IEEE Instrumentation and Measurement
Technology Conference
Vail, CO, USA, May 20-22, 2003

Soft-Test/Repair of CCD-based Digital X-Ray Instrumentation

B. Jin, N. Park†, K.M. George
Department of Computer Science
Oklahoma State University, Stillwater, OK 74078-1053
{byoungj,npark,kmg}@cs.okstate.edu

M. Choi
Department of Electrical and Computer Engineering
University of Missouri-Rolla, Rolla, MO 65409-0040
choim@umr.edu

M.Yeary
Department of Electrical and Computer Engineering
University of Oklahoma, Norman, OK 73019-1023
yeary@ou.edu

Y.B. Kim
Department of Electrical and Computer Engineering
Northeastern University, Boston, MA 02115
ybk@ece.neu.edu

Abstract – Modern x-ray imaging systems evolve toward digitization for reduced cost, faster time-to-diagnosis and improved diagnostic confidence. For the digital x-ray systems, CCD (Charge Coupled Device) technology is commonly used to detect and digitize optical x-ray image. This paper presents a novel soft-test/repair approach to overcome the defective pixel problem in CCD (Charge Coupled Device)-based digital x-ray system through theoretical modeling and analysis of the test/repair process. There are two possible solutions to cope with the defective pixel problem in CCD; one is the hard-repair approach and another is the proposed soft-test/repair approach. Hard-repair approach employs a high-yield, expensive reparable CCD to minimize the impact of hard-defects on the CCD, which occur in the form of noise propagated through A/D converter to the frame memory. Therefore, less work is needed to filter and correct the image at the end-user level while it maybe exceedingly expensive to practice. On the other hand, the proposed soft-test/repair approach is to detect and tolerate defective pixels at the digitized image level; thereby it is inexpensive to practice and on-line repair can be done for non-interrupted service. It tests the images to detect the detective pixels and filter noise at the frame memory level, and caches them in a flash memory in the controller for future repair. The controller cache keeps accumulating all the noise coordinates, and preprocesses the incoming image data from the A/D converter by repairing them. The proposed soft-test/repair approach is particularly devised to facilitate hardware level implementation ultimately for real-time tele-diagnosis. Parametric simulation results demonstrate the speed and virtual yield enhancement by using the proposed approach; thereby highly reliable, yet inexpensive soft-test/repair of CCD-based digital x-ray systems can be ultimately realized.

Keywords – CCD (Charge Coupled Device), digital x-ray, defective pixels, testing, repair, tele-diagnosis, tele-radiology, diagnostic confidence, yield, virtual yield.

† N. Park is the contact author

I. INTRODUCTION

Modern x-ray imaging systems evolve toward digitization for reduced imaging cost and higher diagnostic confidence [8]. To provide faster and efficient processing and manipulation of image data, digitization of image data is emerging as a promising alternative technology over conventional analog data-based image processing technology [10]. Today's *filmless digital imaging technology* is emerging as a standard in medical applications such as *telemedicine and teleradiology*, due to its promising perspectives such as cost-effectiveness, improved lifetime, reliability, and maintainability [9].

Timely x-ray film read/processing is also one of the most critical requirements to provide high quality service. Under certain harsh environments such as geographical isolation and tactical emergency, x-ray films should be remotely sent to radiologist for timely diagnosis. Filmless digital x-ray system can solve this problem by efficiently transmitting digital x-ray image data over the network to radiologist virtually in real time. Hence, filmless digital x-ray systems provide a promising solution especially for processing and delivery of time-sensitive medical cases, still yet a few problems to be resolved such as hardware reliability and slow software level calibration.

Besides the speed factor of x-ray processing, another critical factor is the *reliability* of the image for higher diagnostic con-

0-7803-7705-2/03/$17.00 ©2003 IEEE

fidence. Excessive x-ray exposure possibly damages CCD pixels and make them defective [3], [6]. Hence, it is required for digital x-ray systems to be maintained regularly by using costly and time-consuming software-based image calibration and tuning. Once a defective pixel hit by all means, the pixel creates a salt-and-pepper noise on target image, since it cannot receive and sense any photon; therefore, a noticeable darker noise point than any other image pixels becomes visible [4], [7]. The reliability is determined either by software or hardware factor. In reality, most CCDs suffer from defective pixels; therefore performance degradation is also experienced consequentially [7]. High-yield CCDs with less defects help resolve this problem at excessive cost in conjunction with complex calibration procedure [1]. The calibration procedure is generally practiced on software level and off-line for detecting/correcting defective pixels and performing optical corrections such as barrel correction. The approach proposed in [7] removes defective pixels on CCD of a digital camera by periodically executing new off-line calibrations to update old calibration results under a new exposure. However, conventional off-line software-level calibration may create an excessive delay on digital x-ray image processing, which may not be acceptable under stringent processing constraints of today's digital x-ray applications.

The main objective of this paper is to propose a new cost and performance-effective approach to detect and repair CCD hardware pixel defects by proposing a novel yet effective theoretical model for yield and repair rate. Unlike the legacy hard-repair approaches, the proposed repair approach mainly depends on post-processing of the digitized x-ray image data in a real-time processing environment implemented on a FPGA (Field Programmable Gate Arrays). Note that the proposed work is not to develop new filtering or calibration algorithms, but to propose a hardware-oriented image quality enhancement approach with respect to speed and hardware reliability-driven quality of service. For implementation purpose, any off-the-shelf image processing algorithms can be employed and realized on hardware level. An ultimate implementation plan would be on single chip-level fabrication (i.e. System-on-chip (SoC)) to utilize the performance benefits of SoC technology. Fast run-time dynamic filtering of digital image data on SoC-level is the ultimate goal of the proposed approach.

II. REVIEW AND PRELIMINARIES

A typical digital x-ray system is shown in Figure (1). The optical block captures the light generated by phosphor which emits light when it receives x-ray. The CCD image sensor contains numerous pixels and each of which senses photons using electronic well. CCD converts accumulated photons in the electronic well to a corresponding voltage. Then, an analog amplifier, such as OP-Amp, amplifies the signals before it directs the signals to A/D converter for digitization. Thereafter, the sensed image data is propagated all the way to the frame memory through the A/D converter under the coordination of the controller. The size of the frame memory is determined by the required digital image quality. Unfortunately, CCDs are not

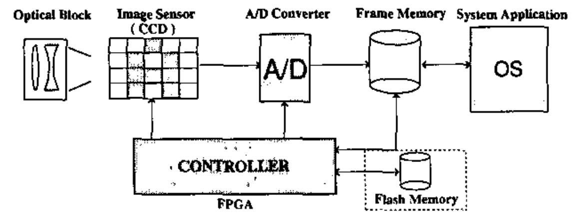

Fig. 1. Block Diagram of Digital X-ray CCD System

free from hardware defects. Imperfect fabrication and improper processing may induce defects (referred to as *hard-defects*) on the photo-sensitive pixels and supporting system components in CCD[2]. 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.

The A/D converter reads analog image data (i.e. voltage) and convert it to corresponding digital values onto the frame memory storage. In reality, CCDs may contain the mega-scale number of pixels, and they may be either bad or defective (e.g. dead) pixels. In safety-, mission-, and deadline-critical applications, defective pixels may result in devastating consequences. However, defective CCD pixels cannot be effectively replaced by using traditional approach which relies on redundant defect-free pixels, because each CCD pixel can sense only the image pixel on its exact and unique physical position. Therefore, reliability and quality enhancement efforts should be practiced on some other level such as A/D converter or frame memory [7].

The main idea of the proposed approach is to capture and detect noises (i.e. soft-defects) hit on the frame memory in digital x-ray system, which have been propagated all the way from CCD (i.e. hard-defects) through A/D converter to frame memory as shown in Figure (1). An reprogrammable and run-time dynamic flash memory is also used to store and keep track of up-to-date and cumulative *noise history data map*, which is used to pre-process incoming image data to enable skipping testing and repairing previously identified noise pixel positions. The proposed soft-testing and repair approach can be performed in a dynamic manner, since the proposed approach dynamically updates the pixel noise map on flash memory cache, while conventional software-level calibration or filtering approaches can be categorized as static. Thus, the dynamic pixel noise map in the flash memory can be constructed in an acceptable amount of execution time referred to as *pixel noise saturation time*. The improvements due to the proposed hardware implemented soft-repair approach is referred to as *virtual CCD yield enhancement* and it can be implemented at a minimal hardware

cost of flash memory caching without costly extra calibration procedures.

III. THE PROPOSED SOFT-TEST/REPAIR PROCESS

A general calibration process in digital x-ray systems considered in this paper is shown in Figure (2). Based on the reference calibration process shown in Figure (2), the main characteristics of the proposed soft-repair process are summarized as follows.

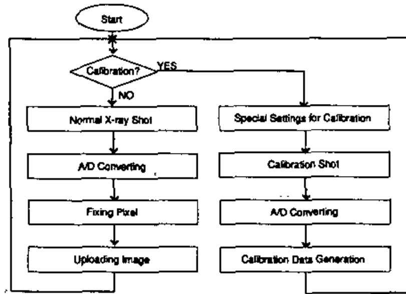

Fig. 2. Flow Chart of the calibration CCD System

1. The hard-defects on the pixels on CCD is assumed to follow the Poisson distribution (i.e. $e^{-\lambda t}$). Note that clustered defects are not considered in this paper.
2. It is assumed that only CCD contains defective pixels (i.e. dead pixels or hard-defects), and all other components (i.e. the A/D converter, the frame memory and the flash memory) are assumed to be defect-free.
3. Without loss of generality, it is also assumed that the defective pixels are propagated from the CCD to the frame memory (i.e. soft-defects) through the A/D converter.

In this paper, a simple mean filter as a criterion is used as shown in Figure (3). The proposed soft-test equation is given as follows.

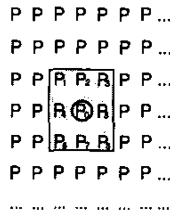

Fig. 3. an example of 3×3 Filter

$$\left| \frac{\sum_{k=1}^{N} P(k)}{N} - P(0) \right| \leq C \tag{1}$$

where $P(1) \cdots P(N)$ are the surrounding pixels of the tested pixel $P(0)$. The constant C is the threshold for determining whether it is defective or not in testing (e.g. 10%). This means the average value and the tested pixel value have almost same value. If Equation (1) holds, then the tested pixel is diagnosed as normal, otherwise it is a defective pixel. It indicates that the tested pixel is too bright or too dark compared to its neighboring pixels. Actually, only a defective pixel can be too much bright or dark than its neighboring pixels because of the Gaussian effect (i.e. each nine pixel contains each other's shading information).

After testing and repair process completed, the controller updates the noise history data map in the cache (i.e. non-volatile memory such as flash memory or E^2PROM). The proposed noise history data map caching technique allows for at-speed repair with minimal overhead as shown in soft-test/repair cycles in Figure (4). There are generally three possible failure modes such as low sensitivity, stuck low, and stuck high [5]. On the frame memory, defective pixels are relatively brighter or darker to result in relatively larger or smaller digitized data words compared to its neighboring pixels, which can be used for testing purpose.

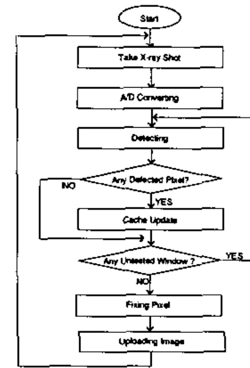

Fig. 4. Flow Chart of Proposed the caching CCD System

Each pixel on the frame memory can be cached in two bits of flash memory. The states of caching a pixel on the flash memory can be defined as follows.

1. 00 state : low sensitivity (i.e. F_s)
2. 01 state : stuck low (i.e. F_l)
3. 10 state : stuck high (i.e. F_h)
4. 11 state : normal pixel

The co-relation between each type of defective pixels and the total number of defective pixels, i.e. F_{fault}, can be defined as follows.

$$F_{fault} = F_s + F_h + F_l \tag{2}$$

The detection approaches and threshold equations for different type of defective pixel can be shown as follows.

1. 00 state: low sensitive pixels can be detected by the following equation.

$$\left|\frac{\sum_{k=1}^{N} P(k)}{N} - P(0)\right| \geq C \quad (3)$$

where $C = 50\%$. 50% is the half value of the digital value converted from A/D converter. This means that a low sensitive pixel displays an half the average filter value. If Equation (3) holds, then the pixel can be categorized as a low sensitive pixel.

2. 01 state: the stuck low pixels can be detected by the following two equations.

$$\left|\frac{\sum_{k=1}^{N} P(k)}{N}\right| \geq C_{011} \quad (4)$$

$$P(0) \leq C_{012} \quad (5)$$

where C_{011} and C_{012} are 50% and 10% respectively. If both Equation (4) and (5) hold, the pixel can be categorized as a stuck low pixel.

3. 10 state: the stuck high pixels can be detected by the following equation.

$$\left|\frac{\sum_{k=1}^{N} P(k)}{N}\right| \leq C_{101} \quad (6)$$

$$P(0) \geq C_{102} \quad (7)$$

where C_{101} and C_{102} are 50% and 90% respectively. If both Equation (6) and (7) hold, then the pixel can be tested as a stuck high pixel.

Stuck low and stuck high pixels (i.e. State 01 and 10) can be repaired by replacing the defective pixel values by using the following equation. Since a defective pixel does not have any repair information, the defective pixel value is to be replaced by the average value of its neighboring pixel values.

$$P(0) = \frac{\sum_{k=1}^{N} P(k)}{N} \quad (8)$$

Note that the repair for a defective pixel defect of the state 00 depends on how much the pixel is insensitive. Thus, the following equation can be used to take into account the insensitivity.

$$P(0) = (1-p) \cdot \frac{\sum_{k=1}^{N} P(k)}{N} + p \cdot P(0) \quad (9)$$

where p ($0 \leq p \leq 1$) is the insensitivity ratio of the defective pixel under test.

The proposed CCD soft-testing/repair process scans for the soft-defects on the frame memory for a certain amount of time (i.e. referred to as T_{test}). The proposed soft-test/repair process repeats as many times as the total number of pixels within a temporal window of the process (i.e. within time T_{test} in Equation (10)). The pixels on the frame memory detected as soft-defects are repaired, and then the locations are cached and accumulated in the flash memory. The time for each test/repair process cycle is referred to as *window* (W_T), and can be expressed as follows.

$$W_T = T_{test} + T_{repair} \quad (10)$$

where T_{test} is the time for testing and detecting the defective pixels and T_{repair} is the time for repairing defective pixels. Within a certain number of test/repair cycles, all pixels will be tested (and repaired, if needed). If the system capacity allows, it can test and repair all pixels in one cycle (i.e. if W_T is long enough to test and repair all pixels captured and stored on the frame memory). The image data is stored in the frame memory, pixel by pixel. D_n is the number of defective pixels propagated from the CCD at the n_{th} test/repair cycle, and can be calculated as follows.

$$D_n = D_T \cdot r_{defect}{}^{n-1} \quad (11)$$

where D_T is the total number of soft-defects hit on the frame memory, and r_{defect} is the decrease rate of D_n after each repair cycle. Since D_T is the total number of defective pixels, the following equation can be derived as well.

$$D_T = D_n + R_n \quad (12)$$

where R_n is the number of repaired pixels which are detected by the soft-test, and D_T is a constant assumed to be a known characteristic of the CCD. On the other hand, F_{test} is the number of pixels that can be tested within the test time T_{test}, and W_T is the window size (i.e. $T_{repair} + T_{test}$). Also, the number of defective pixels (i.e. F_{fault}) can be expressed as follows.

$$F_{fault} = F_{test} \cdot (1 - Y_H) \quad (13)$$

Therefore, the F_{repair} can be expressed by dividing T_{repair} by $T_{net\ repair}$ as follows.

$$F_{repair} = \frac{W_T - T_{test}}{T_{net\ repair}} \quad (14)$$

where $T_{net\ repair}$ is the repair time for a defective pixel, and F_{repair} is the number of repaired pixels that can be repaired within $W_T - T_{test}$. From Equation (13) and (14), the repair ratio (i.e. $r_{repair}(n)$) can be expressed as follows.

$$r_{repair}(n) = \frac{min(F_{repair}, F_{fault})}{F_{test} \cdot (1 - Y_H)} \quad (15)$$

The decrease ratio r_{defect} can be defined as follows.

$$r_{defect} = 1 - r_{repair}(n) \quad (16)$$

Then, the number of repaired pixels after n cycles, R_n of the CCD system can be given as follows.

$$R_n = \sum_{k=1}^{n}(D_{k-1} - D_k) \quad (17)$$

$$= D_T(1 - r_{defect}{}^{n-1}) \quad (18)$$

Also, Equation (18) can be derived from Equation (11) and (12). By definition of normalization, $\overline{R}_n$ can be formulated as follows.

$$\overline{R}_n = \frac{D_T(1 - r_{defect}{}^{n-1})}{D_T} \quad (19)$$

$$= 1 - r_{defect}{}^{n-1} \quad (20)$$

From Equation (16) and (15), the repair rate can be calculated as follows.

$$\overline{R}_n = 1 - \left[1 - \frac{min(F_{repair}, F_s + F_l + F_h)}{F_{test} \cdot (1 - Y_H)}\right]^{n-1} \quad (21)$$

Therefore, the virtual yield Y_V is given by

$$Y_V(n) = Y_H + (1 - Y_H) \cdot C_{st} \cdot \overline{R_n} \quad (22)$$

$$= Y_H + (1 - Y_H) \cdot C_{st} \cdot (1 - r_{defect}{}^{n-1}) \quad (23)$$

where Y_H is the CCD Hard Yield, and C_{st} is the Soft-Test Coverage (i.e. the rate of detecting defective pixels out of the total number of actual defective pixels). Therefore, from Equation (16) and (15), the overall virtual yield can be re-expressed as follows.

$$Y_V(n) = Y_H + (1 - Y_H) \cdot C_{st} \cdot \left[1 - \left(1 - \frac{min(F_{repair}, F_s + F_l + F_h)}{F_{test} \cdot (1 - Y_H)}\right)^{n-1}\right] \quad (24)$$

IV. PARAMETRIC ANALYSIS

In this section, the effect of the proposed soft-test/repair process on the virtual yield of CCD will be evaluated through numerical simulations based on Y_V derived in the previous section. Note that the bare yield of CCD without applying the proposed soft test/repair process is referred to as *hard yield* while the yield of CCD processed with the proposed soft test/repair is referred to as *virtual yield*. Also, the time period to process the image data input between the frame memory and the flash memory cache is referred to as *window*, and for an extensive comparison purpose in the simulation, we assume *large, medium and small* windows.

For the simulation, we assumed that the large window is given by the time to scan and fix defective pixels by 30% of total pixel (i.e. 2048 × 3072). Likewise, the medium window size is given by 20% and the small window size is given by 10%.

By comparing the results of Figures (5)-(10), the following observations can be drawn.

1. The proposed soft-test/repair approach is beginning to outperform the the high yield CCD system after a certain number of test/repair cycles in terms of virtual yield. In Figure (9), the repair rate approaches 100% at n=5 with the large window size. Therefore, just a certain number of initial image shots are needed to repair the defective pixels building a complete noise history data map on the cache.
2. The proposed approach achieves high Virtual Yield after a certain point compared to the conventional approach regardless of the Hard-Yield and expensive CCDs being used in the conventional approach, as shown in Figures (6), (8), and (10) in which the CCDs have $Y_H = 90\%$, $Y_H = 93\%$ and $Y_H = 97\%$, respectively.
3. In Figures (5), (7), and (9), the hard yield Y_H affects the repair rate. All the yields approach up to 100% regardless of the low initial hard yields. However, note that this does not mean that any low hard yield such as $Y_H = 30\%$ can virtually be enhanced to 100%. CCDs may or may not have reparable defects (i.e. not clustered defects).
4. In Figures (5), (7), and (9), the increase rate of the repair rate is shown and it depends on the window size. The higher hard-yield CCD quickly approaches 100% repair rate. However, even the small window size can achieve 100% repair rate just in a few more repair cycles. From this result, even if new defective pixels hit, the repair rate can achieve 100% by using the proposed soft-test/repair process.
5. The resulting virtual yields are shown in Figures (6), (8), (10) based on Equation (23). The hard yields determine the initial virtual yields. After a certain number of repair cycles, all the virtual yields converge to 100%.

From the results and findings shown so far, it can be concluded that the hard-defects which mapped on the frame memory can be effectively repaired by the proposed soft-test/repair approach. Also, the repair rates and the virtual yields approach 100% in a small number of repair cycles. Furthermore, the proposed approach can enhance the repair rate as high as up to 100%, even though new defective pixels hit due to physical shocks or exposure to excessive x-ray.

V. DISCUSSION AND CONCLUSIONS

This paper has presented a soft-test/repair approach for CCD-based digital x-ray systems through sound establishment of a novel theoretical modeling and analysis of the proposed test/repair procedure. There are two possible solutions to cope with the defective pixel problem in CCD; one is the hard-repair approach and another is the proposed soft-repair approach. The proposed soft-repair approach is to circumvent defective pixels at the digitized image level; thereby it is inexpensive to practice and on-line repair can be done for non-interrupted service. It tests the images to find the defective pixels and filter the defects at the frame memory level, and caches them in a flash

memory in the controller for future use. The controller cache keeps accumulating all the noise coordinates, and preprocesses the incoming image data from the A/D converter by repairing them. The algorithms can be implemented on hardware level (i.e. on the controller) to speed up the process. Unlike the calibration approaches shown in [4], [7], the proposed approach stores the noise history map dynamically on hardware level and always keeps the up-to-date data within proper window size. Numerical simulations have revealed that the proposed soft/hard approach using the proposed soft-testing and repair process will outperform the conventional hard approach after a certain break-even point in terms of virtual yield, thereby ultimately realizing high QoS of digital x-ray systems.

References

[1] H.A Beyer, "Accurate calibration of CCD-cameras," *Proc. IEEE on CVPR in Computer Society, pp. 96-101*, June 1992

[2] G. Chapman, Y. Audet, "Creating 35mm camera active pixel sensors," *International Symposium on Design and Fault Tolerance in VLSI Systems, pp. 22-30*, Nov 1999

[3] G. R. Hopkinson, C. Chlebek, "Proton damage effects in an EEV CCD imager," *IEEE Trans. on Nuclear Science, Vol. 36, pp. 1865-1871*, 1989

[4] I. Koren, G. Chapman, Z. Koren, "Advanced fault-tolerance techniques for a color digital camera-on-a-chip," *Proc. IEEE Int. Symp. on Defect and Fault Tolerance in VLSI Systems, pp.3-10*, 2001

[5] I. Koren, G. Chapman, Z. Koren, "A self-correcting active pixel camera," *IEEE Int. Symp. on Defect and Fault Tolerance in VLSI Systems, pp.56-64*, 2000

[6] N. Meidinger, B. Schmalhofer, and O. Struder, "Alpha particle, proton, and x-ray damage in fully depleted PN-junction CCD detectors for x-ray imaging and spectroscopy," *IEEE Trans. on Nuclear Science, Vol. 45, pp. 2849-2856*, 1998

[7] X. Zhang, N. Kubo, Y. Obuchi, T. Kanbe, "An Approach to detect defective CCD in digital cameras," *Proc. IEEE Conf. on IECON, Volume: 2, pp. 553-558*, 1999

[8] S.A. Pavlopoulos, A.N. Delopoulos, "Designing and implementing the transition to a fully digital hospital," *IEEE Trans. on Information Technology in Biomedicine, Volume:3 Issue:1, pp.6-19*, March 1999

[9] B.A. Levine, K. Cleary, S.K. Mun, "Deployable Teleradiology : Bosnia and Beyond," *IEEE Trans. on Information Technology in Biomedicine Volume:2 Issue:1, pp.30-34*, March 1998

[10] H. Mosser, "Real time imaging service," *Proceedings of the National Forum, Research, Practice, and Opportunities, Military Telemedicine On-Line Today, pp.101-105*, March 1995

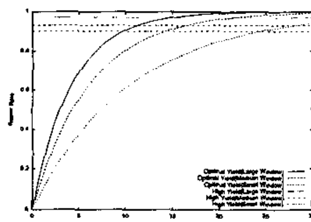

Fig. 5. Repair Rate (Hard-Yield 90%)

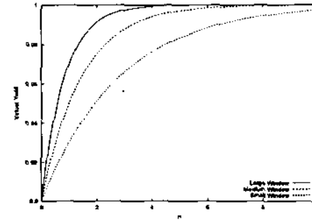

Fig. 6. Virtual Yield (Hard-Yield 90%)

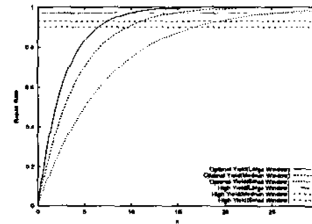

Fig. 7. Repair Rate (Hard-Yield 93%)

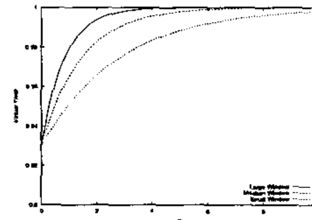

Fig. 8. Virtual Yield (Hard-Yield 93%)

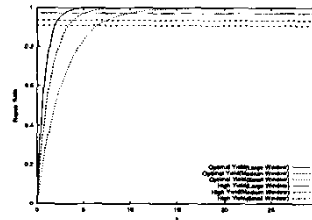

Fig. 9. Repair Rate (Hard-Yield 97%)

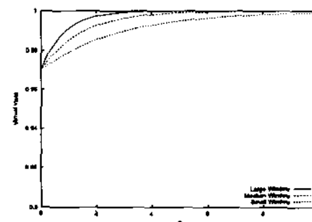

Fig. 10. Virtual Yield (Hard-Yield 97%)