Age of Information in Multiple Sensing of a Single Source

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Abstract—Having timely and fresh knowledge about the current state of information sources is critical in a variety of applications. In particular, a status update may arrive at its destination much later than its generation time due to processing and communication delays. The freshness of the status update at the destination is captured by the notion of age of information. In this study, we consider a network with a single source, a single monitor (destination), and \( n \) sensors. In this setting, a single source of information is being sensed independently by different sensors and the data is sent to the monitor. We assume that updates about the source of information arrive at the sensors according to a Poisson random process. Each sensor sends its update to the monitor through a direct link, which is modeled as a queue. The service time to transmit an update is considered to be an exponential random variable. We derive a closed-form expression for the average age of information in our model under a last-come-first-serve (LCFS) queue. Then, we compare different queue setups of first-come-first-serve (FCFS), LCFS, and LCFS with preemption in waiting in terms of the average age of information. It is observed that LCFS is the best queue among the service disciplines.

Index Terms—Age of information, wireless sensor network, status update, queuing analyses, monitoring network.

I. INTRODUCTION

Widespread sensor network applications such as health monitoring using wireless sensors [1] and the Internet of things (IoT) [2], as well as applications like stock market trading and vehicular networks [3], require sending several status updates to their designated recipients (called monitors). Outdated information in the monitoring facility may lead to hazardous situations if decision making is involved. As a result, having the data at the monitor as fresh as possible is crucial.

In order to have a sense of the freshness of the received status update, the age of information (AoI) metric was introduced in [4]. For an update received by the monitor, AoI is defined as the time elapsed since the generation of the update. AoI captures the timeliness of status updates, which is different from other standard communication metrics like delay and throughput. It is affected by the inter-arrival time of updates and the delay that is caused by queuing during update processing and transmission.

In this paper, we consider AoI in a single-source multiple-server network. We assume that a shared source is sensed and then the data is transmitted to the monitor by \( n \) independent servers. For example, the source of information can be some shared environmental parameter, and any sensor in the surrounding area may obtain such information. For another example, the source of information can be the stock market status which is transmitted to the user by multiple service providers. Throughout this paper, a sensor or a service provider is called a server, since it is responsible to serve this update to the monitor. We assume that status updates arrive at the server according to a Poisson random process, and the server is modeled as a queue whose service time for an update is exponentially distributed.

In [4], authors considered the single-source single-server and first-come-first-serve (FCFS) queue model and determined the arrival rate that minimizes AoI. Different cases of multiple-source single-server under FCFS and last-come-first-serve (LCFS) were considered in [5] and the region of feasible age was derived. In [6], [7], the system is modeled as a source that submits status updates to a network of parallel and serial servers, respectively, for delivery to a monitor and AoI is evaluated. The parallel-server network is also studied in [8] when the number of servers is 2 or infinite, and the average AoI for FCFS queue model was derived.

Minimizing AoI in a wireless camera network with correlated updates from the information source was considered in [9]. Authors in [10] formulated a discrete-time decision problem in order to find a scheduling policy for minimizing the expected weighted sum of AoI. A multiple-source multi-hop setting in broadcast wireless networks was investigated in [11] and a fundamental lower bound on the average AoI was derived. Different scheduling policies with throughput constraints were considered in [12] to minimize AoI. Another age-related metric of peak AoI was introduced in [13], which corresponds to the age of information at the monitor right before the receipt of the next update. The average peak AoI minimization in IoT networks and wireless systems then was considered in [14], [15]. The problem of minimizing the average age in energy harvesting sources by manipulating the update generation process was studied in [16], [17]. Maximizing energy efficiency of wireless sensor networks that include constraints on AoI is investigated in [18].

In this paper, we study the age of information following the definition of [4]. We first consider LCFS with preemption...
in service queue model, namely, upon the arrival of a new update, the server immediately starts to serve it and drops any old update being served. We derive a closed-form formula of the average AoI for LCFS with preemption in service. To obtain such a result, we use the stochastic hybrid system (SHS) analysis similar to [5], [6]. Moreover, LCFS with preemption in service, LCFS with preemption in waiting and FCFS queue models are compared in terms of the average AoI through simulation. We also provide optimal arrival rate for a given service rate in the FCFS case numerically.

This paper is organized as follows. In Section II, we formally introduce the system model of interest, and provide preliminaries on SHS. In Section III, we apply SHS method to our model and derive the average age of information formula. In Section IV, simulation results are provided and the conclusion follows in section V.

II. SYSTEM MODEL AND PRELIMINARIES

Notation: in this paper, we use boldface for vectors, and normal font with a subscript for its elements. For example, for a vector \( \mathbf{x} \), the \( j \)-th element is denoted by \( x_j \).

In this section, we first present our network model, and then briefly review the stochastic hybrid system analysis from [5].

A source of information is being sensed by \( n \) independent servers as illustrated in Figure 1. Updates after going through separate links are aggregated at the monitor side. The interest of this paper is the average AoI at the monitor. Server \( i \) collects updates following a Poisson random process with rate \( \lambda_i \) and service time of updates is an exponential random variable with average \( \frac{1}{\mu_i} \), independent of all other servers, \( 1 \leq i \leq n \). In this paper, we assume that the servers are homogeneous, and \( \lambda_i = \lambda, \mu_i = \mu, \) for all \( 1 \leq i \leq n \).

Suppose the freshest update at the monitor at time \( t \) is generated at time \( u(t) \), the age of information at the monitor (in short, AoI) is defined as \( \Delta(t) = t - u(t) \), which is the time elapsed since the generation of the last received update.

From the definition, it is clear that AoI linearly increases at a unit rate with respect to \( t \), except some reset jumps to a lower value at points when the monitor receives a fresher update from the source. The age of information of our network is shown in Figure 2. Let \( t_1, t_2, \ldots, t_N \) be the generation time of all updates at all servers in increasing order. The black dashed lines show the age of every update. Let \( T_1, T_2, \ldots, T_N \) be the receipt time of all updates. The red solid lines show AoI.

We note a key difference between the model in this work and most previous models. Updates come from different servers, therefore they might be out of order at the monitor and thus a new arrived update might not have any effect on AoI because a fresher update is already delivered. As an example, from the 6 updates shown in Figure 2 useful updates that change AoI are updates 1, 3, 4 and 6, while the rest are disregarded as their information when arrived at the monitor is obsolete. Thus among all the received updates for AoI analyses, we only need to consider the useful ones that lead to a change in AoI.

The average AoI is the limit of the average age over time \( \Delta \triangleq \lim_{T \to \infty} \frac{1}{T} \int_0^T \Delta(t) \, dt \), and for a stationary ergodic system, it is also the limit of the average age over the ensemble \( \Delta = \lim_{T \to \infty} \mathbb{E}[\Delta(t)] \).

In the paper, we view our system as a stochastic hybrid system (SHS) and apply a method first introduced in [5] in order to calculate AoI. We can thus obtain the average AoI under LCFS with preemption in service, or in short, LCFS.

In SHS, the state is composed of a discrete state and a continuous state. The discrete state \( q(t) \in Q \), for a discrete set \( Q \), is a discrete Markov chain (e.g., to represent the number of idle servers in the network), and the continuous state \( x(t) = [x_0(t), x_1(t), \ldots, x_n(t)] \in \mathbb{R}^{n+1} \) is the stochastic process for AoI. We use \( x_0(t) \) to represent the age at the monitor, and \( x_j(t) \) for the age at the \( j \)-th server, \( j = 1, 2, \ldots, n \). Graphically, we represent each state \( q \in Q \) by a node. For the discrete Markov chain \( q(t) \), transitions happen from one state to another through directed transition edge \( l \) with the rate \( \lambda(l) \). Note that it is possible to transit from the same state to itself. The transition occurs when an update arrives at a server, or an update is received at the monitor. The transition rate is the update arrival rate or the service rate. Denoted by
For our purpose, we consider the discrete state probability
\[
\pi_\delta(t) \triangleq \mathbb{E} \left[ \delta_{\tilde{q}, q}(t) \right] = P[q(t) = \tilde{q}],
\]
and the correlation between the continuous state \(x(t)\) and the discrete state \(q(t)\):
\[
\mathbb{V}_q = \begin{bmatrix} v_{q0}(t), \ldots, v_{qn}(t) \end{bmatrix} \triangleq \mathbb{E} \left[ x(t) \delta_{\tilde{q}, q}(t) \right].
\]
Here \(\delta_{\cdot, q}\) denotes the Kronecker delta function. When the discrete state \(q(t)\) is ergodic, \(\pi_\delta(t)\) converges uniquely to the stationary probability \(\pi_q\), for all \(q \in Q\).

A key result we use to develop AoI for our LCFS queue model is the following lemma of [5], which was derived from the general SHS results in [19].

**Lemma 1.** [5] If the discrete-state Markov chain \(q(t)\) is ergodic with stationary distribution \(\pi\) and we can find a non-negative solution of \(\{v_q, q \in Q\}\) such that
\[
\mathbb{V}_q \sum_{l \in L_q} \lambda^{(l)} = \mathbb{B}_q \pi_q + \sum_{l \in L_q} \lambda^{(l)} \mathbb{V}_l \mathbb{A}_l, \quad q \in Q,
\]
then the average age of information is given by
\[
\Delta = \sum_{q \in Q} v_{q0}.
\]

### III. AoI in the LCFS Queue Model

In this section, we present AoI calculation with the LCFS queue for the single-source \(n\)-server homogeneous network. In this network, upon arrival of a new update, each server immediately drops any previous update in service and starts to serve the new update. Note that to compute the average AoI, Lemma 1 requires solving \(|Q| (n+1)\) linear equations of \(\{v_q, q \in Q\}\). To obtain explicit solutions for these equations, the complexity grows with the number of discrete states. Since the discrete state typically represents the number of idle servers in the system for homogeneous servers, \(|Q|\) should be \(n+1\). In the following, we introduce a method inspired by [6] to reduce the number of discrete states and efficiently describe the transitions.

We define our continuous state \(x\) at a time as follows: the first element of \(x\) is AoI at the monitor \((x_0)\), the second is always the freshest update among all updates in the servers, the third is always the second freshest update in the servers, etc. With this definition we always have \(x_1 \leq x_2 \leq \ldots \leq x_n\), for any time. Note that the index \(i\) of \(x_i\) does not represent a physical server index, but the \(i\)-th smallest age of information among the \(n\) servers. The physical server index for \(x_i\) changes with each transition. We say that the server corresponding to \(x_1\) is the \(i\)-th virtual server.

A transition \(l\) is triggered by (i) the arrival of an update at a server, or (ii) the delivery of an update to the monitor. Recall that we use \(x\) and \(x'\) to denote AoI continuous state vector right before and after the transition \(l\).

When one update arrives at the monitor and the server for that update becomes idle, we put a *fake update* to the server using the method introduced in [6]. Thus we can reduce the calculation complexities and only have one discrete state indicating that all servers are virtually busy. We denote this state by \(q = 0\). In particular, we put the current update that is in the monitor to an idle server until the next update reaches this server. This assumption does not affect the final calculation for AoI, because even if the fake update is delivered to the monitor, AoI at the monitor does not change.

When an update is delivered to the monitor from the \(k\)-th virtual server, the server becomes idle and as previously stated, receives the fake update. The age at the monitor becomes \(x'_0 = x_k\), and the age at the \(k\)-th server becomes \(x'_k = x'_0 = x_k\). In this scenario, consider the update at the \(j\)-th virtual server, for \(j > k\). Its delivery to the monitor does not affect AoI since it is older than the current update of the monitor, i.e., \(x_j \geq x_k = x'_0\). Hence, we can adopt a *fake preemption* where the update for the \(j\)-th virtual server, for all \(k \leq j \leq n\), is preempted and replaced with the fake current update at the monitor. Physically, these updates are not preempted and as a benefit, the servers do not need to cooperate and can work in a distributed manner.

By utilizing virtual servers, fake update, and fake preemp-
tion, we reduce SHS to a single discrete state with linear transition \( A_1 \). We illustrate our SHS with discrete state space of \( Q = \{0\} \) in Figure 3. The stationary distribution \( \pi_0 \) is trivial and \( \pi_0 = 1 \). We set \( b_q = [1,...,1] \) which indicates that the age at the monitor and the age of each update in the system grows at a unit rate. The transitions are labeled \( l \in \{0,1,...,2n-1\} \) and for each transition \( l \) we list the transition rate and the transition mapping in Table II. For simplicity, we drop the index \( q = 0 \) in the vector \( v_0 \), and write it as \( v = [v_0,v_1,...,v_n] \). Because we have one state, \( xA_1 \) and \( vA_1 \) are in correspondence. Next, we describe the transitions in Table II.

**Case I.** \( l = 0,1,...,n-1 \): When a fresh update arrives at virtual server \( l + 1 \), the age at the monitor remains the same and \( x_{l+1} \) becomes zero. This server has the smallest age, so we take this zero and reassign it to the first virtual server, namely, \( x'_1 = 0 \). In fact virtual servers 1,2,...,\( l + 1 \) all get reassigned virtual server numbers. Specifically, after transition \( l \), virtual server \( l + 1 \) becomes virtual server 1, and virtual server 1 becomes virtual server 2,..., virtual server \( l \) becomes virtual server \( l + 1 \). The transition rate is the arrival rate of the update, \( \lambda \). The matrix \( A_1 \) is

\[
0 \quad 1 \quad 2 \quad \ldots \quad l + 1 \quad l + 2 \quad \ldots \quad n \\
0 \\
1 \\
: \\
l + 1 \\
l + 2 \\
: \\
n
\begin{pmatrix}
1 \\
0 \\
. \\
1 \\
0 \\
. \\
1
\end{pmatrix}
\]

**Case II.** \( l = n,n+1,...,2n-1 \): When an update is received at the monitor from virtual server \( l + 1 - n \), the age at the monitor changes to \( x_{l+1-n} \) and this server becomes idle. Using fake updates and fake preemption we assign \( x'_j = x_{l+1-n} \), for all \( l \leq j \leq n \). The transition rate is the service rate of a server, \( \mu \). The matrix \( A_1 \) is

\[
0 \quad 1 \quad \ldots \quad l-n \quad l+1-n \quad \ldots \quad n \\
0 \\
1 \\
: \\
l-n \\
l+1-n \\
l+2-n \\
: \\
n
\begin{pmatrix}
0 \\
1 \\
. \\
1 \\
0 \\
. \\
0
\end{pmatrix}
\]

Below we state our main theorem on the average AoI for the single-source \( n \)-server network.

**Theorem 1.** The age of information at the monitor for homogeneous single-source \( n \)-server network where each server has a LCFS queue is:

\[
\text{AoI} = \sum_{j=2}^{n} w_j + \frac{1}{n\lambda} + \frac{\lambda}{n\mu} w_n,
\]

where

\[
w_2 = \frac{1}{(n-1)\lambda + \mu},
\]

\[
w_j = \frac{1}{(n-1)\lambda + \mu} \prod_{i=2}^{j-1} \left( \frac{\lambda(n-i+1)}{\mu + (n-i)\lambda} \right), 3 \leq j \leq n.
\]

**Proof.** Recall that \( v \) denotes the vector \( v_0 \) for the single state \( q = 0 \). By Lemma 1 and the fact that there is only one state, we need to calculate the vector \( v \) as a solution to (5), and the 0-th coordinate \( v_0 \) is AoI at the monitor. As mentioned \( vA_1 \) is in correspondence with \( xA_1 \), so we have:

\[
(n\lambda + n\mu)v = \begin{bmatrix} 1,1,1,1,1,1,1,\ldots,1 \end{bmatrix}
\]

\[
+ \lambda[v_0,v_0,v_0,v_1,v_0,v_1,v_3,v_4,...,v_n]
\]

\[
+ \lambda[v_0,v_1,v_1,v_1,v_3,v_4,...,v_n]
\]

\[
+ \lambda[v_0,v_0,v_1,v_2,v_4,...,v_n]
\]

\[
\vdots
\]

\[
+ \lambda[v_0,v_0,v_1,v_2,v_3,...,v_{n-1}]
\]

\[
+ \mu[v_1,v_1,v_1,v_1,v_1,v_1,...,v_1]
\]

\[
+ \mu[v_1,v_2,v_2,v_2,v_2,...,v_2]
\]

\[
+ \mu[v_3,v_3,v_3,v_3,...,v_3]
\]

\[
\vdots
\]

\[
+ \mu[v_n,v_1,v_2,\ldots,v_{n-1},v_n].
\]

From the 0-th coordinate of (10),

\[
(n\lambda + n\mu)v_0 = 1 + n\lambda v_0 + \mu \sum_{j=1}^{n} v_j,
\]

\[
\implies v_0 = \frac{1}{n\lambda} + \frac{\sum_{j=1}^{n} v_j}{n}.
\]

From the 1st coordinate of (10), we can easily see that

\[
v_1 = \frac{1}{n\lambda}.
\]

Then, for calculating \( v_0 \) we have to calculate \( v_i \) for \( i \in \{2,...,n\} \). From the \( i \)-th coordinate of (10),

\[
((n-i+1)\lambda + (i-1)\mu)v_i = 1 + \mu \sum_{j=1}^{i-1} v_j + \lambda(n-i+1)v_{i-1}.
\]

For \( i \in \{2,3,\ldots,n-1\} \) we write

\[
(i\mu + (n-i)\lambda)(v_{i+1} - v_i) = \lambda(n-i+1)(v_i - v_{i-1}).
\]
Besides, by putting $i=2$ in equation (14) we have

$$(n-1)\lambda + \mu)v_2 = 1 + \mu v_1 + \lambda(n-1)v_1.$$  

(17)

As a result by replacing $v_1$ with $\frac{1}{n\lambda}$, we get $v_2 = \frac{2-1/n+\mu}{\mu+(n-1)\lambda}$. Therefore $w_2 = v_2 - v_1 = \frac{2-1/n+\mu}{\mu+(n-1)\lambda} - \frac{1}{n\lambda} = \frac{1}{(n-1)\lambda+\mu}$. Finally, setting $i=n$ in (14),

$$(\lambda + (n-1)\mu)v_n = 1 + \mu \sum_{j=1}^{n-1} v_j + \lambda v_{n-1},$$

implying $\mu \sum_{j=1}^{n} v_j = \mu \sum_{j=1}^{n-1} v_j + \mu v_n = (\lambda + (n-1)\mu)v_n + \mu v_n - 1 - \lambda v_{n-1}$. Hence,

$$\frac{1}{n} \sum_{i=1}^{n} v_i = \frac{\lambda}{n\mu} w_n + v_n - \frac{1}{n\mu}.$$  

(19)

Combining (11) and (19), we obtain the average AoI at the monitor as

$$\text{AoI} = v_0 = v_n + \frac{\lambda}{n\mu} w_n = \sum_{j=2}^{n} w_j + \frac{1}{n\lambda} + \frac{\lambda}{n\mu} w_n.$$  

(20)

Thus the proof is completed.

IV. NUMERICAL RESULTS

In this section, we show simulation results and study AoI for varying number of servers, different queue models, and different service task assignment schemes.

A. Comparing different number of servers in LCFS

When the arrival rate $\lambda$ for each server is fixed, Figure 4 shows that the average AoI is reduced between 35% to 45% for the range of $\lambda$ between 0.1 to 2 when the number of servers changes from 2 to 4. Figure 4 shows AoI when the total arrival rate $n\lambda$ is fixed. We observe that for up to 4 servers, a significant decrease in AoI occurs with the increase of $n$. However, increasing the number of servers beyond 4 provides only a negligible decrease in AoI.

B. Comparing 3 different queue models

In Figure 5, LCFS, FCFS with preemption in waiting, and FCFS queue models are compared. As can be seen from the figure, LCFS outperforms the other two queue models. In fact, when the update arrival rate of each server $\lambda$ increases above a certain point, the performance of FCFS degrades because updates wait in the queues for too long. The optimal arrival rate for FCFS queue is computed through a simulation and listed in Table II. We observe that the optimal arrival rate for FCFS queue is around 0.5 for all the number of servers.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
$n$ & 1 & 2 & 3 & 4 & 10 & 50 \\
\hline
$\lambda^*$ & 0.53 & 0.52 & 0.51 & 0.51 & 0.52 & 0.5 \\
\hline
\end{tabular}
\caption{Optimal arrival rate for FCFS queue, $\mu = 1$.}
\end{table}

C. Comparing Theorem 2 With \cite{6}

Next, we compare the network model with that in \cite{6}, as they both have $n$ transmission links in parallel. In \cite{6} a single source is sensed by a single sensor at the rate $\lambda'$, and then the update is assigned to one of the $n$ parallel servers, each directly connected to the monitor. The figure of merit is the average AoI at the monitor. The assignment strategy is as follows. New update arrivals are assigned to an idle server, and if all the servers are busy, the new update is assigned to the server with the oldest update. When an update is delivered to the monitor, any older update at the servers are physically preempted. In this strategy, servers need to cooperate. The servers and the sensor need to keep track of log information including the age at all servers and the packet delivery status of all servers.

The model in our work can be viewed as a different assignment strategy for the problem in \cite{6}. In particular, an equivalent view of our model can be that the single source...
is sensed by one sensor at the rate \( n \lambda \), which then assigns the update randomly to one of the \( n \) parallel servers. Note that even though in our SHS analysis fake preemption is used, physically no preemption occurs unless a server receives an update. Unlike \[6\], the delivery of an update from a server does not affect other servers. As a result, the servers do not need to cooperate or share any log information, thus enabling a simple distributed sensing network. Next, we compare strategies in \[6\] and in our model. In order to have a fair comparison, we set \( \lambda' = n \lambda \). As we can see from Figure 7, assigning the new arriving update to the server containing the oldest update results in having less AoI compared to assigning them randomly to each server, which is as expected.

V. Conclusion

In this paper, we studied the age of information in the presence of multiple independent sensors monitoring a single source. We derived AoI for the LCFS queue model using SHS analysis. From the simulation, it is observed that LCFS outperforms LCFS with preemption in waiting and FCFS. Future directions include heterogeneous sensing networks, where the update arrival rate and/or the service rate are different among the sensors.

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