Performance of MCS Selection for Collaborative Hybrid-ARQ Protocol

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Abstract. We propose a Modulation and Coding Scheme (MCS) selection algorithm for the collaborative hybrid Automatic-Repeat-reQuest (ARQ) protocol in order to provide high data rates. The collaborative hybrid ARQ protocol is designed to benefit from diversity gain. It exploits not only the broadcast nature of wireless channels, but also spatial diversity by formation of virtual antenna arrays and collaboration between a base station and relay nodes through Space-Time Block Coding (STBC). The proposed algorithm estimates both the effective Signal-to-Noise-Ratio (SNR) and the average throughput of each MCS level, and then selects the MCS level maximizing the average throughput. Simulation results show that the proposed algorithm outperforms conventional MCS selection algorithms in terms of the total throughput and satisfies packet delay constraints.

1 Introduction

In wireless communication systems, signals experience the shadow fading and multi-path fading, which degrade the performance such as throughput and packet delay. To mitigate these fading effects, spatial diversity techniques using multiple antennas have been thoroughly investigated in many literatures. However, even in single antenna systems, spatial diversity can be exploited through the collaborative hybrid ARQ protocol. In this protocol, a base station and relay nodes form virtual antenna arrays and collaborate through STBC during retransmissions [1][2]. If the base station transmits a packet to a mobile node, not only the mobile node but also the relay nodes near the base station can receive it. When the packet should be retransmitted (the mobile node fails to decode the packet correctly and requests retransmission), the relay nodes which have the successfully decoded packet and the base station transmit a space-time codeword on the same radio channel simultaneously. Therefore, the performance of the mobile node can be improved because it benefits from spatial diversity.

In general, link adaptation, or adaptive modulation and coding (AMC) scheme, is considered indispensable to provide high data rates because of the time varying nature of wireless channels. It denotes the matching of the MCS level to the channel quality, e.g., SNR. To perform link adaptation, a mobile node should measure the channel quality and report it to the base station periodically.

Then, the base station determines an MCS level according to the information reported by the mobile node and transmits packets in the determined MCS level.

However, the time delay between measurement and transmission may cause packets to be received erroneously at the mobile node because the channel quality may be changed during this time delay. To compensate for this performance degradation of AMC, therefore, most practical systems employ the hybrid ARQ protocol which is combination of two basic error control schemes, ARQ and Forward-Error-Correction (FEC) [3]. The collaborative hybrid ARQ protocol can be regarded as the extension of the conventional hybrid ARQ protocol to benefit from diversity gain. Details of the collaborative hybrid ARQ protocol are presented in Section 2.

Though the hybrid ARQ protocol can compensate for the performance degradation of AMC, determination of MCS levels still has a significant effect on the performance. Too low MCS levels waste radio resources thus degrading throughput. On the other hand, too high MCS levels increase the number of retransmissions, which could violate packet delay constraints. For the conventional hybrid ARQ protocol, an MCS selection algorithm for improving throughput has been proposed in [4]. It estimates the average throughput of each MCS level and selects the MCS level which maximizes the average throughput. However it is not suitable for the collaborative hybrid ARQ protocol because it has no consideration of spatial diversity. In this paper, therefore, we propose an MCS selection algorithm maximizing the average throughput by estimating both the effective SNR and the average throughput of each MCS level for the collaborative hybrid ARQ protocol.

The rest of the paper is organized as follows: Section 2 states the system model of the collaborative hybrid ARQ protocol. Section 3 discusses related works of MCS selection algorithms for the conventional hybrid ARQ protocol. In Section 4, we propose an MCS selection algorithm for the collaborative hybrid ARQ protocol, and its performance is compared with other MCS selection algorithms in Section 5. Finally, we conclude the paper in Section 6.

2 System Model

The system model assumed in this paper is shown in Fig. 1. The channel gain at time t is represented as $h_{i,j}(t)$ where i and j can be a base station, relay node and mobile node. A base station and relay node transmit packets with power P_{BS} and P_{RN}, respectively.

The type of hybrid ARQ used in this paper is synchronous Chase combining. Chase combining implies that erroneous packets are preserved for soft combining with the currently received packet in order to improve SNR thus increasing the probability of successful decoding [5]. On the other hand, synchronous hybrid ARQ implies that retransmissions for a certain hybrid ARQ process are restricted to occur at known time instants [6].

The procedure of packet transmission in the system using the collaborative hybrid ARQ is as follows: A base station transmits a packet to a mobile node.

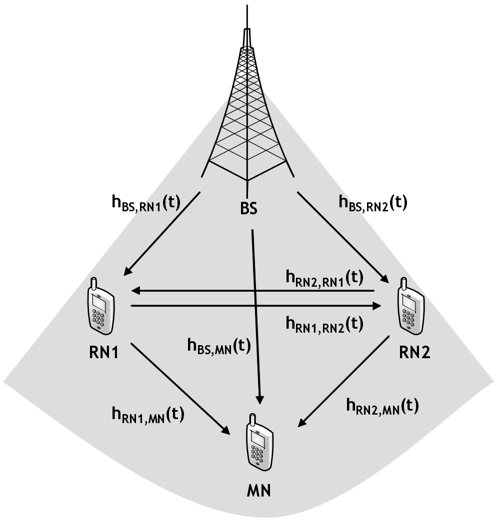

Fig. 1. System model

Because packets are broadcasted in wireless channels, not only the mobile node but also the relay nodes near the base station receive the packet. If the mobile node decodes the packet successfully, it transmits an ACK message to the base station and then transmission of the packet is completed. However, in the case that the mobile node fails to decode the packet, it transmits a NACK message to the base station in order to request retransmission. After the predefined interval, the base station and the relay nodes which have the successfully decoded packet form virtual antenna arrays and transmit a space-time codeword on the same radio channel simultaneously. Therefore, the mobile node receives multiple packets and exploits spatial diversity because each packet is transmitted over a different path thus experiencing independent fading. Prior to decoding the currently received packets at the mobile node, they are combined with previously received packets. After combining them, decoding is performed at the mobile node. Retransmission continues until the base station receives an ACK message from the mobile node or the number of retransmissions exceeds the predefined value T_{max}.

3 Related Works

In most practical systems using the conventional hybrid ARQ protocol, the MCS level is determined in order to satisfy Frame Error Rate (FER) of 10% or 1%; in this case, most packets are successfully transmitted without retransmission or with one retransmission. Such MCS selection algorithms are designed to satisfy packet delay constraints. However, in the case of non-real-time traffic which is insensitive to packet delay, throughput can be improved through fully exploiting time diversity even though packet delay can be slighted increased. For the conventional hybrid ARQ protocol, an MCS selection algorithm has been proposed in [4] to maximize the average throughput. This algorithm estimates the average throughput of each MCS level and selects the MCS level which maximizes the average throughput. If we define MCS set as M, the expected number of transmissions to successfully transmit a packet at time t when the MCS level is $m \in M$ is given by

$$E[Z(t)|m] = \sum_{n=1}^{\infty} n \cdot P\{Z(t) = n|m\} \ . \tag{1}$$

Therefore, we can select the MCS level which maximizes the average throughput at time t as follows:

$$R(t) = \operatorname*{argmax}_{m \in M} \frac{B_m}{\tau \cdot E[Z(t)|m]} \tag{2}$$

where τ denotes the required time per transmission (the frame length multiplied by the retransmission interval), and B_m is the information bits in a frame when the MCS level is m. To calculate $P\{Z(t) = n|m\}$ in (1), we define the effective SNR from the base station to mobile node u at n_{th} transmission as follows (we assume that the first transmission occurs at time t):

$$SB_{MN_u}^{(n)}(t) = \sum_{k=1}^{n} |h_{BS,MN_u}(t + \tau(k-1))|^2 \cdot \frac{P_{BS}}{N} \tag{3}$$

where $h_{BS,MN_u}(t)$ denotes the channel gain from the base station to mobile node u at time t, and N denotes the noise power. In Chase combining, the effective SNR is the sum of SNR of each transmission. With the effective SNR calculated in (3), $P\{Z(t) = n|m\}$ in (1) is then calculated as follows:

$$P\{Z(t) = n|m\} = (1 - F_m(SB_{MN_u}^{(n)}(t))) \cdot \prod_{k=1}^{n-1} F_m(SB_{MN_u}^{(k)}(t)) \tag{4}$$

where $F_m(x)$ represents FER when SNR is x and the MCS level is m. This value can be obtained from the result of link level simulation. Therefore, (2) is represented as follows:

$$R(t) = \operatorname*{argmax}_{m \in M} \frac{B_m}{\tau \cdot \sum_{n=1}^{\infty} n \cdot (1 - F_m(SB_{MN_u}^{(n)}(t))) \cdot \prod_{k=1}^{n-1} F_m(SB_{MN_u}^{(k)}(t))} \tag{5}$$

Moreover, for a given bound on the maximum number of retransmissions T_{max}, (5) is modified as follows [4]:

$$R^{T_{max}}(t) = \operatorname*{argmax}_{m \in M} \frac{X^{T_{max}}(t|m)}{Y^{T_{max}}(t|m)} \tag{6}$$

where $X^{T_{max}}(t|m)$ and $Y^{T_{max}}(t|m)$ are given by

$$X^{T_{max}}(t|m) = B_m \cdot (1 - \textstyle\prod_{k=1}^{T_{max}+1} F_m(SB_{MN_u}^{(k)}(t))) \tag{7}$$

and

$$\begin{aligned} Y^{T_{max}}(t|m) = \tau \cdot \textstyle\sum_{k=1}^{T_{max}+1} k \cdot (1 - F_m(SB_{MN_u}^{(k)}(t))) \cdot \prod_{q=1}^{k-1} F_m(SB_{MN_u}^{(q)}(t)) \\ + (T_{max}+1) \cdot \textstyle\prod_{k=1}^{T_{max}+1} F_m(SB_{MN_u}^{(k)}(t)) \ . \end{aligned} \tag{8}$$

4 MCS Selection for the Collaborative Hybrid ARQ Protocol

In this section, we propose an MCS selection algorithm for the collaborative hybrid ARQ protocol. We first estimate the expectation of the effective SNR at n_{th} transmission (we assume that the first transmission occurs at time t as in Section 3). For relay node i, the expectation of the effective SNR at n_{th} transmission when the MCS level is m can be calculated as follows:

$$S_{RN_i}^{(n)}(t|m) = \sum_{k=1}^{n} \{SB_{RN_i}^{(k)}(t) + SR_{RN_i}^{(k)}(t|m)\} \tag{9}$$

where $SB_{RN_i}^{(k)}(t)$ and $SR_{RN_i}^{(k)}(t|m)$ are given by

$$SB_{RN_i}^{(k)}(t) = |h_{BS,RN_i}(t+\tau(k-1))|^2 \cdot \frac{P_{BS}}{N} \tag{10}$$

and

$$SR_{RN_i}^{(k)}(t|m) = \sum_{j=1, j\neq i}^{L} |h_{RN_j,RN_i}(t+\tau(k-1))|^2 \cdot (1 - F_m(S_{RN_j}^{(k-1)}(t|m))) \cdot \frac{P_{RN}}{N} \tag{11}$$

where L denotes the total number of relay nodes. The summation notation in (9) reflects the SNR gain of Chase combining. $SB_{RN_i}^{(k)}(t)$ represents the effective SNR from the base station to relay node i at k_{th} transmission, and $SR_{RN_i}^{(k)}(t|m)$ represents the expectation of the effective SNR from the relay nodes which have the successfully decoded packet to relay node i at k_{th} transmission when the MCS level is m. A relay node transmits the packet at n_{th} transmission only if the relay node decoded the packet successfully at $(n-1)_{th}$ transmission. Because there are no relay nodes which can transmit packets at the first transmission, therefore, we have

$$F_m(S_{RN_i}^{(0)}(t|m)) = 1 \qquad \text{for all } t > 0,\ 1 \leq i \leq L\ ,\ m \in M\ . \tag{12}$$

In a similar way, for mobile node u, the expectation of the effective SNR at n_{th} transmission when the MCS level is m can be calculated as follows:

$$S_{MN_u}^{(n)}(t|m) = \sum_{k=1}^{n} \{SB_{MN_u}^{(k)}(t) + SR_{MN_u}^{(k)}(t|m)\} \tag{13}$$

where $SB^{(k)}_{MN_u}(t)$ is defined in (3), and $SR^{(k)}_{MN_u}(t|m)$ is given by

$$SR^{(k)}_{MN_u}(t|m) = \sum_{j=1}^{L} |h_{RN_j,MN_u}(t+\tau(k-1))|^2 \cdot (1-F_m(S^{(k-1)}_{RN_j}(t|m))) \cdot \frac{P_{RN}}{N} \ . \quad (14)$$

$SB^{(k)}_{MN_u}(t)$ represents the effective SNR from the base station to mobile node u at k_{th} transmission, and $SR^{(k)}_{MN_u}(t|m)$ represents the expectation of the effective SNR from the relay nodes which have the successfully decoded packet to mobile node u at k_{th} transmission when the MCS level is m.

For the collaborative hybrid ARQ protocol, therefore, (4) is modified as follows:

$$P\{Z_P(t) = n|m\} = (1 - F_m(S^{(n)}_{MN_u}(t|m))) \cdot \prod_{k=1}^{n-1} F_m(S^{(k)}_{MN_u}(t|m)) \quad (15)$$

Consequently, we can select the MCS level which maximizes the average throughput by applying (15) to (5) or (6) for the collaborative hybrid ARQ protocol as follows:

$$R_P(t) = \underset{m \in M}{\text{argmax}} \frac{B_m}{\tau \cdot \sum_{n=1}^{\infty} n \cdot (1 - F_m(S^{(n)}_{MN_u}(t|m))) \cdot \prod_{k=1}^{n-1} F_m(S^{(k)}_{MN_u}(t|m))} \quad (16)$$

or

$$R_P^{T_{max}}(t) = \underset{m \in M}{\text{argmax}} \frac{X_P^{T_{max}}(t|m)}{Y_P^{T_{max}}(t|m)} \quad (17)$$

where $X_P^{T_{max}}(t|m)$ and $Y_P^{T_{max}}(t|m)$ are given by

$$X_P^{T_{max}}(t|m) = B_m \cdot (1 - \prod_{k=1}^{T_{max}+1} F_m(S^{(k)}_{MN_u}(t|m))) \quad (18)$$

and

$$\begin{aligned} Y_P^{T_{max}}(t|m) = \tau \cdot \textstyle\sum_{k=1}^{T_{max}+1} k \cdot (1 - F_m(S^{(k)}_{MN_u}(t|m))) \cdot \prod_{q=1}^{k-1} F_m(S^{(q)}_{MN_u}(t|m)) \\ + (T_{max}+1) \cdot \textstyle\prod_{k=1}^{T_{max}+1} F_m(S^{(k)}_{MN_u}(t|m)) \ . \end{aligned} \quad (19)$$

5 Simulation Results

We carried out the simulation to compare the performance of various MCS selection algorithms. The simulation environments are summarized in Table 1, and the deployment of the base station and relay nodes is shown in Fig. 1. The number of mobile nodes is set to 10, and their locations are randomly distributed in the shaded area in Fig. 1. The distance between the base station and a mobile node is limited up to 500 m. In each frame, one mobile node is scheduled according to the Proportional Fair (PF) scheduling algorithm [7][8], and the time delay between measurement and transmission is set to 1 frame.

Table 1. Simulation environments

Items	Description
Channel model	Pedestrian B, 1 km/h [9]
Fast fading	Jakes model [10]
Slow fading	Log-normal distribution with standard deviation of 8.9 dB
System bandwidth	10 MHz
Transmission power of base station	43 dBm
Transmission power of relay node	30 dBm
Noise power density	-173 dBm/Hz
Traffic model	Full queue
Distance between base station and relay node	250 m
Distance between base station and mobile node	0 - 500 m
The number of base stations	1
The number of relay nodes	2
The number of mobile nodes	10
Frame length	5 ms
Retransmission interval	3 frame
Maximum number of retransmissions (T_{max})	4
Time delay between measurement and transmission	1 frame
Simulation time	500 frame
Type of hybrid ARQ	Synchronous Chase combining
Scheduling algorithm	Proportional Fair

FERx selects the MCS level as follows:

$$R_{FERx}(t) = \underset{m \in M}{\operatorname{argmax}} \left\{ B_m \middle| F_m(|h_{BS,MN_u}(t)|^2 \cdot \frac{P_{BS}}{N}) < x \right\} \tag{20}$$

On the other hand, Thrpt selects the MCS level by using (6), and the proposed algorithm selects the MCS level by using (17). In the cases of Thrpt and the proposed algorithm, we calculate the effective SNR under the assumption that the channel gain is unchanged during a hybrid ARQ process because it is difficult to predict the future channel conditions in practice.

Figure 2 shows the cumulative distribution function (CDF) of the average number of transmissions to transmit a packet, which is a measure of packet delay. As shown in Fig. 2, the average number of transmissions of the proposed algorithm is larger than those of any other algorithms. Though the proposed algorithm shows the longest packet delay, we can see that the proposed algorithm satisfies packet delay constraints because there is no case that the average number of transmissions exceeds $T_{max} + 1$.

Figure 3 shows the CDF of the total throughput. The proposed algorithm outperforms FER0.1, FER0.5, FER0.9, and Thrpt algorithms by about 30 %, and FER0.01 algorithm by about 60 % in terms of the total throughput because FERx and Thrpt algorithms are designed without consideration of spatial diversity. Though the proposed algorithm shows longer packet delay than any

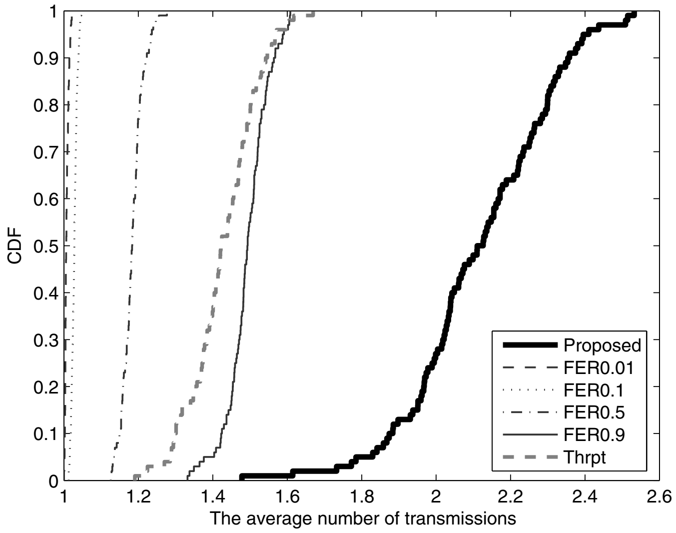

Fig. 2. CDF of the average number of transmissions to transmit a packet

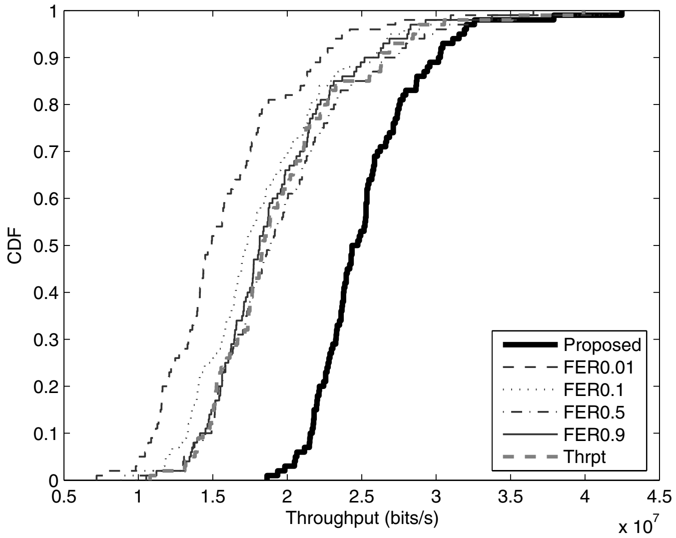

Fig. 3. CDF of the total throughput

other algorithms, selection of higher MCS levels with satisfying packet delay constraints results in higher throughput. Moreover, we can see that FER0.01 algorithm shows the worst throughput because it selects too low MCS levels thus wasting radio resources.

6 Conclusion

In this paper, we have proposed an MCS selection algorithm for the collaborative hybrid ARQ protocol. It selects the MCS level which maximizes the average throughput by estimating the effective SNR and the average throughput of each MCS level. The simulation results have shown that the proposed algorithm outperforms any other MCS selection algorithms by 30 % – 60 % in terms of the total throughput. Though the proposed algorithm shows longer packet delay than other algorithms, it is shown that the proposed algorithm satisfies packet delay constraints.

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