Adaptive Wireless Networking

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***Abstract*—This paper presents the *Adaptive Wireless Networking (AWGN)* project. The project aims to develop methods and technologies that can be used to design efficient adaptable and reconfigurable mobile terminals for future wireless communication systems. An overview of the activities in the project is given. Furthermore our vision on adaptivity in wireless communications and suggestions for future activities are presented.**

***Index Terms*—Adaptivity, Software defined radio, Reconfigurable heterogeneous architecture, UMTS, MIMO**

I. INTRODUCTION

A key issue of future wireless communication systems is that they have to be adaptive. These systems have to adapt to changing environmental conditions (e.g. varying number of users in a cell or varying channel parameters due to reflections or user movements) as well as to changing user demands (bandwidth, traffic patterns and QoS). When the system can adapt – at run-time – to the environment significant savings in computational costs can be obtained [1]. Furthermore, the hardware architectures have to be extremely efficient and cost effective as they are used in battery-operated consumer terminals.

Traditional algorithms in wireless communications are rather static, like algorithms discussed in [2]. The recent emergence of new applications that require sophisticated adaptive, dynamic algorithms based on signal and channel statistics to achieve optimum performance has drawn renewed attention to run-time reconfigurability.

The *Adaptive Wireless Networking (AWGN)* project aims to develop digital signal processing (DSP) technologies that can be used to design efficient adaptable and reconfigurable base stations and terminals for third and fourth generation wireless communication systems, such as UMTS. In order to achieve this, the project consists of two activities.

The goal of the *Mapping DSP algorithms to a reconfigurable architecture* activity of the *AWGN* project is to map a set of adaptive DSP algorithms, for wireless communication systems, on a reconfigurable heterogeneous architecture. The reconfigurable heterogeneous architecture is heterogeneous in the sense that signal processing is performed in general purpose processors, bit-level reconfigurable hardware or word-level reconfigurable hardware.

The goal of the *Adaptive DSP Algorithms for UMTS* activity of the *AWGN* project is to deliver a set of adaptive DSP algorithms that can be used in UMTS communication systems. This set of algorithms will be mapped to a heterogeneous reconfigurable architecture by the *Mapping DSP algorithms to a Reconfigurable Architecture* activity of the *AWGN* project.

In this paper we will give an introduction to the *Adaptive Wireless Networking (AWGN)* project. Research related to our project will be briefly described in section II. Our vision on adaptivity will be presented in section III. Both activities within the project will be highlighted in sections IV and V. A concluding summary will be given in section VI and directions for future work will be presented in section VII.

II. RELATED WORK

Spread spectrum communications techniques in the form of Code Division Multiple Access (CDMA), the multiple access technique on which UMTS is based, have been used in the commercial IS-95 second generation cellular wireless communication system for almost ten years [3]. Therefore techniques as fast power control and RAKE receiving, that are used in all cellular CDMA systems have been studied extensively. Spread spectrum communications techniques have already been used in military communications for over half a century, primarily because of their anti-jamming and covertness properties. So the basic techniques behind spread spectrum communications in general have been studied for an even longer time.

The improved internet and multimedia capabilities of third generation wireless communication systems require a variety of data services from low to very high bit rates. One way of achieving this in CDMA systems is through the use of orthogonal variable spreading-factor (OVSF) spreading [4]. This technique is used in UMTS. Since most internet and multimedia applications are asymmetric, downlink (base-station to mobile) traffic is expected to dominate in UMTS and other third generation wireless communication systems. To further increase the throughput, reduce delay and achieve high peak rates in the UMTS downlink advanced techniques like for example adaptive modulation and coding (AMC) and hybrid automatic repeat request (hybrid ARQ) are needed. These advanced techniques have been studied extensively [5] in the 3rd Generation Partnership Project (3GPP), the UMTS standards development group, resulting in the High Speed Downlink Packet Access (HSDPA) mode of UMTS, included in Release 5 of the UMTS specification.

Recently, the deployment of multiple antennas at both ends of a wireless communication link, resulting in so called multiple-input multiple-output (MIMO) communication systems, has received a lot of attention, because of the significant increases in capacity that these systems promise [6]. Multiple-input single-output (MISO) systems have received a lot of attention as well, because they avoid the extra costs and complexities of multiple antennas at the receiver and still provide some of the advantages of MIMO systems. MISO techniques as closed loop transmit diversity and space-time transmit diversity (STTD) based on orthogonal space-time block codes have already been included in the UMTS specification [7]. The performance of closed loop transmit diversity, STTD and other MISO and MIMO techniques in UMTS is being evaluated in the IST *I-METRA* project [8] and recently also in the 3GPP [9], [10].

So far most algorithmic level research on reconfigurability in UMTS, as for example in the *MuMoR* [11] and *Fitness* [12] projects, has focussed on multi-mode reconfigurability to enable Software Defined Radios (SDRs) supporting multiple communication system standards. The *EASY* project [13] aims at developing a power/cost efficient System-on-Chip (SoC) implementation of the HiperLAN/2 standard. In the *Adaptive Wireless Networking (AWGN)* project, however, we would like to use reconfigurability to allow the communications system to adapt to changing environmental conditions. Therefore we would like to study how techniques that are used in UMTS, as for example variable spreading factor spreading, RAKE-receiving, adaptive modulation and coding, MISO and MIMO, can be made adaptive to environmental conditions and how these techniques can make use of the reconfigurability of a heterogeneous reconfigurable architecture.

Recently, there have been several announcements of heterogeneous reconfigurable architectures on a single chip [14], [15]. For example, Xilinx delivers a combination of Virtex II FPGA technology and one or more PowerPC 405 – on a single chip –, the Virtex-II Pro. However, conventional reconfigurable processors are bit-level reconfigurable and are far from energy-efficient. At the University of Twente in the *Chameleon* project [16] the first steps have been made to define an energy-efficient heterogeneous reconfigurable System-on-Chip architecture. *Pleiades* at the University of California, Berkeley, is exploring reconfiguration of coarser-grain application-specific building blocks with an emphasis on low-power computations [17]. Chameleon Systems created one of the first practical commercial implementation of coarse-grain reconfigurable technology for data intensive Internet, DSP and other high performance telecommunication applications [18]. Furthermore, Quicksilver's *adaptive computing machine (ACM)* technology is intended for low-power mobile devices [19], whereas PACT [20] proposes an *extreme processor platform (XPP)* based on clusters of coarse-grained processing array elements.

III. ADAPTIVITY

In our opinion there are two kinds of adaptivity:

1) *Algorithm adaptivity*
   Parameters of an algorithm can be adapted in real-time, on-the-fly.
2) *Algorithm selection adaptivity*
   Assume that a function can be performed by different algorithms. One algorithm out of the set of different algorithms can be selected and used through reconfiguration of the hardware. The selection procedure of a suitable algorithm depends on the conditions of the wireless channel and the user demands (the number of interfering users, the required QoS, etc.) and has to be done at run-time.

Both the base station and the terminal show possibilities for application of these kinds of adaptivity.

A. Examples of algorithm adaptivity

The number of RAKE fingers can be changed according to the conditions of the wireless channel. It is known that the number of multi-path components varies due to scattering in the environment. Research on an adaptive RAKE receiver is done in the *Chameleon* project [1].

Utilizing multiple antennas can increase the capacity or improve the performance of a wireless communication system. Adapting the gain factors of the signals from different antennas will lead to different behaviour of the multiple antenna system. Hence, changing the combining rules of the signals from different antennas will change

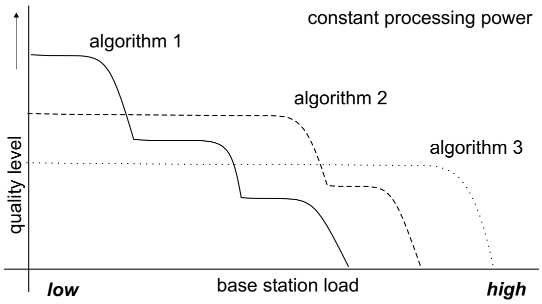

Fig. 1
QUALITY LEVEL/BASE STATION LOAD TRADE-OFF.

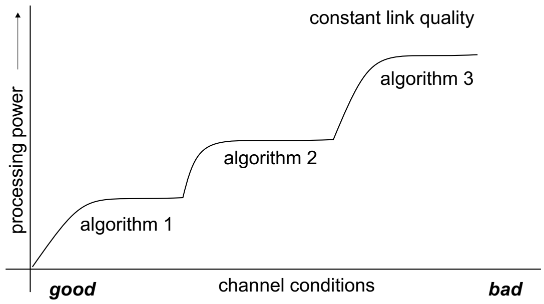

Fig. 2
PROCESSING POWER/CHANNEL CONDITIONS TRADE-OFF.

the behaviour of the multiple antenna system from beamforming to diversity, or vice versa.

B. *Examples of algorithm selection adaptivity*

Assume that a certain function in a UMTS base station has three quality levels. Assume also that this function can be performed by three different algorithms and that a fixed amount of processing power is available at the base station. The first algorithm meets the highest quality level but also requires the highest amount of processing power. The second algorithm only meets the middle quality level but with the available amount of processing power it can handle a higher base station load for that quality level than the first algorithm can. The third algorithm only just meets the lowest quality level but with the available amount of processing power it can handle a higher base station load for that quality level than the first and second algorithm can. So by switching between the three algorithms depending on the base station load it is possible to achieve a higher quality level over a base station load range than with the use of just one algorithm, see Fig. 1.

Assume, in another example, that a certain function in a UMTS terminal requires a constant link quality independent of the number of interfering users. Assume also that this function can be performed by three different algorithms, which require different processing power levels while they supply equal link quality levels for different conditions (for example different Multiple Access Interference (MAI) levels), see Fig. 2. Algorithm 1, which requires the least processing power, can be utilized in case there exists a small number of interfering users in a cell. When the MAI due to interfering users increases, so when the conditions of the wireless channel become worse, the terminal receiver should spend more effort in order to supply the same link quality level. However, the link quality level cannot be met by algorithm 1 anymore and the receiver should switch to a more complex receiver algorithm, algorithm 2. As a consequence of the complexity of the algorithm, it requires more processing power. When the channel conditions become even worse, the receiver should switch to the most sophisticated algorithm, i.e. algorithm 3, in order to fulfill the quality requirements on the supplied wireless link.

Nowadays, terminal receivers are designed according to worst-case conditions. Hence, algorithm 3 will always be used in a terminal in order to satisfy to the link quality level. However, in real-life the behaviour of the wireless channel is most often better than the worst-case scenario and so more power-efficient algorithms can be used.

IV. MAPPING DSP ALGORITHMS TO A RECONFIGURABLE ARCHITECTURE

The *Mapping DSP algorithms to a reconfigurable architecture* activity will mainly focus on the terminal part of the downlink of a UMTS communication system. The focus will be on mapping DSP algorithms on a heterogeneous reconfigurable architecture. The reconfigurable architecture consists of general purpose processors, bit-level reconfigurable hardware and word-level reconfigurable hardware. The following approach is taken:

1) We start with studying the state-of-the-art in baseband processing algorithms for Bluetooth, HiperLAN/2 and UMTS. A multi-standard communication system is considered because in next generations (3G+ / 4G) the reconfigurable hardware has to support the integration of multiple standards.
2) Next we define a set of typical algorithms to be mapped on the heterogeneous reconfigurable platform.
3) Finally the set of algorithms is mapped onto the reconfigurable platform.

The main questions that this research will answer are:

- On which part of the reconfigurable hardware have the algorithms to be mapped?

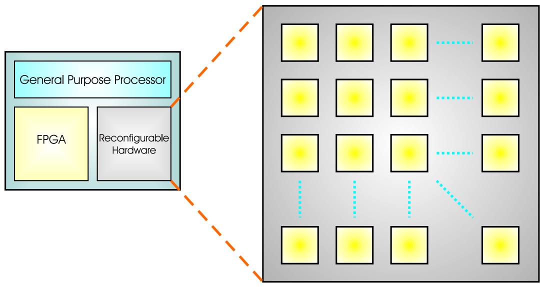

Fig. 3
CHAMELEON HETEROGENEOUS SOC ARCHITECTURE

- How have the different algorithms to be scheduled over the heterogeneous reconfigurable platform?

A. Reconfigurable heterogeneous architecture

In the *Chameleon* project [16] at the University of Twente a dynamically reconfigurable heterogeneous System-on-a-Chip (SoC) is being defined. The SoC contains a general purpose processor, a fine-grain reconfigurable part (consisting of FPGA tiles) and a coarse-grain reconfigurable part (see Fig. 3). The latter comprises several MONTIUM processor tiles. The algorithm domain of the MONTIUM comprises 16-bit digital signal processing (DSP) algorithms that contain multiply accumulate (MAC) operations. A MONTIUM-tile is designed to execute highly regular computational intensive DSP kernels [21]. The irregular parts of the algorithms run on the general purpose processor. The SoC yields a combination of performance, flexibility and energy-efficiency.

B. State of the art

By studying the state-of-the-art in Software Defined Radio (SDR) for Bluetooth, HiperLAN/2 and UMTS, we will define a set of typical DSP algorithms used in wireless communications. Currently, the physical layers of two communication systems are subject of our research: a rather complex wireless LAN system, the HiperLAN/2 standard that has the same physical layer as IEEE 802.11a, and a less complex communication system, the Bluetooth standard. These two communication standards have been selected, because they are already part of ongoing research at the University of Twente [22] and they are different enough to give an indication whether our approach is feasible or not. For both communication systems we analyzed the feasibility of implementing the systems in the target architecture. We considered the MONTIUM architecture and assumed that the clock frequency of the MONTIUM-tiles was 100 MHz [23].

As a first experiment we have mapped the baseband processing part of the HiperLAN/2 receiver onto MONTIUM-tiles. We described the most important functions (most computational intensive) that are being subject to further research, in order to map the functionality on the MONTIUM architecture. We only considered the receiver part of the HiperLAN/2 physical layer, although the transmitter part can be described in a similar way.

In order to perform all receiver processing (excluding the synchronization and control processing part), 2 or 3 MONTIUM-tiles are required (depending on modulation type), when we assume the tiles to run at a clock frequency of 100 MHz. We estimated the processing delay in the receiver of one OFDM symbol to be about 11 μs when 64-QAM modulation is applied. Furthermore, the processing delay using BPSK modulation will be about 8 μs. Hence, we have an adaptable HiperLAN/2 receiver, which can be implemented in 2 or 3 MONTIUM-tiles depending on modulation scenario. In this way the baseband processing of one OFDM symbol is pipelined over multiple MONTIUM-tiles, since every 4 μs a new OFDM symbol has to be processed. The actual modulation type used depends on the channel conditions. This initial experiment shows that adapting to the channel conditions is useful for saving baseband processing.

The functionality of the Bluetooth receiver appeared to have a fairly simple signal processing part, which can be implemented in the MONTIUM architecture quite well. The computation delays of the different receiver parts seem to be a few clock cycles. The processing while receiving one bit takes about 130 ns, when a FIR filter with 50 coefficients is applied and the clock frequency of the MONTIUM-tile is 100 MHz.

This experiment showed the flexibility of the MONTIUM. An HiperLAN/2 receiver was implemented, which can adapt to the used modulation scheme, as well as a flexible Bluetooth receiver on the same architecture. Long-term as well as short-term reconfiguration of the MONTIUM has been demonstrated. The implementation of both Bluetooth and HiperLAN/2 baseband processing in the MONTIUM architecture shows the ability of the MONTIUM architecture for long-term configuration. Furthermore, the HiperLAN/2 baseband receiver showed the ability of short-term reconfiguration, while the configuration depends on the used modulation type.

V. ADAPTIVE DSP ALGORITHMS FOR UMTS

The *Adaptive DSP Algorithms for UMTS* activity will focus on the downlink of a UMTS communication system including its High Speed Downlink Packet Access (HSDPA) mode. The focus will be on developing adaptive

DSP algorithms for use in the receiver of a UMTS terminal. The development of these adaptive DSP algorithms will consist of the following research steps:

1) Study the algorithms that are currently used in the UMTS terminal receiver and determine if and how they can be made adaptive.
2) Determine the downlink capacity and energy improvements that can be achieved by using adaptive algorithms in the UMTS terminal receiver.
3) Determine whether there are functions in the UMTS terminal receiver that can be implemented with different algorithms that have a different processing power/channel conditions trade-off.
4) Find criteria for switching between the algorithms that implement these functions.
5) Determine the downlink improvements that can be achieved by switching between different algorithms for implementation of functions in the UMTS terminal receiver.

The two main questions that this research will answer are:

- Can the algorithms that are currently used in a UMTS terminal receiver be made adaptive and what are the downlink improvements that can be achieved by the adaptive versions of these algorithms?
- Is it possible to implement functions in the UMTS terminal receiver with algorithms that have a different processing power/channel conditions trade-off for a given link quality level and what are the downlink improvements that can be achieved by switching between these algorithms?

A. DSP Algorithms in the UMTS Downlink

The first research step in the *Adaptive DSP Algorithms for UMTS* activity consists of studying the algorithms that are currently used in the UMTS terminal receiver and determining if and how these algorithms can be made adaptive. In order to be able to do that these algorithms first have to be identified. A brief summary of the algorithms used in the UMTS terminal receiver, with references to the UMTS specification, will therefor be given in this section.

As already stated, UMTS uses orthogonal variable spreading-factor spreading [24]. To combat multipath fading in the UMTS terminal a RAKE receiver is used for despreading. On the UMTS downlink closed-loop power control is used. This means that the base station transmit power is controlled by transmit power control (TPC) commands sent by the terminal. To generate these TPC commands the terminal receiver should be able to estimate the received signal-to-interference ratio [25]. Since the UMTS transmitter can use closed loop transmit diversity or space-time transmit diversity (STTD) [7] the terminal will have to be able to generate channel state information (CSI) that is used for closed loop transmit diversity and the terminal will have to be able to do space-time decoding. In UMTS convolutional or Turbo channel coding can be used [26], so the receiver will have to implement decoding functions for both channel coding methods.

To support HSDPA the terminal receiver will have to be able to generate channel quality indicator (CQI) messages [25] used by the base station for adaptive modulation and coding. Since the transmitter can use 16-QAM modulation in HSDPA, next to the QPSK modulation that is normally used in the UMTS downlink [24], the terminal receiver will have to implement 16-QAM as well as QPSK demodulation. Furthermore the HSDPA enabled receiver will have to support hybrid ARQ [26].

B. State of the art

To start the study on adaptivity in the UMTS receiver we have build a simulator of an UMTS transmitter and receiver. The simulated transmitter supports orthogonal variable-spreading factor spreading and QPSK and 16-QAM modulation. The simulated receiver supports orthogonal variable-spreading factor RAKE-receiving and QPSK and 16-QAM demodulation. To simulate an actual UMTS receiver realistically, cell-search, path-search and channel estimation have been implemented in the simulated receiver as well. The simulator can simulate multipath AWGN channels and multipath Rayleigh fading channels with doppler spread due to motion of the terminal. Currently simulations are performed to study the performance of the UMTS downlink receiver under various channel conditions and to study how this performance is influenced by changing transmitter and receiver parameters.

Of the algorithms in the UMTS downlink receiver that have been implemented thus far, the *path-search* and *channel estimation algorithms* seem to be the most suitable algorithms for adaptivity that depends on environmental conditions, because their performance relies strongly on the experienced channel conditions. The performance of these algorithms can be influenced by changing receiver parameters such as for example filter lengths.

VI. SUMMARY

The *Adaptive Wireless Networking (AWGN)* project aims to develop methods and technologies that can be used to design efficient adaptable and reconfigurable base stations and terminals for third and fourth generation wireless communication systems, such as UMTS. In the project we study the use of reconfigurability to allow wireless communication systems to adapt to changing environmental conditions and user demands.

Therefore we would like to study how techniques that are used in UMTS can be made adaptive to environmental conditions and how these techniques can make use of the reconfigurability of a heterogeneous reconfigurable architecture.

The project consists of two activities:

1) Mapping DSP algorithms to a reconfigurable architecture
2) Adaptive DSP Algorithms for UMTS

The first activity considers the hardware level, while the second activity studies the algorithmic level of wireless communication systems.

The focus of the first activity will be on mapping DSP algorithms on a heterogeneous reconfigurable architecture.

The first research step in the second activity consists of studying the algorithms that are currently used in the UMTS terminal receiver and determining if and how these algorithms can be made adaptive. In order to be able to do that these algorithms have to be identified first. Furthermore one has to investigate what downlink improvements can be achieved by the adaptive versions of these algorithms.

VII. Future work

A. Mapping DSP algorithms to a reconfigurable architecture

The set of multi-standard algorithms is rather incomplete. In further research, more adaptive algorithms should be considered. An interesting case will be systems that adapt to changing environmental conditions as well as to changing user demands (QoS). A control system that is able to adapt the WCDMA receiver in order to minimize the energy consumption, while satisfying the quality constraints at run-time is presented in [1]. These adaptations should be done at run-time to deal with the continuously changing external environment.

Power consumption is another important issue, since energy-efficiency is a major issue in mobile terminals. At the moment, the energy consumption of the MONTIUM architecture is estimated at 5 mW per tile in .12 technology with a size of 2.7 mm^2 per tile. Comparison of the algorithm mappings as compared to other types of architectures should be done in terms of performance and power consumption.

Finally, scheduling of tasks on the reconfigurable heterogeneous architecture can be implemented in different ways: Multiple tiles can perform different functions instantaneously, while the data in the tile is changing dynamically or the data stays in one tile, while the tile is reconfigured dynamically. Simulations have to show the advantages and disadvantages of these scheduling strategies, therefore a high-level reconfigurable architecture simulator will be developed using OMNeT++ [27].

B. Adaptive DSP Algorithms for UMTS

Future research in the *Adaptive DSP Algorithms for UMTS* activity can follow two paths: The first path starts with the implementation of channel coding support in the simulator. When the generation of channel quality indication (CQI) messages is implemented as well, this will enable us to study adaptive modulation and coding. Studying hybrid ARQ in addition will require the implementation of cyclic redundancy checks (CRCs) and of course the hybrid ARQ algorithms themselves. The second path starts with the implementation and simulation of closed loop and space-time transmit diversity. After that MIMO techniques that require multiple receive antennas at the terminal can be considered.

Signal to interference ratio (SIR) estimation algorithms that are used in power control are another set of algorithms that are interesting from an adaptivity on environmental conditions point of view.

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