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Shielding and Duplication for Adaptive Crosstalk-Aware Error Control Coding in On-Chip Communication

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Abstract

On-chip communication reliability is becoming a challenging issue due to different noise sources and the effect of coupling between adjacent interconnects. This led to the introduction of many coding schemes as solutions to address these two issues jointly. The main approach used was combining error control coding with a crosstalk avoidance technique, mainly duplication. This paper extends the efforts of designing adaptive joint coding schemes based on switching between duplication and shielding as crosstalk avoidance technique by exploring the possibility to incorporate this technique in the other joint coding schemes to provide different levels of error protection. Accordingly, the paper analyzes the effect of switching between shielding and duplication on reliability, power consumption, and area. The results show that there are some restrictions that limit the effectiveness of this technique mainly when the error protection provided by the different modes is very close. On the other hand, the other schemes achieved power savings when working in reduced protection mode achieving up to 26% savings.

Keywords: Error control coding; fault tolerance; crosstalk; on chip interconnect.

Introduction

The continuous downscaling of semiconductor structures raised many challenging issues in electronic design with reliability being among the major challenges. From reliability perspective, on chip communication is highly affected by different noise sources that cause transient faults [1, 2]. In addition, the small inter-wire distance increased the coupling capacitance leading to increased crosstalk induced bus delay (CIBD) [1, 2]. Transient faults and CIBD were addressed by several works either independently or jointly. Transient faults were addressed by different error control coding schemes like parity and Hamming codes [3, 4]. On the other hand, CIBD was addressed through crosstalk avoidance codes (CAC) or non coding techniques like shielding, duplication, transition time adjustment, and repeater insertion [2, 5]. Addressing both issues was the goal of some works that proposed joining crosstalk avoidance with error control coding schemes. These schemes achieved from single error correction in Duplicate Add Parity (DAP) [5] to seven errors detection in Duplicated Two-Dimensional Parities (DTDP-7ED)[6].

In [7], the paper provided three modes of operation each having a different level of protection from errors by switching between shielding and duplication as crosstalk avoidance approach and between HARQ and FEC as error control policy. The scheme switches between duplicated SECDED (represented by JTEC-SQED), shielded SECDED (represented by Hamming SECDED), and shielded SEC (Hamming SEC). The scheme achieved power savings in reduced protection modes and small overhead in high protection mode as compared to the original non-adaptive scheme (JTEC-SQED) [8].

In this paper we argue that using the techniques of shielding and duplication to provide adaptive error control coding can be applied to any joint error control coding scheme based on duplication and is not restricted to JTEC-SQED. To support the claim we analyze the complexity of adding this adaptivity and the resulting savings and overheads.

Incorporating Shielding and Duplication into Error Control Coding

From delay perspective, both techniques aim to reduce the coupling effect on the wires. According to the model shown in Figure 1(a) showing the wires' self and coupling capacitance, the worst case CIBD occurs when a victim wire transitions in opposite direction to its adjacent wires transitions, namely (↓↑↓) and (↑↓↑). These cases result into a delay of $(1+4\lambda)\tau_0$ [9]. Where λ is the ratio of wire coupling capacitance to bulk capacitance and τ_0 is the crosstalk-free wire delay. Both techniques, shielding and duplication, provide crosstalk reduction by reducing the adjacent switching activity. It should be noted that both techniques reduce the worst case CIBD to $(1+2\lambda)\tau_0$, since they restrict their worst case transitions to those shown in Figure 1 (b) and (c).

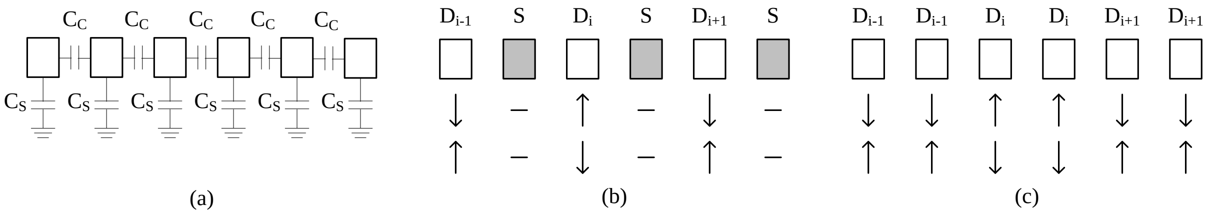

Fig 1: (a) Simplified wire model showing self and coupling capacitance, (b) worst case transitions in shielding technique, and (c) worst case transitions in duplication technique.

The two techniques differ in their power consumption and information redundancy provided. In the shielding technique the shield wires are silent thus having no switching power consumption whereas the duplicated wires consume power due to their switching activity. On the other hand, duplication technique adds information redundancy thus increasing the Hamming distance which allows higher error detection/correction a property that shielding lacks. The power savings that shielding achieves over duplication comes from the reduced self switching activity of the whole bus due to the reduced number of active wires as can be noticed from Figure 1.

The switching between shielding and duplication can be theoretically applied to any joint code but its effectiveness depends on the implementation and the effective use of the information redundancy. In this paper, DAP [5], JTEC-SQED [8], MBEC [10], and DTDP-7ED [6] will be considered. For MBEC, the crosstalk reduction technique applied is triplication, so in its case we consider switching between triplication and shielding.

DAP. In its basic structure, DAP works as single error correction coding scheme while providing crosstalk avoidance by duplicating all data bits and adding a single parity calculated over all data bits [5]. By replacing the duplicated bits with shields the crosstalk avoidance is maintained while the coding scheme redundancy is reduced. The encoded flit is composed of one copy of all data bits and one parity bit, thus working as simple parity coding scheme. Simple parity is capable of detecting all odd number of errors while it misses all even numbers of errors. This coding scheme is an ARQ scheme which requests retransmission for any detected error. This requires the inclusion of retransmission buffer in the sender and a retransmission request signal from the receiver to the sender as shown in the adaptive DAP scheme in Figure 2. In shielding mode the retransmission buffer is enabled whereas the Copy B flip flops in the receiver are disabled since only one copy is sent. These changes are represented by the diagonally patterned modules.

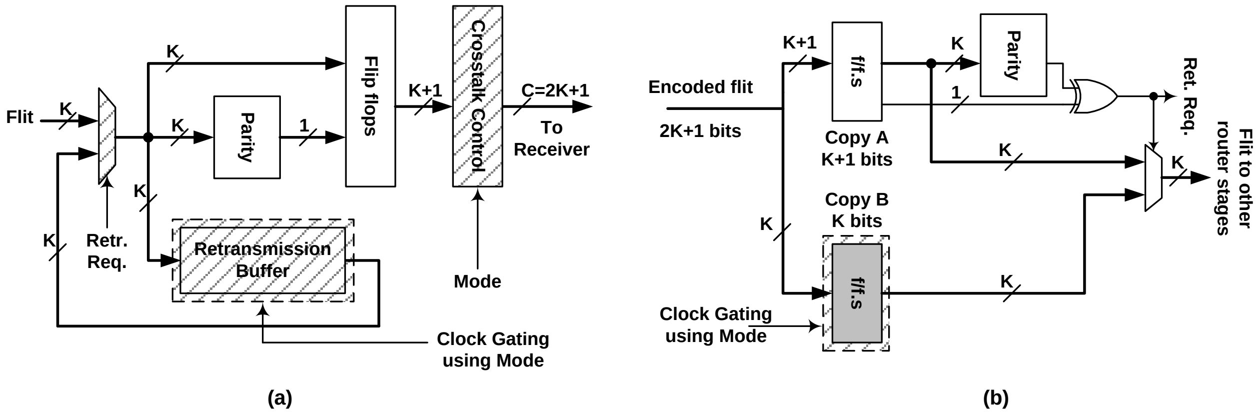

Fig 2: Adaptive DAP coding scheme (a) encoder and (b) decoder.

JTEC-SQED. As detailed in [8], JTEC-SQED can correct three errors and detect four by passing the data through a Hamming SECDED encoding followed by duplication of all data and check bits. This scheme was modified in [7] to provide two lower protection modes by switching to shielding while maintaining SECDED coding and by switching to shielding while modifying the coding to SEC instead of SECDED. In this work we consider the effect of changing only the crosstalk avoidance technique while maintaining the error coding scheme. Thus we modify the adaptive JTEC-SQED scheme in [7] to work in two modes only, namely duplication with SECDED (D_SECDED) and shielding with SECDED (S_SECDED). The former is a 3EC4ED (JTEC-SQED) while the latter is SECDED. Figure 3 shows the adaptive JTEC-SQED that works in two modes only. It should be noted that the retransmission buffer is always active and cannot be clock gated since both modes are HARQ.

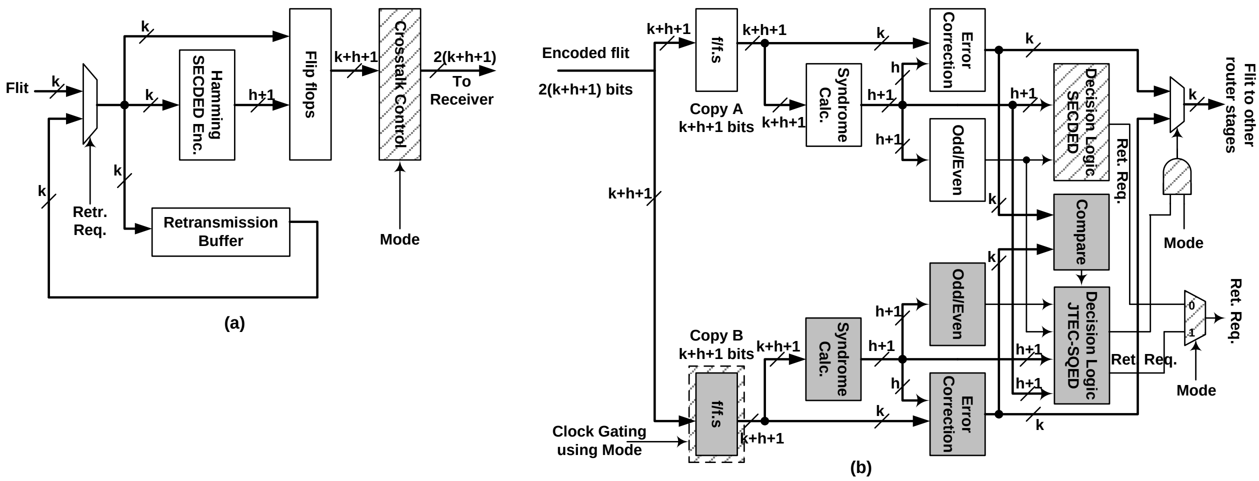

Fig 3: Adaptive JTEC-SQED coding scheme (a) encoder and (b)decoder.

MBEC. MBEC scheme [10] is an FEC based joint coding scheme providing up to five errors correction which is the highest error correction available among the joint codes. The encoder uses an $(K+h+1,K)$ Hamming SECDED encoder followed by a triplication stage applied to all the data and check bits. In the decoding algorithm, the three copies are separated and decoded using Hamming SECDED decoder. According to the syndromes, the received data, and the decoded data a decision is made to select one of the three decoded copies. The triplication technique provides crosstalk avoidance and enhances the Hamming SECDED coding to be able to correct up to five errors.

By switching the crosstalk avoidance technique to shielding instead of triplication, the coding scheme is brought back to SECDED, which is an HARQ scheme. To achieve this, the encoder side has to incorporate a retransmission buffer to retransmit data when double errors are detected as shown in Figure 4. This buffer is disabled (clock gated) when triplication is activated thus working as FEC scheme. On the decoder side, only one Hamming SECDED decoding module and one set of flip flops are required when working in low protection mode. As a result, in low protection mode the decoder side will provide power savings due to the disabled flip flops and many of the decoding modules. On the other hand, the encoder should enable the retransmission buffer which increases the power consumed. But the main power saving factor in low protection mode is the reduced number of switching wires.

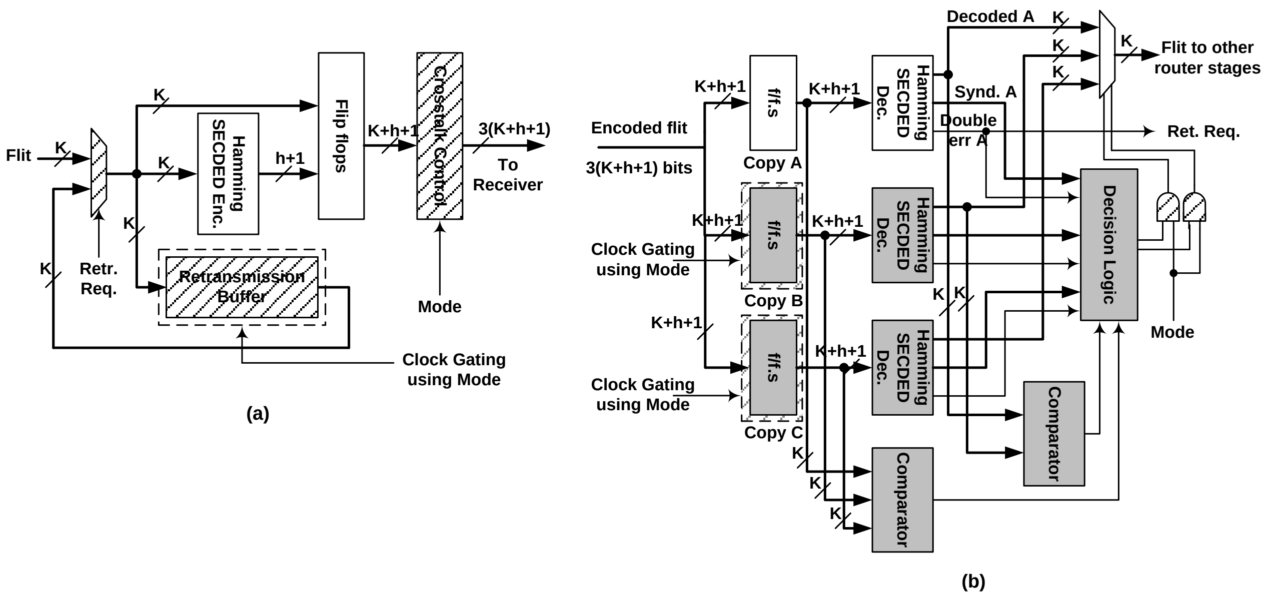

Fig 4: Adaptive MBEC coding scheme (a) encoder and (b)decoder.

DTDP-7ED. This coding scheme calculates the two dimensional parities for the data and then duplicates all the data and parities [6]. It was shown that this allows up to seven errors to be detected. DTDP-7ED is an ARQ scheme requiring a retransmission buffer to be available at the sender. In the case of any error detected at any row or column decoder a retransmission is requested. If shielding is applied to DTDP-7ED, only one copy of the data and the two dimensional parities is maintained which allows up to three errors to be detected (3ED) since the Hamming distance is reduced to 4. The scheme in this mode will be named Shielded Two Dimensional Parities 3 Error Detection (STDP-3ED). The lower protection mode selected, STDP-3ED, is an ARQ scheme as well. Thus in both modes the retransmission buffer is required which does not reduce the power consumed on the encoder side. On the other hand, the decoder side will need to store only one copy in the STDP-3ED mode which allows the clock gating of the Copy B flip flops as shown in Figure 5. In addition, the rows and columns decoders are modified from DTDP-7ED to allow the adaptive scheme to switch to STDP-3ED. This is achieved by the multiplexer in each row and column decoder. The changes to the DTDP-7ED (represented by the diagonally patterned blocks), which provide adaptiveness include the crosstalk control at the encoder side, and the multiplexers in each row and column decoder and clock gating of copy B flip flops at the decoder side.

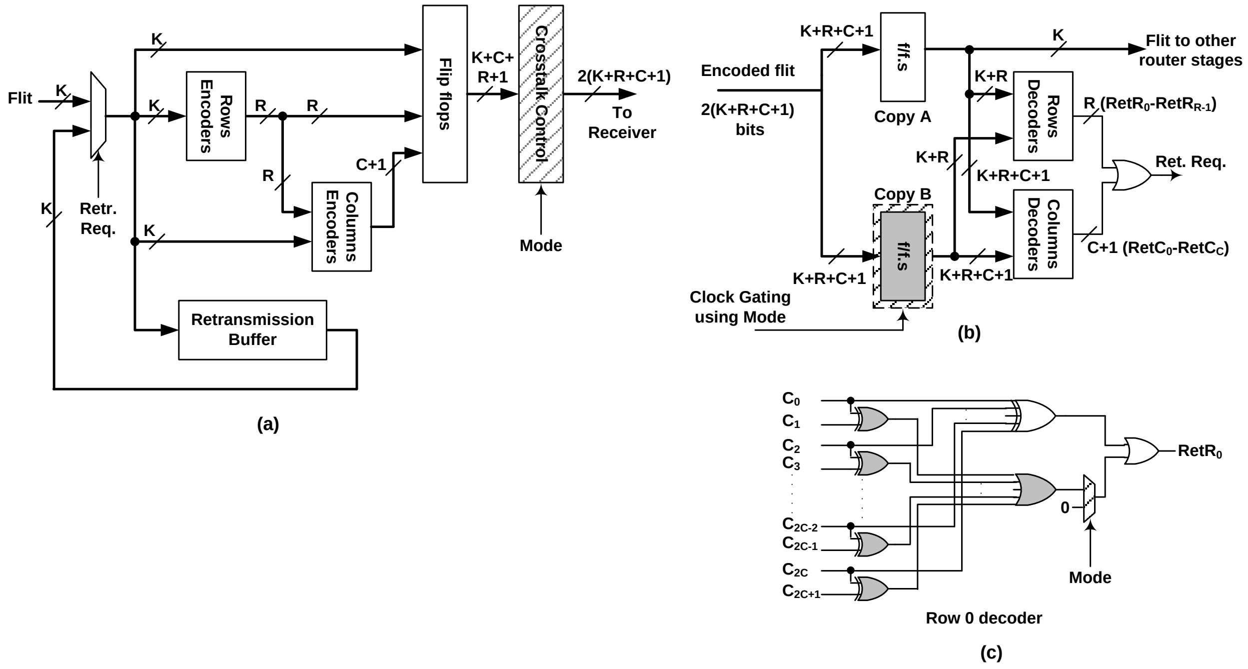

Fig 5: Adaptive DTDP-7ED coding scheme (a) encoder, (b) decoder, (c) Row 0 decoder.

Reliability

The reliability provided by each coding scheme can be quantified by the undetected error probability (P_{und}), which is defined as the probability that a codeword with errors passes undetected by the decoder [11]. A simple estimation that can be used assumes that the undetected case occurs whenever the number of errors exceeds the maximum detection capability of the coding scheme. For any coding scheme X that can detect up to td errors and for small bit error rate ε, the probability of (td+1) errors dominates, and P_{und} can be approximated to:

$$P_{und-X} = \binom{L}{td+1} \varepsilon^{td+1} \tag{1}$$

where L is the codeword size.

The main issue with adaptive DAP is that both modes can protect against single errors which leads to close reliability. The P_{und} models for both modes are given below and for $P_{und\text{-}DAP}$ it was derived in [5]:

$$P_{und-DAP} = \frac{3K(K+1)}{2} \varepsilon^2 \tag{2}$$

$$P_{und-PAR} = \binom{K+1}{2} \varepsilon^2 \tag{3}$$

The undetected error probability models for JTEC-SQED and Hamming SECDED are given below according to the fact that they can detect up to four and two errors respectively:

$$P_{und-JTEC-SQED} = \binom{2K+2h+2}{5} \varepsilon^5 \tag{4}$$

$$P_{und-Ham-SECDED} = \binom{K+h+1}{3} \varepsilon^3 \tag{5}$$

Based on the fact that MBEC fails with six errors, its undetected error probability model is approximated below:

$$P_{und-MBEC} = \binom{3K+3h+3}{6} \varepsilon^6 \tag{6}$$

The undetected error probability models for DTDP-7ED and STDP-3ED are given below:

$$P_{und-DTDP-7ED} = \binom{2(K+R+C+1)}{8} \varepsilon^8 \tag{7}$$

$$P_{und-STDP-3ED} = \binom{K+R+C+1}{4} \varepsilon^4 \tag{8}$$

where R and C represent the number of rows and columns that the data was arranged into.

According to the undetected error probability models of the different schemes, Figure 6 compares the two reliability models of the two modes in each adaptive scheme with the uncoded case shown for reference assuming 32 bit data size. As previously highlighted, DAP and PAR provide very close reliability as shown in Figure 6(a), this comes from the fact that both can protect against single errors and fail on two errors. Therefore there is no advantage in switching between the two schemes and they will be neglected in our further results and analysis. On the other hand, the other schemes show clear difference between the two modes.

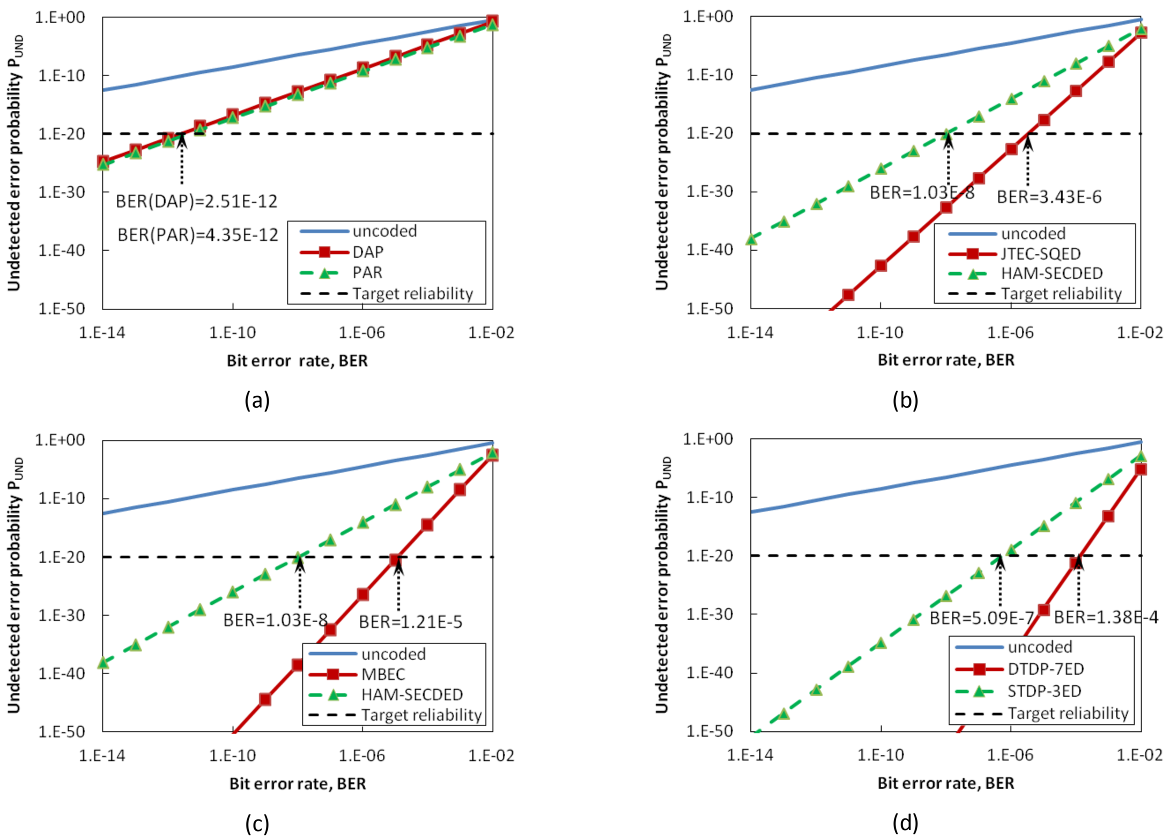

Fig 6: Undetected error probability (P_{und}) as a function of bit error rate for the uncoded case and the two modes of (a) Adaptive DAP, (b) Adaptive JTEC-SQED, (c) Adaptive MBEC, and (d) Adaptive DTDP-7ED

As can be seen in Figure 6(b), Hamming SEC-DED can provide the minimum target reliability level, represented by $P_{und}=10^{-20}$, for bit error rates (BER) up to 1.03×10^{-8}. At higher bit error rates Hamming SEC-DED cannot sustain the required reliability, thus a higher protection scheme must be used. JTEC-SQED can maintain the target reliability in the presence of bit error rates of up to 3.43×10^{-6}. According to these results, the adaptive JTEC-SQED can work in mode 0 (Hamming SEC-DED) for BER<1.03×10^{-8} and switches to mode 1 (JTEC-SQED) at higher BER. So this value represents the switching point between the two modes while BER=3.43×10^{-6} represents the maximum BER that the system can withstand while maintaining $P_{und}\leq10^{-20}$. Similarly, the switching point for the adaptive MBEC is BER=1.03×10^{-8} whereas the maximum sustainable BER is 1.21×10^{-5}. For the adaptive DTDP-7ED, the switching BER between the two modes is 5.09×10^{-7} and the maximum BER that the scheme can sustain is 1.38×10^{-4}. It can be noticed that the maximum BER for the adaptive DTDP-7ED is the highest among the other adaptive schemes, this is due to its higher protection, namely seven errors detection. Although not shown in the figures, the uncoded case intersects with the 10^{-20} reliability line at BER=3.13×10^{-22} this clearly indicates that coding is unnecessary only in very low error rates.

Area and Power

The different schemes, including their adaptive counterparts, were implemented in Verilog HDL and verified using ModelSim. The encoders/decoders were synthesized for 714 MHz target frequency using Synopsys Design Compiler with 45-nm Nangate library working on 1.1 V supply voltage. Table 1 compares the number of wires for the different schemes, showing the switching and total number of wires for the adaptive scheme. The codec area of the adaptive schemes in JTEC-SQED and DTDP-7ED is higher than that of their original schemes by only 1%. This overhead is contribute by different resources including the crosstalk control circuitry on the encoder side, the configuration hardware on the decoder side, and the incorporation of clock gating circuitry at the decoder. On the other hand, the adaptive MBEC has higher area overhead, namely 29% with respect to the original MBEC scheme. This is due to the inclusion of retransmission buffer in the adaptive MBEC, a resource not required in the original MBEC. As a result, it is clear that using this technique for FEC schemes may add noticeable area overhead if the lower protection scheme is not an FEC based as well.

Table 1 also shows the codec power consumption of all the schemes considered. It can be seen that the adaptive schemes working in mode 0 show small savings on the encoder side as compared to the original schemes, except MBEC were there is 133% overhead. As in the area results this comes from the retransmission buffer required in the low protection mode (Hamming SEC-DED). At the higher protection mode (mode 1), the schemes show small power overhead with respect to the original schemes not exceeding 4.91%. At the decoder side, the adaptive DTDP-7ED shows 7.43% overhead when working in mode 1 as compared to the original DTDP-7ED whereas JTEC-SQED and MBEC show 4.51% and 4.27% respectively. In mode 0, the adaptive MBEC decoder has the highest savings as compared to its original scheme achieving 57.66%. Whereas for the adaptive DTDP-7ED and JTEC-SQED, the decoder power savings in mode 1 are 25.56% and 38.52% respectively. The high savings in MBEC decoder working in mode 0 comes from the large number of flip flops clock gated since two copies of the codeword are clock gated as opposed to the other schemes where only one copy is clock gated. The high overhead in mode 0 of the MBEC encoder is counterbalanced by the savings on the decoder side leading to an overall codec savings of 14%. On the other hand, the mode 0 of adaptive DTDP-7ED and JTEC-SQED achieve 12% and 21% codec power savings. In mode 1, all the adaptive schemes have codec power overhead not exceeding 4%.

Table 1. Number of Wires, Area, and Codec Power for Different Schemes. Normalized Codec area and power are calculated with respect to the original scheme of each group.

<table>
<tr><th rowspan="2">Scheme</th><th rowspan="2">No. of wires</th><th colspan="2">Area (μm²)</th><th rowspan="2">Normalized Codec Area</th><th colspan="2">Power (mW)</th><th rowspan="2">Normalized Codec Power</th></tr>
<tr><th>Enc.</th><th>Dec.</th><th>Enc.</th><th>Dec.</th></tr>
<tr><td>JTEC-SQED</td><td>78</td><td>1116</td><td>1261</td><td>1.00</td><td>1.47</td><td>1.61</td><td>1.00</td></tr>
<tr><td>JTEC-SQED mode 0</td><td>39/78*</td><td rowspan="2">1127</td><td rowspan="2">1273</td><td rowspan="2">1.01</td><td>1.45</td><td>0.99</td><td>0.79</td></tr>
<tr><td>JTEC-SQED mode 1</td><td>78/78*</td><td>1.48</td><td>1.68</td><td>1.03</td></tr>
<tr><td>MBEC</td><td>117</td><td>546</td><td>1795</td><td>1.00</td><td>0.69</td><td>2.3</td><td>1.00</td></tr>
<tr><td>MBEC mode 0</td><td>39/117*</td><td rowspan="2">1148</td><td rowspan="2">1866</td><td rowspan="2">1.29</td><td>1.61</td><td>0.97</td><td>0.86</td></tr>
<tr><td>MBEC mode 1</td><td>117/117*</td><td>0.73</td><td>2.4</td><td>1.04</td></tr>
<tr><td>DTDP-7ED</td><td>90</td><td>1128</td><td>875</td><td>1.00</td><td>1.49</td><td>1.12</td><td>1.00</td></tr>
<tr><td>DTDP-7ED mode 0</td><td>45/90*</td><td rowspan="2">1141</td><td rowspan="2">878</td><td rowspan="2">1.01</td><td>1.46</td><td>0.84</td><td>0.88</td></tr>
<tr><td>DTDP-7ED mode 1</td><td>90/90*</td><td>1.50</td><td>1.21</td><td>1.04</td></tr>
</table>

*active/total

While the encoder and decoder power results were extracted from the synthesis power results, the average link power can be evaluated using [12]:

$$P_{link} = (L \cdot C_L \cdot \alpha_{wire} + (L-1) \cdot C_C \cdot \alpha_C) \cdot \frac{1}{2} \cdot V^2 \cdot f \quad (9)$$

Where L is the number of wires in the link, C_L is the wire self capacitance, α_{wire} is the wire self-transition activity factor, C_C is the coupling capacitance between wires, α_c is the wire coupling transition activity factor, V is the supply voltage, and f the frequency of operation. The coupling and self capacitances are dependent on the wire dimension and inter-wire spacing, which are given in Table 2. From the predictive technology model [13] the coupling and self capacitances were found to be 106.26 fF/mm and 43.85 fF/mm respectively.

Table 2. Wire dimensions and parameters.

Width (μm)	Space (μm)	Thickness (μm)	Height (μm)	Dielectric constant
0.077	0.077	0.18	0.11	3.1

Considering the same operating conditions used in synthesis, 714 MHz frequency, 1.1 V supply voltage, and 0.5 data switching activity, Figure 7 shows the power consumption of the two modes for each adaptive scheme normalized to the corresponding original scheme. This is applied at different link lengths since the total power considered is the sum of the codec power and link power. The power overhead in mode 1, changes from 1.5%, 2.3%, and 1.7% at 1 mm link length to 0.5%, 0.8%, and 0.6% at 5 mm for JTEC-SQED, MBEC, and DTDP-7ED respectively. It can be seen that the power overhead in mode 1 decreases with the increased link length, since this overhead is caused by the codec overhead. As the link length increases the proportion of codec power to the total power decreases which diminishes its overhead and savings. In mode 0, all the adaptive schemes achieve some level of power savings which is mainly dependent on the link power savings achieved. The savings in the link power comes from the reduction in the number of switching wires by making a group of wires work as shields which is the core idea behind this work. This technique eliminates the switching power of this group of wires by making them silent but the coupling effect to adjacent wires remains. Accordingly, the power savings converge to the value contributed by the self switching of this group of wires. This in return, depends on the number of wires made silent and the proportion of self switching power to coupling power. The adaptive MBEC in mode 0 converges to higher power savings due to its higher number of silent wires in mode 0, as only one out of three copies is kept switching as opposed to duplication based schemes where one copy out of two is kept switching. The adaptive MBEC power savings converge towards 26% whereas JTEC-SQED and DTDP-7ED converge towards 15% savings.

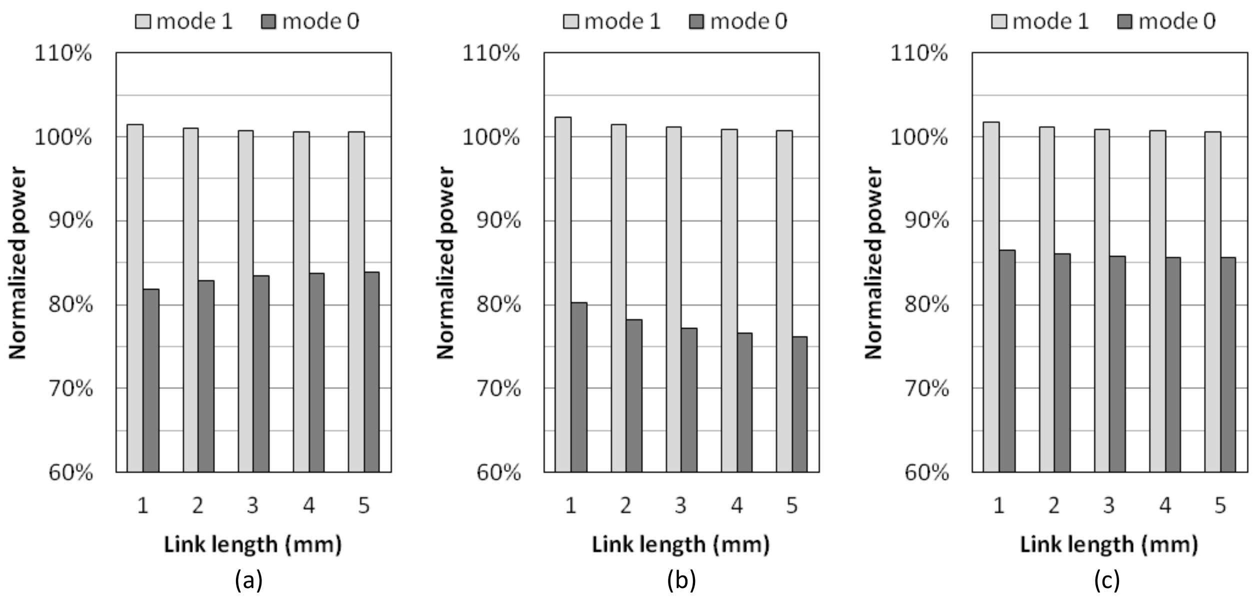

Fig 7: Power consumption normalized to the original non-adaptive counterpart for (a) Adaptive JTEC-SQED, (b) Adaptive MBEC, and (c) Adaptive DTDP-7ED.

Conclusions

Joint error coding and crosstalk avoidance is an effective approach but may provide more protection than required thus consuming unnecessary power. By using duplication in high error rates and shielding in lower error rates adaptiveness can be incorporated into existing joint coding schemes. Shielding provides crosstalk avoidance and reduces the number of switching wires but does not provide information redundancy thus leading to low power and low error protection. On the other hand, duplication achieves the same crosstalk avoidance that shielding provides but increases the information redundancy thus enabling higher error protection. This comes at the cost of higher number of switching wires which increases the power consumption. It was shown that this technique can be effectively applied to joint coding schemes with the exception of DAP where the two modes provide the same protection level thus diminishing its effectiveness. The other schemes considered achieved up to 26% power savings in reduced protection mode at the cost of 2.3% power overhead in high protection mode and 29% area overhead.

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