An OFDM Based Adaptive Modulation Scheme Employing Variable Coding Rate in Dynamic Parameter Controlled OF/TDMA Systems

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Abstract—In this paper, we introduce variable coding rate (VCR) control to OFDM adaptive modulation scheme (OFDM AMS) in order to realize high throughput with relatively simple transceiver configurations in a dynamic parameter controlled-orthogonal frequency and time division multiple access (DPC-OF/TDMA). In the proposed system, multilevel transmit power control (MTPC) is not employed to simplify hardware. Instead, we will introduce a VCR control technique that reduces the required signal to interference plus noise power ratio (SINR) gap between adjacent modulation and coding scheme (MCS) in the OFDM AMS, thereby reducing surplus power between the actual received SINR and the required SINR. Furthermore, this paper also presents a bit loading algorithm to effectively transmit MAC payloads with certain fixed lengths. Throughput performances obtained from computer simulations confirm that the proposed VCR OFDM AMS can be a good alternative to the OFDM AMS/MTPC.

Keywords—OFDM, adaptive modulation scheme, variable coding rate, bit loading, DPC-OF/TDMA, one-cell reuse TDMA

I. INTRODUCTION

Future wireless communications systems called beyond 3G (B3G) or 4G systems need to provide multimedia services including voice and data communications. Especially in data communications for the Internet access, to support peak user rate of more than 100 Mbit/s with a wide coverage area is one of the strong requirements in the B3G and 4G systems. To satisfy such requirements, we have proposed a dynamic parameter controlled-orthogonal frequency and time division multiple access (DPC-OF/TDMA) [1]. As for wireless access techniques for B3G systems, there are several proposals; variable spreading factor-orthogonal frequency and code division multiplexing (VSF-OFCDM) [2] and variable spreading and chip repetition factors (VSCR)-CDMA [3] as the CDMA-based systems, and TDMA-based systems [4], and our system is also based on one-cell reuse TDMA.

The most important advantage of TDMA systems is that they have potential high peak user rate because there is no intra-cell interference source although there are a few inter-cell interference (ICI) sources [1], [5], [6]. However, the throughput is limited by huge path loss and maximum transmit power available at the access point (AP) and mobile station (MS) as well as the impact of ICI. Hence, in the DPC-OF/TDMA systems, we will employ OFDM based adaptive modulation scheme (OFDM AMS) that adaptively controls modulation and coding scheme (MCS) for each subcarrier in order to improve throughput and ICI immunity at the same time even in the one-cell reuse environments by fully utilizing nature of the frequency selective fading channel.

In the DPC-OF/TDMA systems, time and system frequency band are divided into many physical (PHY) channel units which transmit 32–512 bytes of medium access control (MAC) payload, and AP dynamically allocates one or more PHY channel units to one MS in order to satisfy various service requirements.

Among various OFDM AMS, the most promising technique in terms of throughput is the OFDM AMS with multilevel transmit power control (OFDM AMS/MTPC) [7] that maximizes throughput by the joint allocation of MCS and transmit power for each subcarrier. However, implementation of OFDM AMS/MTPC is not easy, especially for MS, because it requires rather high computational load and careful design of feedback channel for delay profile and interference plus noise level which should be known at the transmitter.

In this paper, therefore, we will propose an efficient AMS OFDM techniques which does not employ the MTPC but realizes almost the same throughput as that of the OFDM AMS/MTPC. A key point for keeping high throughput without the MTPC is how to efficiently reduce surplus transmit power that corresponds to the difference between the received SINR and target SINR for the selected MCS, because such transmit power does not contribute to further increase of throughput. To solve this problem, we will propose a variable coding rate (VCR) introduced OFDM AMS in which the required SINR gaps between adjacent MCS modes are reduced.

Another important problem for the DPC-OF/TDMA is that the number of bits mapped onto the PHY channel unit should be equal to one of the MAC packet sizes even though MCS for each subcarrier is dynamically controlled in the PHY layer. Therefore, we will also propose a bit loading algorithm that satisfies this requirement.

The rest of this paper is structured as follows. We first describe the concept of the DPC-OF/TDMA in Section II, and then describe problems for the OFDM AMS/MTPC in Section III. The proposed VCR OFDM AMS is presented in Section IV. Section V gives simulation results, and Section VI concludes this paper.

II. MAC AND PHY LAYER CONFIGURATIONS IN DPC–OF/TDMA

To flexibly support various types of terminals in the same system as well as to ensure simple connectivity to various types of internet protocol (IP) based wireless access systems, we have proposed a MAC frame as shown in Fig. 1 [1] in which the following three types of MAC channels are employed: Frame control message slot (FCMS) is a downlink control slot to be used for broadcasting system information and slot assignment information, as well as for transmitting user specific control signals, activation slot (ACTS) is an uplink control slot to be used mainly for initial terminal
association to the system, and message data slot (MDS) is used for IP packet transmission in both the uplink and downlink and it is allowed to allocate two or more MDS in a frame to one user when the user demands higher throughput and the traffic condition in the cell is not so heavy. In the downlink, the first slot in a MAC frame is used for FCMS, and the following eight slots are used for MDS. On the other hand, in the uplink, the first 0.5 ms duration, corresponding to two slots length, is divided into four mini-slots to accommodate four ACTS signals. Therefore, there are seven MDS slots in the uplink.

Fig. 2 shows the frame format for the PHY layer, and Tab. 1 shows specifications for the proposed DPC-OF/TDMA system. A physical radio resource unit (it will be called a physical (PHY) channel unit in the following) consists of 64 subcarriers with its time duration of 0.25 ms. Because the proposed system employs 768 subcarriers, 12 subcarrier blocks are multiplexed in the frequency domain. In the proposed system, one MAC slot shown in Fig. 1 is mapped onto each PHY channel unit. Moreover, MAC control will be conducted on each 64-subcarrier block. This means the DPC-OF/TDMA has 12 MAC channels to accommodate low-data-rate terminals using 64 subcarriers and high-data-rate terminals using 128 or more subcarriers at the same time.

When MDS is transmitted in the PHY channel unit, the frame format shown in Fig. 3 is used. When we use AMS in the data part of this frame, size of the data to be transmitted depends on PHY channel conditions. Therefore, MDS payload size should be as flexible as possible from the viewpoint of maximizing throughput. However, there is a practical limitation in the number of MDS payload sizes when considering simplicity of the MAC protocol. Therefore, we prepared 7 MDS transmission modes as shown in Tab. 2. Note that a fixed size overhead, header (12 bytes) and CRC (2 bytes), is appended to the payload when transmitting MDS, thus total size of MDS is $D(l) + 14$ bytes. For example, when QPSK with a rate-1/2 convolutional coding is employed on all the 64 subcarriers, we can transmit 144 bytes, so MDS mode 3 is selected. If channel condition is better, larger MDS mode number will be selected, and vice versa.

### III. PROBLEMS OF OFDM AMS/MTPC

Basic operation of the OFDM AMS is to select an MCS that achieves the highest transmission rate while satisfying a target bit error rate (BER) according to the channel state information (received SINR). In such a case, however, because there are required SINR gaps between the adjacent MCS modes, there exists surplus transmit power that does not contribute to further increase of user rate. Since the MTPC reallocates such surplus power to the other subcarriers in order to step up their MCS, it is an effective technique to maximize throughput while keeping total transmit power constant.

For this purpose, however, accurate received SINR for each subcarrier should be known at the transmitter to employ the MTPC. Therefore, the receiver feeds back delay profile via the delay profile information (DPI) subframe (see Fig. 3) using analog quadrature amplitude modulation (QAM) and code division multiplexing (CDM) [8], [9]. In addition, the interference plus noise $(I + N)$ level for each subcarrier is estimated by the measurement of vector error, where reference symbols are regenerated by re-encoding the Viterbi-decoded data stream [10]. In this process, vector errors in the adjacent subcarriers in the same PHY channel unit are averaged to improve accuracy and to reduce the amount of feedback information. The receiver finally transmits the averaged values in the interference level information (ILI) subframe, where CDM technique is used to increase the received SNR of the QAM modulated ILI signals.

When the transmitter sends user data, MCS information is also transmitted via the modulation level information (MLI) subframe for proper demodulation process in the receiver side. In the proposed system, the MLI represents MCS for each “AMS control unit” consisting of one or more adjacent subcarriers.

As we have mentioned above, configuration for the OFDM AMS/MTPC is rather complex at both sides of the transceiver. Therefore, it is not easy to employ the OFDM AMS/MTPC for data transmission.
transmission to/from a small size terminals with small batteries. In addition, subcarrier transmit power control in the MTPC process makes variation of ICI level more dynamic than that for non-MTPC employed systems, which requires more frequent feedback of interference plus noise level information.

IV. VARIABLE CODING RATE INTRODUCED OFDM AMS

A. Advantages of the proposed scheme

When we employ only the OFDM AMS, because the received SINR for each subcarrier are continuous random variables whereas the required SINR for MCS have only certain discrete levels, there is power margin (surplus transmit power) that does not contribute to increasing throughput. Since the MTPC efficiently utilizes such surplus transmit power to increase the throughput, if we just remove the MTPC, the throughput will decrease. However, the reason for existence of the surplus power is that the SINR gaps between the required SINRs of two adjacent MCS modes are so large. Therefore, throughput can be improved if we reduce the SINR gaps by using more MCS modes by introducing variable coding rate (VCR) control.

Fig. 4 shows configuration of transmitter and receiver for the proposed VCR OFDM AMS. Since subcarrier transmit power control is not employed in this case, feedback of the DPI and ILI is not indispensable. Adaptive allocation of MCS can be performed at the receiver, and the receiver returns a request for MLI (RMLI) to the transmitter side. Therefore, we can expect huge reduction of computational complexity as well as the improvement of frame efficiency in the case of the VCR OFDM AMS. Even if the receiver feeds back the DPI and ILI subframe for the sake of more advanced control, it can feed back interference plus noise level averaged over larger blocks than those in the case of the MTPC, because the ICI level fluctuation in frequency domain is suppressed by non-employment of the dynamic control of subcarrier transmit power.

B. Modulation and coding schemes (MCS)

Tab. 3 shows the MCS to be used in the proposed VCR OFDM AMS and OFDM AMS/MTPC in this work. Coding rate of the original convolutional encoder is 1/2, and we employ two types of bit puncturing scheme and combine them with the modulation scheme to create MCS set which has approximately 1.5 dB of the required SINR gap. In the first column in Tab. 3, modulation schemes are shown. Since 1/2-rate BPSK [11] is included in both cases, the “AMS control unit” defined in Section III is 2 subcarriers. In the first column, the numbers of coded bits conveyed in an AMS control unit are shown as \(m\). \(r_1\) in the second column represents the coding rate realized by bit puncturing using the conventional bit deletion map [12]. In this paper, we call this process “first bit puncturing”. In the second bit puncturing process, one bit is deleted every \(i_p\) bits. Because this process can be regarded as the reduction of coded bit by \((i_p - 1)/i_p\), we can equivalently regard the overall coding rate as \(r = r_1/r_2\), where \(r_2 = i_p/(i_p - 1)\).

In Tab. 3, selectable MCS set for A) OFDM AMS/MTPC and for B) VCR OFDM AMS are shown in the fifth and sixth column, respectively. In the case of the OFDM AMS/MTPC, we have already confirmed that high throughput is achieved when the SINR gaps are approximately 3 dB [5]. In contrast, in the case of the VCR OFDM AMS, the SINR gaps are reduced to approximately 1.5 dB. In addition to the MCS modes in Tab. 3, there is a carrierhole mode in both schemes. Thus, the number of MCS modes is 9 and 16 in the case of the OFDM AMS/MTPC and VCR OFDM AMS, respectively. Since MCS modes for each AMS control unit can be represented in 4 bits and the number of AMS control unit in a frame is \(64/2 = 32\), total bit length for MLI is given by \(4 \times 32 = 128\). Therefore, we will transmit these information over two OFDM symbols using QPSK with rate-1/2 convolutional coding.

C. Bit loading algorithm

When an adaptive modulation scheme is introduced, the number of transmittable bits changes dynamically slot by slot. However, there are only 6 payload sizes for MDS prepared in the MAC layer as shown in Tab. 2 to simplify MAC protocol. Therefore, how to efficiently map an MDS onto each PHY channel unit is a critical problem.
In the proposed system, these numbers are calculated in the transmitter side using the MLI to be applied to the next transmission. At the same time, we also have to satisfy that these numbers can be accurately estimated in the receiver side using the MLI in the received signal. When these requirements are satisfied, the detection procedure becomes very simple; after the number of bits for each coding rate is detected, the bit-level branch metric sequence is calculated, and bit metrics of 0 are inserted in the appropriate positions in the sequence, followed by a conventional Viterbi decoding process.

Calculation for the number of the sub-blocks is as follows:

Let us assume that coding rate for the first and second puncturing, and transmittable coded bits in the s-th OFDM symbol of j-th OFDM symbol in a PHY channel unit are expressed as \( r_1(s, j) \), \( r_2(s, j) \), and \( m(s, j) \), respectively, where the selectable numbers for these values are shown in Tab. 3. Moreover, we will define that the end of block (EOB) as \( b \), which corresponds to the last OFDM symbol that the MAC data are mapped on.

When the MLI is obtained, because coding rate for the first and second puncturing as well as the modulation scheme can be obtained using Tab. 3, we can know how many coded bits can be loaded in each AMS control unit. Therefore, the number of transmittable coded bits after the second puncturing for the coding rate of \( r_1 = R_1 \) and \( r_2 = R_2 \), and EOB of \( b \) is given by the following iterative form:

\[
n_{\text{punc2}}(R_1, R_2, b) = n_{\text{punc2}}(R_1, R_2, b - 1) + \sum_{r_1(s, j) = R_1}^{r_2(s, j) = R_2} m(s, b)
\]

Because this is the number of coded bits after the second puncturing, the number of coded bits before the second puncturing (after the first puncturing) can be obtained as

\[
n_{\text{punc}}(R_1, R_2, b) = \lceil n_{\text{punc}}(R_1, R_2, b) \cdot R_2 \rceil
\]

where \( \lceil x \rceil \) denotes the largest integer value less than or equal to \( x \).

Then, the total coded bit length for the coding rate of \( r_1 = R_1 \) can be obtained as

\[
n_{\text{punc1}}(R_1, R_2) = \sum_{R_1} n_{\text{punc1}}(R_1, R_2, b)
\]

We then calculate the total coded bit length just before the first puncturing \( n_{\text{punc1}}(R_1, b) \). Here, although \( n_{\text{punc1}}(R_1, b) \) is unique, the \( n_{\text{punc2}}(R_1, R_2) \) is not always unique. However, when we add a restriction, to load as many information bits as possible, we can get a unique number as

\[
n_{\text{puncall}}(R_1, b) = \sum_{R_1} n_{\text{puncall}}(R_1, b)
\]

On the other hand, when the payload size for MDS slot is \( D(l) \), where \( l \) is the MDS mode number, the MDS data size is given by

\[
n_{\text{MDS}} = D(l) + \text{Header} + \text{CRC} + (K - 1)
\]

Therefore, we will check whether or not the following conditions are satisfied.

\[
n_{\text{puncall}}(R_1, b) \geq 2 n_{\text{info}}
\]

\[
n_{\text{puncall}}(R_1, b) = \text{even number}
\]

When these conditions are satisfied, and \( n_{\text{puncall}}(R_1, b) \) and \( n_{\text{punc2}}(R_1, R_2, b) \) are larger than \( n_{\text{punc1}}(R_1, R_2) \), \( n_{\text{punc1}}(R_1, R_2) \) and \( n_{\text{punc2}}(R_1, R_2, b) \) will be updated to \( n_{\text{punc1}}(R_1, b) \) and \( n_{\text{punc2}}(R_1, R_2, b) \). Moreover, allocatable MDS mode \( l \) is also updated. This process will be continued until \( b \) reaches \( N_s \), where \( N_s \) is the number of the OFDM symbols in a PHY channel unit. In this process, initial values for \( n_{\text{punc1}} \), \( n_{\text{punc2}}(R_1, R_2) \) as well as \( l \) are zero. When \( l \) is still zero after the process for \( b = N_s \) is finished, no MDS data will be transmitted. On the other hand, when \( l \) is non zero value, encoding process shown in Fig. 5 will start using the obtained values, and the data after the second puncturing will be mapped onto the first \( b \) symbols of a PHY channel unit.

\[\text{Tab. 4. Simulation parameters}\]

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>100 kbps</td>
</tr>
<tr>
<td>Num. of subcarriers</td>
<td>64</td>
</tr>
<tr>
<td>FEC</td>
<td>Convolutional coding</td>
</tr>
<tr>
<td>Target QoS</td>
<td>BER = 10^{-7}</td>
</tr>
<tr>
<td>TPC target C/N0</td>
<td>90 dB Hz</td>
</tr>
<tr>
<td>Max. Tx Power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>15 dBi (AP), 3 dBi (MS)</td>
</tr>
<tr>
<td>Noise figure</td>
<td>7 dB</td>
</tr>
<tr>
<td>Cell radius</td>
<td>100 m</td>
</tr>
<tr>
<td>Cell model</td>
<td>7-cell wrapping model by 3-sector cells</td>
</tr>
<tr>
<td>Number of interference sources</td>
<td>3</td>
</tr>
<tr>
<td>Path loss model</td>
<td>ITU-R outdoor to indoor &amp; pedestrian test environment [13]</td>
</tr>
<tr>
<td>Shadowing</td>
<td>Log-normal distribution standard deviation = 8 dB</td>
</tr>
<tr>
<td>Channel model</td>
<td>Exponential decaying</td>
</tr>
<tr>
<td>R.m.s. delay spread</td>
<td>100, 200 ns</td>
</tr>
<tr>
<td>f0</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

V. COMPUTER SIMULATION

A. Simulation setup

Throughput performances on the downlink are evaluated by computer simulation. We used the frame format shown in Fig. 3
In both figures, we show throughput curves of the proposed VCR OFDM AMS that employs the 9 modes in Tab. 3. As a reference, the VCR OFDM AMS/MTPC is degraded with increase of the block size due to the FER degradation. For example, in Fig. 7 its peak value is 1.1 Mbps when the block size is 8, but it falls to 0.98 Mbps when the block size is 64, which is 10% reduction of the throughput. In contrast, the VCR OFDM AMS and conventional OFDM AMS does not experience such serious degradation. Furthermore, the VCR OFDM AMS outperforms the conventional OFDM AMS in any situations, and even the OFDM AMS/MTPC in the region when the block size is large.

VI. Conclusions

In this paper the VCR OFDM AMS is proposed as an alternative transmission technique to the OFDM AMS/MTPC when low complexity in the transceiver is of interest in the DPC–OF/TDMA systems. In order to achieve high throughput without using the MTPC, we introduced an MCS set that has relatively small SINR gaps of approximately 1.5 dB. We also introduced the adaptive bit loading algorithm for subcarriers to efficiently transmit fixed size MAC payload in PHY channel unit controlled by the OFDM AMS. Computer simulation confirmed that the VCR OFDM AMS realizes high throughput equivalent to that of the OFDM AMS/MTPC.

Fig. 6. Average throughput vs. block size (delay spread = 100 ns)

Fig. 7. Average throughput vs. block size (delay spread = 200 ns)

and simulation parameters shown in Table 4. Throughput is defined as the number of transmitted bits per second over error-free PHY channel units. Therefore, throughput for whole the system is 96 times (12 subcarrier-blocks times 8 time-slots) more. Each cell is sectorized into three, and its radius is 100 m, which is wrapped by 6 cells to equivalently simulate ICI for infinitely and continuously covered service area. We assume that MSs are located randomly in the 7-cell area, and each MS searches an AP with the highest received pilot signal in the downlink. Total level TPC is applied to control total received signal level constant. We assume that channel estimation and notification of DPI and ILI work perfectly because we have already developed such techniques [7], [9], [10].

B. Simulation results

Fig. 6 and Fig. 7 show average throughput performances vs. the block size, where the block size means the number of consecutive subcarriers over which interference plus noise level is averaged. In both figures, we show throughput curves of the proposed VCR OFDM AMS that uses the 16 MCS modes and the OFDM AMS/MTPC that uses only the 9 modes in Tab. 3. As a reference, the figures also include throughput for the conventional OFDM AMS that employs the same MCS set as the OFDM AMS/MTPC but no use for MTPC. In both figures, throughput of the OFDM

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