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Power Control for Multiple Access Communication Systems with Multi-Packet Reception Capability

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***Abstract*—This paper addresses the power control problem in wireless multiple access communication systems with a multi-packet reception (MPR) channel. Driven by advances in signal processing and multiuser detection (MUD) technologies such as UWB and MIMO, it has become possible for a wireless node to simultaneously receive several packets from other transmitters. In this case, the receiver node can determine the set of transmitters from which it wants to receive data and instruct them to adjust their transmit power levels in order to maximize the overall network capacity by exploiting the MPR capability. We first show that the efficiency of the MPR channel utilization can be maximized by equalizing the transmission durations of simultaneously transmitting nodes, and then propose a power control that increases/decreases the transmit power of the nodes to equalize the transmission durations. Under the proposed power control, a node with a long transmission duration is allowed to use a higher transmit power if the next higher transmission rate is achievable with the increased transmit power. Through extensive simulations, we show that the proposed power control significantly improves the overall network capacity in multiple access.**

***Index Terms*—Power control, Multi-packet reception (MPR)**

I. INTRODUCTION

In traditional wireless local area networks (WLANs), a station can receive only one packet at a time. If more than one transmission exists, it is regarded as packet collision. However, as the technological level of signal processing and multiuser detection (MUD) increases, it has become possible to receive multiple packets simultaneously, provided receivers contain MUD and multiple antennas [1]–[4]. This multi-packet reception (MPR) capability results in enhanced throughput compared to general wireless networks with only single packet reception. The problem, however, is that the existing means to achieve higher throughput performance does not function well in the MPR network. Therefore, a somewhat different, which takes the MPR capabilities into consideration, is required [3], [5]–[8].

An MPR system consists of several packet transmissions occurring simultaneously and varying in duration depending on the packet lengths and transmission rates. The result is degradation in the MPR channel utilization because the following transmission attempts are allowed only when all of the ongoing transmissions have completed. Therefore, as the time difference between the longest and shortest transmissions increases, the MPR channel utilization degrades.

In this paper, we propose a power control algorithm for improving the MPR channel utilization within a multi-rate multi-packet reception system. Our proposed power control algorithm maximizes the MPR channel utilization by equalizing the transmission durations of packets, allowing them to be transmitted at the same time and thereby improving the overall network capacity. To verify the performance of the proposed power control algorithm, extensive simulation studies were conducted based on our system model. Through these simulations, we demonstrate that our proposed scheme significantly improves the aggregate throughput in comparison to other power control methods.

The remainder of this paper is organized as follows. Section II describes the system model for MPR and Section III presents the proposed power control algorithm. The performance evaluation is shown in Section IV through realistic simulations and conclusions are provided in Section V.

II. SYSTEM MODEL

We consider an uplink synchronous CDMA system with randomly generated spreading codes and a single-cell system that is coordinated by a base station (BS) with MPR capability. A variety of receivers using MUD techniques are available to successfully decode multiple packets and maximize the signal-to-interference-plus-noise ratio (SINR) of each signal at the same time. In this paper, we adopt the SINR model of the successive interference cancelation (SIC) receiver to detect and decode received signals by separating the already successfully decoded signals from the remaining signals. Thus, interference with the following decoded signals is reduced [9].

The receiver vector for the node i at an SIC receiver is given as

$$\mathbf{c}_i^{SIC} = \left(\prod_{j=1}^{i-1} (I - \mathbf{s}_j \mathbf{s}_j^T) \right) \mathbf{s}_i \quad \text{for} \quad i = 1, \cdots, N,$$

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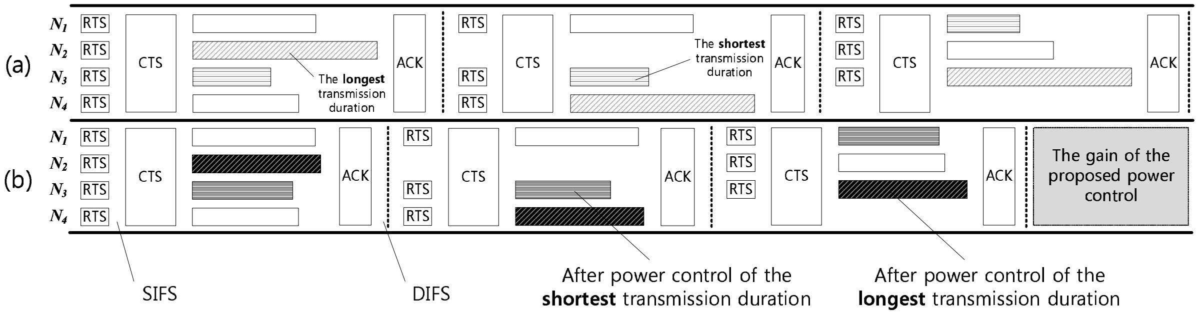

Fig. 1. The channel usage for multi-packet reception. (a) No power control (b) The proposed power control algorithm.

where s_i is the ith signature sequence with a spreading gain L. The SINR for the node i is given by

$$SINR_i^{SIC} = \frac{g_i p_i}{\sum_{j=i}^{i-1} \frac{\alpha_{ij}}{\alpha_{ii}} g_j p_j + \frac{1}{L} \frac{\beta_i}{\alpha_{ii}} \sum_{j=i+1}^{K} g_j p_j + \frac{\beta_i}{\alpha_{ii}} \sigma^2}, \tag{1}$$

where g_i is the channel gain coefficient, p_i is the transmit power of the ith node, K is the number of nodes, the constant $\alpha_{ij} = E(\mathbf{c}_i^{SIC^T} \mathbf{s}_j)^2$, $\beta_i = E(\mathbf{c}_i^{SIC^T} \mathbf{c}_i^{SIC})^2$, and σ^2 is the thermal noise [10].

III. Proposed Power Control Algorithm

In MPR systems, a wireless node simultaneously receives several packets from other transmitting nodes. However, due to the fact that each transmitter sends packets with a different length and at a different transmission rate, the duration of each transmission is different, even though they occur simultaneously. The result is that the MPR channel is not fully utilized, resulting in MPR performance degradation. In this section, we propose a novel power control scheme to prevent this inefficient use of the MPR channel.

A. Overview

First, we consider a simple MAC protocol for wireless networks with MPR capability, as depicted in Fig. 1. In this case, the maximum number of simultaneously successful transmissions (M) is 4. Any nodes in the MAC protocol that want to send a packet are required to transmit an RTS frame to the intended receiver, which is responsible for coordinating the packet transmissions from competing transmitters. On receiving multiple RTS frames, the receiver broadcasts a CTS frame, which includes a set of transmitters that are permitted to transmit.

As shown in Fig. 1. (a), without power control scheme, every node finishes its transmission at different times, depending on the packet length and transmission rate. For example, in the first data transmission session depicted in Fig. 1, the second transmitter (N_2) has the longest transmission duration, while the other three nodes have shorter durations. As a result, the other transmitters must wait for the completion of N_2's transmission. This example clearly demonstrates the possible inefficiency of using an MPR channel without power control scheme in multi-rate wireless networks supporting variable packet length due to different transmission durations.

To overcome this problem, we propose a power control scheme that adjusts the transmission rates in a way to adjusts the transmit rates so to equalize the transmission durations for all simultaneously transmitting nodes. In other words, the power level of nodes is either increased or decreased with respect to the longest and the shortest transmission durations. For instance, in the first session of Fig. 1. (b), N_2 with the longest transmission duration is enabled to increase its transmit power to achieve the next higher transmit rate, thus reducing its transmission duration. On the other hand, N_3, which had the shortest duration, decreases its transmit power in order to minimize its interference to neighboring nodes. The proposed power control achieves the temporal gain (in the shaded area of Fig. 1. (b)), resulting in the performance improvement in terms of channel utilization and aggregate throughput.

B. Detailed Procedure

Assuming that each node sends packets with a different transmission rate and that the packet lengths are not fixed, the transmission duration (D_i) for the node i is given as,

$$D_i = \frac{L_i}{R_i},$$

where L_i and R_i are the packet length and the transmission rate of the node i, respectively.

Under the proposed power control algorithm, the BS identifies both the node with the longest transmission duration and with the shortest. The node with the longest transmission duration is allowed to use a higher transmit power as long as the next higher transmission rate is obtainable with the increased transmit power. In the same manner, the transmit power for the node with the shortest transmission duration is decreased if the next lower transmission rate is achievable. The BS then derives the minimum transmit power level of the remaining nodes with which they can sustain the intended transmission rate. Finally, the BS broadcasts a CTS frame which includes the computed power level of the nodes and minimizes the difference among the transmission durations.

The detailed procedure of the proposed power control scheme is as follows:

(S1) The stations with a packet to send transmit an RTS frame to the BS with an initial power level.
(S2) If the BS successfully receives multiple RTS frames simultaneously, it obtains the SINR value and the pending data frame length.
(S3) Based on the obtained values, the BS calculates the transmission duration of each node, and identifies the nodes N_l with the longest transmission duration ($l = \mathrm{argmax}_{i=1,\ldots,M}\left(D_i\right)$), and N_s with the shortest transmission duration ($s = \mathrm{argmin}_{i=1,\ldots,M}\left(D_i\right)$).
(S4) The BS derives the minimum transmit power that supports the next higher and lower transmission rate of N_l and N_s, respectively.
(S5) The BS broadcasts a CTS frame which includes the power information for the permitted nodes.
(S6) The permitted nodes send a DATA frame with the instructed transmit power and rate, then wait for an ACK frame.

Let I_N denote the denominator part of (1) as

$$I_N = \sum_{j=i}^{i-1} \frac{\alpha_{ij}}{\alpha_{ii}} g_j p_j + \frac{1}{L}\frac{\beta_i}{\alpha_{ii}} \sum_{j=i+1}^{K} g_j p_j + \frac{\beta_i}{\alpha_{ii}}\sigma^2,$$

and then, I_N can be written as

$$I_N = \frac{g_i p_i}{SINR_i^{curr}},$$

where $SINR_i^{curr}$ is the current SINR value of node i.

Let p_i^* be the target power level of the transmitter i, with which the SINR value for the transmitter i should be greater than the SINR threshold. This relation is expressed as follows:

$$\frac{g_i p_i^*}{I_N + \Delta} \geq SINR_i^{th},$$

where $SINR_i^{th}$ is the SINR threshold for the intended transmission rate, and Δ is a potential variation of interference, caused by the transmit power increase/decrease of the other nodes under the power control algorithm. This yields

$$\begin{aligned} p_i^* &\geq \frac{I_N}{g_i} SINR_i^{th} + \frac{\Delta}{g_i} SINR_i^{th}, \\ &= p_i \frac{SINR_i^{th}}{SINR_i^{curr}} + \frac{\Delta}{g_i} SINR_i^{th}. \end{aligned}$$

Among the target power levels of transmitters, we focus on the transmit power levels (p_l^*, p_s^*) of two nodes with the longest and shortest transmission duration (N_l, N_s). These power levels are expressed as

$$\begin{aligned} p_l^* &\geq p_l \frac{SINR_l^{th}}{SINR_l^{curr}} + \frac{\Delta_s}{g_l} SINR_l^{th}, \\ p_s^* &\geq p_s \frac{SINR_s^{th}}{SINR_s^{curr}} + \frac{\Delta_l}{g_s} SINR_s^{th}, \end{aligned}$$

where Δ_l and Δ_s are the interference variations by the increased and decreased transmit power level of the N_l and N_s. Under the assumption that the received power of N_s is higher than those of N_l (e.g., $g_s p_s > g_l p_l$), Δ_s and Δ_l can be written as

$$\Delta_s = g_s\left(p_s^* - p_s\right), \Delta_l = \frac{1}{L} g_l \left(p_l^* - p_l\right).$$

Since g_l is small and L is large, the growth of interference caused by the increased p_l^* is not significant. Finally, we obtain the simultaneous linear equations with p_l^* and p_s^*,

$$\begin{aligned} p_l^* &= p_l \frac{SINR_l^{th}}{SINR_l^{curr}} + \frac{g_s\left(p_s^* - p_s\right)}{g_l} SINR_l^{th}, \\ p_s^* &= p_s \frac{SINR_s^{th}}{SINR_s^{curr}} + \frac{\frac{1}{L} g_l \left(p_l^* - p_l\right)}{g_s} SINR_s^{th}, \end{aligned}$$

which give a unique solution of p_l^* and p_s^*. By using the solution of (p_l^*, p_s^*), the BS can appropriately assign the transmit power of each node.

IV. PERFORMANCE EVALUATION

To evaluate the performance of the proposed power control algorithm, extensive simulations have been carried out using MATLAB. In our simulation study, we considered an uplink synchronous CDMA system with spreading gain L = 128 and a single-cell system with a BS. For a more realistic scenario, we used a disk region with a radius of 250m the BS located at the center of the region. All nodes were located randomly in the given area, and the maximum transmission power of the transmitter was configured so that the BS was within the transmission range of all nodes.

Using the simulation results, we compare the performance of the proposed algorithm with that of the following methods:

(i) *w/o PC (No Power Control)* - A protocol that uses a fixed transmission power with no power control.

(ii) *w/ PC (Max/Min Rate)* - The schemes that increase transmission power of the nodes with the strongest/weakest received signal power.

Fig. 2 shows the aggregate throughput with respect to the MPR capability. As can be seen, the proposed algorithm significantly improves the aggregate throughput by equalizing the transmission duration of each transmitter. In the case of *w/ PC (Max Rate)*, there is a slight difference in comparison with *w/o PC*. When a node with the highest SINR increases its transmission power, it becomes the dominant source of interference at the BS, thereby causing the other nodes to encounter a significantly decreased SINR. In other words, the throughput gain introduced by increasing the transmission power of the node with the best SINR compensates for the aggregate throughput reduction. On the other hand, in the case of *w/ PC (Min Rate)*, even though the node with the lowest SINR increases its transmission power, it does not cause increased interference at the BS, resulting in improved aggregate throughput. In the proposed algorithm, we attain the best throughput performance not by increasing the transmission power of the nodes with the lowest SINR, but of those with the longest transmission duration. As we increase M, in all

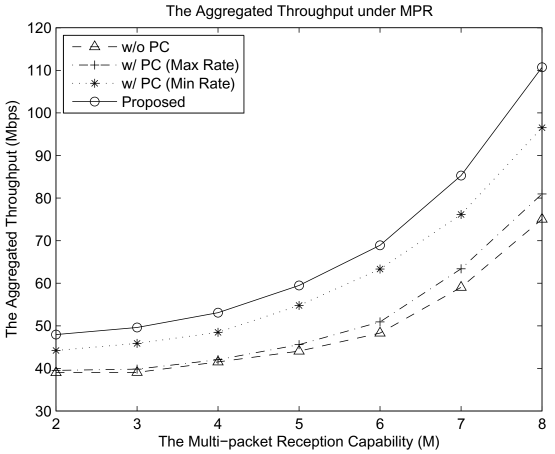

Fig. 2. The aggregate throughput performance with respect ot the multi-packet reception capability.

cases, the aggregate throughput gradually increases. However, as M increases, the throughput improvement is more notable when the proposed power control scheme is used.

V. CONCLUSION

The main objective of our power control algorithm is to enhance the overall network capacity by exploiting the rate diversity with MPR capability. For this objective, we have proposed the power control algorithm of which the receiver instructs the intended transmitters to adjust their transmit power levels to equalize the transmission durations of simultaneously transmitting nodes. Specifically, the nodes which have the longest and shortest transmission duration increase and decrease their transmit power, respectively, in order to use the immediate higher and lower transmission rates. As a result, the proposed algorithm can make the transmission durations of all transmitting nodes nearly equal, that increases the channel utilization. The simulation results show that our proposed power control algorithm achieves the performance improvement in terms of the aggregate throughput.

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