High Throughput Radix-4 SISO Decoding Architecture with Reduced Memory Requirement

Wooseok Byun, Hyeji Kim, and Ji-Hoon Kim

Abstract—As the high-throughput requirement in the next generation communication system increases, it becomes essential to implement high-throughput SISO (Soft-Input Soft-Output) decoder with minimal hardware resources. In this paper, we present the comparison results between cascaded radix-4 ACS (Add-Compare-Select) and LUT (Look-Up Table)-based radix-4 ACS in terms of delay, area, and power consumption. The hardware overhead incurred from the retiming technique used for high speed radix-4 ACS operation is also analyzed. According to the various analysis results, high-throughput radix-4 SISO decoding architecture based on simple path metric recovery circuit is proposed to minimize the hardware resources. The proposed architecture is implemented in 65 nm CMOS process and memory requirement and power consumption can be reduced up to 78% and 32%, respectively, while achieving high-throughput requirement.

Index Terms—Add-compare-select, high-throughput, retiming technique, SISO decoder, signal processing

I. INTRODUCTION

ACS units which compose the SISO decoder play the key role in many FEC (Forward Error Correction) decoders such as Viterbi decoder and Turbo decoder. As the throughput requirement for building infrastructure of

the communication increases, it becomes more important to implement the high speed ACS unit which usually limits the maximum operating frequency.

The ACS unit consists of three basic computations such as addition, comparison, and selection. The purpose of ACS operation is updating the path metrics, recursively, using the addition of path metric and branch metric, and the selection of maximum or minimum value among the addition results. In this paper, the maximum selection is exploited but the proposed architectures can be applicable to the minimum selection algorithm. This whole operation for a conventional cascaded radix-4 ACS unit can be represented by the following equation;

$$P_{NEW} = \max\{\max(P_A, P_B), \max(P_C, P_D)\} \quad (1)$$

where $P_X = P_k + \gamma_k$

where P_{NEW} is output value of radix-4 ACS unit, which denotes the original path metric to be updated. P_X is the pre-compare metric where the X belongs to $\{A, B, C, D\}$. The P_k and the γ_k are the path metric and the branch metric, respectively, where the k belongs to $\{0, 1, 2, 3\}$. The elements of X and k are matched sequentially. These pre-compare metrics are the sum of path metric and branch metric. Eq. (1) indicates the maximum value can be obtained from two local maximum values.

This recursive operation feature leads to the long critical path delay of radix-4 ACS unit, and becomes the bottleneck and the throughput limitation of SISO decoders. Outputs of ACS unit could not be obtained by applying the pipeline architecture to the ACS unit since ACS units perform the recursive operation caused by

Markov chain.

To increase the throughput of SISO decoders, there are several methods such as the increase of parallelism of decoder [1-10], the improvement of operating frequency [11], and the high radix architecture [12-14]. This paper is focused on high operating frequency of radix-4 ACS unit for the high-throughput of radix-4 SISO decoders.

This paper is organized as follows. In Section II, the retimed cascaded radix-4 ACS and retimed LUT-based radix-4 ACS with several signal processing techniques were comparatively explained. In Section III, to reduce the memory requirement of both retimed ACS units, memory requirement of radix-4 SISO decoder was introduced and proposed memory reduction technique for path metrics which are also called forward/backward metrics was presented. The comparison of implementation results between the cascaded radix-4 ACS units and the LUT-based radix-4 ACS units in Samsung 65 nm CMOS process were presented in Section IV with reduced memory requirement and power consumption.

II. HIGH SPEED ACS UNIT ARCHITECTURE

To reduce the critical path delay of high-radix ACS unit, several signal processing techniques can be applied such as common operator migration and retiming [15]. Application of these signal processing techniques to widely used previous radix-4 ACS architectures such as conventional cascaded radix-4 ACS and LUT-based radix-4 ACS is introduced as follows [17]. In this paper, the word length of all kind of metrics is set to 12-bit.

1. Retiming of Cascaded Radix-4 ACS Unit

As indicated in Fig. 1(each component name is described in Fig. 2(b)), *Type-C1*, the conventional radix-4 ACS unit which consists of two cascaded 2-input ACS units denotes the most straightforward hardware architecture of Eq. (1). More precisely, *Type-C1* has following equation.

$$P_{NEW.C1} = \max \{ \max(P_0 + \gamma_0, P_1 + \gamma_1), \max(P_2 + \gamma_2, P_3 + \gamma_3) \} - P_{NORM} \quad (2)$$

Each hardware component has computational latency

Fig. 1. Architecture of *Type-C1*: the conventional cascaded radix-4 ACS unit.

Fig. 2. Illustration of (a) comparing procedure inside the comparison block, (b) legend describing the name of hardware components. P_{NORM} denotes the normalization metric.

represented by T with subscript. The critical path delay of the *Type-C1*, $T_{CRIT.C1}$, is represented as

$$T_{CRIT.C1} = 2T_{ADD} + 2T_{CMP} + 2T_{MUX} \quad (3)$$

where T_{ADD} , T_{CMP} , and T_{MUX} indicates the computational latency of adder, comparison block, and multiplexor (MUX), respectively. In Fig. 2(a), the comparison block has T_{CMP} latency. The most significant bit (MSB) of output value C represents the sign of the result and indicates whether or not the second input is bigger than the first input.

In *Type-C1*, there is no concurrent processing through the whole computation path. All operations are performed sequentially. This operation scheme characterizes the architecture that has long critical path delay. For the improved decoding throughput, several

Fig. 3. Architecture of *Type-C1-A*: modified conventional cascaded radix-4 ACS unit with common operator migration.

hardware components should perform their operations, concurrently.

To reduce the critical path delay, common operation which is equally applied to all of the computation paths can be moved to other place and performed with other operations, concurrently. In Fig. 1, all computation paths of *Type-C1* have normalization adder which can be moved between the branch metric adder and the first stage 2-to-1 MUX. The result of moving the normalization adder becomes *Type-C1-A* as indicated in Fig. 3. The result of common operator migration, *Type-C1-A*, has following equation.

$$P_{NEW.C1A} = \max \{ \max(P_0 + \gamma_0 - P_{NORM}, P_1 + \gamma_1 - P_{NORM}), \max(P_2 + \gamma_2 - P_{NORM}, P_3 + \gamma_3 - P_{NORM}) \} \quad (4)$$

The normalization adder is concurrently operated with comparison block. Since the computational delay of adder is bigger than that of comparison block in 65 nm CMOS process as indicated in the bottom of Fig. 8, even though the comparison block completes its operation, the first stage MUX of *Type-C1-A* should wait for normalization adder to select the accurate value. For this reason, T_{ADD} should be considered rather than T_{CMP} to define the critical path delay in *Type-C1-A*. The computational latency T_{CMP} is reduced from *Type-C1* and the critical path delay of *Type-C1-A* represented as below.

$$T_{CRIT.C1A} = T_{CRIT.C1} - T_{CMP} = 2T_{ADD} + T_{CMP} + 2T_{MUX} \quad (5)$$

This signal processing technique, so called common operator migration, brings reduced critical path delay in comparison with Eq. (3).

Retiming is the transformation technique which can be used to change the locations of registers in a circuit without affecting the input/output characteristics of the circuit [15]. In Fig. 3, the top/bottom registers cut off the recursive operation of radix-4 ACS unit. If this recursive operation was represented in the form of loop scheme, there will be a one register through the entire computation loop because the $P_{NEW}[n+1]$ in *Type-C1-A* denotes the output value of certain register located in the top of Fig. 3 in time instance $n+1$. For applying common operator migration again to *Type-C1-A*, it is necessary to change locations of several registers for parallel process of several hardware components. In Fig. 3, registers of *Type-C1-A* can be moved between branch metric adder and comparison block of first stage. According to the migration of registers, that is retiming, the comparison in the second stage and branch metric addition can be performed directly without waiting for the clock edge as shown in Fig. 4(a). Finally, common operator migration of branch metric addition to the location before the second stage MUX of *Type-C1-B* brings reduced critical path delay amount of T_{CMP} and this retimed architecture is described in Fig. 4(b) as *Type-C2*. In the retimed radix-4 ACS unit, the metrics to be stored in forward memory are not the original path metrics. These four metrics are recursive path metrics and denoted as R_k where k belongs to $k = \{0, 1, 2, 3\}$. The nodes before the branch metric calculation in the retimed radix-4 ACS unit is called R_α and R_β , respectively. The equation of *Type-C2* operation and its critical path delay is represented as below.

$$\begin{aligned} R_\alpha &= \max(R_0[n] - P_{NORM}, R_1[n] - P_{NORM}) \\ R_\beta &= \max(R_2[n] - P_{NORM}, R_3[n] - P_{NORM}) \\ R_k[n+1] &= \max(R_\alpha + \gamma_k, R_\beta + \gamma_k) \end{aligned} \quad (6)$$

$$T_{CRIT.C2} = T_{CRIT.C1A} - T_{CMP} = 2T_{ADD} + 2T_{MUX} \quad (7)$$

It is clear that the critical path delay of *Type-C2*, Eq.

Fig. 4. Modified architectures of *Type-C1-A* with applying the retiming technique (a) *Type-C1-B*: the register moved architecture, (b) *Type-C2*: the retimed architecture which is obtained through the common operator migration on the *Type-C1-B*.

(7), is smaller than the both of Eqs. (3) and (5).

Even though *Type-C1* is transformed into *Type-C2* with reducing the computational latency amount of $2T_{CMP}$ through several signal processing techniques, *Type-C2* still maintains its cascaded hardware architecture. It cannot complete a one iteration of computation until both the two stage are completely operated sequentially.

2. Retiming of LUT-Based Radix-4 ACS Unit

Fig. 5 shows the basic form of LUT-based radix-4 ACS unit, *Type-L1*, which contains the LUT combinational logic [17]. It is not cascaded form of three 2-input ACS units but single form of 4-input ACS unit which computes the four path metrics and branch metrics at once. This section explains briefly the algorithm of LUT-based radix-4 ACS operation and presents the results of applying signal processing techniques to the *Type-L1*.

After the addition between the path metrics ($P_0[n]$ to $P_3[n]$) and the branch metrics (γ_0 to γ_3), the four addition results which are called pre-compare metrics (P_A to P_D) should be compared for finding the maximum value. As indicated in Fig. 5, the pre-compare metrics are the four results of addition between the path metrics and the branch metrics at time instance n . To find the maximum value among four pre-compare metrics, the comparison blocks should compare each magnitude of

Fig. 5. Architecture of *Type-L1*: the basic form of LUT-based radix-4 ACS unit.

them and find out the relationship as indicated in [17]. This *Type-L1* has following equation.

$$P_{NEW.L1} = \max (P_0 + \gamma_0, P_1 + \gamma_1, P_2 + \gamma_2, P_3 + \gamma_3) - P_{NORM} \quad (8)$$

To obtain all the magnitude relationships of different four pre-compare metrics, it is required the number of combinations of four different pre-compare metrics, taken two at a time, without repetitions as represented by the following equation;

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \quad (9)$$

Table 1. Four groups of magnitude-ordered combinations

	G1									G2				G3	G4
Composition Name	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
P_A	•			•		•	•	∇	∇	•		•	•	•	
P_B	•	•			•		•	•	•	•	•		•	•	
P_C		•	•			•	∇	•	∇	•	•	•		•	
P_D			•	•	•		∇	∇	•		•	•	•	•	

*G1: 1st group, G2: 2nd group, ..., G4: 4th group

*If several pre-compare metrics have the same mark in each composition, these are repetitions.

*All blank cells indicate non repetitions in each composition.

Table 2. Compositions of six MSBs for all combinations of pre-compare metrics

	Order of $P_{\{X\}}$	C_0	C_1	C_2	C_3	C_4	C_5
S1	(A B) C D	0	0	0	0	0	0
	(A B) D C	0	0	0	0	0	1
	C (A B) D	0	1	0	1	0	0
	C D (A B)	0	1	1	1	1	0
	D (A B) C	0	0	1	0	1	1
	D C (A B)	0	1	1	1	1	1
S7	(A B) (C D)	0	0	0	0	0	0
	(C D) (A B)	0	1	1	1	1	0
S10	(A B C) D	0	0	0	0	0	0
	D (A B C)	0	0	1	0	1	1
S14	(A B C D)	0	0	0	0	0	0

*The first column represents the composition name of Table 1.

where n is the number of different things and k is the number of values taken at a time. For the result of Eq. (9) where n is 4 and k is 2, all magnitude relationships are come out through the six combinations. These combinations perform the comparison as indicated in Fig. 2(a) and its six results, C_0 to C_5 , represent whether or not the second input is bigger than the first input.

To perform the six comparison operations, the six pairs of pre-compare metrics and the comparison results are defined as follows;

$$\begin{aligned}
 C_0 &= MSB(P_A - P_B) \\
 C_1 &= MSB(P_A - P_C) \\
 C_2 &= MSB(P_A - P_D) \\
 C_3 &= MSB(P_B - P_C) \\
 C_4 &= MSB(P_B - P_D) \\
 C_5 &= MSB(P_C - P_D)
 \end{aligned} \quad (10)$$

where all the C_k ($0 \leq k \leq 5$) have 1-bit width and $C = MSB(A - B)$ operation is described in Fig. 2(a). The set of $\{C_0, C_1, C_2, C_3, C_4, C_5\}$ can have the number of 2^6 cases. The MUX_CTRL signal in LUT-based radix-4 ACS unit denotes the MUX control signal to select the maximum value among four inputs of MUX. The maximum value among the four pre-compare metrics is determined by the composition of $\{C_0, C_1, C_2, C_3, C_4, C_5\}$ and pointed by MUX_CTRL encoded into 00, 01, 10,

11 for P_A, P_B, P_C, P_D , respectively. This whole information is converted into the truth table.

The process of finding the maximum value using six MSBs is described following. To find the entire combinations of four pre-compare metrics in magnitude order, repetitions should be considered. Table 1 denotes entire available compositions of pre-compare metrics with considering the cases when some pre-compare metrics have the same value. As indicated in Table 1, there are three groups of magnitude-ordered combinations with repetitions. The elements of first group have a pair of two same metrics or two pair of two same metrics. There are three same metrics and one different metric in second group, and four same metrics in third group. In addition, there is the 4th group which has no repetitions and the number of its elements is the number of permutations of four different pre-compare metrics taken all at a time. The number of these permutations is represented by factorial 4!. Table 2 represents only four examples among the all of these combinations with the composition of six MSBs. All of these combinations of three groups and 24 permutations are valid. Except these valid combinations of pre-compare metrics and its matched composition of six MSBs, there are a lot of invalid cases. These invalid cases will never occur logically. This truth table only determines the maximum value of four pre-compare metrics, it cannot find out the second biggest value.

Fig. 6. Architecture of *Type-L1-A*: modified original LUT-based radix-4 ACS unit with common operator migration.

Fig. 7. Architecture of *Type-L2*: modified *Type-L1-A* by applying the retiming technique.

To reduce the critical path delay, the signal processing techniques explained in the previous section can be also applied to *Type-L1*.

Fig. 6 and Eq. (11) represent the *Type-L1-A* which is the result of applying common operator migration to *Type-L1*. The normalization adder of *Type-L1* which is lastly performed for updating the path metric is moved between the branch metric adder and the 4-to-1 MUX to reduce the computational latency T_{ADD} as following

equation;

$$P_{NEW.L1A} = \max(P_0 + \gamma_0 - P_{NORM}, P_1 + \gamma_1 - P_{NORM}, P_2 + \gamma_2 - P_{NORM}, P_3 + \gamma_3 - P_{NORM}) \quad (11)$$

$$\begin{aligned} T_{CRIT.L1} &= 2T_{ADD} + T_{CMP} + T_{LUT} + T_{MUX} \\ T_{CRIT.L1A} &= T_{CRIT.L1} - T_{ADD} \\ &= T_{ADD} + T_{CMP} + T_{LUT} + T_{MUX} \end{aligned} \quad (12)$$

where T_{LUT} indicates the computational latency of LUT combinational logic. Between the operations of branch metric adder and 4-to-1 MUX, comparison block and LUT combinational logic were performed with involving the normalization addition $T_{ADD} < T_{CMP} + T_{LUT}$.

After the *Type-L1-A* is obtained through common operator migration, the critical path delay also can be reduced using retiming technique. As indicated in Fig. 7, registers in *Type-L1-A* are moved to the node which denotes the pre-compare metrics. Finally, the branch metric adders which are the common operation of *Type-L1-A* for each branch metrics are moved to the in front of 4-to-1 MUX and these were performed with comparison block and LUT combinational logic, concurrently. The result of retiming to *Type-L1-A*, *Type-L2*, is indicated in Fig. 7, and it has following equation where the k belongs to $\{0, 1, 2, 3\}$.

$$\begin{aligned}
 R_k[n+1] &= \max (R_0[n] - P_{NORM} + \gamma_k, R_1[n] - P_{NORM} + \gamma_k, \\
 &\quad R_2[n] - P_{NORM} + \gamma_k, R_3[n] - P_{NORM} + \gamma_k)
 \end{aligned} \quad (13)$$

In *Type-L2*, there are two data paths for completing the whole computations. One of them is *[comparison block → LUT combinational logic → MUX]* path and the other is *[normalization adder → branch metric adder → MUX]* path. To determine the computational latency between the node of pre-compare metrics and MUX, the longest delay path should be determined first. From a common-sense point of view, since LUT combinational logic has six 1-bit inputs and a 2-bit output in contrast with the branch metric adder or normalization adder which has two 12-bit inputs and a 12-bit output, it is clearly determined what has smaller computational latency. The LUT combinational logic has smaller delay compared to adders and it brings the reduced critical path delay as follows;

$$\begin{aligned}
 T_{CRIT.L2} &= T_{CRIT.L1A} - T_{ADD} + 2T_{ADD} - (T_{CMP} + T_{LUT}) \\
 &= 2T_{ADD} + T_{MUX}
 \end{aligned} \quad (14)$$

where $2T_{ADD} - (T_{CMP} + T_{LUT})$ is the additional delay caused by migrating the branch metric adder.

Fig. 8. Prediction of critical path delay for each type represented as Eqs. (3), (7), (12) and (14) based on Samsung 65 nm CMOS process.

3. Comparative Analysis

For the comparative analysis of four radix-4 ACS units (*Type-C1*, *Type-C2*, *Type-L1*, and *Type-L2*), Fig. 8 illustrates the critical path delay with computational latency of hardware components. In Fig. 8, four bar graphs describe computation flow of ACS operation and denote equations of critical path delay indicated in Eqs. (3), (7), (12) and (14). *Type-L2* has the shortest critical path delay which is obtained by comparing the magnitude of six pre-compare metrics all together. As indicated in Fig. 4(b) and Fig. 8, *Type-C2*, the retimed form of cascaded radix-4 ACS unit performs the operations of adder and MUX twice. It is an obstacle in reducing the critical path delay.

III. PROPOSED RADIX-4 SISO DECODING ARCHITECTURE

By applying several signal processing techniques, the both retimed results, *Type-C2* and *Type-L2*, can be the most appropriate ACS unit to achieve high-throughput radix-4 SISO decoder. However, even though the SISO decoding architecture uses sliding window technique, the SISO decoder which consists of *Type-C2* or *Type-L2* requires huge memory resources to store path metrics and branch metrics. To reduce the branch metric memory requirement, previous work [16] can be exploited. This paper proposes the memory reduction technique for forward memory in MAP(maximum a posteriori)-based radix-4 SISO algorithm for turbo decoder.

Fig. 9. Sliding window diagram with dummy calculation for indicating the memory requirement of upward and downward directions.

1. Memory Requirement of Radix-4 SISO Decoder

As indicated in Fig. 9, the sliding window technique, where a large frame is split into a number of small windows and the decoding algorithm is applied to each window independently, is used for reducing the memory size required to store path metrics [16]. The forward metrics are calculated prior to backward metrics and these will be stored on forward memory. To obtain reliability on error rate, the window size L is set to 64. Since the initial values at the border of each window should have reliability, the dummy calculation is performed for the backward metrics. To perform the path

metric related calculation, there are two memory banks and the forward memory requirement for a radix-4 SISO decoder can be found as Table 3. Each retimed ACS unit, *Type-C2* and *Type-L2*, has four outputs which will be stored in forward memory. Since the radix-4 SISO decoder requires eight radix-4 ACS units for upward direction and eight radix-4 ACS units for downward direction, one radix-4 SISO decoder has sixteen radix-4 ACS units for the path metric calculation. In brief, the number of path metrics which will be stored increased four times, from 8 to 32, in consequence of retiming.

2. Proposed Memory Reduction Technique

In the retimed ACS units, the metrics to be kept in the registers during the recursion are different from original path metrics as indicated in Figs. 4(b) and 7. Therefore, as explained above, the number of metrics to be stored in the forward memory during the recursion increases from 8 to 32. To reduce the forward memory requirement, we propose the simple recovery circuit to retrieve the original path metric as shown in Figs. 10 and 11. We obtain the original path metric from the node before the branch metric addition.

As indicated in Figs. 10 and 11, $P_{NEW}[n+1]$ is the recovered metric which is the original path metric to be updated and to be stored in forward memory. The recursive path metrics, $R_0[n+1]$ to $R_3[n+1]$, are not stored in forward memory and temporarily kept during the recursion. Each operational equation of recovery

Fig. 10. Architecture of *Type-L3*: modified *Type-L2* with adding the recovery circuit which is shown in dotted line.

Table 3. Forward memory requirement for a radix-4 SISO decoder and comparison results between the cascaded ACS units and the LUT-based ACS units for path metric calculation

		Cascaded ACS		LUT-based ACS	
		<i>Type-C2</i> (32 ¹)	<i>Type-C3</i> (7 ¹)	<i>Type-L2</i> (32 ¹)	<i>Type-L3</i> (7 ¹)
Forward Memory Requirement		2 banks, 64*(12*32) bits/bank	2 banks, 64*(12*7) bits/bank	2 banks, 64*(12*32) bits/bank	2 banks, 64*(12*7) bits/bank
		49152 bits (100%)	10752 bits (22%)	49152 bits (100%)	10752 bits (22%)
Gate Count [K]	ACS Units	44.40 (100%)	46.92 (106%)	57.78 (100%)	60.12 (104%)
Area [μm²]	ACS Units	56827 (100%)	60058 (106%)	73953 (100%)	76954 (104%)
	Mem.	125687 (100%)	37281 (30%)	125687 (100%)	37281 (30%)
	Total	182514 (100%)	97339 (53%)	199641 (100%)	114235 (57%)
Power [mW]	ACS Units	36.96 (100%)	40.51 (110%)	41.34 (100%)	45.66 (110%)
	Mem.	35.27 (100%)	8.35 (24%)	35.27 (100%)	8.35 (24%)
	Total	72.23 (100%)	48.86 (68%)	76.61 (100%)	54.01 (71%)

* Forward memory is compiled memory in Samsung 65 nm CMOS process

* All ACS units were operated at fixed frequency of 400MHz

† The number of stored metrics of sixteen ACS units at one state

Fig. 11. Architecture of *Type-C3*: modified *Type-C2* with adding the recovery circuit which is shown in dotted line.

circuit in *Type-C3* and *Type-L3*, Eqs. (15) and (16), is added to Eqs. (6) and (13), respectively.

$$P_{NEW.C3}[n+1] = \max\{R_\alpha, R_\beta\} \quad (15)$$

$$\begin{aligned} P_{NEW.L3}[n+1] \\ = \max(R_0[n] - P_{NORM}, R_1[n] - P_{NORM}, \\ R_2[n] - P_{NORM}, R_3[n] - P_{NORM}) \end{aligned} \quad (16)$$

Even though the cost of hardware overhead incurred by recovery circuit is increased in terms of one MUX and one register, the critical path of *Type-C3* and *Type-L3* is maintained to have same delay with that of *Type-C2* and *Type-L2*, respectively. The requirement of forward memory which stores original path metric instead of recursive metrics is hugely reduced by more than 75% compared to previous retimed radix-4 SISO decoder architectures without recovery circuit. In addition, since all path metrics are normalized by subtracting the P_{NORM} which is same with one of the eight path metrics at the same state for avoiding overflow, one path metric among the eight path metrics does not need to be stored. The number of metrics to be stored can be reduced from 8 to 7 [16].

IV. EXPERIMENTAL RESULTS

In this Section IV, experimental results are presented such as minimum achievable delay, area, and power consumption for the cascaded radix-4 ACS units and the LUT-based radix-4 ACS units in the post-layout implementation. The minimum achievable delay means the maximum operating clock frequency. The six types of radix-4 ACS units, *Type-{C1, C2, C3, L1, L2, L3}*, were described in Verilog HDL and implemented in Samsung 65 nm CMOS process.

1. Comparison among Retimed Results

Reducing the critical path delay of radix-4 ACS units leads to the increase of hardware complexity. The common operator migration and retiming technique leads to hardware complexity increment as the amount of increased hardware: 4 times of normalization adder, 2 times of branch metric adder for the *Type-C2* and 4 times for the *Type-L2*, and several MUXs.

In Fig. 12, the gate count is indicated with minimum achievable delay for *Type-{C1, C2}* and *Type-{L1, L2}*. This figure represents the changes of gate count and minimum achievable delay caused by applying retiming technique. Accordingly, the minimum achievable delay of *Type-C1* can be reduced by 34% and 42% at the expense of 52% and 122% hardware overhead for *Type-C2* and *Type-L2*, respectively. The amount of increased hardware overhead in *Type-L2* is huge compared to that

Fig. 12. The NAND2 equivalent gate count and minimum achievable delay comparison between one retimed radix-4 ACS unit (*Type-C2, L2*) and one original radix-4 ACS unit (*Type-C1, L1*).

of *Type-C2*, while the amount of reduced minimum delay is approximately equal.

By the result, the retimed cascaded radix-4 ACS unit, *Type-C2*, is the best choice for high-throughput radix-4 SISO decoding operation to minimize the hardware overhead and power consumption.

2. Implementation Results

In Table 3, the implementation results in terms of forward memory requirement, area, and power consumption are compared between the proposed architecture (*Type-C3, L3*) and the non-recovery circuit architecture (*Type-C2, L2*) at the operating frequency of 400MHz. With the proposed path metric recovery technique, the forward memory size is reduced by 78% for both cascaded type and LUT-based type at the expense of 6% and 4% hardware overhead of *Type-C3* and *Type-L3*, respectively, and 10% power consumption increment of both *Type-C3* and *Type-L3*. We obtained the huge reduction of forward memory requirement from the cost of small increase of hardware resources and power consumption. The total area is reduced by 47% and 43% with the reduction of 32% and 29% power consumption for the path metric calculation logic with forward memory based on *Type-C3* and *Type-L3*, respectively.

Therefore, the proposed SISO decoding architecture can reduce efficiently the forward memory requirement, hardware complexity, and power consumption. In detail,

since the area and power consumption of cascaded ACS architecture is smaller than that of LUT-based ACS architecture with similar critical path delay, the proposed *Type-C3* is appropriate to be exploited for high-throughput radix-4 SISO decoder with low memory requirement.

V. CONCLUSIONS

To obtain the high-throughput radix-4 SISO decoding architecture with reduced memory requirement, path metric recovery technique is proposed. This technique is applied on the retimed radix-4 ACS units, and analyzed for finding the most appropriate high-throughput radix-4 SISO decoding architecture. The proposed recovery circuit eliminates the need to store four metrics of one retimed radix-4 ACS unit to the forward memory. It recovers the original path metric and reduces the entire forward memory size by 78% with small increase of hardware overhead. The comparison results between cascaded radix-4 ACS architecture and LUT-based radix-4 ACS architecture is presented in terms of delay, area, and power consumption. Even though the retimed cascaded radix-4 ACS unit and the retimed LUT-based radix-4 ACS unit have similar reduced critical path delay, the increase of hardware overhead and power consumption is represented to have significant difference. The retimed cascaded radix-4 ACS unit is effective in reducing the total hardware complexity and power consumption based on recovery circuit compared to the retimed LUT-based radix-4 ACS unit. The proposed architecture which is applied on the cascaded radix-4 ACS and LUT-based radix-4 ACS is implemented in Samsung 65 nm CMOS process.

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power digital VLSI circuit and SoC design.

Wooseok Byun received the B.S. degree in the Department of Electronics Engineering in 2013, from Chungnam National University, Daejeon, Korea, where he is currently working toward the M.S degree. His interests include low-

include the design of VLSI architectures for communication modem and digital signal processing.

Hyeji Kim received the B.S degree in the Department of Electronics Engineering in 2013, from Chungnam National University, Daejeon, Korea, where he is currently working toward the M.S degree. Her current research interests

Ji-Hoon Kim received the B.S. (summa cum laude) and Ph.D. degrees in electrical engineering and computer science from KAIST, Daejeon, Korea, in 2004 and 2009, respectively. His Ph.D. work focused

on design of high performance CPU and baseband modem for mobile hand-held devices. In 2009, he joined Samsung Electronics, Suwon, Korea, where he worked on the SoC architecture design for next generation cellular modem. He is currently with Chungnam National University, Daejeon, Korea, as an Assistant Professor. He is a member of the steering committee of the IC Design Education Center (IDEC), KAIST. His current interests include embedded processor, communication modem, and ultra low power SoC design for IoT (Internet of Things) devices.