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Off-Device Fault Tolerance for Digital Imaging Devices

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Abstract *– Charge-Coupled Device (CCD) is one of the widely-used optical sensing device technologies for various digital imaging systems such as digital cameras, digital camcorders and digital x-ray imaging systems. Pixels on a CCD may suffer from defective or faulty pixels due to numerous causes such as imperfect fabrication, excessive exposure to light, radiation and sensing element aging to mention a few. As the use of high-resolution CCDs increase, defect and fault tolerance of such devices demands immediate attention. In this context, this paper proposes a testing and repair technique for defects/faults on such devices with inability of on-device fault tolerance, referred to as off-device fault tolerance. Digital image sensor devices such as CCD are, by their nature, can not readily utilize traditional on-device fault tolerance techniques because each pixel on the device senses a unique image pixel coordinate. No faulty pixel can be replaced nor repaired by a spare pixel as any displacement of an original pixel coordinate can not sense the original image pixel. Therefore, to effectively provide and enhance the reparability of such devices with inability of on-device fault tolerance, a novel testing and repair method for defects/faults on CCD is proposed based on the soft testing/repair method proposed in our previous work [1] under both single and clustered distribution of CCD pixel defects. Clustered fault model due to unwanted diffusion should be considered as a practical model and for comparison purpose with single fault model. Also, a novel defect/fault propagation model is proposed to effectively capture the on-device defects and faults off the device for an effectiveness and practicality of testing and repair process. The efficiency and effectiveness of the method is demonstrated with respect to the yield enhancement by the soft-testing/repair method under a clustered fault model as well as single fault model, as referred to as soft yield. Extensive numerical simulations are conducted.*

Keywords *– CCD, digital image sensor, testing, repair, clustered defects, soft fault tolerance*

I. INTRODUCTION

Many applications of digital imaging technology can be found in such system as digital cameras, digital camcorders and digital x-ray diagnosis systems to mention a few. Among the currently available digital optical sensing devices, CCDs and APSs (Active Pixel Sensors) are the two most commonly used ones. In practice, pixels on such digital image sensing devices may contain defective pixels due to various causes such as improper fabrication, excessive exposure to light and radiation, and aging of sensing element. Therefore, in high-resolution digital imaging sensors, defect and fault tolerance is stringently required to assure quality of service.

Extensive works have been conducted on defect modeling, testing, and repair in semiconductor devices which in general, 2-dimensional array architecture can be assumed to model such devices. Traditionally, most of the techniques employ a method of replacement of faulty cells or blocks with spare cells or blocks, respectively. However, the traditional technique cannot be effectively employed for image sensing devices for testing and repair. No displacement is allowed for CCD pixels because each pixel has a unique x-y coordinate that cannot be backed up or replaced in case of a defect. Thus, the traditional redundancy-based repair techniques for memory systems cannot be applied to digital image sensing devices.

Our previous work [1] for testing and repairing defective CCD pixels is an efficient and practical method for testing and repairing faulty CCDs. There also have been a few hardware-based methods proposed to design a reliable CCD based on digital signal processing system [2], [3], [4], [5]. Digital cameras employ high resolution color CCD for high resolution image sensing. [5] proposed that defects on color CCD can be detected by checking which color is corrupted among the three colors (i.e. red, green and blue), and repaired by replacing a faulty color pixel with a spare CCD pixel provided. These hardware redundancy-based approaches rely on spare row and column-replacement of CCD pixels, and are thus impractical to be practiced for the displacement of image sensing pixels and the additional cost to the already expensive CCDs [4], [5].

Unlike traditional test/repair methods, the proposed soft-test/repair of CCDs is performed by software yet targetting at hardware-defect/fault testing/repair. The overall yield enhancement of CCD has been demonstrated by the soft-test/repair methods with efficiency and effectiveness from our previous work [1].

In this paper, a propagation of the hardware-defects/faults (i.e., defective pixels) from CCD to frame memory is modeled based on practical *clustered defective pixels* in comparison with the single defect/fault model in our previous work [1]. Clustered defect/fault model for testing and repair process is to be considered for realistic and practical faulty pixels. The objective of this paper is to propose a testing and repair method for CCD imaging system with inability of on-device repair (i.e., off-device fault tolerance) under clustered CCD pixel defect/fault model. To effectively capture the on-device pixel defects and faults off the device intact, a novel propagation-tracing method of the defects and faults is proposed. The efficiency and effectiveness of the proposed methods is demonstrated by enhancement of yield (i.e., soft-yield) under clustered defect/fault model as well as single fault model.

This paper is organized as follows. In the next section (Section II), previous works are reviewed, and basic principles of the proposed approach are introduced. In Section III, the proposed soft-testing and repair process for single and clustered faulty pixels is evaluated. In Section IV, parametric simulations with respect to CCD yield, soft-repair rate are shown. Then, conclusions and discussions are presented in Section V.

II. REVIEW AND PRELIMINARIES

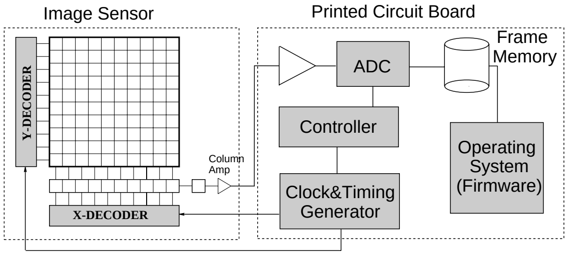

Fig. 1. Block Diagram of CCD System

In this work, a CCD imaging system will be modeled considering not only single faults but also clustered faults. CCDs are the most widespread image sensors for digital imaging systems and are becoming more prevalent these days, because of its many advantages such as high-resolution, manufacturability and image quality, to mention a few. Unfortunately, CCDs are not free from hardware faults like other semiconductors and the faults could increase the overall cost (i.e., both manufacturing and maintenance costs). Imperfect fabrication and improper processing may induce defects (referred to as *hard-defects*) on the photo-sensitive pixels and supporting system components in CCDs. In [3], the main causes of CCD hard-defects are categorized as follows.

1. Failure of row/column pixels (either line or read-out/control transistors/circuit).
2. Failure of row select/reset shift register.
3. Failure of column sense amplifiers.
4. Failure of A/D converter.
5. Failure of buffers.
6. Failure of read-out/reset transistors on each photo-diode.

In practice, all the defects of the above-mentioned types affect the quality of the raw image data on the frame memory, since the hard-defects that propagated all the way from the CCD to the frame memory through the A/D converter as shown in Fig. (1). The effect of a hard-defect observed on the frame memory is referred to as *soft-defect*. Notably, a soft-defective pixel on the frame memory usually shows an abnormal value compared to its neighboring pixel values. Without loss of generality, one-on-one correspondence between a hard-defect on the CCD and a soft-defect on the frame memory can be assumed, unless other component failures than CCD failures are taken into account. In this context, it is feasible to test and repair (i.e. soft-testing/repair) CCD hard-defects on soft memory-mapped level in the form of soft-defects on the frame memory.

From our previous work [1], following equations were derived.

$$Y_V(n) = Y_H + (1-Y_H)\cdot C_{st}\cdot\left[1-\left(1-\frac{min(F_{repair},F_{fault})}{F_{test}\cdot(1-Y_H)}\right)^{n-1}\right] \qquad (1)$$

$$= Y_H + (1-Y_H)\cdot C_{st}\cdot\left[1-\left(1-\frac{min(F_{repair},F_s+F_l+F_h)}{F_{test}\cdot(1-Y_H)}\right)^{n-1}\right] \qquad (2)$$

where Y_H is the CCD Hard Yield, Y_V is the CCD virtual Yield, C_{st} is the Soft-Test Coverage, F_{test} is the number of tested pixels and F_{repair} is the number of repaired pixels. F_s, F_l and F_h are the number of under sensitive, the number of stuck low, and the number of stuck high pixel respectively.

The previous model just handled with single faults. Hence, in case of clustered faults, it is indispensable to consider clustered fault model for more precise modeling. Next section will describe the proposed soft-test/repair model extended to clustered fault model.

III. THE PROPOSED SOFT-TEST/REPAIR MODEL

Each pixel of image sensors can be modeled as an electron well in Fig. (2) in general. Photons (i.e. light) are accumulated in electron well when it light come through the window. By electric field, the potential wells are controlled.

In general, CCD operation can be modeled as shown in Fig. (3). Initially, CCD is in the flushing state where it is discharging electrons before accumulating for next shot. During the flushing state, CCD cannot accumulate electrons as shown in Fig. (2). Then, by electronic or mechanical shutter operation, the electrons are being accumulated in an electron (potential) well during exposure time. The number of accumulated electrons, Q, can be expressed as follows.

$$Q(x,y,t) = \int_0^t \left[n(x,y,t)\cdot e\right] dt \qquad (3)$$

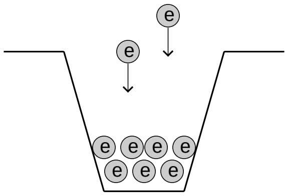

Fig. 2. Electron (Potential) Well

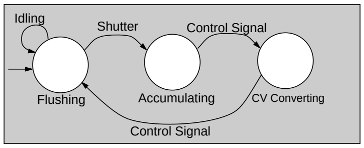

Fig. 3. State Diagram of CCD

where $n(x, y, t)$ is the number of electrons at each pixel, e is a unit electron (photon), x and y are the coordinates of the electronic well, and t is the exposure time manipulated by the shutter (from 0 to t). Once the exposure is completed, the charged electrons are transfer to the column amplifier from the electron wells (i.e., pixels) by the controller as shown in Fig. (1). The charged electrons in each pixel are then converted to a voltage value by column amplifier as follows.

$$v(x, y) = Q(x, y, t) \cdot A_c \tag{4}$$

where $v(x, y)$ is the voltage (i.e., analog) value of a pixel (i.e., electron well), and A_c is the gain of charge-to-voltage converter. By the ADC (Analog to Digital Converter), each pixel voltage value is converted to a digital value $V(x, y)$ as follows.

$$V(x, y) = v(x, y) \cdot A_d \tag{5}$$

where A_d is the analog to digital gain determined by the characteristics of the image sensors. Note that $v(x, y)$ is a floating number and $V(x, y)$ is an integer number. From Equation (3),(4) and (5), the final digitized voltage value can be derived as followings.

$$V(x, y) = A_c \cdot A_d \cdot \int_0^t \left[n(x, y, t) \cdot e \right] dt \tag{6}$$

$V(x, y)$ of each pixel is propagated to and then stored in the frame memory as shown in Fig. (1). $V(x, y)$ can be characterized into five sets.

1. $Q_h = \{V | V \text{ is high-stuck-pixels}\}$
   A high-stuck-pixel cannot sense the amount of electrons and always display high value even for dark light.
2. $Q_l = \{V | V \text{ is low-stuck-pixels}\}$
   A low-stuck-pixel cannot sense the amount of electrons and always display low value even for bright light.
3. $Q_{os} = \{V | V \text{ is over-sensitive-pixels}\}$
   A over-sensitive-pixel can sense the amount of electrons but too sensitive (i.e., out of tolerance). In this case, compare to other normal pixels, it has always higher value than normal pixel.
4. $Q_{us} = \{V | V \text{is under-sensitive-pixels}\}$
   A under-sensitive-pixel can sense the amount of electrons but less sensitive (i.e., out of tolerance). In this case, compare to other normal pixels, it has always lower value than normal pixel.
5. $Q_n = \{V | V \text{ is normal pixel}\}$
   A normal pixel can sense exact (i.e., within tolerance) amount of electrons.

Each set of pixels can be tested as follows.

1. Q_h : Test Input : No light to CCD and take a shot.
   Test Output : Raw Image
   All the pixel values V should be $min(V)$. Others can be classified as high-stuck-pixels in Fig. (4). In the figure, only the high-stuck-pixels can clearly be decided. The found defective pixel map should be saved on non-volatile memory such as flash memory for later use.
2. Q_l : Test Input : Use very bright light and take a shot.
   Test Output : Raw Image
   All the pixel values V should be near $max(V)$. Others can be classified as low-stuck-pixels in Fig. (5). In the figure, only the low-stuck-pixels can surely be decided. The found defective pixel map should be saved on non-volatile memory such as flash memory for later use.
3. Q_{os} : Test Input : Use mid light and take a shot.
   Test Output : Raw Image
   In this case, the pixel value distribution should be like in Fig. (6). For detecting over-sensitive-pixels, very high quality light source is needed such as parallel and even light. In the figure, the over-sensitive-pixel is out range, especially right bound, of the normal value. The found defective pixel map should be saved on non-volatile memory such as flash memory for later use.
4. Q_{us} : Test Input : Use mid light and take a shot.
   Test Output : Raw Image
   In this case, the pixel value distribution should be like in Fig. (6). For detecting under-sensitive-pixels, very high quality light source is needed such as parallel and even light. In the figure, the under-sensitive-pixel is out of range of the normal value. The found defective pixel map should be saved on non-volatile memory such as flash memory for later use.
5. Q_n : Test Input : Use mid light and take a shot.
   Test Output : Raw Image
   In this case, the pixel value distribution should be like in Fig. (6). For detecting under-sensitive-pixels, very high quality light source is needed such as parallel and even light. In the figure, the window of normal value should be generally 10% of ($max(V) - min(V)$). It is depend on the light source and optical characteristics of CCD.

In addition, V(x,y) can be divided into two clustering categories.

1. Clustered Fault : a pixel has any kind of functional fault and its adjacent pixels also have kinds of functional fault like label B in Fig. 7.
2. Single Fault : a pixel has any kind of functional fault yet its neighboring pixels have no functional faults. In Fig. 7, label A is an example.

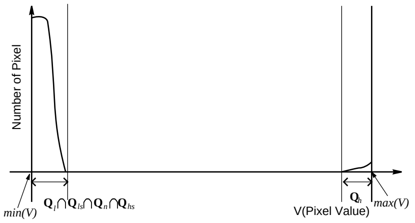

Fig. 4. Distribution of CCD pixel values; Q_h is separated.

Fig. 5. Distribution of CCD pixel values; Q_l is separated.

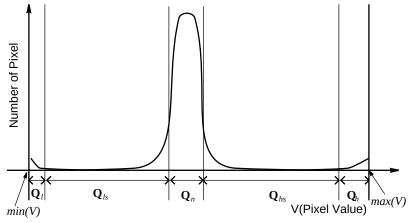

Fig. 6. Distribution of CCD pixel values; all combined.

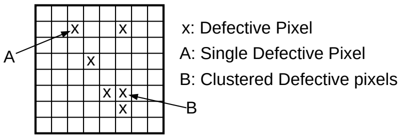

Fig. 7. Clustered Fault Pixels and Single Fault Pixels

It is important because clustered faults cannot be repaired perfectly.

From the union of functional and clustering categories, there will be four kinds of fault as follows.

$$Q_l = Q_{l,c} \cup Q_{l,r} \tag{7}$$
$$Q_h = Q_{h,c} \cup Q_{h,r} \tag{8}$$
$$Q_{us} = Q_{us,c} \cup Q_{us,r} \tag{9}$$
$$Q_{os} = Q_{os,c} \cup Q_{os,r} \tag{10}$$
$$\tag{11}$$

where $Q_{l,c}$ is a set of low stuck and clustered pixels (i.e., each of pixel in the set of $Q_{l,c}$ is not only a defective pixel but also having at least a neighboring defective pixel). The subscript c stands for clustered and r stands for single pixels. Theoretically, the following three equations can be formulated as follows.

$$Q_c = Q_{l,c} \cup Q_{h,c} \cup Q_{us,c} \cup Q_{os,c} \tag{12}$$
$$Q_r = Q_{l,r} \cup Q_{h,r} \cup Q_{us,r} \cup Q_{os,r} \tag{13}$$
$$Q = Q_c \cup Q_r \cup Q_n \tag{14}$$

From the definition of the yield, the hard yield Y_H can be expressed as follows.

$$Y_H = \frac{\int_{sectionQ_n} P(V)dV}{\int_{min(V)}^{max(V)} P(V)dV} \tag{15}$$
$$= 1 - \frac{|Q_{l,c}| + |Q_{h,c}| + |Q_{s,c}|}{|Q|} - \frac{|Q_{l,r}| + |Q_{h,r}| + |Q_{s,r}|}{|Q|} \tag{16}$$
$$= 1 - \frac{|Q_c| + |Q_r|}{|Q|} \tag{17}$$

where P is the distribution of pixel number.

Repair methods should be considered both the single and clustered faults. Followings are just for single fault repairing. Clustered faults will be explained later.

- Stuck-low and stuck-high pixels (i.e. Q_l and Q_h) can be repaired by replacing the defective pixel scale values. Since a defective pixel does not have any significant information, the defective pixel value is to be replaced by the average value of its neighboring pixel values.

$$V(0) = \frac{\sum_{k=1}^{N} V(k)}{N} \tag{18}$$

where $V(0)$ is the center pixel which is tested, the $\sum_{k=1}^{N} V(k)$ means the sum of neighboring pixel and the N is the number of neighboring pixel in Fig. 8.

- The repair for a defective pixel of in Q_{os} and Q_{us} depends on how much the pixel is insensitive or oversensitive. Thus, the following equation can be used to take into account the insensitivity and oversensitive.

$$V(0) = p \cdot V(0) \tag{19}$$

where p is a gain factor for fixing pixels in Q_{os} and Q_{us}. To fix the pixel in Q_{os} and Q_{us}, the gain factor has to be stored in memory in advance.

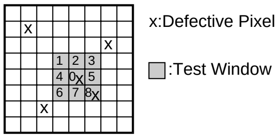

Fig. 8. Repairing of Clustered Fault

Repair of the clustered fault should be considered the neighboring pixels whether they are defective or not. Otherwise, the repairing results in diffusion of the defective area because of fake repair. In Fig. 8, the repairing pixel V(0) should not be replaced by Equation (18). Instead, it should be replaced by following equation.

$$V(0) = \frac{\sum_{k=1}^{8} V(k) - V(8)}{N - 1} \tag{20}$$

To generalize this equation, it can be expressed as follows.

$$V(0) = \frac{\sum_{k=1}^{N} V(k) - \sum_{l}^{M} D(l)}{N - M} \tag{21}$$

where N is the number of pixel in testing area and M is the number of defective pixels in testing area. M is referred to as *Acceptance Level (AL)*. AL means how many defective pixels will be accepted for testing area. As see in Equation (21), M should not equal to N, which means the repairing pixel cannot be repaired from all defective pixels because no other pixels have any information about repairing pixel. Proper AL should be smaller than 4, which means at least half of the pixels in testing area are normal. Note that the defective pixel values (i.e., $D(l)$ is removed (i.e., subtracted) for preventing diffusion effect.

The soft yield Y_S can be derived as follows. Single defective pixel can be repaired by soft-repair method. Therefore, the single defective pixel repair ratio can be 1.

$$\begin{aligned} Y_S = \ & 1 - \frac{|Q_{l,c}| \cdot (1 - R_{l,c}) + |Q_{h,c}| \cdot (1 - R_{h,c})}{|Q|} \\ & - \frac{|Q_{us,c}| \cdot (1 - R_{us,c}) + |Q_{os,c}| \cdot (1 - R_{os,c})}{|Q|} \\ & - \frac{|Q_{l,r}| \cdot (1 - R_{l,r}) + |Q_{h,r}| \cdot (1 - R_{h,r})}{|Q|} \\ & - \frac{|Q_{us,r}| \cdot (1 - R_{us,r}) + |Q_{os,r}| \cdot (1 - R_{os,r})}{|Q|} \qquad (22) \\ = \ & 1 - \frac{|Q_{l,c}| \cdot (1 - R_{l,c}) + |Q_{h,c}| \cdot (1 - R_{h,c})}{|Q|} \\ & - \frac{|Q_{us,c}| \cdot (1 - R_{us,c}) + |Q_{os,c}| \cdot (1 - R_{os,c})}{|Q|} \qquad (23) \\ = \ & Y_H + \frac{|Q_s|}{|Q|} + \frac{|Q_{l,c}| \cdot R_{l,c} + |Q_{h,c}| \cdot R_{h,c}}{|Q|} \\ & + \frac{|Q_{l,c}| \cdot R_{l,c} + |Q_{h,c}| \cdot R_{h,c} +}{|Q|} \qquad (24) \end{aligned}$$

IV. PARAMETRIC SIMULATION

The impact of the clustered fault model on the soft yield (i.e., Y_S) is shown in this section by using the proposed off-device testing/repair methods. In the simulation the defect/fault propagation model is used to capture the impact of the on-device defects and faults off the device intact.

A CCD of 6 Mega pixels (2K×3K) is assumed in this simulation. Three CCDs of such capacity and each of which 8%, 5% and 2% defective pixels are considered respectively (i.e. 5% is $(2048 \times 3072)/20$). For the simulation, a map of defective pixels is generated using a single defect/fault model as shown in Fig. (9).

The defective pixel map is generated by single number generation of built-in function in C language. The consecutive two random numbers are assigned to the coordinate of the defective pixel. This process continues until the number of defect pixel meets. If the generated pixel is out of bound or duplicated with other pixels already mapped then the generated pixel is discarded.

From the results in Fig. (10)-(11), the following observations can be drawn.

1. Fig. (10)-(11) show not only the single faults (i.e., AP=1) but also clustered fault (i.e., AP > 1). Where AL (Acceptance Level) is the number of defective pixel contained in testing window except the testing pixel.
2. Repair rate of single defective pixels (exclude clustered defective pixels) was 51% for 92% hard yield CCD, 66% for 95% hard yield CCD, and 85% for 98% hard yield CCD. Where the single defective pixel means a pixel which has no other defective pixels in the test window (i.e., 3X3 in this simulation) like the pixel labeled A in Fig. 7. From this simulation and theoretically, high yield CCDs have less clustered defective pixel.
3. Repair rate for just single defective pixel is too low than the expectation. In other words, 49% for 92% hard yield CCD, 44% for 95% hard yield CCD, and 15% for 98% hard yield CCD are clustered fault. This means that there exist many clustered defective pixels and considering the clustered fault model is indispensable.
4. AL (Acceptance Level) = 4 for the size of 3×3 window is enough for achieving perfect repairing in the clustered model for high yield CCDs. It is very important factor in clustered fault model. If it were impossible and had to use larger filter, the detect/repair time would be increased exponentially. If the AL=4 were not secured, adopting larger testing window would be unavoidable.
5. From the simulation results, the size of 3×3 of the area under test is still very sufficient for repairing clustered faults. This means real time implementation is possible in low performance hardware.
6. Soft-test/repair results in increase the soft yield. From Fig. 10, all test model secured 100% repair rate from AL=3. Optimal yield (i.e., reparable by soft-test/repair) CCD could be used more widely and decrease the cost of CCD without degrading image quality.

V. DISCUSSION AND CONCLUSIONS

This paper has presented a testing and repair technique for defects/faults on CCD image system with inability of on-device fault tolerance, referred to as *off-device fault tolerance*. Digital image sensor devices such as CCD are, by their nature, can not readily utilize traditional on-device fault tolerance techniques because each pixel on the device senses a unique image pixel coordinate. No defective/faulty pixel can be replaced nor repaired by a spare pixel as any displacement of an original pixel coordinate can not sense the original image pixel. Therefore, to effectively provide and enhance the reparability of such devices with inability of on-device fault tolerance, a novel testing and repair method for defects/faults on CCD is proposed based on the *soft testing/repair* method proposed in our previous work [1] under both single and clustered distribution of CCD pixel defects. Also, a novel defect/fault propagation model is proposed to effectively capture the on-device defects and faults off the device for an effectiveness and practicality of testing and repair process. The efficiency and effectiveness of the method is demonstrated with respect to the yield enhancement by the soft-testing/repair method under a clustered fault model as well as single fault model, as referred to as *soft yield*. Extensive numerical simulations are conducted, and it has been demonstrated that the clustered fault model has a significant impact on the soft yield in comparison with the soft yield of the single fault model.

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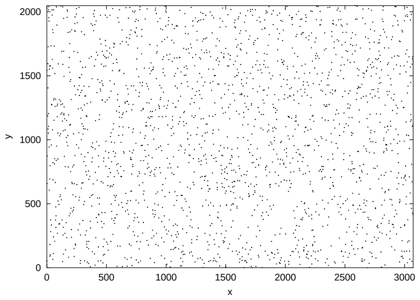

Fig. 9. Defective Pixel Map

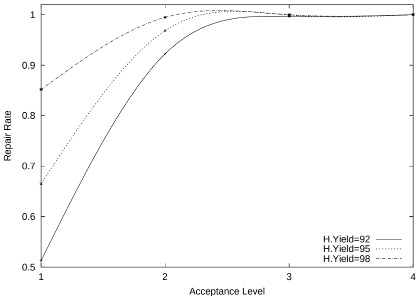

Fig. 10. Repair Rate

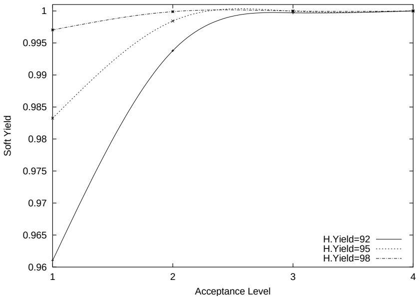

Fig. 11. Virtual Yield