EXPLOITING 2-DIMENSIONAL SOURCE CORRELATION IN CHANNEL DECODING WITH PARAMETER ESTIMATION FOR UNKNOWN SOURCE

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To my beloved wife, family, friends and teachers

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ABSTRACT

Source redundancy does not contain any significant information for transmission in a communication system and therefore, one of the approaches to overcome this issue is by exploiting the source redundancy for error-correction via Joint Source Channel Coding (JSCC) design. Existing JSCC systems were developed to exploit 1-Dimensional (1D) correlation exhibited by a source and later, a JSCC system exploiting 2-Dimensional (2D) source correlation known as the 2D JSCC system was introduced and had been proven to outperform the 1D JSCC system in terms of Bit Error rate (BER). However, the source correlation knowledge in the 2D JSCC system has been assumed to be perfectly known at the receiver. In a real communication system, source correlation knowledge may not always be available and thus, this research aims to develop a high performance 2D JSCC system for the unknown source correlation knowledge. A parameter estimation technique had been developed based on the Baum-Welsh algorithm and employed jointly with iterative channel decoding. Simulation results revealed that the proposed 2D JSCC system with parameter estimation (2D-JSCC-PET1) for an unknown source correlation knowledge can achieve performance very close to the ideal 2D JSCC system with a known source correlation knowledge by a difference of 0.05 dB. Furthermore, the proposed 2D-JSCC-PET1 system outperformed the benchmark 2D JSCC system using a different estimation technique (2D-JSCC-PET2) by 0.84 dB at a source correlation of $p = 0.7$ and the performance difference became larger with the increase of source correlation strength. The effectiveness of the proposed 2D-JSCC-PET1 system is demonstrated through image transmission simulations and the simulation results reveal that despite the correlation knowledge is unknown, the proposed 2D-JSCC-PET1 system can perform very close to the ideal 2D JSCC system with only 0.26 $\%$ and 0.06 $\%$ difference in Pixel-error percentage for an image exhibiting strong and weak correlation, respectively.

ABSTRAK

Sumber berulang tidak mengandungi sebarang maklumat penting untuk penghantaran dalam sistem komunikasi dan oleh itu, salah satu pendekatan untuk mengatasi masalah ini adalah dengan memanfaatkan sumber berulang untuk pembetulan ralat melalui reka bentuk Pengkodan Sumber Bersama (JSCC). Sistem JSCC yang sedia ada telah dibangunkan untuk mengeksploitasi korelasi 1-Dimensi (1D) yang dipamerkan oleh sumber dan kemudian, sistem JSCC mengeksploitasi korelasi sumber 2-Dimensi (2D) yang dikenali sebagai sistem JSCC 2D telah diperkenalkan dan ia telah terbukti dapat mengatasi sistem JSCC 1D dari segi Kadar Ralat Bit (BER). Walau bagaimanapun, pengetahuan sumber korelasi dalam sistem JSCC 2D diandaikan telah diketahui dengan sempurna di penerima. Dalam sistem komunikasi yang sebenar, pengetahuan sumber korelasi tidak selalunya diketahui dan oleh itu, penyelidikan ini bertujuan untuk membangunkan sistem JSCC 2D berprestasi tinggi untuk maklumat korelasi sumber yang tidak diketahui. Teknik penganggaran parameter dibangunkan berdasarkan algoritma Baum-Welsh dan digunakan bersama dengan penyahkodan saluran berulang. Hasil simulasi menunjukkan bahawa sistem JSCC 2D yang dicadangkan dengan teknik anggaran parameter (2D-JSCC-PET1) untuk maklumat korelasi sumber yang tidak diketahui dapat mencapai prestasi yang sangat baik dengan sistem JSCC 2D yang ideal dengan maklumat korelasi sumber yang diketahui dengan hanya perbezaan 0.05 dB. Tambahan pula, sistem 2D-JSCC-PET1 yang dicadangkan dapat mengatasi sistem penanda aras JSCC 2D yang menggunakan teknik penganggaran yang berbeza (2D-JSCC-PET2) sebanyak 0.84 dB pada korelasi sumber p = 0.7 dan perbezaan prestasi mereka menjadi lebih besar dengan peningkatan kekuatan korelasi sumber. Keberkesanan sistem 2D-JSCC-PET1 yang dicadangkan dapat dibuktikan melalui simulasi penghantaran gambar dan hasil simulasi menunjukkan bahawa walaupun pengetahuan sumber korelasi tidak diketahui, sistem 2D-JSCC-PET1 yang dicadangkan dapat menyaingi sistem 2D JSCC yang ideal dengan perbezaan hanya 0.26% dan 0.06% perbezaan dalam peratusan ralat piksel untuk imej yang menunjukkan korelasi yang kuat dan lemah.

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LIST OF ABBREVIATIONS

1D	-	1-Dimensional
2D	-	2-Dimensional
2D-JSCC-PET1	-	2D JSCC System with the Parameter Estimation Technique 1
2D-JSCC-PET2	-	2D JSCC System with the Parameter Estimation Technique 2
3G	-	Third Generation
4G	-	Fourth Generation
5G	-	Fifth Generation
ARQ	-	Automatic Repeat Request
ASCII	-	American Standard Code for Information Interchange
AWGN	-	Additive White Gaussian Noise
BCH	-	Bose-Chaudhuri-Hocquenghem
BCJR	-	Bahl-Cocke-Jelinek-Raviv
BER	-	Bit Error Rate
BPSK	-	Binary-Phase-Shift-Keying
BWA	-	Baum-Welch Algorithm
CCC	-	Constellation Constraint Capacity
CMC	-	Coupled-Markov-Chain
CSI	-	Channel State Information
DCT	-	Discrete Cosine Transform
DPCM	-	Differential Pulse Code Modulation
DRI	-	Decoder Reliability Information
DVC	-	Distributed Video Coding
EBCDIC	-	Extended Binary Coded Decimal Interchange Code

EM - Expectation-Maximization

EXOR - Exclusive OR

FEC - Forward Error Correction

FLC - Fixed Length Codes

FTN - Faster-than-Nyquist

HMM - Hidden Markov Model

ISCD - Iterative Source-Channel Decoding

JPEG - Joint Photographic Expert Group

JSCC - Joint Source Channel Coding

KLT - Karhunen-Loéve Transform

LDPC - Low-Density Parity-Check

LLR - Log-Likelihood Ratio

LPC - Linear Predictive Coding

MAP - Maximum A Posteriori

MD - Multi-Dimensional

MEX - MATLAB Executable

MPEG - Moving Picture Experts Group

PCM - Pulse Code Modulation

PET1 - Parameter Estimation Technique 1

PET2 - Parameter Estimation Technique 2

PSNR - Peak-Signal-Noise-Ratio

RSCC - Recursive Systematic Convolutional Code

SAI - Source A posteriori Information

SNR - Signal-to-Noise Ratio

SPCC - Single Parity Check Code

SSI - Source Significance Information

TSPCC - Turbo Single Parity Check Code

VLC - Variable-Length Codes

LIST OF SYMBOLS

A - 2D matrix of Markov transition probabilities distribution

a - Markov transition probability

$\hat{a}$ - Estimated Markov transition probability

B - HMM observation symbol probability distribution

b - HMM observation symbol probability at state j

$\hat{b}$ - Estimated HMM observation probability

$\mathbf{c}$ - Vector of encoded sequence

c - Coded bit after inner encoder

C - Channel code

C^{-1} - Channel decoder

C^{cap} - Capacity of the channel

C_{in} - Inner channel code

D - Direction of the source correlation

E_b - Energy per bit

G - Generator polynomial for convolutional codes

$\mathbf{g}$ - vector of transmitted signal

$H(.)$ - Entropy

i - Binary value emitted from previous Markov state

j - Binary value emitted from current Markov state

k - Index

K - Length of information bits that input to a channel encoder

K_{UT} - Total frame length of information bits

K_D - Length in bits for a specific dimension of a 2D source

l - Index used for addressing the component code of a TSPCC

$L(.)$ - LLR

$L_{app}(.)$ - *A posteriori* LLR

$L_a^l(.)$ - *A priori* LLR inputs from other TSPCC component decoders to TSPCC component decoder

$L_a^i n(.)$ - *A priori* LLR inputs to inner decoder

$L_a^{l,in}(.)$ - *A priori* LLR inputs from inner decoder to component decoder l of TSPCC

$L_e(.)$ - Extrinsic LLR output

$L_e^i n(.)$ - Extrinsic LLR outputs from inner decoder

M - Index

N - Codeword length of a channel code

$\mathbf{n}$ - A vector of AWGN samples

N_0 - Noise power spectral density

N_s - Length of bit in coded sequence output

N_ψ - Number of possible transmitted symbols

o_t - Current parameter vector of HMM observation symbol

p - Transition probability for symmetric Markov source

$P(.)$ - Probability

$\hat{p}^D$ - The estimated transition probability at specific dimension of 2D source

p_0 - Transition probability from Markov state S_0 to state S_0

p_1 - Transition probability from Markov state S_1 to state S_1

P_e - Probability of error

$q(.)$ - Known input

$\mathbf{r}$ - Vector of received signals after demodulation

R_c - Coding rate for channel coding

S - Set of trellis state

s	-	Trellis state
S_0	-	State that corresponds to bit 0
S_1	-	State that corresponds to bit 1
t	-	Time index
u	-	Information bit
U	-	Random variable of a source
$\mathbf{u}$	-	Vector of information bits u
$\hat{u}$	-	Estimated information bit u
V	-	Set of the observation symbol
v	-	Parity bit sequence
$\mathbf{w}$	-	Vector of coded bit sequence
$\mathbf{z}$	-	Vector of received signals from a channel
α	-	Trellis forward state probability
β	-	Trellis backward state probability
γ	-	Trellis state transition probability
δ_{min}	-	Minimum Hamming distance
$\epsilon(t)$	-	Observed state
λ	-	A set of an HMM
μ	-	Stationary state distribution for a Markov chain
$\mu(t)$	-	Output state
μ_0	-	Stationary state distribution corresponds to bit 0
μ_1	-	Stationary state distribution corresponds to bit 1
ν	-	Observation symbol
ξ	-	Joint probability of 2D Markov source
Π	-	Interleaver
π	-	Initial probability distribution over states
ϖ	-	The marginal probability of 2D Markov source
Π_2	-	Block Interleaver
Π^{-1}	-	De-interleaver

Π_{in}	-	Random interleaver separating outer code (e.g., TSPCC) and inner code
Π_{in}^{-1}	-	De-interleaver between outer code (e.g., TSPCC) and inner code
σ^2	-	Variance of a noise distribution
Υ	-	Constraint length of the encoder memory
ψ	-	Transmitted symbol

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CHAPTER 1

INTRODUCTION

1.1 Background

People began to communicate long distance using wireless since the electromagnetic wave technology was introduced via the development of wireless telegraph system in 1894 by Guglielmo Marconi. This technology has brought a lot of benefits to people to convey their message in a reliable and efficient way. Wireless technologies, such as Third Generation (3G) and Fourth Generation (4G) have helped people to transfer information that require a lot of memory, such as videos and images, at a transfer rate up to 2 Mb/s. Furthermore, the current development of Fifth Generation (5G) technology can transmit large data that requires a huge memory to be processed in the blink of an eye with data rate up to 10 Gb/s.

However, regardless of how advanced the technology is, there is still a constraint. The speed to transmit information still has a limit and the limit is given by the Shannon's capacity theorem which implies that transmission without error can only be achieved if the entropy of the information is lower than the channel capacity [1]. In real communication systems, especially within urban area, distortion such as noise and interferences may occur and this leads to the error in the transmitted data at the receiver. Therefore, in a communication design, source and channel coding are used to overcome this issue. Source coding allows only necessary information to be transmitted by compressing the data while channel coding protects the data from noise and corrects the errors in the affected data at the receiver. Source and channel coding have been improved over the years including the advent of turbo codes which demonstrate very high performance near to the Shannon's limit [2].

Source and channel coding can be designed separately to obtain reliable transmission without loss in overall performance including zero delay as stated by Shannon's separation theorem [1]. However, it is not possible to achieve the ideal performance with zero delay as restriction on latency definitely occurs. One of the approaches is exploiting the redundancy left in source encoders [3]. Therefore, the Joint Source and Channel Coding (JSCC) was introduced and well adopted in many applications such as video transmission [4, 5] and image transmission [6]. The JSCC system also has been shown in many research works using binary Markov source [7–10] and Hidden Markov Model [11, 12]. In a JSCC system, source coding removes any redundancy that is unnecessary information to compress the data sequence while channel coding adds redundancy for error correction of the data sequence.

In previous research [13–15], 2-Dimensional (2D) source correlation was exploited in a JSCC system and utilized in the system design to improve Bit Error Rate (BER) performance. However, these studies assumed that the source correlation knowledge is perfectly known at the receiver. This assumption improves the performance, but it affects the reliability of the information of source correlation to be exploited at the receiver. Practically, source correlation knowledge is unknown and needs to be estimated. Thus, many researchers have taken up this issue and developed various parameter estimation techniques to estimate the source correlation at the receiver to ensure the performance is improved and applicable in real practices. This research looks into this problem by estimating the source correlation specifically on the 2D source correlation of binary Markov sources.

1.2 Problem Statement

A JSCC system has been investigated and implemented in many research and has shown capability of considering jointly the source and channel properties in a communication system [7–10]. At the receiver, the JSCC system utilizes the residual redundancy left in the compressed bit stream by a source encoder at the channel decoder. The residual redundancy appearing in the bit stream is used to decrease the search space for the encoded source sequences.

The existing JSCC works [7–10] considered 1-Dimensional (1D) source correlation to be exploited at the receiver. However, several studies [13–15] have suggested that the system performance can be improved if the multi-dimensional source correlation, for example 2D source correlation, is exploited. The exploitation of source redundancy in 2D could provide more knowledge of the sources as compared to the 1D source correlation. As an example, the 2D source correlation knowledge has the information of the source correlation in the horizontal and vertical directions. Hence, the knowledge of the sources from both directions can be utilized to improve the capability of the error correction and further improve the system performance. The JSCC system exploiting the 2D source correlation or also known as the 2D JSCC system has been done in previous work of [14] using high rate Turbo Bose-Chaudhuri-Hocquenghem (BCH) codes and showed that this coding scheme outperforms the 1D source correlation and other conventional systems without exploiting source correlation.

The existing works on 2D JSCC systems of [13–15] assumed that the knowledge related to the source correlation such as the transition probabilities are known and perfectly available at the receiver and thus, ensuring the system achieves optimum performance. However, in reality, this source correlation knowledge is unknown and needs to be estimated. Furthermore, achieving ideal performance is difficult due to the existence of noise and fading effect in the channel. Hence, the reliability of the results cannot be guaranteed.

Several methods of parameter estimation have been presented in various studies based on a Hidden Markov Model (HMM) such as the Baum-Welch Algorithm (BWA) [11, 12] This enables the decoder to utilize the estimated statistics of the source correlation knowledge in channel decoding to improve the system performance. However, previous works on parameter estimation techniques [12, 16] were only developed for 1D source correlation. Despite the good performance of the HMM, the complexity and memory requirements are disadvantageous for actual applications.

This research addresses the mentioned concerns and investigates a parameter estimation technique using the BWA for the 2D JSCC system for unknown source correlation knowledge.

1.3 Research Objectives

The primary aim of this research is to develop a high performance JSCC system exploiting 2D source correlation in channel decoding for unknown source correlation knowledge at the receiver. To achieve this primary aim, the following specific objectives are derived:

1. To investigate on parameter estimation techniques for 2D JSCC systems.
2. To develop a parameter estimation technique for the 2D JSCC system with unknown source correlation knowledge performing near to the ideal 2D JSCC system with known source correlation knowledge.
3. To evaluate the effectiveness of the proposed 2D JSCC system assisted with parameter estimation by image simulations.

1.4 Scope of Research

The research aims to design and propose a 2D JSCC system with parameter estimation for unknown source correlation knowledge. The proposed 2D JSCC system is implemented on an Additive White Gaussian Noise (AWGN) wireless channel with Binary-Phase-Shift-Keying (BPSK) signaling. The binary sources are considered and characterized using the first-order Markov chain.

The proposed estimation technique is based on the BWA to achieve a near optimum performance system approaching the ideal system of known source correlation knowledge. The modified Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm as derived in [14] is used at the receiver for the proposed 2D JSCC system to exploit the source correlation during channel decoding providing the information about the source. The performance of the proposed system is simulated using the MATLAB software.

The BER performance is evaluated and compared to various systems including the 2D JSCC system with the perfect assumption on source correlation knowledge known as the ideal 2D JSCC system, the 2D JSCC system with different estimation technique, the 2D JSCC system without parameter estimation and the non-JSCC system. The efficiency of the proposed JSCC system is demonstrated via simulations of image transmission.

1.5 Research Contribution

The contributions of this research can be listed as follows:

1. Investigation on parameter estimation techniques for JSCC and 2D JSCC systems [17].
2. Development of an accurate parameter estimation technique for the 2D JSCC system with unknown source correlation knowledge [17].
3. Development of the high performance 2D JSCC system with the implementation of combined parameter estimation technique blocks for unknown source correlation knowledge [17].
4. Development of the high performance 2D JSCC system with parameter estimation for unknown source correlation knowledge performing very close to the ideal 2D JSCC system with the increasing number of iterations [17].
5. Demonstration of the effectiveness of the proposed 2D JSCC system with parameter estimation for unknown source correlation knowledge via image transmission for image with strong correlation and image with weak correlation [18].

1.6 Structure of the Thesis

The thesis consists of six chapters and it is structured as follows:

Chapter 2 investigates and reviews the background and previous works related to this research. The overview and implementation of source and channel coding are described. The basic concept of JSCC is presented together with the various types of JSCC methods. The different types of JSCC techniques and the latest works related to JSCC are studied and reviewed. The concept of 2D source correlation used in a JSCC technique is explained based on previous works related to JSCC. Also, different parameter estimation techniques are reviewed along with the examples of parameter estimation techniques that have been used in HMM.

Chapter 3 presents the overview of the proposed system model used throughout the thesis. The methodology of this research is presented in the form of a flowchart in this chapter. The proposed system design, including the model of the transmitter and receiver are briefly introduced. An iterative decoder is invoked to decode and recover the original source. The metrics used to measure the performance of the proposed system are presented.

Chapter 4 proposes the 2D JSCC system with parameter estimation. The source model, which is based on the first order Markov process, is described. The proposed 2D JSCC system with parameter estimation is thoroughly elaborated in this chapter. The algorithm to estimate the correlation parameter is detailed. The performance of the proposed system with unknown source correlation knowledge is compared to the ideal 2D JSCC system with perfect assumption on the availability of the source correlation knowledge at the receiver. The proposed 2D JSCC system is also compared with the 2D JSCC system relying on a different estimation technique, the 2D JSCC system without employing any parameter estimation technique and the non-JSCC system.

Chapter 5 demonstrates the effectiveness of the proposed system via image simulations using two image tests. The first image test considers the transmission of an image exhibiting weak correlation while the second image test considers the transmission of an image exhibiting strong correlation. The proposed system is then compared to other systems in terms of the quality of the decoded images.

Chapter 6 summarizes the thesis and suggests potential future works.

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