johansson at Uppsala University handled the economy administration.

2 Scientific results of the program

The original plan for the Wireless IP program is described in the SSF application from November 2001. In that proposal, we outlined our goals for performing algorithmic research and system design, with the purpose of being able to integrate the ideas into a 4G system concept at the end of 2005. The research plan foresaw significant efforts in five areas:

1. Prediction of fading channels.
2. Link layer and MAC (Medium Access Control) layer optimization, leading to the design of an adaptive OFDM mobile wireless broadband system proposal.
3. Transport protocol performance over fading wireless links.
4. Very long-term channel prediction, of potential use in congestion control and resource allocation.
5. Resource allocation in heterogeneous systems.

The project was funded at half of the proposed budget level (10 MSEK for three years mid 2002-mid 2005 while the proposal assumed 20 MSEK). The research plan was modified to accommodate this reduction. Research on the least mature and least critical research subjects, items 4 and 5 above, was deferred. Some points in the subject areas 1-3 were also delayed and were planned to be completed during the project extension phase in 2006-2008. On the other hand, the effort spent on system design and integration issues was increased, compared to our original plans.

Thanks to our subsequent involvement in the WINNER and WINNER II project, we have attained the most important goals of our modified project plan. In particular:

- The research by the Wireless IP project has helped to demonstrate the viability of adaptive OFDM transmission in packet data systems in a wide variety of circumstances, for fixed as well as vehicular terminals, as summarized in [9].
- The research results are now integrated into a complete 4G system concept, in the form of the WINNER system concept [75] and the WINNER II system concept [2], [3], [4] [7] [80], [81], [82].

The obtained results at the end of the extension phase (Dec. 2008) are outlined and compared to the original plans in more detail below.

2.1 4G System design

Active researchers: Mikael Sternad, UU, Anders Ahlén, UU, Sorour Falahati, UU, Anna Brunström, KAU, Tony Ottosson, CTH, Tommy Svensson, CTH, and Arne Svensson, CTH.

The Wireless IP project group started discussions on a novel 4G system design concept in the year 2000, within the SSF-funded PCC program. At the end of 2001, this work had led to a set of inter-related ideas that formed our vision for how such a system might be designed. They were presented at the Swedish RVK 2002 conference [64–66]. These ideas formed the initial basis for our continued work.

2.1.1 The WIP adaptive OFDM downlink design

During 2002-2003, the WIP program performed an intense design effort, which resulted in the design and evaluation of a downlink for an adaptive OFDM system. The work was summarized in a set of conference papers [50], [53], [54], [55], [56], [57] and white papers [59]. The technical results are described in more detail in a set of project reports [R1]-[R4]. The work discussed and offered answers to the following questions:

- Can a balanced adaptive OFDM-based downlink be designed without too much overhead due to guard-bands and control signaling? What multiuser scheduling gains may be attained in such systems [53], [57] [R3],[R4]?
- What spectral efficiency may be expected by using adaptive OFDM-based downlinks in a multicellular system [54], [R2]?
- What are the most promising ways to integrate multi-antenna transmission with adaptive transmission, so that reinforcing advantages are created [R1]?
- What are the effects of realistic prediction errors on the attainable performance if the terminals move at vehicular velocities, and the link adaptation design takes the prediction uncertainty into account [R4], [50], [56]?

In mid-2004 we could conclude that the results obtained so far were very promising. No show-stoppers had been found. Continuing the work from this point on required evaluation in a multi-cellular context that took an increasing number of system design issues into account. Fortunately, we were at this point able to continue the system design effort in collaboration with the main European effort aiming at new radio systems beyond 3G, the EU 6FP project WINNER. This has helped our work to progress and to obtain a larger impact.

2.1.2 The Wireless IP effort within the EU WINNER project

The WINNER and WINNER II Integrated Projects involves 40 partners during 2004-2007, with Nokia-Siemens Network acting as leader. They included all major Telecom equipment providers in Europe, and also the major North American equipment manufacturers, as well as DoCoMo in Japan. The largest European operators participated as well as numerous academic partners. The WINNER projects had massive support from the European wireless industry. The major players essentially focused their research on systems beyond 3G via WINNER and its sister projects with other focus within the so-called Wireless World Initiative. Based on WINNER results and on input from important wireless operators[2], an intense standardization effort started in 2006, that in 2008 resulted in the 3GPP LTE standard (Release 8 of UMTS).

The WINNER projects developed a flexible radio interface that can be introduced in any available spectrum, and that supports flexible spectrum use. Peak data rates above 100 Mbit/s were targeted by integrating transmission over multiple antennas into the foundation of the design. Improved economy and flexibility of deployment were

[2] Operators formulated desired properties of next-generation wireless systems also within the Next Generation Mobile Networks (NGMN) cooperation, see e.g. NGMN Beyond HSPA and EVDO White Paper, version 3.0 December 2006.

also striven for, partly by evaluating the concept of relay-enhanced cellular systems, where cheap fixed relay nodes are used to improve the coverage and data rates.[3]

The Wireless IP constellation, with Chalmers acting as a full partner and Uppsala Univ. and Karlstad Univ. contracted as third parties, was invited to participate in the WINNER project from its start in 2004. We constituted the second largest academic partner within the project. During 2004, we introduced methods, ideas and results from the Wireless IP program into the evolving WINNER design and assessment effort [42], [48], [67], [68], [69], [D2]. These ideas and concepts, spanning channel adaptive predictive scheduling, advanced link adaptation, the use of orthogonal OFDM signaling for adaptive transmission and the use of interference avoidance between base stations were well received. They were integrated into the WINNER system concept.

During 2005, the members of the Swedish Wireless IP project took a leading role in the development of the WINNER *system concept*, the main outcome of project phase I [36], [40], [75]. In particular, Mikael Sternad and Tommy Svensson led the work on MAC layer design [31], [32] and multiple access technologies. We played an important part in the discussion on integration of spatial transmission schemes [36] and spatial division multiple access, new relay-enhanced deployment concepts, adaptive transmission and retransmission design, interference avoidance between cells and dynamic spectrum allocation and trading [37].

During the WINNER II phase in 2006-2007, the system concept was evolved into a complete flexible 4G system proposal, that was evaluated in three important deployment scenarios: wide-area systems with cells up to 2 km radius, metropolitan area systems and short-range systems. Peak data rates of 1000 Mbit/s were demonstrated deployment of isolated short-range cells. The WIP project group played an important and leading role in the continued design effort and our continued algorithm research results were evaluated within this framework.

In particular, we led the work on MAC layer design (Mikael Sternad) [2], [4], [20] and multiple access technologies (Tommy Svensson) [4], [5], [78]. We participated in the over-all system design, [4], [21] and the continued refinement of adaptive transmission techniques. We proposed and evaluated a novel OFDM-based schemes for multiple access, *Block-IFDMA*, that combines power efficiency, robustness, flexibility and scalability [5], [26], [27]. It became used as the multiple access scheme for diversity-based transmission of the WINNER II system concept [82].

2.1.3 Summarizing our results by Invited papers in Proceedings of the IEEE

In 2007, the technology of adaptive transmission had reached a level of maturity that made it appropriate to summarize its different aspects in a special issue of the Proceedings of the IEEE (December 2007). Wireless IP project members authored three invited papers of this issue, drawing on knowledge and experience that had been gained on over-all design and performance aspects [9], on link adaptation [10], and on compression of feedback information required for the adaptation [11].

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[3]For more information, see http://www.ist-winner.org and http://projects.celtic-initiative.org/winner+/.

2.2 Prediction of fading channels

Active researchers: Daniel Aronsson, UU, Mikael Sternad, UU, Ming Chen, CTH and Mats Viberg, CTH, together with Torbjörn Ekman, NTNU, Trondheim (formerly UU).

Channel prediction is an important enabling technology for adaptive transmission, if such transmission is to be performed to/from moving terminals. Work on prediction was started up already before and within the SSF PCC program phase of the work in 2000-2001 and has continued throughout the project.

2.2.1 Results

1. Based on theoretical considerations and a very extensive evaluation on measured channel data, we have designed a predictor for the received power of fading channels [63]. This unbiased quadratic predictor can be shown to have optimal structure. It can be implemented in the frequency domain as well as in the time domain [55].

2. When adaptive transmission is to be performed in uplinks, the channels from many terminals has to be predicted simultaneously. We thus have to predict one multiple input single output (MISO) channel for each receiver antenna. This problem is more difficult than predicting single-input-single output (SISO) channels but it can be solved by taking the time-frequency correlation of the channels into account. We have developed Kalman-based predictors and smoothing filters that have reasonably low complexity, and that utilize the available channel correlation in both the time and the frequency domain [24], [25], [45], [L1]. These estimators have been integrated into and evaluated for the newly developed Block-IFDMA multiple access techniques for WINNER II uplinks [18].

3. Our so far used prediction methods are based on least squares autoregressive modelling of the time variability statistics of fading channels, The use of sinusoidal modelling of the fading channel offers the possibility of using a more efficient parameterization of the fading of MIMO channels, from multiple transmit antennas to multiple receive antennas. Sinusoidal modelling methods have been investigated [12], [41], [51], [L4], [D1]. However, this approach has so far not provided consistently better performance than our present autoregressive-based modelling when evaluated on measured channel data.

2.2.2 Comparison with topics proposed in the original proposal (Nov. 2001)

The project proposal from November 2001 outlined a set of important research problems. The outcomes of the project are briefly compared with that list below.

- Prediction methods for the time-frequency properties of fading OFDM channels. **Solved.**

- Very long-term prediction, for use in long-term resource allocation. **Discontinued.** We concluded that prediction of e.g. shadow fading with realistic accuracy levels are likely to be of rather limited value in long-term resource allocation problems.

- Prediction of MIMO channel quality information and channel state information. **Solved**, with algorithms and results reported in the theses [L1] and [F1] by Daniel Aronsson.
- Prediction of SINR (Signal-to-Interference-and-Noise Ratio) and the predictability of interference. This problem area is important but was not sufficiently studied in our present research. It will be investigated within the EU FP7 project Artist4G, where we are involved from January 2010.

2.3 Link layer and MAC layer optimization

Active researchers: Mikael Sternad, UU, Tommy Svensson, CTH, Wei Wang, CTH, Bartosz Mielczarek, CTH, Tony Ottosson, CTH, Arne Svensson, CTH Sorour Falahati, UU, Nilo Casimiro Ericsson, UU, and Mathias Johansson, UU.

The type of wireless packet data transmission investigated by the Wireless IP program is centered on a *scheduler*: An optimization algorithm that allocates time-varying transmission resources to packet flows with time-varying requirements. A transmission resource (variously called a bin, a resource block or a chunk layer) consist of a set of adjacent subcarriers during a short time interval, within a spatial transmission channel (layer). The transmitter adjusts the transmission scheme to the quality of each bin. This is called link adaptation and we denote such a transmission scheme *frequency-adaptive transmission*. Since it cannot be used in all situations and for all types of data, it should be complemented by a good diversity-based (averaging) scheme, which we denote *non-frequency adaptive transmission* [9].

Link adaptation and scheduling have been active research areas within the project. Architecture issues, on how to bring all the necessary feedback information and control signaling together, have been an important area of investigation in the WINNER [9] [31], [32], [36], [37], [75] and WINNER II [2], [20], [82] projects. The main results are summarized below.

2.3.1 Results

1. *Link adaptation optimized by taking the uncertainty of the channel prediction into account.* We have here developed a methodology for adjusting the rate limits of adaptive modulation and coding schemes to the uncertainty of the channel prediction. This makes it possible to attain bit error rate constraints also in the presence of prediction errors [16], [35], [42], [52], [56], [60], [68], [D5]. Alternatively, we may optimize the throughput in correctly received segments or packets [50], [R4]. These techniques are key tools that, when combined with our channel power predictors, enable adaptive transmission also to mobile terminals at vehicular velocities, even at high (5 GHz) carrier frequencies.

2. *Adaptive OFDMA (Orthogonal Frequency Division Multiple Access) versus adaptive TDMA (Time Division Multiple Access).* In an adaptive OFDMA system, we utilize the variation of the channel in both time and frequency. When multiple users have channels that vary independently, this maximizes the chances that good channels can be made available for all users. The resulting increase in total throughput when increasing the number of active users is called the *multiuser*

scheduling gain. It is an important property of adaptive multiuser transmission techniques. In a TDMA system, the whole available frequency band is allocated to a single user. If the band is wide, the fading of its different frequencies will cancel. This will reduce the channel variability. While that would be good in a conventional averaging-based design, it might be a disadvantage in novel adaptive transmission systems since the attainable multiuser scheduling gain is then reduced. A reduced performance of adaptive TDMA schemes in comparison to adaptive OFDMA has been demonstrated and investigated for multi-carrier-based downlinks in [68] and for single-carrier TDMA uplinks in [38], [L3].

3. *The sensitivity of adaptive uplinks to synchronization errors.* In adaptive OFDMA uplinks, multiple users will simultaneously transmit over the assigned bandwidth. If the synchronization errors are too large, this will deteriorate the performance of such schemes. In [34] and [L3], it is found that the deterioration is insignificant for the synchronization error levels that can be expected within the WINNER system design.

4. *Compression of channel quality feedback.* Adaptive transmission requires channel state information at the scheduler. In systems that use FDD (Frequency Division Duplex), adaptive downlink transmissions from base to terminals would require that channel prediction estimates are produced at the terminals and then quickly reported to the scheduler, that is located in the fixed network. The required amount of feedback information might then become unreasonably large if special precautions are not taken. We have designed and investigated a very efficient scheme for compressing the required information [68], described in the IEEE Proceedings Invited paper [11].

5. *Turbo-coded transmission.* Turbo coding was studied during the PCC phase of our work and at the beginning of the Wireless IP project [15], [17], [61], [62]. [D4]. Adaptive turbo-coding was later developed to combine capacity-approaching coding with our OFDM link adaptation. This method uses an inner convolutional code concatenated with an outer convolutional code [35].

6. *Integration of multi-antenna systems into an adaptive OFDM systems.* It has been found that antenna resources at transmitters and receivers can be used in a very flexible way, in combination with adaptive transmission [6], [33], [36], [82].

7. *Scheduling architecture.* The total scheduling problem is very complicated, while a low-complexity solution is required. Otherwise, the computation times would prevent the channel quality information to be used in a timely manner. A key solution, proposed and investigated in the Ph.D Thesis [D2] by Nilo Casimiro Ericsson is to partition the total scheduler into two hierarchical levels, one that works on the time-scale of the packet inflows, and another, faster, algorithm that works on the time-scale of the short-term fading of the time-varying channels. These two entities could be localized in different network nodes.

8. *Scheduling algorithms.* With a two-layered scheduling architecture, very fast and efficient algorithms can be designed. For example, the channel-adaptive scheduling can be solved by minimizing a local linear approximation of a quadratic criterion which takes the buffer levels, the channel capacities of each user and the

priorities of each flow into account [D2]. Channel variations can thus be utilized while quality of service constraints are taken into account. The computational complexity of the resulting algorithm is low. It grows linearly with the number of scheduled resources and with the number of scheduled data flows.

Novel scheduling algorithms that take both the channel statistics and the packet flow variability statistics into account are described in [14] and in the Ph.D. Thesis [D3] by Mathias Johansson.

9. *Fairness issues in scheduling.* Scheduling of multiple flows over a shared transmission resource raises the question of how fairness between flows can be defined, measured and handled. This issue has been investigated within the project [39], [49] and [L2]. Fairness measures have been defined for channel-adaptive scheduling schemes.

   Within the WINNER II project, the focus of system-level evaluations has been on maximizing the capacity under user satisfaction constraints: This is done by using a "satisfied user criterion": The maximal data throughput that can be attained under the constraint that at most x % of the users do not obtain a promised quality-of-service (QoS) level [9], [79], [82].

10. *Inter-cell interference avoidance scheduling.* For highly loaded systems with omnidirectional transmission within cells/sectors, simple static reuse partitioning schemes are an efficient method for improving the spectral efficiency of the types of wireless systems we study [54], [R2]. Adaptive schemes are more efficient at intermediate load levels. In [8] and [D3], a powerful method that adapts to the load within each cell is proposed. It is based on using local measurement of the capacity demand, while taking the uncertainty in future demand into account, using Bayesian statistical reasoning.

2.3.2 Comparison with topics proposed in the original proposal (Nov. 2001)

Let us compare our present status with the list of potentially important research topics in link adaptation and MAC design in our original proposal:

- Develop multi-user channel aware scheduling algorithms that attain high throughput at reasonable computational complexity, and that take QoS constraints into account. **Solved**, due to the work presented in [D2].

- Investigate how the mix of fast, slow and stationary users who share a channel will affect the throughput and the QoS for delay-sensitive traffic. **Solved** (essentially) by using OFDMA/TDMA, i.e. by using the channel variability not only in time but also in frequency, and letting several users share the time-slot by using different frequencies of the wide-band link.

- Combining incremental redundancy schemes with adaptive modulation. **Solved**. Partial results were obtained in [D5], The best way to combine an outer (strong) code that uses incremental redundancy with an inner channel-adaptive code was investigated in [35] and in the WINNER II project [76]. The work in WINNER II led to the design that combined LDPC (Low Density Parity Check) coding over large code-blocks with adaptive modulation within the blocks. This adaptive transmission scheme has, to our knowledge, the best ever reported performance over realistic fading channels.

- Investigate the properties of transport level protocols when optimizing scheduling and the link-level ARQ (automatic repeat request) retransmission schemes. **Solved.** Link retransmission over the envisioned fast feedback systems is advantageous. It should be used with high persistence (many retransmission attempts before dropping a segment) [19], [23], [30], [44], [L5].

- The combination of adaptive multiuser scheduling with beamforming and SDMA (spatial division multiple access) schemes. **Solved**, by the work in WINNER and WINNER II. Here we emphasized that spatially compatible users should be grouped together so that they can be served by similar beams (adaptive or fixed grid-of beams). Within each beam, frequency resources are distributed among users by by scheduling [75].

- Ways to use the antenna diversity and the antenna degrees of freedom. **Solved**. This integration became a part of our proposed Block-IFDMA multiple access scheme for OFDM-based non-frequency adaptive (diversity-based) transmission in uplinks [3], [5], [27].

- Investigate the bit rate required in the return channel for transmission of channel quality feedback and scheduling control information. **Solved**, for SISO systems, with our developed methods for compression of the feedback information [11], [68]. Generalization to compression of feedback for MIMO channels remains an interesting and important research problem.

- Study different methods for coordinating the time-slot use of transmission from neighboring base stations, to reduce the co-channel interference. **Ongoing**, with interesting methods having been derived [8], [D3]. This work is now continuing within follow-on projects.

- Investigate schemes to reduce peak-to-average power ratio of transmitted signal. **Investigated** in connection to the multiple access schemes, where the Block-IFDMA multiple access scheme [5], [27] provides a flexible means for controlling the signal envelope variations in uplinks by using DFT-precoding of an OFDM signal.

- Obtaining wide area coverage by using lower radio frequencies, e.g. TV bands. **Not pursued actively**. We did not have resources to focus on this aspect in the Wireless IP project. The WINNER projects in the end focused their efforts on higher carrier frequencies, and used test scenarios and design optimized for high frequencies. It would have been interesting to investigate this aspect, since re-farming of TV bands (the digital dividend) has been decided in the US and in many countries of Europe, including Sweden. The 3GPP LTE standard was designed to work well at these lower frequencies.

- Inter-layer interaction has been studied extensively for physical, link, and transport layers. A study has also investigated the use of lower-layer decoding information at the highest application layer. We have, for example, found that the use of soft channel decoding information, that would be available in a terminal during a downlink transmission, can improve JPEG2000 image decoding [13], [46].

2.4 Transport protocols over fading wireless links

Involved researchers: Stefan Alfredsson, KAU, Anna Brunström, KAU, Mikael Sternad, UU.

We have developed a transmission system emulator WIPEMU [44], [47]. It runs multiple real TCP streams over an emulated downlink that includes scheduling, link adaptation and link-level retransmission over simulated fading OFDM channels to multiple users. The interaction of the variable data rates, the variable channel capacities and the transmission control algorithms on the MAC level and the transport control protocols can thus be studied.

Our results obtained with this tool [9], [19], [23], [30], [L5] show that the evolving adaptive 4G system has properties that interact advantageously with higher layer control algorithms. In particular, with a fast transmission control feedback loop, link retransmission can be used without negative interactions with the TCP flow control algorithm. Use of channel-adaptive scheduling and fast retransmission at lower layers will hide the “difficult” properties of the wireless fading channel from higher layers. The channel perceived by the data stream will be more like a service with slowly varying capacity, a situation that present TCP algorithms are well equipped to handle.

An important aspect in future high data rate wireless systems is that the distinction between delay sensitive and best effort traffic classes will tend to diminish and perhaps disappear. Due to the properties of the TCP rate control protocol, large delay variabilities cannot be tolerated by “best-effort” data streams, they would reduce their throughput by an intolerable amount. Thus, fast link retransmission and low link delay will be a key property of future high data rate wireless systems, for most traffic classes.

3 The graduates of the program

Graduate training within the program has been performed in cooperation with the SSF-funded graduate schools PCC and PCC++. All except one of our Ph.D. students have participated in these programs.

The so far obtained exams of involved students are listed in Appendix A.7 and A.8.

4 Impact of the program- to industry and society

4.1 Relevant results of the project

Relevance, and the potential to be included into future wireless standards, has been used as a key criterion for the research problems investigated and described in Section 2.

The results and insights have been spread among the Swedish and European wireless industries via the WINNER collaborative projects described in Subsection 2.1.2. Regarding the industrial and societal relevance of these projects, where we made a very significant contribution, we would like to cite Dr. Johan Nyström, head of 4G research at Ericsson, in a comment to collaborators (July 2009):

"All new and old Winner people should know that the concept behind LTE originally was conceived and developed in Winner I, started 2004 before LTE even existed. When the necessity of an LTE concept arose in 3GPP, the basic concept was taken from Winner, but downscaled to small BW! A natural platform to develop into an Advanced system of course."

Let us also cite a brochure by the EU 7th framework program[4]:

"LTE networks enable fixed to mobile migration of applications such as Internet telephony, watching videos, music downloading, mobile TV and provide the capacity to support an increasing demand for connectivity from various devices.

With LTE, there is strong potential to generate vast economies of scale unmatched by any previous generation of broadband access technology. LTE could extend the high speed Internet access enjoyed by urban and suburban users today to isolated and rural areas. It will also contribute towards eliminating the 'digital divide' in Europe.

EU R& D outcomes: and the WINNER is ... LTE!

The key for Europe to remain competitive in the global market is to exploit its expertise and offer innovative solutions. To remain creative, the industry needs investment in research and development.

WINNER, which stands for Wireless World Initiative New Radio, is a EU-funded project that ended in 2007. The project took the challenge to define a concept of what the beyond third generation access infrastructure might look like and explore how to implement new technologies.

WINNER focused on enhancing the radio access system by taking into account the interoperability with other systems. The project brought a very clear understanding

[4] Heading towards full European mobile broadband: Long Term Evolution (LTE) and beyond, February 2009, http://cordis.europa.eu/fp7/ict/future-networks

ow what the system should look like. It has developed an entire system concept and a related reference design for a future air interface.

The role of WINNER was to develop, optimize and validate that technology leading to the LTE standard itself. With these results and through a consensus building approach, the WINNER partners have made important inputs to the LTE standard.

The next step will be LTE-Advanced that is currently being standardized for the use in frequency bands expected to become available in the near future."

4.2 Ensuring that people are utilized by society/industry

We believe that the Wireless IP project has produced a set of outstanding graduates, who are, and will continue to, provide significant contributions to Swedish and international IT industries. Let us here briefly summarize their subsequent career choices: Of the graduates within the project,

- Dr. Sorour Falahati [D5] and Dr. Ming Chen [D1] are at present active as researchers at Ericsson Research.
- Dr. Nilo Casimiro Ericsson [D2] and Dr. Mathias Johansson [D3] have both acted successfully as CEOs of a small high-tech company, Dirac Research AB.
- Dr. Bartosz Mielczarek [D4] was active as researchers in wireless systems at the University of Alberta, Canada, and has then moved to industry.
- Krister Norlund [L2] was industrial Ph.D student within the WIP project, working at Ericsson in Göteborg while doing his research. He is continuing at Ericsson.
- Wei Wang [L3] moved to Ericsson in Göteborg after her Licentiate exam.
- Daniel Aronsson, UU [L1] and Stefan Alfredsson, KaU [L5] are still at university, finishing their Ph.D theses [F1], [F2].

4.3 Collaboration with industry

Collaboration with industry has primarily been through the interaction with partners of the WINNER projects (Subsection 2.1.2).

In addition, Ericsson Research and Ericsson in Göteborg have been industrial partners from the beginning of the project. Krister Norlund has been industrial Ph.D student, employed by Ericsson.

4.4 Intellectual property rights

No patents have been produced by the project participants directly related to the research results produced.

5 Impact of the program - to the academic system

5.1 Inter-disciplinary cooperation

The structure of the Wireless IP project has at its origin the need for researchers in communication systems, signal processing and data communication to work closely together to solve the problem of designing a novel type of packet data system.

Attaining cross-disciplinary understanding at a level that makes collaboration easy takes time and effort. We attained it gradually, by holding in total 37 common project meetings from 1999 to 2008 and by working together on joint papers and as co-supervisors of our Ph.D students.

The main outcome cross discipline research has been our ability to understand and contribute to most relevant aspects of adaptive transmission, perhaps best summarized in the survey paper [9]. Examples of specific investigations that require this cross-disciplinary approach are the investigations of the use of soft physical layer information in application layer image decoding [13] and our investigation on the impact of channel variability and adaptive wireless transmission techniques on transport protocol behavior [19], [23].

5.2 Cooperation between universities

The university departments involved:

- Signals and Systems Division, Dept of Engineering Sciences, Uppsala Univ.
- Signals and Systems Department, Chalmers University of Technology,
- Department of Computer Science, Karlstad University

have collaborated closely within the project. As a result of this collaboration, we have also taken part in several other joint efforts, in particular the Wireless World Research Forum, the EU Networks of Excellence Newcom and Newcom+, the WINNER follow-on Celtic project Winner+ and a new EU FP7 project Artist4G. We are also jointly developing research proposals to Swedish funding agencies to strengthen our collaboration.

5.3 Cooperation with other foundation programs

Three of the PhD students (Daniel Aronsson, Stefan Alfredsson and Wei Wang) were enrolled in the SSF-funded graduate school PCC++. Two of the senior researchers (Arne Svensson and Mikael Sternad) were actively engaged within PCC++.

The SSF IT-program with interests closest to ours is WINTERNET. Members of WIP have regularly attended the WINTERNET yearly workshops.

5.4 International cooperation

We have international cooperation with the following partners and projects:

- Foremost is the EU Integrated project WINNER, described in Section 2.

- The Wireless World Research Forum (WWRF), in which we have taken active parts in discussions, research reports (white papers) and have presented our results. See www.wireless-world-research.org
- We had active and fruitful contact with the two Norwegian projects with similar focus, BEATS, and CUBAN, led by prof. Geir Öien, NTNU, Trondheim. We jointly organized joint workshops in Loen, Norway, in June 2003 in Visby in August 2004 and in Dar Zarrouk, Tunisia, May 2005. See Appendix A.5.
- We participated in the European Network of Excellence NewCom and NewCom+ These collaborations were significant in particular with respect to development of new software tools for simulation.
- We collaborate with Prof. Saverio Mascolo, Politechnico di Bari, Italy, on issues relating to TCP algorithms and data flow control.
- We (Chalmers and UU) were members of COST 289 and participate regularly in its activities. Several COST 289 students and researchers have commenced research initiated by the Wireless IP project.

6 Lessons from the program

We have learned a major lesson from this program, which is of some importance in a research funding perspective. We started out in a decentralized network organization (the PCC program). A number of years ago, such networked distributed research efforts were popular with funding agencies. Since then, the pendulum of fashion within research funding has swung hard to the other extreme, with geographically concentrated creative research environments being the thing to support. A main reason for this was the difficulty of creating true collaboration and efficient high-quality research in widely distributed new-formed groups.

A main lesson from our program is: *It is possible to create a creative research group that works well and closely together, while being located at three universities*. It is not easy and it takes time, but for us the effort has been worthwhile.

An important prerequisite for such groups to be successful is that they are allowed to self-organize. That model is far superior to collaborations (geographically distributed or concentrated centers of excellence) that are created mainly in response to constraints in the funding mechanisms.

7 Outlook

As for the future, we continuing our collaboration between the three research groups.

We confidently expect a large part of our ideas and concept that have been studied within the present project to have been introduced into wireless systems standards within 10 years. In particular, we expect full-scale predictive and frequency-adaptive transmission to be introduced, without compromises in future variants of the LTE standard. In the present first release of the LTE standard, rather severe limits have been placed on feedback information bandwidth, which prevents the full potential of these techniques to be harnessed.

While these developments mature, it is time to take the next steps. As our long-sought goal of contributing to the birth of the wireless environment of the next decade has been fulfilled, we are exploring the next steps beyond the concepts and ideas that are being integrated into 4G. We at present feel that the direction to go is beyond cellular systems, towards large-scale optimization of distributed transmission resources.

8 Economic report

A summary of the annual economic reports earlier presented to the Foundation is given below.

The table below gives a summary of the first three-year budget from mid-2002 to mid-2005:

University, Department	Leader	**Total**	**2002**	**2003**	**2004**	**2005**
Project administration	M. Sternad	**800**	200	250	250	100
Travel and project meetings		**800**	200	300	200	100
Karlstad U., Informationsteknologi	A. Brunström	**1400**	100	550	550	200
Chalmers, Signaler och system	T. Ottosson	**3800**	400	1400	1400	600
Uppsala U., Teknikvetenskaper	M. Sternad	**3200**	200	1300	1300	400
Sum (kkr)		**10000**	**1100**	**3800**	**3700**	**1400**

(The funding for travel and project meetings has been allocated to the partners on a year by year basis.)

The table below gives a summary of the distribution between partner universities of the follow-on project budget for mid-2006 to the end of 2008:

University, Department	Leader	**Total**
Project administration	M. Sternad	**300**
Karlstad U., Informationsteknologi	A. Brunström	**850**
Chalmers, Signaler och system	T. Ottosson	**1550**
Uppsala U., Teknikvetenskaper	M. Sternad	**1900**
Högskolemoms		**400**
Sum (kkr)		**5000**

A Appendices

A.3 Researchers

The following persons have been involved as researchers, Ph.D supervisors and Post-docs in the project.

University, Department.				Function in project:	Gender
Uppsala U., Teknikv.	Ahlén	Anders	Prof.	Researcher, supervisor	M
Uppsala U., Teknikv.	Sternad	Mikael	Prof.	Superv, researcher proj. manager	M
Uppsala U., Teknikv.	Falahati	Sorour	Dr.	Postdoc 2003, res. in WINNER	F
Karlstad U, Inf.tekn.	Brunström	Anna	Prof.	Superv, researcher	F
Chalmers, Sign & Syst.	Svensson	Arne	Prof.	Supervisor (2002-2004)	M
Chalmers, Sign & Syst.	Viberg	Mats	Prof.	Supervisor	M
Chalmers, Sign & Syst.	Svensson	Tommy	Assistant Prof.	Researcher in WINNER	M
Chalmers, Sign & Syst.	Ottosson	Tony	Prof.	Researcher	M

A.4 Publications

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A.5 Events

In cooperation with the Norwegian Beats and Cuban projects the Wireless IP project has organized three workshops, with around 25-30 participants and three days of mixed presentation and discussion sessions.

- The first joint workshop was held in Loen, Norway, on June 4-6 2003. Invited guest speakers were Erik Dahlman, Ericsson Research, Helmut Bölcskei, ETH Zurich and Mohamed Slim-Aloiuini, Univ. of Minnesota.
- The second workshop was held in Visby on August 24-26 2004[5]. Invited guest speakers were Ralf R. Muller, FTW Wien, Saverio Mascolo, Politechnico di Bari Matthias Pätzold, Agder College and and David Gesbert, Eurescom.
- The third workshop was held at Sidi Bou Said, Tunisia on May 23-25 2005.[6] Invited guest speakers were Erik Dahlman, Ericsson, Giuseppe Caire, Eurescom and David Gesbert, Eurescom.

A.7 Ph.D. Exams

D1 Ming Chen, Male, Chalmers. *Radio Channel Prediction Based on Parametric Modeling*. Ph.D. Thesis, Chalmers University of Technology, ISBN 978-91-7385-009-4, October 2007. Supervisor: Mats Viberg.

D2 Nilo Casimiro Ericsson. Male, born 1971, Uppsala Univ,. *Revenue Maximization in Resource Allocation: Applications in Wireless Communication Networks*. Ph.D. Thesis, Uppsala University, ISBN 91-506-1773-7, September 2004. Supervisors: Mikael Sternad and Anders Ahlén.

D3 Mathias Johansson. Male, born 1976, Uppsala Univ. *Resource Allocation under Uncertainty - Applications in Mobile Communications*. Ph.D. Thesis, Uppsala University, ISBN 91-506-1770-2, September 2004. Supervisors: Anders Ahlén and Mikael Sternad.

D4 Bartosz Mielczarek. Male, Chalmers. *Turbo Codes and Channel Estimation in Wireless Systems*. Ph.D. Thesis, Signals and Systems, Chalmers University of Technology, Göteborg, Oct. 2002. Technical report 430. Supervisor: Arne Svensson.

D5 Sorour Falahati. Female, born 1971, Chalmers. *Adaptive Modulation and Coding in Wireless Communications Systems with Feedback.* Ph.D. Thesis, Signals and Systems, Chalmers University of Technology, Göteborg, Sept. 2002. Technical report 434. Supervisor: Arne Svensson.

A description of subsequent carreers and present employers is given in Section 4.2.

[5] http://www.signal.uu.se/Research/PCCWIP/Visby.html
[6] http://www.signal.uu.se/Research/PCCWIP/Tunisia.html

A.8 Licentiate Exams

L1 Daniel Aronsson. Male, born 1976, Uppsala U. *Channel Estimation and Prediction from a Bayesian Perspective.* Licenciate Thesis, Signals and Systems, Uppsala University, June 2007. Supervisor: Mikael Sternad.

L2 Krister Norlund. Male, Born 1976, Chalmers/Ericsson (Industrial Ph.D. Student). *Scheduling in Multiservice Wireless Networks.* Licentiate Thesis, Chalmers University of Technology, Göteborg, November 2006. Supervisor Tony Ottosson.

L3 Wei Wang. Female, Chalmers. *Multiple-Access Techniques for Adaptive Wireless Systems.* Licentiate Thesis, Chalmers University of Technology, Göteborg, January 2006. Supervisor: Tony Ottosson.

L4 Ming Chen. Male, Chalmers. *Channel Prediction Based on Sinusoidal Modeling.* Licentiate Thesis, Chalmers University of Technology, Göteborg, September 2005. Technical Report R026/2005 Signals and Systems, Chalmers. Supervisor: Mats Viberg.

L5 Stefan Alfredsson. Male, Karlstad U. *TCP in Wireless Networks: Challenges, Optimization and Evaluations.* Licentiate Thesis, Karlstad University, May 2005. Karstad University Studies 2005:13. Supervisor: Anna Brunström.

A description of subsequent carreers and present employers is given in Section 4.2.

A.9 Future Exams

F1 Daniel Aronsson, UU, Channel estimation and prediction for OFDMA systems. Ph.D. Thesis in preparation, March 2010.

F2 Stefan Alfredsson, KAU, Transport level protocol performance in wireless mobile systems. Ph.D. Thesis in preparation, May 2010.

A.10 No Exams

1. Anna Ewerlid, UU.