Update or Wait: How to Keep Your Data Fresh

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Abstract—In this work we study how to manage the freshness of status updates sent from a source to a remote monitor via a network server. A proper metric of data freshness at the monitor is the status update age, which is defined as how old the latest update is since the moment this update was generated at the source. A logical policy is the zero wait policy, i.e., the source submits a fresh update once the server is free, which achieves the maximum throughput and the minimum average delay. Surprisingly, this zero wait policy does not always minimize the average age. This motivates us to study how to optimally control the status updates to keep data fresh and to understand when the zero wait policy is optimal. We introduce a penalty function to characterize the level of “dissatisfaction” on data staleness, and formulate the average age penalty minimization problem as a constrained semi-Markov decision process (SMDP) with an uncountable state space. Despite of the difficulty of this problem, we develop efficient algorithms to find the optimal status update policy. We show that, in many scenarios, the optimal policy is to wait for a certain amount of time before submitting a new update. In particular, the zero wait policy can be far from optimality if (i) the penalty function grows quickly with respect to the age, and (ii) the update service times are highly random and positive correlated.

I. INTRODUCTION

In recent years, the proliferation of mobile devices and applications has significantly boosted the need for real-time information updates, such as news, weather reports, email notifications, stock quotes, social updates, mobile ads, etc. Timely status updates are also critical in network-based monitoring and control systems, including sensor networks used in temperature and air pollution monitoring, surrounding monitoring in autonomous vehicles, and phasor data updates in power grid stabilization systems.

A common need in these applications is to maximize the freshness of the data at the monitor. In light of this, a metric called status update age, or simply age, was defined in [1]. At time $t$, if the latest update at the monitor has a time stamp $U(t)$, the status update age is $\Delta(t) = t - U(t)$. Hence, the age is the time elapsed since the latest packet was generated.

Most existing research on status update age focuses on an “enqueue-and-forward” model [1]–[2], where status updates are generated or arrive randomly at a source node. The source enqueues these updates and forwards them later to a remote monitor through a network cloud. It is worth noting that the goal of age minimization differs from those of throughput maximization and delay minimization: A high update frequency improves the system utilization, but may also induce a large waiting time in the queue which in turn increases the age; on the other hand, a low update frequency can reduce the queuing delay, but the monitor may end up having stale status information due to not enough updates [1], [3], [7]. In [2], it was found that a good policy is to discard the old packets waiting in the queue if a new sample arrives, which can greatly reduce the queuing delay.

In this paper, we study a “generate-at-will” model depicted in Fig. 1. In this model, the server keeps monitoring the network server’s idle/busy state, and in contrast to [1]–[7], is able to generate status updates at any time by its own will. Hence, no updates need to be generated when the server is busy, which completely eliminates the waiting time in the queue and hence the queue in Fig. 1 is always idle. A simple zero wait policy, also known as the work-conserving policy in queueing theory, that submits a fresh update once the server becomes idle, achieves the maximum throughput and the minimum average delay. Surprisingly, this zero wait policy does not always minimize the average age of the information [8]. The following example reveals the reason behind this phenomenon:

**Example:** Suppose that the source submits a stream of update packets to a remote monitor. The service times of these updates form a periodic sequence

$$0.1, 0.1, 1.7, 1.7, 0.1, 0.1, 1.7, 1.7, \ldots$$

Update 1 is generated and submitted at time $t$ and delivered at time $t + 0.1$. Under the zero wait policy, update 2 is generated at time $t + 0.1$ and delivered at time $t + 0.2$. However, despite of its short service time, update 2 has not brought much fresh information to the monitor after update 1 is delivered, because update 2 was generated only 0.1 seconds later than update 1. Therefore, update 2 is inefficiently used! The same issue occurs periodically over time: Whenever two consecutive updates have 0.1 seconds of service times, the second update of the two is inefficiently used. Therefore, every fourth update in this sequence is inefficiently used in the zero wait policy!

For comparison, consider a policy that waits for 0.6 seconds after an update with a service time of 0.1 seconds is completed, and does not wait after an update with a service time of 1.7 seconds is completed. The average age of the zero wait policy is 1.706 seconds, and the average age of the second policy is
The key contributions of this paper:

- We further investigate when the zero wait policy is optimal.

1.604 seconds. Hence, the zero wait policy is not optimal.

This example points out a key difference between status update and data communication systems: In status update systems, an update packet is useful only if it carries fresh information to the monitor; however, in communication systems, all packets are equally important. While the theory of data communications is quite mature, the optimal control of status updates remains open.

For a source that can insert waiting times between updates, the aim of this paper is to answer the following questions: How to optimally send update packets to the remote monitor? When is the zero wait policy optimal? To that end, the following are the key contributions of this paper:

- We generalize existing status update studies by introducing two new features: age penalty functions and non-i.i.d. service processes. We define an age penalty function \( g(\Delta) \) to characterize the level of “dissatisfaction” for data staleness, where \( g(\cdot) \) is measurable, non-negative, and non-decreasing, which is determined by the specific application. The update service process is modeled as a stationary ergodic Markov chain with an uncountable state space, which generalizes the i.i.d. service processes studied in previous work [1]–[9].

- We formulate the average age penalty minimization problem as a constrained semi-Markov decision process (SMDP) with an uncountable state space. Despite of the difficulty of this problem, we solve it in several steps: We first prove that there exists a stationary randomized policy that is optimal for this problem (Theorem 1). Further, we prove that there exists a stationary deterministic policy that is optimal for this problem (Theorem 2). Finally, we develop a low-complexity algorithm to find the optimal stationary deterministic policy (Theorem 3).

- We further investigate when the zero wait policy is optimal. For the special case of proportional penalty function and i.i.d. service times, we devise a simpler solution to minimize the average age (Theorem 4). This solution explicitly characterizes when the zero wait policy is optimal, and when it is not. For general age penalty functions and correlated service processes, sufficient conditions for the optimality of the zero wait policy are provided (Lemma 3).

- Our theoretical and simulation results demonstrate that, in many scenarios, the optimal policy is to wait for a certain amount of time before submitting a new update. In particular, the zero wait policy can be far from optimality if (i) the penalty function grows quickly with respect to the age, and (ii) the update service times are highly random and positive correlated.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a system depicted in Fig. 1 where a source generates status update packets and sends them to a remote monitor through a network server. This server provides First-Come First-Served (FCFS) service to the submitted update packets. The service of an update packet is considered complete, when it is successfully received by the monitor. After that, the server becomes available for sending the next packet.

The source generates and submits updates at successive times \( S_0, S_1, \ldots \). Update \( i \) is submitted at time \( S_i \), and is delivered at time \( D_i = S_i + Y_i \), where \( Y_i \geq 0 \) is the service time of update \( i \). Suppose that update 0 is submitted to an idle server at time \( S_0 = -Y_0 \) and delivered at \( D_0 = 0 \), as shown in Fig. 2. The source has access to the idle/busy state of the server and is able to generate updates at any time by its own will. Hence, the source should not generate update \( i + 1 \) when the server is busy processing update \( i \), because this will incur an unnecessary waiting time in the queue. After update \( i \) is delivered at time \( D_i \), the source may introduce a waiting time \( Z_i \in [0, M] \) before submitting update \( i + 1 \) at time \( S_{i+1} = D_i + Z_i \), where \( M \) represents the maximum amount of waiting time allowed by the system. The source can switch to a low-power sleep mode during \( [D_i, S_{i+1}) \). We assume that the service process \( (Y_0, Y_1, \ldots) \) is a stationary and ergodic Markov chain with a possibly uncountable state space and a positive mean \( 0 < \mathbb{E}[Y_i] < \infty \), which generalizes the i.i.d. service processes in previous studies [1]–[9]. The ergodicity of this Markov chain is assumed in the sense of ergodic theory [10], which allows the Markov chain to be periodic.

At any time \( t \), the monitor’s most recently received update packet is time-stamped with \( U(t) = \max\{S_i : D_i \leq t\} \). The status update age \( \Delta(t) \) is defined as

$$\Delta(t) = t - U(t), \quad (1)$$

which is also referred to as age-of-information or simply age. As shown in Fig. 2, the age \( \Delta(t) \) is a stochastic process that increases linearly with \( t \) between updates, with downward jumps occurring when updates are delivered. Specifically, when update \( i \) is sent at time \( t = S_i \), it is delivered at time \( D_i = S_i + Y_i \) with age \( \Delta(D_i) = D_i - S_i = Y_i \). After that, the age increases linearly and reaches \( \Delta(D_{i+1}^-) = Y_i + Z_i + Y_{i+1} \) just before update \( i + 1 \) is delivered. Then, at time \( D_{i+1} \), the age drops to \( \Delta(D_{i+1}^-) = Y_{i+1} \).

We introduce an age penalty function \( g(\Delta) \) to represent the level of “dissatisfaction” for data staleness or the “need” for new information update, where the function \( g : [0, \infty) \to [0, \infty) \) is assumed to be measurable, non-negative, and non-decreasing, which is determined by the specific application. Some examples of \( g(\cdot) \) are power function \( g(\Delta) = \Delta^a \), exponential function \( g(\Delta) = e^{a\Delta} \), and the stair-step function \( g(\Delta) = [a\Delta] \), where \( a \geq 0 \) and \([x] \) is the largest integer no greater than \( x \). Two examples of age penalty functions

\footnote{To compute the average age, one need to use \[3, 12\], and refer to Fig.
\footnote{Its matlab code is provided in Appendix A.}}

\footnote{The results in this paper can be readily extended to a more general model where the Markov chain \((Y_0, Y_1, \ldots) \) has a longer memory, i.e., the sequence \((W_0, W_1, \ldots) \) forms a Markov chain, with \( W_i \) defined as \( W_i = (Y_i, Y_{i+1}, \ldots, Y_{i+k}) \) for some finite \( k \).}
satisfying available. Let controlling the sequence of waiting times of future service times denote the set of all causally feasible policies. We consider a status update policy. We consider into a sum of disjoint components:

\[ g_1(\Delta) = \sum_{i=0}^{n-1} Q_i, \]

where

\[ Q_i = \int_{Y_i}^{Y_i+Y_i+Z_i} g(\tau) d\tau. \]

Let us define

\[ q(y, z, y') = \int_y^{y+z+y'} g(\tau) d\tau. \]

Then, \( Q_i \) can be expressed as \( Q_i = q(Y_i, Z_i, Y_{i+1}) \). We assume that

\[ \mathbb{E}[q(Y_i, M, Y_{i+1})] < \infty. \]

Our goal is to minimize the average age penalty by controlling the sequence of waiting times \((Z_0, Z_1, \ldots)\). Let \( \pi \triangleq (Z_0, Z_1, \ldots) \) denote a status update policy. We consider the class of causal feasible policies, in which control decisions are made based on history and current information of the system, as well as the distribution of the service process \((Y_0, Y_1, \ldots)\). Specifically, \( Z_i \) is determined based on the past realizations of \((Y_0, Y_1, \ldots, Y_i)\), without using the realizations of future service times \((Y_{i+1}, Y_{i+2}, \ldots)\); but the conditional distribution of \((Y_{i+1}, Y_{i+2}, \ldots)\) based on \((Y_0, Y_1, \ldots, Y_i)\) is available. Let II denote the set of all causally feasible policies satisfying \( Z_i \in [0, M] \) for all \( i \).

The average age penalty can be represented by

\[ \limsup_{n \to \infty} \frac{\mathbb{E}\left[ \int_0^{D_n} g(\Delta(t)) dt \right]}{\mathbb{E}[D_n]}. \]

Using this, the stochastic optimization problem for minimizing the average age penalty can be formulated as

\[ \tilde{g}_{\text{opt}} = \min_{\pi \in \Pi} \limsup_{n \to \infty} \frac{\mathbb{E}\left[ \sum_{i=0}^{n-1} q(Y_i, Z_i, Y_{i+1}) \right]}{\mathbb{E}\left[ \sum_{i=0}^{n-1} (Y_i + Z_i) \right]} \]

subject to \( \liminf_{n \to \infty} \frac{1}{n} \sum_{i=0}^{n-1} (Y_i + Z_i) \geq T_{\min} \),

where \( \tilde{g}_{\text{opt}} \) is the optimum objective value of Problem \( 4 \), the expectation \( \mathbb{E} \) is taken over the stochastic service process \((Y_0, Y_1, \ldots)\) for given policy \( \pi \), and \( T_{\min} \) is the minimum average update period of the source due to hardware and physical constraints (e.g., limited power resource and cooling capacity). We assume \( M > T_{\min} \) such that Problem \( 4 \) is feasible and \( \tilde{g}_{\text{opt}} < \infty \).

Problem \( 4 \) belongs to the class of constrained semi-Markov decision processes (SMDP) with a possibly uncountable state space, which is well-known for its difficulty. In this problem, \( Y_i \) is the state of the embedded Markov chain, \( Z_i \) is the control action taken after observing \( Y_i, Y_i + Z_i \) is the update period, and \( q(Y_i, Z_i, Y_{i+1}) \) is the reward related to both stage \( i \) and \( i + 1 \). The class of SMDPs include Markov decision problems (MDPs) [13, 15] and optimization problems of renewal processes [16] as special cases. Most existing studies on SMDPs deal with (i) unconstrained SMDPs, e.g., [11, 13, 17, 18], or (ii) constrained SMDPs with a countable state space, e.g., [19–22]. However, the optimality equations for solving unconstrained SMDPs are not applied to constrained SMDPs [23], and the studies for problems with a countable state space cannot be directly applied to Problem \( 4 \), which has a possibly uncountable state space.

### III. Optimal Status Update Policy

In this section, we develop a chain of novel theoretical results to solve Problem \( 4 \). First, we prove that there exists a stationary randomized policy that is optimal for Problem \( 4 \). Further, we prove that there exists a stationary deterministic policy that is optimal for Problem \( 4 \). Finally, we develop a low-complexity algorithm to find the optimal stationary deterministic policy that solves Problem \( 4 \).

#### A. Optimality of Stationary Randomized Policies

A policy \( \pi \in \Pi \) is said to be a stationary randomized policy, if it observes \( Y_i \) and then chooses a waiting time \( Z_i \in [0, M] \) based only on the observed value of \( Y_i \). In this case, \( Z_i \) is determined according to a conditional probability measure \( p(y, A) \triangleq \Pr[Z_i \in A | Y_i = y] \) that is invariant for all \( i = 0, 1, \ldots \). We use \( \Pi_{\text{SR}} \) (\( \Pi_{\text{SR}} \subset \Pi \)) to denote the set of stationary randomized policies such that

\[ \Pi_{\text{SR}} = \{ \pi : \text{After observing } Y_i = y_i, Z_i \in [0, M] \text{ is chosen according to probability measure } p(y_i, A), i = 0, 1, \ldots \}. \]

Note that \((Y_i, Z_i, Y_{i+1})\) is stationary and ergodic for all stationary randomized policies. In the sequel, when we refer
to the stationary distribution of a stationary randomized policy $\pi \in \Pi_{SR}$, we will remove subscript $i$. In particular, the random variables $(Y, Z, Y_{i+1})$ are replaced by $(Y, Z, Y')$, where $Z$ is chosen based on the conditional probability measure $\Pr[Z \in A | Y = y] = p(y, A)$ after observing $Y = y$, and $(Y, Y')$ have the same joint distribution as $(Y_0, Y_1)$. The first key result of this paper is stated as follows:

**Theorem 1:** (Optimality of Stationary Randomized Policies) If $g(\cdot)$ is measurable and non-negative, $(Y_0, Y_1, \ldots)$ is a stationary ergodic Markov chain with $Y_0 \geq 0$ and $0 < E[Y_1] < \infty$, condition (5) is satisfied, then there exists a stationary randomized policy that is optimal for Problem (4).

**Proof sketch of Theorem 1** For any policy $\pi \in \Pi$, define finite horizon average occupations

$$a_{n, \pi} \triangleq \frac{1}{n} \mathbb{E} \left[ \sum_{i=0}^{n-1} q(Y_i, Z_i, Y_{i+1}) \right], \quad b_{n, \pi} \triangleq \frac{1}{n} \mathbb{E} \left[ \sum_{i=0}^{n-1} (Y_i + Z_i) \right].$$

Let $\Gamma_{SR}$ be the set of limit points of sequences $((a_{n, \pi}, b_{n, \pi}), n = 1, 2, \ldots)$ associated with stationary randomized policies in $\Pi_{SR}$. We first prove that $\Gamma_{SR}$ is convex and compact. Then, we show that there exists an optimal policy $\pi_{opt}$ of Problem (4), such that the sequence $((a_{n, \pi_{opt}}, b_{n, \pi_{opt}}), n = 1, 2, \ldots)$ associated with policy $\pi_{opt}$ has a limit point $(a^*, b^*)$, where $a^* \leq 0$, and $b^* \geq T_{min}$. Since $(a^*, b^*) \in \Gamma_{SR}$, there exists a stationary randomized policy $\pi^*$ achieving this limit point $(a^*, b^*)$. Finally, we show that policy $\pi^*$ is optimal for Problem (4), which completes the proof. The details are available in Appendix 1.

The convexity and compactness properties of the set of occupation measures are essential in the study of constrained MDPs [24, Sec. 1.5], which dates back to Derman’s monograph in 1970 [23]. Recently, it was used in stochastic optimization for discrete-time queueing systems and renewal processes, e.g., [16, 26]. The techniques in these studies cannot directly handle constrained MDPs with an uncountable state space, like Problem (4). One key idea in our proof is to introduce $\mathcal{F}_{opt}$ in the definition of average occupation in (5), which turns out to be essential in later steps for showing the optimality of the stationary randomized policy $\pi^*$.

By Theorem 1, we only need to consider the class of stationary randomized policies $\Pi_{SR}$. Therefore, Problem (4) can be simplified to the following functional optimization problem (as shown in Appendix 1):

$$\min_{\pi \in \Pi_{SR}} \frac{\mathbb{E}[q(Y, Z, Y')]}{\mathbb{E}[Y + Z]} \tag{7}$$

s.t. $\mathbb{E}[Y + Z] \geq T_{min}$

$$0 \leq Z \leq M$$

where $p(y, A) = \Pr[Z \in A | Y = y]$ is the conditional probability measure of some stationary randomized policy, and $(Y, Y')$ have the same distribution as $(Y_0, Y_1)$.

**B. Optimality of Stationary Deterministic Policies**

A policy $\pi \in \Pi_{SR}$ is said to be a stationary deterministic policy if $Z_i = z(Y_i)$ for all $i = 0, 1, \ldots$, where $z : [0, \infty) \to [0, M]$ is a deterministic function. We use $\Pi_{SD}$ ($\Pi_{SD} \subseteq \Pi_{SR}$) to denote the set of stationary deterministic policies such that

$$\Pi_{SD} = \{\pi : Z_i = z(Y_i) \text{ for all } i, 0 \leq z(y) \leq M, \forall \ y \geq 0\}.$$

**Theorem 2:** (Optimality of Stationary Deterministic Policies) If $g(\cdot)$ is measurable and non-decreasing, then there exists a stationary deterministic policy that is optimal for Problem (7).

**Proof sketch of Theorem 2** Since $g(\cdot)$ is non-decreasing, $q(y, y')$ is convex. Using Jensen’s inequality, we can show that for any feasible stationary randomized policy $\pi_1 \in \Pi_{SR}$, there is a feasible stationary deterministic policy that is no worse than policy $\pi_1$. The details are provided in Appendix 2.

Let $\mu_Y$ be the probability measure of $Y$, then any bounded measurable function $z : [0, \infty) \to [0, M]$ belongs to the Lebesgue space $L^2(\mu_Y)$ [27] Section 3.1, because

$$\int_0^\infty |z(y)|^2 d\mu_Y(y) \leq \int_0^\infty M^2 d\mu_Y(y) = M^2 < \infty.$$

By Theorems 1 and 2, we only need to consider the class of stationary deterministic policies $\Pi_{SD}$ and Problem (8) is simplified to the following functional optimization problem:

$$\min_{z(\cdot) \in L^2(\mu_Y)} \frac{\mathbb{E}[q(Y, z(Y), Y')]}{\mathbb{E}[Y + z(Y)]} \tag{8}$$

s.t. $\mathbb{E}[Y + z(Y)] \geq T_{min}$

$$0 \leq z(y) \leq M, \forall \ y \geq 0,$$

where $z(\cdot)$ is the function associated with a stationary deterministic policy $\pi \in \Pi_{SR}$. The optimum objective value of Problem (8) is equal to $\mathcal{F}_{opt}$.

**C. A Low Complexity Solution to Problem (8)**

**Lemma 1:** If $g(\cdot)$ is measurable, non-negative, and non-decreasing, then the functional $h : L^2(\mu_Y) \to [0, \infty)$ defined by

$$h(z) = \frac{\mathbb{E}[q(Y, z(Y), Y')]}{\mathbb{E}[Y + z(Y)]}$$

is quasi-convex.

**Proof:** See Appendix 2.

Therefore, Problem (8) is a functional quasi-convex optimization problem. In order to solve Problem (8), we consider the following functional convex optimization problem with a parameter $c$:

$$f(c) = \min_{z(\cdot) \in L^2(\mu_Y)} \frac{\mathbb{E}[q(Y, z(Y), Y')]}{\mathbb{E}[Y + z(Y)]} - c \mathbb{E}[Y + z(Y)] \tag{10}$$

s.t. $\mathbb{E}[Y + z(Y)] \geq T_{min}$

$$0 \leq z(y) \leq M, \forall \ y \geq 0.$$

It is easy to show that $\mathcal{F}_{opt} \leq c$ if and only if $f(c) \leq 0$ [28]. Therefore, we can solve Problem (8) by a two-layer nested algorithm, such as Algorithm 1. In the inner layer, we use bisection to solve Problem (10) for given parameter $c$; in the outer layer, we employ bisection again to search for a $c^*$ such that $f(c^*) = 0$ and thus $\mathcal{F}_{opt} = c^*$. Algorithm 1 has low complexity. It requires at most $\lceil \log_2((u - l)/\epsilon_1) \rceil \times \lceil \log_2((u - \zeta)/\epsilon_2) \rceil$ iterations to terminate. Each iteration involves computing $\mathbb{E}[z_\tau(Y)]$ based on (11). The optimality of Algorithm 1 is guaranteed by the following theorem.
Algorithm 1 Two-layer bisection method for Problem (8)

given \( l = 0 \), sufficiently large \( u > \frac{1}{\gamma_{SD}} \), tolerance \( \epsilon_1 \).

repeat
\[
c := (l + u)/2.
\]
given \( \zeta_t = 0 \), sufficiently large \( \zeta_u > 0 \), tolerance \( \epsilon_2 \).
\[
\zeta := \zeta_t, \nu := \zeta + c.
\]
Compute \( z_\nu(\cdot) \) in (11).

if \( \mathbb{E}[z_\nu(Y)] + \mathbb{E}[Y] < T_{\text{min}} \) then

repeat
\[
\zeta := (\zeta + \zeta_u)/2, \nu := \zeta + c.
\]
Compute \( z_\nu(\cdot) \) in (11).

if \( \mathbb{E}[z_\nu(Y)] + \mathbb{E}[Y] \geq T_{\text{min}}, \zeta_u := \zeta; \) else, \( \zeta := \zeta_u \).

until \( \zeta_u - \zeta_t \leq \epsilon_2 \).

end if

if \( f(c) \leq 0, u := c; \) else, \( l := c \).

until \( u - l \leq \epsilon_1 \).

return \( z(\cdot) := z_\nu(\cdot) \).

Theorem 3: If \( g(\cdot) \) is measurable, non-negative, and non-decreasing, then an optimal solution \( \pi_{\text{opt}} \) to Problem (8) is obtained by Algorithm 1 where the function \( z_\nu(\cdot) \) is determined by
\[
z_\nu(y) = \sup \{ z \in [0, M] : \mathbb{E}[g(y + z + Y')] | Y = y \leq \nu \}. \tag{11}
\]

Proof Sketch of Theorem 3: We use Lagrangian duality theory to solve Problem (8). Different from traditional finite dimensional optimization problems [23], Problem (8) is an infinite dimensional functional optimization problem. Therefore, the KKT conditions for infinite dimensional space [22, 30] and the calculus of variations are required in the analysis. In particular, since the Lagrangian may not be strictly convex for some penalty functions, one-sided Gâteaux derivative (similar to sub-gradient in finite dimensional space) is used to solve the KKT conditions in Lebesgue space \( L^2(\mu_Y) \). The proof details are provided in Appendix E.

The policy spaces \( \Pi, \Pi_{\text{SR}}, \Pi_{\text{SD}}, \) and the obtained optimal policy \( \pi_{\text{opt}} \) are depicted in Fig. 4.

IV. When Is It Better To Wait than To Update?

When \( T_{\text{min}} \leq \mathbb{E}[Y] \), a logical policy is the zero wait policy: the source submits a fresh update once the prior update completes service, i.e., \( \pi_{\text{zero wait}} = (0, 0, \ldots) \). As mentioned before, this zero wait policy is not always optimal to keep data fresh. When \( T_{\text{min}} > \mathbb{E}[Y] \), due to the constraint (9), the minimum possible average waiting time is \( \mathbb{E}[z(Y)] = T_{\text{min}} - \mathbb{E}[Y] \). However, even in this case, the optimal policy may have additional waiting time such that \( \mathbb{E}[z(Y)] > T_{\text{min}} - \mathbb{E}[Y] \). In this section, we will study when it is optimal to submit updates with the minimum wait and when it is not.

A. A Special Case of \( g(\Delta) = \Delta \) with i.i.d. Service Times

Consider the case that \( g(\Delta) = \Delta \) and the \( Y_i \)'s are i.i.d.. In this case, Problem (8) has a simpler solution than that provided by Algorithm 1. Interestingly, this solution explicitly characterizes whether the optimal control \( z(\cdot) \) can have minimum wait such that \( \mathbb{E}[z(Y)] = T_{\text{min}} - \mathbb{E}[Y] \).

Fig. 4. Illustration of the set of causally feasible policies \( \Pi \), the set of stationary randomized policies \( \Pi_{\text{SR}} \), the set of stationary deterministic policies \( \Pi_{\text{SD}}, \) and the obtained optimal policy \( \pi_{\text{opt}} \).

As shown in Fig. 2 \( q(y, z, y') \) is the area of a trapezoid, computed as
\[
q(y, z, y') = \frac{1}{2} (2y + z + y')(z + y').
\]

Because the \( Y_i \)'s are i.i.d., \( Y \) and \( Y' \) in Problem (8) are also i.i.d. Using this, we can obtain
\[
\mathbb{E}[q(Y, z(Y), Y')] = \mathbb{E} \left[ \frac{1}{2} (Y' + z(Y))^2 + (Y + z(Y))'Y' \right] \tag{12}
\]
\[
= \frac{1}{2} \mathbb{E} \left[ (Y + z(Y))^2 \right] + \mathbb{E}[Y + z(Y)] \mathbb{E}[Y'],
\]

where in (12) we have used that \( \mathbb{E}[Y'^2] = \mathbb{E}[Y^2] \). Hence, Problem (8) can be reformulated as
\[
\min_{z \in L^2(\mu_Y)} \mathbb{E}[Y + z(Y)]^2 \tag{13}
\]
\[
\text{s.t. } \mathbb{E}[Y + z(Y)] \geq T_{\text{min}},
\]
\[
0 \leq z(y) \leq M, \forall y \geq 0.
\]

The following lemma tells us that Problem (13) is a functional convex optimization problem.

Lemma 2: The functional \( h_1: L^2(\mu_Y) \to \mathbb{R} \) defined by
\[
h_1(z) = \frac{\mathbb{E}[(Y + z(Y))^2]}{\mathbb{E}[Y + z(Y)]}
\]
is convex on the domain
\[
\text{dom } h_1 = \left\{ z : z(y) \in [0, M], \forall y \geq 0, z \in L^2(\mu_Y) \right\}.
\]

Proof: See Appendix C.

Using the KKT theorem for infinite dimensional space and the calculus of variations, we can obtain

Theorem 4: The optimal solution to Problem (13) is
\[
z(y) = (\beta - y)^M_0, \tag{15}
\]
where \( (x)_b^a \triangleq \min \{ \max \{x, a\}, b\} \) and \( \beta > 0 \) is the root of the following equation:
\[
\mathbb{E} \left[ (\beta)^{M+Y} \right] = \max \left( T_{\text{min}}, \frac{\mathbb{E}[(\beta)^{M+Y}^2]}{2\beta} \right). \tag{16}
\]

Proof: See Appendix C.

Equation (15) has the form of a water-filling solution, where the water-level \( \beta \) is given by the root of equation (16). One can observe that (11) reduces to (15) if \( g(\Delta) = \Delta \), the \( Y_i \)'s are i.i.d., and \( \tau \) is replaced by \( \beta + \mathbb{E}[Y] \). The root \( \beta \) of equation (16) can be simply solved by the bisection search method in.
Algorithm 2 Bisection method for solving Problem (13)

given \( l = 0 \), sufficiently large \( u \), tolerance \( \epsilon \).
repeat
\[
\beta := (l + u)/2. \\
o := \max \{ \beta \} - \max \{ T_{\min}, \frac{\mathbb{E}[(\beta)M+Y]^2}{2\beta} \}, \\
\text{where} \quad (x)^b_a = \min [\max (x, a), b]. \\
\text{if} \ n \geq 0, \ u := \beta; \quad \text{else}, \ l := \beta.
\]
until \( u - l \leq \epsilon. \)
Compute \( z(\cdot) \) by (15).
return \( z(\cdot). \)

Fig. 5. Average age vs. \( T_{\min} \) with i.i.d. discrete service times.

Algorithm 2 We note that Algorithm 2 has a lower complexity than Algorithm 1 in the special case of \( g(\Delta) = \Delta \) and i.i.d. service process, while Algorithm 1 can obtain the optimal policy in more general scenarios.

Interestingly, Theorem 4 provides a closed-form criterion on whether the optimal \( z(\cdot) \) satisfies \( \mathbb{E}[z(Y)] = T_{\min} - \mathbb{E}[Y] \). Specifically, (15) implies \( \mathbb{E}[(\beta)M+Y] = Y + z(Y) \). This and (16) tell us that if \( T_{\min} \geq \frac{\mathbb{E}[(Y+z(Y))^2]}{2\beta} \), then the optimal control \( z(\cdot) \) satisfies
\[
\mathbb{E}[Y + z(Y)] = T_{\min} \geq \frac{\mathbb{E}[(Y+z(Y))^2]}{2\beta}. \tag{17}
\]
such that the optimal policy has the minimum average waiting time \( \mathbb{E}[z(Y)] = T_{\min} - \mathbb{E}[Y] \); otherwise, if \( T_{\min} < \frac{\mathbb{E}[(Y+z(Y))^2]}{2\beta} \), the optimal control \( z(\cdot) \) satisfies
\[
\mathbb{E}[Y + z(Y)] = \frac{\mathbb{E}[(Y+z(Y))^2]}{2\beta} > T_{\min}. \tag{18}
\]
such that the average waiting time \( \mathbb{E}[z(Y)] \) of the optimal policy is larger than \( T_{\min} - \mathbb{E}[Y] \).

Furthermore, we consider the case \( T_{\min} = 0 \), where the constraint (14) is always satisfied and can be removed. Note that we have the same problem for all \( T_{\min} \leq \mathbb{E}[Y] \) and hence we can pick \( T_{\min} = \mathbb{E}[Y] \). By substituting \( T_{\min} = \mathbb{E}[Y] \) into (17) and (18), we can obtain the criterion on whether the zero waiting policy is optimal.

1) Simulation Results: We use “Optimal policy” to refer to the policy provided in Theorem 3 (or its special case in Theorem 4), and compare it with two reference policies:

- “Constant wait”: Each update is followed by a constant wait \( Z_i = const \) before submitting the next update with \( const = T_{\min} - \mathbb{E}[Y] \).
- “Minimum wait”: The update waiting time is given by a deterministic function \( Z_i = z(Y_i) \), where \( z(\cdot) \) is given by (15) and \( \beta \) is chosen to satisfy \( \mathbb{E}[z(Y)] = T_{\min} - \mathbb{E}[Y] \).

When \( \mathbb{E}[Y] = T_{\min} \), both the constant wait and minimum wait policies reduce to the zero wait policy. Two models of the service processes are considered: The first one is a discrete Markov chain with a probability mass function \( \text{Pr}[Y_i = 0] = \text{Pr}[Y_i = 2] = 0.5 \) and a transition matrix
\[
P = \begin{pmatrix}
p & 1 - p \\
1 - p & p \end{pmatrix}.
\]
Hence, the \( Y_i \)'s are i.i.d. when \( p = 0.5 \), and the correlation coefficient between \( Y_i \) and \( Y_{i+1} \) is \( \rho = 2p - 1 \). The second one is a log-normal distributed Markov chain, where \( Y_i = e^{\sigma X_i}/\mathbb{E}[e^{\sigma X_i}] \) and \((X_0, X_1, \ldots)\) is a Gaussian Markov process satisfying the first-order AR equation
\[
X_{i+1} = \eta X_i + \sqrt{1 - \eta^2} W_i,
\]
where \( \eta \in [-1, 1] \) and the \( W_i \)'s are i.i.d. Gaussian random variables with zero mean and unit variance. Then, the \( Y_i \)'s are i.i.d. when \( \eta = 0 \). According to the properties of log-normal distribution, the correlation coefficient between \( Y_i \) and \( Y_{i+1} \) is \( \rho = (e^\eta - 1)/(e^\eta - 1) \). We have \( \mathbb{E}[Y] = 1 \) in both models. The value of \( M \) is chosen as 10 in all simulations.

Figures 5 and 6 illustrate the average age vs. \( T_{\min} \) for discrete service times, where \( T_{\min} \leq \mathbb{E}[Y] \).

Fig. 6. Average age vs. \( T_{\min} \) with i.i.d. log-normal distributed service times.

Fig. 7. Average age vs. the correlation coefficient \( \rho \) between \( Y_i \) and \( Y_{i+1} \).
not active for the optimal solution. Consequently, the average age achieved by the minimum wait policy deviates from the optimum for small values of $T_{\min}$.

### B. General Age Penalties and Correlated Service Processes

For general age penalties and correlated service processes, it is essentially difficult to find closed-form characterization on whether the optimal control $z(\cdot)$ can have minimum wait such that $E[z(Y)] = T_{\min} - E[Y]$. Therefore, we focus on the case of $T_{\min} \leq E[Y]$ and study when the zero wait policy minimizes the average age penalty. Sufficient conditions for the optimality of the zero wait policy are provided as follows:

**Lemma 3**: Suppose that $T_{\min} \leq E[Y]$, $g(\cdot)$ is measurable, non-negative, and non-decreasing. The zero wait policy is optimal for Problem (6) if one of the following is satisfied:

1. The correlation coefficient between $Y_i$ and $Y_{i+1}$ is $-1$;
2. The $Y_i$’s are equal to a constant value;
3. $g(\cdot)$ is a constant function.

**Proof**: See Appendix H.

#### 1) Simulation Results: We now provide some simulation results for general age penalties and/or correlated service processes. Figures 7 and 8 depict the average age vs. the correlation coefficient $\rho$ between $Y_i$ and $Y_{i+1}$ for log-normal distributed service times, respectively. In Fig. 7, the regime of $\rho$ is $[-1, 1]$. We observe that the zero wait policy is optimal when $\rho \in [-1, -0.5]$, and the performance gap between the optimal policy and the zero wait policy grows with $\rho$ when $\rho \geq -0.5$. This is in accordance with the example in the introduction: As $\rho$ grows, the occurrence of two consecutive zero service times (i.e., $(Y_i, Y_{i+1}) = (0, 0)$) increases. Therefore, more and more updates are wasted in the zero wait policy, leading to a larger gap from the optimum. In Fig. 8 the regime of $\rho$ is $[e^{-1} - 1]$. In this case, the sub-optimality gap of the zero wait policy also increases with $\rho$. The point $\rho = 1$ is not plotted in these figures because the corresponding Markov chains are not ergodic.

Figure 9 considers the average age vs. the parameter $\sigma$ of log-normal distributed service times, where $\rho = (e^{0.5} - 1)/(e - 1)$. We observe that the zero wait policy is optimal for small $\sigma$ and is not optimal for large $\sigma$. Note that when $\sigma = 0$, the service times are constant, i.e., $Y_i = 1$ for all $i$.

Figures 10 and 11 show the average age penalty vs. the parameter $\alpha$ of stair-step penalty functions with discrete service times, where $\rho = (e^{0.5} - 1)/(e - 1)$. We observe that the zero wait policy is optimal if $\alpha = 0$, in which case $g(\Delta)$ is a constant function. When $\alpha > 0$, the zero wait policy may not be optimal.

These simulation results suggest that the conditions in Lemma 3 are sufficient but not necessary.

### V. Conclusion

We studied the optimal control of status updates from a source to a remote monitor via a PCFS network server. We generalized the existing studies on status update age to cover general age penalty functions and non-i.i.d. service processes. We developed efficient algorithms to find the optimal status update policy for minimizing the average age penalty. We
 showed that, surprisingly, in many scenarios, the optimal policy is to wait for a certain time before submitting a new update. In particular, the widely-adopted zero wait policy can be far from the optimum if (i) the penalty function grows quickly with respect to the age, and (ii) the update service times are highly random and positive correlated.

**Appendix A**

**MATLAB Code for the Example**

```matlab
sampleNum = 1e6;
Y = zeros(1,sampleNum);
Y(1:4:end) = 0.1; Y(2:4:end) = 0.1;
Y(3:4:end) = 1.7; Y(4:4:end) = 1.7;
YNext = [Y(2:end) 0.1];
Z = zeros(1,sampleNum);
AgeZeroWait = ...
    mean(1/2*(Y+Z).*Y+Z).*YNext)/mean(Y+Z)
Z(1:4:end) = 0.6; Z(2:4:end) = 0.6;
AgeSecond = ...
    mean(1/2*(Y+Z).*Y+Z).*YNext)/mean(Y+Z)
```

**Appendix B**

**Proof of Theorem 1**

### A. An Upper Bound of $\overline{\gamma}_{opt}$

By restricting $\Pi$ in Problem (4) to $\Pi_{SR}$, we obtain the following problem:

$$
\overline{\gamma}_{SR} = \min_{\pi \in \Pi_{SR}} \limsup_{n \to \infty} \frac{1}{n} \sum_{i=0}^{n-1} \mathbb{E}[q(Y_i, Z_i, Y_{i+1})] \\
\text{s.t. } \liminf_{n \to \infty} \frac{1}{n} \sum_{i=0}^{n-1} (Y_i + Z_i) \geq T_{min},
$$

(19)

where $\overline{\gamma}_{SR}$ is the optimum objective value of Problem (19). Since $\Pi_{SR} \subseteq \Pi$, we can obtain

$$
\overline{\gamma}_{SR} \geq \overline{\gamma}_{opt},
$$

(20)

It is easy to show that the $(Y_i, Z_i, Y_{i+1})$'s are stationary and ergodic for all stationary randomized policies. This, together with the condition that $q(\cdot)$ is measurable, tells us that $q(Y_i, Z_i, Y_{i+1})$ is stationary and ergodic [10] Theorems 7.1.1 and 7.1.3. For any stationary randomized policy $\pi = (Z_0, Z_1, \ldots) \in \Pi_{SR}$, we obtain

$$
\frac{1}{n} \sum_{i=0}^{n-1} q(Y_i, Z_i, Y_{i+1}) = \mathbb{E}[q(Y_0, Z_0, Y_1)],
$$

(21)

$$
\frac{1}{n} \sum_{i=0}^{n-1} (Y_i + Z_i) = \mathbb{E}[Y_0 + Z_0].
$$

(22)

Hence, Problem (19) can be reformulated as Problem (7).
B. The Upper Bound of $\mathcal{G}_{\text{opt}}$ is Tight, i.e., $\mathcal{G}_{\text{SR}} = \mathcal{G}_{\text{opt}}$

We will show $\mathcal{G}_{\text{SR}} = \mathcal{G}_{\text{opt}}$ in 4 steps. The following definitions are needed: Since $\mathcal{G}_{\text{SR}}$ is finite, for each causally feasible policy $\pi = (Z_0, Z_1, \ldots) \in \Pi$ we can define $a_{n, \pi}$ and $b_{n, \pi}$ as in (3) and (4), respectively.

Further, define $\Gamma_{\text{SR}}$ as the set of limit points of sequences $((a_{n, \pi}, b_{n, \pi}), n = 1, 2, \ldots)$ associated with all stationary randomized policies $\pi \in \Pi_{\text{SR}}$. Because the renewal reward $q(Y_i, Z_i)$ and renewal interval $Y_i + Z_i$ are stationary and ergodic for all stationary randomized policies $\pi \in \Pi_{\text{SR}}$, the sequence $(a_{n, \pi}, b_{n, \pi})$ has a unique limit point in the form of

$$
(E[q(Y, Z, Y')] - \mathcal{G}_{\text{opt}} E[Y + Z], E[Y + Z]) .
$$

(23)

Hence, $\Gamma_{\text{SR}}$ is the set of all points $(E[q(Y, Z, Y')] - \mathcal{G}_{\text{opt}} E[Y + Z], E[Y + Z])$, where each point is associated with a conditional probability measure $p(y, A) = \text{Pr}(Z \in A | Y = y)$, and the measure of $(Y, Y')$ is the same as that of $(Y_0, Y_1)$. Note that $E[Y] = E[Y']$.

Step 1: We will show that $\Gamma_{\text{SR}}$ is a convex and compact set.

It is easy to see that $\Gamma_{\text{SR}}$ is convex by considering a stationary randomized policy that is a mixture of two stationary randomized policies.

For compactness, let $((d_j, e_j), j = 1, 2, \ldots)$ be any sequence of points in $\Gamma_{\text{SR}}$, we need to show that there is a convergent subsequence $(d_{j_k}, e_{j_k})$ whose limit is also in $\Gamma_{\text{SR}}$. Since $(d_j, e_j) \in \Gamma_{\text{SR}}$, there must exist $(Y, Z_j, Y')$ with conditional probability $p_j(y, A) = \text{Pr}(Z_j \in A | Y = y)$, such that $d_j = E[q(Y, Z_j, Y')] - \mathcal{G}_{\text{opt}} E[Y + Z_j], e_j = E[Y + Z_j]$. Let $\mu_j$ be the joint probability measure of $(Y, Z_j, Y')$, then $(d_j, e_j)$ is uniquely determined by $\mu_j$. For any $L$ satisfying $L \geq M$, we can obtain

$$
\mu_j(Y \leq L, Z_j \leq L, Y' \leq L) = \text{Pr}(Y \leq L, Y' \leq L) \geq \text{Pr}(Y + Y' \leq L) \geq 1 - \frac{E[Y + Y']}{L}, \quad \forall j,
$$

where the equality is due to the fact that $Z_j \leq M \leq L$ and the last inequality is due to Markov’s inequality. Therefore, for any $\epsilon$, there is an $L$ such that

$$
\liminf_{j \to \infty} \mu_j(\{Y \leq L, |Z(j)| \leq L, |Y'| \leq L\}) \geq 1 - \epsilon.
$$

Hence, the sequence of measures $\mu_j$ is tight. By Helly’s selection theorem [10, Theorem 3.9.2], there is a subsequence of measures $\mu_{j_k}$ that converges weakly to a limit measure $\mu_\infty$.

Let $(Y, Z(\infty), Y')$ and $p_\infty(y, A) = \text{Pr}(Z(\infty) = A | Y = y)$ denote the random vector and conditional probability corresponding to the limit measure $\mu_\infty$, respectively. We can define $d_\infty = E[q(Y, Z(\infty), Y')] - \mathcal{G}_{\text{opt}} E[Y + Z(\infty)]$, $e_\infty = E[Y + Z(\infty)]$. Since the function $q(y, z, y')$ is in the form of an integral, it is continuous and thus measurable. Using the continuous mapping theorem [10, Theorem 3.2.4], we can obtain that $q(y, Z(j_k), Y')$ converges weakly to $q(Y, Z(\infty), Y')$. Then, using the condition (3), together with the dominated convergence theorem (Theorem 1.6.7 of [10] and Theorem 3.2.2 of [10]), we can obtain $\lim_{k \to \infty} (d_{j_k}, e_{j_k}) = (d_\infty, e_\infty)$. Hence, $((d_j, e_j), j = 1, 2, \ldots)$ has a convergent subsequence. Further, we can generate a stationary randomized policy $\pi_{\infty, \text{SR}}$ by using the conditional probability $p_\infty(y, A)$ correspond-
Taking the lim sup in this inequality and using (24), yields
\[ \limsup_{n \to \infty} \alpha_n, \pi_{opt} \leq 0. \] (26)
Because \((a^*, b^*)\) is one limit point of \((a_n, \pi_{opt}, b_n, \pi_{opt})\), we have
\[ a^* \leq \limsup_{n \to \infty} a_n, \pi_{opt}, b^* \geq \liminf b_n, \pi_{opt}. \] (27)
By (25)-(27), we have \(a^* \leq 0\) and \(b^* \geq T_{min}\).

**Step 4:** We will show that there exists a stationary randomized policy that is optimal for Problems (4) and (7), and thus \(\gamma_{SR} = \gamma_{opt}\). By the definition of \(\Gamma_{SR}\), \((a^*, b^*) \in \Gamma_{SR}\) must be the limit point generated by a stationary randomized policy \(\pi^* \in \Pi_{SR}\). Let \((Y, Z, Y')\) be a random vector with the stationary distribution of policy \(\pi^*\). Then, (25) implies
\[ (a^*, b^*) = (E[q(Y, Z^*, Y')], E[Y + Z^*], E[Y + Z^*]). \]
Using \(a^* \leq 0\) and \(b^* \geq T_{min}\), we can obtain
\[ E[q(Y, Z^*, Y')] - E[Y + Z^*] \gamma_{opt} \leq 0, \]
\[ E[Y + Z^*] \geq T_{min}. \]
By (28) and \(E[Y + Z^*] > 0\), we have
\[ \frac{E[q(Y, Z^*, Y')]}{E[Y + Z^*]} \leq \gamma_{opt}. \]
Further, the inequality (29) suggests that the stationary randomized policy \(\pi^*\) is feasible for Problem (7). Hence,
\[ \frac{E[q(Y, Z^*, Y')]}{E[Y + Z^*]} \geq \gamma_{SR}. \]
Therefore, \(\gamma_{SR} \leq \gamma_{opt}\). This and (20) suggest that
\[ \frac{E[q(Y, Z^*, Y')]}{E[Y + Z^*]} = \gamma_{SR} = \gamma_{opt}. \]
This completes the proof.

**APPENDIX C**

**PROOF OF THEOREM 2**

Consider an arbitrarily chosen stationary randomized policy \(\pi_1 \in \Pi_{SR}\) that is feasible for problem (7). We will show that there exists a feasible stationary deterministic policy that is no worse than policy \(\pi_1\).

For any \(y\), we can use the conditional probability \(p(y, A)\) associated with policy \(\pi_1\) to compute the conditional expectation \(E[Z|Y = y]\) by
\[ E[Z|Y = y] = \int_0^\infty z p(y, dz). \]
Since the conditional expectation \(E[Z|Y]\) is unique w.p.1 (Section 5.1), there is a deterministic function \(z(\cdot)\) such that \(z(y) = E[Z|Y = y]\) w.p.1. Consider the set \(\Lambda \subset \Pi_{SR}\) of all stationary randomized policies that satisfy \(E[Z|Y] = z(Y)\) w.p.1. Then, the stationary randomized policy \(\pi_1\) is in \(\Lambda\). The stationary deterministic policy \((Z_i = z(Y_i), i = 1, 2, \ldots)\) is also in \(\Lambda\).

Using the iterated expectation,
\[ E[Y + Z] = E[Y + E[Z|Y]], \] (30)
which remains constant for any policy in \(\Lambda\). Because \(\pi_1 \in \Lambda\) is feasible for problem (7), any policy in \(\Lambda\) is feasible for problem (7).

Since \(q(y, z, y')\) is the integral of a non-decreasing function \(g\), it is easy to show that the function \(q(y, z, y')\) is convex. For any policy \(\pi \in \Lambda\), Jensen’s inequality tells us that
\[ E[q(Y, Z, Y')|Y, Y'] \geq q(Y, E[Z|Y, Y'], Y') = q(Y, E[Z|Y], Y') = q(Y, z(Y'), Y'), \] (31)
where (31) is due to the fact that \(Z\) is determined based on \(Y\), but not \(Y'\). Taking the expectation over \((Y, Y')\), yields
\[ E[q(Y, z(Y'), Y')] \leq E[q(Y, Z, Y')] \]
for any policy \(\pi \in \Lambda\), where equality holds if \(Z = z(Y)\). This and (30) suggest that the stationary deterministic policy \((Z_i = z(Y_i), i = 1, 2, \ldots)\) achieves the smallest objective value for problem (7) among all policies in \(\Lambda\). In conclusion, for any feasible stationary randomized policy \(\pi_1 \in \Pi_{SR}\), we can find a feasible stationary deterministic policy that is no worse than policy \(\pi_1\). This completes the proof.

**APPENDIX D**

**PROOF OF LEMMA 1**

We need the following lemma:

**Lemma 4:** If \(l : \mathbb{R} \to \mathbb{R}\) is a convex function, then the functional \(w : L^2(\mu_Y) \to \mathbb{R}\) defined by
\[ w(z) = \int_0^\infty l(z(y)) d\mu_Y(y) \] (32)
is also convex.

**Proof:** For any \(\lambda \in [0, 1]\) and \(z_1, z_2 \in L^2(\mu_Y)\), we have
\[ w(\lambda z_1 + (1 - \lambda) z_2) = \int_0^\infty l(\lambda z_1(y) + (1 - \lambda) z_2(y)) d\mu_Y(y) \leq \int_0^\infty \left[ \lambda l(z_1(y)) + (1 - \lambda) l(z_2(y)) \right] d\mu_Y(y) = \lambda w(z_1) + (1 - \lambda) w(z_2). \] (33)
By this, \(w(z)\) is convex.

We now prove Lemma 1. Since \(q(y, z, y')\) is the integral of a non-decreasing function \(g\), it is easy to show that the function \(q(y, z, y')\) is non-negative and convex. Hence, the conditional expectation \(E[q(Y, Z, Y')|Y = y]\) is also convex. We can obtain
\[ E[q(Y, z(Y'), Y')] = \int_0^\infty E[q(y, z(y'), Y')|Y = y] d\mu_Y(y). \] (34)
According to Lemma 4, \(E[q(Y, z(Y'), Y')]\) is a convex functional of \(z\) and \(E[Y + z(Y')]\) is an affine functional of \(z\). It is known that the ratio of a non-negative convex functional and positive affine functional is quasi-convex (28, p. 103). Hence, \(h(z)\) is quasi-convex, which completes the proof.
We use the Lagrangian duality approach to solve Problem (10). The Lagrangian of Problem (10) is
\[
L(z, \zeta, \gamma, \tau) = \int_0^\infty \mathbb{E}[q(y, z(y), Y')|Y = y] \, d\mu_y(y) - c \int_0^\infty [y + z(y)] \, d\mu_y(y) + \zeta \left[ T_{\min} - \int_0^\infty [y + z(y)] \, d\mu_y(y) \right] - \int_0^\infty \gamma(y)z(y) \, d\mu_y(y) + \int_0^\infty \tau(y)(z(y) - M) \, d\mu_y(y) = \int_0^\infty \left\{ \mathbb{E}[q(y, z(y), Y')|Y = y] - (c + \zeta)[y + z(y)] - \gamma(y)z(y) + \tau(y)[y - M] \right\} \, d\mu_y(y) + \zeta T_{\min}. \tag{35}
\]
Since Problem (10) is feasible, all constraints are affine, the refined Slater’s condition [28, Sec. 5.2.3] is satisfied. According to [29, Proposition 3.3.2] and [30, pp. 70–72], the Karush-Kuhn-Tucker (KKT) theorem remains valid for the Lebesgue space $L^2(\mu_y)$. Hence, if a vector $(z, \zeta, \gamma, \tau)$ satisfies the KKT conditions (36)-(42), it is an optimal solution to (10). The KKT conditions are given by
\[
z = \min_{x \in L^2(\mu_y)} L(x, \zeta, \gamma, \tau), \tag{36}
\]
\[
\zeta \geq 0, \int_0^\infty [y + z(y)] \, d\mu_y(y) \geq T_{\min}, \tag{37}
\]
\[
\gamma(y) \geq 0, z(y) \geq 0, \forall y \geq 0, \tag{38}
\]
\[
\tau(y) \geq 0, z(y) \leq M, \forall y \geq 0, \tag{39}
\]
\[
\zeta \left[ T_{\min} - \int_0^\infty [y + z(y)] \, d\mu_y(y) \right] = 0, \tag{40}
\]
\[
\gamma(y)z(y) = 0, \forall y \geq 0, \gamma(y)z(y) = 0, \tag{41}
\]
\[
\tau(y)(z(y) - M) = 0, \forall y \geq 0. \tag{42}
\]
We now solve the KKT conditions (36)-(42) by using the calculus of variations. The one-sided Gâteaux derivative (similar to sub-gradient in finite dimensional space) of a functional $h$ in the direction of $w \in L^2(\mu_y)$ at $z \in L^2(\mu_y)$ is defined as
\[
\delta h(z; w) \triangleq \lim_{\epsilon \to 0^+} \frac{1}{\epsilon} \left[ h(z + \epsilon w) - h(z) \right]. \tag{43}
\]
If $h$ is a function on $\mathbb{R}$, then [43] becomes the common one-sided derivative. Let $l(z, y, \zeta, \gamma, \tau)$ denote the integrand in (35), and $r(z, y) = \mathbb{E}[q(y, z(y), Y')|Y = y]$. According to Lemma [3] the function $q(y, z, y')$ and functionals $r(z, y), l(z, y, \zeta, \gamma, \tau)$, and $L(z, \zeta, \gamma, \tau)$ are all convex in $z$. Therefore, their one-sided Gâteaux derivatives with respect to $z$ exist [31, p. 709]. Since $g(x)$ is right-continuous, for any given $(y, y')$, the one-sided derivative $\delta q(y, z; w, y')$ of $q$ with respect to $z$ is given by
\[
\delta q(y, z; w, y') = \lim_{\epsilon \to 0^+} \frac{1}{\epsilon} \left\{ q(y, z + \epsilon w, y') - q(y, z, y') \right\}
\]
for all $x > z(y)$, and
\[
\mathbb{E}[g(y+x+Y)|Y = y] - (c + \zeta) - \gamma(y) + \tau(y) \leq 0
\] (50)
for all $x < z(y)$. If the function $g(\cdot)$ is not strictly increasing, the solutions to (49) and (50) may not be unique. In particular, there may exist an interval $[a(y), b(y)]$ such that each $z(y) \in [a(y), b(y)]$ satisfies (49) and (50) for some $y$. In this case, we choose the largest possible solution $z(y) = b(y)$ to make sure that the constraint (2) is satisfied. If $\gamma(y) = \gamma(y) = 0$, then the largest solution satisfying (47) and (48) is given by
\[
z(y) = \sup\{x \in [0, M] : \mathbb{E}[g(y+x+Y)|Y = y] \leq c + \zeta\},
\]
which is exactly (11). If $\gamma(y) > 0$, then by (44), $z(y) = 0$ which is satisfied by (11). If $\tau(y) > 0$, then by (42), $z(y) = M$ which is satisfied by (11). In summary, (47) and (48) have a solution given by (11).

By (37) and (40), the optimal $\zeta$ satisfies
\[
\zeta = 0, \mathbb{E}[Y + z(Y)] \geq T_{\min}
\] (51)
or
\[
\zeta > 0, \mathbb{E}[Y + z(Y)] = T_{\min},
\] (52)
where $\mathbb{E}[Y + z(Y)]$ is determined by the optimal primal solution (11). Since $\mathbb{E}[Y + z(Y)]$ is non-decreasing in $\zeta$, we can use bisection to search for the optimal $\zeta$. By this, an optimal solution to (10) is obtained for any given $c$. Finally, according to Sections 4.2.5 and 11.4 of [28], the optimal $c$ is solved by an outer-layer bisection search. Therefore, an optimal solution to Problem (8) is given by Algorithm 1. This completes the proof.

APPENDIX F

PROOF OF LEMMA 2

Let us rewrite the functional $h_1$ as
\[
h_1(z) = \frac{\int_0^\infty [y + z(y)]^2 d\mu_Y(y)}{\int_0^\infty [y + z(y)] d\mu_Y(y)}.
\]
We need to prove that the functional $h_1$ is convex when restricted to any line that intersects its domain. For any $w \in L^2(\mu_Y)$, consider the function $u : \mathbb{R} \rightarrow \mathbb{R}$ defined as
\[
u(\epsilon) = \frac{\int_0^\infty (z(y) + \epsilon w(y) + y)^2 d\mu_Y(y)}{\int_0^\infty (z(y) + \epsilon w(y) + y) d\mu_Y(y)}
\]
with domain
\[
\text{dom } u = \{\epsilon : z(y) + \epsilon w(y) \in [0, M], \forall y \geq 0, \epsilon \in \mathbb{R}\}.
\]
Since the function $\epsilon \rightarrow [z(y) + \epsilon w(y) + y]^2$ is convex, the function $x \rightarrow \{[z(y) + (\epsilon + x) w(y) + y]^2 - [z(y) + \epsilon w(y) + y]^2\}/x$ is non-decreasing and bounded from above in a neighborhood of 0. By using monotone convergence theorem [10 Theorem 1.5.6], we can interchange the limit and integral operators such that
\[
\frac{d}{d\epsilon} \int_0^\infty [z(y) + \epsilon w(y) + y]^2 d\mu_Y(y) = \int_0^\infty 2[z(y) + \epsilon w(y) + y]^2 d\mu_Y(y).
\]
Similarly,
\[
\frac{d}{d\epsilon} \int_0^\infty [z(y) + \epsilon w(y) + y] d\mu_Y(y) = \int_0^\infty w(y) d\mu_Y(y).
\]
By this, we have
\[
\frac{d^2 u}{d\epsilon^2} = \frac{\int_0^\infty [z(y) + \epsilon w(y) + y] d\mu_Y(y)}{\int_0^\infty [z(y) + \epsilon w(y) + y]^2 d\mu_Y(y)}
\]
\[
\times \int_0^\infty \left[\frac{y + z(y)}{\int_0^\infty [y + z(y)] d\mu_Y(y)} - \frac{w(y)}{\int_0^\infty w(y) d\mu_Y(y)}\right]^2 d\mu_Y(y).
\]
Since $z(y) + \epsilon w(y) \geq 0$ for all $y$ on dom $u$, we have $\frac{d^2 u}{d\epsilon^2} \geq 0$. Hence, the function $u$ is convex for all $w \in L^2(\mu_Y)$. By this, the functional $h_1$ is convex, which completes the proof.

APPENDIX G

PROOF OF THEOREM 4

The Lagrangian of Problem (13) is determined as
\[
L_1(z, \zeta, \tau, \gamma) = \frac{\int_0^\infty [y + z(y)]^2 d\mu_Y(y)}{2 \int_0^\infty [y + z(y)] d\mu_Y(y)} + \zeta \left[T_{\min} - \int_0^\infty [y + z(y)] d\mu_Y(y)\right] - \int_0^\infty \gamma(y) z(y) d\mu_Y(y) + \int_0^\infty \tau(y) (z(y) - M) d\mu_Y(y),
\]
where $\zeta \in \mathbb{R}, \gamma, \tau \in L^2(\mu_Y)$ are dual variables. According to [29 Proposition 3.3.2] and [30 pp. 70-72], the KKT theorem remains valid for the Lebesgue space $L^2(\mu_Y)$. Hence, if a vector $(z, \zeta, \gamma, \tau)$ satisfies the KKT conditions (53)-(60), it is an optimal solution to (13). The KKT conditions are given by:
\[
z = \min_{x \in L^2(\mu_Y)} L_1(x, \zeta, \gamma, \tau),
\] (54)
\[
\zeta \geq 0, \int_0^\infty [y + z(y)] d\mu_Y(y) \geq T_{\min},
\] (55)
\[
\gamma(y) \geq 0, z(y) \geq 0, \forall y \geq 0,
\] (56)
\[
\tau(y) \geq 0, z(y) \leq M, \forall y \geq 0,
\] (57)
\[
\gamma(y) z(y) = 0, \forall y \geq 0,
\] (58)
\[
\tau(y) (z(y) - M) = 0, \forall y \geq 0.
\] (59)

We now solve the KKT conditions by using the calculus of variations. For any fixed $(\zeta, \gamma, \tau)$, the Gâteaux derivative of the Lagrange $L_1$ in the direction of $w \in L^2(\mu_Y)$ at $z \in L^2(\mu_Y)$ is defined as
\[
\delta L_1(z; w, \zeta, \gamma, \tau) = \lim_{\epsilon \rightarrow 0} \frac{L_1(z + \epsilon w, \zeta, \gamma, \tau) - L_1(z, \zeta, \gamma, \tau)}{\epsilon}
\]
Similar to the derivations of (53), we can obtain
\[
\delta L_1(z; w, \zeta, \gamma, \tau) = \int_0^\infty \left[ \frac{y + z(y)}{\int_0^\infty [y + z(y)]d\mu_Y(y)} - \frac{\int_0^\infty [y + z(y)]^2d\mu_Y(y)}{2 \left[ \int_0^\infty [y + z(y)]d\mu_Y(y) \right]^2} \right] \cdot w(y)d\mu_Y(y) + \gamma(y) \cdot \forall w \in L^2(\mu_Y).
\]

Then, (54) if and only if (31) p. 710
\[
\delta L_1(z; w, \zeta, \gamma, \tau) \geq 0, \quad \forall w \in L^2(\mu_Y).
\]
By \( \delta L_1(z; w, \zeta, \gamma, \tau) = -\delta L_1(z; -w, \zeta, \gamma, \tau) \), we deduce
\[
\delta L_1(z; w, \zeta, \gamma, \tau) = 0, \quad \forall w \in L^2(\mu_Y).
\]
Since \( w(\cdot) \) is arbitrary, we have
\[
\int_0^\infty [y + z(y)]d\mu_Y(y) = \frac{\int_0^\infty [y + z(y)]^2d\mu_Y(y)}{2 \int_0^\infty [y + z(y)]d\mu_Y(y)} \cdot \forall y \geq 0.
\]
For notational simplicity, let us define
\[
\beta \triangleq \int_0^\infty [y + z(y)]d\mu_Y(y) = \frac{\int_0^\infty [y + z(y)]^2d\mu_Y(y)}{2 \int_0^\infty [y + z(y)]d\mu_Y(y)}.
\]
If \( \gamma(y) = \tau(y) = 0 \), then by (61) and (62), we obtain \( z(y) = \beta - y \). In this case, we require \( \beta - y \in [0, M] \) by (56) and (57). If \( \gamma(y) > 0 \), then by (59), \( z(y) = 0 \). If \( \tau(y) > 0 \), then by (59), \( z(y) = M \). In summary, the primal solution \( z \) is given by (13).

The value of \( \beta \) is obtained by considering two cases:

Case 1: \( \zeta > 0 \). Then, (58) and (62) imply that
\[
\int_0^\infty [y + z(y)]d\mu_Y(y) = T_{\min, \beta} \geq \frac{\int_0^\infty [y + z(y)]^2d\mu_Y(y)}{2 \int_0^\infty [y + z(y)]d\mu_Y(y)}.
\]
Case 2: \( \zeta = 0 \). Then, (55) and (62) imply that
\[
\int_0^\infty [y + z(y)]d\mu_Y(y) \geq T_{\min, \beta} \geq \frac{\int_0^\infty [y + z(y)]^2d\mu_Y(y)}{2 \int_0^\infty [y + z(y)]d\mu_Y(y)}.
\]
Combining (63) and (64), yields
\[
\int_0^\infty [y + z(y)]d\mu_Y(y) = \max \left( T_{\min}, \frac{\int_0^\infty [z(y) + y]^2d\mu_Y(y)}{2 \beta} \right).
\]
Then, (16) follows by subscribing (15) into this.

The solution of (15) and (16) satisfies the KKT conditions (54)–(60), and is thus an optimal solution to the convex optimization problem (13). This completes the proof.

APPENDIX H

PROOF OF LEMMA 3

1. When the correlation coefficient between \( Y_i \) and \( Y_{i+1} \) is \(-1\), \( Y + Y' \) is equal a constant value with probability one. Choosing \( z(y) = 0 \), \( \zeta = 0 \), \( c = g(Y + Y') \), \( \gamma(y) = \tau(y) = 0 \), one can show that the KKT conditions (56)–(42) are satisfied.
2. If the \( Y_i \)'s are equal to a constant value, \( Y + Y' \) is equal a constant value. The remaining proof follows from part 1.

3. When \( g(\cdot) \) is a constant function, all policies are optimal. This completes the proof.

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