Impact of Channel Memory on the Data Freshness

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Abstract—In this letter, we investigate the impact of channel memory on the average age of information (AoI) for networks with various packet arrival models under the first-come-first-served (FCFS) and the preemptive last-generated-first-served (pLGFS) policies over the Gilbert-Elliott (GE) erasure channel. For networks with Bernoulli and generate-at-will arrival models, the AoI performances under the FCFS and pLGFS policies are derived explicitly as functions of the channel state transition probabilities. In practice, the channel memory, with the additional term related to the packet arrival rate.

Index Terms—AoI, channel memory, GE channel.

I. INTRODUCTION

WITH the emerging of the time sensitive applications, such as remote surgery and automatic driving, data freshness in communication systems has attracted a lot of research interest. Age of information (AoI) is one of the key metrics that describe the freshness attribution at the destination. The performances of the classical scheduling policies with the memoryless service time distribution have been investigated in [1], [2], [3], [4], and [5]. In [1], the authors analyzed the average AoI of M/M/1, M/D/1 and D/M/1 queue models under the first-come-first-served (FCFS) discipline in the continuous system. The peak AoI for finite and infinite server queueing models under the preemptive last-generated-first-served (pLGFS) policy was considered in [2]. The pLGFS policy was proved to be age-optimal with exponentially distributed service time in [3]. Reference [4] and [5] derived general formulas for the stationary distribution of the AoI under various queueing policies in the continuous and discrete system, respectively.

The work [1], [2], [3], [4], [5] mentioned above mainly focus on the channel which is time invariant, e.g., the erasure events in each slot are modeled by independent and identically distributed (i.i.d.) binary random variables. In practice, the communication channel usually has memory, or equivalently time correlation, for consecutive packet transmissions. Gilbert-Elliott (GE) channel is a popular model adopted for channel with memory [6]. Reference [7] derived the expression of the average AoI for the FCFS scheduling policy with Poisson arrival over GE channel in the continuous-time system assuming the packet buffer size being zero or infinite. In [8], the authors considered the GE channel with periodic packet arrival in the discrete system. With long term memory constrained, a threshold structure policy was proposed to minimize the average AoI. The impact of channel memory on the end-to-end (E2E) latency of the communication network with GE channel has been investigated in [9]. However, it is well known that optimizing the latency is fundamentally different from optimizing the AoI [1], since the former focuses on the in-order delivery of all the packets, while the later emphasizes more on the update of the latest information.

To the best of our knowledge, the impact of channel memory under the classical packet arrival models and scheduling policies has not been explicitly derived or systematically studied. This letter aims to investigate the impact of channel memory on the data freshness by deriving the average AoI achieved under various packet arrival models and queuing policies. Specifically, we derive the closed-form expressions for the average AoI for both Bernoulli arrival and generate-at-will models. The novel analysis approach by revealing the AoI gap between the pLGFS and FCFS policies can be generalized to other network models when the analysis for one of the queuing policies is much more challenging than the other. For networks with periodic arrival model, we derive the average AoI explicitly under the pLGFS policy and propose an efficient numerical method for calculating the average AoI for the continuous-time system by assuming the packet buffer size being zero or infinite. The performance of the classical packet arrival models and scheduling policies has not been explicitly derived or systematically studied. This letter aims to investigate the impact of channel memory on the data freshness by deriving the average AoI achieved under various packet arrival models and queuing policies. Specifically, we derive the closed-form expressions for the average AoI for both Bernoulli arrival and generate-at-will models. The novel analysis approach by revealing the AoI gap between the pLGFS and FCFS policies can be generalized to other network models when the analysis for one of the queuing policies is much more challenging than the other. For networks with periodic arrival model, we derive the average AoI explicitly under the pLGFS policy and propose an efficient numerical method for calculating the average AoI for the FCFS policy. The analytical results reveal that the average AoI achieved by pLGFS under the symmetric GE channel is larger than that in the memoryless channel with a constant gap \( \frac{1}{\eta} \) for the Bernoulli, periodic arrival and generate-at-will models, where \( \eta \in [0, 1) \) is the memory of the GE channel. The gap vanishes when the channel memory \( \eta \) approaches 0. For FCFS policy, the average AoI increases even faster with the channel memory, with the additional term related with the packet arrival rate.

II. SYSTEM MODEL

We consider a slotted communication system where packets are generated at the beginning of each time slot. If it is transmitted immediately and not erased by the channel, it will be received at the end of the same slot. We consider the following packet arrival models:

- **Bernoulli arrival**, where a new packet arrives at the transmitter with probability \( \lambda \) at each time slot.
- **Periodic arrival**, where a new packet arrives every \( K \) time slots, i.e., at the \( (iK + 1) \)th slot, where \( i = 0, 1, 2, \ldots \)
- **Generate-at-will**, where the transmitter can generate a packet whenever it wants [10].

AoI is a metric reflecting the freshness of the information at the receiver, which is defined as the time interval between the current time slot and the generation slot of the latest received packet arrival model.
packet. We assume that the generation time slot is equivalent to the arrival slot and the AoI is measured at the beginning of each time slot. Let $t_i$ denote the generation instant of the latest received packet at the receiver by the beginning of the time slot $t$. Then, the AoI of this time slot, denoted by $\Delta_t$, is given by $\Delta_t = t - t_i$ according to the definition [1].

AoI performance is closely related to the transmission policy. In this letter, two classical policies are considered:

- **pLGFS policy**, which is considered in a single packet queue. The latest arrival will be transmitted repeatedly until it is preempted by the next arrival or delivered to the receiver successfully.

- **FCFS policy**, which is considered with infinite buffer space at the transmitter. The packets are served according to their generation slots, which means that a packet can be transmitted only when all the previous packets have been successfully delivered.

To investigate the impact of channel memory on AoI, we consider the GE channel model, which is described by a two-state Markov chain. The Markov chain has a “good” state and a “bad” state, which is denoted as state $G$ and state $B$, with packet erasure probabilities $p_e^G$ and $p_e^B$, respectively. The GE channel transits from state $G$ to $B$ with probability $p$ and transits from state $B$ to $G$ with probability $r$, with memory $\eta = 1 - p - r$. (1)

The GE channel has a persistent memory for $0 < \eta < 1$, and the average packet erasure probability is

$$p_e = \frac{r}{p + r}p_e^G + \frac{p}{p + r}p_e^B. \quad (2)$$

In this letter, we assume $p_e^G = 0$, $p_e^B = 1$ to simplify the analysis and get the insights on the impact of channel memory, which is only related with the state transition probabilities of the GE model.

III. THE AOI WITH BERNOULLI ARRIVAL MODEL

A. Average AoI Under the pLGFS Policy

For the pLGFS policy, the AoI at the receiver is set to the age of the latest generated packet each time the channel is in good state. Hence, the average AoI can be derived by analyzing the number of time slots between two good states and the age of the latest information at each good state. The result is summarized in Lemma 1.

**Lemma 1:** For a network with Bernoulli arrival packets at rate $\lambda$ over GE erasure channel $GE(p, r)$, the average AoI under the pLGFS policy is given by

$$\overline{\Delta}_{BL} = \frac{1}{\lambda} + \frac{p}{r(p + r)} \quad (3)$$

**Proof:** Denote by random variable $N$ the AoI of a packet at the moment when it is successfully delivered. Under the pLGFS queuing policy, this packet must be the latest one in the system. Furthermore, the packet has age $n$ if it is generated $n$ time slots before and not preempted by other packets during the subsequent $(n - 1)$ time slots. Hence, the PMF of the AoI at the receiver when a packet is received is given by

$$P_N(n) = (1 - \lambda)^{n-1} \lambda^n, n = 1, 2, \ldots \quad (4)$$

Denote by $M$ the number of time slots between two consecutive good channel states, i.e., the number of time slots transiting from one good state (inclusive) to the next good state (exclusive). Hence, if the channel stays in good state with probability $(1 - p)$, we have $M = 1$. If $M \geq 2$, it implies that the channel state transits to bad first and then to good again. Mathematically, we have

$$P_M(m) = \begin{cases} 1 - p, & m = 1 \\ p(1 - p)^{m-2}, & m = 2, 3, \ldots \end{cases} \quad (5)$$

Consider the average AoI within the time slots between two consecutive packet deliveries. At the moment when a packet arrives, the AoI is equal to $n$ with probability $P_N(n)$. For the subsequent time slots, the receiver AoI increases by 1 at each time slot, until the next packet arrives. By averaging over the segment length $M$, the expected sum AoI between two successive packet deliveries is

$$\Delta_{BL-M} = \sum_{m=1}^{\infty} P_M(m) \sum_{n=1}^{\infty} P_N(n) \frac{m(2n + m - 1)}{2} = \frac{1}{\lambda} \left(1 + \frac{p}{r}\right) + \frac{p}{r^2}. \quad (6)$$

The expected number of time slots within the segment is:

$$\mu_M = \sum_{m=1}^{\infty} mP_M(m) = 1 + \frac{p}{r}, \quad (7)$$

and the average AoI can be derived as:

$$\overline{\Delta}_{BL} = \frac{\Delta_{BL-M}}{\mu_M} = \frac{1}{\lambda} + \frac{p}{r(p + r)}. \quad (8)$$

To find the impact of channel memory, we consider the symmetric GE channel, i.e., $p = r = \frac{1}{\eta + 1}$, where $\eta$ is the channel memory defined in (1). The average AoI in (3) reduces to a function of $\lambda$ and $\eta$ as

$$\overline{\Delta}_{BL-s} = \frac{1}{\lambda} + 1 + \frac{\eta}{1 - \eta}. \quad (9)$$

B. Average AoI Under FCFS Policy

Directly analyzing the AoI for FCFS policy under GE channel is rather challenging due to the coupling of the packet waiting time, service time with the queue status at the transmitter. To this end, we propose a novel analysis approach by deriving the gap between the AoI curves for the pLGFS and FCFS policies. An illustration diagram for the AoI evolution under the pLGFS and FCFS policies is presented in Fig. 1.

Assuming that the original transmission policy is FCFS, which is depicted in black solid line in Fig. 1. Denote by $T_i = t_i^d - t_i$ the system time of the $i$th packet, where $t_i^d$ is the receiving time slot of the $i$th packet. Define *inter-delivery time* $D_i = t_{i+1}^d - t_i^d, i \geq 1$ as the time interval between two successive deliveries at the receiver, during which the AoI under FCFS is valued as the elapsed time from $t_i^d$.

If the original policy is replaced by the pLGFS one in blue dashed line and a new packet arrives during the system time of the $i$th packet, i.e., from $t_i$ to $t_i^d$, the old packet will be preempted in this case. Moreover, if the preemptive behavior occurs repeatedly before $t_i^d$ (exclusive), the effective packet that contributes to the AoI curve is the last packet only, which is generated at $t_w = \max \{t | t \in [t_i, t_i^d) \wedge t_j \neq 0 \}, j \geq i$. The AoI curve under the pLGFS policy is valued as the elapsed time from $t_w$ accordingly.

Define *preemption time* $Y_i = t_w - t_i^d, i \geq 1$ the time difference between the generation time slot of the preempted packet and that of the effective preempting packet. It is observed that the pLGFS policy introduces a constant AoI drop at value $Y_i \geq 1$, which lasts $D_i$ time slots. On the other hand, if no
packet arrives during the system time, the preemptive event will not occur. The AoI curve under pLGFS still plots the time interval from $t_i$, which is identical with the FCFS case. The corresponding preemption time is $Y_i = 0$ and there exists no queuing delay.

The accumulated AoI gap of the $i$th inter-delivery is $\delta_i = D_i Y_i$, whose expectation could be derived by averaging the geometric parts between the two curves over time. There is no preemption before the first delivery $t_1$ or after the last one $t_{N(\tau)+1}$, the average AoI gap could be expressed as

$$\bar{\Delta}_g = \lim_{\tau \to \infty} \frac{1}{\tau} \sum_{i=1}^{N(\tau)} \delta_i = \lambda \mathbb{E}[DY], \quad (10)$$

where $N(\tau)$ denotes the number of deliveries by time $\tau$. Hence, the average AoI under FCFS could be written as

$$\bar{\Delta}_F = \bar{\Delta}_L + \bar{\Delta}_g = \bar{\Delta}_L + \lambda \mathbb{E}[DY], \quad (11)$$

We then focus on the preemption time $Y$ and inter-delivery time $D$ in (11). For $Y_i \geq 1$, the packet being served under FCFS will be preempted under pLGFS. In this case, the random variable $D$ only depends on the channel parameter, which is equal to the time it takes to transit from one good state to the next good state for the first time. It means that $D$ is independent on $Y$ when $Y_i \geq 1$. With (5) and (7), we have

$$\mathbb{E}[D|Y \geq 1] = 1 + \frac{\lambda}{\eta} \mathbb{E}[DY], \quad (12)$$

Since $Y_i = 0$ does not contribute to the expectation, we write

$$\mathbb{E}[D_i Y_i] = \mathbb{E}[D_i | Y_i \geq 1] \mathbb{E}[Y_i]. \quad (13)$$

Given a typical packet transmission process, whose system time is $T_i = t$. The meaningful value of $Y_i = y$ ranges from 1 to $(t - 1)$ and we have

$$\mathbb{E}[Y_i] = \sum_{t=2}^{\infty} \left( \sum_{y=1}^{t-1} y P_{Y|T}(y | t) \right) P_T(t). \quad (14)$$

The PMF of the system time $T$ is given by

$$P_T(t) = \begin{cases} \frac{r - (p + r)\lambda}{(p + r)(1 - \lambda)}, & t = 1 \\ \frac{p}{p + r} \frac{r - (p + r)\lambda}{(1 - \lambda)^2} (\frac{p + (1-p - r)(1 - \lambda)}{1 - \lambda})^{t-2}, & t \geq 2. \end{cases} \quad (15)$$

The details for deriving (15) are omitted here for brevity and can be found in [11].

For a given system time $t$, $Y_i = y$ means a preemption occurs with $y$ slots after the generation time slot and no packet arrives after this preemption. Hence, we have

$$P_{Y|T}(y | t) = \begin{cases} (1 - \lambda)^{t-1}, & y = 0 \\ \frac{\lambda(1 - \lambda)^{t-1-y}}{(1 - \lambda)^y}, & y = 1, 2, \ldots, t - 1. \end{cases} \quad (16)$$

With the results of (3), (12)-(16) substituted into (11), we derive the average AoI of Bernoulli arrival packets under the FCFS policy, as presented in Lemma 2.

Lemma 2: For a network with Bernoulli packet arrival model at rate $\lambda$ over GE erasure channel $GE(p, r)$, the average AoI under the FCFS queue policy is given by

$$\bar{\Delta}_{BF} = \frac{1}{\lambda} + \frac{p}{r} \left[ \frac{1}{p + r} + \frac{\lambda^2}{(r - (p + r)\lambda)(r - (p + r)\lambda + \lambda)} \right]. \quad (17)$$

The average AoI achieved by the FCFS policy over symmetric GE channel with memory $\eta$ is given by

$$\bar{\Delta}_{BF-s} = \frac{1}{\lambda} + \frac{\eta}{1 - \eta} + \frac{4\lambda^2}{\Delta_1(\eta)} \frac{1}{\Delta_2(\eta)} \frac{1}{1 - 2\lambda(1 - \eta)(1 - (2\lambda)\eta)}. \quad (18)$$

It is observed that when $\eta \in [0, 1)$, $\bar{\Delta}_{BF-s}$ converges if and only if $\lambda \in (0, 0.5)$. This is consistent with expectation since the AoI will grow to infinity if the packet arrival rate exceeds the channel capacity, which is 0.5 here. For a given parameter $\lambda$, the additional AoI term includes two parts, satisfying $\Delta_1(\eta) \geq 0$ and $\Delta_2(\eta) \geq 1$. The former is the same as that under pLGFS policy, while the latter is the additional term related to the packet arrival rate $\lambda$ and caused by the queuing delay. For networks operate close to the capacity, we have $(1 - 2\lambda) \to 0$. The additional AoI penalty, $\Delta_2(\eta)$, is proportional to the factor $\frac{1}{1 - \eta}$, which grows faster as compared with that under pLGFS.

IV. THE AOI WITH PERIODIC ARRIVAL MODEL

A. Average AoI Under pLGFS Policy

The average AoI of periodic arrival packets under the pLGFS policy is presented in Lemma 3.

Lemma 3: For a network with periodic arrival parameter $K$ over GE erasure channel $GE(p, r)$, the average AoI under the pLGFS policy is given by

$$\bar{\Delta}_{pL} = \frac{K + 1 + \frac{p}{r}}{2} \frac{1}{r}. \quad (19)$$

Proof: The derivation of the average AoI under periodic arrival is similar to that with the Bernoulli arrival, except that the packet is generated at the transmitter every $K$ slots, i.e., $P_N(n) = \frac{1}{K}$, $n = 1, 2, \ldots, K$.

The average AoI achieved by the pLGFS policy over the symmetric GE channel with memory $\eta$ is given by

$$\bar{\Delta}_{pL-s} = \frac{K + 1 + \frac{\eta}{1 - \eta}}{2} \frac{1}{r}. \quad (20)$$

We note that the additional AoI due to channel memory for periodic arrival is the same as that for Bernoulli arrival. Besides, for packet arrival process with the same arrival rate, i.e., $\lambda = \frac{1}{K}$, periodic model should achieve smaller AoI than Bernoulli model by a factor of $\frac{K - 1}{2}$.

B. Average AoI Under FCFS Policy

The relationship between the achievable AoI under the FCFS and pLGFS policies still works for the periodic arrival
model. However, the PMF of the preemption time depends on that of the system time, which is intractable for the periodic packet arrival model. Hence, we derive the AoI by its relation with the E2E latency in this case.

Reference [1] has proved that with periodic inter-arrival time $K$, the average AoI under the FCFS policy has a constant gap with the E2E latency, for any distribution of the service time. Mathematically, we have

$$\bar{\Delta}_{pF} = \mathbb{E} [T] + \frac{K - 1}{2}. \quad (21)$$

Hence, deriving the average AoI is equivalent to deriving the expected E2E latency, with queuing delay included. Denote by $T_{n,G}$ and $T_{n,B}$ the expected E2E latency experienced by a packet which arrives when the transmitter has queue length $n$, and the channel is in good and bad state, respectively. According to the analysis in our previous work [9], $T_{n,G}$ and $T_{n,B}$ can be explicitly expressed as

$$T_{n,G} = 1 + n \left( 1 + \frac{p}{r} \right), \quad T_{n,B} = 1 + \frac{1}{r} + n \left( 1 + \frac{p}{r} \right). \quad (22)$$

Further denote by $p_{n,G}$ and $p_{n,B}$ the probabilities for the queue size at the transmitter being $n$, with the channel in good and bad states, respectively. The expected E2E latency is

$$\mathbb{E} [T] = \sum_{n=0}^{\infty} (p_{n,G}T_{n,G} + p_{n,B}T_{n,B}). \quad (23)$$

The key for deriving $\mathbb{E} [T]$ is to derive the probability distributions $\{p_{n,G}, p_{n,B}, n = 0, 1, \cdots \}$, which could be calculated numerically.

Without loss of generality, we consider a segment of time from the 1st to the $(K + 1)$th slot, where the time indexes are relative. Denote by $P(K, n, s'|s)$ the probability that there are $n$ good channel states during $K$ consecutive time slots, leaving the channel state at the $(K + 1)$th time slot being $s'$ given the 1st being $s$, where $s, s' \in \{G, B\}$. For a typical packet, assuming that it arrives when the queue length is $i$, the probability that the next packet arrives at the $(K + 1)$th slot with queue length being $n$ is equivalent to the probability that $(i + 1 - n)$ packets have been delivered during the $K$ time slots. However, if the number of packets that could be delivered is greater than or equal to that is waiting to be transmitted, the minimum value of $n$ is 0. Hence, we can write the following recursive formulas for deriving $p_{n,G}$ and $p_{n,B}$ in two cases:

$$p_{n,s} = \begin{cases} \sum_{i=1}^{K-1} \sum_{s' \in \{G,B\}} p_{i,s',s} P(K, j, s'|s'), & n = 0 \\ \sum_{i=1}^{K+n-1} \sum_{s' \in \{G,B\}} p_{i,s',s} P(K, i+1-n, s'|s') , & n \geq 1, \end{cases} \quad (24)$$

Theoretically, the values of $\{p_{n,G}\}$ and $\{p_{n,B}\}$ for $n = 0, 1, \cdots$ can be solved by combining (24) with the factor

$$\sum_{n=0}^{\infty} (p_{n,G} + p_{n,B}) = 1. \quad (25)$$

However, solving the above equations directly is rather challenging since the number of variables goes to infinity. By observing the recursive structure of the equation in (24), we conjecture that

$$p_{n+1,s} = \beta p_{n,s}, \quad \text{for } n \geq 1, s \in \{G, B\}, \quad (26)$$

which reduces the recursive formula to a single one and (24)-(25) can be simplified to 5 equations with 5 variables $\{p_{0,G}, p_{0,B}, p_{1,G}, p_{1,B}, \beta\}$ as below: (27), shown on the top of the next page, where $s \in \{G, B\}$. An efficient algorithm for solving the equations is presented in Algorithm 1.

Together with (23) and (21), we derive the average AoI with periodic arrival under the FCFS policy as

$$\bar{\Delta}_{pF} = p_{0,G} + \frac{1}{1 - \beta} \left( 1 + \frac{p + r}{r (1 - \beta)} \right) p_{1,G} + \frac{1}{r (1 - \beta)} \left( 1 + \frac{r + \beta p}{1 - \beta} \right) p_{0,B} + \frac{K - 1}{2}, \quad (28)$$

which can be directly computed by substituting the numerical values of $p_{0,G}, p_{0,B}, p_{1,G}$ and $\beta$. Actually, we proved that $p_{1,B} = \beta p_{0,B}$, with more details provided in [11].

Algorithm 1 Average AoI Numerical Algorithm

1: Input: $K, p, r$;
2: Output: AoI $\bar{\Delta}$;
3: Calculate $P(K, i, s'|s)$ recursively for $i = 0, 1, \cdots, K$;
4: Solve $\beta$ with
5: \begin{align*}
\beta &= \sum_{i=0}^{K} \beta P(K,i,B) / \sum_{i=0}^{K} \beta P(K,i,G) \\
\beta &= \sum_{i=0}^{K} \beta P(K,i,G) / \sum_{i=0}^{K} \beta P(K,i,B) \\
\end{align*}
6: Return the average AoI $\bar{\Delta}_{pF}$ with (28).

V. THE AOI WITH GENERATE-AT-WILL MODEL

Under the plGFS policy, the transmitter generates a packet at each time slot to catch up with the next good state, whose AoI performance is equivalent to that under the Bernoulli arrival with $\lambda = 1$ or the periodic arrival with $K = 1$. And the average AoI result under the symmetric GE channel is

$$\Delta_{w1-s} = 2 + \frac{\eta}{1 - \eta}. \quad (29)$$

Under the FCFS policy, to avoid the possible queuing delay, the packet is generated upon its previous packet is delivered to the receiver. With the relative results derived in section III-A, the difference here is that the PMF of initial receiver AoI value $N$. With generate-at-will model, $N$ measures the time interval from the previous good state, which means that the random variable $N$ shares the same PMF with $M$ in section III-A, i.e., $P_N(n) = P_M(n)$, leading to the average AoI:

$$\Delta_{wF} = 1 + \frac{p}{r} + \frac{p}{r (p + r)}. \quad (30)$$

For symmetric GE channel with memory $\eta$, the result is

$$\Delta_{wF-s} = 3 + \frac{\eta}{1 - \eta}. \quad (31)$$

It is observed that for the generate-at-will model, the additional AoI under the two policies are both $\frac{\eta}{1 - \eta}$. This is because there is no queuing delay when the packets are generated at will.

VI. NUMERICAL RESULTS

In this section, numerical results are provided to verify the analytical results for the Bernoulli, periodic arrival and generate-at-will models under the FCFS and plGFS policies.
In this letter, we investigate the impact of channel memory on the data freshness. The analytical results reveal that the average AoI under pLGFS increases with channel memory $\eta$ at $\frac{1}{2}$ over the symmetric GE channel. The AoI under FCFS increases even faster with channel memory due to the additional queuing delay at the transmitter. The analysis approaches introduced in this letter could be applied for deriving the average AoI under other network settings, and the impact of channel memory could guide the design of more efficient AoI-optimal policy for networks with channel memory. In the future, we are going to derive the AoI expression for GE channel with general erasure probabilities and extend this work to multi-point communication networks.

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