System Knowledge-Based Techniques against SEUs for Adaptive Filters

P. Reviriego *Member, IEEE*, P. Reyes, J.A. Maestro *Member, IEEE* and O. Ruano

***Abstract*— In this paper, novel protection techniques against SEUs for adaptive filters are presented. The proposed techniques are based on the use of the system knowledge in terms of the filter structure and functionality, as well as the application tolerance to soft errors. An adaptive echo canceller is used as a case study to show the effectiveness of the proposed techniques.**

***Index Terms*— Single Event Upsets (SEUs), radiation hardening, digital filters, redundancy.**

I. Introduction

One advantage of standard techniques (like TMR o FMTR) when dealing with SEUs is that they are general, and therefore they can be applied to most digital circuits. However, this comes at a high cost in terms of circuit area and power and more so for FTMR. On the contrary, the approach to deal with SEEs in this paper is to apply *circuit specific techniques* that exploit the inherent redundancy or fault tolerance of some circuits, what we call to apply the *system knowledge*. The advantage of this is the production of custom-tailored solutions for each family of circuits, with good protection levels and a quasi-optimal implementation (what general techniques as TMR cannot achieve).

This system knowledge approach has been applied to date to matrix operations [1], Fast Fourier Transform computation [2][3] and some simple filter structures [4]. Alternative approaches, like processing the signals in the sigma-delta domain, have also been proposed for simple filters [5]. In [6] and [7] more general approaches that can be applied to a wider number of signal processing applications have been proposed. However, to the best of our knowledge, there is no previous work on specific system knowledge techniques to protect adaptive filters. Adaptive filters [8] are however good candidates to apply this methodology, as some of their elements can be used effectively to provide protection against soft errors and they are used in a variety of applications.

Adaptive filters [8] are by nature resilient to isolated errors. Standard filters (e.g. FIR filters) are characterized by a set of fixed coefficients, *h*, which determine the output in terms of the input. In other words, the filter output is a linear function of the input and the coefficients *h*, and since these do not change, its behavior is always the same. However, adaptive filters have the property that their coefficients do change (are adapted) depending on the environment, and therefore, their behavior is constantly adapted to this environment. In this way, an SEU striking on a coefficient of an adaptive filter would obviously change the output value (its behavior), but the intrinsic adaptation process would tend to correct this coefficient and bring it back to its right value. Although it may seem that this process makes a specific SEU protection technique unnecessary, reality dictates that the time required to achieve this correction is usually too high, since adaptation is an iterative and long process. Therefore, particular ad-hoc techniques (system knowledge-based) are required in order to meet the time constraints of this kind of problems.

II. Adaptive Filter Case Study: The Echo Canceller

The filter that will be used as a case study is an adaptive echo canceller. Echo cancellation is required in many wireline communication systems, like xDSL [9], ISDN and voiceband modems [10] and in Ethernet Transceivers [11], and it is normally implemented by means of an adaptive filter.

The basic structure of the echo canceller is shown in Fig. 1. The upper part shows the filter implementation and the lower one the adaptation logic that will be shared among all the filter taps. This means that each coefficient *h[i]* will be loaded into the accumulator, adapted for a number of cycles and then written back. This process is repeated in an iterative way for all the coefficients. A detailed explanation of how adaptive filters work can be found in [8], but for the purpose of this paper, the following facts need to be clarified: i) Coefficients *h[i]* are key for the right behavior of the circuit. An SEU on them would produce instability in the system, and therefore they need to be protected; ii) There is an adaptation logic that forces *h[i]* to converge to the right value, but this process is usually slow; iii) This adaptation logic needs to be protected too. In the presented case study, the number of coefficients will be 20 (with 8 bits each) and input *x[n]* will be a two-level signal with values {-1, +1}.

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P. Reviriego is with Universidad Carlos III de Madrid. Av. Universidad, 30 E-28911 Leganés , Spain (email: revirieg@it.uc3m.es).

P. Reyes, J.A. Maestro and O. Ruano are with Universidad Antonio de Nebrija,C/Pirineos, 55 E-28040 Madrid, Spain (phone: +34 914521100; fax: +34 914521110; email: {jmaestro,preyes,oruano}@nebrija.es).

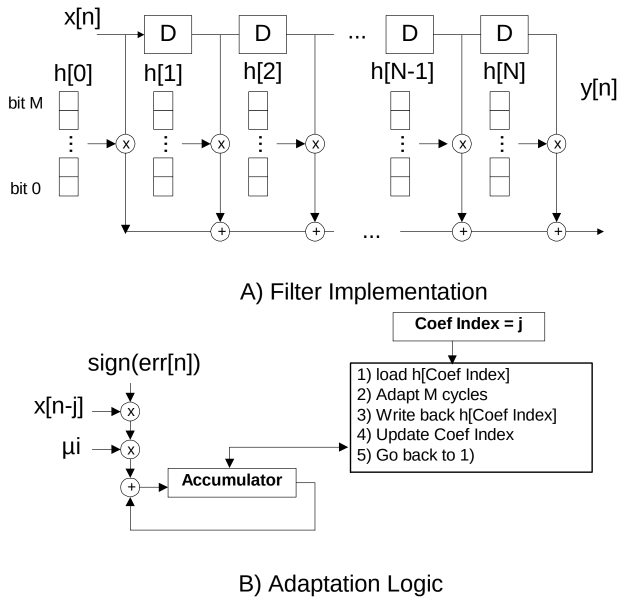

Fig. 1 Proposed Echo Canceller Implementation

III. PROPOSED TECHNIQUES

As we have already mentioned, adaptive filters would recover from errors as part of the adaptation process [8]. The problem is that in steady state the adaptation speed is normally low. This would result in a long recovery time after an SEU on a coefficient bit, as illustrated in Fig. 2 for an SEU on bit 5 of h[9] during cycle 40000. This is a major problem as it would mean that the echo is not cancelled for a large number of cycles (around 25000 in this case) and that would in many systems force a restart or other abnormal conditions. However, if we had a mechanism to detect that an SEU has occurred, we could speed up adaptation and therefore reduce dramatically the recovery time using the already existing logic in the filter.

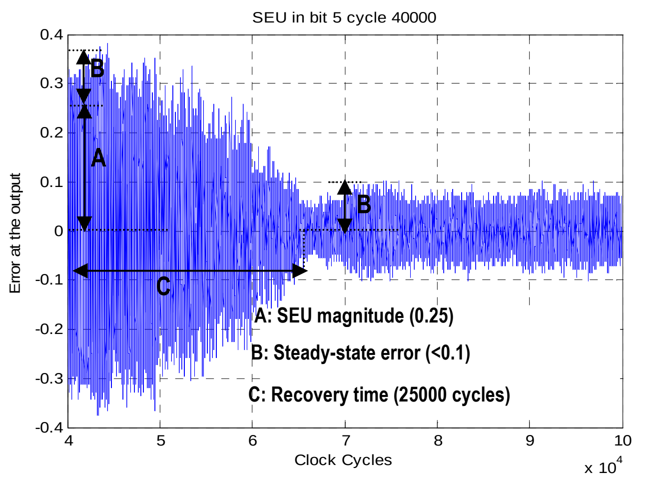

Fig. 2. Recovery Time after an SEU on h[9] for an unprotected filter

A. *Fast Selective Adaptation Technique*

One way to detect that an SEU has occurred in the echo canceller is to add a parity bit to each of the coefficients, and then check the parity back in each clock cycle. The parity bit can be computed as part of the adaptation logic for coefficient updates while the checking is done in place for each coefficient as shown in Fig. 3 (only for h[0]).

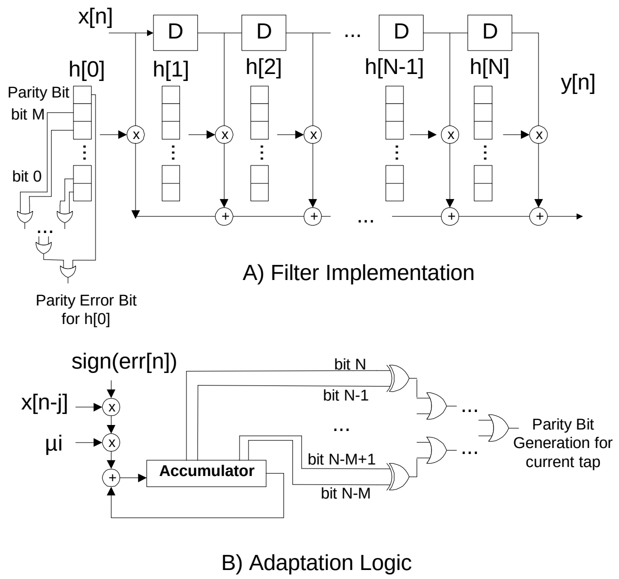

Fig. 3 Filter Implementation with parity and error checking added (only shown for h[0])

Once we have a method for detecting that an SEU has occurred, we can use that information to speed up correction, by adapting the affected coefficient directly (without waiting for its turn) and using a larger adaptation gain. With this simple technique, the recovery time after an SEU is dramatically reduced (see Fig. 4). A further analysis of the different SEU scenarios implies that depending on which bit the error happens, the consequences will vary significantly. The case in which an SEU affects the parity bits must also be considered. For this technique, this will cause the adaptation of the coefficient that corresponds to the parity bit, resulting in a slight increase in the error for a short number of cycles. The ideas behind this technique can be applied to a wide class of adaptive filters of which the case study presented is just a simple example.

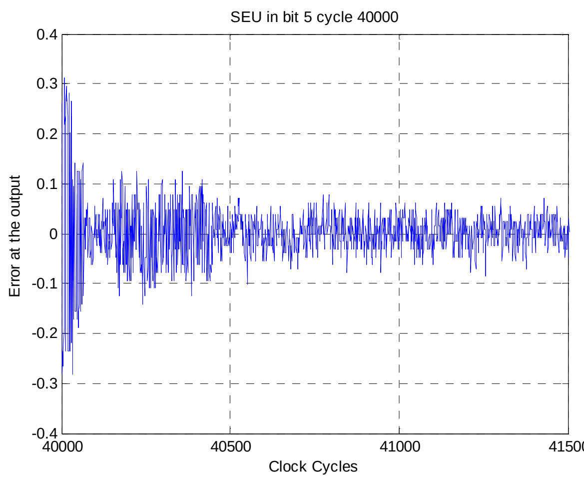

Fig. 4 Recovery Time after an SEU on h[9] for the Fast Selective Adaptation Technique

An alternative way of detecting that an SEU has occurred would be to monitor the output of the echo canceller, and if a sudden increase of the error is observed, then we can attribute that to an SEU. The problem with such an approach is that there may be other effects apart from SEUs on the coefficients that can cause this behavior (e.g. an SEU on the transmitted data delay line or a genuine change in the echo response). Besides, we would not have information of the coefficient that was affected. In order to solve this, a refinement of the explained technique is proposed

B. Direct Error Correction Technique

Although we have seen that the monitoring of the error at the output of the echo canceller is not a reliable method for the detection of SEUs, it can be very helpful in conjunction with the parity bits of the detection method that have been proposed for the Fast Selective Adaptation Technique. The idea is as follows: the parity bits are used to detect that an SEU has effectively occurred and the register that has been affected; then the observed error at the output is used to detect which bit in that register was the one affected by the SEU.

To illustrate the method we can observe the error at the output of the canceller in Fig. 2 during the first 5000 cycles. This corresponds to the effect of the SEU, which in this case has a magnitude of 0.25 plus the steady state error. By examining this value, we can deduce which bit in the coefficient was affected by the SEU, which in this case is bit 5 (considering a fixed-point sign and magnitude representation, bit 7 (MSB) would be the sign, bit 6 would have a magnitude of 0.5, bit 5 of 0.25, …). If the SEU has affected one of the most significant bits in the register then we would expect the error caused by the SEU to be much larger than the steady state error so that from the observed error we can infer the affected bit and simply flip it back to its right value.

The errors on the most significant bits are in fact the ones for which recovery time is critical as they cause a significant error at the filter output. In the case of the least significant bits, steady state adaptation may be sufficient to ensure that the system performance does not degrade significantly. In the case under study, given that the steady state error level is below 0.1 (Fig. 2), we propose to apply the technique to the four upper bits of each coefficient. This technique is illustrated in Fig. 5, where it can be seen how fast the systems recovers from an SEU at cycle 0 (see the error peak). The error during the rest of the cycles corresponds to the mentioned steady state.

Like in the first technique, the case in which an SEU affects the parity bits must also be considered. For this technique it will have no effect as long as the error stays in the steady state levels and will be corrected on the first adaptation after the SEU of the coefficient that corresponds to the parity bit affected.

C. Protecting the adaptation logic

So far, the proposed techniques have focused on protecting the filter coefficients. However the adaptation logic can also be affected by SEUs. To protect it, the obvious alternative would be to use TMR in the upper bits of the accumulator (those that are written back to the coefficient once an adaptation cycle is completed). But by using the system knowledge we can in fact propose a better alternative: we can just duplicate those bits and add the logic to detect a difference between the duplicates. If such a difference occurs, an SEU has affected one of the registers and we can just reload the coefficient and restart the adaptation cycle again, avoiding triplication.

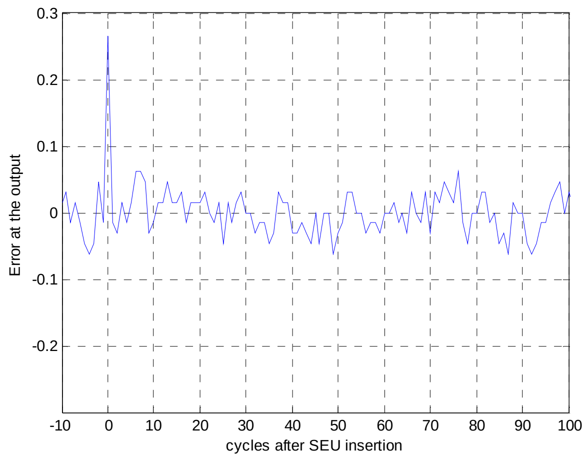

Fig. 5 Recovery Time after an SEU on h[9] for the Direct Error Correction Technique

IV. Experimental Results

Next, the quality of the presented techniques will be studied. These techniques have been implemented in VHDL and then synthesized for a commercial ASIC library. Two experiments have been carried out on the circuits:

1. Using a simulation platform [12] developed by the European Space Agency, several SEUs campaigns have been inserted, and the effectiveness of the protection techniques has been put in perspective. More than 20 test scenarios were reenacted, what implies over 200 impacts of SEUs.
2. The circuits have been synthesized, and their complexity has been compared with the traditional protection techniques.

In this way, the quality of the proposed techniques is measured in effectiveness and complexity.

A. Effectiveness

To evaluate the effectiveness of the protection techniques, we have inserted random SEUs in the filter coefficients and observed the effect on the filter error. The performance is quantified in number of cycles to get back to a level of error that is in the range of the steady state error. That is effectively the number of cycles for which a degraded behavior would be observed in the system. In inserting the SEUs in all taps, it has been checked that the tap number in which the SEU occurs does not influence the observed performance for the proposed techniques, as expected. For the unprotected filter, the recovery time depends on which coefficient is being adapted when the SEU occurs (the recovery time for the average case is reported). The results for each technique and register bit

(MSB to LSB) are summarized in Table I. The results are only presented for the four upper bits which are the ones in which an SEU produces a significant error at the output. The Direct Error Correction technique results in an immediate correction of the error while the Fast Selective Adaptation technique provides a reduction in the recovery time of up to two orders of magnitude.

TABLE I
RECOVERY TIME (IN CLOCK CYCLES) AFTER AN SEU FOR THE DIFFERENT PROTECTION ALTERNATIVES AND BIT POSITIONS

	Unprotected	Fast Selective Adaptation	Direct Error Correction
Bit 7	>60000	5000	1
Bit 6	50000	400	1
Bit 5	22000	400	1
Bit 4	10000	400	1

B. Complexity

In order to compare the complexity of the proposed techniques, two figures of merit will be used. The first one is the relative increment in the total number of gates of the techniques versus the unprotected filter. This will give an indication of the overhead required to provide protection. The second is to compare the proposed techniques with TMR. Although TMR clearly provides a superior level of protection, in many applications the proposed techniques do also meet the protection requirements (for example when the filter is used in a receiver and the SEU rate is low, if the recovery time is small enough the system may still meet the BER specifications) and from that perspective they can be a valid alternative to TMR.

The results are presented in Table II. The Fast Selective Adaptation technique results in an increment of around 20% in terms of area. As we have seen, the reduction of the recovery time for this technique can be of two orders of magnitude. So a large reduction on the impact of SEUs is obtained with an incremental cost increase. The results for the Direct Error Correction technique are similar, as it produces an increment of 24% in terms of area.

TABLE II
IMPLEMENTATION COST FOR THE DIFFERENT ALTERNATIVES

	Number of Gates	Cost Increment
Unprotected	4174	--
Fast Selective Adaptation	5023	20.3%
Direct Error Correction	5182	24.1%
(A) TMR upper four bits	5917	41.8%
(B) TMR upper five bits	6205	48.7%
(C) TMR on all registers	7627	82.7%

To compare the proposed techniques with TMR, three cases are considered. Using the system knowledge we can apply TMR only to the coefficient (upper bits) and adaptation logic registers. In the first case (A), TMR is applied to the four upper bits of the coefficient registers (the same bits that are protected by the Direct Error Correction technique). In the second case (B), TMR is used in the five upper bits of the mentioned coefficients. Finally, in the third case (C), TMR is applied to all the registers in the filter (not only coefficients), what results in an increase of 80% in the number of gates. The first observation that can be made is that the use of the system knowledge results in substantial savings even when applying TMR. The second is that when each of those partial TMR implementations are compared with the Fast Selective Adaptation and the Direct Error Correction techniques respectively, the proposed techniques still result in a significantly lower complexity. The protection technique to use (if any) will depend on the worst case SEU environment envisaged for the device or system and on the application tolerance to the effects of SEUs (in our case to temporary errors at the echo canceller output).

V. CONCLUSIONS

In this paper, new techniques to protect adaptive filter implementations from the effects of SEUs have been presented. These techniques exploit both application and system knowledge in order to provide a more intelligent protection that results in a lower circuit complexity compared to TMR. The proposed techniques have been tested on an echo canceller case study, using an environment that enables a flexible simulation of the effects of SEUs on signal processing circuits. The proposed techniques could also be used for adaptive filters that are implemented in software on a Digital Signal Processor. The same broad idea of using system knowledge to derive protection techniques can also be applied to other types of filters like generic IIR filters, filter banks, etc.

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