Adaptive Wireless Transceivers: Turbo-Coded, Turbo-Equalised and Space-Time Coded TDMA, CDMA, MC-CDMA and OFDM Systems

by

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Prologue

Motivation of the Book

In recent years the concept of intelligent multi-mode, multimedia transceivers (IMMT) has emerged in the context of wireless systems [1–6]. The range of various existing solutions that have found favour in already operational standard systems was summarised in the excellent overview by Nanda *et al.* [3]. *The aim of these adaptive transceivers is to provide mobile users with the best possible compromise amongst a number of contradicting design factors, such as the power consumption of the hand-held portable station (PS), robustness against transmission errors, spectral efficiency, teletraffic capacity, audio/video quality and so forth [2].*

The fundamental limitation of wireless systems is constituted by their time- and frequency-domain channel fading, as illustrated in Figure 13.39 in terms of the Signal-to-Noise Ratio (SNR) fluctuations experienced by a modem over a dispersive channel. The violent SNR fluctuations observed both versus time and versus frequency suggest that over these channels no fixed-mode transceiver can be expected to provide an attractive performance, complexity and delay trade-off. Motivated by the above mentioned performance limitations of fixed-mode transceivers, IMMTs have attracted considerable research interest in the past decade [1–6]. Some of these research results are collated in this monograph.

In Figure 1 we show the instantaneous channel SNR experienced by the 512-subcarrier OFDM symbols for a single-transmitter, single-receiver scheme and for the space-time block code $\mathbf{G}_2$ [7] using one, two and six receivers over the shortened WATM channel. The average channel SNR is 10 dB. We can see in Figure 1 that the variation of the instantaneous channel SNR for a single transmitter and single receiver is severe. The instantaneous channel SNR may become as low as 4 dB due to deep fades of the channel. On the other hand, we can see that for the space-time block code $\mathbf{G}_2$ using one receiver the variation in the instantaneous channel SNR is slower and less severe. Explicitly, by employing multiple transmit antennas as shown in Figure 1, we have reduced the effect of the channels' deep fades significantly. This is advantageous in the context of adaptive modulation schemes, since higher-order modulation modes can be employed, in order to increase the throughput of the system. However, as we increase the number of receivers, i.e. the diversity order, we observe that the variation of the channel becomes slower. Effectively, by employing higher-order diversity, the fading channels have been converted to AWGN-like channels, as evidenced by the scenario employing the space-time block code $\mathbf{G}_2$ using six receivers. Since adaptive modulation only offers advantages over fading channels, we argue that using adaptive modulation might become unnecessary, as the diversity order is increased. Hence, adaptive modulation can be viewed as a lower-complexity alternative to space-time coding, since only a single transmitter and receiver is required.

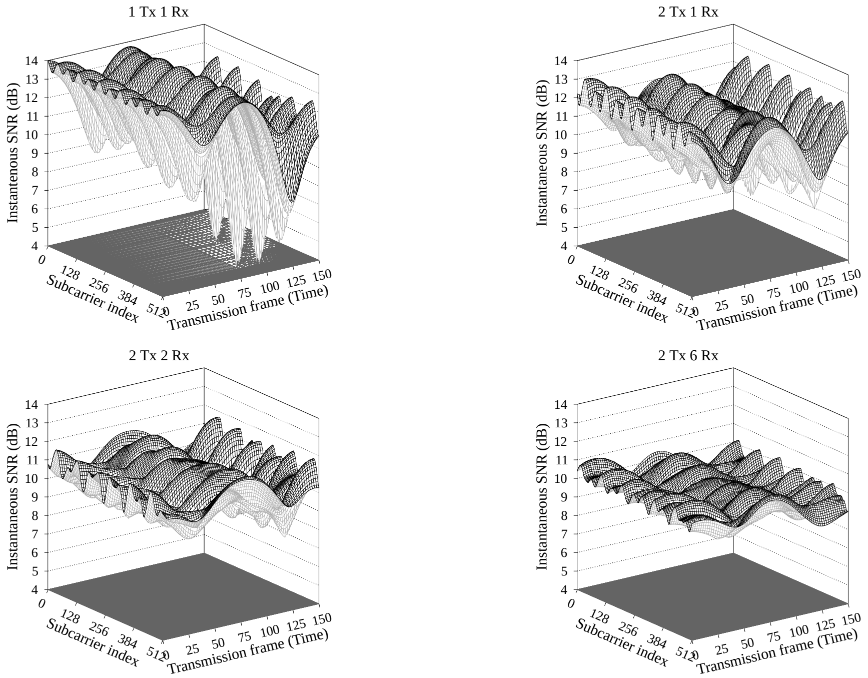

Figure 1: Instantaneous channel SNR versus time and frequency for a 512-subcarrier OFDM modem in the context of a single-transmitter single-receiver as well as for the space-time block code $\mathbf{G}_2$ [7] using one, two and six receivers when communicating over an indoor wireless channel. The average channel SNR is 10 dB. ©IEEE, Liew and Hanzo [8], 2001

Our intention with the book is multifold:

1. Firstly, to pay tribute to all researchers, colleagues and valued friends, who contributed to the field. Hence this book is dedicated to them, since without their quest for better transmission solutions for wireless communications this monograph could not have been conceived. They are too numerous to name here, hence they appear in the author index of the book.

2. Although the potential of adaptive modulation and transmission was recognised some 30 years ago by Cavers [9] and during the nineties the associated research efforts intensified, to date there is no monograph on the topic. Hence it is our hope that the conception of this monograph on the topic will provide an adequate portrayal of the last decade of research and fuel this innovation process.

3. As argued above, adaptive modulation only offers advantages when communicating over fading wireless channels. However, since the space-time coding assisted employment of transmit and receive diversity mitigates the effects of fading, we would like to portray adaptive modulation as a lower-complexity alternative to space-time coding, since only a single transmitter and receiver is required.

4. We expect to stimulate further research by exposing not only the information theoretical limitations of such IMMTs, but also by collating a range of practical problems and design issues for the practitioners. The coherent further efforts of the wireless research community is expected to lead to the solution of the vast range of outstanding problems, ultimately providing us with flexible wireless transceivers exhibiting a performance close to information theoretical limits.

The above mentioned calamities inflicted by the wireless channel can be mitigated by contriving a suite of near-instantaneously adaptive or Burst-by-Burst Adaptive (BbBA) wideband single-carrier [4], multi-carrier or Orthogonal Frequency Division Multiplex [4] (OFDM) as well as Code Division Multiple Access (CDMA) transceivers. The aim of these IMMTs is to communicate over hostile mobile channels at a higher integrity or higher throughput, than conventional fixed-mode transceivers. A number of existing wireless systems already support some grade of adaptivity and future research is likely to promote these principles further by embedding them into the already existing standards. For example, due to their high control channel rate and with the advent of the well-known Orthogonal Variable Spreading Factor (OVSF) codes the thrid-generation UTRA/IMT2000 systems are amenable to not only long-term spreading factor reconfiguration, but also to near-instantaneous reconfiguration on a 10ms transmission burst-duration basis.

With the advent of BbBA QAM, OFDM or CDMA transmissions it becomes possible for mobile stations (MS) to invoke for example in indoor scenarios or in the central propagation cell region - where typically benign channel conditions prevail - a high-throughput modulation mode, such as 4 bit/symbol Quadrature Amplitude Modulation (16QAM). By contrast, a robust, but low-throughput modulation mode, such as 1 bit/symbol Binary Phase Shift Keying (BPSK) can be employed near the edge of the propagation cell, where hostile propagation conditions prevail. The BbBA QAM, OFDM or CDMA mode switching regime is also capable of reconfiguring the transceiver at the rate of the channel's slow- or even fast-fading. This may prevent premature hand-overs and - more importantly - unnecessary powering up, which would inflict an increased interference upon co-channel users, resulting in further potential power increments. This detrimental process could result in all mobiles operating at unnecessarily high power levels.

A specific property of these transceivers is that their bit rate fluctuates, as a function of time. This is not an impediment in the context of data transmission. However, in interactive speech [5] or video [6] communications appropriate source codecs have to be designed, which are capable of promptly reconfiguring themselves according to the near-instantaneous bitrate budget provided by the transceiver.

The expected performance of our BbBA transceivers can be characterised with the aid of a whole plethora of performance indicators. In simple terms, adaptive modems outperform their individual fixed-mode counterparts, since given an average number of transmitted bits per symbol (BPS), their average BER will be lower than that of the fixed-mode modems. From a different perspective, at a given BER their BPS throughput will be always higher. In general, the higher the tolerable BER, the closer the performance to that of the Gaussian channel capacity. Again, this fact underlines the importance of designing programmable-rate, error-resilient source codecs - such as the Advanced Multi-Rate (AMR) speech codec to be employed in UMTS - which do not expect a low BER.

Similarly, when employing the above BbBA or AQAM principles in the frequency domain in the context of OFDM [4] or in conjunction with OVSF spreading codes in CDMA systems, attractive system design trade-offs and a high over-all performance can be attained [6]. However, despite the extensive research in the field by the international community, there is a whole host of problems that remain to be solved and this monograph intends to contribute towards these efforts.

Adaptation Principles

AQAM is suitable for duplex communication between the MS and BS, since the AQAM modes have to be adapted and signalled between them, in order to allow channel quality estimates and signalling to take place. The AQAM mode adaptation is the action of the transmitter in response to time–varying channel conditions. In order to efficiently react to the changes in channel quality, the following steps have to be taken:

- *Channel quality estimation:* In order to appropriately select the transmission parameters to be employed for the next transmission, a reliable estimation of the channel transfer function during the next active transmit timeslot is necessary.
- *Choice of the appropriate parameters for the next transmission:* Based on the prediction of the channel conditions for the next timeslot, the transmitter has to select the appropriate modulation and channel coding modes for the subcarriers.
- *Signalling or blind detection of the employed parameters:* The receiver has to be informed, as to which demodulator parameters to employ for the received packet. This information can either be conveyed within the OFDM symbol itself, at the cost of loss of effective data throughput, or the receiver can attempt to estimate the parameters employed by the remote transmitter by means of blind detection mechanisms [4].

Channel Quality Metrics

The most reliable channel quality estimate is the bit error rate (BER), since it reflects the channel quality, irrespective of the source or the nature of the quality degradation. The BER can be estimated invoking a number of approaches.

Firstly, the BER can be estimated with a certain granularity or accuracy, provided that the system entails a channel decoder or - synonymously - Forward Error Correction (FEC) decoder employing algebraic decoding [10].

Secondly, if the system contains a soft-in-soft-out (SISO) channel decoder, the BER can be estimated with the aid of the Logarithmic Likelihood Ratio (LLR), evaluated either at the input or the output of the channel decoder. A particularly attractive way of invoking LLRs is employing powerful turbo codecs, which provide a reliable indication of the confidence associated with a particular bit decision in the context of LLRs.

Thirdly, in the event that no channel encoder / decoder (codec) is used in the system, the channel quality expressed in terms of the BER can be estimated with the aid of the mean-squared error (MSE) at the output of the channel equaliser or the closely related metric of Pseudo-Signal-to-Noise-Ratio (Pseudo-SNR) [6]. The MSE or pseudo-SNR at the output of the channel equaliser have the important advantage that they are capable of quantifying the severity of the inter-symbol-interference (ISI) and/or Co-channel Interference (CCI) experienced, in other words quantifying the Signal to Interference plus Noise Ratio (SINR).

As an example, let us consider OFDM. In OFDM modems [4] the bit error probability in each subcarrier can be determined by the fluctuations of the channel's instantaneous frequency domain channel transfer function H_n, if no co-channel interference is present. The estimate $\hat{H}_n$ of the channel transfer function can be acquired by means of pilot–tone based channel estimation [4]. For CDMA transceivers similar techniques are applicable, which constitute the topic of this monograph.

The delay between the channel quality estimation and the actual transmission of a burst in relation to the maximal Doppler frequency of the channel is crucial as regards to the adaptive system's performance. If the channel estimate is obsolete at the time of transmission, then poor system performance will result [6].

Transceiver Parameter Adaptation

Different transmission parameters - such as the modulation and coding modes - of the AQAM single- and multi-carrier as well as CDMA transceivers can be adapted to the anticipated channel conditions. For example, adapting the number of modulation levels in response to the anticipated SNR encountered in each OFDM subcarrier can be employed, in order to achieve a wide range of different trade–offs between the received data integrity and throughput. Corrupted subcarriers can be excluded from data transmission and left blank or used for example for Crest–factor reduction. A range of different algorithms for selecting the appropriate modulation modes have to be investigated by future research. **The adaptive channel coding parameters entail code rate, adaptive interleaving and puncturing for convolutional and turbo codes, or varying block lengths for block codes [4].**

Based on the estimated frequency–domain channel transfer function, **spectral pre–distortion at the transmitter of one or both communicating stations can be invoked, in order to partially of fully counteract the frequency–selective fading of the time–dispersive channel**. Unlike frequency–domain equalisation at the receiver — which corrects for the amplitude– and phase–errors inflicted upon the subcarriers by the channel, but which cannot improve the SNR in poor quality OFDM subchannels — spectral pre–distortion at the OFDM transmitter can deliver near–constant signal–to–noise levels for all subcarriers and can be viewed as power control on a subcarrier–by–subcarrier basis.

In addition to improving the system's BER performance in time–dispersive channels, spectral pre–distortion can be employed in order to perform all channel estimation and equalisation functions at only one of the two communicating duplex stations. Low–cost, low power consumption mobile stations can communicate with a base station that performs the channel estimation and frequency–domain equalisation of the uplink, and uses the estimated channel transfer function for pre–distorting the down–link OFDM symbol. This setup would lead to different overall channel quality on the up– and downlink, and the superior pre-equalised downlink channel quality could be exploited by using a computationally less complex channel decoder, having weaker error correction capabilities in the mobile station than in the base station.

If the channel's frequency–domain transfer function is to be fully counteracted by the spectral pre-distortion upon adapting the subcarrier power to the inverse of the channel trans-

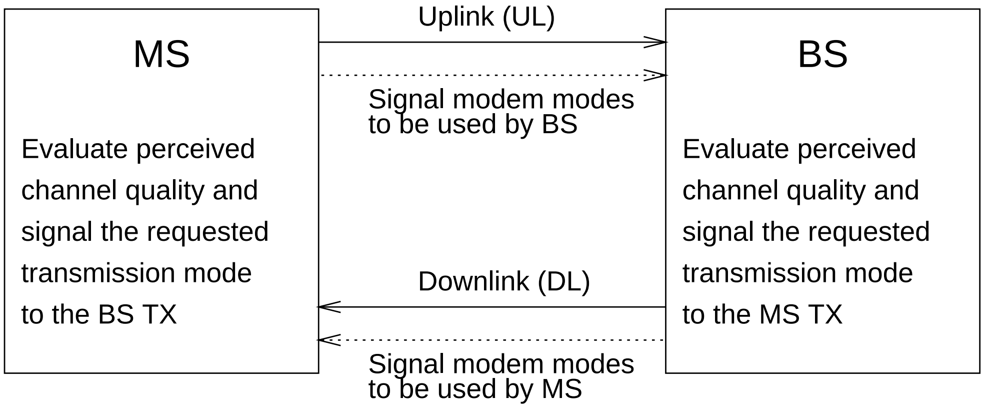

Figure 2: Parameter signalling in BbBA OFDM, CDMA and AQAM modems, IEEE Press-John Wiley, 2000, Hanzo, Webb, Keller [4].

fer function, then the output power of the transmitter can become excessive, if heavily faded subcarriers are present in the system's frequency range. In order to limit the transmitter's maximal output power, hybrid channel pre–distortion and adaptive modulation schemes can be devised, which would de–activate transmission in deeply faded subchannels, while retaining the benefits of pre–distortion in the remaining subcarriers.

BbBA mode signalling plays an important role in adaptive systems and the range of signalling options is summarised in Figure 2 for **closed–loop signalling**. If the channel quality estimation and parameter adaptation have been performed at the transmitter of a particular link, based on open–loop adaptation, then the resulting set of parameters has to be communicated to the receiver in order to successfully demodulate and decode the OFDM symbol. Once the receiver determined the requested parameter set to be used by the remote transmitter, then this information has to be signalled to the remote transmitter in the reverse link. If this signalling information is corrupted, then the receiver is generally unable to correctly decode the OFDM symbol corresponding to the incorrect signalling information, yielding an OFDM symbol error.

Unlike adaptive serial systems, which employ the same set of parameters for all data symbols in a transmission packet [4], adaptive OFDM systems [4] have to react to the frequency selective nature of the channel, by adapting the modem parameters across the subcarriers. The resulting signalling overhead may become significantly higher than that for serial modems, and can be prohibitive for example for subcarrier–by–subcarrier based modulation mode adaptation. In order to overcome these limitations, efficient and reliable signalling techniques have to be employed for practical implementation of adaptive OFDM modems.

If some flexibility in choosing the transmission parameters is sacrificed in an adaptation scheme, like in sub–band adaptive OFDM schemes [4], then the amount of signalling can be reduced. Alternatively, blind parameter detection schemes can be devised, which require little or no signalling information, respectively [4].

In conclusion, fixed mode transceivers are incapable of achieving a good trade-off in terms of performance and complexity. The proposed BbB adaptive system design paradigm is more promising in this respect. A range of problems and solutions were highlighted in conceptual terms with reference to an OFDM-based example, indicating the areas, where substantial future research is required. A specific research topic, which raised substantial research interest recently is invoking efficient channel quality prediction techniques [11]. Before we commence our indepth discourse in the forthcoming chapters, in the next section we provide a brief historical perspective on adaptive modulation.

Milestones in Adaptive Modulation History

Adaptive Single- and Multi-carrier Modulation

Following Cavers' classic contribution [9], BbB-AQAM has been suggested by Webb and Steele [1], stimulating further research in the wireless community for example by Sampei *et al.* [12], showing promising advantages, when compared to fixed modulation in terms of spectral efficiency, BER performance and robustness against channel delay spread. Various systems employing AQAM were also characterised in [4]. The numerical upper bound performance of narrow-band BbB-AQAM over slow Rayleigh flat-fading channels was evaluated by Torrance *et al.* [13], while over wide-band channels by Wong *et al.* [14, 15]. Following these developments, the optimization of the BbB-AQAM switching thresholds was carried employing Powell-optimization using a cost-function, which was based on the combination of the target BER and target Bit Per Symbol (BPS) performance [16]. Adaptive modulation was also studied in conjunction with channel coding and power control techniques by Matsuoka *et al.* [17] as well as Goldsmith and Chua [18, 19].

In the early phase of research more emphasis was dedicated to the system aspects of adaptive modulation in a narrow-band environment. A reliable method of transmitting the modulation control parameters was proposed by Otsuki *et al.* [20], where the parameters were embedded in the transmission frame's mid-amble using Walsh codes. Subsequently, at the receiver the Walsh sequences were decoded using maximum likelihood detection. Another technique of estimating the required modulation mode used was proposed by Torrance *et al.* [21], where the modulation control symbols were represented by unequal error protection 5-PSK symbols. The adaptive modulation philosophy was then extended to wideband multi-path environments by Kamio *et al.* [22] by utilizing a bi-directional Decision Feedback Equaliser (DFE) in a micro- and macro-cellular environment. This equalization technique employed both forward and backward oriented channel estimation based on the pre-amble and post-amble symbols in the transmitted frame. Equalizer tap gain interpolation across the transmitted frame was also utilized, in order to reduce the complexity in conjunction with space diversity [22]. The authors concluded that the cell radius could be enlarged in a macro-cellular system and a higher area-spectral efficiency could be attained for micro-cellular environments by utilizing adaptive modulation. The latency effect, which occurred, when the input data rate was higher than the instantaneous transmission throughput was studied and solutions were formulated using frequency hopping [23] and statistical multiplexing, where the number of slots allocated to a user was adaptively controlled [24].

In reference [25] symbol rate adaptive modulation was applied, where the symbol rate or the number of modulation levels was adapted by using $\frac{1}{8}$-rate 16QAM, $\frac{1}{4}$-rate 16QAM, $\frac{1}{2}$-rate 16QAM as well as full-rate 16QAM and the criterion used to adapt the modem modes was based on the instantaneous received signal to noise ratio and channel delay spread. The slowly varying channel quality of the uplink (UL) and downlink (DL) was rendered similar by utilizing short frame duration Time Division Duplex (TDD) and the maximum normalised delay spread simulated was 0.1. A variable channel coding rate was then introduced by Matsuoka *et al.* in conjunction with adaptive modulation in reference [17], where the transmitted burst incorporated an outer Reed Solomon code and an inner convolutional code in order to achieve high-quality data transmission. The coding rate was varied according to the prevalent channel quality using the same method, as in adaptive modulation in order to achieve a certain target BER performance. A so-called channel margin was introduced in this contribution, which adjusted the switching thresholds in order to incorporate the effects of channel quality estimation errors. As mentioned above, the performance of channel coding in conjunction with adaptive modulation in a narrow-band environment was also characterised by Chua and Goldsmith [18]. In this contribution, trellis and lattice codes were used without channel interleaving, invoking a feedback path between the transmitter and receiver for modem mode control purposes. The effects of the delay in the feedback path on the adaptive modem's performance were studied and this scheme exhibited a higher spectral efficiency, when compared to the non-adaptive trellis coded performance. Pearce, Burr and Tozer [26] as well as Lau and McLeod [27] have also analysed the performance trade-offs associated with employing channel coding and adaptive modulation as efficient fading counter measures.

Subsequent contributions by Suzuki *et al.* [28] incorporated space-diversity and power-adaptation in conjunction with adaptive modulation, for example in order to combat the effects of the multi-path channel environment at a 10Mbits/s transmission rate. The maximum tolerable delay-spread was deemed to be one symbol duration for a target mean BER performance of 0.1%. This was achieved in a Time Division Multiple Access (TDMA) scenario, where the channel estimates were predicted based on the extrapolation of previous channel quality estimates. Variable transmitted power was then applied in combination with adaptive modulation in reference [19], where the transmission rate and power adaptation was optimised in order to achieve an increased spectral efficiency. In this treatise, a slowly varying channel was assumed and the instantaneous received power required in order to achieve a certain upper bound performance was assumed to be known prior to transmission. Power control in conjunction with a pre-distortion type non-linear power amplifier compensator was studied in the context of adaptive modulation in reference [29]. This method was used to mitigate the non-linearity effects associated with the power amplifier, when QAM modulators were used.

Results were also recorded concerning the performance of adaptive modulation in conjunction with different multiple access schemes in a narrow-band channel environment. In a TDMA system, dynamic channel assignment was employed by Ikeda *et al.*, where in addition to assigning a different modulation mode to a different channel quality, priority was always given to those users in reserving time-slots, which benefitted from the best channel quality [30]. The performance was compared to fixed channel assignment systems, where substantial gains were achieved in terms of system capacity. Furthermore, a lower call termination probability was recorded. However, the probability of intra-cell hand-off increased as a result of the associated dynamic channel assignment (DCA) scheme, which constantly searched for a high-quality, high-throughput time-slot for the existing active users. The application of adaptive modulation in packet transmission was introduced by Ue, Sampei and Morinaga [31], where the results showed improved data throughput. Recently, the performance of adaptive modulation was characterised in conjunction with an automatic repeat request (ARQ) system in reference [32], where the transmitted bits were encoded using a cyclic redundant code (CRC) and a convolutional punctured code in order to increase the data throughput.

A recent treatise was published by Sampei, Morinaga and Hamaguchi [33] on laboratory test results concerning the utilization of adaptive modulation in a TDD scenario, where the modem mode switching criterion was based on the signal to noise ratio and on the normalised delay-spread. In these experimental results, the channel quality estimation errors degraded the performance and consequently a channel estimation error margin was devised, in order to mitigate this degradation. Explicitly, the channel estimation error margin was defined as the measure of how much extra protection margin must be added to the switching threshold levels, in order to minimise the effects of the channel estimation errors. The delay-spread also degraded the performance due to the associated irreducible BER, which was not compensated by the receiver. However, the performance of the adaptive scheme in a delay-spread impaired channel environment was better, than that of a fixed modulation scheme. Lastly, the experiment also concluded that the AQAM scheme can be operated for a Doppler frequency of $f_d = 10$Hz with a normalised delay spread of 0.1 or for $f_d = 14$Hz with a normalised delay spread of 0.02, which produced a mean BER of 0.1% at a transmission rate of 1 Mbits/s.

Lastly, the latency and interference aspects of AQAM modems were investigated in [34, 35]. Specifically, the latency associated with storing the information to be transmitted during severely degraded channel conditions was mitigated by frequency hopping or statistical multiplexing. As expected, the latency is increased, when either the mobile speed or the channel SNR are reduced, since both of these result in prolonged low instantaneous SNR intervals. It was demonstrated that as a result of the proposed measures, typically more than 4dB SNR reduction was achieved by the proposed adaptive modems in comparison to the conventional fixed-mode benchmark modems employed. However, the achievable gains depend strongly on the prevalant co-channel interference levels and hence interference cancellation was invoked in [35] on the basis of adjusting the demodulation decision boundaries after estimating the interfering channel's magnitude and phase.

The associated principles can also be invoked in the context of parallel modems. This principle was first proposed by Kalet [36] and was then further developed for example by Czylwik *et al.* [37] as well as by Chow, Cioffi and Bingham [38]. The associated concepts were detailed for example in [4] and will be also augmented in this monograph. Let us now briefly review the recent history of the BbB adaptive concept in the context of CDMA in the next section.

Adaptive Code Division Multiple Access

The techniques described in the context of single- and multi-carrier modulation are conceptually similar to multi-rate transmission [39] in CDMA systems. However, in BbB adaptive CDMA the transmission rate is modified according to the near-instantaneous channel quality, instead of the service required by the mobile user. BbB-adaptive CDMA systems are also useful for employment in arbitrary propagation environments or in hand-over scenarios, such as those encountered, when a mobile user moves from an indoor to an outdoor environment or in a so-called 'birth-death' scenario, where the number of transmitting CDMA users changes frequently [40], thereby changing the interference dramatically. Various methods of multi-rate transmission have been proposed in the research literature. Below we will briefly discuss some of the recent research issues in multi-rate and adaptive CDMA schemes.

Ottosson and Svensson compared various multi-rate systems [39], including multiple spreading factor (SF) based, multi-code and multi-level modulation schemes. According to the multi-code philosophy, the SF is kept constant for all users, but multiple spreading codes transmitted simultaneously are assigned to users requiring higher bit rates. In this case - unless the spreading codes's perfect orthogonality is retained after transmission over the channel - the multiple codes of a particular user interfere with each other. This inevitebly reduces the system's performance.

Multiple data rates can also be supported by a variable SF scheme, where the chip rate is kept constant, but the data rates are varied, thereby effectively changing the SF of the spreading codes assigned to the users; at a fixed chip rate the lower the SF, the higher the supported data rate. Performance comparisons for both of these schemes have been carried out by Ottosson and Svensson [39], as well as by Ramakrishna and Holtzman [41], demonstrating that both schemes achieved a similar performance. Adachi, Ohno, Higashi, Dohi and Okumura proposed the employment of multi-code CDMA in conjunction with pilot symbol-assisted channel estimation, RAKE reception and antenna diversity for providing multi-rate capabilities [42, 43]. The employment of multi-level modulation schemes was also investigated by Ottosson and Svensson [39], where higher-rate users were assigned higher-order modulation modes, transmitting several bits per symbol. However, it was concluded that the performance experienced by users requiring higher rates was significantly worse, than that experienced by the lower-rate users. The use of M-ary orthogonal modulation in providing variable rate transmission was investigated by Schotten, Elders-Boll and Busboom [44]. According to this method, each user was assigned an orthogonal sequence set, where the number of sequences, M, in the set was dependent on the data rate required – the higher the rate required, the larger the sequence set. Each sequence in the set was mapped to a particular combination of $b = (\log_2 M)$ bits to be transmitted. The M-ary sequence was then spread with the aid of a spreading code of a constant SF before transmission. It was found [44] that the performance of the system depended not only on the MAI, but also on the Hamming distance between the sequences in the M-ary sequence set.

Saquib and Yates [45] investigated the employment of the decorrelating detector in conjunction with the multiple-SF scheme and proposed a modified decorrelating detector, which utilized soft decisions and maximal ratio combining, in order to detect the bits of the different-rate users. Multi-rate transmission schemes involving interference cancellation receivers have previously been investigated amongst others by Johansson and Svensson [46, 47], as well as by Juntti [48]. Typically, multiple users transmitting at different bit rates are supported in the same CDMA system invoking multiple codes or different spreading factors. SIC schemes and multi-stage cancellation schemes were used at the receiver for mitigating the MAI [46–48], where the bit rate of the users was dictated by the user requirements. The performance comparison of various multiuser detectors in the context of a multiple-SF transmission scheme was presented for example by Juntti [48], where the detectors compared were the decorrelator, the PIC receiver and the so-called group serial interference cancellation (GSIC) receiver. It was concluded that the GSIC and the decorrelator performed better than the PIC receiver, but all the interference cancellation schemes including the GSIC, exhibited an error floor at high SNRs due to error propagation.

The bit rate of each user can also be adapted according to the near-instantaneous channel quality, in order to mitigate the effects of channel quality fluctuations. Kim [49] analyzed the performance of two different methods of combating the near-instantaneous quality variations of the mobile channel. Specifically, Kim studied the adaptation of the transmitter power or the switching of the information rate, in order to suit the near-instantaneous channel conditions. Using a RAKE receiver [50], it was demonstrated that rate adaptation provided a higher average information rate, than power adaptation for a given average transmit power and a given BER [49]. Abeta, Sampei and Morinaga [51] conducted investigations into an adaptive packet transmission based CDMA scheme, where the transmission rate was modified by varying the channel code rate and the processing gain of the CDMA user, employing the carrier to interference plus noise ratio (CINR) as the switching metric. When the channel quality was favourable, the instantaneous bit rate was increased and conversely, the instantaneous bit rate was reduced when the channel quality dropped. In order to maintain a constant overall bit rate, when a high instantaneous bit rate was employed, the duration of the transmission burst was reduced. Conversely, when the instantaneous bit rate was low, the duration of the burst was extended. This resulted in a decrease in interference power, which translated to an increase in system capacity. Hashimoto, Sampei and Morinaga [52] extended this work also to demonstrate that the proposed system was capable of achieving a higher user capacity with a reduced hand-off margin and lower average transmitter power. In these schemes the conventional RAKE receiver [50] was used for the detection of the data symbols. A variable-rate CDMA scheme – where the transmission rate was modified by varying the channel code rate and, correspondingly, the M-ary modulation constellations – was investigated by Lau and Maric [53]. As the channel code rate was increased, the bit-rate was increased by increasing M correspondingly in the M-ary modulation scheme. Another adaptive system was proposed by Tateesh, Atungsiri and Kondoz [54], where the rates of the speech and channel codecs were varied adaptively [54]. In their adaptive system, the gross transmitted bit rate was kept constant, but the speech codec and channel codec rates were varied according to the channel quality. When the channel quality was low, a lower rate speech codec was used, resulting in increased redundancy and thus a more powerful channel code could be employed. This resulted in an overall coding gain, although the speech quality dropped with decreasing speech rate. A variable rate data transmission scheme was proposed by Okumura and Adachi [55], where the fluctuating transmission rate was mapped to discontinuous transmission, in order to reduce the interference inflicted upon the other users, when there was no transmission. The transmission rate was detected blindly at the receiver with the help of cyclic redundancy check decoding and RAKE receivers were employed for coherent reception, where pilot-symbol-assisted channel estimation was performed.

The information rate can also be varied in accordance with the channel quality, as it will be demonstrated shortly. However, in comparison to conventional power control techniques - which again, may disadvantage other users in an effort to maintain the quality of the links considered - the proposed technique does not disadvantage other users and increases the network capacity [56]. The instantaneous channel quality can be estimated at the receiver and the chosen information rate can then be communicated to the transmitter via explicit signalling in a so-called closed-loop controlled scheme. Conversely, in an open-loop scheme - provided that the downlink and uplink channels exhibit a similar quality - the information rate for the downlink transmission can be chosen according to the channel quality estimate related to the uplink and vice versa. The validity of the above channel reciprocity issues in TDD-CDMA systems have been investigated by Miya *et al.* [57], Kato *et al.* [58] and Jeong *et al.* [59].

Outline of the book

In order to mitigate the impact of dispersive multi-path fading channels, equalization techniques are introduced, which are subsequently incorporated in a wideband adaptive modulation scheme. The performance of various wideband adaptive transmission scheme was then analysed in different environments, resulting in the following outline:

- **Chapter 1**: Square Quadrature Amplitude Modulation (QAM) schemes are introduced and their corresponding performance is analysed over Gaussian and narrow-band Rayleigh fading channels. This is followed by an introduction to equalization techniques with an emphasis on the Minimum Mean Square Error (MMSE) Decision Feedback Equalizer (DFE). The performance of the DFE is then characterised using BPSK, 4QAM, 16QAM and 64QAM modems.

- **Chapter 2**: The recursive Kalman algorithm is formulated and employed in an adaptive channel estimator and adaptive DFE in order to combat the time-variant dispersion of the mobile propagation channel. In this respect, the system parameters of the algorithm are optimised for each application by evaluating the convergence speed of the algorithm. Finally, two receiver structures utilizing the adaptive channel estimator and DFE are compared.

- **Chapter 3**: The concept of AQAM is introduced, where the modulation mode is adapted based on the prevalent channel conditions. Power control is then implemented and analysed in conjunction with AQAM in a narrow-band environment. Subsequently, a wideband AQAM scheme - which incorporates the DFE - is jointly constructed in order to mitigate the effects of the dispersive multi-path fading channel. A numerical upper bound performance is derived for this wideband AQAM scheme, which is subsequently optimised for a certain target BER and transmission throughput performance. Lastly, a comparison is made between the constituent fixed or time-invariant modulation modes and the wideband AQAM scheme in terms of their transmission throughput performance.

- **Chapter 4**: The performance of the wideband channel coded AQAM scheme is presented and analysed. Explicitly, turbo coding techniques are invoked, where each modulation mode was associated with a certain code rate and turbo interleaver size. Consequently, an adaptive code rate scheme is incorporated into the wideband AQAM scheme. The performance of such a scheme is compared to the constituent fixed modulation modes as well as the uncoded AQAM scheme, which was presented in Chapter 3. Furthermore, the concept of turbo equalization is introduced and applied in a wideband AQAM scheme. The iterative nature of the turbo equalizer is also exploited in estimating the channel impulse response (CIR). The chapter is concluded with a comparative study of various joint coding and adaptive modulation schemes, including Trellis Coded Modulation (TCM), turbo TCM (TTCM), Bit Interleaved Coded Modulation (BICM) and its iteratively detected (ID) version, namely BICM-ID.

  In **Chapter 5**: closed form expressions were derived for the average BER, the average BPS throughput and the mode selection probability of various adaptive modulation schemes, which were shown to be dependent on the mode-switching levels as well as on the average SNR experienced. Furthermore, a range of techniques devised for determining the adaptive mode-switching levels are studied comparatively. The optimum switching levels achieving the highest possible BPS throughput while maintaining the average target BER were developed based on the Lagrangian optimisation method. The chapter is concluded with a brief comparison of space-time coding and adaptive modulation in the context of OFDM and MC-CDMA.

- **Chapter 6**: This chapter presents the practical aspects of implementing wideband AQAM schemes, which includes the effects of error propagation inflicted by the DFE and the more detrimental channel quality estimation latency impact of the scheme. The impact of latency is studied under different system delay and normalised Doppler frequencies. The impact of Co-Channel Interference (CCI) on the wideband AQAM scheme is also analysed. In this aspect, joint detection techniques and a more sophisticated switching regime is utilized, in order to mitigate the impact of CCI.

- In **Chapter 7** we cast channel equalisation as a classification problem. We briefly give an overview of neural network and present the design of some neural network based equalisers. In this chapter we opted for studying a neural network structure referred to as the Radial Basis Function (RBF) network in more detail for channel equalisation, since it has an equivalent structure to the so-called optimal Bayesian equalisation solution [60]. The structure and properties of the RBF network is described, followed by the implementation of a RBF network as an equaliser. We will discuss the computational complexity issues of the RBF equaliser with respect to that of conventional linear equalisers and provide some complexity reduction methods. Finally, performance comparisons between the RBF equaliser and the conventional equaliser are given over various channel scenarios.

- **Chapter 8** commences by summarising the concept of adaptive modulation that adapts the modem mode according to the channel quality in order to maintain a certain target bit error rate and an improved bits per symbol throughput performance. The RBF based equaliser is introduced in a wideband Adaptive Quadrature Amplitude Modulation (AQAM) scheme in order to mitigate the effects of the dispersive multipath fading channel. We introduce the short-term Bit Error Rate (BER) as the channel quality measure. Lastly, a comparative study is conducted between the constituent fixed mode, the conventional DFE based AQAM scheme and the RBF based AQAM scheme in terms of their BER and throughput performance.

- In **Chapter 9** we incorporate turbo channel coding in the proposed wideband AQAM scheme. A novel reduced-complexity RBF equaliser utilizing the so-called Jacobian logarithmic relationship [61] is proposed and the turbo-coded performance of the Jacobian RBF equaliser is presented for the various fixed QAM modes. Furthermore, we investigate using various channel quality measures – namely the short-term BER and the average Log-Likelihood Ratio (LLR) magnitude of the data burst generated either by the RBF equaliser or the turbo decoder – in order to control the modem mode-switching regime for our adaptive scheme.

- **Chapter 10** introduces the principles of iterative, joint equalisation and decoding techniques known as turbo equalisation. We present a novel turbo equalisation scheme, which employs a RBF equaliser instead of the conventional trellis-based equaliser. The structure and computational complexity of both the RBF equaliser and trellis-based equaliser are compared and we characterise the performance of these RBF and trellis-based turbo-equalisers. We then propose a reduced-complexity RBF assisted turbo equaliser, which exploits the fact that the RBF equaliser computes its output on a symbol-by-symbol basis and the symbols of the decoded transmission burst, which are sufficiently reliable need not be equalised in the next turbo equalisation iteration. This chapter is concluded with the portayal and characterisation of RBF-based turbo equalised space-time coded schemes.

- In **Chapter 11** the recent history of smart CDMA MUDs is reviewed and the most promising schemes have been comparatively studied, in order to assist in the design of third- and fourth-generation receivers. Future transceivers may become BbB-adaptive, in order to be able to accommodate the associated channel quality fluctuations without disadvantageously affecting the system's capacity. Hence the methods reviewed in this chapter are advantageous, since they often assist in avoiding powering up, which may inflict increased levels of co-channel interference and power consumption. Furthermore, the techniques characterized in the chapter support an increased throughput within a given bandwidth and will contribute towards reducing the constantly increasing demand for more bandwidth. Both successive interference cancellation (SIC) and Parallel Interference Cancellation (PIC) receivers are investigated in the context of AQAM/CDMA schemes, along with joint-detection assisted schemes.

- In **Chapter 12** we provide a brief historical perspective on Orthogonal Frequency Division Multiplex (OFDM) transmissions with reference to the literature of the past 30 years. The advantages and disadvantages of various OFDM techniques are considered briefly and the expected performance is characterized for the sake of illustration in the context of indoor wireless systems. Our discussions will deepen, as we approach the subject of adaptive subcarrier modem mode allocation and turbo channel coding. Our motivation is that of quantifying the performance benefits of employing adaptive channel coded OFDM modems.

- In **Chapter 13** we provide an introduction to the subject of space-time coding combined with adaptive modulation and various channel coding techniques. A performance study is conducted in the context of both fixed-mode and adaptive modulation schemes, when communicating over dispersive wideband channels. We will demonstrate that in conjunction with space-time coding the advantages of employing adaptive modulation erode, since the associated multiple transmitter, multiple receiver assisted diversity scheme efficiently mitigates the channel quality fluctuations of the wireless channel.

Having reviewed the historical developments in the field of AQAM, **in the rest of this monograph we will consider wideband AQAM assisted single- and multi-carrier, as well as CDMA transceivers, communicating over dispersive wideband channels. We will also demonstrate that the potential performance gains attained by AQAM erode, as the diversity order of the systems is increased, although this is achieved at the cost of an increased complexity. We will demonstrate that this is particularly true in conjunction with space time coding assisted transmitter diversity, since Multiple-Input, Multiple-Output (MIMO) systems substantially mitigate the effects of channel quality**

fluctuations. Hence if the added complexity of MIMOs has to be avoided, BbB-adaptive transceivers constitute powerful wideband fading counter-measures. By contrast, there is no need for the employment of BbB-adaptive transceivers, if the higher complexity of MIMOs is affordable, since MIMOs substantially mitigate the effects of channel quality fluctuations, rendering further fading counter-measuers superfluous.

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