Abstract

Reliability, longevity, availability, and deadline guarantees are the four most important metrics to measure the QoS of long-running safety critical real-time applications. Software aging is one of the major factors that impact the safety of long-running real-time applications as the degraded performance and increased failure rate caused by software aging can lead to deadline missing and catastrophic consequences. Software rejuvenation is one of the most commonly used approaches to handle issues caused by software aging. In this paper, we study the optimal time when software rejuvenation shall take place so that the system’s reliability, longevity, and availability are maximized, and application delays caused by software rejuvenation is minimized. In particular, we formally analyze the relationships between software rejuvenation frequency and system reliability, longevity, and availability. Based on the theoretic analysis, we develop approaches to maximizing system reliability, longevity, and availability, and use simulation to evaluate the developed approaches. In addition, we design the MIN-DELAY semi-priority-driven scheduling algorithm to minimize application delays caused by rejuvenation processes. The simulation experiments show that the developed semi-priority-driven scheduling algorithm reduces application delays by 9.01% and 14.24% over the earliest deadline first (EDF) and least release time (LRT) scheduling algorithms, respectively.

1 Introduction

As technology advances, computer systems become larger and more complex — applications are built on top of operating systems and frameworks; they
run in virtual environments and use third party software components and services. The situation naturally makes it more difficult or virtually impossible to develop a non-trivial system to be completely defect-free. A class of residual software defects produces non-catastrophic results, where applications continue to provide their functionality, but with degraded performance or increased use of resources. This process is typically referred to as software aging. Software aging is an accumulative process whose general characteristic is the gradual performance degradation and/or an increase in the software failure rate [11]. As system aging progresses, the degraded performance and accumulated errors can eventually lead to catastrophes, such as low reliability and/or availability. For instance, the Patriot’s software failure that resulted in loss of human life is caused by accumulated errors [21]. The Mars Surveyor ’98 Orbiter that launched in 1998 was designed for long term mission to study the climate on Mars. Unfortunately it only worked for 83 days before it was lost in the space [26].

In addition to reliability and availability, the system longevity is another important QoS factor for long running applications. In Fermi National Accelerator Laboratory, there are many physics experiments conducted on site, such as the Main Injector Neutrino Oscillation Search (MINOS), Muon g-2, NOvA, and muon-to-electron-conversion (Mu2e), to name a few [1]. These experiments need to run for as long as possible in order to observe desirable results, and at the same time, they need also be highly reliable and available during the experimental time. Hence, not only reliability and availability requirements of the control system need to be met; more importantly, the control systems that support the experiments must also be able to run for long time period because restarting these experiments has large human labors and financial cost. Unfortunately, aging effects significantly impact the longevity of these control systems at Fermilab.

Fig. 1 illustrates a fifteen day CPU utilization and memory usage of LabVIEW [2] running on a Fermilab machine that monitors hundreds of sensors at Fermilab. In theory, the resource consumption of the monitoring tool shall remain constant as it is running on a clean server and the sampling interval and data size are constant. However, from Fig. 1, we can clearly observe that both CPU and memory consumption increase linearly with time. Once CPU and/or memory usage level becomes too high, the system stops working properly.

Both hardware and software aging can potentially impact system’s reliability, availability and longevity. However, hardware wear and tear aging often takes longer time to show effects on computer systems [7]; while on the other hand, software aging happens more frequently compared to hardware aging, and software failures cause more outages than hardware failures in today’s computer systems [10]. As software aging is inevitable [23], software rejuvenation is proposed as a preventive and proactive fault-tolerance technique to deal with the aging issues [14]. Significant amount of research is devoted to address how to perform software rejuvenation and different approaches are proposed to rejuvenating software at different levels. In [9], Cotroneo et al. surveyed over four hundred recent research papers in the area of software aging and rejuvenation techniques. A comparative experimental study of software rejuvenation
overhead can be found in [3].

However, in this paper, rather than study how to perform software rejuvenation, we focus on when to perform software rejuvenation and the relationship between software rejuvenation time points and system QoS in terms of system reliability, availability and longevity. We consider three types of control applications: (1) applications that need high reliability within its given lifetime, (2) applications that need long longevity under a reliability constraint, and (3) applications that need high availability under given reliability and longevity constraints. For each of these three types of applications, we present an optimal software rejuvenation period. In addition, we develop a semi-priority-driven MIN-DELAY scheduling algorithm that minimizes application execution delay caused by performing system rejuvenation.

The rest of the paper is organized as follows: we discuss related work in Section 2. System models and assumptions the paper is based upon are presented in Section 3. A formal definition of the problem the paper is to address is also presented in Section 3. System reliability, longevity, and availability maximizations are discussed in Section 4, Section 5, and Section 6, respectively. We introduce a semi-priority-driven MIN-DELAY scheduling algorithm in Section 7. In each of the sections where mathematical analysis is performed or a new algorithm is developed, i.e., Section 4, Section 5, Section 6, and Section 7, we have a subsection to discuss simulation results. Finally, Section 8 concludes the paper.
2 Related Work

Reliability, availability and longevity are three different but correlated factors that measure a system’s QoS. A highly reliable system often has high availability and can run for a long period of time. Hence, researchers and engineers have been mainly focused on system reliability issues. Many fault-tolerance mechanisms have been developed to improve system’s reliability. A commonly used fault-tolerance mechanism is redundancy [16, 13]. Redundancy refers to systems that use backup components with the same functionality as the running components. When failures occur, systems switch the functionality to their backup components to maintain operation continuity. Replication is also a widely used fault-tolerance mechanism [25]. Replication ensures computation and data are duplicated on the replicas and a voting scheme is used to decide the correct answers of the system. Another widely adapted fault-tolerance technique to deal with system failures is checkpointing and re-execution [8, 18]. With checkpointing, the failed system is recovered from previously stored correct state and re-executed only from the checkpointed state. These fault-tolerance techniques aforementioned may not be able to solve software aging issues unless a failure causes the system to reboot which resets the system to a fresh and healthy state.

Software rejuvenation has become a commonly used preventive and proactive maintenance approach for handling system aging. It is first proposed by Huang et al. [14], and is adopted in different domains, such as telecommunication systems [14, 13] and long-life deep-space mission systems [27, 29, 28].

Huang et al. developed a four-state model in which a computer system operates, i.e., the Robust State, Failure Probable State, Failure State, and Rejuvenation State [14]. Since then, many rejuvenation models have been developed by the research community [14, 13]. For instance, the five-state model [13] adds a new state called Preparing State to represent when a system finishes executing tasks or migrating tasks to another processor if the system has a backup component. Koutras et al. extended the initial rejuvenation model by considering two levels of rejuvenation actions [16, 24], i.e., perfect rejuvenation action and minimal rejuvenation action. The perfect rejuvenation (cold rejuvenation) results in system returning to the Robust State (initial state), while the minimal rejuvenation (warm rejuvenation) results in system returning to the Failure Probable State (the state before rejuvenation). The cost of minimal rejuvenation is much less than the perfect rejuvenation.

To analyze software aging and study aging related failures, Trivedi et al. [31] presented two approaches: analytic modeling approach for determining optimal times to rejuvenate and measurement based approach for failure detection and validation. Tai et al. [29] identified key factors that may impact system reliability and developed an approach to maximizing system reliability by analyzing the optimal interval between maintenances. Okamura et al. [22] discussed an maintenance policy that combines aperiodic rejuvenation and periodic checkpoints to maximize the system availability. The estimators of reliability and availability were analyzed in [24, 17].

In this paper, we study when to perform rejuvenation to improve system’s re-
liability, longevity, and availability for long-running applications with real-time constraints. In the study, both transient failures caused by aging effects and network transmission failures caused by migrating applications between main and backup processing units are taken into consideration in determining an optimal rejuvenation period. In addition, we also study how a task scheduling algorithm can minimize application execution delay caused by system rejuvenation processes.

3 System Models and Problem Formulation

In this section, we first introduce the models and assumptions our work is based upon and then formulate the problem we are to address in the paper.

3.1 Models and Assumptions

Processing Unit State Transition Model

We adopt the same model and assumptions used in [14], i.e., we assume a processing unit has the following four states, and the state transition model is shown in Fig. 2.

- Robust State $S_0$: the processing unit starts in this state.
- Failure Probable State $S_P$: the processing unit goes into this state after continuously running for some time.
- Failure State $S_F$: the processing unit may go into the failure state from the failure probable state $S_P$. Once the processing unit is in failure state it has to be rebooted in order to go back into the robust state $S_0$. The time it takes for the processing unit to reboot is $E_b$.
- Rejuvenation State $S_R$: from the failure probable state $S_P$ the processing unit may also go into the rejuvenation state $S_R$. The processing unit performs software rejuvenation once it enters into the state and goes into the robust state $S_0$ once the rejuvenation process is completed. The time it takes for the processing unit to go through rejuvenation is $E_r$.

The processing unit is unavailable when it goes through either reboot or rejuvenation process. The processing unit downtime caused by each reboot or rejuvenation is assumed to be a constant $E_b$ and $E_r$, respectively. We assume $E_b \gg E_r$. Hence, our goal is to prevent the processing unit ever enters into the failure state $S_F$ through rejuvenation.

System Model

To guarantee timing and QoS constraints, we use the same two-processor architecture as in [29, 12]. More specifically, we assume the system contains two homogeneous and independent processing units, i.e., a main processing unit $P_M$ and a backup processing unit $P_B$. Though the two processing units can be
dedicated to real-time applications and alternate between being idle or going through rejuvenation and processing real-time tasks similar to [29, 12], with this approach, the two processing units are not fully utilized and in fact, most of the time, at least one processing unit is in an idle state. To better utilize both of the processing units and avoid resource waste, we assume that the main processing unit $P_M$ executes real-time tasks and the backup processing unit $P_B$ executes non real-time tasks when the main processing unit operates correctly, and executes real-time tasks when $P_M$ goes through maintenance mode. The system model is shown in Fig. 3.

To avoid failure caused by aging effects, we assume that the main processing unit does rejuvenation periodically with a period $T_r$. Rejuvenation takes $E_r$ to complete, we assume $T_r > E_r$. When the main processing unit starts a rejuvenation process, to guarantee real-time tasks still meet their deadlines, some or all of the real-time tasks on the main processing unit are migrated to the backup processing unit to continue their executions [29]. The backup processing unit temporarily suspends its non real-time tasks and gives higher priority to the real-time tasks migrated from the main processing unit. For planned rejuvenation, the start time of a rejuvenation process is known a priori, hence we can reasonably assume that, from real-time task’s perspective, the overhead for backup processing unit to suspend its execution of non real-time tasks is negligible [29].

Furthermore, as the backup processing unit does not contain tasks with deadline constraints, it can frequently be rebooted or rejuvenated at time when
the main processing unit operates in robust state. Hence, we can further assume that the backup processing unit $P_B$ is always in the robust state when the main processing unit $P_M$ is in rejuvenation state.

**Real-Time Task Model**

The real-time task model considered in this paper is similar to the one defined by Liu and Layland [19]. A task set $\Gamma = \{\tau_1, \tau_2, \ldots, \tau_n\}$ has $n$ independent periodic tasks that are all released at time 0. Each task $\tau_i \in \Gamma$ is a 2-tuple $(T_i, C_i)$, where $T_i$ is the inter-arrival time between any two consecutive jobs of $\tau_i$ (also called period), and $C_i$ is the worst-case execution time (WCET). The deadline of each task is equal to its period. The hyper-period of $\Gamma$ is defined as the LCM (Least Common Multiple) of each task’s period, i.e., $H = \text{LCM}\{T_1, T_2, \ldots, T_n\}$.

In the system, task preemptions and task migrations are permitted. We also assume that the overhead associated with task preemptions and migrations is considered into the task’s worst case execution time.

**Network Failure Model**

As the main processing unit $P_M$ and the backup processing unit $P_B$ may locate on different computers, the task migrations between the two processing units need to be completed over a network. We take the same assumption as in [5] that the network transmission failure model follows Poisson distribution, i.e., it has a constant failure rate $\lambda_0$. Task migrations between $P_M$ and $P_B$ may fail because of network transmission failures. With constant network transmission failure rate, the probability of a successful task migration is hence a constant and it is denoted as $\rho$. If $P_M$ and $P_B$ locate on the same computer, then $\rho = 1$.

**Aging Caused Transient Failure Model**

Since transient faults are more frequent than permanent faults [15], we only consider the transient faults. As the system deteriorates with aging, we assume that the transient failure rate $\lambda(t)$ increases with time $t$ [11, 30]. The CDF (Cumulative Distribution Function) of transient fault is modeled as $F(t) = 1 - e^{-\int_0^t \lambda(x)dx}$ [4].

After each rejuvenation, the system transient failure rate and cumulative distribution function are reset to $\lambda(t_f) = \lambda(0) = 0$ and $F(t_f) = F(0) = 0$, where $t_f$ is the time point when a rejuvenation process completes.

Fig. 4 illustrates the behaviors of system rejuvenation and transient failure rate.

### 3.2 Problem Formulation

The models and assumptions defined in Section 3.1 indicate that the system reliability decreases over time because of the increased failure rate caused by aging effects. To maintain system reliability at the required level, on one hand, the system should perform rejuvenation frequently, but on the other hand, every
rejuvenation requires tasks being migrated to and back from the backup processing unit. Due to unreliable network, frequent migration between processing units can negatively affect the system reliability. Hence, there is a balanced point as to how frequently the system shall perform rejuvenation so that the system reliability can be maximized. When the system reliability requirement is given, the system longevity and availability are also impacted by rejuvenation frequency.

Furthermore, although rejuvenation can slow down aging process, i.e., slow down system transient failure increase rate, and improves system reliability, each rejuvenation not only causes the main processing unit being unavailable to process real-time tasks, it also delays the execution of non real-time applications deployed on the backup processing unit. In other words, system reliability, longevity, availability, and processing delay of non real-time applications can all be affected by the frequencies of software rejuvenation processes. In this paper, we are to address how to maximize system reliability, longevity, and availability and minimize delays for long-running applications with real-time constraints.

More specifically, we consider a real-time periodic task set $\Gamma$ which is deployed on main processing unit ($P_M$), and a backup processing unit ($P_B$) which is connected with the main processing unit through a network. Assume that the main processing unit transient failure rate is $\lambda(t)$ which increases with time, and the network transmission failure rate is a constant $\lambda_0$ which means the probability of successful task migration is also a constant $\rho$, we are to address following four questions:

**Problem 1: (Reliability Maximization)** Given a system longevity $L$, determine an optimal rejuvenation period $T_r$ that maximizes the system reliability $R(L,T_r)$ within its operational interval $[0, L]$.

**Problem 2: (Longevity Maximization)** Given a system reliability constraint $R_0$, determine an optimal rejuvenation period $T_r$ that maximizes the system operational interval $[0, L]$ in which the system reliability is guaranteed at $R_0$.

**Problem 3: (Availability Maximization)** Given system reliability $R_0$ and longevity $L$ constraints, determine an optimal rejuvenation period $T_r$ that maximizes the main processing unit’s availability $A(L,T_r)$ within its operational interval $[0, L]$.
Problem 4: (Delay Minimization) Given system reliability $R_0$ and longevity $L$ constraints, and rejuvenation period $T_r$, design a real-time task scheduling algorithm for the main processing unit that minimizes the delay of non real-time tasks on the backup processing unit.

4 System Reliability Maximization

4.1 Reliability Analysis

System reliability is defined as the probability that the system operates without failure within a given time interval [4]. We refer system longevity as its longest operational interval with guaranteed reliability. Assume the time interval the system operates is $[0, L]$, and the rejuvenation period is $T_r$, then the system performs $(\lceil L/T_r \rceil - 1)$ times rejuvenation, and tasks migrate $2(\lceil L/T_r \rceil - 1)$ times between the main and the backup processing units. Hence, the system reliability within its longevity interval $[0, L]$ is

$$R(L, T_r) = \rho^{2(\lceil L/T_r \rceil - 1)} \cdot \bar{F}(T_r) \cdot \bar{F}(t')$$  

where $t' = L - T_r \cdot (\lceil L/T_r \rceil - 1)$ and $\bar{F}(T_r) = 1 - F(T_r) = e^{-\int_{0}^{T_r} \lambda(t) dt}$ [12].

The following lemma gives the worst case system reliability under the settings defined above.

Lemma 1. Let system longevity be $L$ and rejuvenation period be $T_r$, if $L \mod T_r = 0$, then the system has the lowest reliability given by Eq. (2)

$$R(L, T_r) = \rho^{2(\lceil L/T_r \rceil - 1)} \cdot \bar{F}(T_r)^{\lceil L/T_r \rceil}$$  

Proof. As $L$ and $T_r$ are given, the first two factors in Eq. (1) are fixed. Hence, the reliability is minimal when $\bar{F}(t')$ is minimal.

As $\bar{F}(t)$ decreases with $t$, $\bar{F}(t')$ is minimal when $t' = T_r$, i.e., $L \mod T_r = 0$. Hence, we have Eq. (2). □

In the following discussions on system reliability, longevity, availability, and non real-time application execution delays, we focus on the case where the system has the worst case reliability, i.e., Eq. (2).

4.2 Reliability Maximization

Based on Eq. (2), system reliability is a function of two variables, i.e., $L$ and $T_r$. To identify the relationship between reliability and rejuvenation period, we derive the partial derivative of $R(L, T_r)$ with respect to the variable $T_r$ as
follows.
\[
\frac{\partial R(L, T_r)}{\partial T_r} = \frac{-2L}{T_r^2} \cdot \rho^2 \left(\frac{1}{T_r} - 1\right) \cdot F(T_r) \frac{dF}{dT_r} \cdot \ln \rho + \rho^2 \left(\frac{1}{T_r} - 1\right) \cdot F(T_r) \frac{dF}{dT_r} \cdot \left(-\frac{L}{T_r^2} \cdot \ln F(T_r) + \frac{L}{T_r} F(T_r) \cdot \frac{dF}{dT_r} dT_r\right)
\]

Let \( \frac{\partial R}{\partial T_r}(L, T_r) = 0 \), we have
\[
\frac{T_r}{F(T_r)} \cdot \frac{dF(T_r)}{dT_r} - \ln F(T_r) - 2 \ln \rho = 0. \tag{3}
\]

As Eq. (2) is a concave function, the optimal rejuvenation period that maximizes the system reliability can be calculated by solving Eq. (3) with given \( \lambda(t) \) and \( \rho \).

**Lemma 2.** The optimal rejuvenation period is only influenced by network transmission failure rate \( \lambda_0 \) and transient fault occurrence rate \( \lambda(t) \), but not by system longevity \( L \).

**Proof.** The lemma can be directly proven by Eq. (3), where \( F(t) = e^{-\int_0^t \lambda(x) dx} \), and \( \rho \) is a constant with fixed \( \lambda_0 \).

The Weibull distribution is commonly used to model the distribution of transient faults [4], with failure rate \( \lambda(t) = kt^{k-1}/r^k \) and cumulative distribution function \( F(t) = 1 - e^{-\left(t/r\right)^k} \), where \( r > 0 \) and \( k > 0 \) are scale and shape parameters. The failure rate increases with time \( t \) if \( k > 1 \).

In Section 3.1, we have made the assumption that due to aging effects, the system transient failure rate increases with time. Hence, we can use Weibull distribution with \( k > 1 \) to model aging effects. Substitute \( F(t) = e^{-\left(t/r\right)^k} \) into Eq. (3) and solve the equation, we obtain the optimal rejuvenation period that maximizes the system reliability as follows
\[
T_r^* = \sqrt[2k]{\frac{2r^k \ln \rho}{1 - k}}. \tag{4}
\]

### 4.3 Simulation Results

We use simulation to evaluate the relationship between rejuvenation period and system reliability. The simulation parameters are set as following:

- **Failure rate:** \( \lambda(t) = 3t^2/10^9 \)
- **Probability of a successful task migration between \( P_M \) and \( P_B \):** \( \rho = 0.99999 \)
- **System Longevity:** \( L \in \{100, 1000\} \)
- **Rejuvenation periods:** \( T_r \in \{1, 5, 10, \ldots, 95, 100\} \)
For each rejuvenation period, we use Eq. (1) to calculate the system reliability \( R(L, T_r) \). Fig. 5 shows the system reliability under different rejuvenation periods for both longevity settings.

![Figure 5: Reliability vs Rejuvenation Period](image)

From Fig. 5, we have the following observations:

1. When the rejuvenation period increases, the system reliability first increases and then decreases.

2. Neither too small rejuvenation period nor too large rejuvenation period has positive impact on the system reliability. Too frequent rejuvenation in fact lowers system reliability.

3. The experimental optimal rejuvenation period that maximizes the system reliability is consistent with the mathematical analysis (Eq. (3)). In particular, for both experiment settings the optimal rejuvenation period \( T_r = 20 \) is the nearest value with the mathematical analysis result \( T^*_r = 21.54 \) (Eq. (4)) among all provided rejuvenation periods.

4. The system longevity, i.e., its operation time, does not impact the optimal rejuvenation period for maximizing system reliability which is consistent with Lemma 2. In particular, the optimal rejuvenation is \( T_r = 20 \) for both \( L = 100 \) and \( L = 1000 \) experiment settings.
5 System Longevity Maximization

5.1 Longevity Analysis

System longevity is defined as the system operational time with guaranteed reliability $R_0$. Due to system aging, the system reliability decreases when its operational time increases. If the rejuvenation period $T_r$ is given, there is a maximal longevity with which the system reliability requirement $R_0$ is guaranteed. Our question is to determine the optimal rejuvenation period that maximizes the system's longevity without compromising the system's reliability requirement. Reliability decreasing rate is one of the critical factors that impacts the system's longevity. The slower the reliability function decreases, the longer the system runs reliably. The first derivative of the reliability function Eq. (2) with respect to $T_r$ represents how the reliability $R(L,T_r)$ changes with $T_r$. While the second derivative measures how fast the reliability $R(L,T_r)$ changes with $T_r$, i.e., the reliability decreasing rate. The reliability decreasing rate is given below

$$S(T_r) = \frac{\partial^2 R(L,T_r)}{\partial T^2_r} = \frac{\partial A}{\partial T_r}$$

where $A = -\frac{2L}{T_r^2} \cdot \rho^2 \cdot F(T_r) \cdot \ln \rho + \frac{4L}{T_r} \cdot \ln \rho \cdot \rho^2 \cdot F(T_r) \cdot \frac{\tau}{T_r}$ is the first derivative of $R(L,T_r)$ with respect to $T_r$. Noting that $S(T_r)$ is a concave function.

The problem of maximizing system longevity is now transformed to determine $T_r$ that minimizes the value of $S(T_r)$ given by Eq. (5).

To solve the problem, we obtain the first derivative of $S(T_r)$ and let the derivative be zero to calculate the optimal $T_r$. The first derivative of $S(T_r)$ is
calculated as follows.

\[
\frac{dS(T_r)}{dT_r} = 4L \cdot \ln \rho \cdot A - 2L \cdot \ln \rho \cdot \frac{dA}{dT_r} \\
- \frac{\rho}{T_r} \cdot \ln \rho \cdot R(T_r) + \frac{L}{T_r} \cdot \frac{dR(T_r)}{dT_r} \\
+ \frac{dA}{dT_r} \cdot \left( -\frac{1}{T_r} \cdot \ln R(T_r) + \frac{L}{T_r} \cdot \frac{dR(T_r)}{dT_r} \right) \\
+ 2A \cdot \frac{d}{T_r} \cdot \frac{dF(T_r)}{F(T_r)} - \frac{1}{T_r} \cdot \frac{dF(T_r)}{F(T_r)} \\
\]

\[
\frac{L}{T_r^2} \cdot \frac{dF(T_r)}{F(T_r)} + \frac{L}{T_r^2} \cdot \frac{dF(T_r)}{F(T_r)} \\
- \frac{L}{T_r^2} \cdot \frac{dF(T_r)}{F(T_r)} + \frac{L}{T_r^2} \cdot \frac{dF(T_r)}{F(T_r)} \\
+ B \cdot \frac{d^2F(T_r)}{d^2T_r} + \frac{L}{T_r^2} \cdot \frac{dF(T_r)}{F(T_r)} + \frac{L}{T_r^2} \cdot \frac{dF(T_r)}{F(T_r)} \\
\]

where \( B = -\frac{-L(\frac{dF(T_r)}{F(T_r)})^2}{(T_r \cdot (T_r))^2} \) and \( \frac{dB}{dT_r} = -\frac{-L(\frac{d^2F(T_r)}{dT_r})^2}{(T_r \cdot (T_r))^2} - 2(\frac{dF(T_r)}{F(T_r)})^2 - 2(\frac{dF(T_r)}{F(T_r)})^2 \).

As \( S(T_r) \), i.e. Eq. (5), is a concave function, the value \( T_r \) that satisfies \( \frac{dS(T_r)}{dT_r} = 0 \) is the optimal rejuvenation period that maximizes the system longevity under reliability requirement \( R_0 \).

### 5.2 Simulation Results

We use simulation to evaluate the relationship between rejuvenation period and system longevity under a given reliability constraint. The simulation parameters are set as following:

- Failure rate: \( \lambda(t) = 3t^2/10^9 \)
- Probability of a successful task migration between \( \mathcal{P}_M \) and \( \mathcal{P}_B \): \( \rho \in \{0.99999, 0.999999\} \)
- Reliability requirement: \( R_0 = 0.9997 \)
- Rejuvenation periods: \( T_r \in \{1, 5, 10, \ldots, 95, 100\} \)

As the system reliability decreases when the rejuvenation period increases, we calculate the maximal longevity satisfying \( R_0 \) by increasing the longevity from 0 until \( R_0 \) fails. Fig. 6 shows the maximal longevity that satisfies \( R_0 \) under different rejuvenation periods.

From Fig. 6, we have the following observations:

1. When the rejuvenation period increases, the longevity first increases and then decreases or remains the same. For instance, when \( \rho = 0.99999 \), the longevity increases when \( T_r \) increases from 1 to 25 and starts to decrease when \( T_r \) increases from 25 to 70. For a more reliable network, i.e., when \( \rho = 0.999999 \), the system longevity reaches its maximal value of 1,004 when the rejuvenation period is \( T_r = 10 \).
2. When the rejuvenation period is too short or too long, system’s longevity is short. For instance, $\rho = 0.99999$ and rejuvenation period is 1, the system longevity reaches its minimal value of 17. For a more reliable network, the minimal system longevity is 151. Although it is longer compared with a less reliable networked system, it is much shorter than its optimal longevity, which is 1,004 in this case, as shown in Fig. 6.

The reason behind these observations is that each rejuvenation requires task migrations between the main and backup processing units. Due to possible failures during task migrations, more frequent rejuvenation, i.e., a short rejuvenation period, encounters more transmission failures and hence results in short system longevity. When the network is more reliable, more frequent rejuvenation benefits system longevity as shown depicted in Fig. 6. On the other hand, due to software aging, transient failures increase as rejuvenation period increases. Hence, when the rejuvenation period is too long, the system longevity also decreases.

6 System Availability Maximization

6.1 Availability Analysis

Based on the system state model defined in Section 3, the system availability is defined as the probability that the system is in either robust state ($S_0$) or failure probable state ($S_P$) at a time instant [4]. In essence, system availability is the ratio between the system execution time and its longevity.
Assume within the system’s longevity $L$, the main processing unit $P_M$ performs $(\lceil L/T_r \rceil - 1)$ times of rejuvenations, the system downtime for each rejuvenation is $E_r$, then the availability of the main processing unit $P_M$ is

$$A(L, T_r) = \frac{L - (\lceil \frac{L}{T_r} \rceil - 1) \cdot E_r}{L}$$

(7)

where the rejuvenation cost $E_r$ is a constant.

Fig. 7 plots Eq. (7) under the same setting as for Fig. 6 with $E_r = 0.5$

![Figure 7: Availability vs Rejuvenation Period](image)

6.2 Availability Maximization under Reliability Constraint

Assume the system longevity is $L$, if the rejuvenation number is fixed, then the availability of the main processing unit $P_M$ is also fixed. According to Lemma 1, the system reliability achieves its minimal value when $L \mod T_r = 0$. For the availability maximization problem, we use the worst case reliability (Eq. (2)) to check the reliability requirement.

From Eq. (7), it is easy to see that the availability increases as rejuvenation period increases, i.e., the number of rejuvenation times decreases. If the system does not perform any rejuvenation, the availability is 100%. However, the system also has the reliability requirement $R_0$. According to the analysis in Section 4, it is possible that the system’s reliability decreases below the required level $R_0$ without rejuvenation if the operational time $L$ is long enough. Hence, there is an optimal rejuvenation period that maximizes the availability and at the same time guarantees the satisfaction of reliability requirement. The
MAX-AVA algorithm given in Algorithm 1 is designed to find such an optimal rejuvenation period. In particular, the MAX-AVA algorithm initially assumes that the system does not need to perform rejuvenation, i.e., assumes \( n = 0 \) and \( T_r = L \) (line 1-2). If the reliability requirement is violated when \( T_r = L \), we need to sacrifice availability by increasing the number of rejuvenation times until \( R_0 \) is satisfied (line 3-7). If the number of rejuvenations needed is too large that causes total rejuvenation time exceed the required system longevity, the algorithm returns \(-1\), signaling that the system fails to achieve the reliability requirement (line 8-10). Hence, system reboot becomes necessary.

Once we obtain the rejuvenation period \( (T_r) \) from the MAX-AVA algorithm, system maximal availability can be calculated by Eq. (7). We assume \( A(L, T_r) = 0 \) if the reliability requirement can not be satisfied, i.e., if MAX-AVA returns -1.

**Algorithm 1 MAX-AVA**

**Input:** System longevity \( L \), reliability constraint \( R_0 \).

**Output:** The optimal rejuvenation period \( T_r \) that maximize system availability.

1: \( n = 0 \)
2: \( T_r = L/(n + 1) \)
3: while \( R(L, L/n) < R_0 \land n \leq L \) do
4:   // \( R(L, L/n) \) is calculated according to Eq. (2)
5:   \( n = n + 1 \)
6:   \( T_r = L/(n + 1) \)
7: end while
8: if \( n > L \) then
9:   \( T_r = -1 \) // indicating failure
10: end if
11: return \( T_r \)

### 6.3 Simulation Results

We use simulation to reveal the relationship between rejuvenation period and availability of the main processing unit under a given system reliability constraint. The simulation parameters are set as following:

- Failure rate: \( \lambda(t) = 3t^2/10^9 \)
- Probability of a successful task migration between \( P_M \) and \( P_B \): \( \rho \in \{0.99999, 0.999999\} \)
- Reliability requirement: \( R_0 = 0.9997 \)
- Longevity: \( L = 100 \)
- Rejuvenation time cost: \( E_r = 0.5 \)
- Rejuvenation periods: \( T_r \in \{1, 5, 10, \ldots, 95, 100\} \)
For each rejuvenation period, we use Eq. (7) to calculate availability of the main processing unit. We assume $A(L, T_r) = 0$ if the reliability requirement cannot be satisfied. Fig. 7 shows the availability under different rejuvenation periods. From Fig. 7, we have the following observations:

1. In general, when rejuvenation period increases, system’s availability increases.

2. System availability has a maximum value. In particular, for a given system longevity value $L = 100$, the maximal system availability is 99.5% for both $\rho = 0.99999$ and $\rho = 0.999999$.

3. Too small or too large rejuvenation periods cause system reliability to decrease below the required level, hence causes the system to become unavailable, i.e., availability is 0. In particular, the system is unavailable when $T_r > 60$ for both cases, and when $T_r < 10$ for $\rho = 0.99999$.

By applying Algorithm 1, we obtain that when $T_r = 50$, the system achieves its maximal availability of 99.5%, which is consistent with the simulation results depicted in Fig. 7.

7 Delay Minimization

7.1 Scheduling Algorithm

When the main processing unit is performing rejuvenation process, some or all of the tasks deployed on the main processing unit may have to be migrated to the backup processing unit for their executions. In order to guarantee that real-time tasks satisfy their deadlines, the non real-time tasks deployed on the backup processing unit may have to be postponed. To optimize the system’s QoS, the delay of non real-time tasks on the backup processing unit caused by the main processing unit going through rejuvenation shall be minimized. Clearly, if rejuvenation takes place at the time when the main processing unit is idle, we can utilize the idle time and hence reduce the delay of non real-time tasks on the backup processing unit.

For real-time systems, priority-driven scheduling by definition never intentionally leaves resources idle, i.e., a resource becomes idle only when there is no ready job in the waiting queue [20]. The Earliest Deadline First (EDF) scheduling algorithm is one of the most commonly used priority-driven scheduling algorithms for real-time systems [19]. Fig. 8(a) shows an example of task set $\Gamma$’s schedule based on EDF scheduling algorithm, where $\Gamma = \{\tau_1(3, 1), \tau_2(4, 1), \tau_3(6, 1)\}$. For priority-driven scheduling algorithms, we have the following observation:

**Observation 1.** For priority-driven scheduling algorithms, such as EDF, the longest idle time interval often occurs towards the end of a task set’s hyper-period.
The reverse of EDF is the Latest Release Time (LRT) scheduling algorithm \cite{20} which schedules jobs backwards from the latest deadline of all jobs to the earliest release time. For the same task set given above, Fig. 8(b) gives the schedule based on the LRT scheduling algorithm. For the LRT scheduling algorithm, we have the following observation:

**Observation 2.** For the LRT scheduling algorithm, the longest idle time interval often occurs towards the begin of a task set’s hyper-period. □

Observation 1 and Observation 2 are manifested in Fig. 8, where the longest idle interval is 2 time units, which occur in the interval of \([10, 12]\) (end of hyper-period), and \([0, 2]\) (beginning of hyper-period) with EDF and LRT, respectively.

![Figure 8: EDF and LRT Scheduling for Task Set Γ](image)

The two observations provide us with the design base for our MIN-DELAY algorithm. We use the following example to explain the intuitions.

**Example 1.** Consider the same periodic real-time task set \(Γ = \{τ_1(3, 1), τ_2(4, 1), τ_3(6, 1)\}\) with hyper-period \(H = 12\), assume each rejuvenation takes \(E_r = 2\) to complete and rejuvenation period is \(T_r = 7\), then the first rejuvenation starts at time \(t = 7\).

If we use EDF to schedule the task set \(Γ\), the delay for non real-time tasks on the backup processing unit is \(D = 2\), and the delay time interval is \([7, 9]\), as shown in Fig. 9.

![Figure 9: Non Real-Time Task Delay](image)

However, as shown in Fig. 8, the EDF scheduling has an idle time interval \([5, 6]\). If we start the rejuvenation at time \(t = 5\), we can utilize the idle time to reduce the delay. Additionally, if we push the second idle time interval forward to the rejuvenation starting time, we can further reduce the delay. Based
on Observation 2, we can use the LRT algorithm to schedule jobs that are released after the rejuvenation starting time to maximize the continuous idle time interval.

Fig. 10 shows a schedule that not only guarantees real-time tasks meeting their deadlines, but also allow rejuvenation to take place without delaying any non real-time tasks. In this case, the delay is $D = 0$ and the rejuvenation takes place in time interval $[5, 7]$.

To generalize the strategy used in Example 1, assume a given optimal rejuvenation start time $t$ is within the task set’s $k$th hyper-period, i.e., $kH \leq t \leq (k + 1)H$, the rejuvenation process may take place in a time interval in $[(k - 1)H, (k + n + 2)H]$, i.e., $[t_s, t_s + E_r] \subseteq [(k - 1)H, (k + n + 2)H]$, where $t_s$ is the actual rejuvenation start time which equals to the last idle time before $t$, and $n = \lfloor E_r/H \rfloor$. We use EDF to schedule jobs released within $[(k - 1)H, t_s]$, and use LRT to schedule jobs that are released within $[t_s, (k + n + 2)H]$ to push idle time towards the beginning of the interval, i.e., towards $t_s$. Fig. 11 shows the scheduling strategy. As both EDF and LRT are optimal from schedulability perspective [20], hence, our scheduling strategy has the same schedulability as EDF or LRT scheduling algorithm.

According to above analysis, the actual rejuvenation start time $t_s$ is smaller than the computed optimal rejuvenation start time $t$, which lowers the rejuvenation period $T_r$. During the system longevity $L$, if the rejuvenation period is lowered too much, the rejuvenation number may becomes larger than the original rejuvenation number, which also enlarges the delay $D$ of non real-time applications on the backup processing unit $P_B$. To minimize the delay $D$, the minimal rejuvenation period $T_{\text{min}}$ must guarantee that the rejuvenation number with $T_{\text{min}}$ is equal to the original rejuvenation number with given rejuvenation
period $T_r$, i.e.,

$$T_{\text{min}} = \min\{T_{\text{min}} \in \mathbb{N} || L/T_{\text{min}} = \lfloor L/T_r \rfloor \}$$

(8)

In Example 1, the rejuvenation starts at time 5 which is two time unit earlier than its scheduled rejuvenation time 7. Based on the system reliability analysis in Section 4, shorter rejuvenation period may cause the system not meeting its reliability requirement $R_0$. Hence, we have to verify system reliability requirement before changing the actual rejuvenation start time.

As discussed in Section 4, when the rejuvenation period increases, the system reliability first increases and then decreases. Hence, we can calculate the minimal rejuvenation period $T_0$ that satisfies the system reliability requirement $R_0$ using Eq. (1). To maintain reliability requirement, we must guarantee that the actual rejuvenation start time is no less than $T_0$. Therefore, the actual rejuvenation start time $t_s$ must be no less than $\max\{T_{\text{min}}, T_0\}$ to minimize the delay and maintain system reliability requirement.

We now give the MIN-DELAY scheduling algorithm in Algorithm 2. Given system with longevity $L$, reliability requirement $R_0$, and the optimal rejuvenation period $T_r$, first, we calculate $T_0$ that guarantees $R_0$, $T_{\text{min}}$ that maintains rejuvenation number, and $T$ which is the minimal rejuvenation period satisfying system reliability and rejuvenation number requirements (Line 1-3). In the scheduling process, the algorithm determines the actual rejuvenation start times that satisfies system reliability and rejuvenation number requirements (Line 8-10) and schedules jobs based on EDF or LRT depending on the job release time with respect to the rejuvenation start time (Line 11-14). The complexity of the algorithm is $O(L^2)$.

7.2 Simulation Results

In this section, we evaluate the performance of the proposed MIN-DELAY scheduling algorithm and compare it with EDF and LRT scheduling algorithms [19, 20]. Our evaluation criteria is the delay of non real-time tasks on the backup processing unit.

7.2.1 Task Set Utilization Impact

This set of experiments evaluates the performance of the proposed MIN-DELAY scheduling algorithm under different task set utilizations. The experiment settings are given below.

- Number of tasks in a task set: 5
- Task period range: [10, 20]
- Task set utilizations: $U_T \in \{0.3, 0.4, \ldots, 1.0\}$
- System longevity: $L = 10,000,000$
Algorithm 2 MIN-DELAY

**Input:** Real-time periodic task set $\Gamma$, rejuvenation period $T_r$, rejuvenation cost $E_r$, system longevity $L$, and system reliability requirement $R_0$

1: Calculate $T_0$ that guarantees $R_0$ using Eq. (1)
2: Calculate $T_{\text{min}}$ using Eq. (8)
3: $T = \max\{T_{\text{min}}, T_0\}$
4: $n = \lceil E_r/H \rceil$
5: Initialize actual rejuvenation start time $t_s = T_r$
6: $t_1 = 0$
7: while $L > t_s$ do
8: if EDF has idle time during $[t_s - (T_r - T), t_s]$ then
9: $t_s$ is the first idle begin time during $[t_s - (T_r - T), t_s]$
10: end if
11: Schedule jobs released during $[t_1, t_s]$ with EDF
12: $t_2 = \lfloor t_s/H \rfloor \cdot H$
13: $t_1 = t_2 + (n + 2)H$
14: Schedule jobs released during $[t_s, t_1]$ with LRT
15: $t_s = t_s + E_r + T_r$
16: end while
17: Schedule jobs released during $[t_1, L]$ with EDF

- Optimal rejuvenation period: $T_r = 2,000,000$
- Minimal rejuvenation period: $T_0 = 1,900,000$
- Rejuvenation time cost: $E_r = 100,000$

For each utilization option, we randomly generate 100 task sets with the Uniform algorithm [6]. We schedule each task set and compute delays on the backup processing unit with EDF, LRT, and MIN-DELAY algorithms, respectively. The average value is used to represent the performance of each algorithm.

Fig. 12 shows the delay under different task set utilizations. From Fig. 12, we have the following observations:

1. For all scheduling algorithms, the delay increases when task set utilization increases.
2. The proposed MIN-DELAY algorithm outperforms the EDF and LRT algorithms by as much as 9.01% and 14.24% under different task set utilizations, respectively.
3. The performance advantage of MIN-DELAY algorithm decreases when task set utilization increases. In particular, the MIN-DELAY algorithm results in 9.01% less delay than EDF when task set utilization is 0.3, while the two algorithms have the same delay when task set utilization reaches 1.0.
7.2.2 Rejuvenation Time Cost Impact

The second set of experiments is to evaluate rejuvenation time ($E_r$) impact on the performance of the proposed MIN-DELAY scheduling algorithm. The experiment settings are the same as the previous experiments except that we fix the task set utilization at 0.6 and set $E_r \in \{100,000, 110,000, \ldots, 200,000\}$.

Fig. 13 shows the delay under different rejuvenation time $E_r$. From Fig. 13, we have the following observations:

1. For all scheduling algorithms, the delay increases when the rejuvenation time cost increases.
2. The proposed MIN-DELAY algorithm outperforms the EDF and LRT algorithm by as much as 10.21% and 10.23% under different rejuvenation time costs, respectively.
3. The EDF and LRT scheduling algorithms have similar performance.

Both sets of experiments show that the proposed MIN-DELAY algorithm has advantages over the EDF algorithm with respect to application execution delay on the backup processing unit.

8 Conclusion

In this paper, we use software rejuvenation as a preventive technique to improve system’s QoS for long-running applications with real-time constraints. We have
formally analyzed the relationship between software rejuvenation frequency and system reliability, longevity, and availability. Based on the theoretic analysis, we have developed approaches to maximizing system reliability, longevity, and availability, and minimizing application execution delays on the backup processing unit. The developed semi-priority-driven scheduling algorithm, i.e., the MIN-DELAY scheduling algorithm can reduce application delay by 9.01% and 14.24% over the EDF and LRT scheduling algorithms, respectively.

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