Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.12785/amis/081L43

Optimal Maintenance Policy for High Reliability Load-Sharing Computer Systems with *k-out-of-n:G* Redundant Structure

Xin Qi, Zhan Zhang, Decheng Zuo and Xiaozong Yang*

School of Computer Science and Technology, Harbin Institute of Technology, Harbin 150001, P. R. China

Received: 19 May. 2013, Revised: 13 Sep. 2013, Accepted: 14 Sep. 2013
Published online: 1 Apr. 2014

Abstract: Maintenance plays an important role in system reliability enhancement which is an essential requirement for computer systems in service for critical applications. This paper presents a failure number m based maintenance policy for *k-out-of-n:G* load-sharing computer systems with a goal of maximizing the long-run expected system reward per unit time. Compared to previous study, we take load-sharing into account and employ tampered failure rate (TFR) model to describe failure rate change caused by load-sharing. With some typical numeral examples, we analyzed expected system reward rate under different load stress level and achieved corresponding optimal value of decision variable m. The result shows that component failure has much more impact on heavily loaded system than lightly one, and optimization of maintenance action depends greatly on the load level.

Keywords: maintenance policy, reliability, k-out-of-n, load-sharing, TFR

1 Introduction

The raising demand of computing capability has fostered an unprecedented requirement in computer system reliability, particularly for some critical applications, such as telecommunication service, financial business, etc. Maintenance on these high reliability computer systems plays a critical role in their efficient usage in terms of cost, reliability, and safety, and will be more important than redundancy, production, and construction in reliability[1].

In the past several decades, maintenance policies have been extensively studied in the literature. Although thousands of maintenance models have been proposed, they are designed on two basic maintenance activities: corrective maintenance (CM) and preventive maintenance (PM)[2]. CM is any maintenance that occurs when the system is failed, and some authors refer to it as repair. PM is any maintenance that occurs when the system is operating. Maintenance policies almost exclude simple CM or PM, but are optimized by hybrid activities on base of age replacement policy (ARP) and block replacement policy (BRP)[3]. In recent years, another important class of maintenance policy called condition based maintenance (CBM) is proposed and gets more and more attention[4,5,6]. In condition based maintenance, the maintenance schedule and frequency match the age or health of the system at all times, prolonging the time to replacement (TTR) as a consequence.

From the system structure view, Wang[2] classified maintenance policies into two groups: policies for one-unit (or single-component) systems and policies for multi-unit (or multi-component) systems. Many researches of the first class are carried out with the idea that in lack of detailed knowledge, even a multi-unit system can be analyzed as one entity. In[7], Nakagawa extends the age replacement policy by taking replacement at time T or at number N of failures, whichever occurs first, and undergoes minimal repair at failure between replacements. Sheu[8] presents a policy in which if a unit fails at age $y < t$, it undergoes perfect repair with probability $p(y)$, or a minimal repair with probability $1 - p(y)$. Otherwise, the unit is replaced when the first failure after t occurs or the total operating time reaches age T, whichever occurs first. Wang[9] studies a multi-objective maintenance optimization embedded

* Corresponding author e-mail: zuodc@hit.edu.cn

within the imperfect PM for a one-unit system subject to the dependent competing risks of degradation wear and random shocks. The shocks are classified into fatal ones and nonfatal ones and quasi-renewal sequences are employed to describe the imperfect PM process. Sensitivity analysis for imperfect PM degree and quasi-renewal coefficient is then performed to provide insight into the behavior of the proposed maintenance policies.

Compared to single component system, multi-component system, often with a range of output performance levels and so called multi-state system, is more realistic in analysis and has caught more attention in later research. Zheng[10] proposes an opportunistic maintenance policy. The target system is assumed to have k different types of units. A unit is replaced either when the hazard rate reaches L or at failure with the failure rate in a predetermined interval $(L-u, L)$. Nourelfath[11] extends the redundancy optimization problem (ROP) to find the minimal configuration and maintenance costs of a series-parallel system under reliability constraints. Liu[12] investigates the optimal selective maintenance policy for multi-state system with binary components under Kijima age reduction PM model, and employs universal generating function (UGF) and genetic algorithm (GA) method to solve the optimization problem.

For multi-component system, one preferable and widely applied redundancy form is the *k-out-of-n:G*, or called *k-out-of-n* structure, which consists of n often identical elements. If and only if at least k of its components work, the system works. However, not many maintenance policies on *k-out-of-n* systems are studied. Pham and Wang[13] propose two (τ, T) opportunistic maintenance policies for a *k-out-of-n* system both under perfect PM and imperfect PM. In these two policies, minimal repairs are performed on failed components before time τ, and CM of all failed components is combined with PM of all functioning ones after τ. Also economic dependency is taken into account in the strategy which means that it spends less cost and time to perform maintenance on several components jointly than on each component separately. Park and Pham[14] presents a block replacement model for a *k-out-of-n* system with a goal of preventing system failure and minimizing the expected total system cost. To overcome the drawback that it is wasteful if a preventive replacement happens just after a failure replacement, in the policy, a replacement service for a failure is provided when there are a threshold number of failed components occurring. Dwyer[15] studies on the reliability of a system with time dependant failure rate and *2-out-of-4:G* redundant structure. Minimal repair is performed on failure with a time limit τ, and dependence of the system reliability measures on the allowed repair time τ is analyzed by solutions to two integro-differential-delay equations (IDDEs).

In the previous maintenance policy researches of *k-out-of-n* system, failure rate is assumed either to be constant or to vary according to time. While failure data of large scale computer systems shows that stress of workload has evident impact, even proportionate relationship, on component and system failure rate[16]. Thus, failure rate change caused by load-sharing for component failure unavoidably needs to be taken into consideration in maintenance policies design.

This paper presents a failure number m based maintenance policy for high reliability *k-out-of-n* computer systems. Compared to previous study, we take load-sharing into account which is a commonly employed redundant structure in high reliability computer system design. The evaluation of system reward rate considers load stress level and failure rate change caused by load-sharing. Section 2 introduces TFR model and the reliability model developed on it. Section 3 discusses about maintenance policy, cost and system reward. Section 4 analyzes optimization of the policy under different load stress level by several typical numeral examples, and section 5 concludes the paper.

2 Reliability Model of Load-Sharing System

In high reliability computer systems, active redundancy design is often accompanied by load-sharing. In a load-sharing system, if a component fails, the same workload has to be shared by the remaining components, resulting in an increased load shared by each surviving component [17]. This section presents the tampered failure rate (TFR) model which is employed to describe component failure rate change caused by load-sharing. Then the load distribution is given. At last, the reliability model of a *k-out-of-n:G* load-sharing system is achieved. Component in this paper can refer to node, subsystem or other redundant block according to the specific target system. First of all, we describe assumptions taken on the system in this study:

1. The target system consists of n identical distributed components with exponential failure times.
2. The system is a *k-out-of-n* system. At least k of the n components work, the system works.
3. Failures of components are independent, but will result in of failure rate change on the rest components. The accelerated failure process follows tamped failure rate (TFR) model.
4. The system is subjected to a workload with constant stress L.

The TFR model was first proposed by Bhattacharyya and Soejoeti[18] and then generalized by Madi[19]. The acceleration of failure when the stress is raised from a lower level to a higher level is reflected in the hazard-rate function. For a 2-step accelerated life test (ALT), the TFR model is described as follow.

All components are placed on test at time $t = 0$ with load stress x_1 until time τ_1. Then the load changes to x_2

and test continues. The hazard rate at a higher stress is the hazard rate at a lower stress multiplied by an unknown factor. The hazard rate for the whole simple step-stress ALT is assumed to be

$$h^*_{TFR}(\omega) = \begin{cases} h_0(\omega), 0 \le \omega \le \tau_1 \\ \alpha_1 \cdot h_0(\omega), \omega > \tau_1 \end{cases} \quad (1)$$

Consider a component that is subjected to an ordered sequence of loads, where load $L_i(i = 0,1,,n)$ is applied during the time interval $[\tau_i, \tau_{i+1}]$ where $\tau_0 = 0$. In other words, the load changes at times $\tau_1, \tau_2, \cdots, \tau_n$. According to TFR model, the hazard rate of the component at time t is

$$h(t) = h_i(t) = \delta_i \cdot h_0(t) \quad (2)$$

Where $\delta_0 = 1$, $h_0(t)$ is the hazard rate at the lower load L_0,and δ_i is the tampered factor at load level L_i. The tampered factor is a function of the applied stress. Hence, the TFR model can be expressed as

$$h(t) = \delta(L) \cdot h_0(t) \quad (3)$$

In the *k-out-of-n* system with assumption 4, workload is equally assigned to the n components initially. The total workload stress is L, and the load on each component is $L_0 = L/n$.

On the first failure of components at time τ_1, one component stops working until it is repaired or replaced during maintenance. Thus at time τ_1, $n-1$ good components are left and load stress on each component becomes $L/(n-1)$. The situation holds until next component failure happens at time τ_2. During the time interval between the i^{th} component failure and the $(i+1)^{th}$ component failure$[\tau_i, \tau_{i+1}]$, load stress on each component is $Li = L/(n-i)$. And with Eq. 3 we have

$$h_i(t) = \delta(\frac{L}{n-i}) \cdot h_0(t) = \delta(L_0\frac{n}{n-i}) \cdot h_0(t) \quad (4)$$

According to the TFR model, in this paper, the failure rate is assumed to have a linear relationship with load stress

$$h_i(t) = \frac{L_i}{L_i - 1} h_{i-1}(t) \quad (5)$$

With the assumption that the components are identical distributed with exponential failure times, initial failure rate of each component is a constant value represented by λ_0. Measure $R_i(t)$ is the reliability of component i at time t, then we have

$$R_i(t) = exp(-\int_0^t \lambda_0 du) = e^{-\lambda_0 t} \quad (6)$$

For independent components, measure $R_s(t)$ is the probability that no one component failure happens in time $(0,t]$, and can be calculated by

$$Rs(t) = \prod_{i=1}^{n} R_i(t) = e^{-n\lambda_0 t} \quad (7)$$

So the first component failure happens with failure rate α_1, $\alpha_1 = n \cdot \lambda_0$. Let λ_i be the component failure rate after the i^{th} failure, then the $(i+1)^{th}$ failure happens with failure rate α_{i+1}

$$\alpha_{i+1} = (n-i) \cdot \lambda_i \quad (8)$$

Let $X_i = \tau_i - \tau_{i-1}$ be the time between failure $i-1$ and i. X_i are s-independent and identically exponentially distributed with failure rate α_i. In the case where $\alpha_1 = \alpha_2 \cdots = \alpha_{n-k+1} = \alpha$, system reliability $R(t)$ has a gamma distribution[20, 21]

$$\begin{aligned} R(t) &= gamfc(\alpha t; n-k+1) \\ &= \sum_{j=0}^{n-k} \frac{exp(-\alpha t)(\alpha t)^j}{j!} \end{aligned} \quad (9)$$

Theorem 1. Under the TFR model and load distribution model described by Eq. 4 and Eq. 5, we have $\alpha_1 = \alpha_2 \cdots = \alpha_{n-k+1} = \alpha$.

Proof

Let $\alpha_1 = \alpha$, for $2 \le i \le n-k+1$,with Eq. 5 and Eq. 8

$$\begin{aligned} \alpha_i &= (n-i+1)\lambda_{i-1} \\ &= (n-i+1)\frac{L_{i-1}}{L_{i-2}}\lambda_{i-2} \\ &= (n-i+1)\frac{L_{i-1}}{L_{i-2}} \cdot \frac{L_{i-2}}{L_{i-3}} \cdots \frac{L_1}{L_0}\lambda_0 \\ &= (n-i+1)\frac{L_{i-1}}{L_0}\lambda_0 \end{aligned} \quad (10)$$

according to Eq. 4

$$\begin{aligned} L_{i-1} &= \frac{L}{n-i+1} = \frac{n \cdot L_0}{n-i+1} \\ \rightarrow \frac{L_{i-1}}{L_0} &= \frac{n}{n-i+1} \end{aligned} \quad (11)$$

and thus we get

$$\alpha_i = (n-i+1) \cdot \frac{n}{n-i+1}\lambda_0 = n\lambda_0 = \alpha_1$$

3 Reward Evaluation and Maintenance Policy

Reward of a system considers 2 parts: 1) reward generated when the system is working, and 2) cost of maintenance activities. Whether there are component failures or not, the system generates reward continually. The reward is decided by the number of good components in the system and the reward each component generates.

Note that for a *k-out-of-n* load-sharing system, load redistribution which is caused by failure of one component not only results in failure rate change on the rest good components, but can also slow down the system processing speed and prolong response times of requests. Fig.1 shows an example. It records a stress test on a 4 way 32 core server. Curve in the red square 1 represents the

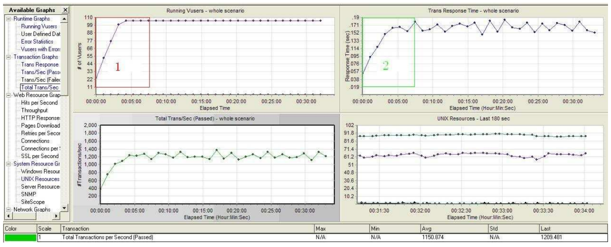

Fig. 1: load stress and response time of a stress test

user number increasing with time, and curve in the green square 2 describes the average response time which increases with load stress on the system.

Even workload stress on the component increases, prolonged response time indicates there is a performance drop for a single request. The exact model is beyond the scope of this paper. In this study, we take the assumption that the average response time ε_i in interval $[\tau_i, \tau_{i+1}]$ for each request is in direct ratio to the load stress L_i, which is measured by the amount of requests per unit time. The average reward per unit time ω_i for each request is in inverse ratio to the average response time.

$$\frac{\varepsilon_i}{\varepsilon_{i-1}} = a_i \frac{L_i}{L_{i-1}}, 1 \le i \le n-k+1 \quad (12)$$

$$\frac{\omega_i}{\omega_{i-1}} = b_i \frac{\varepsilon_i^{-1}}{\varepsilon_{i-1}^{-1}}, 1 \le i \le n-k+1 \quad (13)$$

and we have

$$\omega_i L_i = \frac{b_i}{a_i} \omega_{i-1} L_{i-1} \quad (14)$$

$\omega_i L_i$ is the reward per unit time, or reward rate, of one component during interval$[\tau_i, \tau_{i+1}]$. For $(b_i/a_i) > 1$, the component is not fully used under load $L_i - 1$, and the reward rate increases with a better utilization. For $(b_i/a_i) = 1$, the result implies that in this scenario, a component has a constant reward rate. It is reasonable that in a heavy load application, load increase on one component brings no additional profit but failure rate. $(b_i/a_i) < 1$ indicates that the amount of requests has exceeds the capability of the system, and overheads cost too much.

Three parts are considered in maintenance cost: 1) a fixed cost, 2) cost for replacement of the failed components, and 3) cost for preventive maintenance on the rest good components. The first part is taken as the overhead of maintenance routine, including for example system shut down and restart, completely checking, cable connection, etc. The second part is relative to the number of failure components when maintenance happens, and so is the third part. Replacement doesn't absolutely mean discard of a bad component. It may be returned back to the vendor for repair. For such a case, the cost for replacement is determined by the warranty policy of the vendor. Time cost of maintenance is also non-neglectable. The first part is also considered to have fixed time cost, while times required for replacement action and preventive maintenance action are related to the number of corresponding components.

The maintenance policy for the *k-out-of-n* load-sharing system described in this paper is based on failed component number $m(1 \le m \le n-k+1)$. Different from the method proposed in [13], we never consider minimal repair in maintenance. As field replaceable units (FRUs) are widely applied in modern high reliability computer systems, to replace a failed component costs little while repair in the field cost much. Components are economic dependent since the fixed cost exists. With assumptions taken in this paper, the maintenance policy is presented below.

1. At time $t = 0$, all the n new components are installed and begin to work.
2. On the i^{th} component failure $(1 \le i \le m)$, no actions are taken and the failed components are left idle waiting for maintenance.
3. On the m^{th} component failure, maintenance is performed. The failed components are replaced by new components. The rest good components are preventively maintained with perfect maintenance and are restored to as good as new.
4. After maintenance, time is reset to 0.

We use $C(m)$ to denote the long run expected reward per unit time of the component under policy m. Thus, according to the renewal reward theorem we have

$$C(m) = \frac{\text{the expected reward in a renew cycle}}{\text{the expected length of a renew cycle}}$$

The expected length of a renew cycle T_r, can be achieved by $T_r = E[\tau] + E[z]$, where $E[\tau]$ is the mean time to maintenance, and $E[z]$ is the expected time cost of maintenance. Under policy m, $E[\tau]$ can be calculated according to Eq. 9, $E[\tau] = m/\alpha$. Let Z_f , Z_r, Z_p be separately the fixed time cost, the replacement time of one component, the PM time of one component. Then $E[z] = Z_f + m \cdot Z_r + (n-m) \cdot Z_p$. The expected reward in a renew cycle consists of reward of system working C_w and maintenance cost C_{mc}. According to the above analysis and Eq.9.

$$C(m) = \frac{E[C_w] - E[C_{mc}]}{\frac{m}{\alpha} + Z_f + m \cdot Z_r + (n-m) \cdot Z_p} \quad (15)$$

where

$$C_w = \sum_{i=0}^{m-1} \omega_i L_i (n-i) X_{i+1} \quad (16)$$

C_f denotes the fixed cost in C_{mc}, replacement cost and PM cost of one component is C_{rc} and C_{pc}, then

$$C_{mc} = C_f + m \cdot C_{rc} + (n-m) \cdot C_{pc} \quad (17)$$

4 Numeral examples

Consider 3 typical cases: 1) Load stress has not fully utilized the components until maintenance, and component reward rate increases with the load stress on it. There is no overall reward rate loss. 2) System is under heavy load, and every component has a constant reward rate. 3) Load-sharing causes component reward rate increase, but it doesn't catch the load stress increase for some system overheads, so the overall system reward rate decreases.

For the first case, it holds

$$(n-i)\omega_i L_i = (n-i+1)\omega_{i-1}L_{i-1}\cdots = n\omega_0 L_0 \tag{18}$$

According to Eq. 14, for $1 \le i \le m$

$$\frac{b_i}{a_i} = \frac{n-i+1}{n-i} \tag{19}$$

Example 1. Consider a *2-out-of-8* system. At time 0, MTTF of one component is 8000 minutes, $n\omega_0 L_0 = \omega_0 L = 6000$, $C_f = 8000$, $C_{rc} = 3000$, $C_{pc} = 1000$, $Z_f = 200$, $Z_r = 20$, $Z_p = 10$. The expected reward per unit time according to m is described in Fig. 2.

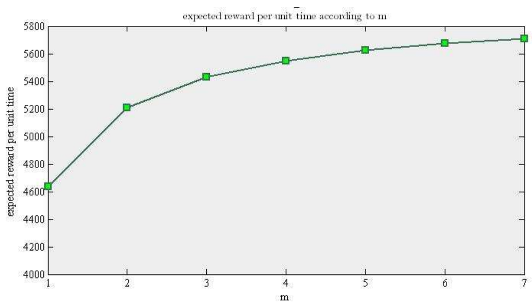

Fig. 2: expected reward per unit time according to m without overall reward loss

In this scenario, reward achieved between two failures is much more than increase of cost. The result shows that the latter maintenance is carried out, the more reward we gain.

Example 2. For the second case, or according to Eq. 14, $b_i/a_i = 1$, $1 \le i \le m$. Consider the system in example 1, let $\omega_0 L_0 = 6000/8$. The expected reward per unit time according to m is described in Fig. 3.

In this scenario, the overall reward drops almost linearly with the failure number since component can't offer more reward from the beginning. From an economic view, maintenance should be carried out as early as we can.

Example 3. Still consider the system in example 2. For the third case, let $b_i/a_i = \sqrt{(n-i+1)/(n-i)}$, hence $(n-i)\omega_i L_i = \sqrt{n(n-i)}\omega_0 L_0$. The expected reward per unit time according to m is described in fig. 4.

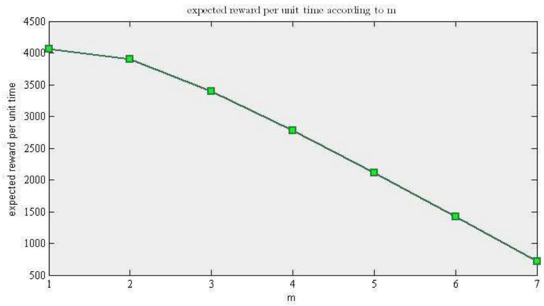

Fig. 3: expected reward per unit time according to m with constant component reward rate

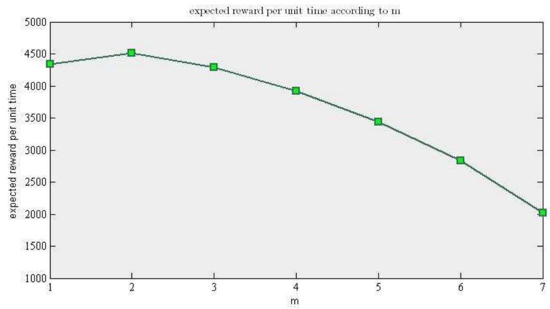

Fig. 4: expected reward per unit time according to m with component reward rate increase and overall reward rate loss

We see that in this scenario, the expected reward rate increases first and then drops down. The optimal policy which maximized the reward rate is at $m = 2$. A reasonable explanation is the competing of fixed cost sharing and performance loss. The fixed cost counted into each unit of time declines as system running, while reward also declines with component failure. If the shared fixed cost drops faster, $C(m)$ increases, otherwise, $C(m)$ decreases.

5 Conclusions

In this study, we present a failure number m based maintenance policy for high reliability load-sharing computer systems with *k-out-of-n:G* redundant structure. The maintenance policy we presented in this paper is relatively simple but practical in field application. Based on the widely accepted exponential failure time distribution and TFR model, we analyzed the expected system reward rate. For some numeral examples under different load stress levels, we achieved corresponding optimal value of policy decision variable m. The result indicates that component failure has much more impact on heavily loaded system than lightly one, and optimization of maintenance action depends greatly on the load level.

The major difference between this policy and previous study is that the covariate we take into consideration to affect component failure rate is the load stress level, versus component age which is usually selected in previous research work. In fact, the factor which contributes most to component failure rate change can be different at different time scale. When observation is taken throughout the component lifecycle, wear out leads to continuous increase on component failure rate. For the scenario where maintenance policy should avoid early replacement to maximize the usage, length of a renew cycle is decided with respect to the expected length of component life, and thus component age is taken as an important factor in failure rate increase. While in the application of high reliability computer systems, maintenance is performed at the idle hour daily or weekly and replacement is usually executed on FRUs instead of repair. On the other hand, as an example, disks usually serve for several years before replacement. The time scale of maintenance schedule is very small compared to component lifecycle. For such cases, failure rate change caused by component aging can be neglected, and vibration on load stress level has more impact on failure rate change than wear out.

The numeral examples show some typical situations but not all. Even b_i/a_i falls into the same region, shape of the curve may vary from one system to another. While for a specific system, with knowledge of the required characteristics, reward rate can also be evaluated by the method in this paper.

Acknowledgement

This work is partially supported by the National Natural Science Foundation of China 61003047, the National Natural Science Foundation of China 61173020, the International Science & Technology Cooperation Program of China 2010DFA14400, and the National Science & Technology Pillar Program of China 2011BAH04B03.

References

[1] T. Nakagawa, Maintenance Theory of Reliability, Springer-Verlag, London, (2005).
[2] H. Wang, European Journal of Operational Research, **139**, 469-489 (2002).
[3] R. Barlow and L. Hunter, Operations Research, **8**, 90-100 (1960).
[4] S. Yang, IEEE Transactions on Reliability, **52**, 373-383 (2003).
[5] C. M. Tan and N. Raghavan, Reliability Engineering and System Safety, **93**, 1138-1150 (2008).
[6] A. Ghasemi, S. Yacout, M. S. Ouali, IEEE Transactions on Reliability, **59**, 426-439 (2010).
[7] T. Nakagawa, Naval Research Logistics, **31**, 543-550 (1984).
[8] S. H.Sheu, C. M. Kuo, T.Nakagawa, Recherche Oprationnelle, **27**, 337-351 (1993).
[9] Y. Wang and H.Pham, IEEE Transactions on Reliability, **60**, 770-781 (2011).
[10] X. Zheng and N. Fard, IEEE Transactions on Reliability, **40**, 237-244 (1991).
[11] M. Nourelfath and D.Ait-Kadi, Reliability Engineering and System Safety, **92**, 1620-1626 (2007).
[12] Y. Liu and H. Z. Huang, IEEE Transactions on Reliability, **59**, 356-367 (2010).
[13] H. Pham and H.Wang, Naval Research Logistics, **47**, 223-239 (2000).
[14] M. Park and H. Pham, IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans, **42**, 453-463 (2012).
[15] V. M. Dwyer, IEEE Transactions on Reliability, **61**, 170-179 (2012).
[16] B. Schroeder and G.Gibson, IEEE Transactions on Dependable and Secure Computing, **7**, 337-351 (2010).
[17] S. V. Amari, K. B. Misra, H. Pham, The 12th Issat International Conference on Reliability and Quality in Design, 30-35 (2006).
[18] G. Bhattacharyya and Z. Soejoeti, Communications in Statistics - Theory and Methods, **18**, 1627-1643 (1989).
[19] M. T. Madi, Communications in Statistics - Theory and Methods, **22**, 295-306 (1993).
[20] E. M. Scheuer, IEEE Transactions on Reliability, **37**, 73-74 (1988).
[21] B. Fisher and A.Kilicman, Applied Mathematics & Information Sciences, **6**, 173-176 (2012).

Xin Qi
A Ph.D. student at the Harbin Institute of Technology, China. His research fields are system reliability and fault injection. In March 2006, Mr. Qi obtained his master degree at Zhejiang University, China under the supervision of professor Wenhai Wang, and, in March 2008, started his work as a Ph.D. candidate under the supervision of professor Xiaozong Yang.

Zhan Zhang
Ph.D., Associate Professor. He obtained his doctor degree in July, 2008 at Harbin Institute of Technology, China under the supervision of professor Xiaozong Yang. His research interests include wearable computing, computer architecture, fault tolerant computing and mobile computing, etc.

Decheng Zuo
Corresponding Author, Professor. He is the director of Fault Tolerant and Mobile Computing Research Center, HIT, expert of the National High Technology R&D Program of China, the administrative vice director of Fault-Tolerant Computing Committee under China Computer Federation. His research interests cover computer architecture, fault tolerant computing, sensor network, mobile computing, etc.

Xiaozong Yang
Professor. He is the director of the Computer Science and Technology Institute, HIT, the head of Computer Architecture Discipline, HIT, and leads the Fault-Tolerant Architecture Group under CFTC. His research interests cover computer architecture, fault-tolerant computing, dependable computing, mobile computing, wearable computing, etc.