# Dynamic Random Testing of Web Services: A Methodology and Evaluation

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***Abstract*—In recent years, Service Oriented Architecture (SOA) has been increasingly adopted to develop distributed applications in the context of Internet. To develop reliable SOA-based applications, an important issue is how to ensure the quality of Web services. In this paper, we propose a dynamic random testing (DRT) technique for Web services, which is an improvement of the widely-practiced random testing (RT). We examine key issues when adapting DRT to the context of SOA, including a framework, guidelines for parameter settings, and a prototype for such an adaptation. Empirical studies are reported where DRT is used to test three real-life Web services and mutation analysis is employed to measure the effectiveness. Our experimental results show that, compared with two baseline techniques, namely RT and Random Partition Testing (RPT), DRT demonstrates higher fault-detection effectiveness with a lower test case selection overhead, and the theoretical guidelines of parameter setting for DRT is validated to be effective. The proposed DRT and the prototype provide an effective and efficient approach to testing Web Services.**

***Index Terms*—Software Testing, Random Testing, Dynamic Random Testing, Web Service, Service Oriented Architecture.**

## I. Introduction

SERVICE oriented architecture (SOA) [2] defines a loosely coupled, standards-based, service-oriented application development paradigm in the context of Internet. Within SOA, three key roles are defined, namely service providers which develop and own services, service requestors which consume or invoke services, and service registry which registers services from service providers and return services to service requestors. In this context, applications are built upon services that expose functionalities by publishing their interfaces in appropriate repositories, and abstracting entirely from the underlying implementation. Published interfaces may be searched by other services or users and then ~~be~~ invoked. Web services are the realization of SOA based on open standards and infrastructures [3]. Ensuring the reliability of SOA-based applications becomes crucial particularly when such applications implement important business processes.

Software testing is a practical method to guarantee quality and reliability of software. However, some features of SOA pose challenges for testing Web services [4]–[6]. For instance, service requestors often cannot access the source code of Web services which are published and owned by another organization, and as a consequence white-box testing techniques become inapplicable. Therefore, testers naturally turn to black-box testing techniques.

Random Testing (RT) [7] is one of the most widely-practiced black-box testing techniques. In RT, test cases are randomly selected from the input domain(which refers to the set of all possible inputs of the software under test).therefore, it is easy to use. In the meanwhile, RT may be inefficient in some situations because it does not make use of information about software under test (SUT) and test history. In recent years, many efforts have been make to improve to RT in different ways [8]–[11]. For example, adaptive random testing (ART) [9] is proposed to improve RT in order to make more diverse distribution of test cases in the input domain.

Different from RT, partition testing (PT) hope to generate test cases in a more "systematic" way, aiming at using fewer test cases reveal more faults. Firstly, the input domain of SUT divided into disjoint partitions. Then test cases are selected from each and every partitions. In PT, each partition is expected to have a certain degree of homogeneity, that is, every test case in same partition should have similar software execution behavior. In the idea case, a partition should be homogeneous in fault detection. In other words, if one input is fault-revealing/non-fault-revealing, all other inputs in the same partition will be fault-revealing/non-fault-revealing too.

RT and PT are based on different intuitions, and they have their own advantages and disadvantages. It is likely that they can be complementary to each other in detecting various types of faults. Therefore, it is nature to investigate the integration of RT and PT ~~for developing new testing techniques~~. Cai et al. [8] have proposed the so-called random partition testing (RPT). In RPT, the input domain is first divided into $m$ partitions $c_1, c_2, \ldots, c_m$, and each $c_i$ is allocated a probability $p_i$. A partition $c_i$ is randomly selected according to the profile $p_1, p_2, \ldots, p_m$, where $p_1 + p_2 + \cdots + p_m = 1$. A concrete test case is then randomly selected from the chosen $c_i$.

In traditional RPT testing, the partitions and corresponding testing profile keep constant during software testing which is not always a good choice. Independent researchers from various areas have individually made an observation that the fault-

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revealing inputs tend to cluster into“continuous regions” [12], [13], that is, the similarity among neighboring software inputs. Following the idea of software cybernetics, Cai et al. proposed ~~the the~~ dynamic random testing (DRT) [8], which is to improve ~~the~~ RT and RPT. Different from the original RPT, where the values of $p_i$ are fixed and kept static along the testing process, DRT attempts to dynamically change the values of $p_i$: If a test case from a partition $c_i$ reveals a fault, the corresponding $p_i$ will be increased by a constant $\epsilon$; otherwise, decreased by the $\epsilon$.

In practice, Web services have been somehow tested at the side of service providers. Those simple or easy-to-test faults are removed and the remaining faults are normally hard to detect. To pursue a higher reliability of Web services, simple RT strategy may not an appropriate candidate technique, especially when the scale of Web services is huge or more stubborn faults ~~need to be detected~~. Some studies show that DRT can improve RT in term of fault detection effectiveness [14]–[16].

In this paper, we present a dynamic random testing (DRT) for Web services, which is an enhanced version of RT and in the meanwhile an adaptation of DRT to the context of SOA. We further examine key issues of such an adaption, and conduct empirical studies to evaluate the feasibility and effectiveness of the proposed DRT. Experimental results show that DRT evidently outperforms RT. The contributions of this work include:

- We develop an effective and efficient testing technique for Web services, including a DRT framework which addresses key issues to testing Web services and a prototype which partially automates the framework.
- We evaluate the performance of DRT through a series of empirical studies on three real Web services. It has shown that DRT has significantly higher fault-detection effectiveness than random testing and random partition testing, while its test case selection overhead is lower.
- We provide the guidelines of parameter settings of DRT in a form of theoretical analysis, and the guidelines are also validated by the empirical studies.

The remaining of the paper is organized as follows. Section II introduces the underlying concepts of DRT, Web services and mutation analysis. Section III presents a framework DRT for Web services, guidelines for parameter settings in DRT, and a prototype which partially automates the DRT. Section IV describes an empirical study where the proposed DRT is used to test three real-life Web services. Section VI discusses related work and Section VII concludes the paper.

## II. Background

In this section, we present the underlying concepts of DRT, Web services, and mutation analysis.

### A. Dynamic Random Testing(DRT)

DRT combines RT and partitioning testing [31] in order to enjoy the benefits of both testing techniques. Assume the test suite *TS* are classified into $m$ partitions denoted as $c_1, c_2, \ldots, c_m$, and suppose that a test case from $c_i(i = 1, 2, \ldots, m)$ is selected and executed. if this test case reveals a fault, $\forall j = 1, 2, \ldots, m$ and $j \neq i$, we set

$$p'_j = \begin{cases} p_j - \dfrac{\epsilon}{m-1} & \text{if } p_j \geq \dfrac{\epsilon}{m-1} \\ 0 & \text{if } p_j < \dfrac{\epsilon}{m-1} \end{cases}, \tag{1}$$

and then

$$p'_i = 1 - \sum_{\substack{j=1 \\ j \neq i}}^{m} p'_j. \tag{2}$$

Otherwise, if the test case does not reveal a fault, we set

$$p'_i = \begin{cases} p_i - \epsilon & \text{if } p_i \geq \epsilon \\ 0 & \text{if } p_i < \epsilon \end{cases}, \tag{3}$$

and then for $\forall j = 1, 2, \ldots, m$ and $j \neq i$, we set

$$p'_j = \begin{cases} p_j + \dfrac{\epsilon}{m-1} & \text{if } p_i \geq \epsilon \\ p_j + \dfrac{p'_i}{m-1} & \text{if } p_i < \epsilon \end{cases}. \tag{4}$$

The detailed algorithm of DRT is given in Algorithm 1. In DRT, the first test case is selected from a partition that is randomly selected according to the initial probability profile $\{p_1, p_2, \ldots, p_m\}$ (Lines 2 and 3 in Algorithm 1). After the execution of a test case, the test profile $\{p_1, p_2, \ldots, p_m\}$ will be updated through changing the values of $p_i$: If a fault is revealed, Formulas 1 and 2 will be used; otherwise, Formulas 4 and 3 will be used. The updated test profile will be used to guide the random selection of the next test case (Lines 8). Such a process is repeated until the termination condition is satisfied (refer to Line 1). The termination condition here can be either “testing resource has been exhausted”, or “a certain number of test cases have been executed”, or “a certain number of faults have been detected”, etc.

**Algorithm 1** DRT

```
Input: $\varepsilon, p_1, p_2, \ldots, p_m$
1:  while termination condition is not satisfied
2:     Select a partition $c_i$ according to the profile $\{p_1, p_2, \ldots, p_m\}$
3:     Select a test case $t$ from $c_i$
4:     Test the software using $t$
5:     if a fault is revealed by $t$
6:        Update $p_j$ ($j = 1, 2, \ldots, m$ and $j \neq i$) and $p_i$ according to Formulas 1 and 2.
7:     else
8:        Update $p_j$ ($j = 1, 2, \ldots, m$ and $j \neq i$) and $p_i$ according to Formulas 3 and 4.
9:     end_if
10: end_while
```

From Formulas 1 to 3, we can see that an update of test profile involves $m$ simple calculations, that is, it requires a constant time. In addition, the selection of $c_i$, the selection and execution of a test case all need a constant time. Simply speaking, the execution time for one iteration in DRT is constant. Therefore, the time complexity for DRT to select $n$ test cases is $O(n)$.

## B. Web Services

A Web service is a platform-independent, loosely coupled, self-contained programmable web-enabled application that can be described, published, discovered, coordinated and configured using XML artifacts for the purpose of developing distributed interoperable applications [2]. A Web service consists of description which is usually specified in WSDL, and implementation which can be written in any programming language. Web services expose their functionalities by publishing interfaces and at run-time are usually deployed in a service container. In order to invoke a Web service, one needs to analyze the input message of its WSDL and assign the expected values.

Web services is basic components of SOA software. The adoption of SOA, in addition to changing the architecture of a system, brings changes in the process of building the system and using it, and this has effects on testing too [5].

- *lack of observability of the service code and structure:* users and service registry only get interfaces of services, which prevents white-box testing approaches.
- *dynamicity and adaptiveness:* Testers always can determine the component invoked, or, ~~at least,~~ the set of possible targets. ~~This is not true for SOA, where a system can be described by means of a workflow of abstract services that are automatically bound to concrete services retrieved from one or more registries during the execution of a workflow instance~~.
- *lack of control:* For traditional software testing, testers can control components under test. However, only the services provider has control over the service.
- *lack of trust:* A service provider may lie, providing incorrect/inaccutrate description of a service's functional and non-functional behavior, which brings uncertainty to testers.

Obviously, SOA testing is more difficult than testing traditional software. RT is a widely used software testing technology, but because of the characteristics of the RT itself, it may not be efficient in Web services.

## C. Mutation analysis

Mutation analysis [17] is widely used to assess the adequacy of test suites and the effectiveness of testing techniques. The mutation analysis technique applies some mutation operators to seed various faults into the program under test, and thus generates a set of variants, namely mutants. If a test case causes a mutant to show a behavior different from the program under test, we say that this test case can kill the mutant and thus detect the fault injected into the mutant. We normally use the mutation score (MS) to measure how thoroughly a test suite can kill the mutants, which is defined as

$$MS(p, ts) = \frac{N_k}{N_m - N_e} \tag{5}$$

where $p$ refers to the program being mutated, $ts$ refers to test suite under evaluation, $N_k$ refers to the number of killed mutants, $N_m$ refers to the total number of mutants, and $N_e$ refers to the number of equivalent mutants. An equivalent mutant refers to one whose behaviors are always the same as those of $p$. It has been pointed out that compared with manually seeded faults, the automatically generated mutants are more similar to the real-life faults, and the mutant score is a good indicator for the effectiveness of a testing technique [18]. In this paper, we will use mutation analysis technique to evaluate the effectiveness of the proposed DRT for Web services.

## III. Dynamic Random Testing for Web Services

We describe a framework of applying DRT to Web services, discuss guidelines for parameter settings in DRT, and present a prototype which partially automates the DRT for Web services.

### A. Framework

Considering the principle of DRT and the features of Web services, we propose a framework of DRT for Web services, as illustrated in Figure III-A. Components in the box are relevant to DRT, and Web services under test are located out of the box. The interactions between DRT components and Web services are depicted in the framework. We next discuss components in the framework individually.

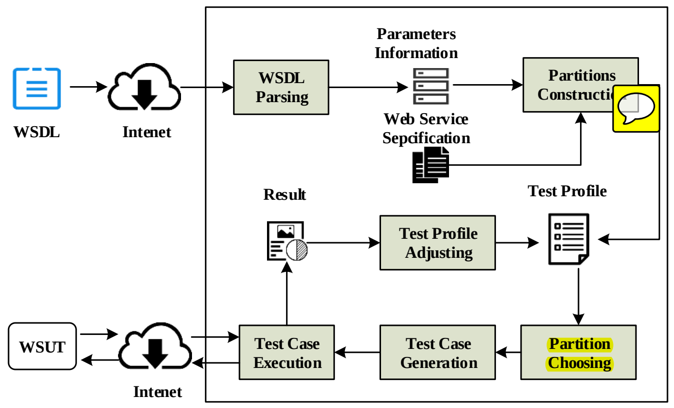


Fig. 1. The framework of DRT for Web services

1 *WSDL Parsing*. Web services are composed of services and consistent WSDL document. By parsing the WSDL document, we can get input information for each operation in the services, including the number of parameters, parameter names, parameter types, and additional requirements related to the input parameters.

2 *Partitions Construction*. Partition testing refers to a class of testing techniques [19]. Although existing partitioning schema may vary from statement, dataflow, branch, path, functionality to risk, we prefer partitions at the specification level to ones at the program level, because DRT is a kind of black-box testing technique combining random testing and partition testing. The principles on achieving convenient and effective partitions have been discussed in some

literature [19]–[22]. According to the specification of Web service under test (WSUT) and parameters parsed, we can choose a appropriate method to partition the input domain of WSUT. After partitioning, the testers can assign ~~partitions corresponding~~ probability distribution as the initial test profile. There are different ways to set the initial test profile. One is to make a uniform probability distribution; the other is to set larger probabilities for those core partitions while smaller probabilities for less important ones.

3 *Partition Choosing*. When the DRT starts, the component is responsible for selecting a partition randomly according to the test profile.

4 *Test case generation*. Suppose the partition $c_i$ is selected, we can randomly and independently generate a test case that belongs to $c_i$. Since we have parsed the WSDL document, generating test cases can be automated and not particularly difficult.

5 *Test Case Execution*. The component receives test case generated by Test Case Generation. During the testing, the component is responsible for converting test cases into input messages, invoking Web services through the SOAP protocol, and intercepting the test results (namely output messages).

6 *Test Profile Adjustment*. After one test is completed, the component decides whether the test passes or fails by comparing the actual output with the expected output. With the evaluation result, Probability Distribution Adjustment accordingly adjusts the probability distribution. In some situation, it may be impossible to decide whether one test succeeds or not (namely the Oracle problem), then metamorphic testing [23] may provide an aid to make decisions.

In general, test case generation in DRT for Web services still follows the principle of random testing; on the other hand, the selection of next test case (corresponding to a partition) is in accordance with the probability distribution. In this way, DRT takes both advantages of random testing (easiness) and partition testing (effectiveness). In addition, some components in the framework of DRT for Web services can be automated, including Partition choosing, Test Case Generation, Test Case Execution, Test Profile Adjustment. In order to make DRT for Web services more efficient and practical, we developed a prototype to be described next.

## *B. Guidelines for parameter settings*

Our previous work found that there may be some relationship between the parameter of DRT and the number of partitions. This section explores their relationship through theoretical analysis. In order to be mathematically easy, we make the following assumptions:

1 The failure rate of test suite is $\theta$ that is the probability of randomly selecting a test case from test suite can reveal a faults. After partitioning the input domain, the failure rate of each partition is $\theta_i (i = 1, 2, \ldots, m)$. When the failure rate of each partition can not obtain, it can be determined by estimation.

2 There are always at least one partition $c_M$ that have greatest failure rate $\theta_M > \theta_i (i \neq M)$.

3 ~~The inefficiencies of each partition remained unchanged during the test~~. During the test, the failure rate $\theta_i (i = 1, 2, \ldots, m)$ remain unchanged, that is, testers do not remove detected faults.

4 A test case is selected and executed still has an opportunity to be selected.

After partitioning the input domain, there is at least one partition $c_M$ that have greatest failure rate $\theta_M$. The major idea of DRT strategy is to increase the selecting probabilities of the partitions that have higher failure rate. Parameter $\epsilon$ update the test profile during the test. However, according to 1 and 3, we can see that the number of partition also effect the speed of update the test profile. Therefore, under a certain number of partitions, set reasonable $\epsilon$ can enable DRT strategy to find the most efficient partition.

During the test, in order to guarantee the highest failure rate of partition $c_M$ is more likely to be selected, we hope that the selected probability $p_M$ is more and more big:

$$E(p_M(n+1)) > p_M(n) \tag{6}$$

where n denotes the number of test cases executed.

Suppose that we start ~~test~~ with testing profile $\{p_1(0), p_2(0), \ldots, P_m(0)\}$. After $n$ test cases have been executed, the testing profile has evolved to $\{p_1(n), p_2(n), \ldots, P_m(n)\}$. Note that the situation $p_i < \epsilon/(m-1)$ or $p_i < \epsilon (i = 1, 2, \ldots, m)$, which is very rare in practice, so we do not consider this. After executing the next test case, the expected value of the testing profile is as follows:

$$\begin{aligned} E(p_i(n+1)) =& p_i(n)\theta_i(p_i(n)+\epsilon) + p_i(n)(1-\theta_i)(p_i(n)-\epsilon) \\ &+ \sum_{j\neq i} p_j(n)\theta_j(p_i(n) - \frac{\epsilon}{m-1}) \\ &+ \sum_{j\neq i} p_j(n)(1-\theta_j)(p_i(n) + \frac{\epsilon}{m-1}) \\ =& p_i(n) + Y_i(n) \end{aligned} \tag{7}$$

where

$$\begin{aligned} Y_i(n) =& \frac{\epsilon}{m-1}(2mP_i\theta_i - p_i m - 2p_i\theta_i + 1) \\ &- \frac{2\epsilon}{m-1}\sum_{j\neq i} p_j\theta_j \end{aligned} \tag{8}$$

$\because \sum_{i=1}^{m} E(p_i(n+1)) = 1$, $\therefore \sum_{i=1}^{m} Y_i(n) = 0$, and $\forall i \in \{1, 2, \ldots, m\} \& i \neq M$ , we can obtain that

$$\begin{aligned} Y_M(n) - Y_i(n) =& \frac{2\epsilon}{m-1}(m(p_M\theta_M - p_i\theta_i) - \\ & \frac{m}{2}(p_M - p_i)) \end{aligned} \tag{9}$$

for $\forall i \in \{1, 2, \ldots, m\} \& i \neq M$, if we can make sure $Y_M(n) > Y_i(n)$ , then we can have $Y_M(n) > 0$, that is

$$\begin{aligned} & Y_M(n) - Y_i(n) > 0 \Longleftrightarrow (p_i(n) - p_M(n)) > \\ & 2(p_i(n)\theta_i - p_M(n)\theta_M) \end{aligned} \tag{10}$$

$\because$ $p_i(n) - p_M(n) > (p_i(n) - p_M(n))\epsilon, 2(p_i(n)\theta_i - p_M(n)\theta_M) < 2(p_i(n)\theta_i - p_M(n)\theta_M)(m+\epsilon)/m)$, $\therefore$ we can guarantee (10), only make sure:

$$(p_i(n) - p_M(n))\epsilon > 2(p_i(n)\theta_i - p_M(n)\theta_M)\frac{m+\epsilon}{m} \quad (11)$$

However, we should consider three kinds conditions to make sure $Y_M(n) - Y_i(n) > 0$ :

1 **if** $p_i = p_M$. In this case, (11) is satisfied when $m > 0 \& \epsilon > 0$.

2 **if** $p_i > p_M$. In this scenarios, $\because 2(p_i(n)\theta_i - p_M(n)\theta_M)(m+\epsilon)/m < 2(p_i(n) - p_M(n))\theta_i(m+\epsilon)/m$ , only guarantee $p_i(n) - p_M(n) > 2(p_i(n) - p_M(n))\theta_i(m+\epsilon)/m$, we can obtain $Y_M(n) - Y_i(n) > 0$, so

$$\frac{m+\epsilon}{m\epsilon} < \frac{1}{2\theta_i} \quad (12)$$

3 **if** $p_i < p_M$. If this condition is ture, (11) can transform to $(p_M(n) - p_i(n))\epsilon < 2(p_M(n)\theta_M - p_i(n)\theta_i)(m+\epsilon)/m$ , $\because$ $2(p_M(n)\theta_M - p_i(n)\theta_i)(m+\epsilon)/m > 2(p_M(n) - p_i(n))\theta_M(m+\epsilon)/m$ , only guarantee $2(p_M(n) - p_i(n))\theta_M(m+\epsilon)/m > (p_M(n) - p_i(n))\epsilon$ , we can obtain $Y_M(n) - Y_i(n) > 0$, so

$$\frac{m+\epsilon}{m\epsilon} > \frac{1}{2\theta_M} \quad (13)$$

From the above, for all $\theta_i (i \in \{1, 2, \ldots, m\} \& i \neq M)$, $E(p_M(n+1) > p_M(n))$ is guaranteed as long as

$$\frac{1}{2\theta_M} < \frac{1}{\epsilon} + \frac{1}{m} < \frac{1}{2\theta_\triangle} \quad (14)$$

where, $\theta_\triangle = max\{\theta_i | i = 1, 2, \ldots, m, i \neq M\}, \theta_\triangle < \theta_M$. $(m+\epsilon)/m\epsilon$ lies in the interval $R = (1/2\theta_M, 1/2\theta_\triangle)$, that is:

$$\frac{1}{m} + \frac{1}{\epsilon} = \frac{1}{2\theta_M} + (\frac{1}{2\theta_\triangle} - \frac{1}{2\theta_M}) * h, (0 < h < 1) \quad (15)$$

### C. Prototype

Figure III-C shows a snapshot of the prototype which partially automates DRT for Web services. To start, testers need to input the address of Web service being tested (namely the URL of WSDL), and press Parse button to analyze input formats and output formats. Next, an operation is selected from the operation list (in the bottom left). As to the partitions and test suites, the prototype provides two options. One is to automatically generate partitions; the other is to upload the predefined partitions and test suites. If the former is selected, the initial test profile will be automatically set; otherwise, this task is left for testers. Before executing tests (the Test button), testers are required to set limits on the number of tests (Test Repetition Limit). During the testing, if a failure is detected without exceeding the limits, the prototype suspends the testing and asks for testers instruction. Testers can choose to remove defects and continue tests or stop tests. When tests are completed, the test report is summarized in a file which may be used for measuring the effectiveness of DRT.

## IV. Empirical Studies

We have conducted a series of empirical studies to evaluate the performance of DRT.

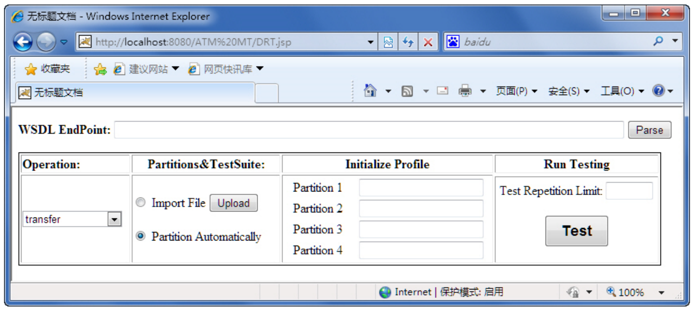


Fig. 2. The snapshot of the prototype interfaces

### A. Research questions

In our experiments, we focus on the following three research questions:

RQ1 How effective is DRT in detecting faults of Web services?
The fault-detection effectiveness is one key criterion to evaluate the performance a testing technique. In this study, three common real-life Web services are selected as subject programs, and mutation analysis is used to evaluate the effectiveness.

RQ2 How does the number of partitions and the parameter of DRT affect the failure detection efficiency of DRT?
In our earlier work [1], we found that the parameter of DRT have a significant effect on DRT efficiency, and the size of the parameter may be related to the number of partitions. The relationship between the parameters and the number of partitions is obtained through theoretical analysis, which is verified through empirical studies.

RQ3 What is the actual test case generation overhead for DRT strategy.
In Section II-A, we have theoretically demonstrated that DRT only require linear time for generating test case. We also wish to empirical evaluate the test case generation overhead of it in detecting Web services faults.

### B. Subject Web services

In our study, we selected three real-life Web services, namely `Aviation Consignment Management Service` (ACMS), `China Unicom billing service` (CUBS), `Parking billing service` (PBS), as the objects of the experiments. Mutation analysis help us generate 1563 mutants for all objects. After identifying equivalent mutants, we only include those mutants being hard to detect for the evaluation. Further to say, every those mutants cannot be detected with less than 20 randomly generated test cases. Table I summarizes the basic information of the object Web services. In following section, we give a detailed description of each Web services.

*1) Aviation Consignment Management Service:* The ACMS helps customs check the weight of free luggage and the cost of checked luggage. According to destinations, flights are

TABLE I
OBJECTS WEB SERVICES

| Web services | LOC | Number of mutants |
|---|---|---|
| ACMS | 116 | 2 |
| CUBS | 131 | 11 |
| PBS | 129 | 4 |

TABLE IV
CELL-PHONE PLAN B

| cell-phone plan(CNY) | | 46 | 66 | 96 | 126 | 156 | 186 |
|---|---|---|---|---|---|---|---|
| contains | free calls(min) | 120 | 200 | 450 | 680 | 920 | 1180 |
| | free date(MB) | 40 | 60 | 80 | 100 | 120 | 150 |
| | free incoming calls | domestic(including video calls) | | | | | |
| overuse | incoming calls(CNY/min) | 0.25 | 0.20 | 0.15 | | | |
| | date(CNY/KB) | 0.0003 | | | | | |
| | video calls(CNY/min) | 0.60 | | | | | |

divided into international and domestic flights.Each aircraft offers three kinds of seats for passengers to choose: economy, business class and first class. Passengers in different cabins can enjoy different weight for free. The detailed billing rules are summarized in Table II, where $price_0$ means economy class fare. When the flight is international, the weight of free luggage is different according to custom is a student or not. If the custom is a student, the weight of luggage is 30, and if not it is 20.

*2) China Unicom billing service:* China Unicom billing service provide a interface in which customs can know how much fee needed to pay according to cell-phone plans, cell-phone calls, and date usage. The detailed cell-phone plans are summarized in Table III,IV,V.

*3) Parking billing service:* Consider a parking billing service, which accepts the parking details of each vehicle, including type of vehicle, type of car, day of week, discount coupon, and hours of parking. This service first rounds up the parking duration to the next full hour, and than calculates the parking fee for a vehicle according to the hourly rates in Table VI. If a discount is presented, a 50% discount off the parking fee will be given.

To facilitate better parking management, at the time of parking, customers can optionally provide an estimation of parking duration in terms of three different time ranges, namely $(0.0, 2.0]$, $(2.0, 4.0]$, and $(4.0, 24.0]$. Suppose a customer providers an estimation. If the estimated hours of parking and the actual hours of parking fall into the same time range, then the customer will receive a 40% discount. If the estimated hours and the actual hours are in different time range, a 20% markup will be added. A customer may also choose to either use a discount coupon, or provide an estimation of parking duration, but not both. Obviously, a customer may also choose to neither provide an estimation, nor use a discount coupon. Note that no vehicles are allowed to park across two consecutive days on a continuous basis.

TABLE V
CELL-PHONE PLAN C

| cell-phone plan(CNY) | | 46 | 66 | 96 |
|---|---|---|---|---|
| contains | free calls(min) | 260 | 380 | 550 |
| | free date(MB) | 40 | 60 | 80 |
| | free date(MB) | domestic(including video calls) | | |
| overuse | incoming calls(CNY/min) | 0.25 | 0.20 | 0.15 |
| | date(CNY/KB) | 0.0003 | | |
| | video calls(CNY/min) | 0.60 | | |

## C. Variables

*1) Independent variables:* The independent variable in our study is the testing technique. The DRT technique must be chosen for this variable. In addition, we selected RPT and RT as the baseline techniques for comparison.

*2) Dependent variables:* The dependent variable for RQ1 is the metric for evaluating the fault-detection effectiveness. There exist quite a few effectiveness metrics, such as the P-measure (the probability of at least one fault being detected by a test suite), the E-measure (the expected number of faults being detected by a test suite), the F-measure (the expected number of test cases to detect the first fault), and the T-measure(the expected number of test cases to detect all faults). Among them, the F-measure and T-measure are the most appropriate metrics for measuring the fault-detection effectiveness of DRT testing techniques. In our study, we use $F_{method}$, $T_{method}$ to represent the F-measure and the T-measure of a testing method, where $method$ can be DRT, RPT, and RT.

As shown in Algorithm 1, the testing process may not be terminated after the detection of the first fault. In addition, the fault detection information can lead to different probability profile adjustment mechanisms. Therefore, it is also important to see what would happen after the first fault is revealed. In our study, we introduce a new metric F2-measure, which refers to how many additional test cases are required to reveal the second fault after the detection of the first fault. Similarly, we use $F2_{method}$ to represent the F2-measure of a testing method.

For RQ3, an obvious metric is the time required on detecting faults. In this study, corresponding to the T-measure, we used the $T - time$ to measure the time for detecting all faults, respectively. Similarly, $F - time$, $F2 - time$, is used to denote these time metrics.

For each of the above four metrics, a smaller value intuitively implies a better performance.

## D. Experimental settings

*1) Partitioning:* In our study, we made use of the decision table [24], [25], a typical PT technique, to conduct the partitioning. A decision table is based on a simple principle: sets of responses for sets of conditions. It is used to present a large quantity of complex information in a simple, straightforward manner. Usually, a decision table is composed of the constrain part and action part. The constraint part specifies valid domains to input parameters and additional constraints. there constraints are the pre-conditions of a contract and have to be resolvable to true or false. The action part specifies valid system responses with respect to constrains sets, called *rules*. The action part represents the post-conditions of a contract. Thus, every rule

TABLE II

| | domestic flights | | | international flights | | |
|---|---|---|---|---|---|---|
| | first class | business class | economy class | first class | business class | economy class |
| Take along(kg) | 5 | 5 | 5 | 7 | 7 | 7 |
| weight for free(kg) | 40 | 30 | 20 | 40 | 30 | 20/30 |
| Overweight billing(kg) | $price_0 * 1.5\%$ | | | $price_0 * 1.5\%$ | | |

TABLE III
CELL-PHONE PLAN A

| | cell-phone plan(CNY) | 46 | 66 | 96 | 126 | 156 | 186 | 226 | 286 | 386 | 586 | 886 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| contains | free calls(min) | 50 | 50 | 240 | 320 | 420 | 510 | 700 | 900 | 1250 | 1950 | 3000 |
| | free date(MB) | 150 | 300 | 300 | 400 | 500 | 650 | 750 | 950 | 1300 | 2000 | 3000 |
| | free incoming calls | domestic(including video calls) | | | | | | | | | | |
| overuse | incoming calls(CNY/min) | 0.25 | 0.20 | 0.15 | | | | | | | | |
| | date(CNY/KB) | 0.0003 | | | | | | | | | | |
| | video calls(CNY/min) | 0.60 | | | | | | | | | | |

TABLE VI
HOURLY PARKING RATES

| Actual hours | Hourly parking rates | | | | | |
|---|---|---|---|---|---|---|
| | Weekday | | | Saturday and Sunday | | |
| | Motorcycle | Car:2-door coupe | Car:others | Motorcycle | Car:2-door coupe | Car:others |
| $(0.0, 2.0]$ | 4.00 | 4.50 | 5.00 | 5.00 | 6.00 | 7.00 |
| $(2.0, 4.0]$ | 5.00 | 5.50 | 6.00 | 6.50 | 7.50 | 8.50 |
| $(4.0, 24.0]$ | 6.00 | 6.50 | 7.00 | 8.00 | 9.00 | 10.00 |

TABLE VII
TWO PARTITION SCHEMAS

| Web services | Schema 1 | Schema 2 |
|---|---|---|
| ACMS | 24 | 7 |
| CUBS | 20 | 3 |
| PBS | 18 | 3 |

of the decision table defines a *contract*. In our study, every contract corresponds to a partition.

After constructing decision table, a test case can be generated by a rule. To investigate the performance of our techniques under various scenarios, we develop two partition schemas shown in Table IV-D1 :

- **Schema 1**: every contract in decision table corresponds to a partition.
- **Schema 2**: After constructing decision table, we can put same responses together, then every contract in decision table corresponds to a partition.

Let us take ACMS as an example and show two schemas of partitioning. In ACMS, there are three main parameters namely *airlineType*, *cabinClass*, *passagnerCategory*. *airlineType* represents the route type: international flight(IF), domestic flight(DF). *cabinClass* represents the different cabins: tourist class(TC), business class(BC), first class(FC). *passengerCategory* represents the passengers category: infant(I), children(C), students(S), major(M). Different parameter combinations can enjoy different free consignment weight.

*2) Initial profile:* Since the test cases are randomly generated during the test processing, it is a conservative and feasible method to use the equal probability distribution as the initial test profile. on the other hand, testers can also be based on past experience to use a unequal probability distribution as the initial test profile.

*3) Constants:* In the experiments, we explore the relationship between the number of partitions and parameter. Therefore, we design a set of parameter values, $\epsilon \in \{1.0E-05, 5.0E-05, 1.0E-04, 5.0E-04, 1.0E-03, 5.0E-03, 1.0E-02, 5.0E-02, 1.0E-01, 2E-01, 3E-01, 4E-01, 5E-01\}$. Note that $\epsilon = 5E-01$ is already a big one. Consider this Scenario: In PBS when the test is carried out under the partition schema I, if we set $\epsilon = 7.5E-01$ and equal probability distribution as test profile, that is, $p_i = 1/3$. Suppose that the first test case belong to $c_1$ was executed and did not reveal any faults, then the value of $p_1$ would be 0. Obviously, it is not unreasonable. The value of $\epsilon$ should not be too big.

## *E. Experimental environment*

Our experiments were conducted on a virtual machine running the Ubuntu 11.06 64-bit operating system. In this system, there were two CPUs and a memory of 2GB. The test scripts were generated using Java. In the experiments, we repeatedly run the testing using each technique for 30 times with 30 seeds to guarantee the statistically reliable mean values of the metrics (F-measure, F2-measure, T-measure, F-time, F2-time, T-time).

## *F. Threats to validity*

*1) Internal validity:* The threat to internal validity is related to the implementations of the testing techniques, which involved a moderate amount of programming work. The code was also cross-checked by different individuals. We are confident that all techniques were correctly implemented.

TABLE XI
NUMBER OF SCENARIOS WHERE THE TECHNIQUE ON TOP ROW HAS SMALLER F-MEASURE THAN THAT ON LEFT COLUMN

| | RT | RPT | DRT |
|---|---|---|---|
| RT | — | **4** | **71** |
| RPT | **2** | — | **63** |
| DRT | **7** | **15** | — |

*2) External validity:* One obvious threat to external validity is that we only considered three object Web services. However, they are real-life Web services. In addition, 17 distinct faults were used to evaluate the performance. Though we have tried to improve the generality by applying different granularities in partitioning and 13 kinds of parameters, we cannot say whether or not similar results would be observed on other types of Web services.

*3) Construct validity:* The metrics used in our study are simple in concept and straightforward to apply, hence the threat to construct validity is little.

*4) Conclusion validity:* We have run a sufficient number of trials to guarantee the statistical reliability of our experimental results. In addition, as to be discussed in Section V, statistical tests were conducted to verify the significance of our results.

## V. EXPERIMENTAL RESULTS AND ANALYSIS

### A. RQ1: Fault detection effectiveness

The experimental results of F-measure, F2-measure and T-measure are summarized in Tables VIII to X. The distributions of F-measure, F2-measure and T-measure on each object program are displayed by the boxplots in Figures 3 to 5. In the boxplot, the upper and lower bounds of the box represent the third and first quartiles of a metric, respectively, and the middle line denote the median value. The upper and lower whiskers respectively indicate the largest and smallest data within the range of $\pm 1.5 \times IQR$, where $IQR$ is the interquartile range. The outliers outside $IQR$ are denoted by hollow circles. The solid circle represents the mean value of a metric.

From Tables VIII to X and Figure 3, 4, 5, we can observe that in general, DRT was the best performer in terms of F-measure, F2-measure, and T-measure, followed by RPT. We further conducted statistical testing to verify the significance of this observation. We used the Holm-Bonferroni method [26] (with p-value being 0.05) to determine which pair of testing techniques have significant difference. The statistical testing results are shown in Tables XI, XII and XIII. Each cell in the tables gives the number of scenarios where the technique on the top row performed better than that on the left column. If the difference is significant, the number will be displayed in bold. For example, the bold 76 in the top right corner in Table XIII indicates that out of 78 scenarios (13 parameters $\times$ 2 partition schemas $\times$ 3 object Web services), DRT had smaller T-measure than RT for 76 scenarios, and the fault-detection capabilities of these two techniques were significantly different.

Tables XI, XII and XIII clearly show that the effectiveness difference between each pair of testing techniques was always significantly different.

TABLE XII
NUMBER OF SCENARIOS WHERE THE TECHNIQUE ON TOP ROW HAS SMALLER F2-MEASURE THAN THAT ON LEFT COLUMN

| | RT | RPT | DRT |
|---|---|---|---|
| RT | — | **5** | **77** |
| RPT | **1** | — | **72** |
| DRT | **1** | **6** | — |

TABLE XIII
NUMBER OF SCENARIOS WHERE THE TECHNIQUE ON TOP ROW HAS SMALLER T-MEASURE THAN THAT ON LEFT COLUMN

| | RT | RPT | DRT |
|---|---|---|---|
| RT | — | **6** | **76** |
| RPT | **0** | — | **69** |
| DRT | **2** | **9** | — |

### B. RQ2: Relationship between partition number and $\epsilon$

In III-B, we have analyzed the relationship between partition numbers and parameter. This section we validate that our theoretical analysis is reasonable to instruct testers set parameter of DRT strategy.

In order to study how the value of $h$ effect the test efficiency of DRT technology, 5 parameters were set $h \in \{0.1, 0.3, 0.5, 0.7, 0.9\}$. According to formula (14), the values of $\epsilon$ in each scenarios for all objective Web services show in Table XIV.

We used three Web services to validate our theoretical analysis. Before starting our test, the failure rates of each partition are obtained by running test cases which belong to corresponding partition until revealed a fault and computing the test cases used. We develop a series of experiments with parameters in accordance with Table XIV, and the distributions of F-measure, F2-measure and T-measure on each object program are displayed by the Figures 6,7,8. Except for the parameters of DRT strategy, other experimental Settings are the same as V-A.

From Figure and Table XIV, we have the following observations:

- From Figires 6,7,8, it is obvious that the boxs of DRT strategy with different theoretical parameters are very narrow, that is, no matter the value of $h(0 < h < 1)$ is, the ability of DRT's detecting faults is very approximate.
- It is clear that DRT strategy with theoretical parameter has better effectiveness than RT and RPT. Moreover, even in scenarios where the DRT strategy performs worst, its fault detection efficiency is still better than RT and RPT.

On the other hand, when the value of $\epsilon$ in DRT is very small(such as $1.0E-06, 1.0E-07$), even many test cases were executed then the test profile is almost constant. In this scenario, DRT may be as efficient as RPT. On the contrary, if the value of parameter in DRT is very big(such as $0.7, 0.8$), it has high probability that when a test case were selected from a partition $c_i$, and it can not reveal any faults, the value of $p_i$ is 0. Therefore the value of parameter in DRT should not be too large or too small. We want to explore the different performance of DRT with parameter in theoretical interval and out of theoretical interval. Results in Figure 9,10,11, show that in most of scenarios, DRT with theoretical parameter have

TABLE VIII
THE RESULTS OF ACMS

| Strategy | | Partition Schema 1 | | | | | | Partition Schema 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | $SD_F$ | NF | $SD_{NF}$ | T | $SD_T$ | F | $SD_F$ | NF | $SD_{NF}$ | T | $SD_T$ |
| RT | | 13.30 | 10.34 | 28.50 | 23.95 | 41.80 | 27.13 | 13.30 | 10.34 | 28.50 | 23.95 | 41.80 | 27.13 |
| RPT | | 11.93 | 11.24 | 24.36 | 22.56 | 35.99 | 25.02 | 8.59 | 8.02 | 22.47 | 19.97 | 27.06 | 18.73 |
| DRT | 1.0E-5 | 12.31 | 11.89 | 24.47 | 24.20 | 36.78 | 26.64 | 5.80 | 6.25 | 20.27 | 17.93 | 26.08 | 19.03 |
| | 5.0E-5 | 11.96 | 11.62 | 22.52 | 21.72 | 34.48 | 24.69 | 6.00 | 6.90 | 21.53 | 19.18 | 27.54 | 20.15 |
| | 1.0E-4 | 11.76 | 11.95 | 23.84 | 23.24 | 35.60 | 26.03 | 6.48 | 7.84 | 20.54 | 18.87 | 27.01 | 20.04 |
| | 5.0E-4 | 11.46 | 10.58 | 22.73 | 22.21 | 34.19 | 23.64 | 6.21 | 7.26 | 21.45 | 19.66 | 27.66 | 20.32 |
| | 1.0E-3 | 12.02 | 11.60 | 22.19 | 21.88 | 34.21 | 24.42 | 6.32 | 7.46 | 21.10 | 19.69 | 27.43 | 20.80 |
| | 5.0E-3 | 11.00 | 9.82 | 20.64 | 19.88 | 31.64 | 21.27 | 6.14 | 6.85 | 20.53 | 18.69 | 26.68 | 19.63 |
| | 1.0E-2 | 11.01 | 9.66 | 18.32 | 15.45 | 29.33 | 18.12 | 5.59 | 5.99 | 20.35 | 18.36 | 25.94 | 19.26 |
| | 5.0E-2 | 8.87 | 6.60 | 13.45 | 10.56 | 22.31 | 11.53 | 6.26 | 7.09 | 20.85 | 17.71 | 26.34 | 18.53 |
| | 1.0E-1 | 9.26 | 6.95 | 12.95 | 9.81 | 22.21 | 11.12 | 5.86 | 5.95 | 21.83 | 17.85 | 26.73 | 18.34 |
| | 2.0E-1 | 9.00 | 6.67 | 13.21 | 9.50 | 22.21 | 10.61 | 5.82 | 6.81 | 22.21 | 18.59 | 26.63 | 18.97 |
| | 3.0E-1 | 8.66 | 6.54 | 13.69 | 9.59 | 21.55 | 10.50 | 5.34 | 6.34 | 22.11 | 18.34 | 26.50 | 18.75 |
| | 4.0E-1 | 8.80 | 6.61 | 13.38 | 9.80 | 22.18 | 10.82 | 5.45 | 6.17 | 22.11 | 17.50 | 26.63 | 18.00 |
| | 5.0E-1 | 8.76 | 6.41 | 13.57 | 10.29 | 22.33 | 11.10 | 5.51 | 5.42 | 22.22 | 17.68 | 26.66 | 18.12 |

TABLE IX
THE RESULTS OF CUBS

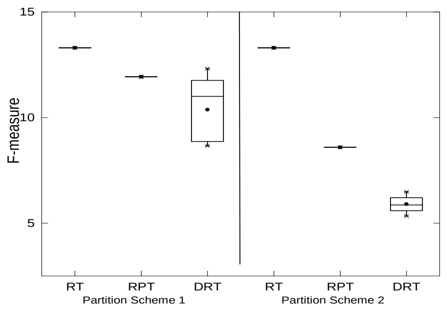
| Strategy | | Partition Schema 1 | | | | | | Partition Schema 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | $SD_F$ | NF | $SD_{NF}$ | T | $SD_T$ | F | $SD_F$ | NF | $SD_{NF}$ | T | $SD_T$ |
| RT | | 20.17 | 16.32 | 16.50 | 13.20 | 252.80 | 191.54 | 20.17 | 16.32 | 16.50 | 13.20 | 252.80 | 191.54 |
| RPT | | 17.71 | 16.78 | 16.72 | 25.12 | 178.91 | 147.96 | 15.64 | 13.4 | 13.97 | 22.24 | 175.00 | 126.88 |
| DRT | 1.0E-5 | 20.83 | 21.16 | 26.81 | 28.42 | 2521.96 | 1866.25 | 21.88 | 20.52 | 26.81 | 26.52 | 4166.31 | 2708.14 |
| | 5.0E-5 | 21.14 | 20.89 | 25.50 | 27.22 | 2523.77 | 1808.06 | 21.39 | 20.49 | 26.01 | 26.23 | 4188.00 | 2798.73 |
| | 1.0E-4 | 21.64 | 20.66 | 26.82 | 26.59 | 2497.56 | 1774.01 | 21.60 | 20.64 | 27.02 | 27.24 | 4077.07 | 2668.71 |
| | 5.0E-4 | 21.29 | 21.22 | 28.37 | 30.68 | 2538.89 | 1882.89 | 22.09 | 22.20 | 25.23 | 26.04 | 4073.15 | 2518.34 |
| | 1.0E-3 | 20.74 | 19.64 | 26.60 | 28.85 | 2449.44 | 1615.91 | 21.95 | 21.01 | 25.35 | 25.45 | 4224.83 | 2582.71 |
| | 5.0E-3 | 20.95 | 19.68 | 25.96 | 27.18 | 2487.14 | 1778.65 | 21.09 | 21.89 | 24.80 | 24.45 | 4045.44 | 2329.75 |
| | 1.0E-2 | 21.54 | 20.94 | 26.42 | 27.05 | 2579.27 | 1809.45 | 21.39 | 19.16 | 25.49 | 26.54 | 3991.68 | 2377.37 |
| | 5.0E-2 | 22.07 | 21.08 | 25.37 | 27.13 | 2662.38 | 1931.18 | 21.46 | 21.95 | 25.56 | 25.70 | 4005.80 | 2557.51 |
| | 1.0E-1 | 21.34 | 21.39 | 27.14 | 28.41 | 2539.91 | 1752.16 | 22.62 | 22.79 | 25.63 | 25.92 | 4016.92 | 2371.21 |
| | 2.0E-1 | 21.75 | 20.10 | 25.39 | 26.44 | 2515.45 | 1780.26 | 23.33 | 21.67 | 26.15 | 25.70 | 4002.59 | 2554.38 |
| | 3.0E-1 | 21.94 | 21.36 | 25.93 | 25.58 | 2531.10 | 1860.04 | 22.01 | 21.24 | 26.56 | 27.54 | 4068.50 | 2448.81 |
| | 4.0E-1 | 22.14 | 21.45 | 26.39 | 27.45 | 2486.92 | 1732.76 | 21.34 | 22.77 | 27.37 | 29.88 | 4215.41 | 2991.54 |
| | 5.0E-1 | 21.85 | 19.91 | 26.33 | 28.81 | 2490.95 | 1703.39 | 21.70 | 22.09 | 25.62 | 26.15 | 4097.77 | 2598.52 |

TABLE X
THE RESULTS OF PBS

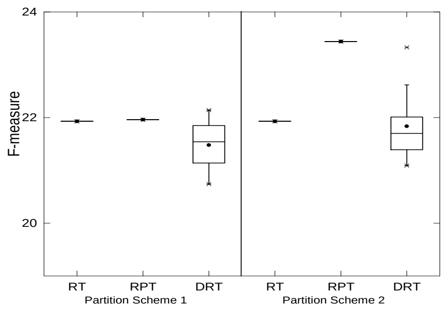
| Strategy | | Partition Schema 1 | | | | | | Partition Schema 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | F | $SD_F$ | NF | $SD_{NF}$ | T | $SD_T$ | F | $SD_F$ | NF | $SD_{NF}$ | T | $SD_T$ |
| RT | | 13.30 | 10.34 | 28.50 | 23.95 | 41.80 | 27.13 | 13.30 | 10.34 | 28.50 | 23.95 | 41.80 | 27.13 |
| RPT | | 11.93 | 11.24 | 24.36 | 22.56 | 35.99 | 25.02 | 8.59 | 8.02 | 22.47 | 19.97 | 27.06 | 18.73 |
| DRT | 1.0E-5 | 16.93 | 17.55 | 16.38 | 23.38 | 169.63 | 136.31 | 15.68 | 13.62 | 12.91 | 21.87 | 173.13 | 133.79 |
| | 5.0E-5 | 17.03 | 19.15 | 14.77 | 22.93 | 174.06 | 141.08 | 16.40 | 14.88 | 11.43 | 19.18 | 172.53 | 135.13 |
| | 1.0E-4 | 16.45 | 15.03 | 16.09 | 24.73 | 167.90 | 137.66 | 15.73 | 14.11 | 12.73 | 19.52 | 172.39 | 131.70 |
| | 5.0E-4 | 16.85 | 17.13 | 15.39 | 22.63 | 174.46 | 142.88 | 16.23 | 14.74 | 13.12 | 21.00 | 171.36 | 127.36 |
| | 1.0E-3 | 16.07 | 16.99 | 14.66 | 21.23 | 177.75 | 149.88 | 15.55 | 13.66 | 13.46 | 21.85 | 174.54 | 125.99 |
| | 5.0E-3 | 17.61 | 18.54 | 15.26 | 23.70 | 179.77 | 157.27 | 15.39 | 15.05 | 12.91 | 21.63 | 169.50 | 123.41 |
| | 1.0E-2 | 17.08 | 19.09 | 15.36 | 27.05 | 173.48 | 139.33 | 15.53 | 14.79 | 12.03 | 22.23 | 168.55 | 127.52 |
| | 5.0E-2 | 17.98 | 17.27 | 15.37 | 23.91 | 174.42 | 142.11 | 16.35 | 14.43 | 13.12 | 22.20 | 180.89 | 133.50 |
| | 1.0E-1 | 17.73 | 18.47 | 15.80 | 22.54 | 176.90 | 141.45 | 15.75 | 13.12 | 12.39 | 20.52 | 173.45 | 132.78 |
| | 2.0E-1 | 17.83 | 18.24 | 14.87 | 23.25 | 178.63 | 140.00 | 15.39 | 14.23 | 13.77 | 21.71 | 176.68 | 140.26 |
| | 3.0E-1 | 16.95 | 17.13 | 14.96 | 21.82 | 175.69 | 143.24 | 15.60 | 14.83 | 12.81 | 20.88 | 172.45 | 128.59 |
| | 4.0E-1 | 16.74 | 17.07 | 14.67 | 23.10 | 178.32 | 137.52 | 15.59 | 13.94 | 13.36 | 20.81 | 171.18 | 125.94 |
| | 5.0E-1 | 18.54 | 18.56 | 14.88 | 23.07 | 178.21 | 138.59 | 15.53 | 14.44 | 13.09 | 21.77 | 172.31 | 128.52 |

TABLE XIV
THE THEORETICAL VALUE OF DRT PARAMETERS

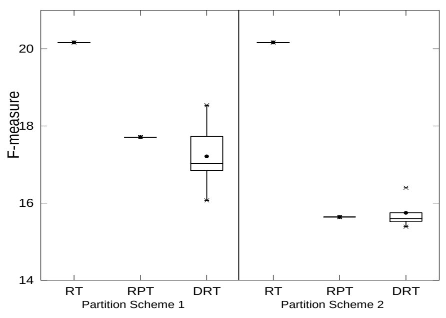
| Web services | partition schema | $\theta_M$ | $\theta_\Delta$ | $h$ | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 |
| ACMS | 1 | 6.452E-2 | 5.452E-2 | 1.274E-1 | 1.229E-1 | 1.188E-1 | 1.149E-1 | 1.113E-1 |
| | 2 | 4.718E-3 | 2.797E-3 | 8.841E-3 | 7.833E-3 | 7.031E-3 | 6.378E-3 | 5.836E-3 |
| CUBS | 1 | 2.332E-2 | 1.112E-2 | 4.218E-3 | 3.515E-3 | 3.016E-3 | 2.642E-2 | 2.349E-2 |
| | 2 | 6.987E-3 | 1.397E-3 | 1.001E-2 | 6.364E-3 | 4.664E-3 | 3.680E-3 | 3.040E-3 |
| PBS | 1 | 4.001E-3 | 3.827E-3 | 7.969E-3 | 7.897E-3 | 7.827E-3 | 7.758E-3 | 7.691E-3 |
| | 2 | 2.516E-3 | 1.492E-3 | 1.001E-2 | 6.364E-3 | 4.664E-3 | 3.680E-3 | 3.040E-3 |



(a) ACMS

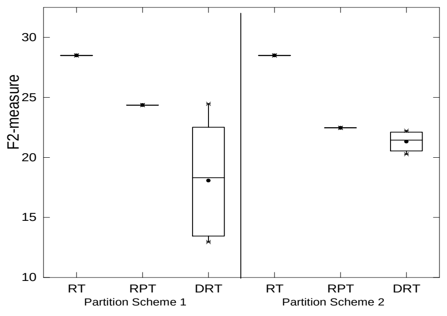


(b) CUBS

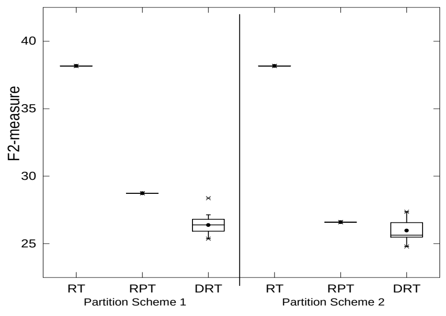


(c) PBS

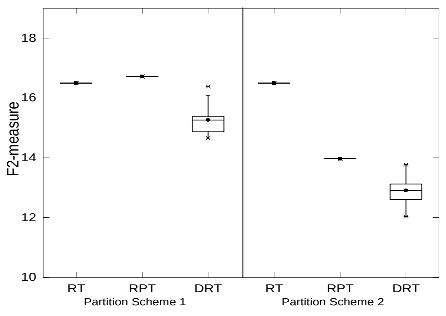
Fig. 3. Boxplots of F-measures on each object program



(a) ACMS

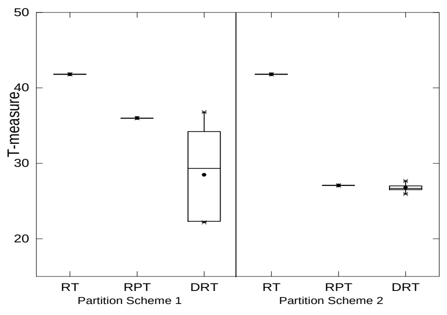


(b) CUBS

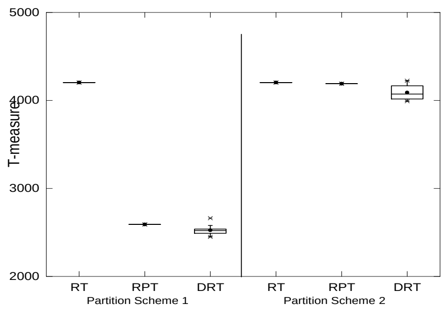


(c) PBS

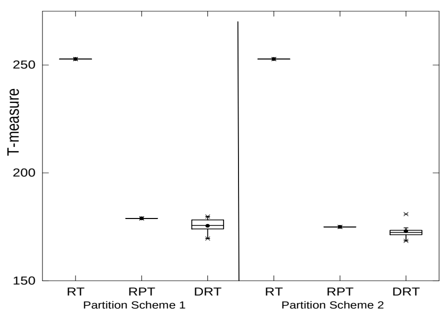
Fig. 4. Boxplots of F2-measures on each object program



(a) ACMS

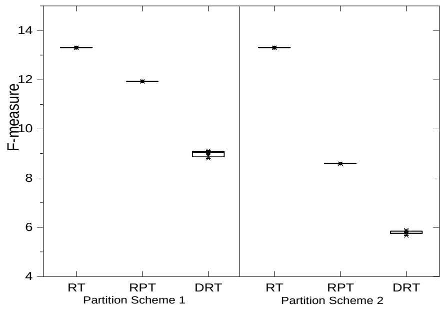


(b) CUBS

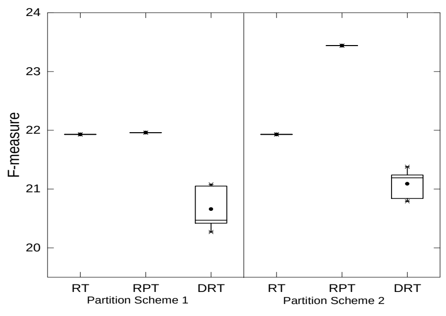


(c) PBS

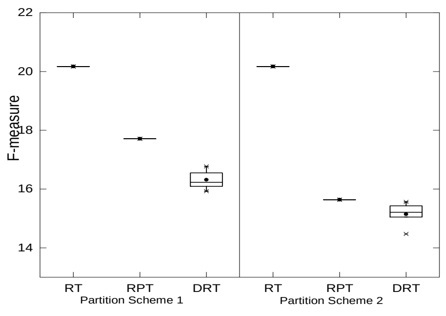
Fig. 5. Boxplots of T-measures on each object program



(a) ACMS

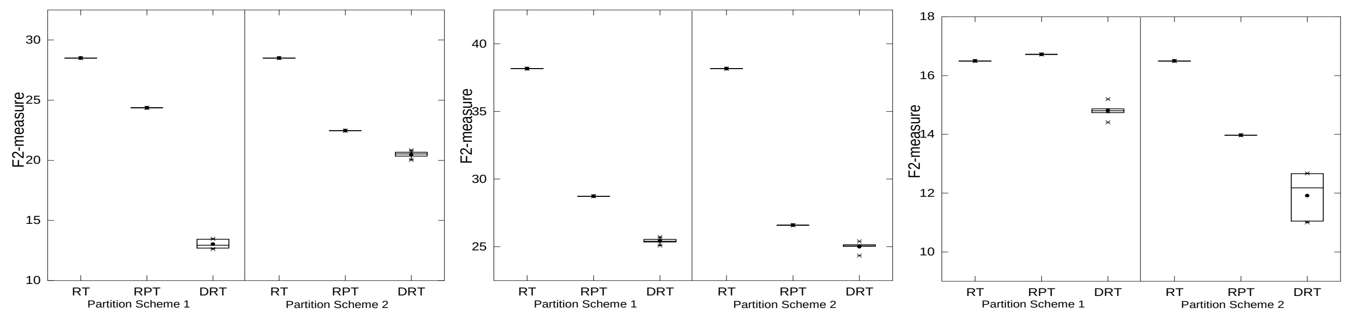


(b) CUBS



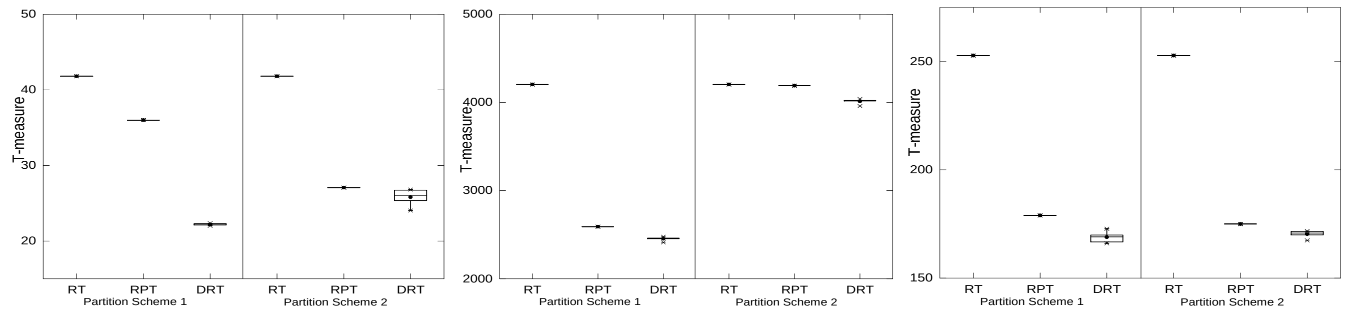
(c) PBS

Fig. 6. Boxplots of F-measure on each object program with theoretical parameter



(a) ACMS (b) CUBS (c) PBS

Fig. 7. Boxplots of F2-measure on each object program with theoretical parameter



(a) ACMS (b) CUBS (c) PBS

Fig. 8. Boxplots of T-measure on each object program with theoretical parameter

TABLE XV
F-time, F2-time and T-time on Web service ACMS (in ms)

| Strategy | | Partition Schema 1 | | | Partition Schema 2 | | |
|---|---|---|---|---|---|---|---|
| | | F-time | F2-time | T-time | F-time | F2-time | T-time |
| RT | | 5.04 | 5.41 | 28.84 | 5.04 | 5.41 | 28.84 |
| RPT | | 4.89 | 5.84 | 30.23 | 3.43 | 4.94 | 25.50 |
| DRT | 1.0E-5 | 5.06 | 5.87 | 30.93 | 2.32 | 5.63 | 24.78 |
| | 5.0E-5 | 4.92 | 5.40 | 29.00 | 2.40 | 5.18 | 26.16 |
| | 1.0E-4 | 4.83 | 5.72 | 29.94 | 2.59 | 5.48 | 25.66 |
| | 5.0E-4 | 4.71 | 5.46 | 28.75 | 2.48 | 5.23 | 26.28 |
| | 1.0E-3 | 4.94 | 5.33 | 28.77 | 2.53 | 5.10 | 26.06 |
| | 5.0E-3 | 4.52 | 4.95 | 26.61 | 2.46 | 4.75 | 25.35 |
| | 1.0E-2 | 4.53 | 4.40 | 24.67 | 2.24 | 4.21 | 24.64 |
| | 5.0E-2 | 3.65 | 3.23 | 18.76 | 2.20 | 3.09 | 25.02 |
| | 1.0E-1 | 3.81 | 3.11 | 18.68 | 1.96 | 2.98 | 25.39 |
| | 2.0E-1 | 3.70 | 3.17 | 18.68 | 1.77 | 3.04 | 25.30 |
| | 3.0E-1 | 3.56 | 3.09 | 18.12 | 1.76 | 2.96 | 25.18 |
| | 4.0E-1 | 3.62 | 3.21 | 18.65 | 1.81 | 3.08 | 25.30 |
| | 5.0E-1 | 3.60 | 3.26 | 18.78 | 1.78 | 3.12 | 25.33 |

TABLE XVI
F-time, F2-time and T-time on Web service CUBS (in ms)

| Strategy | | Partition Schema 1 | | | Partition Schema 2 | | |
|---|---|---|---|---|---|---|---|
| | | F-time | F2-time | T-time | F-time | F2-time | T-time |
| RT | | 13.78 | 19.07 | 2067.46 | 13.78 | 19.07 | 2067.46 |
| RPT | | 13.84 | 14.34 | 1331.54 | 13.72 | 13.74 | 2036.33 |
| DRT | 1.0E-5 | 13.36 | 15.51 | 1527.19 | 13.53 | 14.06 | 2046.32 |
| | 5.0E-5 | 14.03 | 15.53 | 1433.49 | 13.48 | 13.9 | 2107.06 |
| | 1.0E-4 | 12.79 | 13.61 | 1327.54 | 13.88 | 14.02 | 1988.05 |
| | 5.0E-4 | 13.23 | 14.74 | 1385.40 | 14.80 | 13.93 | 2013.44 |
| | 1.0E-3 | 12.52 | 13.97 | 1380.07 | 13.43 | 14.71 | 1926.19 |
| | 5.0E-3 | 13.16 | 14.47 | 1365.75 | 13.87 | 13.32 | 2027.36 |
| | 1.0E-2 | 13.82 | 14.44 | 1329.04 | 14.63 | 13.45 | 1975.64 |
| | 5.0E-2 | 13.66 | 15.53 | 1250.44 | 14.87 | 13.11 | 1918.87 |
| | 1.0E-1 | 13.15 | 14.11 | 1230.99 | 14.25 | 13.38 | 1983.51 |
| | 2.0E-1 | 13.38 | 14.72 | 1279.54 | 13.75 | 13.24 | 2053.69 |
| | 3.0E-1 | 14.12 | 13.52 | 1237.68 | 15.34 | 13.19 | 1962.61 |
| | 4.0E-1 | 14.02 | 13.71 | 1219.80 | 13.84 | 14.11 | 1966.21 |
| | 5.0E-1 | 13.80 | 15.17 | 1200.34 | 14.67 | 13.62 | 2073.06 |

a higher efficiency, and the theoretical interval is generally narrow. Further, our results show that the efficiency of DRT with different theoretical values is similar. Conservatively, we can set $h = 0.5$ for a concrete software under testing.

### *C. RQ3: Selection overhead*

Tables XV to XVII summarize the experimental results of $F - time$,$F2 - time$, and $T - time$, respectively. The results of distribution on every Web services are showed in Figures 12, 13, 14.

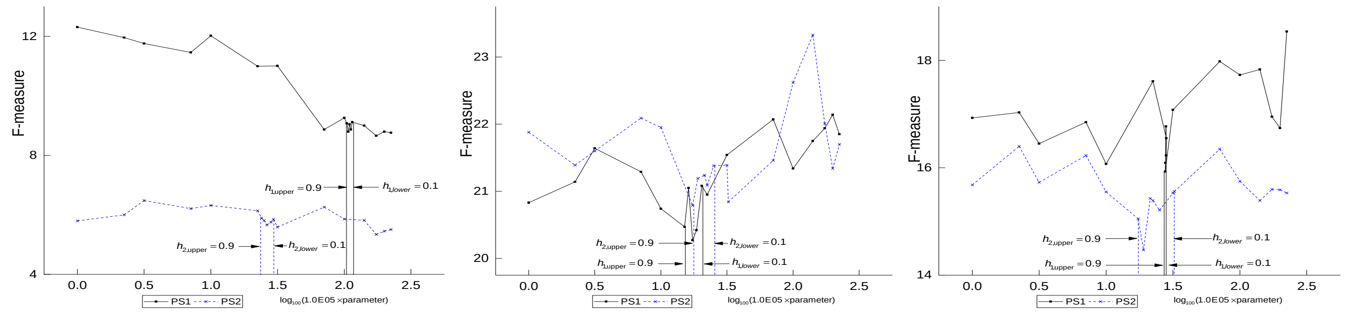
Same as the metrics experimental results, we use the Holm-Bonferroni method to check the different between each pair of testing strategies in terms of $F - time$, $F2 - time$, and $T - time$, showing in tables XVIII, XIX, XX.

We can observe that DRT only slightly outperformed RPT from Tables XVIII, XIX, XX, but DRT significantly better than RT especially in term of T-time.

In short, DRT strategy was considered as a best testing technique across all six metrics, and RPT was marginally outperformed RT.

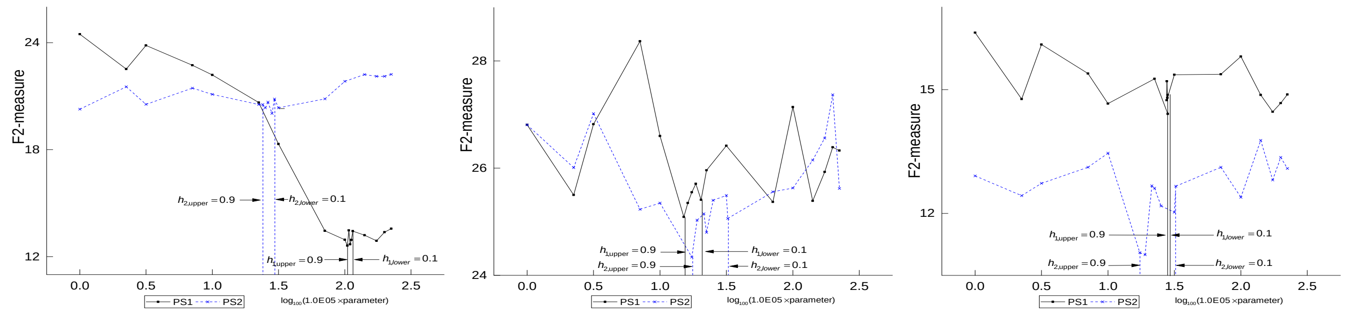
## VI. Related work

In this section, We describe related work in two dimensions, one is related to improvements on RT and PT, and the other is related to testing techniques for Web services.



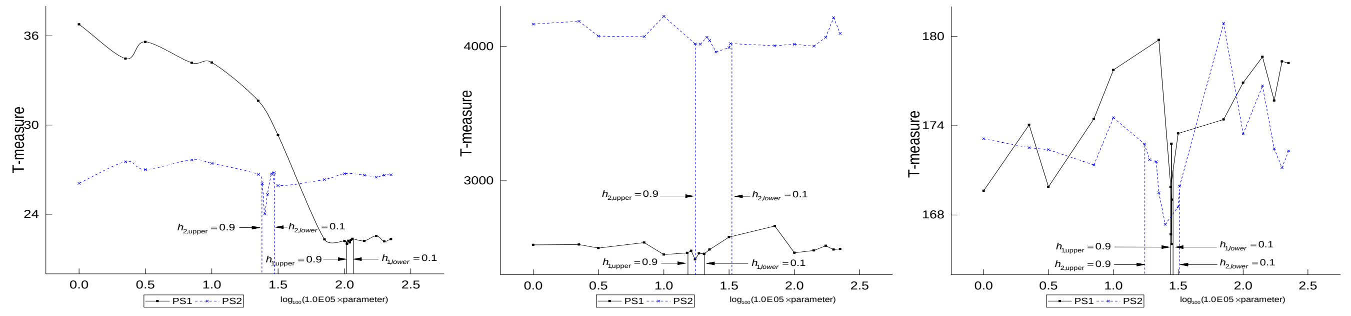
(a) ACMS (b) CUBS (c) PBS

Fig. 9. Boxplots of F-measure on each object program with theoretical parameter



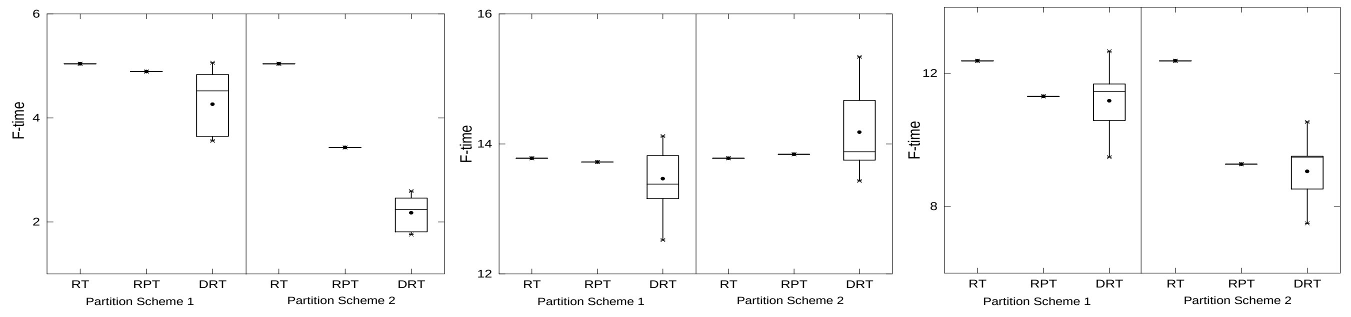
(a) ACMS (b) CUBS (c) PBS

Fig. 10. Boxplots of F2-measure on each object program with theoretical parameter



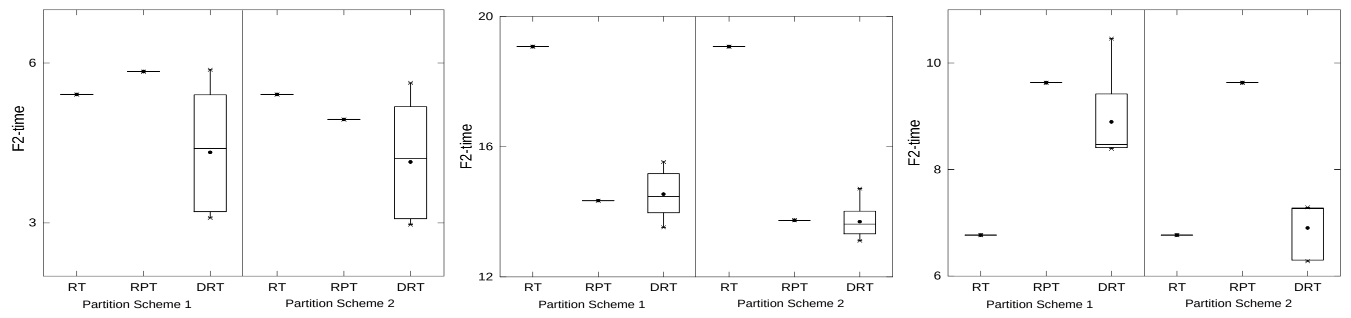
(a) ACMS (b) CUBS (c) PBS

Fig. 11. Boxplots of T-measure on each object program with theoretical parameter



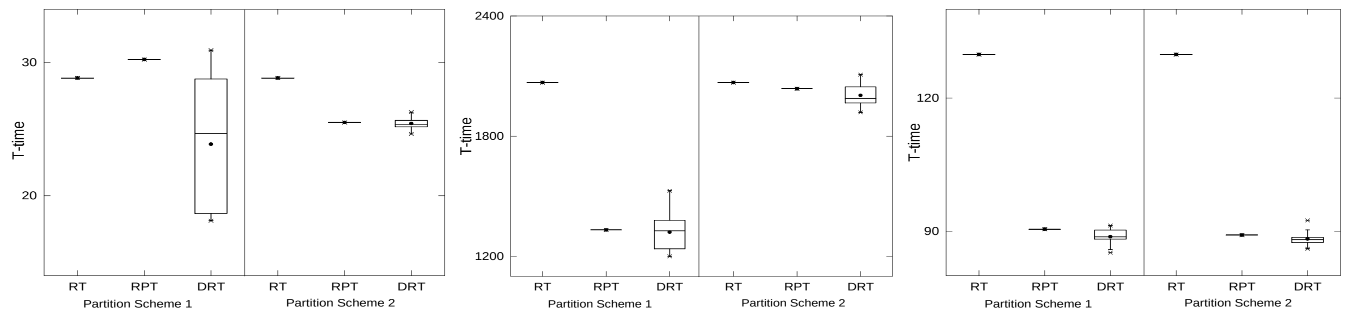
(a) ACMS (b) CUBS (c) PBS

Fig. 12. Boxplots of F-time on each object program



(a) ACMS (b) CUBS (c) PBS

Fig. 13. Boxplots of F2-time on each object program



(a) ACMS (b) CUBS (c) PBS

Fig. 14. Boxplots of T-time on each object program

TABLE XVII
F-TIME, F2-TIME AND T-TIME ON WEB SERVICE PBS (IN MS)

| Strategy | | Partition Schema 1 | | | Partition Schema 2 | | |
|---|---|---|---|---|---|---|---|
| | | F-time | F2-time | T-time | F-time | F2-time | T-time |
| RT | | 12.39 | 6.77 | 129.82 | 12.39 | 6.77 | 129.82 |
| RPT | | 11.32 | 9.63 | 90.46 | 9.28 | 7.22 | 89.14 |
| DRT | 1.0E-5 | 11.46 | 9.46 | 86.19 | 8.54 | 7.29 | 88.47 |
| | 5.0E-5 | 11.46 | 10.46 | 88.74 | 8.50 | 6.30 | 88.16 |
| | 1.0E-4 | 10.47 | 8.47 | 85.17 | 7.50 | 7.29 | 86.05 |
| | 5.0E-4 | 9.49 | 9.49 | 88.74 | 9.52 | 7.28 | 87.56 |
| | 1.0E-3 | 10.48 | 8.48 | 90.27 | 8.51 | 7.27 | 89.19 |
| | 5.0E-3 | 12.42 | 8.42 | 91.29 | 9.50 | 6.29 | 92.43 |
| | 1.0E-2 | 11.69 | 9.40 | 88.23 | 9.54 | 7.28 | 88.63 |
| | 5.0E-2 | 10.59 | 9.42 | 88.74 | 10.55 | 7.28 | 86.61 |
| | 1.0E-1 | 10.67 | 8.39 | 89.76 | 8.54 | 6.30 | 86.13 |
| | 2.0E-1 | 10.62 | 8.41 | 90.78 | 8.53 | 7.26 | 90.28 |
| | 3.0E-1 | 11.65 | 8.40 | 89.25 | 9.55 | 6.28 | 88.12 |
| | 4.0E-1 | 12.68 | 8.39 | 85.86 | 9.49 | 7.29 | 87.47 |
| | 5.0E-1 | 11.72 | 8.44 | 91.07 | 9.52 | 6.33 | 88.05 |

TABLE XVIII
NUMBER OF SCENARIOS WHERE THE TECHNIQUE ON TOP ROW HAS SMALLER F-TIME THAN THAT ON LEFT COLUMN

| | RT | RPT | DRT |
|---|---|---|---|
| RT | — | **5** | **62** |
| RPT | **1** | — | **47** |
| DRT | **16** | **31** | — |

TABLE XIX
NUMBER OF SCENARIOS WHERE THE TECHNIQUE ON TOP ROW HAS SMALLER F2-TIME THAN THAT ON LEFT COLUMN

| | RT | RPT | DRT |
|---|---|---|---|
| RT | — | **3** | **52** |
| RPT | **3** | — | **48** |
| DRT | **26** | **30** | — |

TABLE XX
NUMBER OF SCENARIOS WHERE THE TECHNIQUE ON TOP ROW HAS SMALLER T-TIME THAN THAT ON LEFT COLUMN

| | RT | RPT | DRT |
|---|---|---|---|
| RT | — | **5** | **73** |
| RPT | **1** | — | **58** |
| DRT | **3** | **20** | — |

## *A. Improvement on RT and PT*

Based on the observation that failure causing inputs tend to cluster into contiguous regions within the input domain [12], [13], many works have been done to improve RT. Adaptive random testing [27] is a family of advanced random testing techniques aimed to improve the failure detection effectiveness by evenly spread test cases executed. The most known ART is the Fixed-Size Candidate Set ART technique (FSCS-ART), which is the most widely studies. Others ART algorithms have been developed and their effectiveness are validated by simulation experiments [9], [28], [29].

Adaptive testing (AT) [20] is based same observation, which outperformed both RT and RPT. However, it requires very long execution time in practice. To alleviate this problem, Cai et al. [8] proposed DRT, which uses testing information dynamically adjusted testing profile. There are several aspects that affect the test efficiency of DRT such as testing profile, parameters etc. Yang et al. [30] proposed A-DRT, which adjusts parameters during testing process. Li et al. [31] developed O-DRT technique, which will changed test profile to a theoretically optimal one when the pre-defined criterion is satisfied. Lv et al. [32] studied the relationship of parameters in DRT, but he did not give the relationship between parameters and the number of partitions.

### *B. Testing techniques for Web services*

In recent years, many efforts have been made to test Web services. Some of the approaches found in the literature are mainly focusing on developing automatic Web Services testing tool or test case generations. Others propose frameworks/platforms to do stress and authorization tests. A large group focuses on test case generation based on the WSDL description of the Web Service. Some of the methods focus on black-box concepts, behavior testing, and others focus on white-box concepts, fault injection and fault coverage techniques. Based on the Web Services testing approaches found in the literature, we classified the existing approaches into following four classes:

*WSDL-Based test case generation*: Bai [33] presented a WSDL-based test case generating as a part of the testing framework that includes test cases generation, test controller, test agents, and test evaluator. Hanna and Munro proposed a framework that can be used to test the robustness quality attribute of a Web Service [34]. This framework is based on analyzing the Web Service Description Language (WSDL) document of Web Services to identify what faults could affect the robustness attribute and then test cases were designed to detect those faults.

*Mutation based test case generation*: In [35], [36] presented mutation analysis mechanism to test Web Services. It is a fault based testing method that measures the adequacy of a set of externally created test cases. Mutation analysis induces faults into software by creating many versions of the software, each containing one fault and is called a mutant. A mutant is killed when the output of the mutant is different from that of the original program.

*Model Driven Testing*: Feudjio and Schieferdecker [37] introduced the concept of test patterns as an attempt to apply the design pattern approach broadly applied in object-oriented software development to model-driven test development. Noikajana and Suwannasart presented a Web Service test case generation approach based on Decision Tables [38].

All existing testing techniques for Web services assume that for each test case, the computed output is verifiable. However, the assumption is not always true in practice and thus these testing techniques may be inapplicable in some situations. To address the outstanding oracle problem with testing Web services, a metamorphic testing technique was proposed, which not only alleviates the oracle problem, but also presents a feasible and efficient choice for testing Web services [39].

The proposed DRT for Web services has the following advantages: (1) it is easier to use; (2) it is more efficient because it enhances partition testing with dynamic test profiles updates and the resulting overhead is very limited. DRT is applicable whenever partition testing is applicable.

## VII. Conclusion

We have presented a dynamic random testing technique for Web services to address the challenges of testing SOA-based applications. The proposed technique employs random testing to generate test cases, and while selects test cases for execution from different partitions in accordance with the test profile of partitions which is dynamically updated in response to the test date collected online. In this way, the proposed test technique takes benefits of both random testing and partition testing.

We proposed a framework which examines key issues when applying DRT to testing Web services, and developed a prototype to make the method practical and effective. In order to guide testers flexibly set parameter of DRT strategy according to concrete testing objects, we use the theoretical analysis method to get the relationship between number of partitions, parameter of DRT and the failure rates of partitions. Validating the feasibility and effectiveness of our approach and the reasonable theoretical analysis, three real Web services are used to experimental objects. The results of empirical study show that not only DRT strategy is best technique comparing RT and RPT, but also when the parameters lie in our theoretical interval, DRT strategy has a outstanding and stable performance. This means that our theoretical analysis truly guide testers set parameters according to different objects.

In our future work, we plan to conduct experiments on more Web services to further validate the effectiveness and identify the limitations of our method.

## Acknowledgment

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