Comparing Top-down and Bottom-up Strategies for Generating Incremental Covering Arrays

Xintao Niu*, Changhai Nie*, Hareton Leung†, Jeff Y. Lei‡ and Xiaoyin Wang§
*State Key Laboratory for Novel Software Technology
Nanjing University, China, 210023
Email: niuxintao@gmail.com, changhainie@nju.edu.cn
†Department of Computing Hong Kong Polytechnic University
Kowloon, Hong Kong
Email: cshleung@comp.polyu.edu.hk
‡ Dpartment of Computer Science and Engineering
The University of Texas at Arlington
Email: ylei@cse.uta.edu
§ Department of Computer Science
University of Texas at San Antonio
Email: Xiaoyin.Wang@utsa.edu

***Abstract*—Combinatorial Testing (CT) is an effective technique for testing the interactions of factors in the Software Under Test (SUT). By designing an efficient set of test cases, i.e., a covering array, CT aims to check every possible valid interaction in SUT. Most existing covering array generation algorithms require a given *degree t* in prior, such that only the interactions with no more than t factors are to be checked. In practice, however, the value of t cannot be properly determined, especially for systems with complex interaction space. Hence, incremental covering arrays are preferred. In this paper, we propose two strategies for generating incremental covering arrays which can increase the coverage strength when required. A preliminary evaluation of the two strategies is presented, which shows that both strategies have their own advantages with respect to covering array size.**

***Index Terms*—Combinatorial Testing, Covering Array, Incremental Covering Array, Bottom-up and Top-down strategy**

I. Introduction

With the growing complexity and scale of modern software systems, various factors, such as input values and configure options, can affect the behaviour of a system. Even worse, some interactions between them can trigger unexpected negative effects on the software. To ensure the correctness and quality of the software system, it is desirable to detect and locate these *bad* interactions. The simplest way to solve this problem is to perform exhaustive testing for all the possible valid interactions of the system. It is, however, not practical due to the combinatorial explosion. Therefore, the selection of a group of representative test cases from the whole testing space is required.

Combinatorial testing has been proven to be effective in sampling an effective set of test cases[1]. It works by generating a relatively small set of test cases, i.e., a covering array, to test the interactions involving a given number of factors that may affect the behavior of a system. The number of factors involved in those selected interactions is limited in a moderate range, which is usually from 2 to 6 [2].

Many algorithms have been proposed to generate covering arrays. Despite many differences between them, those works all assume that the degree t is a given priori. The degree t indicates the largest number of factors involved in the interactions to be covered, and the corresponding covering arrays which can satisfy this coverage criteria is called t-way covering arrays. In practice, however, the value of t is difficult to determine due to two reasons as follows. First, many software systems suffer from complex interaction space which make it challenging to estimate t. In such case, even experienced testers can make mistakes and estimate a wrong value for t, which can significantly affect the effectiveness and efficiency of CT. Specifically, if t is estimated to be larger than required, many redundant test cases will be generated, which is a waste of computing resource. And if t is estimated to be smaller than required, then the generated covering array is not sufficient to obtain an effective test set. Second, even though t has been properly determined, there may not be enough time to completely execute all the test cases in the covering array. This is because testing software only makes sense before the next version is released. This time interval between two release versions may sometimes be too short for a complete testing of a high-strength covering array, especially in the scenario of continuous integration [3].

To address these shortcomings of traditional covering arrays, the notion of incremental covering array [3] has been proposed. Such object can be deemed as adaptive covering array, which can increase the degree t when required. As it can generate higher strength covering array based on lower strength covering array, it can reduce the cost when comparing with generating multiple ways of covering arrays. Additionally, it can be better applied on testing the software of which the released time is frequently changed and cannot be predicted. Another advantage for generating incremental covering array is that, testers can detect most faults in the software as soon as possible. This is because according to [2], most faults (about 70% to 80%) are caused by 2-degree interactions, and almost all faults can be covered by 6-way covering arrays. As incremental covering arrays first cover those lower-degree interactions, the faults caused by them will be detected sooner.

In consideration of the size of the total number of test cases, we argue that this approach of generating incremental covering array may produce too many test cases. This is obvious, as generating higher-strength covering array based on the lower-strength covering array (called *bottom-up* strategy later) does not aim to optimize the size of the higher-strength covering array. As a result, it may generate more test cases than those approaches that focus on generating a particular higher-strength covering array.

Then, a natural question, and also the motivation of this paper is, **is it possible to generate an incremental covering array with the same number of the overall test cases as those by the particular high-way covering array generation algorithms ?** Due to the obvious conclusion that any high way covering array must cover all the lower way interactions, the answer for this question is *yes*, as we can just apply a particular covering array generation algorithm to generate the high-strength covering array, and then generate the lower-strength covering arrays by extracting some subset of the test cases which can cover all the lower degree interactions. We refer to this strategy as the *top-down* strategy.

In this paper, we propose these two strategies and evaluate their performance by comparing them at constructing several incremental covering arrays. The results of the experiments showed that the *top-down* strategy has an significant advantage at the size of the higher-strength covering array, while the *bottom-up* strategy is better at constructing those lower-strength covering arrays with smaller size.

Our contributions include:

1) We propose two strategies for generating incremental covering arrays.
2) We conduct a series of experiments to compare and evaluate these two strategies.
3) We offer a guideline for selecting which strategy when generating incremental covering array in practice.

II. Background

This section gives some formal definitions related to CT. Assume that the behaviour of SUT is influenced by k parameters, and each parameter p_i has a_i discrete values from the finite set V_i, i.e., a_i = $|V_i|$ (i = 1,2,..k). Then a *test case* of the SUT is a group of values that are assigned to each parameter, which can be denoted as $(v_1, v_2, ..., v_k)$. An t-degree interaction can be formally denoted as $(-, ..., v_{n_1}, -, ..., v_{n_2}, -, ..., v_{n_t}, -, ...)$, where some t parameters have fixed values and other irrelevant parameters are represented as "-". In fact, a test case can be regarded as a k-degree interaction.

A. Covering array

Definition 1. A t-way *covering array* $MCA(N; t, k, (a_1, a_2, ..., a_k))$ is a test set in the form of $N \times k$ table, where each row represents a *test case* and each column represents a parameter. For any t columns, each possible t-degree interaction of the t parameters must appear at least once. When $a_1 = a_2 = ... = a_k = v$, a t-way covering array can be denoted as $CA(N; t, k, v)$.

For example, Table I (a) shows a 2-way covering array $CA(5; 2, 4, 2)$ for the SUT with 4 boolean parameters. For any two columns, any 2-degree interaction is covered. Covering array has proven to be effective in detecting the failures caused by interactions of parameters of the SUT. Many existing algorithms focus on constructing covering arrays such that the number of test cases, i.e., N, can be as small as possible.

B. Incremental covering array

Definition 2. An incremental covering array $ICA([N_{t_1}, N_{t_1+1}, ..., N_{t_2}]; [t_1, t_2]\ , k, (a_1, a_2, ..., a_k))$ is a test set in the form of $N_{t_2} \times k$ table, where $t_1 < t_2$ and $N_{t_1} < N_{t_1+1} <, ..., < N_{t_2}$. In this table, the first N_{t_i} lines ($t_1 \leq t_i \leq t_2$) is a covering array $MCA(N_{t_i}; t_1 + i, k, (a_1, a_2, ..., a_k))$.

When $a_1 = a_2 = ... = a_k = v$, an incremental covering array can be denoted as $ICA([N_{t_1}, N_{t_1+1}, ..., N_{t_2}]; [t_1, t_2], k, v)$.

Table I shows an example of incremental covering array, in which the two-way covering array $CA(5; 2, 4, 2)$ is a subset of the three-way covering array $CA(9; 3, 4, 2)$, which is also an incremental covering array $ICA([5, 9]; [2, 3], 4, 2)$.

TABLE I: Experiment of Incremental covering array

(a) *CA(5;2,4,2)*

0	0	1	0
1	0	0	0
1	1	1	0
0	1	0	1
1	0	1	1

(b) *CA(9;3,4,2)* && *ICA([5,9];[2,3],4,2)*

0	0	1	0
1	0	0	0
1	1	1	0
0	1	0	1
1	0	1	1
0	1	0	0
0	0	0	1
0	1	1	1
1	1	0	1

Theorem. For each covering array $MCA(N_{t_2}; t_2, k, (a_1, a_2, ..., a_k))$, we can find an $ICA([N_{t_1}, N_{t_1+1}, ..., N_{t_2}]; [t_1, t_2]\ , k, (a_1, a_2, ..., a_k))$, s.t., their test cases are the same.

Proof: We just need to prove that for any covering array, $MCA(N_t; t, k, (a_1, a_2, ..., a_k))$, we can find a $MCA(N_{t-1}; t-1, k, (a_1, a_2, ..., a_k))$, such that, $N_{t-1} < N_t$ and for any test case $f \in MCA(N_{t-1}; t-1, k, (a_1, a_2, ..., a_k))$, it has $f \in MCA(N_t; t, k, (a_1, a_2, ..., a_k))$.

First, $MCA(N_t; t, k, (a_1, a_2, ..., a_k))$ itself must be an $MCA(N_t; t-1, k, (a_1, a_2, ..., a_k))$, as it must cover all the $(t-1)$-degree interactions.

Then, assume to obtain a $(t-1)$-way covering array, any one test case in $MCA(N_t; t, k, (a_1, a_2, ..., a_k))$ can not be reduced. With this assumption, any test case will cover at least one $(t-1)$-degree interaction that only appears in this test case. Without loss of generality, let test case $(v_1, v_2, ..., v_k)$ cover the $(t-1)$-degree interaction $(-, ..., v_{p_1}, ...-, ...v_{p_2}, ..., -, ..., v_{p_{t-1}}, ... - ..., v_{p_t}, ..., -, ...)$ which only appears in the test case. Then obviously the t-degree interaction $(v'_1, ..., v_{p_1}, ...-, ...v_{p_2}, ..., -, ..., v_{p_{t-1}}, ... - ..., v_{p_t}, ..., -, ...)$ $(v'_1 \neq v_1)$ will never be covered by any test case in $MCA(N_t; t, k, (a_1, a_2, ..., a_k))$, and hence $MCA(N_t; t, k, (a_1, a_2, ..., a_k))$ is not a t-way covering array (Note this is based on that the parameter can take on more than one value).

This is a contradiction, and means that we can reduce at least one test case in $MCA(N_t; t, k, (a_1, a_2, ..., a_k))$, so that it is still a $(t-1)$-way covering array. ■

This theorem shows the existence of the incremental covering arrays. As discussed before, generating the incremental covering arrays is of importance, as it supports adaptively increasing the coverage strength. According to this theorem, when testing a SUT, testers can firstly execute the lowest-strength covering array in the incremental covering arrays, and then execute additional test cases from those higher-strength covering arrays as required. The reuse of previously executed test cases will reduce the cost for generating multiple different-ways covering arrays.

III. Generating incremental covering arrays

This section presents two strategies to generate the incremental covering arrays. The first strategy, i.e., the *bottom-up* strategy starts from generating the lowest-strength covering array and then the higher-strength ones. The second strategy, i.e., the *top-down* strategy firstly generated the highest-strength covering array, then the lower-strength covering array.

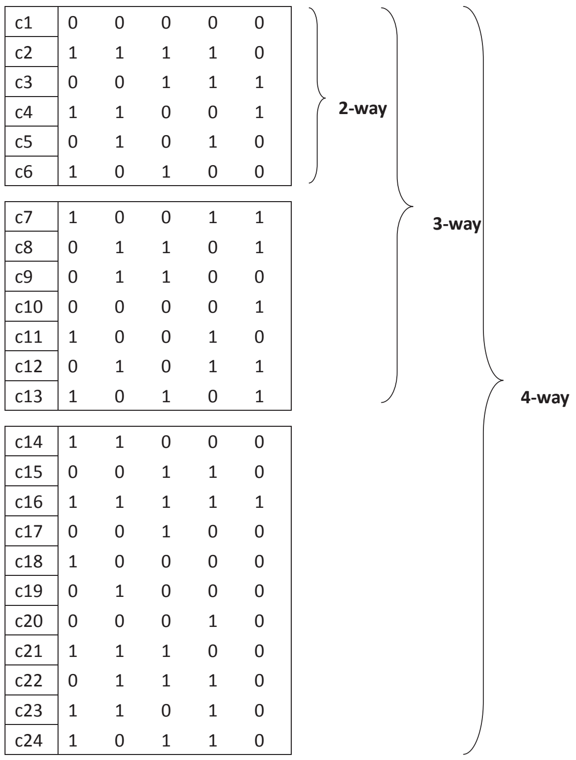
A. Bottom-up strategy

This strategy is listed as Strategy 1. The inputs for this strategy consists of the values for each parameter of the SUT –$Params$, the lowest strength t_1 of the covering array in the incremental covering array, and the highest strength t_2 of the covering array . The output of this strategy is an incremental covering array – ICA.

Strategy 1 Bottom-up strategy

```
Input:  $Params$              ▷ Parameters (and their values)
        $t_1$                 ▷ the lowest strength
        $t_2$                 ▷ the highest strength
Output: $ICA$                 ▷ the incremental covering arrays
 1: $ICA \leftarrow EmptySet$
 2: for $t_i = t_1;\ t_i \leq t_2;\ t_i\ ++$ do
 3:     $CA_i \leftarrow EmptySet$
 4:     if $t_i == t_1$ then
 5:         $CA_i \leftarrow CA\_Gen(Params, t_i)$
 6:     else
 7:         $CA_i \leftarrow extend(Params, t_i, CA_{i-1})$
 8:     end if
 9:     $ICA.append(CA_i)$
10: end for
11: return $ICA$
```

This strategy generates the covering array from lower-strength to higher-strength (line 2). If the current coverage strength t_i is equal to t_1, it just utilizes a covering array generation algorithm to generate the particular covering array (line 4 - 5). Otherwise, it will first take the previous generated covering array CA_{i-1} as seeds, and then utilize covering array generation algorithm to append additional test cases to satisfy higher coverage criteria (line 6 - 7).


2-way
3-way
4-way

c1	0	0	0	0	0
c2	1	1	1	1	0
c3	0	0	1	1	1
c4	1	1	0	0	1
c5	0	1	0	1	0
c6	1	0	1	0	0
c7	1	0	0	1	1
c8	0	1	1	0	1
c9	0	1	1	0	0
c10	0	0	0	0	1
c11	1	0	0	1	0
c12	0	1	0	1	1
c13	1	0	1	0	1
c14	1	1	0	0	0
c15	0	0	1	1	0
c16	1	1	1	1	1
c17	0	0	1	0	0
c18	1	0	0	0	0
c19	0	1	0	0	0
c20	0	0	0	1	0
c21	1	1	1	0	0
c22	0	1	1	1	0
c23	1	1	0	1	0
c24	1	0	1	1	0

Fig. 1: Bottom-up strategy example

Fig.1 presents an example for constructing $ICA([6, 13, 24]; [2, 4], 5, 2)$ by this strategy. In this example, the covering array generation algorithm used is AETG [4]. The two-way covering array (test cases c_1 to c_6) is directly generated, and the three-way covering array (test cases c_1 to c_{13}) is generated by adding additional test cases (test cases c_7 to c_{13}) based on the previous two-way covering array. The four-way covering array (test cases c_1 to c_{24}) is constructed on the previous three-way covering array. In total, to reach the 4-way covering array, 24 test cases are needed for this strategy.

B. Top-down strategy

This strategy is listed as Strategy 2, which generates covering arrays in the opposite order (line 2) of the bottom-up strategy. Similarly, if the current coverage strength t_i is equal to t_2, it directly generates the particular covering array (line 4 - 5). Otherwise, it will extract the covering array from a higher covering array (CA_{i+1}) (line 6 - 7). The extraction process is a greedy approach in this paper. At each iteration, the test case

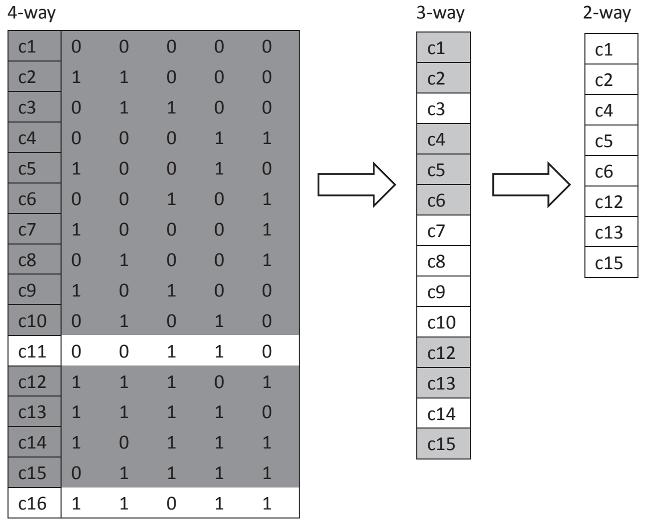


Fig. 2: Top-down strategy example

which can cover most uncovered t_i-degree interactions will be selected from the t_{i+1}-way covering array. Note that this greedy selection does not promise to obtain the CA_i covering array with the minimal size. But to get the minimal size, we need to exhaustively check every possible subset of the higher-covering array CA_{i+1}. This is impractical if the size of CA_{i+1} is too large.

Strategy 2 Top-down strategy

```
Input:  $Params$        ▷ Parameters (and their values)
        $t_1$           ▷ the lowest strength
        $t_2$           ▷ the highest strength
Output: $ICA$           ▷ the incremental covering arrays
1:  $ICA \leftarrow EmptySet$
2:  for $t_i = t_2;\ t_i \geq t_1;\ t_i\ --$ do
3:      $CA_i \leftarrow EmptySet$
4:      if $t_i == t_2$ then
5:          $CA_i \leftarrow CA\_Gen(Params, t_i)$
6:      else
7:          $CA_i \leftarrow extract(Params, t_i, CA_{i+1})$
8:      end if
9:      $ICA.append(CA_i)$
10: end for
11: return $ICA$
```

An example for this strategy is given in Fig.2. In this example, we first generated the 4-way covering array $CA(16; 4, 5, 2)$. Then we selected 14 test cases to form a three-covering array $CA(14; 3, 5, 2)$. Next the two-way covering array $CA(8; 2, 5, 2)$ is extracted from $CA(14; 3, 5, 2)$. The rows with dark background from the higher-strength covering arrays represent those selected test cases.

From the two examples, an obvious observation is that for the *top-down* strategy, it has a significant advantage over the *bottom-up* strategy with respect to the size of the 4-way covering array (16 for *top-down* and 24 for *bottom-up*). But when considering the lower-strength covering arrays, the *bottom-up* strategy performs better (13 and 6 for *bottom-up*, while 14 and 8 for *top-down* respectively). To evaluate the generality of this observation , we conduct experiments in the next section.

TABLE II: The parameters of the SUT

$SUT_1(4^7)$	$SUT_2(2^{15})$	$SUT_3(2^5 3^2 5^1)$
$SUT_4(2^{10} 3^2)$	$SUT_5(3^7 4^2)$	$SUT_6(2^8 9^1)$
$SUT_7(2^9 3^2 5^2)$	$SUT_8(2^8 4^3)$	$SUT_9(2^8 3^3 4^1)$

IV. Preliminary Evaluation

This section describes the experiments. We have randomly prepared 9 SUT with their parameters as shown in Table II. The parameters are presented in the abbreviated form $\#values^{\#number\ of\ parameters}$..., e.g., $7^3 6^2$ indicates the software has 3 parameters that can take 7 values and 2 parameters take 6 values. We didn't choose SUT with many parameter values because we will generate covering arrays with the coverage strength reaching to 5, which is quite time-consuming for AETG algorithm.

Then for each SUT, we generate 3 incremental covering arrays, which are $ICA([N_2, N_3]; [2, 3], k, v)$, ICA $([N_2, N_3\ , N_4]; [2, 3, 4], k, v)$, and $ICA([N_2, N_3, N_4, N_5]$; $[2, 3, 4, 5], k, v)$, respectively. Each incremental covering array will be repeatedly generated 30 times by two strategies. Finally, we will compare their average sizes. The results are shown in Table III.

For each subject in this table, we list the results of the two strategies for the three incremental covering arrays. In detail, for each incremental covering array, we list the average size of the covering array and the corresponding standard deviation of the 30 repeated experiments. For example, consider the result of $ICA([N_2, N_3]; [2, 3], k, v)$ for SUT_1. There are two columns, representing the results of 2-way covering array and 3-way covering array, respectively. For each cell in this table, the result is shown in the form *' average size / standard deviation'*.

One observation is that the result is relatively stable according to the small standard deviation against the average value. In fact, the deviation is about 1 to 2 for the 2-way covering array, 1 to 3 for the 3-way covering array, 1 to 7 for 4-way, and 6 to 15 for the 5-way. The stability of the results is owe to the covering array generation algorithm AETG, by which the size of the covering array is similar for different runs.

With respect to comparison of the size of incremental covering array for the two strategies, one observation is that *bottom-up* strategy obtained smaller size of the lower-strength covering array in the incremental covering array, while *top-down* strategy achieved smaller size of the higher-strength covering array. To make the observation more clear, we depict the average sizes of the covering arrays by the two strategies in Fig3.

In Fig.3, there are three main rows, representing the results of three incremental covering arrays , $ICA([N_2, N_3]; [2, 3],$

TABLE III: Experiment results

		$ICA([2,3])$ (avg/stdev)		ICA $([2,3,4])$ (avg/stdev)			$ICA([2,3,4,5])$ (avg/stdev)			
SUT_1	Bottom-up	26.2/0.91	126.07/2.16	26.73/1.12	127.13/2.38	519.23/3.88	26.8/0.95	125.9/1.62	519.9/0.95	1906.17/8.01
	Top-down	30.87/1.06	123.53/2.46	30.77/0.8	137.93/1.95	509.23/0.8	30.17/1.04	139.13/1.93	553.07/1.04	1865.5/7.75
SUT_1	Bottom-up	85.53/1.98	226.23/3.95	85.87/2.03	227.1/4.78	703/7.51	86.1/1.76	227.8/4.28	704.07/1.76	1466.1/13.88
	Top-down	90.03/0.75	167.87/3.3	84.93/1.88	244.47/2.26	661.93/1.88	84.1/1.58	246.63/2.39	610.27/1.58	1340.83/12.63
SUT_3	Bottom-up	17.27/0.96	54.13/1.71	17.03/0.98	54.97/1.97	138.37/3.02	16.97/0.87	55.13/1.89	138.93/0.87	302.23/5.04
	Top-down	19.03/0.98	53.5/2.47	19.23/0.8	55.83/1.75	135.67/0.8	18.53/0.92	56.7/2.12	136.2/0.92	291.33/3.47
SUT_4	Bottom-up	12.23/1.05	32.97/1.2	12.8/1.22	33.27/1.44	87.1/4.37	12.67/1.11	33.13/1.65	87.5/1.11	212.13/7.91
	Top-down	12.47/0.72	31.43/1.58	12.53/0.76	33.2/1.22	83.33/0.76	12.87/1.02	34.4/1.11	83.4/1.02	200.13/8.2
SUT_5	Bottom-up	21.9/1.47	85.4/2.12	21.67/1.11	85.73/1.93	307.9/3.46	21.73/1.34	85.63/2.17	306.7/1.34	984.1/6.39
	Top-down	23.43/0.96	84.97/1.82	23.93/0.85	91.1/1.83	300.87/0.85	23.73/0.77	92.9/1.87	318.87/0.77	962.37/6.87
SUT_6	Bottom-up	85.9/1.72	228.27/3.63	86.5/2.01	226.97/3.7	701.57/7.93	86.1/1.49	226.23/3.78	700.6/1.49	1457.73/14.43
	Top-down	90.17/0.58	167.13/2.2	85.5/2.14	244.33/2.05	663.53/2.14	83.8/1.7	245.87/2.95	612.07/1.7	1341.23/15.25
SUT_7	Bottom-up	29.53/2.12	100.33/2.57	29.33/2.33	100.67/2.71	336.8/7.07	29.27/2.06	100.43/3.19	334.53/2.06	953.97/15.52
	Top-down	29/1.51	96.13/3.26	29.07/1.59	103/1.67	324.87/1.59	28.6/1.45	103.93/2.24	312.97/1.45	896.07/13.89
SUT_8	Bottom-up	21.13/1.12	76.83/4.45	21.2/0.95	75.23/3.4	218.27/4.84	21.17/1.29	75.7/3.56	216.23/1.29	557.53/9.34
	Top-down	21.43/1.05	75.17/3.66	21.57/1.12	76.23/2.26	203.67/1.12	21.43/0.96	76.2/2.41	211.37/0.96	516.93/7.78
SUT_9	Bottom-up	17/0.89	55.03/1.72	17/0.89	55.13/1.02	167.1/4.22	16.6/0.71	54.6/1.76	164.83/0.71	444.1/9.64
	Top-down	17.6/0.92	53.13/1.82	18.1/0.87	56.17/1.63	160.67/0.87	17.8/0.79	57.33/1.51	160.03/0.79	418.1/12.46

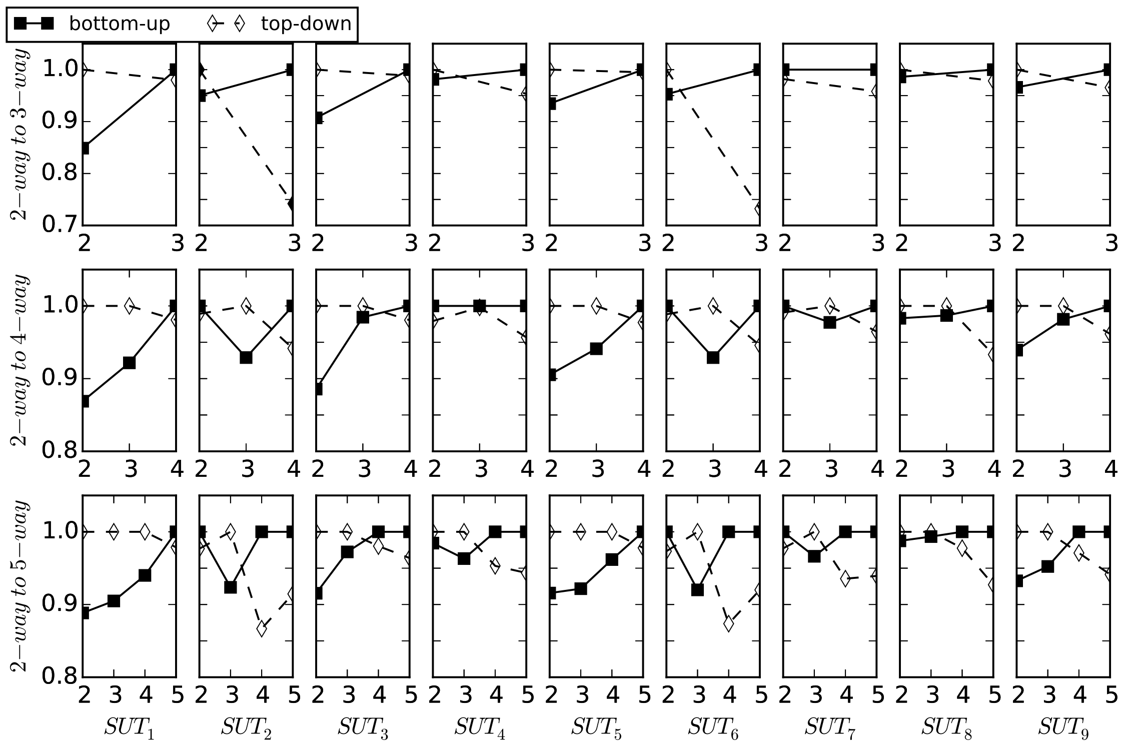


Fig. 3: The comparison of the two strategies

$k, v)$, ICA $([N_2,\ N_3\ ,N_4]; [2,3,4], k, v)$, and $ICA([N_2, N_3\ ,N_4,\ N_5]\ ; [2,\ 3, 4, 5], k, v)$, respectively. The nine columns represents the nine SUTs in Table II. For each sub-figure in Fig.3, the horizontal axis depicts the results of covering arrays of different strengths, and the vertical axis represents the size of the covering array. Note that we do not directly show the value of the size; instead, we normalize them so that they can be put into one figure. In detail, for each covering array of a subject, the point in the figure for one strategy indicates the proportion of the average size obtained by this strategy and the larger one of the two strategies.

From Fig.3, we can observe that, for most cases, the *top-down* strategy obtained smaller higher-strength covering arrays (about 90 % of that of *bottom-up*), while the *bottom-up* strategy performed better at the lower-strength covering arrays. This conclusion coincides with the case study presented in Section 3. There are also some exceptions; for example in the second row in Fig. 3 ($ICA([N_2, N_3, N_4]; [2,4], k, v)$), the *top-down* strategy generated smaller 2-way covering arrays for SUT_2, SUT_4, and SUT_6 than that of *bottom-up*. One possible explanation for the exception is that the covering array generated by greedy approach AETG sometimes may produce more test cases than needed.

Above all, the preliminary results suggested that when the coverage strength of the final covering array is low, the *bottom-up* strategy is preferred; otherwise, the *top-down* strategy is a better choice.

Besides this, it is noted that the *top down* strategy may generate larger lower strength arrays which are definitely to be executed while the *bottom up* strategy may generate larger higher strength arrays which may not be executed. This usually happens when the current software under testing is expired for the releasing of the next version. In that case, the *bottom-up* strategy is recommended.

V. Related work

Combinatorial testing has been proven to a effective testing technique in practice [5], especially on domains like configuration testing [6], [7], [8] and software inputs testing [4], [9], [10]. The most important task in CT is to generate covering arrays, which support the checking of various valid interactions of factors that influence the system under testing.

Nie et al. [1] gave a survey for combinatorial testing, in which the methods for generating covering arrays are classified. However, traditional static covering arrays can be hardly directly applied in practice, hence many adaptive methods are proposed.

Cohen et al. [11], [12] studied the constraints that can render some test cases in the covering array invalid. They proposed a SAT-based approach to avoid the impact. Further, Ylimaz [13], [14] proposed a feed-back approach which can support dynamically detect and identify the unknown constraints, i.e., *masking effects*. This approach can help to avoid the constraints in the latter generated test cases. Nie et al.[15] proposed a model for adaptive CT, in which both the failure-inducing interactions and constraints can be dynamically detected and removed in the early test cases generation iteration. Further, the coverage strength of covering array can be adaptively changed as required. S.Fouché et al. [3] proposed the incremental covering array, and gave a method to generate it. The method can be deemed as a special case of *bottom-up* strategy, with the only difference being that it used multiple lower-strength covering arrays instead only one in this paper to construct the higher-strength covering array. This is because their work needs to characterize the failure-inducing interactions in the covering array, in which ,multiple covering arrays can support a better diagnosis.

VI. Conclusions and future works

This paper proposed two strategies for generating incremental covering arrays. Experimental results show that both strategies have their own advantages; *top-down* strategy is better at generating higher-strength covering arrays, while *bottom up* strategy performs better at lower-strength ones .

As a future work, we will apply more covering array generation algorithms, to compare their performance at generating incremental covering arrays. Another interesting work is to combine the two strategies, so that we can first select a median coverage strength t and generate incremental covering arrays by *top-down* strategy. Then if the maximal-way covering array is generated, we can use *bottom-up* strategy to generate further higher-strength covering arrays. We believe such a combination strategy may offer a better performance.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 61272079), the Research Fund for the Doctoral Program of Higher Education of China (No.20130091110032), the Science Fund for Creative Research Groups of the National Natural Science Foundation of China(No. 61321491), and the Major Program of National Natural Science Foundation of China (No. 91318301)

References

[1] C. Nie and H. Leung, "A survey of combinatorial testing," *ACM Computing Surveys (CSUR)*, vol. 43, no. 2, p. 11, 2011.

[2] D. R. Kuhn and M. J. Reilly, "An investigation of the applicability of design of experiments to software testing," in *Software Engineering Workshop, 2002. Proceedings. 27th Annual NASA Goddard/IEEE.* IEEE, 2002, pp. 91–95.

[3] S. Fouché, M. B. Cohen, and A. Porter, "Incremental covering array failure characterization in large configuration spaces," in *Proceedings of the eighteenth international symposium on Software testing and analysis.* ACM, 2009, pp. 177–188.

[4] D. M. Cohen, S. R. Dalal, M. L. Fredman, and G. C. Patton, "The aetg system: An approach to testing based on combinatorial design," *Software Engineering, IEEE Transactions on*, vol. 23, no. 7, pp. 437–444, 1997.

[5] D. R. Kuhn, R. N. Kacker, and Y. Lei, "Practical combinatorial testing," *NIST Special Publication*, vol. 800, p. 142, 2010.

[6] C. Yilmaz, M. B. Cohen, and A. A. Porter, "Covering arrays for efficient fault characterization in complex configuration spaces," *Software Engineering, IEEE Transactions on*, vol. 32, no. 1, pp. 20–34, 2006.

[7] M. B. Cohen, J. Snyder, and G. Rothermel, "Testing across configurations: implications for combinatorial testing," *ACM SIGSOFT Software Engineering Notes*, vol. 31, no. 6, pp. 1–9, 2006.

[8] X. Qu, M. B. Cohen, and G. Rothermel, "Configuration-aware regression testing: an empirical study of sampling and prioritization," in *Proceedings of the 2008 international symposium on Software testing and analysis.* ACM, 2008, pp. 75–86.

[9] M. N. Borazjany, L. Yu, Y. Lei, R. Kacker, and R. Kuhn, "Combinatorial testing of acts: A case study," in *Software Testing, Verification and Validation (ICST), 2012 IEEE Fifth International Conference on.* IEEE, 2012, pp. 591–600.

[10] L. S. G. Ghandehari, M. N. Bourazjany, Y. Lei, R. N. Kacker, and D. R. Kuhn, "Applying combinatorial testing to the siemens suite," in *Software Testing, Verification and Validation Workshops (ICSTW), 2013 IEEE Sixth International Conference on.* IEEE, 2013, pp. 362–371.

[11] M. B. Cohen, M. B. Dwyer, and J. Shi, "Exploiting constraint solving history to construct interaction test suites," in *Testing: Academic and Industrial Conference Practice and Research Techniques-MUTATION, 2007.* IEEE, 2007, pp. 121–132.

[12] ——, "Constructing interaction test suites for highly-configurable systems in the presence of constraints: A greedy approach," *Software Engineering, IEEE Transactions on*, vol. 34, no. 5, pp. 633–650, 2008.

[13] E. Dumlu, C. Yilmaz, M. B. Cohen, and A. Porter, "Feedback driven adaptive combinatorial testing," in *Proceedings of the 2011 International Symposium on Software Testing and Analysis.* ACM, 2011, pp. 243–253.

[14] C. Yilmaz, E. Dumlu, M. Cohen, and A. Porter, "Reducing masking effects in combinatorialinteraction testing: A feedback drivenadaptive approach," *Software Engineering, IEEE Transactions on*, vol. 40, no. 1, pp. 43–66, Jan 2014.

[15] C. Nie, H. Leung, and K.-Y. Cai, "Adaptive combinatorial testing," in *Quality Software (QSIC), 2013 13th International Conference on.* IEEE, 2013, pp. 284–287.