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ONLINE BIT ERROR RATE ESTIMATION-BASED STOPPING CRITERION FOR TURBO DECODING

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By

ROSLINA MOHAMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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This thesis is dedicated to

My parents, Mr Mohamad Bin Ali and Mrs Salmiah Binti Ellan, My late mother-in-law, Allahyarhammah Mrs. Faziah Binti Mohamad and father-in-law, Mr Mohamad Anas Bin Mahpoz

Whose affection, love, encouragement and prays of day and night make me able to get success. Without their love and support, this work would not have been possible.

My family, my lovely husband Mr Nuzli Mohamad Anas and my cutie son Nu'man Ramzi Bin Nuzli

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For giving me strength to reach for the stars and chase my dreams.

My niece and nephews, Misha, Imran, Ashman, Irfan and Irsyad.

Who have made my life brighter everyday.

"Read in the name of your Lord who created"
"Created man, out of a (mere) clot of congealed blood"
"Read, and your Lord is the most Generous"
"Who taught by the pen"
"Taught man that which he knew not."

(Holy Qur'an, 96:1-5)

The Prophet Muhammad (ﷺ – peace be upon him) said: "A servant of God will remain standing on the Day of Judgment until he is questioned about his (time on earth) and how he used it; about his knowledge and how he utilized it; about his wealth and from where he acquired it and in what (activities) he spent it; and about his body and how he used it."

(Tirmidhi, Hadith 148)

"I visualize a time when we will be to robots what dogs are to humans, and I'm rooting for the machines."

(Claude Shannon, Father of Information Theory)

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the Degree of Doctor of Philosophy

ONLINE BIT ERROR RATE ESTIMATION-BASED STOPPING CRITERION FOR TURBO DECODING

By

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April 2016

Chairman : Associate Professor Harlisya Harun, PhD
Faculty : Engineering

Iterative turbo decoding is crucial for achieving superior bit error rate (BER) performance. Nevertheless, each subsequent decoding iteration suffers from a high complexity in decoding system latency. Thus, convergence and non-convergence-output (CNCO) stopping criteria (CNCOSC) were developed. These stopping criteria can terminate with an optimal average iteration number (AIN) at various signal-to-noise ratios (SNRs). However, the threshold computation and termination rules in CNCOSC require an accurately estimated SNR, thereby increasing the complexity of the receiver. Thus, the aim of this thesis is to develop a low complexity and robust stopping criterion, referred to as the online BER estimation (OBE) stopping criterion (OBEsc), that works in a varying SNR environment and SNR mismatch, without requiring the knowledge of channel SNR. To achieve this particular target, the convergence and non-convergence behaviours of BER in iterative decoding are investigated. In addition, the enhancement of CNCO detection is formulated using the OBE algorithm. The study then develops BER thresholds calculation to determine the correct thresholds according to a given turbo code structure. Finally, termination rules based on the enhanced CNCO detection and BER thresholds are developed.

The results show that the OBEsc is capable of detecting the correct CNCO by achieving a lower AIN performance (the lowest AIN = 1) at a varying SNR environment than the benchmark stopping criterion (Bsc) while maintaining the BER performance. OBEsc is also capable of coping with the SNR mismatch by saving approximately 85.71% AIN compared to Bsc, and maintaining the earliest termination at low SNRs compared to the well-known CNCOSC. Furthermore, OBEsc has a better BER performance and faces a smaller BER performance degradation (less than 0.5 dB) than CNCOSC. This shows that OBEsc is capable of operating as a robust stopping criterion without requiring SNR estimation in its stopping rule. In terms of time taken for the predefined threshold simulation, the OBEsc possesses the lowest execution time of 1.59×10^4 seconds. The computational complexity of the OBEsc is the second lowest complex, only requiring around 2N+2 to 2N+14 real operations compared to the lowest and highest complexity of CNCOSC, which are N+1 and 7N+28 real operations, respectively. In addition, the OBEsc does not require the SNR estimator. Thereby, it significantly reduces complexity at the receiver compared to CNCOSC. The robust

performance of OBEsc indicates that it is better suited for use with a turbo decoder than CNCOSC in a varying SNR environment. At the same time, OBEsc can reduce the complexity in the receiver and decrease the delay in turbo iterative decoding.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KRITERIA PEMBERHENTIAN BERDASARKAN DALAM TALIAN ANGGARAN KADAR RALAT BIT UNTUK PENYAHKODAN TURBO

Oleh

ROSLINA MOHAMAD

April 2016

Pengerusi : Profesor Madya Harlisya Harun, PhD
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Penyahkodan lelaran turbo adalah penting untuk mencapai keunggulan prestasi kadar ralat bit (BER). Walau bagaimanapun, setiap penyahkodan lelaran berturutan terkesan daripada kerumitan yang tinggi dari segi kependaman sistem penyahkodan itu. Oleh itu, kriteria pemberhentian output tumpu dan tak tumpu (CNCOSC) telah dibangunkan. Kriteria pemberhentian ini mampu memberikan nombor purata lelaran (AIN) yang optimum pada pelbagai nisbah isyarat-hingar (SNRs). Namun, kerumitan pada penerima meningkat kerana ambang pengiraan dan syarat penamatan dalam CNCOSC memerlukan anggaran SNR yang tepat. Maka, tujuan tesis ini adalah untuk membangunkan kriteria pemberhentian yang berkerumitan rendah serta kukuh yang dipanggil sebagai kriteria pemberhentian anggaran BER (OBE) dalam talian (OBEsc). Ia berfungsi dalam persekitaran SNR yang berubah-ubah dan tidak sepadan tanpa memerlukan maklumat saluran SNR. Untuk mencapai sasaran berkenaan, kelakuan BER tertumpu dan tak tumpu dalam lelaran penyahkodan dikaji. Selain itu, penambahbaikan dari segi pengesanan CNCO dirumus dengan menggunakan algoritma OBE. Kemudian, kajian ini membangunkan tatacara pengiraan ambang BER untuk menentukan ambang yang betul berdasarkan struktur kod turbo yang diberikan. Akhir sekali, syarat penamatan telah dibangunkan berdasarkan pengesanan CNCO yang ditambah baik dan ambang BER.

Keputusan kajian menunjukkan bahawa OBEsc mampu mengenal pasti CNCO yang betul dengan mencapai prestasi AIN yang lebih rendah (AIN terendah = 1) dalam persekitaran SNR yang berubah-ubah berbanding penanda aras kriteria pemberhentian (Bsc), dan pada masa yang sama mengekalkan prestasi BER. OBEsc juga dilihat mampu menangani ketaksamaan SNR dengan menjimatkan lelaran kira-kira 85.71% AIN, berbanding Bsc dan mengekalkan penamatan terawal pada SNR yang rendah berbanding CNCOSC yang lebih terkenal. Tambahan pula, OBEsc memiliki prestasi BER yang lebih baik dan hanya mengalami sedikit kemerosotan BER (kurang daripada 0.5 dB) berbanding CNCOSC. Keputusan tersebut menunjukkan bahawa OBEsc mampu bertindak sebagai kriteria pemberhentian yang kukuh tanpa memerlukan anggaran SNR dalam syarat pemberhentiannya. Dari segi masa yang diambil untuk simulasi ambang yang telah ditetapkan, OBEsc mencatatkan masa pelaksanaan terendah: 1.59×10^4 saat. Tahap kerumitan pengiraan OBEsc berada pada tempat kedua

akhir, yang hanya memerlukan 2N+2 hingga 2N+14 operasi perpuluhan berbanding tahap kerumitan pada tempat terbawah (N+1) dan teratas (7N+28) CNCOSC. Tambahan pula, OBEsc tidak memerlukan penganggar SNR. Oleh itu, ia nyata mengurangkan kerumitan kepada penerima jika dibandingkan dengan CNCOSC. Kekukuhan prestasi OBEsc menunjukkan bahawa ia lebih sesuai digunakan pada penyahkod turbo berbanding CNCOSC dalam persekitaran SNR yang berubah-ubah. Pada masa yang sama, OBEsc boleh mengurangkan kerumitan pada penerima serta mengurangkan sela masa dalam penyahkodan lelaran turbo.

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I certify that a Thesis Examination Committee has met on 28 April 2016 to conduct the final examination of Roslina binti Mohamad on her thesis entitled "Online Bit Error Rate Estimation-Based Stopping Criterion for Turbo Decoding" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

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LIST OF ABBREVIATIONS

3G	Third Generation.
4G	Fourth Generation.
ADD	Addition/ Substraction.
AE	Average-Entropy.
AIN	Average Iteration Number.
AWGN	Additive White Gaussian Noise.
BER	Bit Error Rate.
BPSK	Binary Phase Shift Keying.
Bsc	Benchmark Stopping Criterion.
CCSDS	Consultative Committee for Space Data Systems.
CE	Cross-Entropy.
CECR	Constant Estimated Channel Reliability.
CMP	Comparison.
CNCO	Convergence and Non-Convergence Output.
CNCOSC	Convergence and Non-Convergence Output Stopping Criteria.
CO	Convergence Output.
COSC	Convergence Output Stopping Criteria.
CRC	Cyclic Redundancy Check.
DVB-RCS	Digital Video Broadcasting - Return Channel via Satellite.
DVB-RCT	Digital Video Broadcasting - Return Channel Terrestrial.
EXIT	Extrinsic Information Transfer.
ECE	Enhancement of CE.
EHDA	Enhancement of HDA.
ESA	European Space Agency.

ESCR	Enhancement of SCR.
FEC	Forward Error Correction.
FI	Fixed-Iteration.
GAMML	Gaussian Model Maximum Likelihood.
HDA	Hard-Decision-Aided.
HLS	Hoeher, Land and Sorger.
IHDA	Improved Hard-Decision-Aided.
IMDL	Improved Minimum Descriptive Length.
IOC	Input-Output Consistency Check.
LLR	Log-Likelihood Ratio.
log-MAP	Logarithm Maximum A Posteriori.
LTE	Long Term Evolution.
MAP	Maximum A Posteriori.
Max-log-MAP	Maximum Logarithm Maximum A Posteriori.
MDL	Minimum Descriptive Length.
ME	Mean Estimation.
MHDA	Modified HDA.
MinabsLLR	Minimum Absolute Value of LLR.
MOR	Measurement of Reliability.
MSC	Mean-Sign-Change.
MULT	Multiplication/ Division.
NASA	National Aeronautics and Space Administration.
OBE	Online Bit Error Rate Estimation.
OBEsc	Online Bit Error Rate Estimation Stopping Criterion.
PDF	Probability Density Function.
SCR	Sign-Change-Ratio.

SDR	Sign-Difference-Ratio.
SNRs	Signal-to-Noise Ratios.
SOVA	Soft-Output Viterbi Algorithm.
STR	Memory/ Storage.
TP	Turning Point.
TV	Interactive Television.
UMTS	Universal Mobile Telecommunications System.
VE	Variance Estimation.
VLSI	Very-Large-Scale Integration.
WiMAX	Worldwide Interoperability for Microwave Access.

LIST OF NOTATIONS

c_k	encoder input bit at time k
co	convergence stage
d	binary input
dB	pseudo unit "decibel"
$D(.)$	ratio of sign-differences
$E[.]$	mean function
g	generator polynomial
$H(.)$	entropy function
$H_{av}(.)$	average-entropy per bit function
$H_b(.)$	binary entropy function
ΔH_{av}	difference between average-entropy
i	iteration number
$i_{\max}$	maximum iteration number
$\hat{I}_{ex}$	mutual information between extrinsic output
I_{tp}	mutual information at TP
$J^{-1}(.)$	inverse J function
k	discrete-time index/ frame number index
K	constraint length
L_c	channel reliability value
$L_{ex(1)}$	extrinsic information LLR 1
$L_{\text{ex}(2)}$	extrinsic information LLR 2

$L_{llr(1)}$	*a posteriori* LLR 1
$L_{llr(2)}$	*a posteriori* LLR 2
m	final iteration number
$M(.)$	mutual information improvement function
$M_k(.)$	mutual information improvement per bit function
MDL(.)	MDL detection function
n	number index
nc	non-convergence stage
N	frame length/size
$p(.)$	belief in the estimated bits function
p_0	prescribed BER threshold
$\bar{p}_b$	BER estimation
p_b	mean of the bit error probability/OBE
$\tilde{p}_b$	OBE in $\log_{10}$
$\hat{p}_{b,k}$	estimated bit error probability at time k
$\Delta p_b^{(i)}$	OBE differences for two consecutive iterations
$\Delta\tilde{p}_b$	OBE differences for two consecutive iterations in $\log_{10}$
P_b	BER
$\tilde{P}_b$	BER in $\log_{10}$
$\lvert\tilde{P}_b\rvert$	absolute value of log P_b
$\Delta P_b^{(i)}$	BER differences for two consecutive iterations
$\Delta\tilde{P}_b^{(i)}$	BER differences for two consecutive iterations in $\log_{10}$

r_k	received signal at time k
R	code rate
$\boldsymbol{s}$	scaled bit vector/sequence
SNR_{fix}	fixed estimated SNR
SNR_{mis}	fixed SNR mismatch
Th	predefined threshold
Th_{ber}^{nc}	BER threshold at non-convergence stage
ΔTh_{ber}^{nc}	delta BER threshold at non-convergence stage
Th_{ber}^{co}	BER threshold at convergence stage
ΔTh_{ber}^{co}	delta BER threshold at convergence stage
Th_{ber}^{p}	BER threshold at peak point
w_k	AWGN signal at time k
y_k	transmitted BPSK modulation signal at time k
$\boldsymbol{z}$	turbo decoder output hard decision bit vector/sequence
z_k	turbo decoder output hard decision bit at time k
∂	gradient of the line graph at the ramp-up region
Δ	differences value
γ	reliability of LLR output
γ_e	reliability of extrinsic output
γ_k	reliability of LLR value at time k
κ	iteration number
$\mathcal{N}$	AWGN parameter
$\Re_n$	termination rule number

σ^2	noise variance/data variance
$\hat{\sigma}^2$	estimated variance
ω_{co}	constant value at convergence stage

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

A leading candidate of forward error correction (FEC) codes for superior performance near the Shannon capacity limit was introduced by Berrou et. al [1, 2], and it is known as turbo codes. Various fields, including deep-space and satellite communications, have extensively used them to reduce the error of probability in received data. Two important factors behind the success of turbo codes is due to iterative turbo decoding and maximum a posteriori (MAP) probability algorithm [3, 4]. However, the implementation of iterative turbo decoding with a MAP algorithm requires additional computations, high memory cost and decoding system latency [5-7]. In response, the stopping criterion is leveraged with optimized MAP algorithm (e.g., logarithm MAP (log-MAP)) for early termination in iterative decoding to achieve optimal iteration numbers while maintaining or having little degradation in turbo code performance [7, 8].

Iterative turbo decoding stopping criteria are mainly used in deep space, satellite, and wireless communication systems such as in the Consultative Committee for Space Data Systems (CCSDS) standard [9-11], digital video broadcasting - return channel via satellite (DVB-RCS) and digital video broadcasting - return channel terrestrial (DVB-RCT) standards [12-14], and third generation (3G) [15-18] and fourth generation (4G) [19-23] mobile telephony standards. In general, stopping criteria development aims to obtain quite similar performance as a fixed number of decoder iteration, reduce iteration numbers, and result in low complexity. Stopping criteria can be categorised according to the capability of early termination based on the detection of turbo decoder output conditions, including convergence output (CO) and convergence and non-convergence output (CNCO).

CO stopping criteria (COSC) can stop the iterative decoding early once they detect the convergence output, which occurs at high signal-to-noise ratios (SNRs). However, at low SNRs, the decoder cannot decode properly due to high noise and interference on the received data and produces the non-convergence output, which leads to a high error of probability. At this level, COSC fail to detect the non-convergence output, thus causing the decoder to iterate to the maximum iteration number. The maximum iteration number for a high error of probability leads to wastage in computational complexity, storage, and the speed of a turbo decoder at low SNRs.

In real-time application, especially for deep-space and satellite communication, the turbo decoder deals with a varying SNR environment, limitation in transmission power and long distance communication [10, 24, 25]. COSC do not suit use in a varying SNR environment, especially when the received data comes from low SNRs [6, 26]. Several CNCO stopping criteria (CNCOSC) such as measurement of reliability (MOR) [26], average-entropy (AE) [27] and improved minimum descriptive length (IMDL) [6] have been developed to detect non-convergence and convergence outputs and terminate the iterative decoding early to achieve good performance [6, 26].

1.2 Problem Statement

Correct threshold computation for accurate CNCO detection mainly determines the success of CNCOSC in terminating turbo iterative decoding early while maintaining the bit error rate (BER) performance in a varying SNR environment. There are two different types of thresholds: predefined thresholds and real thresholds. CNCOSC require the predefined thresholds which are computed either in an offline simulation (MOR and AE [26, 27]) or directly from real time implementation (IMDL [6]). These predefined thresholds are compared with the real thresholds (real-time computation) to stop the iterative decoding once a non-convergence or convergence output is detected.

However, the real thresholds computation for CNCO detection and termination rules in MOR [26] and AE [27] require an accurately estimated SNR channel. This requires an SNR estimation to be available at the receiver and will increase the complexity of the receiver itself. In addition, an inaccurately estimated SNR channel may occur resulting in an incorrect real threshold computation [28-31]. If an incorrect threshold is used in CNCOSC, there are two possible failures in CNCO detection [6, 16, 17, 31, 32]. First, it may cause the CNCOSC to detect the decodable output as a non-convergence output or convergence output and cease the iterative decoding too early. Second, the threshold can result in the CNCOSC detecting the convergence or non-convergence output as the decodable output and cause the decoder to iterate rather than terminate the iteration.

Although the IMDL proposed in [6] can compute thresholds without a known channel SNR, the complexity of the stopping criterion is high, especially at low SNRs, which may not be suitable in real-time applications. In addition, SNR estimation error (SNR mismatch) may happen [13, 29, 31] and lead to an incorrect threshold computation. This would increase the error of probability, resulting in additional computational complexity and delay the actual performance of the CNCOSC with the correct threshold.

1.3 Objectives of the Study

This thesis aims to develop a low complexity and robust stopping criterion that works properly in a varying SNR environment and SNR mismatch without requiring the knowledge of channel SNR for thresholds computation and termination rules through the following objectives:

1. Design and formulate an enhanced CNCO detection mathematical model based on the mean of bit error probability and online BER estimation (OBE) of the turbo decoder output.
2. Develop predefined thresholds computation, called as BER thresholds, determine and calculate the BER thresholds values.
3. Develop real thresholds computation and termination rules based on enhanced CNCO detection and BER thresholds.

1.4 Scope and Limitation of the Study

In this study, the development of the proposed stopping criterion is for the application of iterative turbo decoding (log-MAP decoder) in deep space, satellite and wireless communications communication specifically for a varying SNR environment. The channel in consideration is the additive white Gaussian noise (AWGN), which is an appropriate model for deep-space [33-35], satellite [11, 34, 36], and wireless [4, 13, 16] communications. AWGN has been used by most of the research [8, 11, 16, 17, 37] to test the capability of the stopping criteria. The proposed stopping criterion is evaluated based on same code structures and various frame sizes used for BER thresholds computation. The limitation of the study is BER thresholds used only for the tested specification (AWGN channel, code structure, frame size) of turbo codes since the BER performance of turbo codes varies according to noise channel, code structures and frame sizes [38, 39]. For other turbo code structures and specifications, such as decoding algorithm, interleaver type, and noise channel, the performance could either help or deteriorate performance. Repeating the computation and measurement can determine the correct BER thresholds for other turbo code structures. The performance of the proposed stopping criterion are only evaluated for the specific SNR ranges due to the fact that performance may worsen for higher SNRs due to the error floor existence in turbo codes [40-43].

1.5 Research Contributions

This research contributes to deep space, satellite and wireless communication systems based on iterative turbo decoding stopping criteria research as follows:

- The limitations of existing CNCO detection are identified and the enhanced CNCO detection mathematical model is formulated based on convergence and non-convergence behaviour of BER in iterative turbo decoding. The model can detect the CNCO accurately without requiring SNR information.
- The predefined thresholds computation is designed and determined based on BER information for CNCO detection. The computation is simple, accurate and requires less execution time and human effort compared to existing CNCOSC. The predefined threshold computation for non-convergence output is also designed. It is often difficult to accurately determine the thresholds at low SNRs.
- The real thresholds computation and termination rules are developed for OBE based stopping criteria to stop iterative decoding in a varying SNR environment without requiring known channel SNRs in thresholds computation and in termination rules.
- A low complexity and robust CNCOsc, based on OBE, is developed. The proposed stopping criterion is effective in a varying SNR environment, as well as in an SNR mismatch situation. The stopping criterion is also the most robust stopping criterion as compared to existing CNCOSC and has low complexity at both offline and online simulation stages.

1.6 Thesis Outline

This thesis consists of five chapters. Chapter 1 introduces turbo codes and the stopping criteria, the background of the problem, objectives, scope and limitation of this study, and research contributions.

Chapter 2 reviews the history and development of turbo codes, discusses the process of iterative turbo decoding, the application of stopping criteria in communication systems and the benchmark of stopping criteria, such as Genie and fixed-iteration (FI).

Moreover, the chapter presents a brief review of COSC and CNCOSC, development processes, and performances; presents the algorithm and rules for CNCOSC; and discusses the potential of OBE as a stopping criterion. Finally, this chapter investigates the problems in CNCO detection in iterative decoding and introduces alternate method to solve the problems, by investigating the non-convergence and convergence behavior of proximity of BER.

Chapter 3 presents the design process of the enhanced CNCO detection mathematical model based on OBE of the turbo decoder output as well as the development of BER thresholds computation. Toward the end, the chapter discusses the real thresholds computation, termination rules and early stopping strategy of the proposed stopping criterion.

Chapter 4 presents the simulation results of BER thresholds and the performance of proposed stopping criterion. Comparative study on the robustness performance of the proposed stopping criterion and CNCOSC, computational complexity and the performance of the stopping criterion in deep-space communication are also evaluated and discussed. Lastly, Chapter 5 offers a conclusion and recommendations for future work.

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