Forward Error Correction Decoding for WiMAX and 3GPP LTE Modems

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Abstract— **In this paper, we review the requirements for forward error correction (FEC) decoding for next generation wireless modems – mobile Worldwide Interoperability for Microwave Access (WiMAX) and third generation partnership project long term evolution (3GPP LTE). FEC decoder consists of mainly three components: control channel decoder, data channel decoder, and hybrid automatic repeat query (HARQ) combining. Control channel decoder is constrained by latency budget which impacts buffering as well as power management of modem signal processing chains. For WiMAX, both Viterbi and Turbo decoders are required to receive control channel while for LTE, only Viterbi decoder is required. For data-channel, a high-throughput Turbo decoder is required to support high data rate. HARQ combining is mainly dominated by memory size and bandwidth requirements given the maximum data rate, maximum number of HARQ processes and re-transmission formats. We analyze the requirements and discuss possible candidate architectures for three components.**

Keywords - Long-Term Evolution; LTE; WiMAX; Turbo decoder; HARQ; Forward Error Correction; FEC

I. INTRODUCTION

With high-speed broadband wireless service increasingly in demand, there have been two main emerging mobile broadband technologies: third generation partnership project (3GPP) Long-Term Evolution (LTE) [1-4] and mobile Worldwide Interoperability for Microwave Access (WiMAX) [5-6]. In both mobile-broadband wireless systems, the orthogonal-frequency-division multiplexing (OFDM)-based frequency-division multiple-access (OFDMA) technology is employed to schedule multiple mobile stations in a frame where each mobile station is assigned a subset of the sub-carriers for schedule, and each sub-carrier is scheduled exclusively to each mobile station.

Since multiple mobile stations are scheduled in one frame, a base-station (so called as “eNodeB” in 3GPP LTE [1]) transmits frame control information first at the beginning of each frame. The frame control information tells each mobile station in a cell whether it is scheduled in the current frame and how each mobile station decodes the data scheduled by a base-station. The control channel message is short (in the range of 32 ~ 71 bits [2]) in comparison with data channel message, and a convolutional code is employed in 3GPP LTE and WiMAX. The control channel is critical to decoding the data channel, and hence is protected via using low code-rate. The average throughput requirement of control channel decoder is not comparable to that of data channel decoder. The throughput for control channel dictates the amount of buffering in OFDMA modem because of delay in decoding control message. Modem cannot process data scheduled for each mobile station till the end of control channel decoding.

Once a mobile station figures out its schedule in the current downlink frame, a channel equalization module begins to process the sub-carriers scheduled for a mobile station out of received OFDM symbols. The peak throughput requirement for downlink data-channel is about 100 Mbps (Category 3) for 3GPP LTE [4] and 65 Mbps for WiMAX [5-6]. Since the application is for mobile devices, the key challenge for data channel decoder is to design low-power solution supporting such high throughput requirement.

The data scheduled for a mobile station is transmitted in packets which is medium-access-control (MAC) protocol data units (PDU). To guarantee the reliable data transmission over wireless channels, 3GPP LTE and WiMAX employ hybrid ARQ. A hybrid ARQ (HARQ) scheme [7] incorporates forward error correction code with the retransmission scheme to ensure reliable transmission of data packets. The fundamental difference in comparison with ARQ scheme is that hybrid ARQ combines the previous transmission data with subsequent retransmission data in order to improve reliability. But, to implement such hybrid ARQ protocol at a modem receiver, it has to store all transmitted data until one data packet is completely received and an acknowledgement message (ACK) is sent back to a base-station, leading to a large buffer requirement (a few Mega bits for 3GPP LTE [4]).

In this paper, we address the issues in designing downlink dual-mode (3GPP LTE and mobile WiMAX) forward error correction (FEC) architecture with focus on control channel decoder, high-throughput Turbo decoder, and hybrid ARQ combining. The remainder of this paper is organized as follows. Section II presents the downlink frame structure of 3GPP LTE and mobile WiMAX system. Section III addresses the control channel decoder architecture issues. We also discuss tail-biting Viterbi decoder implementation. Section IV presents dual-mode high-throughput Turbo decoder architecture supporting duo-binary WiMAX Turbo code and binary 3GPP LTE Turbo code. Section V discusses hybrid ARQ implementation issues by addressing how to manage the previous transmission data which directly impact on memory area and power consumption. Section VI summarizes the conclusions from this paper.

II. Frame Structure

In this section, we present the downlink frame structure of 3GPP LTE and WiMAX standards. Here, we consider frequency division multiplexing between uplink and downlink for 3GPP LTE and time division multiplexing between uplink and downlink for mobile WiMAX.

A. 3GPP LTE

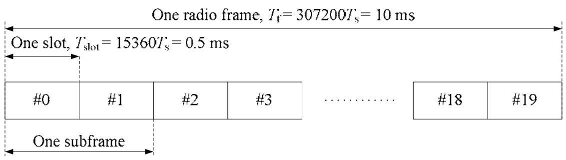

Figure 1 3GPP LTE Downlink Frame Structure [1]

Figure 1 shows 3GPP LTE downlink frame which is composed of 10 sub-frames and each sub-frame has 1m second period. For a normal cyclic-prefix (CP) uni-cast sub-frame [1], one sub-frame has 14 OFDM symbols and can carry 5 physical channels: physical broadcast channel (PBCH), physical control format indicator channel (PCFICH), physical hybrid ARQ indicator channel (PHICH), physical downlink control channel (PDCCH), and physical downlink shared channel (PDSCH). The PBCH is scheduled only in the first sub-frame of each radio frame and delivers system information per cell.

Given system information per cell, the PCFICH sub-carrier locations are known to all mobile stations in a cell and the decoded PCFICH message tells each mobile station how many OFDM symbols are scheduled for delivering control channels. 1, 2, or 3 OFDM symbols can be allocated for control channels (PCFICH, PHICH, and PDCCH). Once each mobile station decodes the PCFICH, it comes to know where the PDCCH and PHICH sub-carriers are scheduled and get ready to begin PHICH and PDCCH processing. The PHICH delivers ACK/NACK message on the uplink hybrid ARQ. The PDCCH carries control channel element (CCE) messages for multiple mobile stations and the control channel element (CCE) message decoded in a mobile station carries all the information by which the mobile station can decode the data-channel (PDSCH) scheduled for the current sub-frame. The PBCH and PDCCH are encoded via tail-biting convolutional code while the PCFICH and PHICH are coded via simple repetition codes [2].

B. Mobile WiMAX

Figure 2 shows one typical Mobile WiMAX frame structure for an example where one frame is divided into downlink and uplink frames. Each frame starts with Preamble symbol followed by the partial usage of sub-carriers (PUSC) zone where the frame control header (FCH) and downlink MAP (DL-MAP) bursts are scheduled. The FCH message is encoded via tail-biting convolutional code and delivers the size of DL-MAP burst in terms of the number of scheduled slots (a slot is a set of 48 sub-carriers spanning frequency and time in WiMAX frame) and DL-MAP encoding information (convolutional code or Turbo code). The FCH message is encoded via tail-biting convolutional code. Once the FCH message is decoded, each mobile station gets ready to decode the DL-MAP burst. It carries all information by which each mobile station can decode data scheduled for the current downlink frame. In mobile WiMAX, each data-channel is called as "data burst" [6] and each mobile station can have multiple data bursts per a downlink frame out of many data bursts as shown in Figure 2.

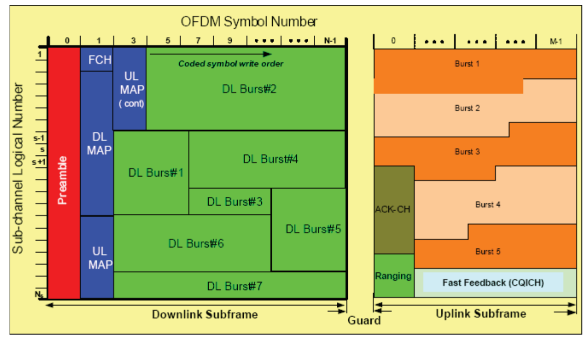

Figure 2 Mobile WiMAX Structure [6]

III. Control Channel Decoder

In this section, we present control channel decoder architecture requirement for 3GPP LTE and mobile WiMAX. Since the two standards employ different frame structure in order to deliver control channel message to each mobile station as described in Section II, the only common logic is the tail-biting Viterbi decoder which is used for WiMAX FCH and DL-MAP decoder (if DL-MAP is encoded via convolutional code) and 3GPP LTE PDCCH. Hence, the standard specific de-interleaving and de-scrambling sub-modules cannot be shared and 3GPP LTE PCFICH and PHICH decoders are not shared with mobile WiMAX, but the silicon area of these standard specific sub-modules is not comparable to that of tail-biting Viterbi decoder, where the constraint length (K) is 7 (64-state), in dual-mode control channel decoder implementation.

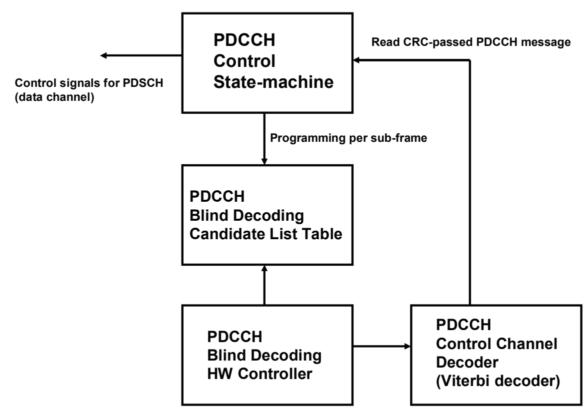

Figure 3 Data-path for 3GPP LTE PDCCH Blind Decoder

A. 3GPP LTE PDCCH Blind Decoding

In case of mobile WiMAX DL-MAP burst, each user can decode all the received codewords allocated in DL-MAP burst though some decoded codewords are other mobile station control messages [6]. But, for 3GPP LTE, each mobile station PDCCH location is scrambled at each sub-frame [3] and the control message is also scrambled using radio network temporary identifier (RNTI) of each mobile station. Hence, each mobile station is required to monitor all PDCCH candidates [3] and to run cyclic redundancy check (CRC) on each PDCCH codeword to find out the PDCCH control message allocated to each mobile station.

Figure 3 depicts the data-path for a blind decoder data-path. After a modem receiver decodes PCFICH which delivers the number of OFDM symbols for control channel, PDCCH control state machine generates possible PDCCH candidate list (at maximum 41 candidates [3]) and then blind decoder HW control dispatches each candidate codeword to tail-biting Viterbi decoder. The decoder output is passed to CRC logic and only if CRC is successful, then, the decoded message is employed to program the rest of the modem receiver to do further processing on PDSCH (data-channel).

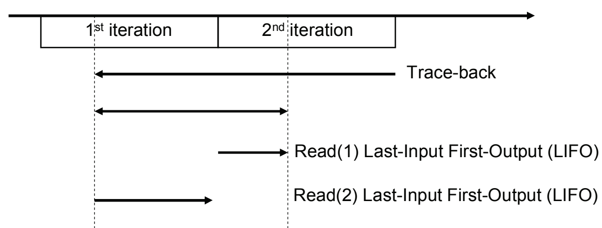

Figure 4 Tail-biting Viterbi Decoder Top-level Control

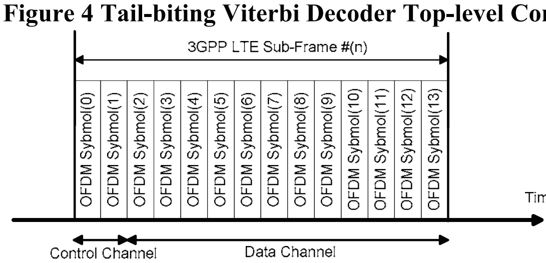

Figure 5 A 3GPP LTE sub-frame example where 2 OFDM symbols are allocated on control channel

B. TAIL-BITING VITERBI DECODER

3GPP LTE employs K=7 $[133,171,165]_8$ convolutional encoder with 1/3 mother code-rate [2] while mobile WiMAX employs K=7 $[171,133]_8$ convolutional encoder with 1/2 mother code-rate [6] and both employs tail-biting scheme. Hence, the Viterbi decoder supporting 3GPP LTE encoder can support mobile WiMAX by controlling branch metric computation due to mother code-rate mismatch. To decode the tail-biting encoded stream, we decide to run 2 iterations as shown in Figure 4. If N is the number of information bits in 3GPP LTE codeword, 3N soft-decision-bits (channel equalization output) are fed into tail-biting Viterbi decoder twice. Then, once we accumulate the path selection cost over 6N soft-decision-bits, we begin to trace back to find the maximum likelihood path. The very first a few decoded-bytes from tracing-back is not taken as decoded message since they are used for training-period to make the trace-back path be more reliable and the middle part of the traced-back path is the decoded output. If N=40, 80 bits are decoded from trace-back, the decoded 40-bit message is [41:56,17:40] out of [1:80] trace-back output as shown in Figure 4.

Although the number of decoded bits per one downlink frame is small, we have to define the Viterbi decoder architecture requirement by considering the impact of control channel decoder latency on receiver modem signal-processing chain. If the control channel decoding latency is 3 OFDM symbol period, a modem receiver has to buffer OFDM symbol (2) – (4) in Figure 5 until the control channel message is completely decoded because the data-channel (PDSCH) cannot be processed without control channel message. Hence, the smaller the latency is, the more the OFDM symbol buffer requirement is reduced. Another advantage of having smaller latency in case of no data-channel being allocated for the current sub-frame is that it can enable micro-power-management by shutting down some of receiver modem signal processing chains.

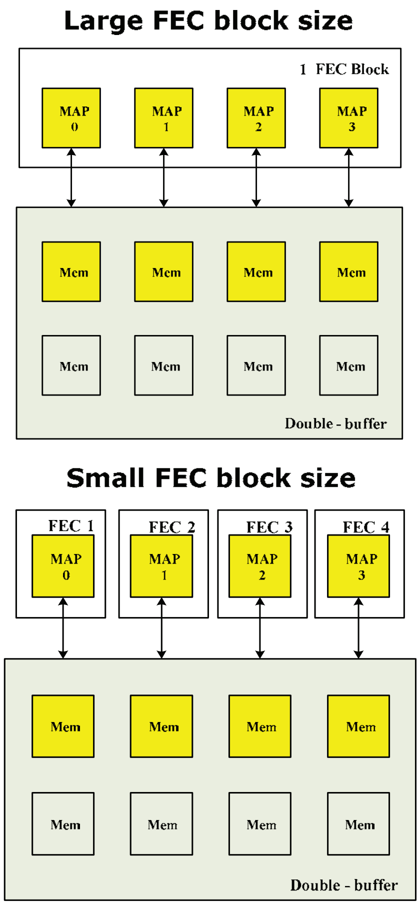

Figure 6 Codeword-size Scalable Parallel Turbo Decoder

IV. DATA CHANNEL DECODER

3GPP LTE employs Turbo encoder which is a parallel concatenated convolutional code (PCCC) with two 8-state constituent encoders (mother code-rate is 1/3) and one internal interleaver [2]. Mobile WiMAX adopts Turbo encoder which uses a double binary circular recursive systematic convolutional code (mother code-rate is 1/3) with one internal interleaver [6]. In this section, we present the architecture challenges to design high throughput (~100M bit per second for category3 3GPP LTE device [4]) Turbo decoder for dual-mode functionality with small overhead (less than 10%).

A. Codeword Scalable Parallel Turbo Decoder Architecture

To achieve high data rates [4], we adopt a parallel turbo decoder architecture. The issue in designing parallel turbo decoding architecture is known to be the interleaver parallelism due to the memory access collision issue. To address the data channel decoding throughput issue, both 3GPP LTE and mobile WiMAX employs "contention-free" interleaver [2,6] which enables one codeword to be divided into P sub-codewords and use P maximum *a posteriori* (MAP) decoders to decode each sub-codeword concurrently leading to P-level parallel architecture [8]. The parameter P can be tailored to a given codeword size. For smaller codeword, it was found out that P=1 decoding meets the throughput requirement with less logic complexity. There are several P values that can achieve the contention-free across all large codeword sizes. In our design, we decide the maximum parallelism to be P=4. The interleaver implementation issues and dual-mode MAP decoder data-path design were well addressed in [8]. As shown in Figure 6, we have P=4 memory banks and depending upon the codeword size, we configure P=4 MAP decoders accordingly to meet the throughput requirement for different codeword sizes. The designed dual-mode Turbo decoder has ~7.5% area overhead in comparison with a single-mode decoder [8].

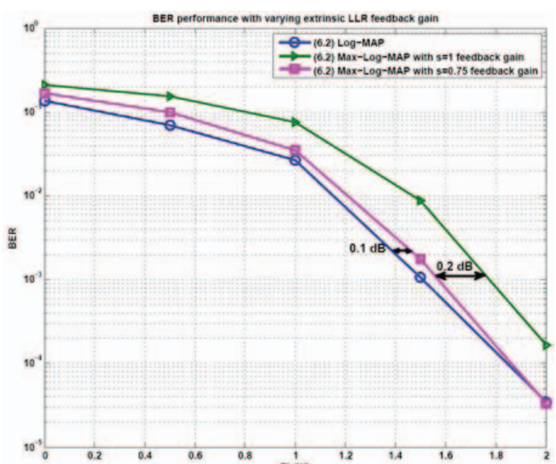

Figure 7 Simulation Result for Extrinsic LLR Scaling Method

B. Area Optimization

Though we design dual-mode Turbo decoder with limited overhead, we investigated some techniques to achieve further area-saving. When the MAP decoding kernel is designed, there are couple of implementation options on the function, $\log(e^a + e^b)$. In this work, we considered two options: Log-MAP where $\log(e^a + e^b) \approx \max(a,b) + C$ (C is a correction factor) and max-Log-MAP where $\log(e^a + e^b) \approx \max(a,b)$. If max-Log-MAP is used, the performance loss in comparison with Log-MAP is about 0.3 dB (Figure 7) with about 15% logic area saving. To reduce the performance gap against log-MAP decoder, we introduced a scaling factor on the extrinsic LLR values [9] as shown in Figure 8 resulting in 0.1 dB loss with 15% logic area saving. With this optimization for dual-mode Turbo decoder using max-Log-MAP, we could achieve silicon area which is comparable to Log-MAP single-mode Turbo decoder.

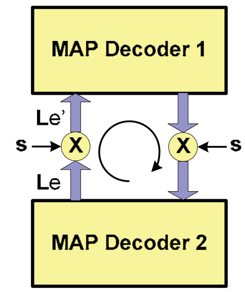

Figure 8 Extrinsic Log-Likelihood Ratio (LLR) Scaling Method

V. Hybrid ARQ

In this section, we discuss memory management issues in implementing hybrid ARQ functionality. Both 3GPP LTE and mobile WiMAX adopt hybrid ARQ scheme to enable reliable transmission [2, 6]. We developed a statistical buffering scheme to allow all the codewords from all the HARQ channels and processes to share the HARQ memory. In addition, LTE introduced a codeword CRC to improve the pipelining capability of the receiver chain. This codeword CRC may be exploited to gain additional benefit of HARQ memory and decoder power savings for LTE. Figure 9 shows one example scenario where one data channel in a sub-frame is composed of 3 codewords (CW1, CW2, and CW2) and the second codeword (CW2) fails in CRC. Hence, a mobile station sends back negative ACK (NACK) on the received data-channel message to a base-station. Then, a mobile station expects the base station to re-transmit the entire failed data-channel message though two codewords are successfully decoded at the mobile station.

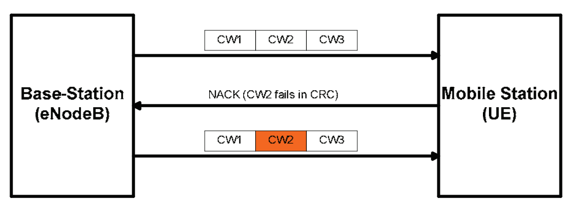

Figure 9 Example Case for Failed Data Transmission.

In order to combine the failed-transmission soft-decision bits (LLRs) with the re-transmission LLRs, a modem receiver has to store the LLRs of the failed-transmission in a buffer. For the example scenario of Figure 9, we have two options: to store three codeword LLRs or to store only the failed codeword (CW2) LLRs since CW1 and CW3 are successfully decoded. We implemented the second approach by instantiating two buffers: soft-bit buffer and re-sequence buffer as shown in Figure 10.

When each codeword is decoded and its CRC is checked, we stored the successfully-decoded (CRC-passed) codeword into the re-sequence buffer and the CRC-failed codeword LLRs into the soft-bit buffer. The mother code rate is 1/3 and the LLR of each received bit is assumed to have 6-bit precision. Hence, we need to store 1-bit per 1 information bit for the successfully-decoded codeword instead of storing 3 LLRs (18-bit) per 1 information bit. In addition to memory area saving, this scheme also saves dynamic power consumption of Turbo decoder since the successfully-decoded codewords (CW1 and CW3 in Figure 9) do not need to be re-decoded.

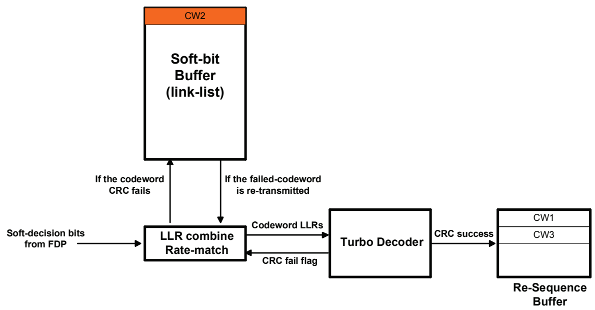

Figure 10 Hybrid ARQ Memory Management

VI. CONCLUDING REMARKS

We studied dual-mode forward error correction architecture to support two emerging OFDMA-based mobile wireless broadband access technologies: 3GPP LTE and WiMAX. We first identified three common sub-modules: control channel decoder, Turbo decoder, and HARQ combining. For control channel decoder, the dual-mode tail-biting Viterbi decoder was designed which runs two iterations. We also discussed the trade-off between Viterbi decoder complexity and OFDM buffer requirement caused by control channel decoding latency. For data channel decoder, dual-mode Log-MAP Turbo decoder was designed at 7.5% area overhead (in comparison to single mode decoder) supporting duo-binary WiMAX and binary 3GPP LTE Turbo codes. The designed parallel Turbo decoder throughput is scalable to the codeword sizes. We also proposed the area optimization techniques such as extrinsic value scaling which could achieve 15% area saving at the cost of 0.1 dB coding gain in case of AWGN channel. For HARQ, we present memory management scheme using re-sequence buffer which reduces the memory requirement by a factor of 18 in case of successfully-decoded codewords as well as the Turbo decoder dynamic power.

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