Special Issue on Adaptive Modulation and Transmission in Wireless Systems

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The demand for high-quality mobile services similar to the fixed services that we have enjoyed in homes and offices for a number of years has significantly increased lately. Therefore, we can see an enormously increased amount of information that needs to be transmitted on wireless links. The spectrum available for these services is, however, currently very limited and the spectrum at all suitable for radio transmission is also quite limited. In order to cope with future demand, the available spectrum has to be used much more efficiently, and most likely more spectrum also must be made available for these systems. This Special Issue discusses the recent advances in technology for efficient utilization of the radio spectrum by means of adaptive modulation and transmission.

The radio links and communication systems must be designed to use the spectrum as efficiently as possible. At the same time, the quality of the link must be good enough for the service that is transmitted on the link. However, usually the quality should not be better either, since this, in general, is a waste of power, which is also a limited resource (at least in many battery powered units), besides the fact that it also increases the level of co-channel interference in multiuser systems. These two requirements are, however, mostly contradictory requirements. A spectrally efficient link usually requires more transmit power than a less spectrally efficient link, but transmit power also very much depends on the maximum transmission distance of the system.

This issue attempts to give the reader an understanding of the current status of the emerging field of adaptive modulation and transmission for wireless channels.

A radio channel behaves like a time-varying filter; the received version of the transmitted signal is a distorted version of the transmitted signal, and the distortion varies with time. On top of this, the channel attenuates the transmitted power exponentially with increasing distance between the transmitter and receiver, with an exponent which is typically between 2 and 5. Obstacles in the propagation path may also lead to a slow fluctuation in the received signal (so-called shadowing). In the receiver antenna, usually also interference from other radio transmitters are added to the desired received signal. Still, the receiver must be able to decode the data carried in the signal with an error probability which is equal or lower than the required performance. In many cases, the channel distortion and power attenuation can be estimated in the receiver and these estimates can be used to improve the performance of the data detection. However, lately it has been

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realized, first in academic circles by the early 1990s (Goldsmith, Hanzo, etc.), and then quickly after that in some of the currently used systems that it would be even better if the distortion and power attenuation (or rather signal-to-noise-to-interference ratio in the receiver) were known already in the transmitter such that the transmitted signal could be designed to work well for the given conditions.[1] As an illustration, we can think of a network of roads which carries vehicles of various kinds. Here, it is easy to understand that the traffic flow will be significantly improved if the road conditions are known already when you enter the road. Then, we can avoid having big trucks entering a narrow and windy road where they would get stuck anyway, while smaller cars can travel at high speed on excellent highways. The same is true for radio channels. If we already in the transmitter know that the channel and/or signal-to-noise-to-interference ratio in the receiver leads to poor conditions for high-rate data transmission, we would avoid such transmission, since the information would not be received with the required quality anyway. If, on the other hand, we know that the link quality is very good, we can use a transmission mode that allows the transmission of more information bits per symbol and, thus, increase the spectral efficiency.

One example of a communication system where this is used is a telephone line modem. During initiation of the modem, it measures the channel quality and adapts the transmitted signal to the given channel. With this technique, it is currently possible to transmit more than 10 bits of information in 1 Hz of bandwidth. This can be compared with cellular systems where not even 1 bit of information can currently be transmitted in 1 Hz of bandwidth. The telephone channel is, however, quite easy to work with since it does not change much over time which means that the channel measurements can be done seldom. The transmission quality on many radio channels, on the contrary, change very quickly with time due to mobility of users and burstiness of interference. Thus, the transmission quality has to be measured much more often to have reliable information about it.

Systems where channel information is available in the system and/or transmitter can use adaptive modulation and transmission techniques. A lot of effort has lately been put into the design and analysis of such systems and it is clear that adaptive systems are able to use the limited radio spectrum and transmit power in a much more efficient way as compared with systems which are not adaptive in this sense. This Special Issue is devoted to a state-of-the art description of adaptive modulation and transmission in wireless communication systems.

This Special Issue includes eleven papers. The first paper presents, in a tutorial form, the information theoretic framework underlying the adaptive modulation techniques used to improve spectral efficiency. First, the authors review fading channel models, channel state information assumptions, and related capacity results. Then, they treat the case of input power constrained communications, where the optimal input distribution is Gaussian. Finally, they address the case of discrete modulations. It is shown that when powerful coding schemes are used, the design of adaptive coded modulations become surprisingly simple and that the adaptive schemes become powerful.

To realize the potential of adaptive modulation and transmission, the transmitter needs accurate channel state information (CSI) for the upcoming transmission frame. In most mobile radio systems, the CSI is estimated at the receiver and fed back to the transmitter. However, unless the mobile speed is very low, the estimated CSI cannot be used directly to select the parameters of adaptive transmission systems, since it quickly becomes outdated due to the rapid channel variation caused by multipath fading. To enable adaptive transmission for mobile radio systems, prediction of future fading channel samples is required. This is the topic of paper number two, which gives an overview of the latest developments in channel prediction. One conclusion is that channel quality can indeed be predicted with enough accuracy in many situations, and thus that gains promised by adaptive transmission, therefore, can indeed be obtained.

The predicted channel information must be made available to the transmitter and/or system. This often requires transmission of radio channel parameters over a radio channel and, thus, must be done in an efficient way, so as not to lose all the spectral efficiency gains of the adaptive scheme. The third paper presents an in-depth study of the literature in this area, and evaluates the performance of several state-of-the-art channel quality feedback schemes. By illustrating the compromise between system throughput and feedback channel rate for various schemes, the authors are able to give valuable insight in choice of method for feedback rate reduction. A major conclusion is that for multicarrier systems, a lossy compression scheme is the best choice, while for single-carrier systems, schemes limiting feedback to only high-SNR users show good performance.

Paper four gives a reasonably simple introduction to adaptive modulation for simple flat fading channels. Both the case when the channel gain is perfectly known in the transmitter and the case when the channel gain is predicted is discussed. Some optimum adaptive modulations for both cases are explained and their performance improvements compared with nonadaptive schemes are illustrated. From this paper, it is clear that tremendous gains in spectral efficiency can be obtained on single radio links. The reader who is not familiar to the topic of this Special Issue, should probably read this paper before most of the other papers. Some of the next

[1] Actually, this was realized as early as the late 1960s, but practical implementation constraints (in particular, setup of fast and reliable feedback) delayed the emergence of these schemes.

papers discuss more advanced adaptive modulation and transmission schemes.

One of the great challenges of wireless communications is that it is difficult to obtain perfect CSI, since the CSI that the transmitter employs is inherently noisy and outdated. Over the last decade, the authors of paper five have championed the idea of choosing the appropriate transmitted signal based on statistical models for the current channel state conditioned on the channel measurements. In this semitutorial paper, they overview how this class of methods has been developed for single-antenna systems, and then present novel recent designs for multiple-antenna systems. Numerical results demonstrate that such an approach provides a robust method for improving system data rate versus the standard practice of employing link margin to compensate for such uncertainties.

The next two papers present adaptive transmission schemes for two typical types of radio interfaces. In paper six, a single carrier system is studied, while in paper seven, a multicarrier system is dealt with. In paper six, the authors introduce adaptive link control techniques for multiple-input–multiple-output (MIMO) systems with broadband single carrier signaling. Soft cancellation and minimum mean- squared error (SC-MMSE) turbo equalization is assumed, where matching between coding and equalization plays crucial roles to achieve high throughput. This paper describes the use of multilevel bit interleaved coded modulation (ML-BICM) with linear mapping as a core part of the transmission, on top of which this paper applies automatic repeat request (ARQ) with adaptive coding (AC) for link control. This represents a quite advanced single carrier adaptive link.

Adaptive high-speed down-link packet access (HSDPA) style multicarrier systems are reviewed in paper seven. HSDPA is an extension to one of the 3G standards [wideband code-division multiple-access (WCDMA)] and is already in limited operational use. Their most critical design aspects are identified. These systems exhibit numerous attractive features, rendering them eminently eligible for employment in next-generation wireless systems. It is argued that orthogonal frequency-division multiplex (OFDM) modems counteract the near instantaneous channel quality variations and, hence, attain an increased throughput or robustness in comparison to their fixed-mode counterparts. This paper investigates a combined system constituted by a constant-power adaptive modem employing space–time coded diversity techniques in the context of both OFDM and MC-CDMA.

In paper eight, the authors focus on the overall network capacity as a measure of system performance. The problem of resource allocation and adaptive transmission in multicell scenarios are considered. As a key instance, the problem of joint scheduling and power control simultaneously in multiple transmit-receive links, which employ capacity-achieving adaptive codes is studied. In principle, the solution of such an optimization hinges on tough issues such as the computational complexity and the requirement for heavy receiver-to-transmitter feedback and, for cellular networks, cell-to-cell CSI signaling. The authors give asymptotic properties pertaining to rate-maximizing power control and scheduling in multicell networks. They then present some promising leads for substantial complexity and signaling reduction via the use of newly developed distributed and game theoretic techniques.

Scheduling amounts to allocating optimally channel, rate, and power resources to multiple connections with diverse quality-of-service (QoS) requirements. Paper nine develops a unified framework for channel aware QoS-guaranteed scheduling protocols for use in adaptive wireless networks. The unification encompasses downlink and uplink with time-division or frequency-division duplex operation; full and quantized CSI; different types of traffic; uniform and optimal power loading; offline optimal scheduling schemes; as well as online scheduling algorithms capable of dynamically learning the intended channel statistics. The take-home message offers an important cross-layer design guideline: judiciously developed, yet surprisingly simple, channel-adaptive, online schedulers can approach information-theoretic rate limits under QoS constraints.

The last two papers represent the more complete system design of systems using adaptive modulation and transmission. Paper ten presents a beyond 3G system design based on adaptive OFDM. The overall challenge is high data rate packet scheduling and adaptive radio transmission for multiple users over multiple antennas, with frequency-selective channels. The basic simplifications to obtain feasible solutions used in this paper are clustering of antennas into cells, orthogonal transmission by use of cyclic-prefix OFDM, and a time-scale separation view of the link adaptation, scheduling, and intercell coordination problem. An overview of the design problems, such as the dimensioning of the allocated time-frequency resources, the influence of duplexing schemes, adaptation control issues for downlinks and uplinks, timing issues and their relation to the required performance of channel predictors are given. These results indicate that high-performance adaptive OFDM transmission systems are indeed feasible, also at vehicular velocities, high carrier frequencies, and high bandwidths.

Finally, paper eleven discusses system design strategies and performance evaluations for adaptive modulation techniques used in new and up-and-coming wireless access systems. This paper discusses how to design a narrowband time division multiple-access/time-division duplex (TDMA/TDD)-based adaptive modulation system and confirms through laboratory experiments that the narrowband TDMA/TDD-based adaptive modulation system dramatically enhances system robustness to multipath fading and flexibility in throughput and transmission quality control. Next, as an extension to many fields of application for adaptive modulation, this paper discusses subcarrier-level adaptive modulation for OFDM-based one-cell reuse broadband cellular systems. Finally, this paper explains the dynamic parameter controlled OFDM/TDMA (DPC-OF/TDMA) system as an example of a practical scheme for one-cell reuse broadband wireless access systems.

This Special Issue aims to give the reader an idea of the current status of adaptive modulation and transmission for wireless channels. This is an emerging field and, as is clear from the papers, a lot more research needs to be done to get the full benefits of these kinds of systems. We welcome anyone interested in contributing to further development of this field. However, it is interesting to note that some of the simpler versions of the techniques are already included in standards and systems which have recently been taken or are about to be taken into operation. The papers in this Special Issue are written by leading experts in the field. They were first contacted about two years ago and the present Special Issue has been made possible only due to the significant time and effort the authors have invested. We are very grateful for their contributions. We would also like to recognize the many contributions of the reviewers who helped the authors to improve the quality of their manuscripts. Without their help, this Special Issue would not have been the same. Finally, we would like to thank the Editor-in-Chief (at that time), Fawwaz Ulaby for inviting us to propose this Special Issue, the Editorial Board Member Prof. Norman C. Beaulieu for recommending a Special Issue on this topic, the Managing Editor Jim Calder for his continuing support, and the Publications Editor Margery Meyer and Jo Yu-chiao Sun in the editorial office for their help in many practical matters. ■

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Arne Svensson (Fellow, IEEE) was born in Vedåkra, Sweden, on October 22, 1955. He received the M.Sc. (Civilingenjör) degree in electrical engineering, and the Dr. Ing. (Teknisk Licentiat) and Dr. Techn. (Teknisk Doktor) degrees from the Department of Telecommunication Theory, University of Lund, Lund, Sweden, in 1979, 1982, and 1984, respectively.

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Dr. Sampei received the Shinohara Young Engineering Award, the Achievements Award from the Institute of Information and Communication Engineers (IEICE), the Telecom System Technology Award from the Telecommunication Advancement Foundation, and the DoCoMo Mobile Science Award from the Mobile Communication Fund. He is a member of the Institute of Image Information and Television Engineers (ITE) and the IEICE.