IMPLEMENTATION ISSUES OF ADAPTIVE OFDM IN MOBILE RADIO ENVIRONMENT

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ABSTRACT

A review of adaptive modulation with other related issues as part of link adaptation in an OFDM system is presented. Issues such as channel estimation, channel coding, Multiple Input and Multiple Output (MIMO) system are discussed as efforts in increasing throughput and reducing Bit Error Rate (BER). Significant works related to the issues are reviewed in details while others are summarized and tabulated for comparison purposes. Other potent issues that require further considerations in implementing adaptive OFDM system such as channel state information metrics, subband adaptation and adaptive antennas are presented and discussed as current and future direction of research in this area.

Keywords : *OFDM, adaptive modulation, coded adaptive modulation, and 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 coming 4th Generation (4G) broadband mobile communication system. This is because it is able to deliver high 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 are 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, etc. The focus of this review is to provide a thorough study of this link adaptation method particularly adaptive modulation and its related issues in various OFDM systems.

The organization of this paper is as follows. Section II gives an overview of a typical OFDM system. Section III reviews significant adaptive modulation approaches contributed by several authors in detail. This section also include literatures in multiple-input multiple-output (MIMO) and coded OFDM as well as a comparative summary of related research in adaptive OFDM. Section IV discusses pertinent issues related to the implementation of the system and followed by conclusion in Section V.

OVERVIEW OF OFDM SYSTEM

The N-subcarrier OFDM system shown in Figure 1 [5], [6] and [7] generates N data symbols, S_n, $0 \leq S_n \leq N\text{-}1$, which are multiplexed to the N subcarriers. The time domain samples, s_n transmitted during one OFDM symbol are generated by the inverse fast Fourier transform (IFFT) and transmitted over radio channel after cyclic prefix (CP) has been inserted. The channel is usually modeled by its time-variant impulse response $h(\tau,t)$ and additive white Gaussian noise (AWGN). At the receiver, the cyclic prefix is removed from the received time-domain samples, and the data samples r_n are fast Fourier transformed (FFT), in order to yield the received frequency-domain data symbols R_n.

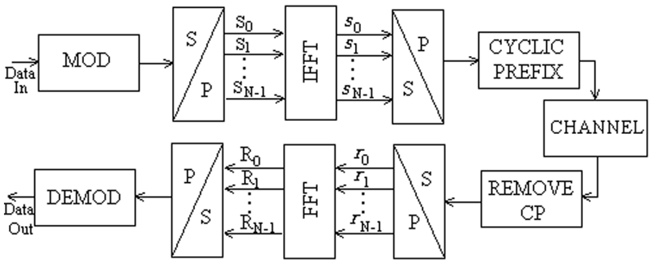

Figure 1: OFDM Model

The channel response is approximately constant for the duration of one OFDM symbol because it has been subdivided into N subchannels, each with small enough bandwidth, Δf [3], [5] and [8], and is referred to as the frequency domain channel transfer function H_n. The received data symbols R_n can be expressed as [5], [6]:

$$R_n = S_n \ H_n + n_n \tag{1}$$

where n_n is an AWGN sample.

Since the noise energy in each subcarrier is independent of channel frequency domain transfer function H_n, the local signal-to-noise-ratio (SNR) in subcarrier n, can be expressed as [5], [6]:

$$\gamma_n = |H_n|^2 \cdot \gamma \tag{2}$$

where γ is the overall SNR. If no signal degradation due to intersubcarrier interference (ISI) or interference from other sources appears, then the value γ_n determines the bit error probability for the transmission of data symbols over the subcarrier *n* [5].

Next, common parameters found in a typical OFDM system are discussed and how they are determined to meet design requirements.

Choice of OFDM Parameters

The choice of OFDM parameters is a tradeoff between various requirements. Normally there are three main requirements that need to be determined first, i.e. bandwidth, bit rate and delay spread.

The delay spread directly dictates the cyclic prefix (CP) (or also known as guard time) such that the length of the cyclic prefix is at least as long as the maximum delay of the channel [3]. In order to ensure that the received time-domain OFDM symbol is demodulated from the channel's steady-state rather than from its transient response, each time-domain OFDM symbol is extended by this cyclic prefix. CP plays a role to overcome the inter OFDM-symbol interference due to channel memory [6]. As a rule introduced by van Nee and Prasad [1] the cyclic prefix should be about two to four the root mean square of the delay spread to ensure that the channel transient response has died down after exciting the channel with a time-domain OFDM-symbol. This CP value also depends on the type of coding and modulation levels where higher order modulation is more sensitive to inter-channel interference (ICI) and ISI than Quadrature Phase Shift Keying (QPSK); while complex coding reduces the sensitivity to such interference.

Once CP is fixed, symbol duration can be set. To minimise the SNR loss caused by CP, it is preferable to have the symbol duration much larger than the CP. Van Nee and Prasad [1] noted that the duration should not be arbitrarily large or it may cause phase noise and frequency offset as well as an increased peak-to-average power ratio. A practical design would set symbol duration at least five times the CP.

Next the number of subcarrier can be determined. The number of subcarriers can be determined by the required bit rate divided by the bit rate per subcarrier. The bit rate per subcarrier is defined by the modulation type, coding rate, and symbol rate [1].

An additional requirement that would affect the chosen parameters is the demand for an integer number of samples both within the FFT/IFFT interval and the symbol interval. The solution is normally to change one of the parameters slightly to meet the integer constraint as described in [1].

As an example, supposed it is required to design OFDM parameters based of the initial requirements as shown in Table 1 [9].

Parameters	Values	Remarks
Bit rate	50 Mbps	requirement
Bandwidth, B	35 MHz	requirement
Tolerable delay spread	200 ns	typical indoor environment
OFDM Parameter Design		
Cylic prefix, T_{CP}	800 ns	2 - 4 times delay spread
Symbol duration, T_s	4.8 μs	At least 4 -5 times T_{CP}
OFDM subcarrier spacing, Δf	250 kHz	$(T_s - T_{CP})^{-1}$
FFT-Points	128	Higher number of FFT-points may be used for oversampling purposes
Number of subcarriers, N	120	$N \times \Delta f \leq B$

Table 1. System Requirements and OFDM Parameters

Note that in order to achieve 50 Mbps, 240 bits per OFDM symbol (50 Mbps x 4.8μs) would be required. 16-QAM modulation with 4 bits/symbol/subcarrier (using 60 subcarriers) or 4-QAM with 2 bits/symbol/subcarrier (using 120 subcarriers) may be chosen. Either option will lead to the use of less than available bandwidth of 35 MHz. If option 2 is chosen using 120 subcarriers to carry the symbols, the remaining 8 subcarriers maybe used for control or training purposes.

ADAPTIVE MODULATION FOR OFDM

Adaptive modulation or adaptive OFDM simply defined by Rohling and Grunheid [10] as varying the modulation level on each subcarrier, depending on individual SNR. Others like Souryal and Pickholz [3] defined adaptive modulation by adapting bits and power allocation to the amplitude response of the frequency selective channel. In general the goal of adaptive modulation is to choose the appropriate modulation mode for transmission in each subcarrier, given the local SNR, in order to achieve good tradeoff between throughput and overall BER [5]. Barmada and Jones [8] used adaptive modulation for a DVB system to improve capacity as well as bandwidth efficiency, Keller and Hanzo [5], [6] for WLAN, while many others (e.g. [2], [3], [8], [10] and [11]) for the same reason, focused on future mobile systems.

Figure 1 can be modified slightly to represent OFDM adaptive modulation system. Adaptive modulator is inserted before the IFFT while the adaptive demodulator is after the FFT operation. The adaptive modulator and demodulator have to be synchronised by a signaling channel, which is disregarded by Czylwik [12] by assuming ideal carrier and clock recovery. Su *et al.* [13], Souryal and Pickholz [3] and Tang *et al.* [14], on the other hand performed channel estimation after FFT and fed the information back to the adaptive modulator for the bit and power loading.

Czylwik [12] and [15] started the work of adaptive modulation in Germany. She compared channel capacity (or throughput) of a wideband radio channel (with fixed antenna and with frequency-selective fading) to the achievable data rate using adaptive OFDM. In her investigation she concluded that with adaptive OFDM the fraction of channel capacity which can be achieved depends on the average signal-to-noise ratio (SNR) and the propagation scenario. Also she showed that with adaptive OFDM, the required power for an error probability of 10^{-3} can be reduced by 5 to 15 dB compared with fixed OFDM. Her results have spawn new interest and led new direction of OFDM research particularly in mobile radio communications (eg. [16], [17] and [18]).

Su *et al.* [13] and [19] investigated the performance of adaptive modulation in OFDM under the constant bit rate (CBR) requirement and channel mismatch condition. Under perfect channel estimation, a large gain over non-adaptive system is possible. However Su *et al.* [13] and a few other authors [7], [20], [21] and [22] showed that with channel mismatch, which occurs with channel estimation errors and feedback delay, gain of adaptive modulation may diminish. Su *et al.* [13] proposed two approaches to mitigate the effect of mismatch by using coding technique, which further assisted by differential channel information; and a robust loading scheme. This robust loading scheme is accomplished in a bit-by-bit manner in which every iteration assigns one more bit to the subchannel, which has the least power increase among all the subchannels. This proposal is experimented further by Wong et al. [23] and Torabi and Soleymani [24], which will be further detailed in our later discourse.

In CBR case [13], the goal is to minimise the average BER for a given SNR per bit. A few loading algorithm has been proposed by [25], [26], [27], [28], [29] and [30]. Su *et al.* [13] chose to use the loading technique proposed by Fischer and Huber [26], which is said to be less computationally intensive. The algorithm allocates more bits to 'good' subchannels that are those with high channel frequency response values, while less or even no bits to 'bad' ones. Su *et al.* [13] defined a subchannel as 'bad' when $|H_t(n)/H_{t-\tau d}|^2 < -3$ dB where $H_t(n)$ denotes the frequency response at time t for the n-th channel, and τ_d is the feedback delay.

The performance of the system is investigated when perfect information about the multipath channel at the receiver is also available at the transmitter. BER performance, without coding, plotted against E_b/N_o shows when perfect channel information is available at the transmitter, a very large gain in performance is possible when adaptive modulation is employed.

To use adaptive modulation effectively, accurate channel state information is needed at the transmitter to decide the optimal bit and power distribution [13]. The Frequency Division Duplex (FDD) scenario considered by Su *et al.* [13] and Barmada and Jones [31] required channel response to be estimated at the receiver and fed back to the transmitter. This estimation is subject to noise, and accuracy is measured by mean square error between the estimated channel and the actual channel response. Since Su and Schwartz [32] showed that noisy estimation only causes minimal deterioration with the current channel estimation techniques, the focus of Su *et al.* [13] is on the channel mismatch caused by the delay between the time the channel is measured at the receiver, and the time when the receiver detects the data.

For 802.11 wireless LAN applications, channel mismatch is not a problem because both Doppler spread and delay are small. However, if the range of these high-speed wireless LANs is extended to a wide-area high mobility outdoor environment, the resulting channel mismatch will cause significant performance degradation.

Similar to Su *et al.* [13], Souryal and Pickholz [3], investigated the impact of imperfect channel information on the performance of an adaptive modulation in OFDM. To gain insight into the impact, [3] has considered a non-ideal, band-limited channel with additive Gaussian noise as given by Proakis [33] which says that the optimum power distribution that would maximises channel capacity is as follows,

$$P(f) = \begin{cases} K - \Phi_n(f) / |H(f)|^2 & f \in W \\ 0 & f \notin W \end{cases} \qquad (3)$$

where $P(f)$ is the power density of the signal, $\Phi_n(f)$ is the power spectral density of the additive Gaussian noise, $H(f)$ is the frequency response of the channel with bandwidth W, and K is a constant which determines the total power to be allocated. Allocation of power in OFDM is performed across a uniformly spaced frequency bins. Note that equation (3) shows that more power is allocated at frequencies which have greater channel magnitude response or lower noise power.

Channel capacity of an OFDM system is given by Proakis [33] as:

$$C \cong \Delta f \sum_{i=1}^{N} \log_2 \left[1 + \frac{p_i |H_i|^2}{\Phi_i} \right] \qquad (4)$$

where P_i, H_i, and Φ_i are the signal power, channel frequency response, and additive Gaussian noise power, respectively, in subchannel i. P_i is constant for all i for a uniform non-adaptive power distribution. On the contrary, using power distribution of equation (3), capacity can be maximised to yield,

$$C_{opt} \cong \Delta f \sum_{i=1}^{N} \log_2 \left[\max(K \frac{|H_i|^2}{\Phi_i}, 1 \right] \qquad (5)$$

Souryal and Pickholz [3] further examined that, if instead of using the optimal distribution of equation (3) based on $\Phi_i / |H_i|^2$, they were to use the estimate $\hat{\Phi}_i / |\hat{H}_i|^2$ the resulting sub-optimal capacity would be,

$$C_{subopt} \cong \Delta f \sum_{i=1}^{N} \log_2 \left[1 + \max\left(K - \frac{\hat{\Phi}_i}{|\hat{H}_i|^2}, 0\right) \frac{|H_i|^2}{\Phi_i} \right] \tag{6}$$

Using Equation (6), capacity for some imperfectly known channel transfer function with Φ_i constant (white noise) can be calculated to gain indication of the impact of the use of imperfect channel information in the distribution of power. In the presence of time-varying condition, a time delay between the collection of channel estimate and the adaptation of the modulation at the transmitter results in a mismatch between the estimate and the actual channel. Ignoring this channel estimator inaccuracy, and letting $\hat{H}(f, t) = H(f, t - \tau)$, where τ represents time delay, Souryal and Pickholz [3] showed results that estimator inaccuracy deviated only slightly from the optimal, using equation (5) and (6). These results indicate a greater potential impact on performance due to outdated adaptations than due to the error of channel estimators.

The successive bit allocation algorithm is used to allocate 0, 2, 3 or 4 bits to each subchannel corresponding to subcarrier modulation of 4-, 8-, or 16-QAM. A total of 512 information bits is transmitted in each OFDM frame, for an average of 2 bits/subchannel. Power is allocated uniformly across subchannels with Rayleigh channel model. Results of BER versus SNR per bit for adaptive and uniform modulation over a channel with a maximum Doppler frequency of 10 Hz for perfect and estimated channel state information (CSI) shows that the effect of imperfect channel information is greater with adaptive modulation than with uniform modulation.

Moreover, results of BER versus SNR with adaptive modulation for increasingly faster time-varying channels showed performance degradation with the increase in Doppler spread, due to growing mismatch between the adaptation [2], [3], [13], which is performed every eighth OFDM frame, and subsequent frames.

Souryal and Pickholtz [3] further examined the impact of channel prediction to BER performance. In the system model, channel estimator used for adaptation is replaced with an FIR Wiener predictor of an equal complexity (i.e. length 5) to obtain an estimate of the channel 4 frames ahead. The use of channel prediction is shown to decrease the BER by a factor of two relative to the case without prediction.

Rohling and Grunheid [10] investigated the performance of an adaptive OFDM system in Time Division Multiple Access / Time Division Duplex (TDMA/TDD) communication. The performance of OFDM-TDMA transmission system is studied in a frequency-selective and time-variant radio channel and the BER performance.

Similar to [3], Rohling and Grunheid [10] used information about different subcarrier-dependent attenuations caused by the radio channel by leaving out weak subcarriers and adapting the modulation level individually for each carrier. This method would reduce the BER even at small signal-to-noise ratios, and can serve as a basis for an effective use of channel coding techniques.

In a realistic system however, the question arises on how the receiving station can gain knowledge about the used subcarriers. Rohling and Grunheid [10] assumed this information is known for the first time. For the subsequent intervals, this can be made possible by transmitting the information of subcarriers that are modulated, in the form of an allocation table. Different method is proposed so as to avoid signaling. This is done by ranking of received subcarrier amplitudes and decides on the basis of the *a priori* knowledge how many subcarriers say, K_a are to be left out and which are used in the next uplink frame.

Similarly at the base station, a ranking of the received amplitudes is performed, and the K_a smallest values are assumed to be the ones left out by the mobile station. The same allocation will then be used for the downlink frame. In addition, the base station transmits pilot symbols on the unused carriers, so that mobile station can gather information about samples of the channel transfer function on all subcarriers which serves as basis for a new allocation.

Using this algorithm a simulation is performed and results show that a higher BER occurs because of the effect of base station mixes up the information of used and unused carrier, when a noisy used carrier has lower amplitude than a noisy unused carrier. However, the degradation become small and no difference can be observed for a BER < 10^{-3}.

Up to now, discussion is focused on adaptive OFDM for single user. In the next section discussion is extended to multi-user adaptive OFDM.

Adaptive Modulation in Multi-User OFDM

Recent work published by C. Y. Wong *et al.* [23] has gone one step further by introducing the multi-user OFDM adaptive subcarrier, bit and power allocation algorithm with adaptive modulation in order to minimise total transmit power. As different subcarriers experience different fades and transmit different number of bits, the transmit power level must be changed accordingly. This is done by assigning each user a set of subcarriers, and determining the number of bits and transmit power level for each subcarrier based on the instantaneous fading characteristics of all users. C. Y. Wong *et al.* [23] formulated the multi-user subcarrier, bit, and power allocation problem by first considering only a single user. This formulation is further extended to a multi-user system.

C. Y. Wong *et al.* [23] use this multi-user algorithm to simulate three different situations as follows:

- OFDM-TDMA: where each user is assigned a predetermined TDMA time slot and can use all the subcarriers within that time slot exclusively.
- OFDM-FDMA: where each user is assigned a predetermined band of subcarriers and can only use those subcarriers exclusively in every OFDM symbol.
- OFDM Interleaved-FDMA: To avoid a situation where all

subcarriers of a user are in deep fade, an enhanced version of OFDM-FDMA is introduced. This scheme is similar to OFDM-FDMA, except that subcarrier assigned to a user are interlaced with other users' subcarriers in the frequency domain. This scheme has already been introduced by Caswell [34] but his work is limited to DPSK and DQPSK only. It is also noted that this scheme could be used effectively in the downlink of a cellular radio system.

The three schemes are illustrated in Figure 2.

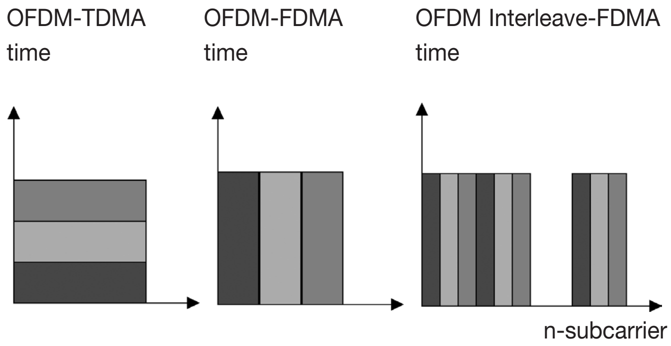

Figure 2: Subcarrier and time-slot allocations of different schemes [23]

Simulations results show that when using equal bit allocation (EBA) all three schemes have the same performance in an uncoded system because average SNR needed is a function of only the marginal probability density function (pdf) of each subcarrier gain. It is also observed that the proposed multi-user adaptive (MAO) OFDM scheme is better than static subcarrier allocation with optimal bit allocation (OBA), which are in turn better than that with EBA. Wong *et al.* [23] also found out that when OBA is used, OFDM interleaved-FDMA scheme and the OFDM-TDMA scheme have very similar performance, and both of them outperform the OFDM-FDMA scheme.

Similar to [23], Moon *et al.* [35] investigated the performance and throughput of an adaptive bit allocation and variable rate algorithm depending on channel state information (CSI) and a transmit power in a multi-user OFDM transmission.

According to Moon *et al.* [35] multi-rate OFDM using adaptive modulation can increase bandwidth efficiency by controlling constellation size and to adapt proper service for each user in this multi-user OFDM according to channel condition and transmit power while maintaining quality of service (QoS) at the receiver.

Moon *et al.* [35] stated that fixed rate adaptive OFDM using several modulation levels is inappropriate as a multi-rate multi-user services, if users are requiring various services. An algorithm developed is used to maximise the total throughput by assigning different bit and rate for each user assuming that channel conditions for all user is known at the base-station.

The system model proposed is as follows [35]:

- Variable number of user with data rate r_k bit/OFDM symbol.
- At the transmitter each subcarrier is adaptively modulated by adaptive bit allocation.
- Then different number of subcarrier is reallocated according to the required bit rate for each service.
- $b_{k,n}$ is the number of bits of kth user assigned to nth subcarrier.
- The adaptive modulator allows $b_{k,n}$ to assign value in set B={0,1,2,3,4,5,6} which correspond to no bit, BPSK, QPSK, 8-PSK, 16-QAM, 32-QAM and 64-QAM, respectively.
- Users per OFDM symbol are reallocated from allocated bit size and IFFT/FFT size which consist of R = {0,1,2,4,8,16,32,64,128,256,512} in which
    - R_0 = {1} for telephone service
    - R_1 = {2,4,8} for low rate service
    - R_2 = { 16,32,64} for high rate service
    - R_3 = {128, 256, 512} for multimedia internet service
- At the receiver demodulated symbol of subcarrier assigned of user *k* are extracted using required bit rate information and start position of subcarrier for the k^{th} user assuming the receiver knows the required bit rate and the start position.
- Required QoS for different services are as follows:
    - Speech: 10^{-2} for uncoded OFDM or 10^{-3} for coded OFDM
    - Video: 10^{-3} for uncoded OFDM
    - Data: 10^{-5} for uncoded and 10^{-7} for coded OFDM

Capacity of overall subcarriers is obtained by integration of each subcarrier. Total capacity, *C* was analysed and results showed that capacity of the adaptive multi-rate OFDM for the multi-user system can be changed adaptively for various services [35].

The review so far shows good performance increase in terms of BER and throughput, however flat fading on each subchannel can still degrade the system performance when utilizing high level modulation to achieve high spectral efficiency [36]. Recent works is now focused on increasing spectral efficiency with the incorporation of coding, multiple input and multiple output (MIMO) system, and forward error correction (FEC).

Adaptive Modulation with Coded and MIMO OFDM

In Hong Kong the work of C. Y. Wong *et al.* [23] is continued by K. K. Wong *et al.* [36] and few others (eg. [37], [38], [39] and [40]) for an adaptive MQAM with trellis coded multiple input and multiple output OFDM. This is a rather thorough investigation of adaptive OFDM which include adaptive modulation, channel coding, power optimization, and multiple antenna configurations at both transmitter and receiver.

In their work, K. K. Wong *et al.* [36] termed their method as Adaptive Spatial-Subcarrier Trellis Coded MQAM (Adaptive SSCTCM) with the objective of 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.

The system model of MIMO/OFDM proposed by [36] is shown in Figure 3. Serial to parallel buffer segments the R_b information bit sequence into $\sum_{c=1}^{N_c} r_c$ frames where r_c is the number of parallel subchannels at the c^{th} subcarrier and N_c is the total number of subcarriers. Each parallel output stream can contain a different number of bits, $m_{c,i}$ such that

$$R_b = \sum_{c=1}^{N_c} \sum_{i=1}^{r_c} m_{c,i} \tag{9}$$

Each of them can be independently encoded, interleaved, and modulated to form the modulated symbol $z_{c,i}$. Antenna weighting with K antenna weights is then performed so that K parallel streams (set) of N_c streams are formed. These streams are then translated to different subcarriers by passing through an IFFT. CP is later added to reduce ISI effect and inter-subcarrier interference. These sample streams are then parallel to serial converted for transmission.

The configuration of the antenna weighting module at the base station (BS) is shown in Figure 4 where $z_{c,i}$, the modulated symbol of the i^{th} spatial subchannel of the c^{th} subcarrier is multiplied by controllable complex weight, $a_{i,k}^{c}$ before being transmitted by the k^{th} antenna.

At the receiver side, the cyclic prefix of each received signal is removed, and the subcarrier signals are passed to the FFT. The output symbols from the different antennas are weighted and combined to produce the array of output signals. The transmitted data are then estimated from the combined symbols and finally the detected bits are converted back into serial form and decoded to recover the data bits.

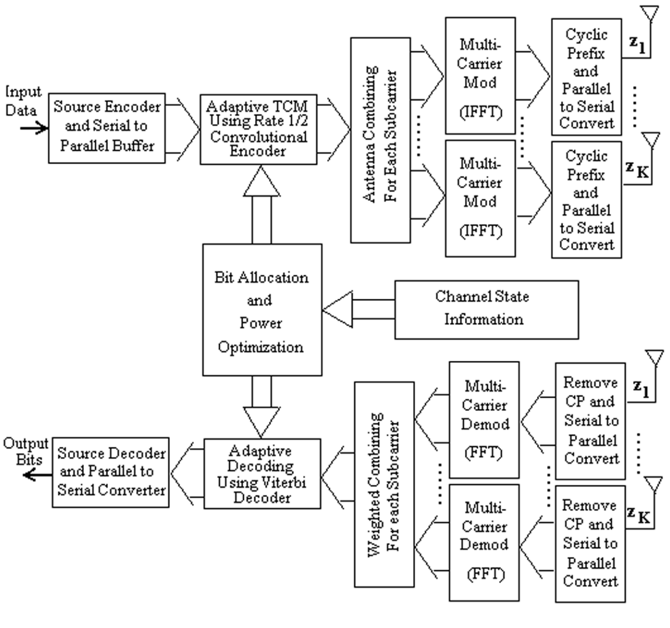

Figure 3: System Configuration of MIMO / OFDM [36]

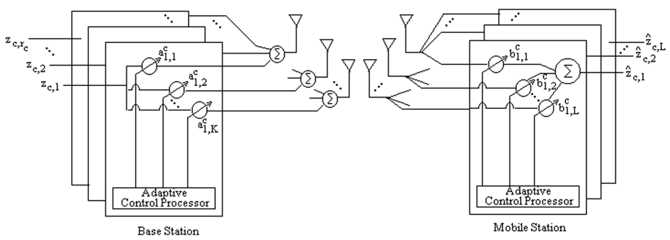

Figure 4: System configuration of antenna weighting networks for the c-th subcarrier at the base station (BS) and mobile station (MS) [36]

The configuration of the weighted combining is shown in Figure 4 at the mobile station (MS) side with L antennas. Here, the c^{th} subcarrier signals received by the antennas are multiplied by a controllable complex weight vector, $[\, b_i^c, \cdots, b_{i,L}^c \,]$, to generate, $\hat{Z}_{c,i}$, the received symbol of the i^{th} spatial subchannel of the c^{th} subcarrier.

The channel used is characterised by a multipath fading channel and the model can be represented by its impulse response using N-ray model defined as

$$c_{k,l}(t) = \sum_{n=0}^{N-1} \beta^{n}_{k,l}\, \delta(t - \tau^{n}_{k,l}) \tag{10}$$

where the subscripts k,l refer to the channel between the k^{th} antenna at the BS and the l^{th} antenna at the MS, and N is the total number of paths. Likewise the $\beta^n_{k,l}$ and $\tau^n_{k,l}$ are respectively, the complex gain and time delay for the n^{th} path of the diversity channel. The complex gain is modeled by zero mean, complex Gaussian random variable, and the power of the path with different delays are assumed to follow the exponential power delay profile.

Each received signal will effectively be the transmitted symbol weighted by a channel gain and corrupted by white noise. This approach, according to K. –K Wong *et al.* [36], allows multiple parallel transmissions in each subcarrier OFDM symbol, such that significant capacity improvement is achieved.

TCM schemes that use the same rate-½ convolutional encoded is applied to each spatial subcarrier transmission. Together with power optimisation and bit allocation algorithm to each spatial subcarrier channel, the best variable power and variable rate ATCM for each MIMO/OFDM transmission is obtained.

Table 2 shows the best combination of coding and modulation for different data rates. Table 3 on the other hand shows the optimal combinations of code rate and modulation in the sense that for a given data rate $m_{c,i}$ bit/subchannel/symbol, this coding rate and modulation will lead to the least required transmit power for a given average bit error probability [36].

The algorithm used for bit allocation is similar to [27] but simulations that produced Table 2 and 3 helped the joint optimization of corresponding power allocation as well.

$m_{i,c}$ (data)	1	2	3	4	5
MQAM	4	16	32	64	64
N_1 (coded)	1	2	2	2	1
N_2 (uncoded)	0	0	1	2	4

Table 2: The best ATCM schemes using a rate $^1/_2$ encoder [36]

BER	$m_{i,c} = 1$	$m_{i,c} = 2$	$m_{i,c} = 3$	$m_{i,c} = 4$	$m_{i,c} = 5$
10^{-3}	1.95	4.17	6.18	8.10	10.10
10^{-4}	2.72	5.01	7.05	8.87	11.38
10^{-5}	3.25	5.65	7.75	9.58	12.78
10^{-6}	3.65	6.20	8.20	10.35	13.85

Table 3: Required average E_b/N_0 [36]

Simulation results showed that selection diversity (SD) / maximum ratio combining (MRC) with ATCM and TCM have almost the same error rate performance. The reason is that SD/MRC alone can effectively reduce and recover the deep fade. As such, adaptive modulation does not help much. Results also show that the best way to implement adaptive coded modulation in MIMO/OFDM is Adaptive SSCTCM. About 4 dB gain in power efficiency is achieved when compared to SD/MRC with ATCM or with TCM.

A summary of the discussed papers and other research efforts done by various authors throughout the world is tabulated and presented in Table 4.

DISCUSSION

Various approaches investigated by different researchers that exploited variations of wireless channel by dynamically adjusting certain key transmission parameters to the changing environment and interference conditions observed between the base station and mobile users have been discussed. Indeed, 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 adaptations performed (e.g. as in [2], [3], [5], and [6]) are based on CSI, particularly the instantaneous SNR with instantaneous feedback. Method of determination for this type of LA solution is straightforward and fast, and can be summarised as follows [4]:

1) Measure the SNR at the receiver
2) Convert the SNR information into BER information for each mode candidate
3) Based on a target BER, select for each SNR measurement the mode that yields the largest throughput while remaining within the BER target bounds
4) Feed back the selected mode to the transmitter

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] show results that greater impact is caused by outdated adaptation and is further concluded by [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 that the coherence time (the time duration over which the channel impulse responses remain strongly correlated and essentially invariant [41, 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], [42]. Catreux *et al.* [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 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 capture how much power is measured at the receiver on average, while the second moment of the SNR over the time (or frequency) dimension captures some information on the time (frequency) selectivity of the channel within the adaptation window [4]. Higher order moments 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 polarisation. 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], [42]. This issue will be further discussed in later discourse.

Another approach that can be taken to estimate CSI is through Packet Error Rate (PER) or BER information [4]. This method relies on the estimation of PER statistics which can 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 may be 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 reinitialise the LA [4].

To alleviate the problem, Catreux *et al.* [4] proposed the use of incremental redundancy, a proposed standards for IS-136

Ref.	System Environment	Modulation Levels	TDD/ FDD	Code Rate	CSI Metrics	Loading Algorithm	MIMO	Remarks
[2]	4G Mobile 125 subcarrier, 18 paths Rayleigh fading	BPSK, QPSK, 8-, 16-QAM	-	Convolutional code rate ½ with length 7	Predicted using adaptation interval, which is long enough to allow the transmission of at least one data packet and short enough to react quickly to changes in SNR. Use Mean Least Square (MLS) algorithm to calculate power using the present received power.	-	No	Simulation at target BER 10^{-2} and 10^{-3} in high Doppler frequency up to 180 Hz. Predicted feedback information scheme reduces the transmission time of feedback information from the receiver to the transmitter.
[3]	Mobile Applications 256 subcarriers, Rayleigh multipath GSM model	4-,8-,16-QAM	TDD	No	Used pilot symbol for prediction to avoid outdated CSI. Consecutive Bit Allocation Vectors (BAVs) are separated by an interval of 8 OFDM frames. Channel estimator replaced with FIR Wiener predictor of equal complexity (length 5) to obtain estimate of the channel 4 frames ahead.	Succesive bit allocation algorithm similar to C. Y. Wong *et al.* [11]	No	Analyse effects of channel mismatch and channel estimator inaccuracy to system performance.
[5]	WLAN 512 subcarriers divided into 16 subbands	No transmission, BPSK, QPSK, 16-QAM	TDD	Trellis-based, with convolutional code length 7	Assume perfect CSI, using the most recent received symbol for channel estimation. Modulation scheme M_n is selected if the instantaneous channel SNR exceeds the switching level l_n.	Adaptation based on fixed threshold algorithm	No	Adaptation based on subband rather than subcarrier
[10]	Mobile 256 subcarriers	2-,4-,8-DPSK	TDMA / TDD	TCM With constraint length 7	Perfect CSI knowledge at BS to decide on modulation levels used and that information is perfectly known at receiver. Leaving out weak subcarriers based on the instantaneous SNR.	Allocation table	No	Applying TCM code to the selected subcarriers
[12]	Outdoor mobile, 256 subcarrier, Simulation of OFDM system with measured time-variant transfer function	2-, 4-PSK, 8-, 16-, 32-, 64-, 128-, and 256-QAM	-	-	Adaptation of bit and power using average SNR	Computationally not efficient, successive bit and power allocation	No	Only a gain of 1 dB is obtained for optimum power distribution, recommended to ignore power optimization to avoid additional computation and/or signaling for synchronization.
[13]	CBR 1024 subchannels, Multipath Raleigh fading with exponential delay profile	QPSK, 16-, 64-, 256-QAM	FDD	-	Channel mismatch	Use loading algorithm as in Fischer and Huber [26]	No	Conclude that accurate CSI is needed at the transmitter for effective use of adaptive modulation

Ref.	System Environment	Modulation Levels	TDD/ FDD	Code Rate	CSI Metrics	Loading Algorithm	MIMO	Remarks
[23]	Mobile 128 subcarriers, fading, path loss and log-normal shadowing.	4-, 16-, 64- QAM	TDMA FDMA Inter leaved	-	Assumed perfect channel estimation	Efficient adaptive bit and power allocation	Yes	Outage probability also simulated for 5 different users independently and uniformly distributed within a cell.
[35]	Mobile 512 subcarriers, 4 multipaths fading with various delay spreads.	BPSK, QPSK, 8PSK, 16-, 32-, and 64- QAM	-	-	Instantaneous SNR Perform bit allocation algorithm using instantaneous SNR taking into account the required QoS. Then, each user's data rate is determined using rate allocation algorithm for different services.	-	Yes	Multi rate, multi user system
[36]	Mobile 256 subcarriers, maximum of 2 antennas at BS and MS, 3 multipath fading with exponential profile	4-, 16-, 32- 64- QAM	-	TCM	Assumed perfect channel information	Fast and less complex compared to Hughes- Hartogs algorithm	Yes	Employed adaptive spatial-subcarrier TCM

TABLE 4: A COMPARATIVE SUMMARY OF ADAPTIVE OFDM RESEARCH EFFORTS

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 closed to perfect channel estimation is required to ensure the effectiveness of adaptive modulation in OFDM. Two methods discussed above, if combined together 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], [42].

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.

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.

Simulation can be performed to examine the suitability or complexity of implementing this method.

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 (SDMA) in an OFDM system. K. -K. Wong *et al.* [19] showed that in multiple antenna system, selection diversity (SD) / maximum ratio combining (MRC) can effectively reduce and recover the deep fade even without the incorporation of adaptive TCM or TCM. This is due to the fact that in a space-time-frequency adaptation scheme, MRC 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 electronically pointed to mobile station locations adaptively will lead to an increase in capacity and reduces interferences [43]. 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 because, similar to non-adaptive antenna system, the channel estimation is also the key parameter to be considered. In TDD system the channel estimate called spatial covariant matrix (SCM) [43] can be used directly if channel shows sufficient grade of reciprocity, which is the case in TDD systems. But FDD systems which utilise 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 to the adaptive antenna system. A compromise between computational complexity and system performance has to be found.

CONCLUSIONS

Adaptive modulation with other related issues as part of link adaptation in an OFDM system have been reviewed. Contributions by various authors show tremendous improvement to system capacity and BER. However issues such as those discussed in Section IV can be further scrutinised in the implementation of an OFDM system.

Adaptive modulation and coding techniques that can track time-varying characteristics of wireless channel (especially in wide cellular environment) carry the promise of significantly increasing data rates, reliability, and spectrum efficiency of future wireless data-centric networks [4]. Efficient adaptive modulation must incorporate robust transmission mode (e.g. BPSK and QPSK) with small code rate in order to extend the reach of BS and increase robustness to interference, while providing high data rates modes (e.g. 64 QAM with high code rate) to improve spectrum efficiency.

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

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ANNOUNCEMENT

APCChE Presidency now held by Malaysia, 2006 Congress to be hosted by KL

27 May – 1 June 2006

At the recently held APCChE 2004 Congress in Kitakyushu, Japan, the Council of the Asian Pacific Confederation of Chemical Engineers (APCChE), confirmed Ir Prof. Dr Mohd. Ali Hashim as President of its Council, effective from October 2004. He will hold this position until May 2006 when the next APCChE Congress is to be held in Kuala Lumpur.

The Institution of Engineers, Malaysia congratulates him on this prestigious appointment. The Presidency of the Asian Pacific Confederation of Chemical Engineers (APCChE) is traditionally held by the host country of the next Congress.

The 11th APCChE Congress will be held on 27 May – 1 June, 2006 and is expected to draw 1200 delegates from the Asia Pacific area and Europe. Congress preparations are now well under way. An exhibition will also be held alongside the Congress, and include a show-case of Malaysian Chemical Engineering achievement. A regional Chem-E-Car competition will also be held on the sidelines. Interested congress participants, sponsors and exhibitors can contact Puan Siti at IEM Secretariat (03-79684001/02) for details of the Congress, Exhibition and Showcase.