Multiuser Scheduling for Minimizing Age of Information in Uplink MIMO Systems

Abstract

This paper studies the user scheduling problem in a multiuser multiple-input multi-output (MIMO) status update system, in which multiple single-antenna devices aim to send their latest statuses to a multiple-antenna information-fusion access point (AP) via a shared wireless channel. The information freshness in the considered system is quantified by a recently proposed metric, termed age of information (AoI). Thanks to the extra spatial degrees-of-freedom brought about by the multiple antennas at the AP, multiple devices can be granted to transmit simultaneously in each time slot. We aim to seek the optimal scheduling policy that can minimize the network-wide AoI by optimally deciding which device or group of devices to be scheduled for transmission in each slot given the instantaneous AoI values of all devices at the beginning of the slot. To that end, we formulate the multiuser scheduling problem as a Markov decision process (MDP). We attain the optimal policy by resolving the formulated MDP problem and develop a low-complexity sub-optimal policy. Simulation results show that the proposed optimal and sub-optimal policies significantly outperform the state-of-theart benchmark schemes.

Keywords: Age of Information (AoI), Multiple-Input Multiple-Output(MIMO), Markov decision process (MDP), multiuser scheduling.

1 Introduction

The paper investigates a multiuser Multiple-Input Multiple-Output (MIMO) status update system, where multiple single-antenna devices aim to promptly update their latest statuses to a multiple-antenna access point. The objective of the paper is to determine an optimal multi-user scheduling strategy to minimize the overall AoI in the network.

The multiuser scheduling algorithm proposed in the paper considers both communication interference among users and channel state information. It schedules users based on their priorities and communication requirements. By effectively allocating system resources and scheduling users, the algorithm optimizes system performance and reduces the AoI. This research marks the first application of multi-antenna technology to mitigate AoI in multiuser networks.

The study presented in the paper holds significant importance for enhancing the real-time responsiveness of wireless communication systems, contributing to the advancement of real-time applications.

2 Related works

Early research on AoI turned to queueing theory to analyze the average AoI performance of point-to-point systems with various status update generation models (e.g., generate-at-will and stochastic arrival) and queueing disciplines (e.g., first-come-first-serve and last-come-first-serve). Refer to [7] for a comprehensive survey.

Recent efforts on AoI have been shifted towards minimizing the network-wide AoI in more practical multisource networks. Within this research domain, studies concentrating on the link scheduling problem are pertinent to this work [2,3,8,10]. In these works, the number of users that can be scheduled to transmit in each time slot is strictly constrained by the quantity of physical orthogonal channels available in the system. For instance, if all users share a common channel, at most one of them can be scheduled to transmit in each time slot to prevent collisions.

3 Method

3.1 System model and problem formulation

Consider a multiuser MIMO status update system consisting of an information-fusion AP equipped with N antennas and K end-devices, as depicted in Figure 1. All devices are assumed to be equipped with a single antenna. Each device wishes to send its latest status to the AP via the public wireless uplink channel.

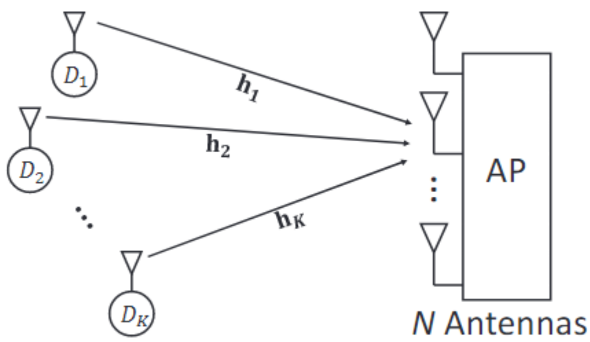


Figure 1. The considered multiuser MIMO status update system with one AP and N end-devices.

The "generate-at-will" model is considered: When the AP schedules device Di to update in one time slot, it first samples the fresh information and prepares a status update packet for transmission at the beginning of the time slot. Subsequently, the fresh status from node Di will be delivered to the AP. Otherwise, Di will keep silent within the time slot.

To elaborate the signal processing at the AP, we consider the special case that all devices are scheduled to transmit in a certain time slot.

The received signal at the AP can be expressed as

$$\mathrm{y} = \sum_{i=1}^{K} \sqrt{P_i}\mathrm{h}_i x_i + \mathrm{n} = \mathrm{H}\mathrm{x} + \mathrm{n}. \tag{1}$$

In this paper we concentrate on the symmetric network topology. In this case, the error probability for each data stream will only depend on the number of devices scheduled to transmit at the same time.When the AP schedules k out of K devices to transmit simultaneously in the uplink, the achievable error (outage) probability for each scheduled device can be expressed as

$$P_e\left(k\right) = 1 - \sum_{i=0}^{N-k} \frac{\left(\frac{\sigma^2}{P\Omega}\gamma_{\text{th}}\right)^i}{i!} \exp\left(-\frac{\sigma^2}{P\Omega}\gamma_{\text{th}}\right). \tag{2}$$

According to the principle of linear zero-forcing receiver [1], the information transmitted by multiple nodes will be recovered via

$$\hat{\mathrm{x}} = \mathrm{H}^{\dagger}\mathrm{y} = \mathrm{x} + \mathrm{H}^{\dagger}\mathrm{n}. \tag{3}$$

3.1.1 System expected AoI

Define the age vector $\delta\left(t\right) = \left\{\delta_1\left(t\right), \ldots, \delta_K\left(t\right)\right\}$.

the evolution of the instantaneous AoI for the device Di can be expressed as

$$\delta_i\left(t+1\right) = \begin{cases} 1, & \text{if } I_i\left(t\right) = 1, \text{and} J_i\left(t\right) = 1, \\ \delta_i\left(t\right) + 1, & \text{otherwise}, \end{cases} \tag{4}$$

Based on the AoI evolution, the expected AoI of the system can be formally defined as

$$\bar{\delta}_s = \lim_{T \to \infty} \frac{1}{TK} \sum_{t=1}^{T} \sum_{i=1}^{K} \delta_i\left(t\right). \tag{5}$$

3.1.2 Problem formulation

For a given age vector δ(t), which devices should be scheduled for transmission in time slot t to minimize the expected Age of Information (AoI) of the system. As the number of scheduled devices increases in each batch, the update frequency of devices also increases, but this leads to a higher error rate. Therefore, our goal is to find the optimal scheduling policy to minimize the expected AoI of the system : $\min_\pi \bar{\delta}_s(\pi)$.

3.2 Optimal and suboptimal policies

The paper recast the problem into an MDP problem, described by a 4-tuple $\{\mathcal{S}, \mathcal{A}, P_{\mathbf{a}}, r\}$, where

· State space $\mathcal{S} = \mathbb{Z}^{+K}$: the state in time slot t is composed by the instantaneous AoI of all clients, $s_t \triangleq (\delta_1(t), ..., \delta_K(t))$.

· Action space $\mathcal{A} = \{0, 1\}^K$: the action in time slot t is a binary vector $\mathbf{a}_t = (I_1(t), ..., I_K(t))$.

· Transition probability : $P_{\mathbf{a}}\left(\mathrm{s}, \mathrm{s}'\right) = \Pr\left(\mathrm{s}_{t+1} = \mathrm{s}' | \mathrm{s}_t = \mathrm{s}, \mathrm{a}_t = \mathrm{a}\right)$.

· $r\left(\mathbf{s}, \mathbf{a}\right) : \mathcal{S} \times \mathcal{A} \to \mathbb{R}$ is the one-stage reward received in time slot t, defined as $r\left(\mathbf{s}, \mathbf{a}\right) = \frac{1}{K}\sum_{i=1}^{K} \mathbf{s}(i)$.

Given any initial state s_0, the infinite-horizon average reward under any feasible policy $\pi \in \Pi$ can be expressed as

$$C(\pi, \mathrm{s}_0) = \lim_{T \to \infty} \sup \frac{1}{T} \sum_{t=0}^{T} \mathbb{E}_{\mathbf{s}_0}^{\pi}[r(\mathrm{s}_t, \mathrm{a}_t)]. \tag{6}$$

The problem is converted to : $\min_\pi C(\pi, \mathbf{s}_0)$.

We refer to [9] and apply the relative value iteration (RVI) for attaining the optimal policy with a truncated finite state space, which can approximate that of the countable but infinite state space.

3.2.1 Action elimination

To minimize the one-stage reward of the next time slot, the AP should always schedule the devices with larger instantaneous ages. Specifically, if the AP decides to schedule k nodes, it should ask the devices with the maximum k ages to transmit in the current time slot. By doing this, we can reduce the number of possible actions from 2^K to K + 1, which will significantly lower the computation complexity for finding the optimal policy.

3.2.2 A sub-optimal policy

The paper propose a low-complexity suboptimal policy inspired by the maximum weight policy developed in [4–6]. The AP chooses the action that minimizes the expected reward of the next state, termed one-step expected next step reward.Then, perform action elimination. One-step expected next step reward $\mathbb{E}[r(\mathbf{s}'|\mathbf{s}, \mathbf{a}(k))]$ is

$$\mathbb{E}[r(\text{s'}|\text{s}, \text{a}(k))] = \frac{1}{K}\left(\sum_{i=1}^{K}\delta_i'' + K - (1 - P_e(k))\sum_{i=1}^{k}\delta_i''\right). \tag{7}$$

The optimal action for the state s under the suboptimal policy π' can be expressed as

$$\pi'(\mathbf{s}) = \arg_{\mathbf{a}(k), k\in\{0,1,\dots,K\}} \min \mathbb{E}[r(\mathbf{s}'|\mathbf{s}, \mathbf{a}(k)]). \tag{8}$$

Compared with the MDP-based optimal policy, the suboptimal policy is simple to calculate and easy to implement.

4 Implementation details

The code implementation mainly consists of two parts: functional functions and the main function.

Functional functions include: 'mdpipnew.m' is used to generate state transition probability matrix consisting of state index and probability. 'myMDP.m' performs relative value iteration to compute the optimal policy on a truncated state space. 'step.m' is a step function that calculates the next state after taking action in the current state.

main function calculates average AoI performance of three clients under different policies: (a) MDP policy; (b) Transmission by two clients; (c) Transmission by three clients; (d) Maximum weight policy; (e) Transmission by one client;

In the future, to minimize AoI in uplink MIMO systems, the following innovative points can be considered:

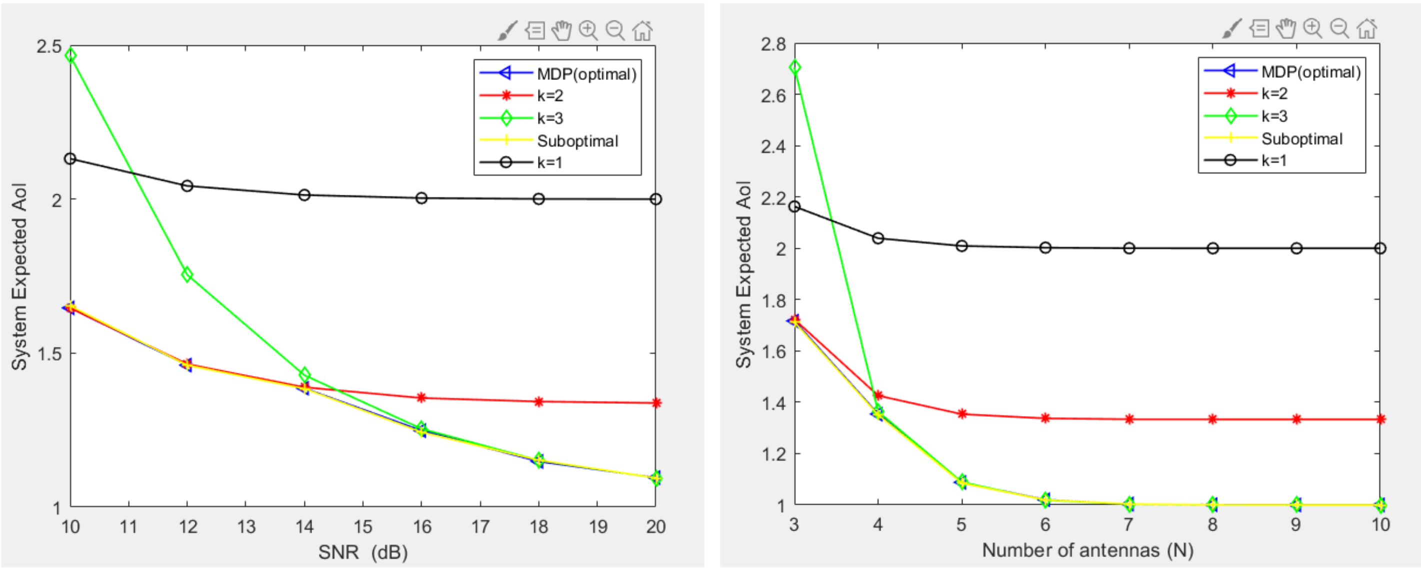
· Optimization of multiuser scheduling algorithms: For scenarios with multiple users, exploring more efficient scheduling algorithms, such as neural network-based algorithms using deep learning, can lead to improved resource allocation and time management strategies, thereby reducing AoI.

· Adaptive retransmission mechanism: Designing an adaptive retransmission mechanism that dynamically adjusts the number of retransmissions and the timing of retransmissions based on channel conditions and user requirements can help reduce transmission error rates, enhancing the reliability of AoI.

· Joint optimization design: Conducting joint optimization design of uplink MIMO systems with other communication systems (e.g., downlink MIMO systems) enables collaborative work and resource sharing, leading to increased system capacity, throughput, and a reduction in AoI.

5 Results and analysis

Numerical simulations are provided to compare the performance of the proposed optimal and sub-optimal policies with that of conventional scheduling policies in the considered MIMO status update system over different setups.



(a) The performance comparison of different policies versus SNR, when the total number of antennas are 3, i.e., N = 3

(b) The performance comparison of different policies versus the number of antennas N.

Figure 2. Simulation results.

In Figure 2a, we depict the expected AoI performance curves of various strategies concerning the SNR, where the number of antennas at the access point (AP) is set to 3. The performance of the optimal policy based on MDP, the suboptimal policy, and the stationary policies scheduling a fixed number of devices (k = 1, 2, 3) is compared. It can be observed from Figure 2a that the proposed suboptimal policy can approximate the optimal policy based on MDP in all simulation cases. Additionally, they are significantly superior to the stationary policies that schedule a fixed number of devices.

In Figure 2b, we present the expected AoI performance curves of various strategies concerning the number of antennas. Similar phenomena to those in Figure 2a can be observed from Figure 2b. The performance of the suboptimal policy is nearly consistent with that of the optimal policy. The optimal and suboptimal adaptive policies proposed in this paper consistently outperform the stationary policies that schedule a constant number of nodes in each time slot. The performance of all schemes simulated in Figure 2b tends to saturate when the value of N is sufficiently large. This is because the transmission error probability decreases as N increases. When N is large enough, scheduling the maximum number of devices (i.e., k = K) will lead to the best system performance.

6 Conclusion and future work

In this paper, we address the problem of minimizing information age in a multiuser MIMO state-update system. Specifically, we investigate the multiuser scheduling problem and formulate it as a Markov Decision Process (MDP) problem. To reduce the computational complexity of finding the optimal policy, we exploit key features of the MDP problem to perform action elimination. Furthermore, we develop a suboptimal policy that optimizes the expected reward for the next step only. Simulation results are provided to demonstrate that the proposed policies outperform baseline testing policies, which schedule a fixed number of devices to transmit in each time slot.In this paper, we enforce $N \geq K$ to ensure that the AP can schedule all the devices to access the channel simultaneously if needed. More complex scenarios and constraints can be considered in the futurewe can consider the case with $N < K$ as a future work.

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