ADAPTIVE TECHNIQUES IN ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING IN MOBILE RADIO ENVIRONMENT

N. K. Noordin, B. M. Ali, N. Ismail, and S.S. Jamuar
Faculty of Engineering, Universiti Putra Malaysia, Serdang, Malaysia
E-mail: nknordin@eng.upm.edu.my

ABSTRACT

In this paper, a review of various link adaptation techniques employed in the transmission of adaptive Orthogonal Frequency Division Multiplexing (OFDM) is presented. Significant research effort in coded OFDM and adaptive modulation based on second moment adaptation are simulated and presented. Results show that coded OFDM performs at least 5 dB better in terms of signal to noise ratio (SNR) requirements as compared to uncoded system in any QAM modulation. Results on second moment adaptation show that, for adaptation up to 4 bits per symbols, second moment adaptation is about 3 dB more superior than adaptation by mean channel SNR. Other related issues are discussed to formulate future research direction in an effort to achieve higher throughput, lower bit error rate and better overall system performance.

Key words: *Orthogonal Frequency Division Multiplexing, OFDM, Adaptive Modulation, Channel Coding, Multicarrier Transmission*

INTRODUCTION

Mobile communications is increasingly required to provide a variety of multimedia applications for mobile users. The current 3rd generation (3G) mobile system introduced in some of European countries and in Japan is not promising enough to provide such broadband multimedia services with its one carrier transmission system. So the challenge to provide high data rate over hostile mobile environment with limited spectrum and inter-symbol interference (caused by multipath fading) has led to the introduction of multi-carrier transmission system. This type of transmission system, namely Orthogonal Frequency Division Multiplexing (OFDM) has been identified as a potential candidate for the forth coming 4th Generation (4G) broadband mobile communication system. This is because it is able to deliver rate data by splitting them into a number of lower rate streams that are transmitted simultaneously over a number of subcarriers [1]. Besides it can also combat inter-symbol-interference commonly found in mobile communication system [2].

OFDM was initially introduced in broadcasting system such as Digital Audio Broadcasting (DAB) and Digital Video Broadcasting (DVB) in Europe, IEEE 802.11 Wireless LAN, High-performance LAN (HIPER-LAN) type2, and Multimedia Mobile Access Communication (MMAC) for wireless LAN [3]. These OFDM standards were designed for indoor environment with relatively short delay spreads. Many research efforts are now looking into possibility of utilizing OFDM in wider macrocellular-area that would provide multimedia-rich internet access to the user.

An approach called link adaptation (LA) techniques has emerged as a tool to increase data rate and spectral efficiency [4]. In this technique, modulation, coding rate, and/or other signal transmission parameters are dynamically adapted to the channel condition to increase the system performance in terms of Bit Error Rate (BER) and throughput (bps) in various conditions such as channel mismatch, Doppler spreads, fading, etc. The focus of this paper is to provide a review of these link adaptation techniques and also to develop research related to the implementation of OFDM transmission system. We identify the followings as techniques currently proposed by researchers in implementing OFDM system:

- Adaptive modulation
- Coded OFDM
- Multi-antenna system

ADAPTIVE MODULATION FOR OFDM

Adaptive modulation or adaptive OFDM is a technique used in OFDM transmission that adapt bit and power allocation to the amplitude response of a frequency selective channel. The goal of this technique is to choose the appropriate modulation mode for transmission in each carrier, given the local signal-to-noise ratio (SNR) [3],

ISSN 1823-1039 © 2004 FEIIC

[5]. Early simulation results showed that adaptive modulation showed significant benefits in terms of channel capacity (throughput) and BER for high-speed data transmission when OFDM is employed [2], [3], [5]-[15]. Nevertheless, implementing adaptive modulation for OFDM transmission systems is not a straight forward method. Some specific issues, such as the those discussed below, would require special attention when dealing with adaptive modulation in and OFDM system to increase throughput and system performance:

- **Channel state information:** A schematic model of adaptive OFDM shown in Fig. 1 requires synchronization by signaling channel between the adaptive modulator and demodulator so that the transmitter knows which channel state information (CSI) is being fed by the receiver before deciding on the bits and power allocation for the next transmission. However, this would reduce bandwidth efficiency since some of the spectrum will be used for signaling, thus many works appeared in the literature that have disregarded the use of signaling by assuming ideal carrier and clock recovery at the expense of channel mismatch [5, 7, 9, 11 and 15]. A large gain is possible under perfect CSI over non-adaptive system as demonstrated in [10]. A few works, on the other hand, used multiple estimates to mitigate the effects of CSI delay [2, 3, 10] since greater impact on performance is due not to error in channel estimators, but to outdated adaptations that lead to channel mismatch [3]. For 802.11 wireless LAN applications, channel mismatch is not a problem because both Doppler spread and delay are small. However, if we are to extend the range of these high-speed wireless LANs to a wide-area high mobility outdoor environment, the resulting channel mismatch will cause significant performance degradation. An approach to mitigate this problem will be discussed in our later discourse.

- **Loading algorithm:** The use of loading algorithm in adaptive modulation is another important issue to ensure that the system is robust and yet less computationally intensive. A few bit and power loading algorithms currently available [16],[17] are, however, computationally complex and would require a high power consumption at the base station (BS). A simpler bit and power allocation proposed by [15] formed a faster and lesser complex algorithm that would not power-burden the BS and based mainly on the optimum power distribution and channel capacity given in [18]. Another approach that avoids the use of signaling would be to rank the received subcarrier amplitudes and decides on the basis of *a priori* knowledge on how many subcarriers are to be left out and which will be used in the next uplink frame [7]. Similarly at the base station, a ranking of the received amplitudes is performed, and the same allocation will be used for the downlink frame. In addition, the BS will transmit pilot symbols on the unused subcarrier, so that mobile station can gather information about samples of the channel's transfer function on all subcarriers that will serve as a basis for a new allocation.

- **Multiple access techniques:** Adaptive OFDM can be implemented in all multiple access techniques. Recent work published [11], shows that Interleaved-Frequency Division Multiple Access (FDMA), a variant of FDMA, in which subcarriers assigned to a user are interlaced with other users' subcarriers in the frequency domain, is an effective scheme in the downlink of a cellular radio system. Space Division Multiple Access Scheme (SDMA), on the other hand, would be best implemented when Time Division Duplex (TDD) is employed such that channel estimate can be directly used for both uplink and downlink. OFDM that employs Cod Division Multiple Access (CDMA) (also known as MC-CDMA) in which all users use all subcarriers simultaneously loses its orthogonality in the uplink due to distortion in multipath fading channels. This would make complicated equalization techniques necessary that introduce a loss in SNR performance and diminish complexity advantage of OFDM over single-carrier techniques [1]. TDMA, on the other hand, can be best exploited according to the modulation level and can control the bandwidth by simply changing the number of assigned slots in each TDMA frame. This multiple access scheme would enable the system to cope with various bit rates for multimedia services [19].

CODED OFDM

Reliable communication hinges on effective ways to add redundancy to the data in order to protect it from the random disturbances introduced by the channel. The following channel error control coding schemes have been explored in conjunction with adaptive OFDM:

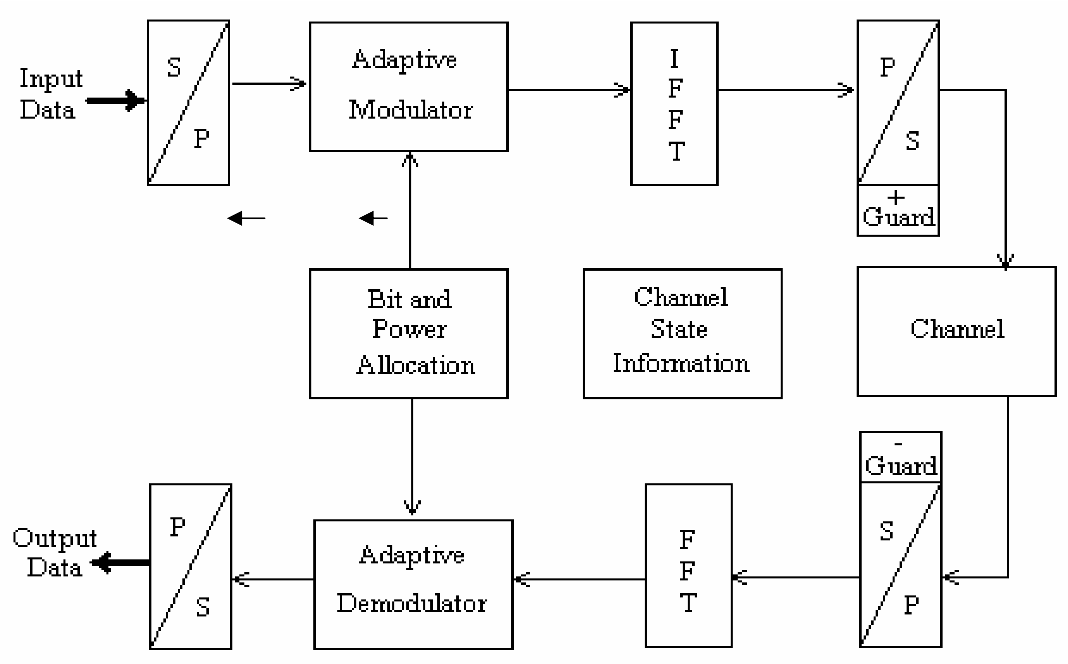

Figure 1.0 Adaptive OFDM Schematic Diagram

- **Trellis coding:** Channel coding commonly employed with adaptive OFDM is Trellis Coded Modulation (TCM) with various rates and lengths. A variant of TCM termed as Adaptive Spatial-Subcarrier TCM (ASSTCM) has been introduced and explored in multiple-input multiple-output adaptive OFDM [15]. It aims at minimizing the total transmit power required for each OFDM transmission. This is achieved by optimizing power allocation, code rate and modulation scheme in each spatial-subcarrier while maintaining data rate and bit error probability.

- **Adaptive coding:** A strategy that vary the number of bits per transmitted symbol as a function of channel fade level has recently emerged [20], [21]. Redundant residue number (RRNS) system codes [21], [22] and coset codes [20] are applied in the context of adaptively coded symbol-by-symbol in adaptive OFDM. Trellis and lattice codes, a special set of coset codes are well suited for adaptive coded modulation since the code design and modulation design are separable [23]. As for adaptive rate RRNS codes, in addition to subcarrier, the coding rate is adapted in response to the time and frequency dependent estimated channel conditions. However, the proposed technique is limited to point to point duplex communication. Further research can be explored in conjunction with multiple antenna systems.

- **Combined coding:** Introduced by [24], is a scheme that provides both error control capability and also reduces peak to mean envelope power ratio. The technique claimed to be agreeable with any standard block code, requiring simple processing but with no additional redundancy. This technique employs common linear block codes to achieve the error control property and utilizes the inherent redundancy in the code to minimize the peak to mean power ratio. Further research on this combined coding can be explored by employing convolutional coding for comparison purposes.

OFDM-BASED MULTI ANTENNA SYSTEM

Deploying multiple antennas at both the transmitter and receiver for a wireless system has shown improvements in system performance in terms of spectral efficiency and BER [11]. The corresponding technology, known as spatial multiplexing, allows an increase in data rate without additional power or bandwidth consumption [25]. OFDM is currently been proposed for in broadband multi-antenna system. But again, in order to implement this OFDM-based multi-antenna system CSI issues, namely blind estimation and pilot-based are to be considered.

- **Blind channel identification:** Similar to non MIMO system, accurate CSI is necessary to produce an increase in data rate. For accurate CSI, channel condition is best estimated by sending training sequence but at the expense of overheads. This is not so crucial in single antenna system but more crucial in MIMO channels. To avoid the overheads problem blind channel identification is used. This technique can identify the channel based on known statistical properties of the data symbols. The algorithm proposed recently [25] performs non-redundant nonconstant-modulus precoding in the transmitter such that the cyclostationary statistics allow a separate identification of the individual scalar subchannels. This is achieved by providing each transmit antenna with a different signature in the cyclostationary domain with the signatures chosen such that for a given cycle, all but one transmit antennas are nulled out.

- **Pilot-based channel estimation:** Pilot-symbol assisted modulation has been long introduced in single carrier system. In OFDM-based systems, pilots can be used and are more desirable in MIMO systems so as to avoid signaling. Channel estimates based on pilot tones is independent of the other data symbol and is not affected by channel spectral nulls [26].

INCORPORATING OTHER ISSUES

We have discussed various approaches investigated by different researchers that exploit variations of wireless channel by dynamically adjusting certain key transmission parameters to the changing environment and interference condition observed between the base station and mobile users. Adaptive modulation provides tremendous performance improvement in terms of BER and throughput. However there are issues that need further consideration in implementing adaptive modulation as a link adaptation scheme in an OFDM transmission system such as the followings:

- Channel state information (CSI) metrics
- Subband adaptation
- Adaptive antenna

Channel State Information Metrics

Most of the adaptation performed (e.g. as in [2], [3], [5], and [6]) is based on CSI, particularly the instantaneous SNR with instantaneous feedback. Method of determination for this type of LA solution is straightforward and fast.

It should be noted that the conversion from mean SNR to BER can be made only if the mean SNR is measured in a very short time window that sees a constant non-fading channel. As discussed earlier, Souryal and Pickholz [3] showed that greater impact is caused by outdated adaptation and is further confirmed in [4]. In practice, however, the feedback delay and other implementation constraints will not allow for mode adaptation on an instantaneous basis, and update rate may be much slower than the coherence time (the time duration over which the channel impulse responses remain strongly correlated and essentially invariant [27, p. 165]).

One approach that would mitigate this problem is the use of second or higher order statistics of the SNR instead of just the mean [4], [28]. Catreux *et al.*, in [4] claimed that with moment-based CSI, the adaptation thresholds which is based on multiple statistics of the received SNR do not rely on any particular channel conditions. It is an estimation of limited statistical information from the probability density function (*pdf*) of the SNR such as the *k*-order moment over the adaptation window, in addition to the pure mean (first order moment).

The first order moment captures how much power is measured at the receiver on average, while the second moment of the SNR over time (or frequency) dimension captures some information on the time (frequency) selectivity of the channel within the adaptation window [4]. Higher order moments (k>2) give further information on the *pdf* but should be avoided for computation efficiency.This type of adaptation thresholds remain valid for any Doppler spread, delay spread, Ricean *K*-factor, number of antennas used as well as antenna polarization. The effect of these factors is captured by the low order moments of the SNR ($k>1$), and , to a large extent, by the first and second order moments alone. For rapidly time varying channel, however, to arrive at reliable performance estimates, the effects of the time varying narrow band channel have to be averaged over a high number of transmission burst [6], thus the needs for subband by subband adaptation rather than subcarrier by subcarrier adaptation [4]. We will discuss this further in the next section. It is also important to note that the second order statistics is usually experimented in MIMO systems due to the fact that MIMO could not tolerate overheads [25].

Another approach that can be taken to estimate CSI is through Packet Error Rate (PER) or BER information. This method relies on the estimation of PER statistics that might require up to several thousands of packets to be transmitted for a given mode in order to obtain reliable estimate, thus making the adaptation loop slow. Only large scale channel variations maybe exploited unless one decides to use a training packet at regular frequent times. Moreover this method is very traffic dependent, where in absence of traffic, one loses track of channel quality and may have to reinitialize the LA [4].

To alleviate the above-mentioned problem, Catreux *et al.* [4] proposed the use of incremental redundancy, a proposed standards for IS-136 and EDGE, in which additional redundancy information is incrementally transmitted as long as decoding of a packet fails. The additional information is combined with the previously received information, resulting in enhanced coding.

A close-to-perfect channel estimation is required to ensure the effectiveness of adaptive modulation in OFDM. The two methods discussed above, combined with optimal training sequence [26], may yield both accuracy and robustness over a wide range of channels, adaptation rates, and traffic conditions, especially when delay is involved. This can be experimented further through simulations.

Subband Adaptation

The ideal adaptive modulation should be based on subcarrier but this is hard to implement physically, due to large signaling overhead and heavy computation. Thus the next best thing is to aggregate subcarriers into subbands and adapt the modes on a per-subband basis [4].

However the drawbacks of subband adaptation in terms of throughput depends on the frequency-domain variation of the channel transfer function [5]. If the subband bandwidth is lower than the channel's coherence bandwidth, then the assumption of constant channel quality per subband is met, and the system performance is equivalent to that of subcarrier-to-subcarrier adaptive scheme [5]. Otherwise, invoking for example the lowest quality subcarrier in a subband for channel estimation, will lead to a pessimistic channel estimate for the entire subband.

An alternative scheme would be to calculate the expected overall BER for all available modulation schemes in each subband. For each subband the scheme with the highest throughput, whose estimated BER is lower than a given threshold is then chosen. This would lead to capacity improvement as compared to the one discussed earlier. Unfortunately this would introduce further power loading to the system.

Adaptive Antenna

The deployment of a smart array antenna with several antenna elements opens up the spatial dimension and permits the use of space-division multiple access in an OFDM system. Wong *et al.* [15] showed that in multiple antenna systems, selection diversity (SD)/maximum ratio combining (MRC) can effectively reduce and recover the deep fade even without the incorporation of adaptive or non-adaptive coding. This is due to the fact that in a space-time-frequency adaptation scheme, maximum ratio combining has captured the effects of all three parameters to express the channel quality and therefore the adaptation thresholds.

The ability to set up multiple beams that are electronically pointed to mobile station locations adaptively will lead to an increase in capacity and reduces interferences [29]. However it will lead to heavy power loading for computational purposes. It is noted that this adaptive antenna is best adapted when TDD is employed. In TDD systems, the channel estimate called spatial covariant matrix (SCM) can be used directly if channel shows sufficient grade of reciprocity, which is the case in TDD systems [22], [29]. But Frequency Division Multiplex (FDD) systems which utilize different frequency for uplink and downlink would require SCM transformation. This entails the use of pilot tones during the uplink stage. Again, this will increase computational loading, hence a compromise between computational complexity and system performance has to be found.

SOME SIMULATED RESULTS

We have simulated an OFDM system using subband to subband adaptation based on second order moments and compare the results with system using mean channel SNR as adaptation method. Results in Figure 7.1 show that for adaptation up to 4 bits per symbols, second moment adaptation is about 3 dB more superior than adaptation by mean channel SNR in terms of BER performance.

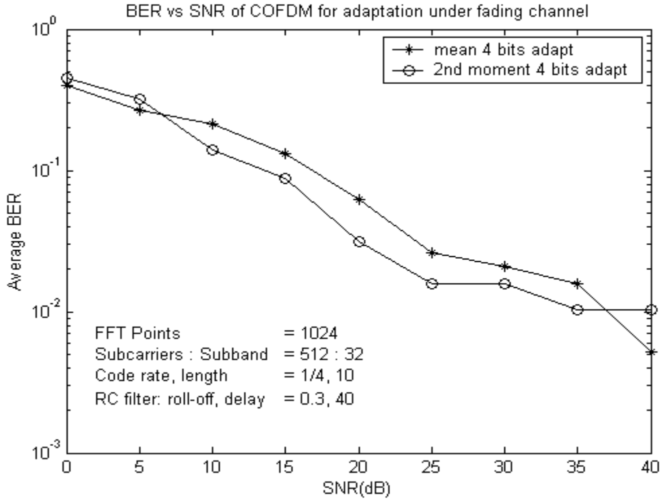

Figure 2.0 BER versus SNR of of 1-4 bits adaptation

We have also simulated coded OFDM transmission employing 2-QAM to 256-QAM using various rates and lengths of convolutional encoder. Results show that ¼ rate convolutional encoder with constant length of 10 outperforms other rates and lengths as shown in Figure 7.2. For more results please refer to [30]. Figure 7.3 and Figure 7.4 show coded OFDM and uncoded OFDM performance, respectively. These figures show that coded OFDM outperforms non-coded OFDM by at 3-10 dB in terms of SNR requirement to achieve certain BER, depending on the QAM modulation.

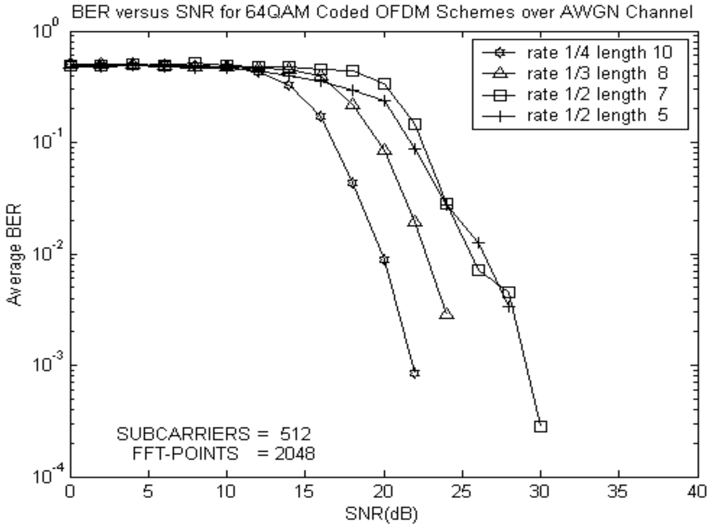

Figure 3.0 BER versus SNR for 64-QAM Coded OFDM using different types of convolutional encoder

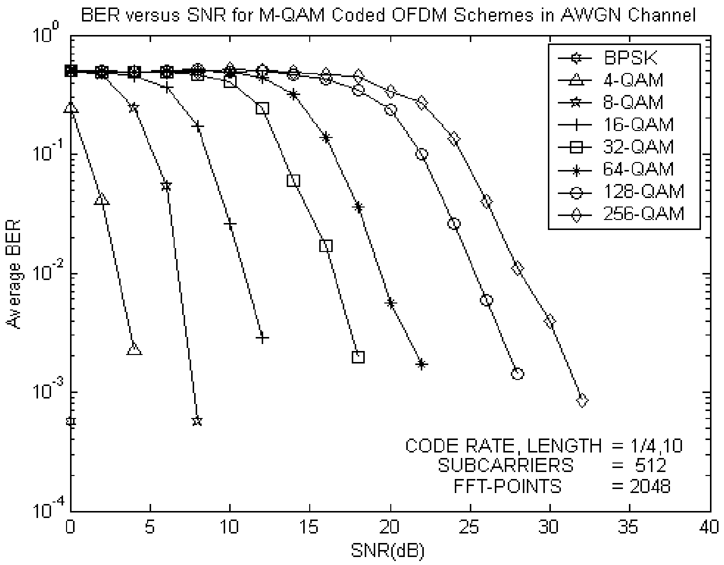

Figure 4.0 BER versus SNR for M-QAM Coded OFDM at ¼ rate with length 10.

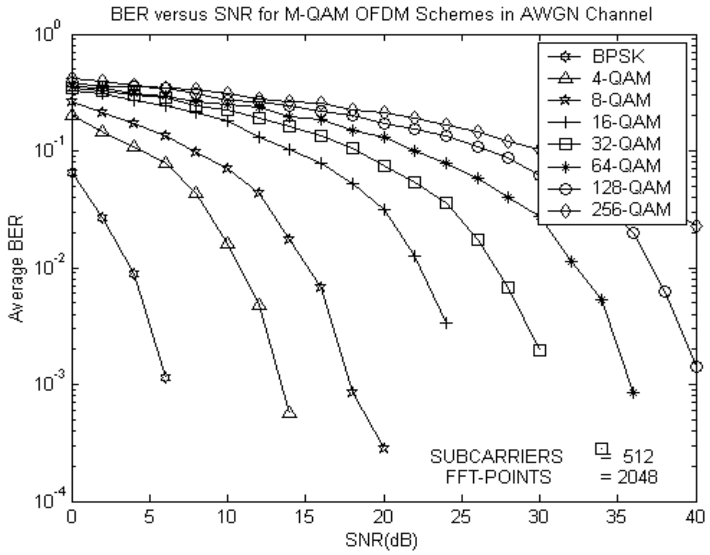

Figure 5.0 BER versus SNR for M-QAM OFDM in AWGN channel with FFT-points = 2048

CONCLUSION

This paper reviewed adaptive modulation with other related issues as part of link adaptation in an OFDM system. Contributions by various authors show tremendous improvement to system capacity and BER. However specific issues such as those highlighted in section 6 can be further scrutinized in the implementation of a perfect OFDM system.

We have also provide preliminary outcomes based on the suggested techniques such as coded OFDM transmission as well as subband and second order moments adaptations.

The future mobile communications would require a link adaptation solution. Adaptive OFDM for both single and multi user system should integrate temporal, spatial, and spectral components to achieve higher data rate to benefit future broadband mobile communications. It can be further enhanced with the introduction of more practical adaptation techniques, like subbands and higher order moments of channel quality, as well as adaptive antenna system.

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