

Bandwidth-Efficient and Adaptive Transmission Schemes for Wireless Multimedia Communications

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1 Introduction and motivation

An acceptable Quality of Service (QoS) for future wireless 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. Since *bandwidth* is becoming an ever-scarcer resource as the number of systems, users, and services increase, there is thus a need for novel transmission schemes. The schemes must provide bandwidth-efficient, robust communication with low delay, supporting multiple users on broadband wireless channels. Due to *time-varying channel conditions*, future mobile systems should exhibit a high degree of *adaptivity* in order to reach these goals [1].

2 The BEATS project

The research project BEATS (Bandwidth-Efficient and Adaptive Transmission Schemes for wireless multimedia communications) was initiated at NTNU in November 2000, financed by NFR's ICT-2010 programme. A full project description can be found on <http://www.tele.ntnu.no/projects/beats>. The topics covered are:

1. *Rate-adaptive transmission schemes.*
2. *Smart antennas.*
3. *Joint source-channel coding.*
4. *Transcoding in heterogenous systems.*
5. *Orthogonal Frequency Division Multiplexing.*
6. *Channel estimation and analysis.*

Figure 1 depicts how these components fit into a proposed architecture for a future wireless multimedia transmitter. The terminal accepts multiple analog (e.g. video, images, audio, speech) as well as digital (e.g. text, computer graphics, data files) inputs simultaneously. The components covered by our research are depicted as boxes drawn using thick (bold) lines in the figure.

3 Adaptive coding/modulation

Adaptive Coding and Modulation (ACM) is a promising bandwidth-efficient transmission strategy with short overall delay for *narrowband* channels. *Broadband* channels may be decomposed, using Orthogonal Frequency Division Multiplexing (OFDM), into a set of narrowband subchannels. By employing ACM on

each individual subchannel, broadband transmission schemes supporting rates much higher than in today's wireless systems may be designed.

Many authors [2]–[9] have contributed to the development of ACM. An ACM scheme typically utilizes a set of 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.

Hole and Øien [8] have shown that ACM based on multidimensional Trellis Coded Modulation with fixed average transmit power achieves an *Average Spectral Efficiency* (ASE), measured in bits/s/Hz, which is much larger than the spectral efficiency of today's wireless systems. The performance of ACM in an urban microcellular network with a large number of active terminals, where each individual wireless link is modelled as a narrowband fading channel, has also been studied.

3.1 BEATS research

We have analyzed a general ACM scheme employed on single-user OFDM broadband fading channels, deriving the average spectral efficiency for a given target bit-error-rate, and analyzing the scheme's dependence on important system parameters: transmit power, coding schemes, receiver antenna structure, noise level, fading dynamics). Such analysis enables design or selection of good channel coding and modulation schemes for adaptive wireless systems, prediction overall system performance for given system parameters, and setting of these parameters such that QoS demands are satisfied.

ACM based on *Quadrature Amplitude Modulation* (QAM) is of particular interest because QAM allows us to achieve large average spectral efficiencies on all subchannels. We have shown that it is possible to determine the total ASE of OFDM/ACM/QAM systems, and that these expressions may be optimized for different parameters of practical interest.

We are currently studying broadband *wireless networks* where OFDM/ACM is used on the individual wireless links. Both cellular networks and *ad hoc* networks are of interest. We generalize our results for narrowband networks described in [10], to derive

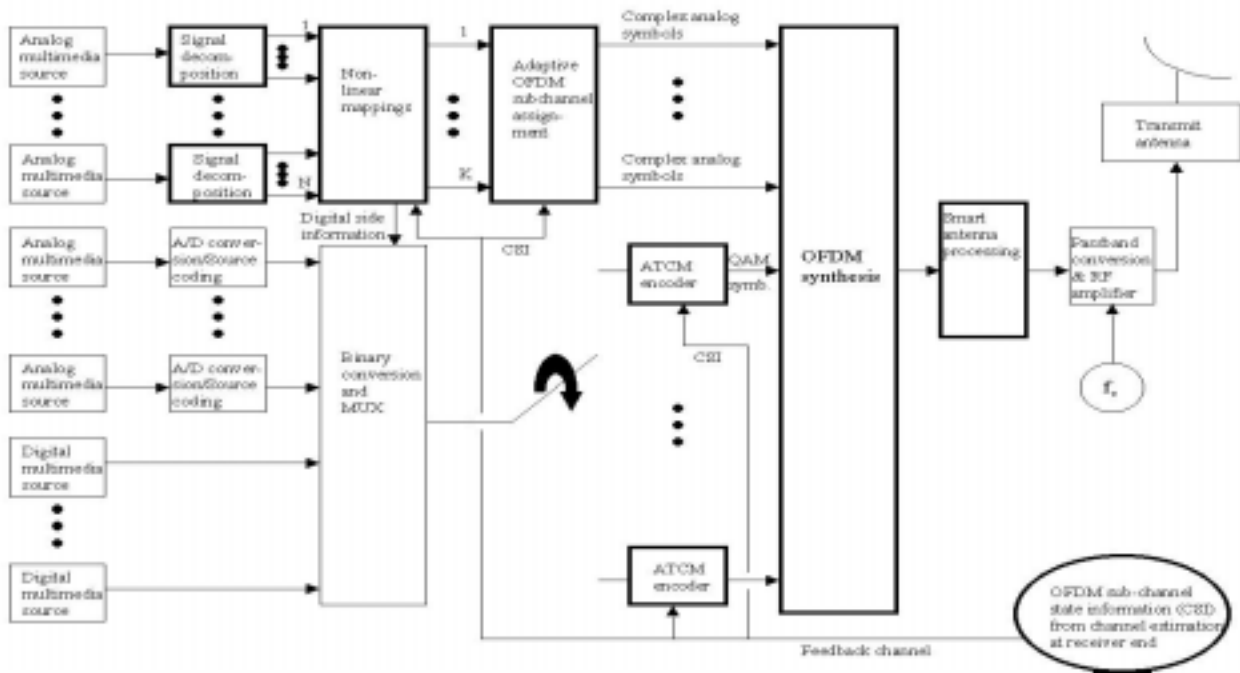


Figure 1: A possible multimedia transmitter structure.

quantitative performance measures which will enable designers to select parameters (coding schemes, cell size, carrier frequency reuse, transmit power control, *etc.*) which optimize system performance.

4 Smart antennas

In the early days of mobile wireless communications, base stations were equipped with antennas with a static omnidirectional radiation pattern. However, 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, *sectorization* of mobile cells was introduced. Each base station then has *several array antennas*.

Also, 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 use the array antennas as adaptive spatial filters, and thus has the ability to exploit a dynamically changing environment by adapting its radiation pattern. Because of this ability, the expression “adaptive antenna” or “smart antenna” is used. A relatively complete list of smart antenna references can be found at <http://www.ee.vt.edu/rertel/aa/ref.html>.

The introduction of space as a new degree of freedom has also led to the expression *space-time processing*. When spatial diversity is used both at the transmitter and receiver sides, the resulting system is called a *MIMO* (Multiple-Input Multiple-Output) system. Huge capacity gains have been predicted for such systems [13], making MIMO theory one of the hottest current topics in communication theory.

4.1 BEATS research

Our research is directed towards adaptive signal processing algorithms and MIMO algorithms utilizing the space dimension, particularly investigating novel algorithms for optimized reception and transmission of broadband signals in an OFDM/ACM setting. Another interesting topic is the effect of imperfect channel state information (due to estimation errors and channel dynamics) on the performance of a system utilizing smart antennas and spatial diversity, and how to control the degradation. This problem is analyzed to see how practical systems may differ from the idealized model in [13].

5 Joint source-channel coding

Joint source-channel coding (JSCC) is another promising strategy for bandwidth-efficient, reliable wireless communications, typically envisaged used e.g. on the uplink in mobile systems. By jointly exploiting the properties of both information source and communication channel, more robust and bandwidth-efficient transmission schemes may be devised, compared to “separable” schemes. JSCC schemes are specifically optimized with respect to a certain source (signal) model as well as a certain channel model. The challenge lies in *design and optimization* of practical JSCC structures coming close to fulfilling the theoretical potential.

Traditional communication systems are based on *Shannon’s separation theorem* [12] which states that overall optimality can be obtained by cascading an optimal source coder which removes all redundancy and adds imperceptible or acceptable signal noise, and an

optimal channel coder which adds redundant bits for explicit error protection. However, optimizing both coders generally require infinite complexity and delay. In contrast, our goal is to find optimal systems within *complexity and delay constraints*.

The research team at NTNU has performed some pioneering work, yielding results closer to theoretical bounds than other known works in the literature, with regard to performance under complexity and delay constraints. The obtained robustness towards deteriorating channel conditions is quite remarkable and superior to traditional digital systems (See e. g. [14, 15, 16, 17]).

The developed methods are based on time-discrete but amplitude-continuous channel symbols, and can be viewed as “continuous vector quantization.” Source vectors are approximated by points in continuous subsets of some multidimensional space, which are subsequently mapped onto the space of modulation symbols. These two stages can be viewed as a single step using dimension-changing nonlinear mappings which combine N source parameters into K channel parameters. When assuming ideal sampling and an ideal Nyquist channel, compression can be defined as $\eta = K/N$, i.e. the bandwidth reduction factor. In practice several mappings are used, in which case $\eta = E\{K/N\}$, where $E\{\}$ is the expectation operator.

5.1 BEATS research

A complete JSCC system will consist of a unit for signal decorrelation, e.g. a filter bank or a predictor; the mapping devices—usually several of them to adapt to the importance of the different source parameters; and the modulation unit, which e.g. maps the channel parameters to the I- and Q-components in an OFDM system. Figure 1 illustrates how such a system may be fit into the structure of a general multimedia terminal. Current research is directed towards image and video communications over band- and power-limited channels. Both signal decomposition methods and development of sets of optimal maps are considered for different applications and signal statistics.

In the terminal structure of Figure 1, the signal decomposition and the OFDM synthesis can be implemented using filter banks or linear transforms. The decomposition is done in a bandsplitting analysis filter bank, while the OFDM block performs component merging through a synthesis filter bank. The operations inbetween perform bandwidth change through the nonlinear mappings, and further signal-to-channel adaption by assigning appropriate channel bands to the different source parameters, depending on the importance of the source parameters and on the channel conditions. User-required quality in terms of bandwidth and signal quality can be guaranteed by such a resource allocation mechanism.

A final sub-goal is to integrate data and signal communications through reconfigurable channel constellations. In Figure 1 such reconfiguration is the task of both the “Adaptive OFDM channel assigner” and the ACM encoders.

6 Transcoding

The exploding use of telecommunications is mainly due to the emerging availability of affordable services for large groups of people. For cable transmission the advent of optical fibres and the available technology for exploiting them in communications have provided almost unlimited bandwidth. Possibilities for broadband wireless and mobile services on a large scale are, on the other hand, limited by the scarce available electromagnetic spectrum. For point-to-point communication where one or both communicators are mobile, the bottleneck is therefore undoubtedly the mobile connection(s). Special measures such as JSCC should hence be taken to obtain optimal solutions for communicating analog sources over mobile connections.

In the fixed part of the connecting network the “separation principle” philosophy prevails, in the sense that a digitized information stream will be transmitted. This stream should be fully error protected, thus making the network transparent. A natural solution is thus to make the very best effort for the mobile channel—implying JSCC and thus a time-discrete but amplitude-continuous format—and then do re-coding (*transcoding*) of the received analog information in the base station, to produce an efficient digital representation for further transmission.

6.1 BEATS research

The study of transcoding may lead to new optimality constraints on the JSCC algorithms; i.e. optimality for the complete system may call for joint design of the JSCC method and the transcoder. Complexity and delay issues may also impose important constraints.

The transcoding will involve digitization of the JSCC representations, and should provide low extra quantization error with a minimum total number of bits. It is a challenging task to produce first an optimal JSCC representation, and subsequently an optimal digital representation, such that the end result is as good as what would be possible if the original signal were coded “from scratch.”

7 OFDM optimization

OFDM can obtain bandwidth efficiencies close to the theoretical limits by matching different types of higher order modulation to the conditions in each frequency band. A tutorial introduction to OFDM is given in [18].

The majority of OFDM systems use square pulse shapes, and channel dispersion is compensated by using a cyclic prefix [19]. This solution has two drawbacks. Primarily, square pulses give large sidelobes in the frequency domain, which cause unnecessary out of band radiation for single user systems and prevent an efficient system for the uplink direction of a multiuser system. Secondly, a cyclic prefix adds redundant information and hence a reduction of the effective bitrate. These drawbacks can be avoided by using pulse-shaping [20, 21]. Both filter design [21] and efficient

implementation of systems with pulseshaping [20] has been solved for dispersionless channels. Other alternative methods must be found for compensating dispersive channels. One possible approach and an open problem is to design optimum pulseshapes which reduce the sensitivity with respect to the dispersion of the channel.

7.1 BEATS research

The plan is to find efficient methods to compensate for channel dispersion in OFDM systems with pulse shaping. One of the main strategies will be to find pulseshapes which minimise the sensitivity to channel dispersion and also have desired spectral properties. This is mainly a theoretical optimisation problem, but can also be investigated by simulation.

8 Channel estimation/analysis

The success of adaptive transmission is ultimately dependent on good knowledge of the channel at the transmitter. One important challenge is therefore to extract the best possible estimate of the channel conditions at any given time, given a realistic statistical model of the channel variations. This channel state estimate is used to adapt the transmitter in the such that overall information throughput is maximized, subject to the condition that the QoS demands are still met. There will always be a nonzero degradation of system performance compared to the case of perfect channel knowledge, when only imperfect channel state information is at hand [11]. We focus on making this degradation as small and controlled as possible. Analysis of the available channel capacity under various practical constraints is also a problem of great interest. Some preliminary work has already been done by in this area [22].

8.1 BEATS research

This research builds on existing results for idealized narrowband channel models, but takes into account channel estimation errors, practical return channel delays, QoS demands on transmission delay, more complex channel models etc. Methods for efficient channel prediction and estimation are investigated. The ultimate aim is optimization and analysis of such methods in an OFDM setting with antenna diversity.

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