Reliability Measure in Content-Distribution Systems

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Summary
As the telecommunications industry has rapidly evolved, its software functions continuously advance. These changes have to be reflected in all client software before new services can be introduced. An inconsistent system in which client software fails to receive updated content delivers no new service to customers, causing loss of revenue, customers and even goodwill. Therefore, a reliable content delivery service is needed for such a large-scaled service companies to guarantee system consistency. This investigation analyzes the queueing model of a proposed content delivery service and derives the measure of system reliability.

Key words:
Content Delivery, Reliability, Queueing Theory.

1. Introduction

Content distribution is a serious issue that has to be addressed by service-oriented industries with fast-evolving intranet environments and many client installation bases [1, 8, 15, 14]. Uninterrupted customer service is one of the most important operational goals, which is particularly crucial for the large-scale service sectors [3, 5]. If a large service-oriented company stops service, then it is likely to lose hundreds of millions of US dollars a day in revenue. Hence, a large-scaled service company must continue the content delivery service to lower the loss caused by a disaster [11].

A company requires a feasible approach to transmitting content along the organization hierarchy to obtain support from all business units [9, 11]. A large telecom company in Taiwan, originally applied one server to update the contents of all clerks' devices without a disaster avoidance mechanism. The case company has learned that disasters, such as crashed servers, delivered incomplete content, and disconnected network, could stop the content delivery service. A content delivery service called Fire and Forget Distribution System (FnFDS), which distributes the update contents of the case company, has been introduced [13, 14]. This study shows the system reliability by analyzing above system.

The remainder of this paper is organized as follows. In the next section we describe the content delivery system and define the system states. In Section 3, the system reliability is discussed. In Section 4, we study the distribution of fault repair time for a disconnected link. Numerical results are presented in Section 5. Finally, in Section 6, we remark results of this paper.

2. System Description

The Fire and Forget Distribution System (FnFDS) employs a multi-tier architecture comprising layers [13, 14]. Each server on each layer has a balanced tree schema, in which the depth and the number of layers in each branch is the same. The balanced tree schema is utilized for the hierarchical organization [16]. The FnFDS uses a modified pull-based design to send update contents through servers to reduce consuming network resource [2]. That is, devices retrieve content from servers are occurred only when receiving the notification of retrieving content from servers.

This modified pull-based system should be designed so that at least one server is in operable status which indicates whether a device can connect to the server and function correctly. All client devices should successfully retrieve the update content from the server. Additionally, since clerk's devices retrieve updated contents from servers, the content delivery service should stop when communication failures occur on servers.

Among the potential process and communication failures for content delivery service include crashes, general omissions of sent contents and disconnection [4, 7]. A crash signifies that a server or a clerk's device is malfunctioning, and requires time to recover. A general omission means that the server or the clerk's device receives incomplete content. A disconnection means that the network is disconnected between two communicated devices. The error statuses of the content delivery service include "servers are malfunctioning and network link is disconnected." Table 1 summarizes the error statuses.

The further actions for a malfunctioned server include operator's intervention and automatic recovery. The crash needs intervention by an operator. The general omission can be automatically solved, because the recipients retrieve incomplete content later. Partially disconnected cases, such as a malfunctioned network router require intervention by an operator, as well as time to be fixed. Other cases, such

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as a network disconnection due to congested traffic, normally recover automatically within a specific time period [6]. Each error status has various mean times between failures and times spent for repair. Each error-occurred server and link is assigned specific staff members to repair it.

Table 1. Error Statuses

	Server		Link
Error Type	Crash	General Omission	Disconnection
Reasons	1. Hardware problems, such as malfunctioned network adapter, crash database. 2. The sever is burned.	The server receives incomplete contents owing to transmission error.	1. Network equipment is malfunctioned. 2. The wire is cut-off. 3. The network is congested.

3. Measure of System Reliability

To understand the reliability of the FnFDS, this investigation derives the queueing model of FnFDS and analyzes it. There are $s \geq 1$ servers in the system to send downward messages, and they have independent identically distributed (i.i.d.) exponential lifetimes. According to the architecture of our system, FnFDS also has x links in the system to connect servers, where $x \geq 1$. The system will be down if either no server is in operational mode or all links are disconnected.
First, we try to find the probability that no server is in operational mode. Let $1/\alpha_c$ and $1/\alpha_G$ be the mean time to the crash state and general omission state for each server. When a server crashes, it needs mean repair time $1/\beta_c$. Moreover, it takes $1/\beta_G$ to repair a failed server with general omission.

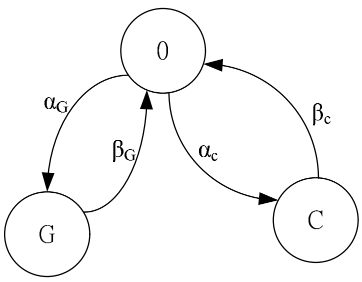

Fig. 1. The State Transition Rate Diagram

This investigation assumes that crash, general omission, and repair times are i.i.d random variables with exponential distribution. The state transition rate diagram (shown in Figure 2) represents that this system can be considered as a Birth-death process with three states. We denotes the steady state probability by

$$\pi = (\pi_0, \pi_C, \pi_G),$$

where π_0, π_C, and π_G represent limiting probabilities of states: regular operation , crash, and general omission. Because flow in equals flow out on each state, we can list the balance equations:

$$\alpha_G \pi_0 = \beta_G \pi_G, \quad \text{(State G)}$$

$$\beta_C \pi_C + \beta_G \pi_G = (\alpha_C + \alpha_G)\pi_0, \quad \text{(State 0)}$$

and

$$\alpha_C \pi_0 = \beta_C \pi_C. \quad \text{(State C)}$$

From the above balance equations, we find the following relationship:

$$\pi_G = \frac{\alpha_G}{\beta_G}\pi_0 \text{ and } \pi_C = \frac{\alpha_C}{\beta_C}\pi_0.$$

With the help of $\pi_0 + \pi_C + \pi_G = 1$, the steady state probability can be derived as follows:

$$\pi_0 = \frac{\beta_C \beta_G}{\beta_C \beta_G + \alpha_C \beta_G + \alpha_G \beta_C}, \quad (1)$$

$$\pi_G = \frac{\alpha_G \beta_C}{\beta_C \beta_G + \alpha_C \beta_G + \alpha_G \beta_C}, \quad (2)$$

$$\pi_C = \frac{\alpha_C \beta_G}{\beta_C \beta_G + \alpha_C \beta_G + \alpha_G \beta_C}. \quad (3)$$

Thus, the FnFDS has a limiting probability of no server in operational mode in the system as follows.

$$\Pr\{\text{no server in operational mode}\} = (\pi_C + \pi_G)^s$$

$$= \left(\frac{\alpha_C \beta_G + \alpha_G \beta_C}{\beta_C \beta_G + \alpha_C \beta_G + \alpha_G \beta_C}\right)^s. \quad (4)$$

Next, we consider the limiting probability that all links are disconnected. Let $1/\alpha_d$ be the mean time to the disconnection state for each link. It takes mean repair time $1/\beta_d$ for a disconnected link. Assume these lifetime and repair time follow exponential distribution. There are r repair teams for repairing disconnected links.

Let $N_{x,r}(t)$ be the number of disconnected links at time t in the Content-Delivery Service system with x links and r repair teams being charge of these links. Here,

$x \ge r \ge 1$. This work considers $\{N_{x,r}(t), t \ge 0\}$ is a birth and death process on state space $\{0,1,\ldots,x\}$, with birth parameter α_d and death parameter β_d. We study such process and its limiting behavior. Let $P_n(x,r) = \lim_{t\to\infty} \Pr\{N_{x,r}(t) = n\}$ be the limiting probability that there are n disconnected links in the system with x links. We find the limiting probability by formulating it as a $M/M/r$ queueing system with finite population x. Hence, the limiting distribution is given in the following theorem (see Kleinrock [12]):

Theorem 1: Let $N_{x,r}(t)$ be the number of disconnected links at time t in the system with x links and r repair teams, and

$$P_n(x,r) = \lim_{t\to\infty} \Pr\{N_{x,r}(t) = n\},\ 0 \le n \le x.$$

Then

$$P_n(x,r) = \begin{cases} \dfrac{x!}{(x-n)!n!}\left(\dfrac{\alpha_d}{\beta_d}\right)^n P_0(x,r), & \text{for } n = 1,\ldots,r-1, \\ \dfrac{x!}{(x-n)!r!r^{n-r}}\left(\dfrac{\alpha_d}{\beta_d}\right)^n P_0(x,r), & \text{for } n = r,\ldots,x \end{cases} \tag{5}$$

where

$$P_0(x,r) = \left[\sum_{n=0}^{r-1} \frac{x!}{(x-n)!n!}\left(\frac{\alpha_d}{\beta_d}\right)^n + \sum_{n=r}^{x} \frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\right]^{-1}. \tag{6}$$

Using the limiting probability in Theorem 1, we also have the following results.

Theorem 2: Let $L(x,r)$ be the expected number of disconnected links in the system with x links and r repair teams in steady state. Then $L(x,r) =$

$$r + \left[\sum_{n=0}^{r-1}(n-r)\frac{x!}{(x-n)!n!}\left(\frac{\alpha_d}{\beta_d}\right)^n + \sum_{n=r}^{x}(n-r)\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\right] P_0(x,r), \tag{7}$$

where

$$P_0(x,r) = \left[\sum_{n=0}^{r-1} \frac{x!}{(x-n)!n!}\left(\frac{\alpha_d}{\beta_d}\right)^n + \sum_{n=r}^{x} \frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\right]^{-1}.$$

Proof: This result can be verified by using $L(x,r) = \sum_{n=0}^{x} nP_n(x,r)$. □

By Little's Law [12], it shows the relation among expected number of disconnected links, expected time taken for repair by a disconnected links, and effective disconnection rate. From this, the theorem follows.

Theorem 3: Let $W(x,r)$ be the expected time taken for repair by a disconnected link in the system with x links and r repair teams in steady state, and let α_d be the disconnection rate of links. Then

$$W(x,r) = \frac{L(x,r)}{\alpha_d\left(x - L(x,r)\right)}. \tag{8}$$

Proof: It is easy to get the expected time, $W(x,r)$, by Little's Law and using the effective disconnection rate $\sum_{n=0}^{x}(x-n)\alpha_d P_n(x,r)$. □

From the result of Theorem 3, this work shows the probability that all links are disconnected in the system

$$\Pr\{\text{all links are disconnected}\} = P_x(x,r) = \frac{x!}{r!r^{x-r}}\left(\frac{\alpha_d}{\beta_d}\right)^x \left[\sum_{n=0}^{r-1} \frac{x!}{(x-n)!n!}\left(\frac{\alpha_d}{\beta_d}\right)^n + \sum_{n=r}^{x} \frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\right]^{-1}. \tag{9}$$

The quantity $P_x(x,r)$ is the fraction of the time that all links are disconnected in the long run. By using the results of (4) and (9), we have the probability that the system is down, i.e.,

$$\begin{aligned} &\Pr\{\text{system is down}\} \\ &= \Pr\{\text{no server in operational mode}\} + \Pr\{\text{all links are disconnected}\} \\ &= \left(\frac{\alpha_C\beta_G + \alpha_G\beta_C}{\beta_C\beta_G + \alpha_C\beta_G + \alpha_G\beta_C}\right)^s \\ &+ \frac{x!}{r!r^{x-r}}\left(\frac{\alpha_d}{\beta_d}\right)^x \left[\sum_{n=0}^{r-1} \frac{x!}{(x-n)!n!}\left(\frac{\alpha_d}{\beta_d}\right)^n + \sum_{n=r}^{x} \frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\right]^{-1} \end{aligned} \tag{10}$$

We find the proper numbers of servers and links, s and x, which can ensure the probability that the content delivery service system will be down is less than six-sigma [10]. We are also interested in learning information concerning how long disconnected links must wait for repair. To do so, this investigation need waiting-time measures which are derived in the next section.

4. Fault Repair Time Distributions of Disconnected Links

To obtain information concerning the time a disconnected link must spend waiting until being repaired, we proceeds to derive the probability distribution for waiting time. When considering individual waiting time, queue discipline must be specified and this work assumes that it is first in, first out. The waiting-time random variable has an interesting property in that it is part discrete and part continuous. Waiting time is a continuous random variable except that there is a nonzero probability that the delay will be zero. That is, a disconnected link enters repair (process) immediately upon it arises disconnection. So let T denote the random variable, which means time spent waiting in the queue, and let $F_T(t)$ denote its cumulative probability distribution. Hence, from the complete randomness of the Poisson, this investigation shows that

$$
\begin{aligned}
&F_T(0)\\
&=\Pr\{T\le 0\}=\Pr\{T=0\}=\sum_{n=0}^{r-1}P_n(x,r)\\
&=x!\left(\frac{\left(\frac{\alpha_d+\beta_d}{\beta_d}\right)^x}{\Gamma(1+x)}-\frac{\left(\frac{\alpha_d}{\beta_d}\right)^r {}_2F_1(1,r-x;1+r;-\frac{\alpha_d}{\beta_d})}{\Gamma(1+r)\Gamma(1-r+x)}\right)P_0(x,r),
\end{aligned}
\tag{11}
$$

where $\Gamma(y)=\int_0^\infty z^{y-1}e^{-z}dz$ is the gamma function and

$$
{}_2F_1(a,b;p;q)=\frac{\Gamma(p)}{\Gamma(b)\Gamma(p-b)}\int_0^1 z^{b-1}(1-z)^{p-b-1}(1-qz)^{-a}dz \tag{12}
$$

is the hypergeometric function. It then remains to find $F_T(t)$ for $t>0$.

Consider $F_T(t)$, the probability of a disconnected link waiting a time less than or equal to t for repair. If there are n disconnected links in the system upon a disconnection arises, in order for the disconnected link to go into repair at a time between 0 and t, all n disconnected links must have been repaired by time t. Since the service distribution is memoryless, the distribution of the time required for n completions is independent of the time of the current disconnection and is the convolution of n exponential random variable. That is, the time required for n completions is an Erlang-n distribution. In addition, since the input is Poisson, the arrival points (disconnection events) are uniformly spaced and hence the probability that an arrival finds n in the system is identical to the stationary distribution of system size. Therefore, we derive the time distribution of waiting for repair.

$$
\begin{aligned}
&F_T(t)\\
&=\Pr\{T\le t\}\\
&=F_T(0)+\sum_{n=r}^{x}\left[P_n(x,r)\cdot\Pr\{(n-r+1)\text{ completions by time }t\,|\,\text{arrival found }n\text{ in system}\}\right]\\
&=\sum_{n=0}^{r-1}P_n(x,r)+\sum_{n=r}^{x}\left[\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n P_0(x,r)\cdot\int_0^t\frac{\beta_d(\beta_d z)^{n-r}}{(n-r)!}e^{-\beta_d z}dz\right]\\
&=\sum_{n=0}^{r-1}P_n(x,r)+P_0(x,r)\sum_{n=r}^{x}\left[\int_0^t\frac{\beta_d(\beta_d z)^{n-r}}{(n-r)!}e^{-\beta_d z}\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n dz\right]\\
&=P_0(x,r)x!\left(\frac{\left(\frac{\alpha_d+\beta_d}{\beta_d}\right)^x}{\Gamma(1+x)}-\frac{\left(\frac{\alpha_d}{\beta_d}\right)^r {}_2F_1(1,r-x;1+r;-\frac{\alpha_d}{\beta_d})}{\Gamma(1+r)\Gamma(1-r+x)}\right)\\
&+P_0(x,r)\int_0^t\beta_d e^{-\beta_d z}\sum_{n=r}^{x}\left[\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\frac{(\beta_d z)^{n-r}}{(n-r)!}\right]dz
\end{aligned}
$$

for $t>0$.

Also of interest would be the total time a disconnected link had to spend in repair process including waiting and being repaired. Denote this random variable by U and its cumulative probability distribution by $F_U(t)$. Then it can be shown that

$$
\begin{aligned}
&F_U(t)\\
&=\Pr\{U\le t\}\\
&=\sum_{n=r}^{x}\left[P_n(x,r)\cdot\Pr\{(n-r+2)\text{ completions by time }t\,|\,\text{arrival found }n\text{ in system}\}\right]\\
&=\sum_{n=r}^{x}\left[\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n P_0(x,r)\cdot\int_0^t\frac{\beta_d(\beta_d z)^{n-r+1}}{(n-r+1)!}e^{-\beta_d z}dz\right]\\
&=P_0(x,r)\sum_{n=r}^{x}\left[\int_0^t\frac{\beta_d(\beta_d z)^{n-r+1}}{(n-r+1)!}e^{-\beta_d z}\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n dz\right]\\
&=P_0(x,r)\int_0^t\beta_d e^{-\beta_d z}\sum_{n=r}^{x}\left[\frac{x!}{(x-n)!r!r^{n-r}}\left(\frac{\alpha_d}{\beta_d}\right)^n\frac{(\beta_d z)^{n-r+1}}{(n-r+1)!}\right]dz
\end{aligned}
$$

for $t>0$.

5. Implementation

In the system applied by the case company, the mean times between failures and the mean time between repairs of a server are 1094.4 hours and 6.4 hours, respectively. The mean times between failures and the mean time between repairs of links are 358.6 hours and 0.8 hours, respectively. The mean times between general omissions and the mean time of retrieval process are 300 hours and 0.00083 hours, respectively.

The empirical results show to adopt one server is definitely unreliable. To adopt two layers comprised one server on the first layer and three servers on the second layer, the times of zero servers is operable is 625 times per 10 thousands hours. To utilize three layers comprised 40 servers on the first, second and third layers, the chance of zero servers is operable is 9.0945x10-13 per hour. Additionally, to utilize 19 servers could make the probability of FnFDS with no server is operable is just lower than six-sigma capable process, in which the chance of zero servers in operable status is 1.90735 times per million hours. Analytical results reveal that adopting 19 servers is sufficient to run the FnFDS with a six-sigma capable process, in which the chance of zero servers in operable status is 3.4 times per million hours.

However, the number of deploying servers must be along the organization hierarchy with balance tree. Hence, to adopt 40 servers is feasible for FnFDS. In practice, the company adopts a system with 40 servers with three layers along the organization hierarchy was found with the chance of zero servers is operable is 9.0945x10-13 per hour. Restated, the reliability of FnFDS using 40 servers is better than that of a six-sigma capable process. Additionally, the practical result shows the average time of sending content with size of 10 mega bytes to 10,000 clerks' devices is 300.08 seconds through the FnFDS with 40 servers that saves 72% time compares to the original content delivery service.

6. Conclusions

Content distribution is an important issue for service-oriented companies with fast-evolving intranet environments and many client installation bases. To analyze the error statuses and solutions, we study a queueing model for a proposed content delivery service system. This investigation shows that the reliability of FnFDS using 19 servers is better than that of a six-sigma capable process. The practical result shows the case company explored herein sends content from 40 servers of three layers with the chance of zero servers is operable is 9.0945×10^{-13} per hour. The reliability of 40 servers is better than that utilizing 19 servers.

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