Reconfigurable Parallel Turbo Decoder Design for Multiple High-Mobility 4G Systems

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Received: 28 June 2012 / Accepted: 4 February 2013 / Published online: 28 February 2013
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Abstract For high-mobility 4G applications of LTE-A and WiMAX-2 systems, this paper presents a dual-standard turbo decoder design with the following three techniques. 1) Circular parallel decoding reduces decoding latency and improves throughput rate. 2) Collision-free vectorizable dual-standard parallel interleaver enhances hardware utilization of the interleaving address generator. 3) One-bank extrinsic buffer design with bit-level extrinsic information exchange reduces size of the extrinsic buffer compared with the two-bank extrinsic buffer design. Furthermore, a multi-standard turbo decoder chip is fabricated in a core area of 3.38 mm² by 90 nm CMOS process. This chip is maximally measured at 152 MHz with 186.1 Mbps for LTE-A standard and 179.3 Mbps for WiMAX-2 standard.

Keywords Turbo codes · WiMAX · LTE · Multi-standard

This work was supported in part by National Science Council, R.O.C., under grants NSC 99-2218-E-155-011 and NSC 97-2220-E-002-012. The material in this paper was presented in part at the IEEE ISIC 2011, Singapore.

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1 Introduction

Convolutional turbo code (CTC) has been a regular forward error correction (FEC) scheme for reliable wireless communications with a rapid growth of multimedia services. Single-binary CTC (SB-CTC) proposed in 1993 achieves high data rates and coding gains close to the Shannon limit [1]. SB-CTC has been adopted in 3rd Generation Partnership Project (3GPP) family standards [2] as an FEC scheme because of its good correction performance. Non-binary CTC (NB-CTC) [3] introduced in 1999 has superior coding performance than the SB-CTC. In recent years, double-binary CTC (DB-CTC) was adopted in Worldwide Interoperability for Microwave Access (WiMAX) family standards [4] as a FEC scheme. Table 1 lists the detailed specifications and CTC schemes of the prevalent wireless standards for wide area networks (WANs).

Recently, there are a large growing emergence and demand for an inexpensive and ubiquitous broadband wireless network. Thus, Long Term Evolution (LTE) and WiMAX standards become prevalent for the broadband wireless network. Meanwhile, fourth generation (4G) cellular wireless communication, the term referred to International Mobile Telecommunications-Advanced (IMT-Advanced) [5], is emerging in high-end broadband wireless devices. Nowadays the 4G compliant versions of LTE and WiMAX are LTE Advanced (LTE-A) and WirelessMAN-Advanced (WiMAX-2), respectively. To achieve a smooth migration for different applications, a CTC decoder that works across the dual IMT-Advanced compliant standards is necessary. Hence, the goal of this work is to design a CTC decoder that can be used in high-mobility 4G communications. The features of the CTC decoder design are

Table 1 Specifications of the prevalent wireless wide area networks.

Standard	3GPP family		WiMAX family	
	LTE	LTE-A	WiMAX	WiMAX-2
Specification	Rel.8	Rel.10	802.16d	802.16 m
Max. data rate	100 Mbps	100 Mbps (High Mobility)	75 Mbps	100 Mbps (High Mobility)
Bit error rate	10^{-5}		10^{-5}	
CTC scheme	Single-binary (SB) CTC		Double-binary (DB) CTC	
Inf. Bits/Block	64~6144		48~4800	

- to achieve the high-throughput requirement targeting at the specifications of LTE-A and WiMAX-2 standards shown in Table 1,
- to achieve parallel decoding for SB-CTC and DB-CTC schemes based on LTE-A and WiMAX-2 standards,
- to design a parallel and reconfigurable interleaver based on the computational similarity of LTE-A and WiMAX-2 standards, and
- to achieve area-efficient and memory-efficient CTC decoder design for the LTE-A and WiMAX-2 standards.

In this paper, circular parallel maximum *a-posteriori* probability algorithm (MAP) decoding is introduced to reduce decoding latency and hardware cost. The circular parallel MAP decoding results in numbers of circular MAP decoding according to its parallelism with a small coding gain loss. Meanwhile, the collision-free vectorizable dual-standard parallel interleaver based on the almost regular permutation (ARP) structure and the quadratic polynomial permutation (QPP) structure is proposed to enhance hardware utilization of the interleaver. Then, the available parallelism of the collision-free CTC decoding is achieved for the LTE-A and WiMAX-2 standards. In order to increase the hardware usage of the CTC decoder, two area-efficient extrinsic buffer designs are described for the dual-standard CTC decoder. Using UMC 90 nm CMOS technology, the proposed CTC decoder chip for WiMAX-2 and LTE-A systems has been fabricated in a core size of 3.38 mm². The throughput rate of 186.1 Mbps can be maximally measured at 152 MHz with power consumption of 148.1 mW.

This paper is organized as follows. In Section 2, the fundamentals of turbo codes for WiMAX-based standard and LTE-based standard are revisited. Section 3 describes the architecture design of the proposed CTC decoder for the dual standards. Section 4 presents the experimental results and comparison of the proposed CTC decoder for the LTE-A/WiMAX-2 standards. Finally, Section 5 concludes this paper.

2 Reviews of Turbo Codes

Background reviews of the CTCs of WiMAX-based standard and LTE-based standard are demonstrated in this section.

2.1 Turbo Codec

The encoder and decoder of CTC are shown in Fig. 1. The encoder consists of two identical recursive systematic convolutional (RSC) encoders, which are connected in parallel by an interleaver. The RSC encoder produces systematic symbol (u_s) and parity symbol (u_p) to the channel. The information stream is reordered by the interleaver and then enters the second RSC encoder. The RSC encoders of SB-CTC encodes 1 bit per time while the RSC encoders of DB-CTC encodes 2 bits per time. The RSC encoders of LTE (SB-CTC) and WiMAX (DB-CTC) standards are shown in Fig. 2. For the trellis termination, the RSC encoder in LTE uses a few redundant bits to terminate the trellis path. However, the RSC encoder in WiMAX adopts two-phase circular encoding [3] where the final trellis state can be the same to initial trellis state.

The decoder is composed of two soft-input soft-output (SISO) decoders that are serially concatenated by the interleaver and de-interleaver. Each SISO decoder uses the received systematic symbol and corresponding parity symbol to computes extrinsic information that is then iteratively fed to the other SISO decoder as the *a priori* information. The hard decision of decoded symbols is made after several iterations between these two SISO decoders.

2.2 CTC Interleaver

The interleaver is one of dominant modules of CTCs and the correction performance of CTCs depends on the structures and length of interleaver. The interleaver is used to permute the order of symbols. This can be done by using an interleaving address generator to access the symbols stored in a buffer. When the c_i denotes normal-order symbol, the interleaved-order symbol $c'_{\pi(i)}$ can be represented as

$$c'_i = c_{\pi(i)}, \quad (1)$$

where $i=0, 1, \dots, (N-1)$ and N is the CTC block size. $c_{\pi(i)}$ is the normal-order symbol c_i stored at interleaving pattern $\pi(i)$ and $\pi(i)$ is generated by interleaving address generator. The algorithms that generate $\pi(i)$ are defined in each standard and described as follows.

Figure 1 Block diagram of **a** CTC encoder and **b** CTC decoder.

The WiMAX interleaver adopts the ARP structure. The interleaving address $\pi_W(j)$ is generated by switching $(j)_{\text{mod}4}$:

$$\begin{aligned} \text{case 0 : } \pi_W(j) &= (P_0 \times j + 1)_{\text{mod}N}, \\ \text{case 1 : } \pi_W(j) &= (P_0 \times j + 1 + P_1)_{\text{mod}N}, \\ \text{case 2 : } \pi_W(j) &= (P_0 \times j + 1 + N/2 + 1 + P_2)_{\text{mod}N}, \\ \text{case 3 : } \pi_W(j) &= (P_0 \times j + 1 + N/2 + 1 + P_3)_{\text{mod}N}, \end{aligned} \quad (2)$$

where j is an increasing value from 1 to N . The parameters P_0, P_1, P_2 , and P_3 defined in WiMAX depend on N . The function of $(x)_{\text{mod}y}$ gets the remainder on division of x by y . The parameters P_0, P_1, P_2 , and P_3 can be stored into a look-up table (LUT). The individual architecture of WiMAX CTC interleaver can be referred to in [6].

The LTE interleaver adopts the QPP structure. The interleaving address $\pi_L(j)$ is generated by

$$\pi_L(j) = (f_1 \times j + f_2 \times j^2)_{\text{mod}N}, \quad (3)$$

where j is an increasing value from 1 to N . The parameters f_1 and f_2 defined in LTE also depend on N . The parameters f_1 and f_2 can be stored into a LUT as well. The individual architecture of LTE CTC interleaver can be referred to in [7].

2.3 MAP Decoding for SB/DB CTC

Maximum *a-posteriori* probability algorithm (MAP) [8] and its derivatives [9–11] are widely employed in the CTC decoding. Furthermore, the enhanced Max-log-MAP (EML-MAP)

proposed in [11] is achieved with a little coding gain degradation for an ease of hardware implementation of the MAP. In the following sections, we use the name MAP for a short abbreviation of the EML-MAP. Given the received block sequence Y , the MAP gives each decoded bit u_k a probability that the bit is 1 or 0. This is equivalent to find *a-posteriori* log-likelihood-ratio (LLR),

$$\Lambda_{apo}(u_k) = \ln \left(\frac{\Pr(u_k = 1|Y)}{\Pr(u_k = 0|Y)} \right). \quad (4)$$

Λ_{apo} can be decomposed as follows

$$\Lambda_{apo}(u_k) = \ln \left(\frac{\sum_{(s',s) \Rightarrow u_k=1} (\alpha_k(s') \cdot \gamma_k(s',s) \cdot \beta_{k+1}(s))}{\sum_{(s',s) \Rightarrow u_k=0} (\alpha_k(s') \cdot \gamma_k(s',s) \cdot \beta_{k+1}(s))} \right), \quad (5a)$$

$$\alpha_{k+1}(s) = \sum_{\text{all } s'} (\alpha_k(s') \cdot \gamma_k(s',s)), \quad (5b)$$

$$\beta_k(s') = \sum_{\text{all } s} (\beta_{k+1}(s) \cdot \gamma_k(s',s)), \quad (5c)$$

$$\gamma_k(s',s) = \Pr(y_k|x_k) \cdot \Pr(u_k), \quad (5d)$$

where α is the forward state metrics; β is the backward state metrics; γ is the branch metrics; k is the decoding time index; s ,

Figure 2 Block diagram of the **a** SB RSC encoder in LTE and **b** DB RSC encoder in WiMAX.

Figure 3 Warm-up sliding-window (SW) MAP decoding.

s' denotes the state indices; $\Pr(y_k|x_k)$ is the conditional received symbol probability; and $\Pr(u_k)$ is the *a priori* probability of decoded bit u_k attained from the other SISO decoder.

During the turbo decoding, extrinsic information is iteratively fed back to the other SISO decoder as *a priori* LLR. The extrinsic information Λ_{ex} is formulated as

$$\Lambda_{ex}(u_k) = \delta(\Lambda_{apo}(u_k) - \Lambda_{apr}(u_k) - \Lambda_{in}(u_k)), \quad (6)$$

where Λ_{in} and Λ_{apr} are the intrinsic information and *a priori* LLR of this SISO decoding, respectively. The extrinsic information in the EML-MAP multiplies a scaling factor ($0 < \delta < 1$). For either the SB-CTC or DB-CTC decoding, the MAP is composed of branch metrics (γ), forward recursion state metrics (α), backward recursion state metrics (β), *a priori* LLR (Λ_{apr}), *a posteriori* LLR (Λ_{apo}), and extrinsic information (Λ_{ex}). For the dual-standard MAP decoding, the radix-4 SB MAP decoding and radix-4 DB MAP decoding are employed because of their similarity. The details of radix-4 SB MAP decoding and radix-4 DB MAP decoding can be referred to in [12].

Figure 4 Block diagram of the proposed CTC decoder for LTE-A/WiMAX-2 Standards.

Figure 5 Vectorizable interleaving address for memory banks.

2.4 Window-Based MAP Decoding

The windowing technique proposed in [13] is used to facilitate the memory cost of CTC decoders. The sliding window (SW) decoding [14] deals with any CTC block size but has an intrinsic low throughput rate. Some VLSI architectures of the sliding window (SW) MAP decoding can be referred to in [15–18]. Figure 3 shows the timing chart of the warm-up SW MAP decoding, and the vertical and horizontal axes denote the decoding symbol and decoding time, respectively. The timing chart of MAP decoding is mainly composed of the branch metric acquisition, forward state metrics recursion, backward state metrics recursion, and *a posteriori* LLR acquisition. In order to achieve the reliable window rim, the warm-up recursion of a basic windows size W is performed. In general, $W = 4v \sim 6v$, where v is the constraint length of RSC encoder. The decoding latency of the warm-up SW MAP decoding is $3W$. The SW MAP decoding deals with any CTC frame size but it has an intrinsic low throughput. The hybrid-window (HW)

MAP decoding described in [12] applies parallel decoding with parallelism P to decode one received block. Because of the warm-up processes of forward states metrics, the decoding latency is prolonged to $4W$. Nevertheless, the HW MAP decoding can shorten the decoding cycles to $N/P+4W$ by working with several sub-blocks simultaneously.

3 Proposed CTC Decoder for LTE-A/WiMAX-2 Standards

In order to support the decoding of both WiMAX-based and LTE-based CTC schemes, our realization of the proposed dual-standard CTC decoder is based on the architecture shown in Fig. 4. The input buffers store the soft received data including the systematic information, non-interleaved parity information, and interleaved parity information. Meanwhile, the internal buffer stores the extrinsic information and the output buffer stores the decoded hard bits. Because at most P warm-up free HW (WFHW) MAP processors work concurrently, each buffer is divided into P banks to be accessed simultaneously. The proposed LTE-/WiMAX parallel interleaver generates collision-free vectorizable addresses for the input buffer and extrinsic buffer. Therefore, the normal-order or interleaved-order data can be correctly processed between the WFHW MAP processors and the buffer subbanks. When the targeted iteration number is reached or the hard bits of two half iteration are the same,

Table 2 Available parallelism for LTE/WiMAX systems.

Inf. Bits	Available parallelism P	
	WiMAX	LTE
48	1	1 2
72	1	1 2 3
96	1 2	1 2 3 4
144	1 2 3	1 2 3 4 6
192	1 2 3 4	1 2 3 4 6 8
216	1 3	1 2 3 4 6 8 9
240	1 2 3 4 5	1 2 3 4 5 6 8 10
288	1 2 3 4 6	1 2 3 4 6 8 9 12
360	1 2 3 4 5 6	1 2 3 4 5 6 8 9 10 12 15
384	1 2 3 4 6 8	1 2 3 4 6 8 12 16
432	1 2 3 4 6 8 9	1 2 3 4 6 8 9 12 16 18
480	1 2 3 4 5 6 8 10	1 2 3 4 5 6 8 10 12 15 16 20
960	1 2 3 4 5 6 8 10 12	1 2 3 4 5 6 8 10 12 15 16 20
1920	1 2 3 4 5 6 8 10 12	1 2 3 4 5 6 8 10 12 15 16 20
2880	1 2 3 4 5 6 8 9 10 12	1 2 3 4 5 6 8 9 10 12 15 16 18 20
3840	1 2 3 4 5 6 8 10 12	1 2 3 4 5 6 8 10 12 15 16 20
4800	1 2 3 4 5 6 8 10 12	1 2 3 4 5 6 8 10 12 15 16 20
6144	–	1 2 3 4 5 6 8 12 16

the CTC decoder finishes the decoding procedure and outputs the hard bits from the output buffer. The design techniques are presented in detail as follows.

Figure 6 Block diagram of the LTE/WiMAX parallel interleaver and CTC controller.

Table 3 Gate-count analysis of the proposed collision-free vectorizable LTE/WiMAX parallel interleaver and CTC controller.

Modules	Gate counts
CTC controller	8.0 K (26.3 %)
Dual-standard address generators	6.9 K (22.7 %)
LTE address generators	5.7 K (18.8 %)
Address decoders	9.8 K (32.2 %)
Overall	30.4 K (100.0 %)

3.1 Collision-Free Vectorizable WiMAX/LTE Parallel Interleaver

The CTC interleaving is used to permute symbols by an interleaving address generator that accesses symbols from the buffers. For parallel decoding, P MAP processors may read and write a same memory bank simultaneously. Since the port of a memory is finite, the simultaneous memory access is prohibited. Without a cautious analysis of the LTE-based and WiMAX-based CTC interleaving, the memory collision occurs frequently and makes the parallel decoding unrealizable [19]. Finding a proper parallelism P has been discussed in [20]. The parallel interleaver is collision-free when it satisfies

Figure 8 Equivalent trellis propagation of backward recursion of the circular parallel MAP decoding as the iteration is increased.

$$\left\lfloor \frac{\pi(t+jW)}{W} \right\rfloor \neq \left\lfloor \frac{\pi(t+kW)}{W} \right\rfloor, \quad (7)$$

where $0 \leq t < W$, and $0 \leq j, k < P$. The terms on both sides in (7) are indices of the memory banks that are accessed by the j^{th} and k^{th} MAP processors at the t^{th} time instant. This inequality need to be true for any time instant t for no memory collision.

For an interleaver design, the complexity of the interleaving address generation is also critical. Each memory bank requires an address decoder to transform the global interleaving address to the local address for each memory bank. As the parallelism P increases, the duplication of address decoder leads to hardware inefficiency. A better

Figure 7 Warm-up free hybrid-window (WFHW) MAP decoding: **a** basic window and **b** overall timing chart. **Figure 9** BER performance of the WiMAX-2 and LTE-A CTC decoding by using the distinct hybrid-window (HW) MAP decoding at fixed 6 iterations. “No warm-up” represents that the HW MAP decoding performs without warm-up scheme and accessing rim state metrics scheme.

Figure 10 Block diagram of **a** warm-up HW MAP processor and **b** WFHW MAP processor.

solution is to use the same address decoder for all memory banks. This vectorizable property requires the interleaving address satisfying

$$(\pi(t + jW))_{\text{mod } W} = (\pi(t))_{\text{mod } W}, \quad (8)$$

where $0 \leq t < W$, and $0 \leq j < P$. The equality implies that each MAP processor accesses data based on the same local address. Based on this vectorizable property, only one decoder is required. All memory banks can merge into a single physical memory with data stored and fetched as vectors as shown in Fig. 5.

A high-level simulation model is constructed to analyze the available parallelism for the LTE-based and WiMAX-based CTC decoding with $24 \leq W \leq 36$. Then, we achieve P MAP processors and S number of decoding window for each MAP processor. Table 2 lists the available parallelism

achieving the collision-free and vectorizable interleaving. To design the proposed dual-standard CTC decoder, the parallelism P is set to 8 for the WiMAX-2 standard and 16 for the LTE-A standard. Figure 6 shows the overall architecture of the proposed collision-free vectorizable dual-standard parallel interleaver and the CTC controller. The CTC controller is used to provide control signals and initial parameters. To perform the radix-4 SB/DB MAP decoding, the proposed dual-standard address generators generate the WiMAX-based addresses or the LTE-based even addresses by adopting a hardware sharing technique. The additional LTE address generators generate the LTE-based odd addresses in the LTE modes. The LTE-based and WiMAX-based interleaving parameters ($P0$, $TP1$, $TP2$, $TP2$, $P(0)$, $H(0)$, $J(0)$, and f_2) can be implemented in two parameter read-only memories (PROMs). The address decoder transforms the interleaving addresses into the collision-free addresses of the memory banks. Table 3 shows total gate counts of the proposed parallel dual-standard interleaver and CTC controller. Compared with the LTE address generators, the overhead of the proposed dual-standard address generators is about 1.2 K gates in order to support the WiMAX interleaving. Besides, the address decoders are less dominant in the design of the dual-standard parallel interleaver and CTC controller.

3.2 Circular Parallel MAP Decoding

To achieve the circular parallel MAP decoding, we first introduce the methods to achieve initial forward and backward state metrics of each frame for the distinct trellis terminations described in Section 2.1. The initial forward and backward state metrics of each frame can be attained by two distinct methods for the WiMAX-based standard and LTE-based standard. The method used in WiMAX-based standard is the circular encoding [21], which ensure the ending trellis state equals the initial trellis state. Thus, the initial values of the forward state metrics $\alpha_0^k(s)$ and backward

Table 4 Area evaluations of the Radix-4 SB/DB Warm-up HW MAP processor and WFHW MAP processor (90 nm Process@150 MHz).

Module	Warm-up HW MAP (μm^2)	WFHW MAP (μm^2)
BMU S1	1095.40	1095.40
BMC	49862.52 (4 single-port SRAMs)	13496.44 (1 dual-port SRAM)
BMU S2s	9597.11	6398.07
RPB	12500.71	12500.71
WRPB	12500.71	—
RPA	12499.69	12499.69
SMC	17892.10 (dual-port SRAM)	14510.82 (dual-port SRAM)
TRP	—	3379.92
LAPO	24678.65	24678.65
RMC	—	25013.21 (2 single-port SRAMs)
Overall	140626.89 (100 %)	113572.91 (80.76 %)

state metrics $\beta_N^k(s)$ of the k^{th} iteration for the circular encoding can be determined by

$$\begin{cases} \alpha_0^k(s) = \begin{cases} 0 & (\text{for } k = 1), \\ \alpha_N^{k-1}(s) & (\text{others}), \end{cases} \\ \beta_N^k(s) = \begin{cases} 0 & (\text{for } k = 1), \\ \beta_0^{k-1}(s) & (\text{others}), \end{cases} \end{cases} \quad (9)$$

where $\alpha_N^{k-1}(s)$ and $\beta_0^{k-1}(s)$ are the final state metrics of the $(k-1)^{\text{th}}$ iteration. The method used in LTE-based standard is to force the trellis terminated at the state 0. Thus, the initial values of $\alpha_0^k(s)$ and $\beta_N^k(s)$ for the 0-state trellis termination can be determined by

$$\begin{cases} \alpha_0^k(0) = \beta_N^k(0) = 0, \\ \alpha_0^k(s') = \beta_N^k(s') = \infty, \end{cases} \quad (10)$$

where s' denotes the states that are not state 0.

We then introduce the WFHW MAP decoding of the circular parallel MAP decoding. Figure 7(b) shows the overall timing chart of the WFHW MAP decoding, which is composed of the basic WFHW window shown in Fig. 7(a). The key concept is to introduce the initial rim forward and backward state metrics of the $(k+1)^{\text{th}}$ iteration to the HW decoding by utilizing the final rim forward and backward state metrics of the k^{th} iteration. Instead of performing a warm-up recursion, each WFHW MAP processor achieves the initial rim state

Figure 11 **a** Two-bank and **b** one-bank extrinsic buffer designs for the LTE/WiMAX standards.

Figure 12 BER performance of the two extrinsic buffer designs for WiMAX-2 CTC schemes by using the circular parallel MAP decoding at fixed 6 iterations.

metrics of current iteration by fetching the final rim state metrics of previous iteration from the rim metrics cache (RMC). The initial forward and backward state metrics of the $(k+1)^{\text{th}}$ iteration can be determined by

$$\begin{cases} \alpha_{j \cdot [N/P]}^{k+1}(s) = \alpha_{j \cdot [N/P]}^k(s), \\ \beta_{t \cdot W}^{k+1}(s) = \beta_{t \cdot W}^k(s), \end{cases} \quad (11)$$

where $1 \leq k \leq \text{maximum number of iteration } I$, $0 \leq t < W$, and $0 \leq j < P$. Then, Fig. 8 shows the circular trellis propagation of backward recursion of the circular parallel MAP decoding as the iteration is increased. The forward recursion can achieve the same effect in the opposite direction. Thus, the circular parallel MAP decoding results in P number of circular MAP decoding as iteration increases. Instead of performing warm-up recursion to get the initial state metrics, the WFHW MAP processor can fetch it from RMC so that the decoding latency can reduce to $1W$. The throughput rates can be improved 18.2 % for $N=2400$ WiMAX-2 CTC decoding and 15 % for $N=3072$ LTE-A CTC decoding compared to the warm-up HW MAP decoding [12]. Figure 9 presents the floating-point simulation results of distinct HW MAP decoding for $N=2400$ WiMAX-2 and $N=6144$ LTE-A CTC schemes with $P=8$ at fixed 6 iterations. The circular parallel MAP decoding

Table 5 Area and power evaluations of the two-bank and one-bank extrinsic buffer designs (90 nm Process@150 MHz).

Design	Two-bank extrinsic buffer design	One-bank extrinsic buffer design
Area (μm^2)	307449.50 (100 %)	204184.26 (66.41 %)
Power (mW)	12.79 (100 %)	8.86 (69.27 %)

Figure 13 BER performance of the CTC decoding by using the prototyping CTC decoder chip.

greatly improves the coding gain compared with the no warm-up HW MAP decoding. Due to the less reliability of extrinsic information exchange, however, the coding gain loss of the circular parallel MAP decoding is less than 0.1 dB at a BER of 10^{-5} compared with the warm-up HW MAP decoding.

Figure 10 shows the block diagram of warm-up HW MAP processor and WFHW MAP processor which are based on the timing chart shown in Figs. 3 and 7, respectively. In order to achieve a high area usage, we apply the radix-4 SB/DB EML-MAP decoding modules [12] to the both MAP processors. The six temporary terms of branch metrics calculated by the first-stage branch metrics unit (BMU S1) are stored into the branch metrics cache (BMC), and then the sixteen branch

Figure 14 Die photo of the prototyping CTC decoder chip. (□ SRAM block).

Table 6 Summary of the prototyping CTC decoder chip.

Technology	UMC 90 nm CMOS
Max. frequency	152 MHz
Core size	$1.84 \times 1.83 \text{ mm}^2$
Max. throughput rate $T @ N=6144$, 6 iterations	186.1 Mbps
Power consumption @ T	148.1 mW

metrics are fetched by the second-stage branch metrics unit (BMU S2). Based on the basic window shown in Fig. 7(a), one set of BMU S1 and two sets of BMU S2 are required for the WFHW MAP decoding. The forward recursion processing element (RPA), warm-up backward recursion processing element (WRPB), and backward recursion processing element (RPB) are composed of radix-4 add-compare-select units (ACSUs). The forward traceback recursion processing element (TRPA) composed of radix-4 traceback units [23] are adopted to reduce the access power of the state metrics cache (SMC). Finally, *a posteriori* LLR module (Lapo) is used to compute *a posteriori* LLR. Table 4 lists the area evaluation obtained by using the 90 nm CMOS process based on the quantization scheme referred to in Table 3 in [12] with $W=36$ and $S=16$. The RMC is evaluated with the WFHW MAP processor to correctly perform the CTC decoding. The RMC is composed of two single-port SRAMs because each SRAM stores the rim state metrics of half iteration. Even the hardware cost of RMC is large. The WFHW MAP processor achieves

Table 7 Parameters and throughputs of the prototyping CTC decoder.

Info. Bits		Active MAPs	S	W	Throughput (Mbps@152 MHz)
WiMAX-2	LTE-A				
48	48	1	1	24	10.8
72	72	1	1	36	11.4
96	96	2	1	24	21.7
144	144	2	1	36	32.5
192	192	4	1	24	43.4
216	216	3	1	36	34.2
240	240	4	1	30	44.7
288	288	4	1	36	65.2
360	360	6	1	30	67.0
384	384	8	1	24	86.8
432	432	8	1	27	88.3
480	480	8	1	30	89.5
960	960	8	2	30	124.0
1920	1920	8	4	30	153.9
2880	2880	8	6	30	167.3
3840	3840	8	8	30	175.0
4800	4800	8	10	30	179.3
—	6144	8	16	24	186.1

area reduction because the hardware cost of WRPB and BMC are majorly reduced compared with the warm-up HW MAP processor. Thus, the proposed CTC decoder for WiMAX-2 and LTE-A standards adopts the circular parallel MAP decoding with the WFHW MAP processor shown in Fig. 10(b).

3.3 Efficient WiMAX/LTE Extrinsic Buffer Design

Because of the radix-4 DB MAP decoding, three extrinsic information values are accessed in an extrinsic buffer in one cycle. The conventional radix-4 DB CTC decoder requires $2400 \times 3n_{ex}$ SRAM to store the three extrinsic information values for WiMAX standard, where n_{ex} denotes the bit-length of an extrinsic information value. Meanwhile, two extrinsic information values are accessed in an extrinsic buffer in one cycle because of the radix-4 SB MAP decoding. Thus, the conventional radix-4 SB CTC decoder requires $3072 \times 2n_{ex}$ SRAM to store the extrinsic information values for LTE standard. In order to increase the hardware usage of extrinsic buffer, Fig. 11(a) shows an efficient two-bank extrinsic buffer design for the dual standards. Compared with a one-bank

Figure 16 Measured power with different operating frequencies at core vdd=1.1 V.

$3072 \times 3n_{ex}$ SRAM design, this two-bank extrinsic buffer design can reduce the size of extrinsic buffer. The two-bank

Figure 15 Shmoo plot of chip testing. This plot is captured by an Agilent 93000 SOC Series Test System. X-axis denotes core vdd from 0.9 V to 1.1 V, and Y-axis denotes frequency from 70 MHz

to 155 MHz. *Light-gray* block means that the chip passes the testing, and *dark-gray* block means that the chip does not pass the testing.

Figure 17 Measured frequency and power of the prototyping CTC decoder chip.

extrinsic buffer design can disable the $2400 \times n_{ex}$ SRAM in LTE mode to reduce the power consumption. To further increase the hardware usage of extrinsic buffer, Fig. 11(b) shows an efficient extrinsic buffer design by using the bit-level extrinsic information exchange method [22]. This method transfers the extrinsic information of radix-4 DB MAP decoding from symbol-level values to bit-level values and makes the extrinsic buffer access only two extrinsic information values. Thus, the extrinsic buffer for the dual standards can be implemented by a one-bank $3072 \times 2n_{ex}$ SRAM and achieve 100 % utilization ratio in LTE mode. Figure 12 illustrates the floating-point simulation results of the two extrinsic buffer designs for WiMAX-2 CTC schemes by using the circular parallel MAP decoding at fixed 6 iterations. The two-bank extrinsic buffer design loses less than 0.2 dB coding gain at a BER of 10^{-5} due to the bit-level extrinsic information exchange method for the WiMAX-2 CTC decoding. Compared to the aforementioned

two-bank design, the one-bank design with the bit-level extrinsic information exchange method reduces 28.1 % size of the extrinsic buffer and eliminates the $2400 \times n_{ex}$ SRAM. Table 5 lists the area evaluation obtained by using the 90 nm CMOS process with $n_{ex}=9$. Compared with the two-bank extrinsic buffer design, the one-bank extrinsic buffer design achieves a low area cost and low power consumption. Hence, the proposed CTC decoder for WiMAX-2 and LTE-A standards adopts the efficient extrinsic buffer design with the bit-level extrinsic information exchange method.

4 CHIP Implementation and Comparisons

The design of the CTC decoder is simulated using C-to-RTL flow with the quantization scheme referred to in Table 3 in [12]. The parameters of the proposed CTC decoder can meet the targeted BER of 10^{-5} for WiMAX-2 and LTE-A standards. Figure 13 shows the simulated BER performance of the distinct CTC schemes decoded by the prototyping CTC decoder based on additive white Gaussian noise (AWGN) channels and 6 iterations. The ideal MAP represents the floating-point CTC decoding with knowing the initiate trellis states and without the windowing technique. The fix-point represents the fixed-point CTC decoding by using the proposed CTC decoder for the LTE-A and WiMAX-2 standards.

4.1 Prototyping Chip Implementation and Measurement Results

The proposed CTC decoder has been implemented in an ASIC by using Verilog HDL codes synthesized with the standard cell library of UMC 90 nm 1P9M CMOS process

Table 8 Comparisons of the CTC decoder chips.

Publication	[24]	[26]	[25]	[27]	Proposed
Technology	130 nm	130 nm	130 nm	90 nm	90 nm
Core voltage	1.2 V	1.2 V	1.2 V	1 V	1.1 V
Standard	UMTS, HSDPA	Mobile WiMAX	LTE-A, WiMAX	LTE	LTE-A, WiMAX-2
Max. Info. Bits	5144	4800	6144	6144	6144
MAP	Radix-2 SB	Radix-4 DB	Radix-4 SB/DB	Radix-2 SB	Radix-4 SB/DB
Parallelism P	1	1	8	8	8
Max. frequency (MHz)	246	200	250	275	152
Core area (mm ²)	1.20	2.24	10.7	2.10	3.38
Max. throughput T (Mbps)	20.2 @ 5.5 iter.	48.5 @ 8 iter.	187.5 @ 8 iter.	130 @ 8 iter.	186.1 @ 6 iter.
Power (mW) @ T	61.5	N/A	N/A	219	148.1
Energy efficiency (nJ/bit/iter.)	0.54 (0.18 ^a)	N/A	0.61 (0.20 ^a)	0.21	0.13
Area efficiency (bit/mm ²)	0.07 (0.15 ^b)	0.11 (0.23 ^b)	0.07 (0.15 ^b)	0.23	0.36

^a Normalized energy factor = $0.33 (= (1.0 \text{ V}/1.2 \text{ V})^2 \times (90 \text{ nm}/130 \text{ nm})^2)$

^b Normalized area factor = $2.09 (= (130 \text{ nm}/90 \text{ nm})^2)$

and packed in a CQFP128 package. This prototyping decoder supports the WiMAX-2 and LTE-A CTC schemes. The chip implementation of the proposed CTC decoder is obtained in a core size of 3.38 mm^2 and contains 232.8 Kb RAM. Figure 14 shows the die photo of the proposed CTC decoder and Table 6 summarizes this chip. The chip is measured by using an Agilent 93000 system-on-a-chip (SoC) Series Test System. The chip is maximally measured at 152 MHz operating frequency. The number of active MAP processors with the distinct design modes is shown in Table 7. At 6 iterations, the chip achieves maximum throughput rate of 179.3 Mbps and 186.1 Mbps for WiMAX-2 and LTE-A, respectively. Besides, Fig. 15 shows the shmoo plot with core vdd from 0.9 V to 1.1 V and operation frequency from 70 MHz to 155 MHz. Then, Fig. 16 shows the measured power consumptions with different operation frequencies at core vdd of 1.1 V. This plot indicates that the power consumptions are 148.1 mW at operation frequency of 152 MHz and core vdd of 1.1 V. Furthermore, to consider reduction of power consumption, the core supply voltage can be reduced from 1.1 V to 0.9 V. The measured maximal operating frequencies and power consumptions are shown in Fig. 17.

4.2 Comparisons

In Table 8, the proposed CTC decoder for LTE-A and WiMAX-2 standards is compared with other chip designs. The works in [24] and [26] perform the radix-2 SB MAP decoding and radix-4 DB MAP decoding for HSDPA and WiMAX systems, respectively. Since the throughput rate requirements are less than 20 Mbps, both of these employ only one MAP processing. To achieve throughput rates higher than 100 Mbps, the work in [27] employs 8 MAP processors and supports LTE CTC schemes. Our proposed CTC decoder employs 8 radix-4 SB/DB WFHW MAP processors with the proposed collision-free parallel interleaver for the dual-standard CTC schemes. It is hard to compare these chips since the coding parameters are different from each other. However, we use normalized energy efficiency (NEE),

$$\text{NEE} = \frac{\text{Power}}{\text{Throughput} \times \text{Iteration}} \times \text{Normalized energy factor}, \quad (12)$$

and normalized area efficiency (NAE),

$$\text{NAE} = \frac{\text{Throughput}}{\text{Area} \times \text{Frequency}} \times \text{Normalized area factor} \quad (13)$$

as the performance indices. The NEE indicates how much energy a decoder chip consumes to process a hard bit at an iteration. The NAE indicates how many hard bits per one mm^2

for a single CTC block a decoder chip decodes. To support the high-mobility 4 G application of the LTE-A/WiMAX-2 CTC decoding, this chip achieves a high NAE of 0.36 bit/mm^2 with a low NEE of $0.13 \text{ nJ/bit/iteration}$.

5 Conclusion

In this paper, a turbo decoder chip supporting distinct block sizes of convolutional turbo code schemes for the high-mobility 4 G applications of both LTE-A and WiMAX-2 systems is proposed. The circular parallel MAP decoding is introduced to achieve high throughput rate and low hardware cost. The collision-free vectorizable dual-standard parallel interleaver is proposed to enhance the hardware usage. The two efficient extrinsic buffer designs are also described in this paper to increase the memory utilization. The CTC decoder chip for LTE-A/WiMAX-2 standards is fabricated to verify the proposed techniques. This decoder chip achieves the both LTE-A and WiMAX-2 data-rate requirements with a high area efficiency and a low energy efficiency.

Acknowledgment The authors would like to thank Chip Implementation Center (CIC) for the support of chip fabrication.

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Transactions on Circuits and Systems II: Express Briefs, vol. 57, no. 7.

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