Performance Modeling of Scheduling Algorithms in a Multi-Source Status Update System

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***Abstract*—Age of Information (AoI) is a widely used metric of information freshness in a status update communication system. In this paper, we study the AoI performance in a multi-source system in which multiple sources generate updates, but only one can be transmitted to a monitor at a time. Scheduling, or selecting the source update to transmit, is an important problem in such a system. We consider a time-slotted system with Bernoulli sources with no buffer. An update selected for transmission in a slot is delivered at the end of the slot. The AoI is analyzed for four different scheduling policies - random scheduling, round robin scheduling, age-greedy scheduling, and the Whittle index-based policy proposed in [1], [2]. Our analytical results are validated with simulation results, and a numerical performance comparison of the scheduling policies is presented.**

I. Introduction

To maintain the information freshness in many mission-critical *real-time* applications, Age of Information (AoI) is proposed in [3] as a metric measuring the freshness of information at the receiver of a status update system. In recent years, the AoI metric has been proposed as a useful metric in numerous applications that require timely availability of information at the receiving end of a communication or remote-controlled system, including autonomous driving or UAV-assisted edge computing network. The AoI has been analyzed and optimized for numerous single-source, single-server systems, e.g., see [4]–[9].

More recently, researchers have started paying attention to multi-source systems [1], [2], [10]–[23]. In particular, [1], [2] are the most closely related papers to our work. In [1], the authors developed the Greedy, Randomized, Max-Weight and Whittle's Index policies in a network in which packets are generated periodically and transmitted through unreliable channels. The authors showed the optimality of Greedy, Whittle's Index, and Max-Weight for the case of symmetric networks, i.e., networks which have equally unreliable channels, and then derived performance guarantees for all four policies. In [2], the authors considered a network with random arrivals and studied the AoI by designing and analyzing four scheduling algorithms, namely, structural Markov Decision Process (MDP) scheduling, index scheduling, MDP-based online scheduling, and index-based online scheduling. The optimality of these algorithms was theoretically investigated. Meanwhile, in [10], the authors developed Juventas, a low-complexity scheduling algorithm that was shown to offer near-optimal and guaranteed performance when there is no synchronization among the source nodes. In [11], the authors investigated the age performance of Whittle's index policy in a network with a central entity over unreliable channels, and provided analytical results on its optimality. The multi-sensor scheduling problem is decoupled into a single sensor level-constrained MDP in [12] where the authors reveal the threshold structure of the optimal stationary randomized policy for the single sensor. They convert the optimal scheduling problem into a linear program, and a truncated scheduling policy that satisfies the hard bandwidth constraint is proposed based on the solution for each decoupled sensor. Two multi-source information update problems in IoT are proposed in [13], named AoI-aware Multi-Source Information Updating (AoI-MSIU) and AoI-Reduction-aware Multi-Source Information Updating (AoIR-MSIU) problems. It is shown in that paper that scheduling terminals in a round-robin fashion where each terminal only retains the most up-to-date packet achieves the optimum asymptotically in a network with a number of terminals sharing a common wireless uplink based on a collision model with random packet arrivals.

These multi-source system papers generally focus on the design of the scheduling algorithm and demonstrating its optimality. On the other hand, there appears to be very limited work on analyzing the AoI of given scheduling algorithms for multi-source systems. In this paper, the AoI is analyzed for four scheduling policies – random scheduling, round robin scheduling, age-greedy scheduling, and the Whittle index-based policy proposed in [1], [2]. To the best of our knowledge, this is the first work that analyzes the AoI performance of these simple scheduling policies.

The paper is organized as follows. We present our system model and preliminaries in Section II. The analysis of the scheduling policies is presented in Sections III, IV, and V. Numerical results and discussion are presented in Section VI, and the paper is concluded in Section VII.

II. System Model and Preliminaries

Similar to [2], we consider a multi-source system with a transmitter sending status updates from N sources, numbered $1, 2, \ldots, N$, to a receiver/monitor as shown in Fig. 1. Time is slotted and each source is a Bernoulli source which generates a status update packet in a slot independent of other sources and other slots. The packet generation probability for source i is denoted by p_i. We use $a_i(t)$ as the indicator of packet generation for source i in slot t; $a_i(t) = 1$ indicates that an update packet is generated for source i at time t. Thus,

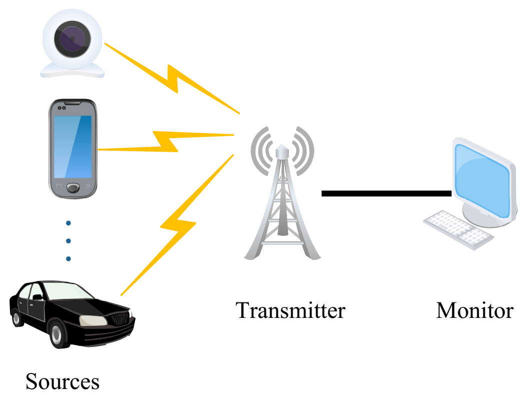

Fig. 1. System Model where multiple sources connect to single transmitter and offload their updates packet to single monitor.

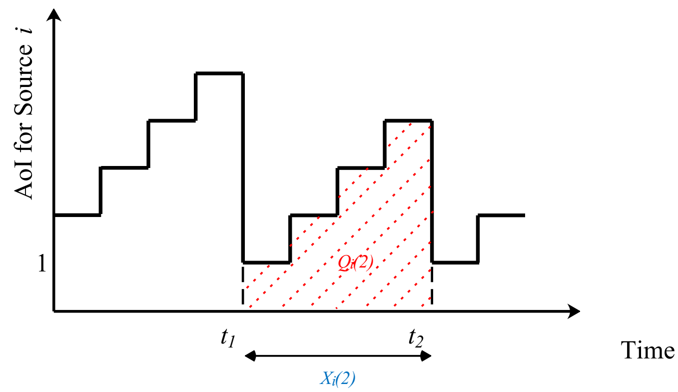

Fig. 2. Evolution of AoI for source i in the multiple sources system.

$P[a_i(t) = 1] = p_i$. At the beginning of each time slot, the transmitter selects a packet for transmission from one of the sources according to a scheduling policy π, and the packet is assumed to be delivered to the monitor at the end that time slot. We use $\pi(t)$ to denote the index of the selected source at time slot t; $\pi(t) = i$ indicates that source i is selected to transmit its update packet at time slot t. If no update packets is selected for transmission at time slot t, we set $\pi(t) = 0$. Following [4], we assume that the sources do not have any buffer, and if a source's packet is not selected for transmission in a time slot, it is dropped.

A. Age of Information

In this multi-source system, the AoI for each source will be counted separately at the monitor. For our time-slotted model, we assume that the AoI for each source will increase by one at the beginning of each time slot and will stay there for the rest of the time slot. If a source with an update packet is selected for transmission at time slot t, then its AoI becomes one at the end of time slot t (equivalently, the beginning of time slot $t + 1$). This is because of our assumption that packets are generated at the beginning of a time slot, and a transmitted packet is delivered to the monitor at the end of that time slot, and the AoI is updated only at time slot boundaries. Therefore, letting $\Delta_i(t)$ denote the AoI for source i at time slot t, we have:

$$\Delta_i(t+1) = \begin{cases} 1 & \text{if } a_i(t) = 1 \text{ and } \pi(t) = i, \\ \Delta_i(t) + 1 & \text{else.} \end{cases} \tag{1}$$

We show the AoI evolution for an arbitrary source i in Fig. 2. For each source i, we index the packets that are delivered to the monitor (as opposed to the packets generated by the source), and let $X_i(n)$ denote the number of time slots elapsed between the delivery of packets with indices $n-1$ and n for source i. (Note that $X_i(n)$ is a function of the scheduling policy π, but this dependence is not shown in the notation for simplicity.) In Fig. 2, the first packet for source i is transmitted at time slot t_1 and the second packet at time slot t_2; therefore $X_i(2) = t_2 - t_1$. Let us define $Q_i(n)$ as the area under the AoI curve between t_{n-1} and t_n. For example, $Q_i(2)$ is shown as the shaded area in Fig. 2.

Now, $Q_i(n) = \frac{X_i(n)(X_i(n)+1)}{2}$. The average AoI for source i can then be written as:

$$\bar{\Delta}_i = \lim_{t\to\infty} \frac{\sum_{n=1}^{n^*(t)} Q_i(n)}{\sum_{n=1}^{n^*(t)} X_i(n)} = \lim_{t\to\infty} \frac{\sum_{n=1}^{n^*(t)} Q_i(n)/n^*(t)}{\sum_{n=1}^{n^*(t)} X_i(n)/n^*(t)}$$

where $n^*(t)$ is the index of the most recent delivered packet for source i at time slot t. Therefore, we have:

$$\bar{\Delta}_i = \frac{E[Q_i]}{E[X_i]} = \frac{E[X_i^2]}{2E[X_i]} + \frac{1}{2} \tag{2}$$

B. Work-Conserving Scheduling Policies

Our focus in this paper is the analysis of four simple scheduling policies including the Whittle index-based policy in [1], [2]. The policies we analyze are all work-conserving policies in the sense that the transmitter will not stay idle if there is an update packet from at least one of the sources. This is because the AoI of any non work-conserving policy can only be worse because of the no-buffer assumption.

III. Random Scheduling Policy

We start by considering the random scheduling policy (Random), in which the transmitter selects one among the sources with an available update with equal probability. Due to the randomness of this policy, we model the interval between two consecutive delivered packets for source i, X_i, as a geometric distribution with probability p_i^*, where p_i^* is the probability that source i has an update and is scheduled for transmission in a time slot. Therefore, we get the average AoI for Random from (2) as:

$$\bar{\Delta}_i = \frac{2 - p_i^*}{2p_i^*} + \frac{1}{2} = \frac{1}{p_i^*}. \tag{3}$$

Next, we show how to derive p_i^* for source i. Since the probability of selection is based on the number of sources with an available update packet at that time slot, we have the conditional probability that source i is selected in time slot t as:

$$P[\pi(t)=i|\mathbf{a}(t)]=\frac{1}{\sum_{k=1}^{N}a_k(t)},$$

where $\mathbf{a}(t)=\{a_1(t),a_2(t),...,a_N(t)\}$ is the vector denoting the the arrival event for all the sources at time slot t. Note that $\mathbf{a}(t)\in\mathbf{A}$ where $\mathbf{A}$ is the state space for all combinations of arrival events, and the occurrence of any state in this state space is independent of all other states and of other time slots. Therefore, we can remove the time variable and rewrite the equation as:

$$P[\pi=i|\mathbf{a}]=\frac{1}{\sum_{k=1}^{N}a_k}. \tag{4}$$

Since only when there is an update packet for source i can it be selected for transmission, we define the state space $\mathbf{A}'_i=\{\mathbf{a}|a_i=1\}\subseteq\mathbf{A}$, which consists of the vectors of $\mathbf{A}$ with $a_i=1$. We can then write the stationary probability for event $\mathbf{a}$ as:

$$S(\mathbf{a})=\prod_{k=1}^{N}(a_kp_k+(1-a_k)(1-p_k)). \tag{5}$$

Therefore, p_i^* can be expressed as:

$$p_i^*=\sum_{\mathbf{A}'}P[\pi=i|\mathbf{a}]S(\mathbf{a}), \tag{6}$$

and the average AoI for RANDOM can be obtained using (3).

A simple closed-form expression can be obtained for the special case of all sources having equal update generation probability, i.e., $p_i=p\ \forall i$. In this case,

$$\begin{aligned}p_i^*&=p\sum_{m=0}^{N-1}\frac{\binom{N-1}{m}p^m(1-p)^{N-m-1}}{m+1}\\&=\sum_{m=0}^{N-1}\frac{(N-1)!}{(m+1)!(N-m-1)!}p^{m+1}(1-p)^{N-m-1}\\&=\frac{(N-1)!}{N!}\sum_{m=0}^{N-1}\binom{N}{m+1}p^{m+1}(1-p)^{N-m-1}\\&=\frac{1}{N}\left[\sum_{x=0}^{N}\binom{N}{x}p^x(1-p)^{N-x}-(1-p)^N\right]\\&=\frac{1}{N}[1-(1-p)^N],\end{aligned}$$

where m is the number of sources with an update packet except source i, and $x=m+1$.

IV. ROUND-ROBIN SCHEDULING POLICY

The next policy we analyze is the work-conserving round-robin scheduling policy (ROUNDROBIN). In ROUNDROBIN, in each time slot, the transmitter selects the next source in sequence with an update packet. If there is no update packet available in a time slot, following the idle slot, the transmitter selects a source with an available update packet randomly in the next slot. For example, if the transmitter has selected source 2 for transmission in time slot t, then in time slot $t+1$, the transmitter will check source 3 to see if there is a generated packet or not. If there is a new packet for source 3, the transmitter will transmit it to the monitor otherwise the transmitter will check source 4, and so on. If none of the sources has an update packet, the transmitter will be idle, i.e., $\pi(t+1)=0$, and in the time slot $t+2$, the transmitter will reset the round and select a source among those sources with generated update packets with equal probability.

First we obtain the conditional probability that source i is selected at time slot t when source j is selected in the previous time slot $t-1$. We have:

$$P[\pi(t)=i|\pi(t-1)=j]=\begin{cases}p_i\prod_{k=j+1}^{i-1}(1-p_k) & \text{if } i>j, j\neq 0\\ p_i\prod_{k=1}^{i-1}(1-p_k)\prod_{l=j+1}^{N}(1-p_l) & \text{if } i\leq j, j\neq 0\\ p_i^* & \text{if } j=0,\end{cases} \tag{7}$$

where p_i^* is from (6).

Let $f_{i,j}(x)$ denote the probability that it takes x time slots to select source i after source j. Clearly, $f_{i,j}(1)=P[\pi(t)=i|\pi(t-1)=j]$. $f_{i,j}(x)$ is then given by the following recurrence relation:

$$f_{i,j}(x)=\sum_{k=0,k\neq j}^{N}f_{k,j}(1)f_{i,k}(x-1). \tag{8}$$

Using the recurrence relation, we can then obtain the first two moments of X_i as:

$$E[X_i]=\sum_{x=1}^{\infty}xf_{i,i}(x),\quad E[X_i^2]=\sum_{x=1}^{\infty}x^2f_{i,i}(x).$$

As a closed-form expression does not seem possible, in order to numerically calculate the average AoI approximately, we assume that X_i is upper bounded by M, which then yields:

$$\begin{aligned}E[X_i]&=\sum_{x=1}^{M}xf_{i,i}(x)\\E[X_i^2]&=\sum_{x=1}^{M}x^2f_{i,i}(x).\end{aligned} \tag{9}$$

Finally, the approximate average AoI for ROUNDROBIN can be derived using (2) and (9). The complexity of computing the average AoI with upper bound M is $O(N^2M)$. We will investigate the effect of M on the accuracy of the results in Section VI.

V. AGE-GREEDY AND WHITTLE-INDEX SCHEDULING POLICIES

A. Age-greedy Scheduling

While RANDOM and ROUNDROBIN are simple scheduling policies that can be implemented without any knowledge about source statistics, they do not attempt to optimize the average AoI for the sources. In contrast, the AGEGREEDY scheduling policy selects the source with the highest instantaneous AoI

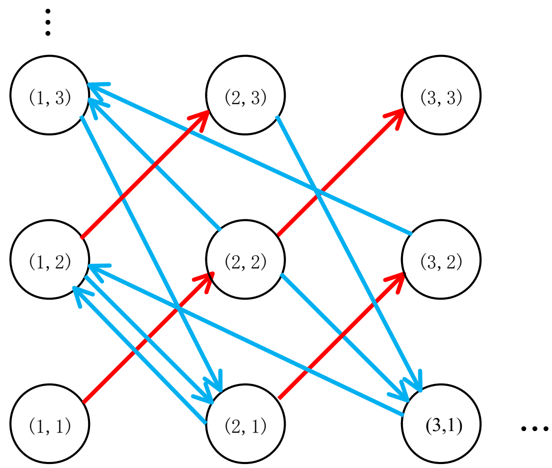

Fig. 3. A Markov chain of AoI states for a two-source system.

among the sources with an available update packet in the current time slot. If there are multiple sources with equal largest AoI, the transmitter selects one among them randomly with equal probability.

To analyze this scheduling policy, we construct an N-dimensional Markov chain which models the evolution of the joint AoI of all the N sources. We show the analysis for a two-source system in this paper, which can be extended to the N-source system in a straightforward manner. The 2-d Markov chain is presented in Fig. 3 where the state (Δ_1, Δ_2) means the age of source 1 is Δ_1 and the age of source 2 is Δ_2. Note that there are three possible transitions from state (Δ_1, Δ_2) – the next state can be $(1, \Delta_2 + 1)$, $(\Delta_1 + 1, 1)$, or $(\Delta_1 + 1, \Delta_2 + 1)$. Since the transition from state (Δ_1, Δ_2) to state $(\Delta_1 + 1, \Delta_2 + 1)$ (which is shown with red arrow in Fig. 3) only happens when both sources have no update packets, the state transition probability $P[(\Delta_1 + 1, \Delta_2 + 1), (\Delta_1, \Delta_2)] = (1 - p_1)(1 - p_2)$.

A transition from state (Δ_1, Δ_2) to state $(1, \Delta_2 + 1)$ or state $(\Delta_1 + 1, 1)$ is caused by the event that at least one of the two sources has an available update packet, and such transitions are shown with blue arrows in Fig. 3. The transition probability from state (Δ_1, Δ_2) to state $(1, \Delta_2 + 1)$ is given by:

$$P[(1, \Delta_2 + 1), (\Delta_1, \Delta_2)] = \begin{cases} p_1 & \text{if } \Delta_1 > \Delta_2 \\ p_1(1 - p_2) & \text{if } \Delta_1 < \Delta_2 \\ p_1(1 - p_2) + \frac{p_1 p_2}{2} & \text{if } \Delta_1 = \Delta_2. \end{cases} \tag{10}$$

The state transition probability from (Δ_1, Δ_2) to $(\Delta_1 + 1, 1)$ can be obtained similarly. To solve the 2-d Markov chain, we assume that the ages for both sources are upper bounded by a constant M. Note that the meaning of the upper bound here is the same as the meaning of the upper bound in the analysis of RoundRobin since both of them are assumed bounds for the instantaneous AoI in the system. Let $F(\Delta_1, \Delta_2)$ denote stationary probability for state (Δ_1, Δ_2). Then we have the average AoI for source 1 as:

$$\bar{\Delta}_1 = \sum_{\Delta_1=1}^{M} \sum_{\Delta_2=1}^{M} \Delta_1 F(\Delta_1, \Delta_2).$$

The average AoI for source 2 can be derived similarly.

B. Whittle Index-based Scheduling

In [1], [2], the authors presented a Whittle index-based scheduling policy (WhittleIndex) for optimizing the AoI in a multi-source system. Unlike the other three policies, this policy requires the transmitter to know the p_i's. As it turns out, this system's AoI can be easily obtained using the methodology used for AgeGreedy. The Whittle index for source i with age Δ_i can be calculated based on equation (8) from [2] as:

$$I_i(\Delta_i(t)) = \begin{cases} 0 & \text{if } a_i(t) = 0 \\ \Delta_i(t)^2 - \frac{\Delta_i(t)}{2} + \frac{\Delta_i(t)}{p_i} & \text{else.} \end{cases} \tag{11}$$

In WhittleIndex [2], the transmitter schedules the source with the largest instantaneous Whittle index in (11) for transmission. Now, we can write the state transition probabilities for WhittleIndex as:

$$P[(1, \Delta_2 + 1), (\Delta_1, \Delta_2)] = \begin{cases} p_1 & \text{if } I_1(\Delta_1) > I_2(\Delta_2) \\ p_1(1 - p_2) & \text{if } I_1(\Delta_2) < I_2(\Delta_2) \\ p_1(1 - p_2) + \frac{p_1 p_2}{2} & \text{if } I_1(\Delta_1) = I_2(\Delta_2). \end{cases}$$

The AoI for each source can then obtained by solving this Markov chain.

VI. Numerical Results

In this section, we present analytical results for the four scheduling policies. We performed simulations for 10^6 time slots to verify the analytical results. The average AoI over all sources calculated as $\frac{\sum_{i=1}^{N} \bar{\Delta}_i}{N}$ are shown in the figures.

We start with Fig. 4 where we compare the Random policy with the RoundRobin policy. We set the update generation probability p_i for each source to be identical and equal to 0.5. As the number of sources N increases, we can observe that the average AoI for each source increases since the recurrence time for the transmitter to re-select the source increases. We can also observe that Random is always worse than RoundRobin since RoundRobin has lower probability to serve the same source in nearby time slots. The analytical results can be seen to closely match the simulation results for Random. For RoundRobin, we can see the impact of the upper bound M in Fig. 4. When $M = 30$, the difference between the simulation and analytical result becomes noticeable as N approaches 10, whereas when $M = 50$, the analytical results match the simulation results very well. As the number of sources increases, the instantaneous AoI for a source has a higher probability to exceed the upper bound when M is small and a larger upper bound M is required to get a good approximation for analytical average AoI.

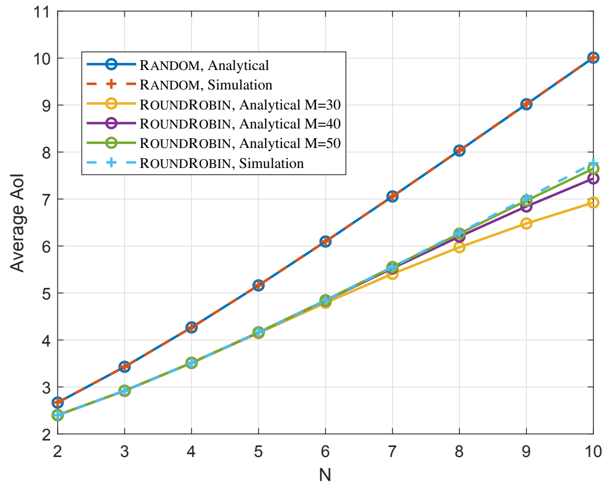

Fig. 4. Average AoI with respect to N for RANDOM and ROUNDROBIN for fixed $p_i = 0.5$ for each source and upper bound $M = 30, 40, 50$ for analytical results of ROUNDROBIN.

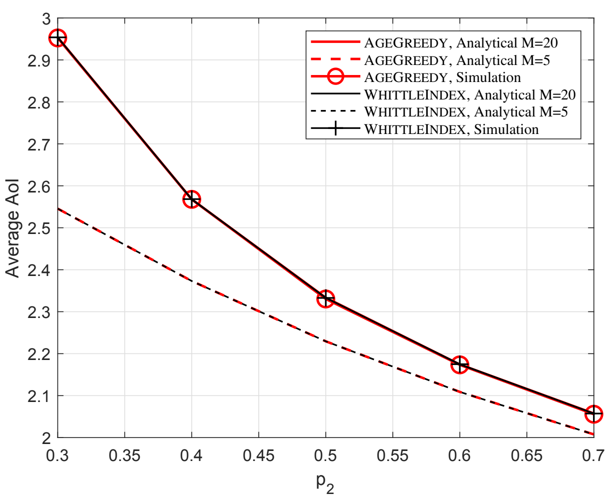

Fig. 5. Average AoI with respect to p_2 for AGEGREEDY and WHITTLEINDEX for fixed $p_1 = 0.5$ and upper bound $M = 20$ and $M = 5$.

Next, we present results for AGEGREEDY and WHITTLEINDEX policies in a two-source system in Fig. 5. We fix the update generation probability for source 1 to $p_1 = 0.5$ and vary the probability for source 2. We can observe that our analytical results match the simulation results extremely well for $M = 20$ whereas $M = 5$ significantly underestimates the average AoI. This shows that $M = 20$ is a sufficiently good upper abound, and we use this in the next figure. Another important observation here is that the performance of AGEGREEDY and WHITTLEINDEX are similar to each other for a two-source system. This is due to the following. In a two-source system, when the difference between p_1 and p_2 is small, the instantaneous AoI is the dominant variable in the Whittle index function, and therefore both WHITTLEINDEX and AGEGREEDY select the source with the larger instantaneous AoI. On the other hand if the difference between p_1 and p_2 is large, there is a high probability that only one source has an update packet in a time slot, and both WHITTLEINDEX and AGEGREEDY will select the source with the update packet.

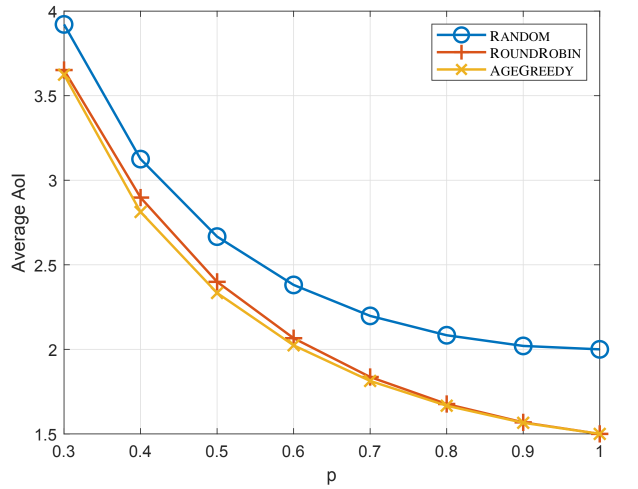

Fig. 6. Average AoI with respect to p for RANDOM, ROUNDROBIN, and AGEGREEDY for a two-source system with upper bound $M = 20$.

Finally, we compare RANDOM, ROUNDROBIN and AGEGREEDY in a two-source system in Fig. 6. (WHITTLEINDEX is not shown here because its performance is similar to AGEGREEDY for this system.) We set $M = 20$ here, which is sufficiently large to get an accurate AoI in this system from our observation in Fig. 4 and Fig. 5. The two sources have identical generation probability p. We can observe that when p is small, the differences between these three polices are small. This is because for a two-source system, there is a high probability that neither or only one source has an update. In the former case, the transmitter will be idle, and in the latter case the source with the update will be scheduled in all three schemes. As p increases, RANDOM performs noticeably worse than the other two. ROUNDROBIN and AGEGREEDY have very similar performance, with AGEGREEDY being slightly better. When $p = 1$, AGEGREEDY and ROUNDROBIN become identical as both policies alternate between the two sources.

VII. CONCLUSION

In this paper, we analyze the AoI performance in a multi-source system in which multiple sources generate status updates, only one of which can be transmitted to the monitor at a time. We compare the performance of four different scheduling policies, namely, random scheduling policy, round-robin scheduling policy, age-greedy scheduling policy, and the Whittle index-based policy proposed in [1], [2]. The analytical results were validated with extensive simulation results.

REFERENCES

[1] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh, and E. Modiano, "Scheduling policies for minimizing age of information in broadcast

wireless networks," *IEEE/ACM Transactions on Networking*, vol. 26, no. 6, pp. 2637–2650, 2018.

[2] Y.-P. Hsu, E. Modiano, and L. Duan, "Scheduling algorithms for minimizing age of information in wireless broadcast networks with random arrivals," *IEEE Transactions on Mobile Computing*, vol. 19, no. 12, pp. 2903–2915, 2020.

[3] S. Kaul, R. Yates, and M. Gruteser, "Real-time status: How often should one update?," in *2012 Proceedings IEEE INFOCOM*, pp. 2731–2735, 2012.

[4] M. Costa, M. Codreanu, and A. Ephremides, "On the age of information in status update systems with packet management," *IEEE Transactions on Information Theory*, vol. 62, no. 4, pp. 1897–1910, 2016.

[5] E. Najm and R. Nasser, "Age of information: The gamma awakening," in *2016 IEEE International Symposium on Information Theory (ISIT)*, pp. 2574–2578, 2016.

[6] Y. Sun, E. Uysal-Biyikoglu, R. Yates, C. E. Koksal, and N. B. Shroff, "Update or wait: How to keep your data fresh," in *IEEE INFOCOM 2016 - The 35th Annual IEEE International Conference on Computer Communications*, pp. 1–9, 2016.

[7] Y. Inoue, H. Masuyama, T. Takine, and T. Tanaka, "A general formula for the stationary distribution of the age of information and its application to single-server queues," *IEEE Transactions on Information Theory*, vol. 65, no. 12, pp. 8305–8324, 2019.

[8] J. P. Champati, H. Al-Zubaidy, and J. Gross, "On the distribution of aoi for the GI/GI/1/1 and GI/GI/1/2* systems: Exact expressions and bounds," in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications*, pp. 37–45, 2019.

[9] P. Zou, O. Ozel, and S. Subramaniam, "Waiting before serving: A companion to packet management in status update systems," *IEEE Transactions on Information Theory*, vol. 66, no. 6, pp. 3864–3877, 2020.

[10] C. Li, S. Li, and Y. T. Hou, "A general model for minimizing age of information at network edge," in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications*, pp. 118–126, 2019.

[11] A. Maatouk, S. Kriouile, M. Assad, and A. Ephremides, "On the optimality of the whittle's index policy for minimizing the age of information," *IEEE Transactions on Wireless Communications*, vol. 20, no. 2, pp. 1263–1277, 2021.

[12] H. Tang, J. Wang, L. Song, and J. Song, "Minimizing age of information with power constraints: Multi-user opportunistic scheduling in multi-state time-varying channels," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 5, pp. 854–868, 2020.

[13] W. Pan, Z. Deng, X. Wang, P. Zhou, and W. Wu, "Optimizing the age of information for multi-source information update in internet of things," *IEEE Transactions on Network Science and Engineering*, pp. 1–1, 2022.

[14] R. D. Yates and S. K. Kaul, "The age of information: Real-time status updating by multiple sources," *IEEE Transactions on Information Theory*, vol. 65, no. 3, pp. 1807–1827, 2019.

[15] X. Chen, C. Wu, T. Chen, H. Zhang, Z. Liu, Y. Zhang, and M. Bennis, "Age of information aware radio resource management in vehicular networks: A proactive deep reinforcement learning perspective," *IEEE Transactions on Wireless Communications*, vol. 19, no. 4, pp. 2268–2281, 2020.

[16] M. A. Abd-Elmagid, H. S. Dhillon, and N. Pappas, "A reinforcement learning framework for optimizing age of information in rf-powered communication systems," *IEEE Transactions on Communications*, vol. 68, no. 8, pp. 4747–4760, 2020.

[17] A. Maatouk, Y. Sun, A. Ephremides, and M. Assaad, "Timely updates with priorities: Lexicographic age optimality," *IEEE Transactions on Communications*, pp. 1–1, 2022.

[18] S. Feng and J. Yang, "Precoding and scheduling for AoI minimization in MIMO broadcast channels," *IEEE Transactions on Information Theory*, pp. 1–1, 2022.

[19] M. Li, C. Chen, H. Wu, X. Guan, and X. Shen, "Edge-assisted spectrum sharing for freshness-aware industrial wireless networks: A learning-based approach," *IEEE Transactions on Wireless Communications*, pp. 1–1, 2022.

[20] Y. Qiu, S. Wu, Y. Wang, J. Jiao, N. Zhang, and Q. Zhang, "On scheduling policy for multi-process cyber-physical system with edge computing," *IEEE Internet of Things Journal*, pp. 1–1, 2022.

[21] C. Li, Q. Liu, S. Li, Y. Chen, Y. T. Hou, W. Lou, and S. Kompella, "Scheduling with age of information guarantee," *IEEE/ACM Transactions on Networking*, pp. 1–14, 2022.

[22] T. He, K.-W. Chin, Z. Zhang, T. Liu, and J. Wen, "Optimizing information freshness in RF-powered multi-hop wireless networks," *IEEE Transactions on Wireless Communications*, pp. 1–1, 2022.

[23] N. Modina, R. El Azouzi, F. De Pellegrini, D. S. Menasche, and R. Figueiredo, "Joint traffic offloading and aging control in 5G IoT networks," *IEEE Transactions on Mobile Computing*, pp. 1–1, 2022.