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Capacity, fairness, and queueing performance analysis of opportunistic scheduling with one-bit feedback

Yoora Kim[*,a], Ganguk Hwang[b], Song Chong[c]

[a] Department of Mathematics, University of Ulsan, Ulsan, Republic of Korea
[b] Department of Mathematical Sciences and Telecommunication Engineering Program, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Republic of Korea
[c] Department of Electrical Engineering, KAIST, Daejeon, Republic of Korea

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ABSTRACT

In this paper, we consider opportunistic downlink scheduling in a cellular network that exploits multiuser diversity using one-bit feedback. To reduce the feedback overhead inherent in opportunistic scheduling, mobile stations are allowed to send one-bit information to the base station only when their channel quality exceeds a given threshold value. The objective of this paper is two-fold: (i) find the threshold value that can optimize queueing performance of the scheduler and (ii) investigate the relationship among capacity, fairness, and queueing performance. To this end, we first derive a formula for the sum-rate capacity as a function of the threshold. Next, we quantify the long-term and short-term fairness using Jain's fairness index. Lastly, we develop a packet-level queueing model and derive QoS measures such as queueing delay and packet loss probability. Based on our analysis, we optimize the threshold value by considering both the traffic condition at the MAC layer and the temporal channel correlation at the PHY layer. Numerical results show that the optimized threshold can significantly reduce the average queueing delay and the packet loss probability. In addition, we find that there is a trade-off between short-term fairness and sum-rate capacity, whose control knob is the threshold. We show that, from a queueing performance perspective, supporting the sum-rate capacity (resp. the short-term fairness) is more important when the traffic is heavy (resp. light) or the wireless channel varies with low (resp. high) temporal correlation.

1. Introduction

In wireless networks, each user experiences different channel conditions at different times due to the time-varying nature of the wireless medium. Moreover, channel variation processes of individual users are usually independent of each other. As a result, different users experience peaks in their channel quality at different times, from which multiuser diversity comes [1,2]. In order to efficiently utilize the bandwidth of the time-varying wireless medium, opportunistic scheduling schemes exploit multiuser diversity by allocating the shared wireless medium to the user under favorable channel condition [3]. For example, the MaxSNR scheme allocates the wireless medium to the user with the best instantaneous received signal-to-noise ratio (SNR). Such an opportunistic scheduling policy can maximize the total information-theoretic capacity of a wireless network both in uplink [1] and downlink [4].

The capacity advantage of opportunistic scheduling can be achieved with the penalty of the following two problems. The first problem is related to fairness. Although the MaxSNR scheme can maximize the total information-theoretic capacity, it can cause unfair scheduling by allowing users under the strongest channel conditions to monopolize the shared wireless medium. To solve this problem, the proportional fair scheduling scheme has been proposed and analyzed (see [5] and references therein), where the scheduler allocates the wireless medium to the user with the best instantaneous normalized rate. Cumulative distribution function (CDF)-based opportunistic scheduling is also well known for its ability to support precise and flexible control of fairness among users while efficiently exploiting multiuser diversity [6]. Recently, CDF-based scheduling has been extended to various networks, including coordinated multi-point systems [7], heterogeneous networks [8], and wiretap networks to improve physical layer security [9].

The second problem is related to the channel state information (CSI) acquisition [10]. Opportunistic scheduling schemes require the scheduler to know the instantaneous channel qualities of all users. For this, each user tracks its channel quality by estimating the signal strength via e.g., a common downlink pilot channel and then feeds back the

* Corresponding author.
E-mail addresses: yrkim@ulsan.ac.kr (Y. Kim), guhwang@kaist.edu (G. Hwang), songchong@kaist.edu (S. Chong).

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estimated channel quality to the scheduler. Hence, as the number of users increases, the feedback load becomes significant and adds to the signaling overhead in the uplink of a wireless network. Moreover, feedback bandwidth and the power expended for feedback transmissions by the non-scheduled users are wasted. To solve this problem, threshold-based feedback reduction algorithms have been studied extensively (e.g., [11–28]). The main idea of these algorithms is to set a threshold and allow users whose channel quality exceeds the threshold value to feed back their (full or partial) CSI to the scheduler. In this way, multiuser diversity can still be exploited while reducing the amount of feedback information.

Gesbert and Alouini [11] proposed a selective feedback scheme in which users whose instantaneous received SNR exceeds the threshold value are allowed to feed back their instantaneous SNR to the scheduler. The fairness issue for the selective feedback scheme is addressed by Yang et al. [12] by considering a normalized SNR threshold. Recently, the selective feedback scheme has been studied in various opportunistic resource allocation problems such as CDF-based opportunistic scheduling in an orthogonal frequency division multiple access (OFDMA) downlink system [13]; joint opportunistic scheduling and selective feedback [14]; and opportunistic beamforming [15].

Making the selective feedback scheme even more economical, a one-bit feedback scheme is proposed by Sanayei and Nosratinia [16]. In their proposed scheme, users whose channel gain exceeds the threshold value are allowed to feed back only one-bit information to the scheduler. It is shown that, in a single-input single-output (SISO) system, the optimal sum-rate capacity growth rate under the full CSI feedback scheme can also be achieved under the one-bit feedback scheme with a carefully selected threshold [16,17]. This result is extended to a multiple-input multiple-output (MIMO) system in [18,19] and to outdated one-bit feedback cases in [20].

The fairness issue for the one-bit feedback scheme is addressed by Hwang and Ishizaki [21] by considering a normalized SNR threshold. In their work, the normalized SNR threshold value is optimized to maximize the sum-rate capacity while maintaining strict fairness among users. Xue and Kaiser [22] considered feedback imperfections caused by a noisy feedback link or an imprecise channel estimate and proposed a scheduling algorithm to exploit multiuser diversity with possibly imperfect one-bit channel state feedback. In their work, the threshold value is optimized to maximize the data rate in the presence of feedback error. Recently, the one-bit feedback scheme has been studied under various scenarios such as for designing proportional fair scheduling [23] and CDF-based opportunistic scheduling [24,25]; for controlling opportunistic user selection in a spectrum sharing system [26]; for supporting non-orthogonal multiple access [27]; and for developing a throughput-optimal rate adaptation policy in multi-user OFDM systems [28].

In this paper, we consider downlink transmission in a cellular wireless network consisting of a base station (BS) and multiple mobile stations (MSs). We assume that an opportunistic scheduler is located at the BS. To alleviate the CSI acquisition and fairness problems addressed above, the opportunistic scheduler considered in this paper exploits multiuser diversity with only one-bit feedback information using a normalized SNR threshold. Such a scheduling and feedback scheme is essentially identical to or is a special case of those proposed in [16–22] under a certain modeling assumption. Previous studies on threshold-based feedback reduction algorithms have mainly focused on the PHY layer performance. The threshold value is optimized from the information-theoretic perspective and is designed independent of MAC layer performance. However, the QoS and user satisfaction level more likely depend on the MAC layer performance such as queue length distribution, packet loss probability, and queueing delay [29]. These performance measures are especially important for real-time applications with stringent QoS constraints. However, it is questionable whether the threshold value optimized with respect to PHY layer performance is still optimal with respect to MAC layer performance. This motivated us to analyze the impact of the threshold value on MAC layer performance. Based on our analysis, we optimize the threshold value in two respects: (i) average queueing delay minimization and (ii) packet loss probability minimization.

It is worthwhile to mention that there are two factors that directly affect MAC layer performance: sum-rate capacity and short-term fairness.[1] As the sum-rate capacity increases, more packets in the queues at the MAC layer can be transmitted through the wireless medium, which can improve the queueing performance in terms of throughput. Intuitively, a short-term fair scheduler can allocate the shared wireless medium equitably across all MSs within a short period of time [30–32]. Hence, as the short-term fairness strengthens, packets in each queue at the MAC layer have greater chance of transmission within a short period of time, which then improves the queueing performance in terms of delay. To better understand the MAC layer performance of the one-bit feedback scheduler, we also analyze the impact of sum-rate capacity and short-term fairness on queueing performance.

The main contributions of this paper are summarized in the following three points.

- We investigate the impact of the threshold value on the performance of opportunistic scheduling with threshold-based one-bit feedback. Our investigation reveals a three-way relationship between capacity, fairness, and queueing performance of the scheduler. Note that there have been studies on the two-way relationship between capacity and fairness in multiuser diversity systems [33–35]. However, to the best of our knowledge, this is the first work to address their impact on queueing performance. This work provides us a comprehensive understanding of system performance, which is essential for better system design.
- We develop a packet-level queueing model and analysis technique that accommodate diverse stochastic dynamics resulting from opportunistic scheduling, the temporally correlated fading process in a wireless channel at the PHY layer, and the random arrivals of packets in a queue at the MAC layer. In addition, our queueing model and analysis technique also work for practical wireless communication systems with unsaturated traffic, finite-size queues, and heterogeneous MSs with different channel statistics.
- We apply our queueing model and analysis technique to find the threshold value that optimizes the MAC layer performance in terms of the average queueing delay and the packet loss probability, which are important QoS measures. We evaluate the QoS performance improvement achieved using the MAC layer optimal threshold as compared to using the PHY layer optimal threshold.

Through numerical studies based on our analysis, we find the following.

- The temporal correlation of a wireless channel directly effects the MAC layer performance: MS under a highly correlated wireless channel should wait for a long period of time until it experiences a favorable channel condition, which can result in delay violations. Therefore, the MAC layer optimal threshold is selected in a cross-layer manner by considering both the traffic condition at the MAC layer and the degree of temporal channel correlation at the PHY layer.
- The threshold value optimized with respect to PHY layer performance is no longer optimal with respect to MAC layer performance. Numerical results show that the average queueing delay and the packet loss probability can be significantly reduced using the MAC layer optimal threshold instead of the PHY layer optimal threshold.
- The discrepancy between the PHY layer optimal threshold and the

[1] In this paper, we distinguish between long-term fairness and short-term fairness. The details are provided in Section 4.