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Entropy-based active learning for wireless scheduling with incomplete channel feedback[☆,☆☆]

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ABSTRACT

Most of the opportunistic scheduling algorithms in literature assume that full wireless channel state information (CSI) is available for the scheduler. However, in practice obtaining full CSI may introduce a significant overhead. In this paper, we present a learning-based scheduling algorithm which operates with partial CSI under general wireless channel conditions. The proposed algorithm predicts the instantaneous channel rates by employing a Bayesian approach and using Gaussian process regression. It quantifies the uncertainty in the predictions by adopting an entropy measure from information theory and integrates the uncertainty to the decision-making process. It is analytically proven that the proposed algorithm achieves an ϵ fraction of the full rate region that can be achieved only when full CSI is available. Numerical analysis conducted for a CDMA based cellular network operating with high data rate (HDR) protocol, demonstrate that the full rate region can be achieved our proposed algorithm by probing less than 50% of all user channels.

1. Introduction

A challenging open problem in wireless networks is the efficient allocation of limited and time-varying resources among multiple users to satisfy their requirements. The problem is exacerbated by the highly dynamic nature of wireless channels due to multiple superimposed random effects caused by mobility and multi-path fading. In many cases, acquiring extensive information on wireless channel characteristics is simply infeasible as a result of prohibitive overhead costs and hard constraints. In yet other cases, the wireless channel may be highly non-stationary that by the time the information is obtained, it becomes outdated due to channels' fast-changing nature. Hence, scheduling decisions should be made based on partial and outdated channel state information.

One of the main assumptions in prior works [2] is that the exact and complete channel state information (CSI) of all users is available at every time slot. Under this assumption, the seminal work by Tassiulas and Ephremides has shown that the opportunistic *Max-Weight* scheduling algorithm is throughput-optimal, i.e., it can stabilize the network whenever this is possible [2]. Max-Weight algorithm is a simple index policy which schedules the user with the largest queue length and rate product at each time slot.

In this paper, we investigate scheduling in a multi-user downlink wireless network where only partial channel state information can be acquired due to the band-limited feedback channel (Fig. 1). We present a joint CSI acquisition and scheduling algorithm which operates without any a priori knowledge on the distribution of channel states. The proposed algorithm tracks the states of the channels by using a learning algorithm and by judiciously probing a set of users whose channel states may have changed. At each slot, the algorithm schedules a user among the set of probed users, which has the highest queue backlog and transmission rate product.

Our work relies on a recent learning and optimization framework developed in [3], wherein the exploration and exploitation trade-off is explicitly quantified as a multi-objective meta optimization problem. In this paper, we investigate a trade-off between scheduling a user with the highest queue-rate product (exploitation), and probing of users with outdated channel observations (exploration). The solution of this trade-off problem requires the prediction of the instantaneous user channel states,

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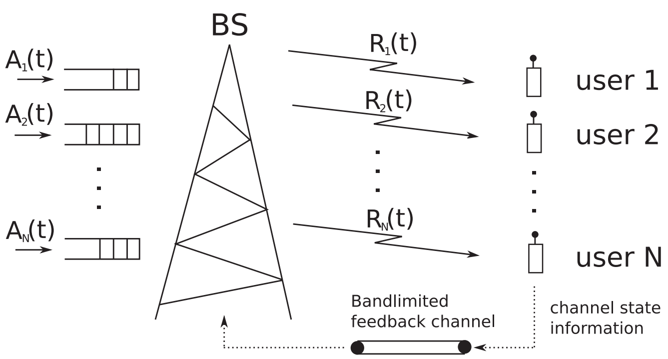

Fig. 1. Cellular downlink network.

and the measurement of the associated level of uncertainty in the prediction. We adopt a Bayesian approach, and use Gaussian processes as a state-of-the-art regression method to predict the instantaneous user channel states.

Gaussian process regression is a powerful nonlinear interpolation tool, where the inference of continuous values are made with respect to a Gaussian process prior [4]. Although the inference of instantaneous channel gains is with a Gaussian process prior, this does not assume that the underlying channel model is Gaussian. In fact, as demonstrated by our numerical experiments, our approach is applicable to a wide range of channel models including time-correlated and even non-stationary channels. Another unique feature of our algorithm is that the uncertainty in the predicted channel state is quantified explicitly by the *entropy measure* from the information theory. Our algorithm weighs the level of uncertainty eliminated by probing a channel against the aspiration to schedule the user with the maximum weight to determine a set of users probed at every slot.

Our contributions are summarized as follows: i-) we first define a general Max-Weight-like policy which makes scheduling decisions based on the predicted values of instantaneous channel rates rather than their exact values. Based on the channel prediction errors, we define the achievable rate region of this algorithm as compared to the full rate region achieved by the Max-Weight algorithm with complete CSI. Specifically, we analytically show that with this policy, ϵ fraction of the full rate region can be obtained. We also explicitly compute ϵ under certain conditions; ii-) Next, based on this general policy we investigate a multi-objective framework where the exploration and exploitation tradeoff of probing different users is identified. In this framework, the information obtained by probing a user channel is modeled with the help of Shannon's entropy formula according to the past observations of the channel; iii-) Then, we specify in detail our channel predictor used to predict instantaneous CSI, and suitable for both stationary and non-stationary channels based on Gaussian Process Regression; iv-) Lastly, we perform an extensive number simulations using High Data Rate (HDR) protocol [5] with a realistic channel model. We compare the performance of our algorithm with that of the state-of-the-art channel prediction method based on Autoregression (AR) [6].

The organization of our paper is given as follows: Section 2 summarizes the literature on opportunistic algorithms scheduling with a partial CSI, and learning methods previously used for the control of wireless networks. Section 3 presents the system model used in this paper. In Section 4, the general Max-Weight type policy and its performance in terms of achievable rate region are presented. In Section 5, GPR is explained in detail. The performance of the proposed algorithm is evaluated numerically in Section 6. Finally, we conclude the paper in Section 7.

2. Related work

It was shown that Max-Weight algorithm scheduling the user with the highest queue backlog and transmission rate product at every time slot is throughput optimal [2]. An important assumption of Max-Weight algorithm is that it requires complete knowledge of channel states at the beginning of each time slot. Investigating the performance of Max-Weight algorithm with incomplete CSI has been an active research area, and we classify the previous works on this area into two main categories: in the first category, it is assumed that the channel distributions of the users are known in advance whereas the main assumption of the works in the second category is that the channel distributions are not known a priori but users have only a specific channel distribution such as iid, Markovian or, in general, a stationary channel distribution.

In [7–9], the authors proposed joint scheduling and channel feedback algorithms by considering the problem of stabilizing the network of queues with incomplete CSI. These algorithms were shown to be throughput-optimal under the assumption that channel distributions are known a priori and they are independent and identically distributed (iid). These works are within the first category in our classification.

For the case when the channel distributions are not known a priori but can only have a specific distribution, which refers to the second category, several joint scheduling and probing algorithms were presented in [10–12], and [13]. In [10] and [11], the authors proposed algorithms that estimate the user channel statistics by assuming that the channels are iid. The problem of joint prediction of channel states and scheduling to optimize a long term metric under stability and other resource constraints was studied in [10]. The work in [11] proposed a probabilistic algorithm which at every slot decides to either explore a user channel state or exploit the slot to transmit data. In [12], the authors have presented a joint scheduling and channel estimation algorithm for correlated ON/OFF Markovian channels. In [13], we have developed an algorithm which probes only those users with sufficiently good channel quality and schedules the user with the maximum weight at each transmission opportunity. The underlying system model considered in [13] is different than the one used in this paper, since in [13] feedback from as many users as needed can be obtained by tolerating a reduction in data transmission rates. The authors in [14–19], studied the problem of scheduling with limited information under various aims and techniques such as utility maximization, thresholds based policies, distributed solution for cost reduction, etc. We refer the readers to [20] for a summary of different techniques used to reduce the overhead of obtaining CSI, e.g., quantization of CSI, beamforming or precoding. It is important to note that the common assumption of all these works is that the wireless channel has a well-defined stationary distribution.

In this work, without making the assumptions in the works in both of these categories, a learning based approached is utilized. Learning algorithms been applied to various problems in communication networks where there is limited information on network states such as routing [21], spectrum allocation [22], interference mitigation [23], multi-channel cognitive networks [24], combinatorial network optimization [25], multi-channel access [26]. These problems were solved by using reinforcement learning [21,22], Q-learning [23] techniques, or by modeling them as multi-armed bandit [24,25], [26], problems. Furthermore, studies have shown that such learning based future channel prediction techniques can provide more efficient spectrum utilization [27].

The studies which apply various learning techniques, [21–26], focused on finding a single solution assuming that the stochastic processes underlying the channel characteristics are stationary. Although these methods may provide provably optimal solutions under some special cases, none of them can adapt to the changes in