A Pragmatic Adaptive OFDM/FDD Cellular System in Frequency-Selective Fading Channels

Kwang Soon Kim, Yun Hee Kim, Jae Young Ahn, and Seung-Ku Hwang

Electronics and Telecommunications Research Institute (ETRI)
161 Gajeong-Dong, Yuseong-Gu, Daejeon 305-350, Korea
Tel: +82-42-860-6702
Fax: +82-42-869-6732
E-mail: kskim@ieee.org, yheekim@etri.re.kr

Subject Area: WG4 subtopic on single- and multi-carrier based air interface for high mobile use

***Abstract*— In this paper, an adaptive transmission scheme using QAM and LDPC code is proposed for an OFDM cellular system employing FDD. By approximating the LLR distribution to a Gaussian distribution, only two parameters, the mean and the normalized standard deviation, are required to be fed back to the transmitter. Thus, only a few more bits are needed compared to the feedback information in currently used single carrier cellular systems, such as cdma2000-1x EV-DO. It is shown by computer simulation that the proposed adaptive transmission scheme can provide up to 3dB gain over the conventional system using the mean SNR only, at the expense of only 3 more bits in feedback information.**

I. Introduction

In order to meet the explosively increasing demand on reliable and high-rate service over wireless channel, orthogonal frequency division multiplexing (OFDM) has been widely accepted as the most promising radio transmission technology for the next generation wireless communication systems due to its advantages such as the robustness to multipath fading, granular resource allocation capability, and low complexity [1]. In addition, it is required to employ some advanced technologies to enhance the system capacity as large as possible. Among such advanced technologies, the link adaptation using adaptive modulation and coding has been considered as a key technology for the next generation wireless communication systems [2]-[4]. The basic idea of the adaptive modulation and coding is that the transmitter selects one of the pre-defined modulation and coding set (MCS) by the aid of the channel state information, which is reported to the transmitter by the receiver in frequency division duplexing (FDD) systems.

In OFDM systems, the bit-loading algorithm is known to be optimum. However, the transmitter has to know the channel state information of all sub-carriers, which is impractical in wireless OFDM systems using large number of sub-carriers. Thus, block-wise adaptive transmission schemes were proposed as sub-optimum algorithms [3][4]. In cellular systems employing FDD, however, even the amount of the feedback information required for the block-wise adaptive transmission schemes is far from that can be supported in practical situation since a cellular system should support both high frequency selectivity and high mobile speed. Thus, in order to be employed in practical OFDM cellular systems, a simple adaptive transmission scheme is required with low feedback rate comparable to that in currently employed cellular systems, such as cdma2000-1x EV-DO. However, in frequency-selective channels, the system capacity would degrade severely if only the mean signal to noise power ratio (SNR) over the whole sub-carriers is used as in a single-carrier system.

On the other hand, low density parity check (LDPC) codes have drawn a lot of attention due to their performance close to the Shannon-limit, low decoding complexity through iterative decoding, error detection capability, and low error floors [5]-[7]. Through the sophisticated code design and efficient hardware implementation, LDPC codes can provide us with a performance similar to or better than turbo codes at the lower complexity [7]. Thus, LDPC codes can be a good candidate for error correcting codes in next generation wireless systems.

In this paper, an adaptive transmission scheme based on the knowledge of the received log-likelihood ratio (LLR) distribution is proposed for an OFDM cellular system using quadrature amplitude modulation (QAM) and LDPC code. By

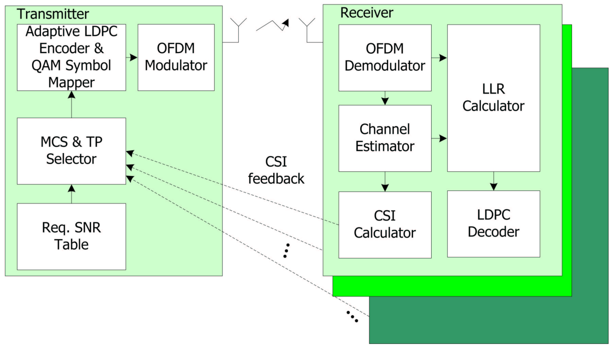

Fig. 1. The system model for the proposed adaptive transmission.

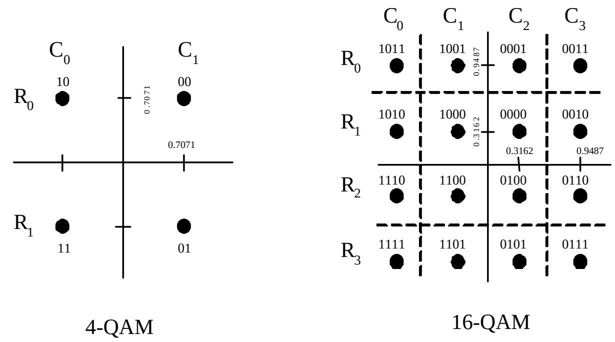

Fig. 2. The Gray encoded 4-QAM and 16-QAM constellations.

approximating the LLR distribution to a Gaussian distribution, only two parameters, the mean and the normalized standard deviation, are required to be sent to the transmitter. Note that only a few more bits are needed compared to the feedback information in currently used single carrier cellular systems, such as cdma2000-1x EV-DO. This paper is organized as follows: In Section II, the system model considered in this paper is shown. The adaptive transmission algorithm proposed in this paper is shown in Section III, and the performance of the proposed scheme is evaluated by computer simulation in Section IV. Finally, concluding remark is provided.

II. System model

A physical layer frame is comprised of a number of consecutive data slots, in which pilot symbols are well distributed in both frequency- and time-domain. In case of multiple access system, all sub-channels in a data slot are also well-distributed in a data slot. In Fig. 1, the system model considered in this paper is shown. In the transmitter side, pilot symbols are transmitted with fixed power P_{pilot}. Then, the channel is estimated by the channel estimator in the receiver side. With the estimated channel, the channel state information (CSI) is generated and sent to the transmitter side. At the transmitter, the MCS and the transmit power (TP) are determined from the received CSI and pre-determined required SNR table. In case of multiple access system, there are a number of receivers with their own CSIs. Then, based on each user's pre-determined quality of service (QoS) and the reported CSI, active users are selected with corresponding MCS and TP by the MCS and TP selector. Then, the adaptively transmitted signal is received and the LLR is calculated from the received symbols and the estimated channel at the receiver side. Finally, the LDPC decoder extracts the transmitted information.

Let x_l be the lth normalized transmitted symbol in a data slot. Then, the lth received symbol at the receiver is given by

$$y_l = Ah_l x_l + n_l, \tag{1}$$

where A^2 is the transmit power, h_l and n_l are the complex channel gain and the additive complex Gaussian noise with mean zero and variance $2\sigma^2$ at the lth symbol location in a data slot, respectively. Then, the decision variable of the lth symbol, z_l is given by

$$z_l = h_l^* y_l / |h_l| = A|h_l|x_l + n_l^{'}, \tag{2}$$

where $n_l^{'} = h_l^* n_l / |h_l|$ is also a complex Gaussian noise with mean zero and variance $2\sigma^2$.

III. The adaptive transmission scheme

A. Received LLR distribution

For a given LDPC code and a decoding algorithm, the performance is determined by the received likelihood distribution [6]. Thus, the transmitter can expect the performance of each MCS option if the received LLR distribution is known. In addition, by parametric modelling of the received LLR distribution, the LLR distribution parameters can be used as a CSI. In this paper, we assume that the LLR distribution is Gaussian. Then, the mean and the standard deviation of the LLR distribution can be used as the CSI and the performance of each MCS option can be well expected by the transmitter with only two parameters.

In this paper, we consider Gray encoded 4-QAM and 16-QAM for modulation options (shown in Fig. 2) and the maximum value approximation of the maximum likelihood (Max-ML) method for LLR calculation algorithm. However, it can be easily extended to higher order QAM modulations, such as 64-QAM. First, we consider the 4-QAM case. In the Gray encoded 4-QAM, the LLR distributions of the two bits in a symbol are the same. Let us define x_l^k as the kth bit in

x_l. Also, define $z_{l,i}$ and $z_{l,q}$ as the real and imaginary parts of z_l, respectively. Then, the LLR of x_l^0, $\Lambda\left(x_l^0\right)$, is given by

$$\begin{aligned}\Lambda\left(x_l^0\right) &= \log\left(\max_{x_l \in X^{0,0}} Pr\left\{z_l|h_l, x_l\right\} Pr\{x_l\}\right) \\ &\quad - \log\left(\max_{x_l \in X^{0,1}} Pr\left\{z_l|h_l, x_l\right\} Pr\{x_l\}\right) \\ &= \frac{\sqrt{2}A|h_l|z_{l,i}}{\sigma^2},\end{aligned} \quad (3)$$

where $X^{k,m}$ denotes the set of symbols in which the kth bit is m. Since the distribution of $z_{l,i}$ when $x_l^0 = 0$ is Gaussian with mean $\frac{A|h_l|}{\sqrt{2}}$ and variance σ^2, the distribution of $\Lambda\left(x_l^0\right)$ when $x_l^0 = 0$ is Gaussian with mean $\frac{A^2|h_l|^2}{\sigma^2}$ and variance $\frac{2A^2|h_l|^2}{\sigma^2}$. Note that the distribution of $\Lambda\left(x_l^1\right)$ is the same to that of $\Lambda\left(x_l^0\right)$. Then, the mean of the LLR distribution over the whole code block when the all-zero codeword is transmitted is given as

$$\begin{aligned}E\left\{\Lambda\left(x_l^0\right)\right\} &= \frac{1}{L}\sum_{l=0}^{L-1}\frac{A^2|h_l|^2}{\sigma^2} \\ &= 2m_{SNR},\end{aligned} \quad (4)$$

where m_{SNR} is defined as $\frac{1}{L}\sum_{l=0}^{L-1}\frac{A^2|h_l|^2}{2\sigma^2}$. Also, we have

$$E\left\{\Lambda^2\left(x_l^0\right)\right\} = \frac{1}{L}\sum_{l=0}^{L-1}\left(\frac{A^4|h_l|^4}{\sigma^4} + \frac{2A^2|h_l|^2}{\sigma^2}\right) \quad (5)$$

and

$$\begin{aligned}Var\left\{\Lambda\left(x_l^0\right)\right\} &= E\left\{\Lambda^2\left(x_l^0\right)\right\} - E^2\left\{\Lambda\left(x_l^0\right)\right\} \\ &= 4m_{SNR} + 4m_{SNR}^2\sigma_{SNR}^2,\end{aligned} \quad (6)$$

where σ_{SNR}^2 is defined as $\frac{1}{m_{SNR}^2 L}\sum_{l=0}^{L-1}\left(\frac{A^2|h_l|^2}{2\sigma^2}\right)^2 - 1$. Thus, we can see that the mean and the normalized standard deviation σ_{SNR} of the received SNR is a sufficient statistic for determining the received LLR distribution.

Now, consider the 16-QAM case. Since we use the Max-ML method, the LLR of a bit in a symbol is proportional to the difference of the Euclidean distance between the received symbol and the nearest constellation points when the bit is 0 and that when the bit is 1. Then, we obtain as follows:

$$\Lambda\left(x_l^0\right) = \begin{cases} \frac{4A|h_l|z_{l,i}}{\sqrt{10}\sigma^2} + \frac{4A^2|h_l|^2}{10\sigma^2} & z_{l,i} \in C_0, \\ \frac{2A|h_l|z_{l,i}}{\sqrt{10}\sigma^2} & z_{l,i} \in C_1 \cup C_2, \\ \frac{4A|h_l|z_{l,i}}{\sqrt{10}\sigma^2} - \frac{4A^2|h_l|^2}{10\sigma^2} & z_{l,i} \in C_3, \end{cases} \quad (7)$$

and

$$\Lambda\left(x_l^2\right) = \begin{cases} \frac{2A|h_l|z_{l,i}}{\sqrt{10}\sigma^2} + \frac{4A^2|h_l|^2}{10\sigma^2} & z_{l,i} \in C_0 \cup C_1, \\ \frac{-2A|h_l|z_{l,i}}{\sqrt{10}\sigma^2} + \frac{4A^2|h_l|^2}{10\sigma^2} & z_{l,i} \in C_2 \cup C_3. \end{cases} \quad (8)$$

Note that $\Lambda\left(x_l^1\right) = \Lambda\left(x_l^0\right)$ and $\Lambda\left(x_l^3\right) = \Lambda\left(x_l^2\right)$ except that $z_{l,i}$ and C_n are replaced with $z_{l,q}$ and R_n, respectively. In addition, the distribution of $z_{l,i}$ when $x_l^k = 0$, $f_{z_{l,i}}(y)$, is given by

$$f_{z_{l,i}}(y) = \begin{cases} \frac{1}{2}\phi(y; v_l, \sigma^2) + \frac{1}{2}\phi(y; 3v_l, \sigma^2), & k = 0, \\ \frac{1}{2}\phi(y; -v_l, \sigma^2) + \frac{1}{2}\phi(y; v_l, \sigma^2), & k = 2, \end{cases} \quad (9)$$

where $v_l = A|h_l|/\sqrt{10}$ and $\phi(y; m, \sigma^2)$ is defined as the Gaussian distribution with mean m and variance σ^2. Then, after tedious mathematical calculations, we can see that the means of the LLR and the squared LLR over a code block are expressed with the sum of v_l^2/σ^2 and v_l^4/σ^2 scaled by some constants. Thus, it is seen again that the mean and the normalized standard deviation of the received SNR is a sufficient statistic for determining the received LLR distribution, also.

B. *Proposed adaptive transmission algorithm*

The CSI is defined as the mean and the normalized standard deviation of the received SNR in a data slot and the SNR is estimated from the received pilot symbols. Then, the CSI indicates the received LLR distribution when the transmit power is P_{pilot}. Now, let SNR_k and $\Delta_{k,\mu}$ be the required mean SNR and the required additional power when the normalized standard deviation of the received SNR is μ for the kth MCS option, respectively. Then, the required transmit power when the kth MCS option is used, $P_{Tx,k}$, is obtained as follows:

$$P_{Tx,k} = P_{pilot} + SNR_k - m_{SNR} + \Delta_{k,\sigma_{SNR}}(dB). \quad (10)$$

Here, SNR_k and $\Delta_{k,\mu}$ can be pre-determined by computer simulation or field-test. From (10), the transmitter can evaluate how much power is required for each user and each MCS option. Then, any optimization process for selecting active user set and MCS option for each user can be adopted.

IV. Simulation results

In Figs. 3 and 4, the packet error probabilities of the MCS option using 4-QAM and 1/3-rate LDPC code and that using 16-QAM and 2/3-rate LDPC code are shown, respectively. Here, the ITU-R pedestrian A fading channel is used and the transmit power is controlled to keep the mean of the received SNR in a packet constant. Also, the packet error probability of the conventional scheme using the mean of the received SNR only, denoted as 'All' in the figures, is also plotted for comparison. In these figures, the normalized standard deviation is quantized into 3 bits (denoted as std0 $\sim$ std7 in the figures). From the results, it is seen that the packet error probability increases as the normalized standard deviation increases. In addition, when the normalized standard deviation is small (std0 case), the proposed scheme requires 1.1dB and 5.5dB less

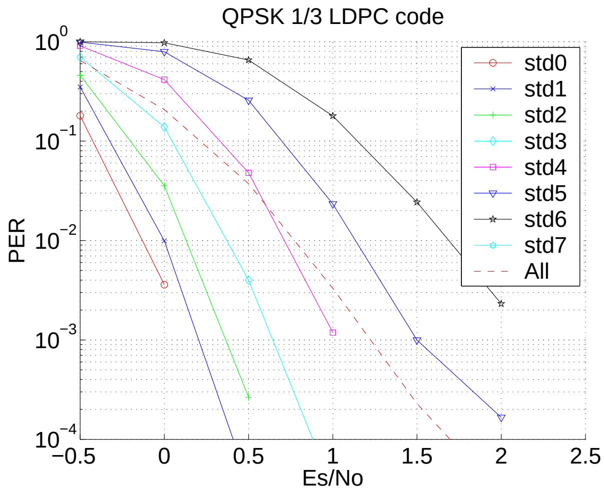

Fig. 3. The packet error probability of the MCS option using 4-QAM and 1/3-rate LDPC code.

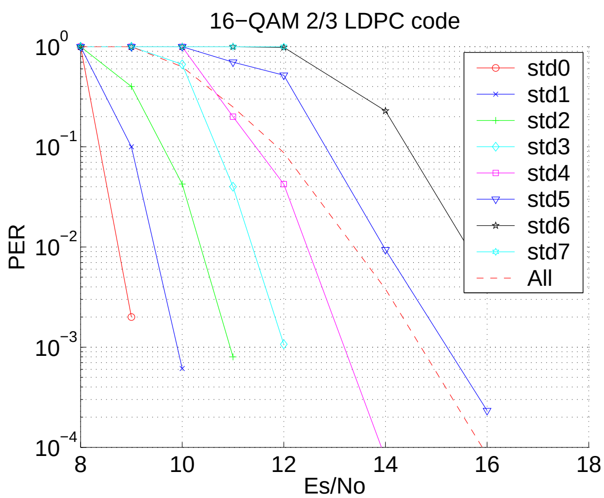

Fig. 4. The packet error probability of the MCS option using 16-QAM and 2/3-rate LDPC code.

transmit power compared to the conventional scheme at the target packet error probability of 1e-3, respectively.

In Fig. 5, the performance of the proposed adaptive transmission scheme is shown. The MCS options used in this simulation are summarized in Table I. Here, the MCS option is selected in order to maximize the throughput under constraint on the transmit power. Here, the target packet error probability is set at 1e-2. From the results, it is seen that the performance of the proposed scheme is up to 3dB better than that of the conventional scheme using the mean of the received SNR only, at the expense of only 3 more bits in the feedback CSI.

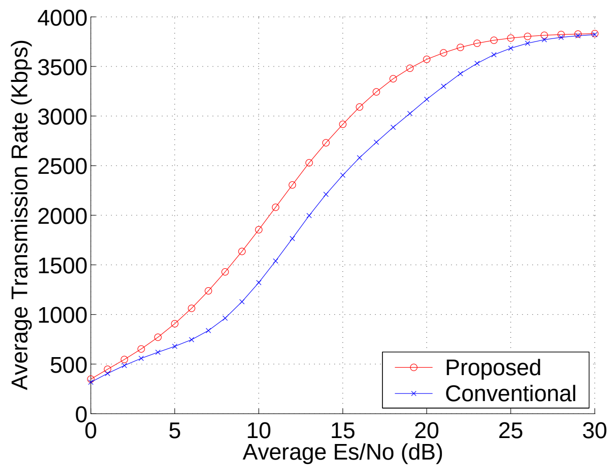

Fig. 5. The performance of the proposed adaptive transmission scheme.

TABLE I

SUMMARY OF THE MCS OPTIONS USED IN THE SIMULATION

MCS option	Modulation	Code Rate	Transmission Rate
0	QPSK	1/6	384 Kbps
1	QPSK	1/3	768 Kbps
2	QPSK	2/3	1.536 Mbps
3	16-QAM	1/2	2.304 Mbps
4	16-QAM	2/3	3.072 Mbps
5	16-QAM	5/6	3.84 Mbps

V. CONCLUDING REMARK

In this paper, an adaptive transmission scheme using QAM and LDPC code was proposed for OFDM-based cellular systems. By assuming the received LLR distribution as Gaussian, the received LLR distribution could be represented by two parameters: the mean and the normalized standard deviation. Also, it was shown that the mean and the normalized standard deviation of the received SNR in a packet were the sufficient statistic for the received LLR distribution. Then, the MCS option and the transmit power could be determined with the pre-determined values of the required mean SNR and the additional transmit power corresponding to the normalized standard deviation for each MCS option. From the simulation results, it was shown that the proposed adaptive transmission scheme could provide up to 3dB gain over the conventional system using the mean SNR only, at the expense of only 3 more bits in feedback information.

Furthermore, the results can be extended to the system employing multiple input multiple output (MIMO) techniques such as spatial multiplexing or space time (frequency) block coding. By transforming the signal vector received through MIMO channels, it can be shown that the mean and the normalized standard deviation of the received LLRs are enough for the feedback information also in MIMO case. Please refer to [8] and [9], for more detailed results on the system with MIMO techniques.

REFERENCES

[1] WWRF/WG4 White Paper, "Broadband multi-carrier based air interface," Oct. 2002.

[2] T. Keller and L. Hanzo, "Adaptive multicarrier modulation: a convenient framework for time-frequency processing in wireless communications," *Proc. IEEE*, vol. 88, no. 5, pp. 611-640, May 2000.

[3] T. Keller and L. Hanzo, "Sub-band adaptive pre-equalized OFDM transmission," *IEEE Vehic. Techn. Confer. (VTC)*, vol. 1, pp. 334-338, Amsterdam, Netherlands, September 1999.

[4] R. Grünheid, E. Bolinth, and H. Rohling, "A blockwise loading algorithm for the adaptive modulation technique in OFDM systems," *IEEE Vehic. Techn. Confer. (VTC)*, vol. 2, pp. 948-951, Atlantic City, NJ, U.S.A., October 2001.

[5] D.J.C. MacKay, "Good error correcting codes based on very sparse matrices," *IEEE Trans. Inform. Theory*, vol. 45, no. 2, pp. 399-431, Mar. 1999.

[6] T.J. Richardson and R.L. Urbanke, "The capacity of low-density parity-check codes under message-passing decoding," *IEEE Trans. Inform. Theory*, vol. 47, no. 2, pp. 599 -618, February 2001.

[7] T.J. Richardson and R.L.Urbanke, "The Renaissance of Gallager's low density parity check codes," *IEEE Commun. Mag.*, vol. 41, no. 8, pp. 638-656, Aug. 2003.

[8] K.S. Kim, Y.H. Kim, and J.Y. Ahn, "An Adaptive Transmission Technique for LDPC Coded OFDM Cellular Systems," *Electr. Letter*, Mar. 2004 (to be published).

[9] K.S. Kim, Y.H. Kim, and J.Y. Ahn, "An adaptive MIMO transmission technique for LDPC coded OFDM cellular systems," *Proc. IEEE Vehic. Techn. Confer. (VTC)*, Milan, Italy, May 2004 (to be presented).