ENCLOSURE A:

In-depth description of the Research Proposal

Bandwidth-Efficient and Adaptive Transmission Schemes for Wireless Multimedia Communications*

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1 Introduction and motivation

Broadband wireless access, e.g. to the Internet, may in the future replace many fixed-wire connections in telecommunications. Wireless technology can be rolled out rapidly, thus bypassing the need for installation of new cables. Wireless broadband technology also encourages *mobility*, allowing people on the move to access interactive multimedia services such as video conferencing, e-commerce, location services, and computer games.

An acceptable Quality of Service (QoS) for future multimedia services (e.g. high audio and video quality, high reliability, strict real-time constraints) can only be achieved by realizing much *higher information rates* than those available in today's wireless systems. At the same time, *bandwidth* is becoming an ever-scarcer resource as the number of systems, users, and services increase. If real-time, high-quality multimedia services are to be supported in future wireless systems, there is thus a need for novel transmission schemes—i.e. compression, modulation, error control, and access techniques. The schemes must provide bandwidth-efficient, robust communication with low delay, supporting multiple users on broadband wireless channels. Since *time-varying*[1] *channel conditions*—and thus *time-varying channel capacity*—is an important feature of wireless and mobile communication systems, future such systems should exhibit a high degree of *adaptivity* on many levels in order to reach these goals [1, 2]. Examples of such adaptivity are: information rate adaption, power control, code adaption, bandwidth adaption, antenna adaption, protocol adaption.

2 Overall goals and project description

This proposal addresses some critical components in future wireless broadband communication systems, with particular emphasis on important transmission technology aspects. The proposal is a follow-up project to the ongoing activity on *efficient channel coding and modulation* (activity A1.2) in the current NFR project WIRAC (WIdeband Radio ACcess).[2] We focus on the development of *bandwidth-efficient and adaptive transmission schemes for broadband wireless multimedia communications.*

2.1 Scope

The main research ideas covered by this proposal are:

- **Design and study of adaptivity and diversity in information transmission schemes**, with *adaptive coded Orthogonal Frequency Division Multiplexing* (OFDM) in combination with *antenna diversity* as the currently most promising scheme for bandwidth-efficient digital communications on broadband radio channels (see Section 3 for further details).
- **Signal processing aspects of smart antennas**, for further increase in bandwidth efficiency (see Section 4).

*Any further questions regarding this proposal may be e-mailed to *G. E. Øien* at *oien@tele.ntnu.no*.

[1] And, to a certain extent, unpredictable.

[2] This activity was recently evaluated as part of the WIRAC mid-project evaluation, and was found by the evaluation committee to have "high academic value".

Although very focused from a technology point of view, our ideas are generic in the sense that they might be exploited both in fixed wireless access and satellite communications, as well as in fourth generation (4G) mobile cellular systems. Also, short-distance wireless communication at much larger rates than those supported by the current Bluetooth standard may be enabled.

A truly optimal system design must start at the physical layer. However, insight into user and market needs, overall system specifications, and network protocols and architectures is of course also important when devising transmission schemes for future communications systems. Some keywords are: foreseen services, demands on Quality of Service (QoS), available frequency bands, fundamental technological limitations, standardization issues, and system costs. We will evaluate our ideas also with such perspectives in mind.

2.2 Personnel

The collaborating researchers are:

- Senior Research Scientist, dr. scient. Kjell J. Hole, Coding Theory Group, University of Bergen (UiB)
- Associate Professor, dr. ing. Geir E. Øien, Signal Processing Group, NTNU (project manager)

Hole and Øien have already collaborated on *Adaptive Trellis Coded Modulation (ATCM)* within the WIRAC A.1.2 activity (see Section 3 and Enclosures D, E for further details on previous research in this field and related fields), and will build on this collaboration in their future research.

For an overview of the partners' previous publication activities within fields relevant for this proposal, we refer to Enclosure D, which contains a complete list of relevant publications sorted by topic.

2.3 Organization, dissemination, costs, and industrial support

The project will be administrated by The Department of Telecommunications at NTNU (see Enclosure E). Our research will be done in cooperation with *one new PhD student*, as well as in interaction with two PhD students already working at NTNU.[3] For the dr. ing. position, we already have an interested and able candidate. We plan to assign research duties in the project as follows:

- Dr. ing. student: **Diversity techniques and signal processing in smart antennas** (Supervisors: Associate Professor Geir E. Øien and Senior Research Scientist Kjell J. Hole).
  - Candidate: Research Scientist *Bengt Holter*, currently with SINTEF Telecom and Informatics. Mr. Holter already has relevant research experience on adaptive and smart antennas through his participation in the WIRAC project over the last two years (see Enclosures D and E).
- Kjell J. Hole: **Adaptive coding and modulation for OFDM systems, and use of diversity in wireless communications.**
- Geir E. Øien: **Adaptive coding and modulation for OFDM systems, channel estimation, diversity and smart antenna signal processing.**

We will integrate all activities through project seminars and lectures, so that all participants are able to see how their own research has a place in the overall system concept and how it fits in with other research performed in the project. Thus all participants will become knowledgeable about all the components studied in the project, as well as the motivation for studying them. This will also enable cross-fertilization of research ideas between the different sub-topics, and, ultimately, publications where ideas from the different sub-topics are united.

We also expect to supervise about 5 final year siv.ing. students each year within the scope of the project.

The research results will be published in acknowledged international journals, as well as in high-quality (refereed) conference proceedings (internationally and nationally). A WWW project page will be set up presenting and documenting our activities. We refer to point 13 "Project Publication Plan" in the standard NFR application form as well as to Sections 3–6 for further details on our plans for publication.

The total cost of the project is approximately NOK 4.100.000,- over four years, of which we apply for approximately NOK 3.700.000,- from The Norwegian Research Council (NFR). A detailed cost plan is submitted in Enclosure C.

[3] These two students are: Henrik Holm (financed by NFR via the WIRAC project; thesis on ATCM for narrowband channels), and Ola Jetlund (Telenor-financed project; thesis on turbo coding for wireless applications).

3 Adaptive coding and modulation for broadband channels

Adaptive Trellis Coded Modulation is a promising bandwidth-efficient transmission strategy with short overall delay for *narrowband* channels. *Broadband* channels may be decomposed, using OFDM, into a set of narrowband subchannels. By employing ATCM on each individual subchannel, broadband transmission schemes supporting rates much higher than those found in today's wireless systems may be designed.

In this section we give a brief overview of the history and current state-of-the-art of ATCM for narrowband fading channels. We also describe how our own research in this field have contributed to the current state-of-the-art. We thereafter describe our plans and ideas for the development of ATCM schemes for multimedia communications over broadband[4] fading channels.

3.1 Background and current state-of-the-art

Many authors [3]–[17] have contributed to the development of ATCM for single-user, slowly varying, narrowband fading channels. An ATCM scheme typically utilizes a set of trellis codes originally designed to combat additive white Gaussian noise (AWGN). A feedback channel between the transmitter and the receiver makes it possible to transmit at high information rates under favorable channel conditions and respond to channel degradation through a smooth reduction of the information rate. The ATCM schemes described in [9, 10, 16] utilize sets of two-dimensional trellis codes [18, 19], while the ATCM scheme described by Hole and Øien [15] may also utilize sets of multidimensional trellis codes, i.e., in practice codes with dimensions 4, 6, and 8 [20, 21, 22]. Multidimensional trellis codes are of particular interest since some such codes offer a significantly better performance/complexity tradeoff than two-dimensional codes [21].

Hole and Øien [15] have shown that multidimensional ATCM with fixed transmit signal power achieves a much larger *Average Spectral Efficiency* (ASE), measured in bits/s/Hz, than the spectral efficiency of today's wireless narrowband systems such as GSM. Moreover, they have analyzed the effect of the delay in the feedback channel and shown how ATCM may support multimedia communications, i.e., parallel transmission of multiple data streams with different quality of service requirements [23].

Most of the above cited research considered ATCM in single-user communications systems. However, wireless systems must support a large number of users (terminals). Hole and Øien [24] have analyzed the performance of ATCM in an urban microcellular network with a large number of active terminals, where each individual wireless link is modelled as a narrowband fading channel.

3.2 Planned research on ATCM for broadband channels

Future wireless systems must support multimedia applications, and it is therefore necessary to determine spectrally efficient modulation and error control techniques for **broadband** fading channels. OFDM may be used to decompose a broadband fading channel into a set of parallel narrowband subchannels [25, 26, 27]. We therefore propose to use ATCM schemes optimized for flat fading channels on individual subchannels of an OFDM system to achieve wireless broadband transmission with large ASE.

3.2.1 Phase 1: Single-user systems

During the first phase of our research we will analyze a general ATCM scheme employed on single-user OFDM broadband fading channels. Initially we will focus on deriving the average spectral efficiency of such a system for a given target bit-error-rate, and see how it is dependent on the system and channel parameters—e.g., transmit power, coding schemes, receiver antenna structure, noise level, fading dynamics, *et cetera*). Such analysis is essential e.g. for being able to design or select good channel coding and modulation schemes for adaptive wireless systems, to predict overall system performance for a given choice of practical system parameters, or to choose these parameters such that the demands on QoS are satisfied.

ATCM based on *Quadrature Amplitude Modulation* (QAM) is of particular interest because QAM allows us to achieve large average spectral efficiencies on all subchannels. Preliminary work has shown that it is possible to determine the total ASE of OFDM/ATCM/QAM systems, and that these expressions may be optimized for different parameters of practical interest. The preliminary results indicate that it is possible to obtain a significantly larger information throughput for a given channel bandwidth than what is obtainable e.g. with the new ETSI standard for OFDM, *HiperLAN2*.

3.2.2 Phase 2: Multi-user systems

In the second phase of our research we want to study *wireless networks* for multimedia communications where OFDM/ATCM is used on the wireless broadband links. We plan to study both cellular networks and *ad hoc* networks. We will start this phase by generalizing our results for narrowband networks described in [24]. We will study the *Average Link Spectral Efficiency* (ALSE) when all links in a network utilize the same (general) OFDM/ATCM scheme, and also analyze the *Average Area Spectral Efficiency* (AASE). The AASE provides

[4] We take the term "broadband channel" to mean a channel with *frequency-selective* channel transfer function.

a measure of the spectral efficiency of a complete network, as opposed to the ALSE which only measures the single-link efficiency. We also want to determine how the AASE depends on the frequency reuse and cell size of a network. The purpose of this research is to find quantitative performance measures which will enable designers to choose link and network parameters (coding schemes, cell size, carrier frequency reuse, transmit power control, *et cetera*) such that overall system performance becomes as good as possible.

Further research will include analysis of data link and network layer *protocols* for efficient utilization of OFDM/ATCM/QAM. We will also analyze whether or not ATCM should be used for satellite communications.

The success of ATCM is ultimately dependent on good knowledge of the channel dynamics at the transmitter. One final important research challenge is therefore to extract the best possible estimate of the overall channel conditions at any given time, given a realistic statistical model of the channel variations in any subchannel. This channel state estimate must then be used to adapt the transmitter in the best possible way (i.e., such that overall information throughput is maximized, subject to the condition that the QoS demands are still met). For this purpose, optimal channel estimation and prediction techniques will be investigated and analyzed. There will always be a nonzero degradation of system performance compared to the ideal case (i.e., that of perfect channel knowledge) when only imperfect channel state information is at hand [28]. We will focus on making this degradation as small and controlled as possible. Some preliminary work has already been done in this area [23].

At least 3 international journal papers and 5 papers in refereed conference proceedings are expected as a result of our ATCM research.

4 Smart antenna signal processing and spatial diversity

4.1 Background

In the early days of mobile wireless communications, base stations were equipped with antennas giving radio coverage with a static omnidirectional radiation pattern. An omnidirectional pattern was chosen because the base station had no way of knowing the exact position of the mobile units.

In the last decade, a rapid growth in the number of mobile subscribers within a limited frequency band has forced the mobile network operators to seek for more capacity by designing new, spectrally efficient transmission schemes. The increased number of mobile units have made the wireless channels more hostile with problems of increased interference due to multipath propagation and co-channel interference. To increase the capacity of the mobile network and to reduce the level of interference, *sectorization* of mobile cells was introduced. Each base station then has *several array antennas* instead of just one omnidirectional antenna.[5]

Sectorization gives radio coverage within a predefined area of the complete mobile cell, and thus higher directivity within a confined area. Sectorization was the beginning of the utilization of space as an additional degree of freedom to be used for capacity increase and radio channel enhancement. Increased computational capacity of digital signal processors (DSPs) have now made it possible to track moving mobile units in real time. The base station can exploit the DSP computational power to use the array antennas as adaptive spatial filters, giving the base station the ability to exploit a dynamically changing radiation environment by adapting its own radiation pattern. This is done such that the channel conditions between the mobile units and the base station are optimized. Because of this ability, the expression "adaptive antenna" or "smart antenna" is used for such base stations.

The introduction of space as a new degree of freedom has led to the expression *space-time processing*. The aim of space-time processing is to combine spatial and temporal processing to attain results which cannot be obtained by either type of processing individually [30]. Array antennas have been used for decades, but it is the combination of antenna theory and digital signal processing algorithms that makes the antenna arrays "smart". In the last decade, the increase in research on this topic has been tremendous [31]. A vast number of research papers has been published, presenting results that predict large improvements by utilizing adaptive antennas in future wireless communication systems. By the beginning of this millennium, the first prototypes of adaptive antennas has been implemented [32, 33] and some are even ready to enter the market [34].

4.2 State-of-the-art and own contributions

Smart antennas is an interdisciplinary field, involving antenna theory, radio channel propagation, and digital signal processing [35]. It is foreseen that work within this field will play a key role in the development of future wireless communication systems. Some important state-of-the-art research results on smart antennas can be found in [36]–[45].[6]

There has also been research activity on smart antennas at SINTEF Telecom and Informatics within the WIRAC project. The research, to which Bengt Holter has contributed significantly, have concentrated on

[5] An antenna array consists of several single element antennas assembled in a specific electrical and geometrical configuration.
[6] A more complete list of smart antenna references can be found at *http://www.ee.vt.edu/rertel/aa/ref.html*.

studying how the channel conditions influence the antenna structure. This has been done with the utilization of *spatial diversity* in mind. Spatial diversity may mitigate the effects of multipath propagation.

An adaptive antenna can be used to filter out just those copies of the received signal which are useful for further processing, by placing nulls in the radiation pattern in the directions of the unwanted signals. To achieve an optimum solution, the number of unwanted copies (i.e. unwanted directions, if all copies come from different directions) must not be too large. A linear antenna array with N antenna elements has $N-1$ degrees of freedom, which implies that the antenna array—in addition to receiving a wanted signal through its main lobe—can place a maximum of $N-1$ nulls in its radation pattern to reduce the total interference level. If the number of interfering signals exceeds $N-1$, there will thus be a gradual degradation from the optimum signal-to-interference level.

The performance of an adaptive antenna within this scenario, utilizing a simple least-mean-squares algorithm, is investigated in [46]. The behaviour of the adaptive antenna is determined by the choice of a suitable adaptive algorithm. Because of this, smart antenna research is focused on analyzing and finding a suitable signal processing algorithm based on knowledge of the propagation environment.

4.3 Planned research

An adaptive antenna is able to do filtering both in time and space. The traditional way of sharing a limited frequency band between several users is either by frequency, time, or code division. With an adaptive antenna, however, spatial filtering can also be used as an access method. This technique is called *Spatial Division Multiple Access (SDMA)* and can be exploited to separate users in space.

Our research will be directed towards adaptive signal processing algorithms utilizing the space dimension in this and related ways. We will particularly investigate novel algorithms for optimized reception of broadband signals transmitted with an OFDM/ATCM transmission scheme (cf. Enclosure B).

Another interesting research topic will be the study of how imperfect channel state information (due to estimation errors and channel dynamics) degrade the performance of a system utilizing smart antennas and spatial diversity, and how the degradation can be controlled. This problem will be analyzed from an estimation- and information-theoretic perspective, to see how a practical system differ from the idealized model in [47].

At least 2 international journal papers and 3 papers in refereed conference proceedings are expected as an outcome of our research on diversity techniques and smart antenna signal processing.

5 Collaborations and possible future follow-up activities

5.1 Present collaborations

Nera Research has a strong interest in our research. Øien and Hole are at present acting as consultants for Nera Research, with the purpose of performing a feasibility study concerning the use of adaptive coding and modulation in *satellite communications*. One planned outcome of this collaboration is a joint research paper by Øien, Hole, and researchers *Bjarne Risløw* and *Pål Orten* at Nera Research. We will also keep in close contact with Nera concerning other facets of our research, cf. the section on predistortion research. Risløw and Orten have agreed to be listed as project collaborators (cf. point 12 in the NFR application form).

Internationally, we have a long history of contact with some of the leading research institutions within signal processing, digital transmission, source and channel coding, and wireless communications—e.g., Washington State University (Prof. Thomas R. Fischer), University of San Diego (Prof. Jack K. Wolf), University of Santa Barbara (Prof. Sanjit K. Mitra), California Institute of Technology (Prof. P. P. Vaidyanathan), Chalmers Institute of Technology (Prof. Arne Svensson), University of Minnesota (Ass. Prof. Mohamed-Slim Alouini), and several others. These contacts have resulted in joint publications, guest researcher exchanges and sabbaticals, student exchange at the graduate and undergraduate level, mutual participation in doctoral defense committees, invited lectures, *et cetera*. We will continue to build on the above and other international contacts in the future, in order to keep strong links between our research and the international state-of-the-art.

5.2 Possible future activities

A natural follow-up to the present research project would be to include the suggested activities in our original IKT-2010 application, submitted to NFR in June 2000. In the present project description, two important research fields had to be left out due to budget cuts:

- joint source-channel coding (led by prof. Tor A. Ramstad)
- digital baseband predistortion (led by prof. Nils Holte).

As suggested in our original system concept we view these fields as important candidate technologies for inclusion in future wireless and mobile multimedia communication systems. We will therefore try to find funding for a PhD student on each of these two topics in the future.

In 2001 we also plan to apply to NFR for money to cover Dr. Kjell J. Hole's wages for the year 2004, which is not a part of our current budget. This extension will be of vital importance, both regarding continuity in our research, and in order to secure supervision for our dr. ing. student for his complete period of studies. Furthermore, we plan to apply for some more funding in order to cover foreseen increases in operating costs, including travel activities, books, equipment upgrades, and software tools.

Activities beyond such an extension could be directed towards a more implementation-oriented project. Such a project should concentrate on practical realization of the ideas that are deemed most promising in our research. The focus of such a follow-up project could be e.g. software radio technology with a particular emphasis on the ATCM/OFDM combination, combined with the use of higher frequency bands (typically 40–60 GHz), reconfigurable networking, adaptive antennas, and digital predistortion. This may lead towards the realization of advanced, adaptive solutions suitable for future low-cost telecommunications products for the mass market. In such a future project, *SINTEF Telecom and Informatics* would be a natural partner since they possess the necessary expertise on microwave technology and software radio implementation. The *Department of Physical Electronics* at NTNU should also be a partner in such a project.

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