A Study of Variable Length Error Correcting Codes and Reversible Variable Length Codes: Analysis and Applications

Synopsis of the Thesis submitted in fulfillment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

By

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May 2013

DECLARATION BY THE SCHOLAR

I hereby declare that the work reported in the Ph.D. thesis entitled **"A Study of Variable Length Error Correcting Codes and Reversible Variable Length Codes: Analysis and Applications"** submitted at **Jaypee Institute of Information Technology, Noida, India,** is an authentic record of my work carried out under the supervision of **Prof. N. Kalyanasundaram** and **Prof. Bhudev Sharma**. I have not submitted this work elsewhere for any other degree or diploma. I am fully responsible for the contents of my Ph.D. Thesis.

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SUPERVISOR'S CERTIFICATE

This is to certify that the work reported in the Ph.D. thesis entitled **"A Study of Variable Length Error Correcting Codes and Reversible Variable Length Codes: Analysis and Applications"**, submitted by **Richa Gupta** at **Jaypee Institute of Information Technology, Noida**, **India,** is a bonafide record of her original work carried out under our supervision. This work has not been submitted elsewhere for any other degree or diploma.

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1. Introduction

Coding Theory has its roots in the pioneering work of Shannon on Communication Theory [1]. During the past 65 years, it has emerged as a major discipline for research, study and application. This is, in a large measure, due to (i) the tremendous growth in communications technology and (ii) the elegant Mathematics which could be used in this branch. Coding has acquired added importance with increasing demands made on it by applications in computers, space communication and distant control systems and electronic devices. Codes are used for data compression, cryptography, error correction and more recently also for network coding. Codes are studied by various scientific disciplines – such as Information Theory, Electrical Engineering, Mathematics and Computer Science – for the purpose of designing efficient and reliable data transmission methods.

Studies in coding initially branched into two directions, one being for noiseless channel and the other for noisy channels. The studies in Noiseless Coding matured quite early. These codes were of variable length. The Kraft inequality is a significant result of the early period [2]. McMillan later extended the result for uniquely decodable codes. Huffman's construction method for optimal instantaneous codes practically answered all questions in the search for the most efficient codes for noiseless channels [3]. The other direction in which the coding developed was the area of error correcting codes, i.e. the coding for noisy channels.

In contrast to constant length codes, the developments in the study of variable length codes for noisy channels have shown little growth, while most of the time we have variable length messages for example password for a file to be opened, messages (voice or text) on a mobile to be sent, data in a file on a computer etc. and moreover there is unwanted redundancy in making the words of constant length. This may be attributed to two major causes, namely

1. *Lack of mathematical tools:* Mathematical techniques, in particular, the algebraic methods that influenced the development of constant length coding, were unavailable for variable length codes. Combinatorial search also lagged behind as algebraic search for constant length codes was kept in focus;

2. *Limited applications:* Asynchronous character inherent in variable length coding schemes required the use of storage buffers for data channels which support data transmission at fixed rates.

The first impediment, the lack of Mathematical tools has continued to be somewhat a significant factor. The algebraic structure and the combinatorial types of results, which played key roles in the development of constant length error correcting codes, are still challenging for variable length codes (VLCs). With the stride in data communications technology, the second impediment is no longer formidable; the asynchronous character of variable length coding seems to be no longer a disadvantage. Indeed variable length codes have found application in communication systems such as Packet Switched Networks and Time Division Multiplexers that gather data transmitted over high speed synchronous channels [4].

Variable-length codes are often associated with channel coding techniques [5] [6] which combine error correction with data compression. Implementing these two operations separately from each other is a direct consequence of Shannon's well known *Separation Theorem* [1], which states that the two operations can be done separately without asymptotic performance loss. However, this theorem neither holds for some classes of sources and/or channels, nor does it offer any guarantee in terms of complexity and practical feasibility. In providing his results, Shannon assumed that we have infinite resources available with us and channel and source are fully known. That is, we can use as much data rate or bandwidth as we desire, can transmit as much power as is required and the delay in transmission of the signal from transmitter to the receiver can be infinitely large. In practical communication systems, mostly there are constraints on available resources. Some of these are as follows:

1. We may be given an upper limit on the maximum permissible delay as for the real time systems,
2. We may have limited power for transmission as in the case of mobile transmitter or in power limited channels,
3. We can use only limited data rate,
4. We can use only limited bandwidth for data transmission,
5. We may deal with non-stationary sources,
6. We may have non-stationary channels,

7. We may not have asymptotically large block of data always available with us for the approximation.

In fact, in most practical communication systems, operating frequency, bandwidth and maximum transmit powers are decided by the regulation authorities in a country [7]. For example, in India, this is regulated by the Wireless, Planning and Coordination Wing of the Ministry of Communications, Government of India and in USA by FCC (Federal Communications Commission). Video Telephony, video conferencing and video-on-demand are the applications with tight delay constraints. Also fading and jamming are some of the impairments under which the statistical description of the channel available to us may be incomplete and thus the source coder may not be able to do a perfect job. Thus the Separation Theorem is not valid for all the above conditions. As we try to operate under more and more restrictive conditions, the separation does not make as much practical sense. It has been mentioned that the Separation Theorem does not hold for all channels. Where it does hold, it requires the use of an optimal source coder channel coder pair which may not be feasible in practice. The solution for these types of problems of channel and source characteristics can be solved by using Joint Source Channel Codes (JSCC). JSCC jointly optimizes both the source code and the channel code. The idea of JSCC has been gaining increasing attention in the recent years.

As briefly given above, some examples of resource constraints include: rate or bandwidth for a data systems, complexity for low cost systems, power for hand held devices, and delay for real-time systems. Joint Source Channel Coding would yield performance improvements in such cases by allowing optimal allocation of a user's resources between the source code and the channel code [8].

Since the aim of source coding is to remove redundancy in the data to be transmitted and the aim of channel coding is to reintroduce redundancy to make the transmitted data error correctable, it requires investigation how to efficiently combine the two techniques to improve the overall system while keeping an acceptable level of complexity [9] [10] [11]. Among the joint coding proposed solutions, one finds the Variable-Length Error Correcting-Codes (VLECs) [12] [13], which offer compression capability simultaneously providing error correction [14]. Another direction in which the codes can be designed is the construction of variable length codes which are resilient to channel errors. These types of codes have been proposed by Takishima in 1995 and have been named as Reversible Variable Length Codes (RVLCs) [15]. RVLC is nowadays being used in several multimedia applications like image compression, video compression and others [9] [16] [17] [18]. This thesis deals with the following two types of joint source channel codes:

1. Variable Length Error-correcting Codes (VLECs);
2. Reversible Variable Length Codes (RVLCs).

The areas of Variable Length Error Correcting-codes and Reversible Variable Length Codes have attracted attention of many researchers. A breakthrough in extending some of the ideas of variable-length noiseless concepts for noisy case was made in Hartnett [19]. A systematic study leading to combinatorial results and VLEC codes was undertaken by Bernard and Sharma [20] [21]. Some of the developed codes and combinatorial results have been referred in the doctoral theses Bernard [22] and Buttigieg [12]. Although, a breakthough was made by Bernard and Sharma, but the area is open.

As mentioned earlier also, to add error resiliency to the data to be transmitted over a noisy channel, RVLCs are nowadays being widely used in multimedia applications. At present, MPEG-4 and H.263++ (and onwards) video coding standards are using RVLCs in place of simple entropy encoder. There is a lot of scope of further research in this area.

Some open problems related to the areas of RVLCs and VLECs are as follows:

1. Study of some more combinational results;
2. Development of special purpose compact Variable Length Error-correcting Codes;
3. Construct an algorithm for Variable Length Error-correcting Codes;
4. Develop a decoding algorithm for Variable Length Error-correcting Codes;
5. Construction of Huffman independent (or may be Huffman dependent) RVLC generating algorithm;
6. Decoding algorithm for RVLCs;
7. Combinatorial bounds for RVLCs;
8. Analysing the role of RVLCs in the communications of multimedia files.
9. The role of VLECs in the communications of multimedia files.

2. Literature Review

The robust transmission of variable-length encoded source signals over wireless channels has become an active research area during the last years. It is motivated by the increasing demand on multimedia and data services in third and fourth generation wireless networks. In such applications source compression is usually carried out using standardized techniques which, in order to achieve high compression gains, often employ using Reversible Variable Length Codes or Variable Length Error-correcting Codes.

As mentioned above, a study of VLECs was initiated by Hartnett et al in 1974 [19]. He proposed some important basic definitions of VLECs. There has been quite some research on VLECs in late 80s and 90s by Bernard and Sharma [20] [21] [22] [23]. Most of the research was on the important derivations and their optimizations related to combinatorial bounds on VLECs [22]. Bernard [22] in her doctoral thesis has proposed some important strong combinatorial results for VLECs, like there we put Kraft inequality [2] for source codes, Singleton type of bound [24] and Hamming bounds [25] for channel codes. These important theorems give

1. Necessary condition for the existence of variable length error correcting-codes [22],
2. Sufficient condition for the existence of variable length error correcting-codes [22],
3. Combinatorial bound on the average codeword length of variable length error correcting-code [22].

These combinatorial results play an important role in the construction of VLEC. The bounds obtained play an important role in designing the construction algorithms based on these bounds [12] [13] [14] [22]. We have proposed an improved combinatorial bound on average codeword length of variable length error correcting codes [23]. A complete proof is also provided.

Some algorithms have been studied in detail and have been implemented on MATLAB. The important three algorithms (Code Anti-code algorithm, Greedy algorithm and Majority Voting algorithm) have been proposed by V. Buttigieg [12] [14]. Here, we propose a new algorithm to construct variable length error correcting codes using constant length error correcting codes. It may be mentioned that there are several decoding methods of variable length error correcting codes, out of which Maximum Likelihood decoding proposed by V. Buttigieg is the best one, as it performs the decoding like Viterbi algorithm does for convolution codes. We have proposed a novel method to decode variable length error correcting code, which decodes VLEC in a Maximum Likelihood way which converts the exponential search into tabular search to reduce complexity of the algorithm.

Variable length codes are of prime importance in the efficient transmission of digital signals with non-uniform occurrence probability distributions. Huffman codes which have the highest efficiency and shortest average code length are most prevalent in practical operation. However, there are other VLC criteria than the transmission efficiency that may be important in the application environment, for example, channel bit-error resilience maximum code word length limitation due to hardware capacity etc. Reversibility of variable length codes that makes instantaneous decoding possible both in the forward and backward directions is one such criterion. Another potential use of this code is in the random access of or in the searching of an entropy coded stream of data. A reversible variable length code, however, must satisfy the suffix condition for instantaneous backward decoding as well as the prefix condition for instantaneous forward decoding.

The additional features of RVLC, as compared with a simple source code, are:

1. It supports the simultaneous decoding, of the received data at the decoder side, in both the forward and reverse direction to speed up the process;
2. In case of the presence of the error, only the frame containing the error will be damaged and the other portion of the binary file can be retrieved. Due to these properties, such types of codes have been named as Reversible Variable Length Codes.

There are two types of RVLCs, one is symmetrical RVLC and the other is asymmetric one. The symmetric RVLC shares the same codeword table when2 decoding in both the forward and backward directions, because the codewords are symmetric. On the other hand, two codeword tables are necessary for decoding the asymmetric RVLC, one for the decoding in forward direction and the other for the decoding in the backward direction. Thus the memory requirement of the symmetric RVLC is less than that of asymmetric RVLC. However the asymmetric RVLCs always provide better efficiency than the symmetric one, because the codeword selection can be more flexible and average codeword length will be less in the former case.

An RVLC must satisfy the suffix condition for instantaneous backward decoding as well as the prefix condition for instantaneous forward decoding. The suffix condition is that each codeword does not coincide with the suffixes of longer codewords; while the prefix condition expresses that there is no coincidence with the prefixes of longer code words. Suffix-free and prefix-free codes are also known as affix-free codes.

There have been several RVLC construction algorithms proposed by the researchers to construct RVLCs. All algorithms have been studied in detail. The algorithms may be arranged in the following categories:

1. Huffman dependent symmetric RVLC;
2. Huffman dependent Asymmetric RVLC;
3. Huffman dependent symmetric RVLC;
4. Huffman dependent Asymmetric RVLC.

The algorithms of all categories have been implemented on MATLAB. Different probability distribution have been used the comparative analysis of all the construction algorithms.

The main role of variable length code is to convert the data (obtained in any coding/compression standard) into binary bit-stream. Variable length codes are of great use in applications like Image coding standards, Video Coding standards; Speech Coding Standards and others. In the earlier days, simple source codes like Huffman codes were used in these applications. But with these source codes, there is always a chance to get the whole file corrupted in the presence of even a single bit error. To make the encoded bit-stream error resilient, source codes were replaced by RVLCs [26] [16]. An RVLC is suffix-free as well as prefix-free; this affix-free nature makes RVLC capable of being decoded in both forward and the reverse directions. Let us consider the case of single bit error introduced at the channel due to noise. If RVLCs are used in encoding, then due to their error resilience capability, we can avoid getting the whole bit-stream file corrupted due to the presence of single bit error. With the use of the forward decoding and the reverse decoding, we can obtain the decoded file at the receiver except for the portion (codeword) containing single bit of error.

Almost all image coding standards, such as the JPEG still image coding standard, the ITU series of H.261 and H.263 video coding standards, the ISO series of MPEG-1 and MPEG-2 standards, adopt variable-length codes as their entropy coding stage. Due to the variable code length nature of VLCs, they are very sensitive to errors occurring in noisy environments. Even a single bit error is extremely likely to induce propagation errors such that the data received after the bit error position becomes useless and results in a serious problem. Reducing the effect of this problem has led to the development of reversible variable length codes, which can be decoded in both the forward and backward directions. RVLCs have received extensive attention only recently, especially during the development of the new video standards H.263++ and MPEG-4, which require enhanced error resilient capabilities.

The role of RVLCs in different applications like image compression and video compression is analysed and the performances of image/video compressions using RVLCs are compared with image/video compression using Huffman code. And it has been contributed that if conventional Golomb-Rice RVLCs are replaced by Yan's RVLCs in H.263++ video coding standard, better performance can be achieved in terms of average codeword length, maximum codeword length and the total number of bits required representing a multimedia file. This work proposes the scope of improvement in the video coding standard.

3. Objective and Scope

The prime objective of this research is to explore methods for robust and efficient communication over wireless channels. As it has been mentioned earlier also, there are some limitations of classical coding theory in which we consider source code in cascade with channel codes. The limitations are in terms of system complexity, source and channel characteristics and system delay. Joint source channel coding is presented as the most promising scheme for communication of analogue/digital sources over wireless channels, due to its ability to cope with varying channel qualities and to approach the theoretical bounds of transmission rates. VLECs and RVLCs are shown to be good candidates for joint source channel coding, providing both robustness and efficiency. Objective and scope of the thesis may be summarized as follows:

- JSCC has been a prime area of research from the last three decades. Some construction algorithms of VLECs and RVLCs have been proposed along with their decoding algorithms by various researchers. The mathematical ground to study VLEC was first given by Hartnett [14]. Later on, some theoretical bounds have been proposed by Bernard [17], however there are some mathematical gaps which need to be filled. The bounds may be improved further and some probabilistic and theoretical results may also be obtained.

- Many construction algorithms of VLECs and RVLCs have been proposed along with their decoding algorithms. Can it be further extended?

- JSCCs can also be used in the communication of multimedia file, such as image, speech and video files. RVLCs have been used in video coding standards since the last decade. There is a scope to get a better compression of a video file using Yan's RVLC in place of conventional RVLC in video coding standard.

4. Description of Research Work

The problems, identified through an extensive review of literature and discussions with area experts, may be briefly given as – Some innovations in the area of JSCC, in the form of tighter bounds, new construction algorithm, better decoding algorithm and the role of RVLCs and VLECs in the multimedia applications. Research work carried out in this thesis may be broadly classified into the following subheads:

G1: To obtain improved combinatorial bound on average codeword length of variable length error-correcting codes;

G2: To construct an algorithm to generate variable length error-correcting code using constant length error correcting codes, and evaluate its performance among the other existing algorithms to generate variable length error-correcting codes;

G3: To decode variable length error-correcting code in Maximum Likelihood (ML) way, using a novel and efficient tabular approach is similar to Viterbi algorithm, which is used to decode convolutional codes;

G4: To improve the performance of image compression or video compression by using RVLCs in place of Huffman code (optimal source code);

G5: To improve the performance of H.263++ video coding standard (video compression) using a different RVLC, in place of the traditional RVLC in vogue.

5. Research Contributions

The idea of joint source channel coding has been gaining increasing attention in recent years. There are several reasons for this. One is the growing importance of wireless communications in which we are forced with channels that are both noisy and band-limited, thus requiring both error control and error compression [11]. In the past, the designs of the source coder and the channel coder have been performed separately. This often makes excellent practical sense and it is theoretically justified by Shannon's Separation Theorem [1]. This Theorem states that the two operations (source coding and channel coding) can be done separately without asymptotic performance loss. However, this theorem neither holds for some classes of sources and/or channels, nor does it offer any guarantee in terms of complexity and practical feasibility [10]. Since the aim of source coding is to remove redundancy in the data to be transmitted and the aim of channel coding is to reintroduce redundancy to make the transmitted data error correctable, it is investigated how to efficiently combine the two techniques to improve the overall system while keeping an acceptable level of complexity [9] [10] [11].

Related to Joint Source Channel Codes, two types of codes are studied in detail- Variable Length Error Correcting Codes and Reversible Variable Length Codes. A brief account of the work done is given in the Chapter wise description of the draft of the thesis.

Chapter 1 introduces the thesis and provides an overview of the work done. Introduction of the Chapter is given in Section 1.1. Overview of coding theory is given in the section 1.2 which includes a brief discussion on source codes, channel codes, variable length codes in noisy channels and error resilient codes. Literature survey on codes is discussed in detail in section 1.3. The basics of source coding and channel coding, along with important definitions, bounds and theorems are given. It may be noted that we have reviewed only the relevant material related to our work. Joint source channel coding, including variable length error correcting codes and reversible variable length codes are also discussed in this section. The objective and the scope of the thesis are given in section 1.4. Description of the research work is given in section 1.5. Research contributions are mentioned in section 1.6. The organisation of the thesis is given in section 1.7. The chapter has been concluded in section 1.8. The list of publications based on the research work is given in section 1.9.

Chapter 2 defines Variable Length Error Correcting-Code which is a type of Joint Source Channel Codes. Introduction of the Chapter is given in Section 2.1. The explanation of the preliminaries of the combinatorial results of VLEC by discussing the necessary condition for the existence of variable length error correcting codes, sufficient condition for the existence of variable length error correcting codes and the combinatorial bound of average codeword length of variable length error correcting codes is given in Section 2.2. All these combinatorial results were given by Margaret Bernard in her Ph.D. dissertation, so the details of the proofs of these results can be obtained from her thesis. ***In Section 2.3, we derive the improved combinatorial bound on the average codeword length of variable length error correcting-codes.*** After that several examples are given to demonstrate this bound. Section 2.4 concludes the Chapter.

- Note: This Chapter is based on my published research papers P.4 and P.6 referred in the list of publications at the end of the synopsis.

This Chapter 3 is devoted to a comparative study of various Code Generating Algorithms of variable length error correcting-codes. In the comparative study reported in this Chapter four algorithms are considered. Three of these are available in the literature and the fourth has been formulated by us. These are as follows:

- Code Anti-code algorithm;
- Greedy algorithm;
- Majority Voting algorithm;
- Alpha prompt code generating algorithm.

The ‘code anti-code algorithm’ is manually implemented. The other algorithms are simulated on MATLAB simulator as these are computer search based algorithms. The Chapter is organized as follows. Section 3.1 is the introduction to the Chapter. Section 3.2 discusses the three known algorithms. ***Section 3.3 presents our proposed algorithm to generate alpha-prompt code.*** Section 3.4 discusses the distributions considered for the comparative analysis of all the algorithms. Section 3.5 compares all the VLEC generating algorithms based on average codeword length, maximum codeword length, computation time and complexity. The conclusion of the chapter is given in section 3.6.

- Note: This Chapter is based on my published research papers P.2 and P.7 referred in the list of publications at the end of the synopsis.

Decoding algorithms play an important role in the development of coding theory, because its complexity decides the time taken at the decoder side to decode the data. Chapter 4 is devoted for the discussion on decoding of variable length error correcting codes. Section 4.1 is the introduction to the Chapter. The overview of decoding techniques is given in Section 4.2. ***Section 4.3 presents the novel modified maximum likelihood method to decode variable length error correcting codes on the analogy of Viterbi algorithm that is used for the decoding of convolution codes.*** Modified ML decoding was given by Buttigieg, but we present a novel way to decode it which converts the exponential search into the tabular search, thus reduces the complexity of the algorithm. Section 4.4 concludes the Chapter.

- Note: This Chapter is based on my published research paper P.5 referred in the list of publications at the end of the synopsis.

Chapter 5 starts with defining another type of Joint Source Channel Code- Reversible Variable Length Codes. The introduction of the Chapter is given in Section 5.1. Section 5.2 discusses seven different RVLC construction algorithms: four algorithms to construction symmetric RVLC and three algorithms to construct asymmetrical RVLC. The algorithms are as follows:

- Takishima’s Symmetrical algorithm [15]
- Huo Jun Yan’s Symmerical Algorithm [27]
- Tsai’s Symmetrical algorithm [28]

- Jeong and Ho's Symmetrical Algorithms [29]
- Takishima's Asymmetrical algorithm [15]
- Tsai's Asymmetrical algorithm [30]
- Golomb Rice Code-algorithm [31]

For the comparative analysis, three distributions of 26- English alphabets are considered. These distributions are widely used in cryptography and in data compression analysis and these are defined for 26 upper-case English alphabets. The considered distributions are –

- Distribution given by Victor Buttigieg [12],
- Distribution given by Tsai [28]
- One gram distribution [32].

The details of these distributions are given in Section 5.3. ***The result of a comparative analysis on the basis of average codeword length and the maximum codeword length- is presented in Section 5.4.*** Section 5.5 concludes the Chapter.

- ➢ Note: This Chapter is based on my published research papers P.1 and P.8 referred in the list of publications at the end of the synopsis.

Chapter 6 discusses the role of RVLC in multimedia applications. The performance of image compression and video compression can be improved by using RVLC in the place of Huffman code. The introduction to the Chapter is given in Section 6.1. The basics of data compression (image compression and video compression) are given in Section 6.2. It also discusses image compression and the brief overview of the hierarchy of the video coders. H.263++ video coding standard has been explained in section 6.3 in detail. The role of RVLC in image and video coding standards is given Section 6.4. Simulation and analysis are given in section 6.5 in the form of the results obtained on the MATLAB simulator. The performance of different RVLCs has been analysed on video coding standard H.263. ***It has been contributed that if conventional Golomb-Rice RVLCs are replaced by Yan's RVLCs in H.263++ video coding standard, better performance can be achieved in terms of average codeword length, maximum codeword length and the total number of bits required representing a multimedia file.*** Section 6.6 concludes the Chapter.

- ➢ Note: This Chapter is based on my published research papers P.3 referred in the list of publications at the end of the synopsis.

The important conclusions drawn from the thesis are presented in Chapter 7 in Section 7.1. The overview of possible and promising future work that might be carried out taking the presented work as a baseline is given in Section 7.2.

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Conclusion

My contributions in the areas of Reversible Variable Length Codes and Variable Length Error-correcting Codes can be summarized as follows:

1. Derived a tighter lower bound on the average codeword length of Variable Length Error Correcting Codes.
2. Develop an algorithm to generate the Variable Length Error Correcting Codes from constant length error correcting codes. Comparative Analysis of construction algorithms of Variable Length Error Correcting Codes was also done.
3. Proposed a modified method to implement Maximum Likelihood decoding of VLECs which converts the exponential search into tabular search to reduce the complexity of the algorithm.
4. The performance of different RVLCs is analyzed on video coding standard H.263++. It is shown that if RVLC generated using Yan's algorithm are used in place of conventional H.263++ RVLC, more compressed version of the file will be obtained for the same perceptual quality.

List of Refereed Publications - Published and Accepted

International Journals:

P.1. **Richa Gupta** and Bhudev Sharma, “Construction of Symmetrical Reversible Variable Length Codes for a Markovian Source”, International Journal of Information Science and Computer Mathematics, ISSN NO: 1829-4969, vol.2, (2010), pp 75-86. [EBSCO indexed journal, Editor in Chief: Prof. Kewen Zhao, University of Qiongzhou, China]

P.2. **Richa Gupta** and Prof Bhudev Sharma, “Generation of Variable Length Error Correcting Codes using Constant Length Error Correcting Codes”, International Journal of Emerging Trends in Engineering and Development, ISSN NO: 2249-6149, Issue 2, Vol. 1, January-2012, pp 269 – 279. [Impact factor=0.91, IC factor= 4.55, Editor in Chief: Dr. Philips Thomas, Oxford University, U. K.]

P.3. **Richa Gupta** and Bhudev Sharma, “Reversible Variable Length Codes in Video Coding Standards”, International Journal of Emerging Trends in Engineering and Development, ISSN NO: 2249-6149, Issue 2, Vol. 3, April-2012, pp 33 – 43. [Impact factor=0.91, IC factor= 4.55, Editor in Chief: Dr. Philips Thomas, Oxford University, U. K.]

P.4. **Richa Gupta** and Bhudev Sharma, “An Improved Bound on Average Codeword Length of Variable Length Error Correcting Codes”, refereed Conference Volume entitled “Some Topics on Current Issues in Mathematical and Statistical Methods” by World Scientific Publishing Co. Ltd, Singapore, Dec 2012.

P.5. **Richa Gupta** and Bhudev Sharma, “A novel, efficient and fast way to decode variable length error correcting codes” has been accepted to “Informatica - An International Journal of Computing and Informatics” and expected to be published in 37th volume.

International Conferences:

P.6. **Richa Gupta** and Bhudev Sharma, “Improved Combinatorial Bound on Variable Length Error Correcting Codes”, Proceedings of the International Conference Statistics 2011, Montreal, Canada-IMST 2011-FIM XX, July 2011, pp 109-121.

P.7. **Richa Gupta** and Bhudev Sharma, "A Comparative analysis of the Variable Length Error Correcting Code Generating Algorithms" Proceedings of Twenty first international conference of Forum for interdisciplinary Mathematics on interdisciplinary Mathematics, statistics and computational techniques , IMSCT 2012-FIM XXI, Chandigarh, Dec 15-17, 2012.

P.8. Bhudev Sharma and **Richa Gupta**, "Directions in Optimal Error Correction Coding: Variable Length Error Coding, a class of Distances and Reversible Variable Length Codes", Proceedings_of the National Symposium on Mathematical Methods and Applications 2009, Indian Institute of Technology Madras, Chennai, pp 1-12, 2009.

REFERENCES

[1] C. E. Shannon, "A Mathematical theory of communications," *Bell Syst. Tech. J.,* vol. 27, no. 1, pp. 379-423, 623-656, 1948.

[2] L. Kraft, "A device for quantizing, grouping and coding amplitude modulated pulses," *M.S. Thesis, Department of EE, MIT, Cambridge,* 1949.

[3] A. Huffman, "Method for the Construction of Minimum Redundancy Codes," *Proceedings of the Institute of Radio Engineers,* vol. 40, pp. 1098-1101, 1962.

[4] J. Martin, Telecommunication and the computer, Englewood Cliffs, N.J.: Prentice Hall, 1976.

[5] T. K. Moon, Error Correcting Coding: Mathematical Methods and Algorithms, Wiley Publishers, 2004.

[6] J. Lin, J. Daniel and D. Costello, Error control coding: fundamentals and applications, New Jersey: Pearson Prentice Hall, 2004.

[7] R. Jain, "An introduction to Joint Source Channel COding," *IETE Journal of Education,* vol. 46, no. 3, pp. 121-127, 2005.

[8] Q. Chen and K. Subbalakshmi, "An Intergrated Source Channel Decoder for MPEG-4 Coded Video," *IEEE Semi-Annual Vehicular Technology Conference,* Oct 2003.

[9] J. Massey, "Joint source and channel coding," *Communication Systems and Random Process Theory, NATO Advanced Studeis Institutes Series E25,* vol. 25, pp. 279-293, 1978.

[10] S. Vembu, S. Verdu and Y. Stinberg, "The Source-Channel Separation Theorem Revisited," *IEEE Transations on Information Theory,* vol. 41, no. 1, pp. 44-54, 1995.

[11] K. Demir N. and Sayood, "Joint Source/Channel Coding for Variable Length Codes," *IEEE Data Compression Conference, Snowbird, UT,* pp. 139-14, 1998.

[12] V. Buttigieg, "Variable-length error-correcting codes," Ph.D. dissertation, University of

Manchester, Manchester, United Kingdom, 1995.

[13] V. Buttigieg and P. Farrell, "Constructions for variable-length error correcting codes," *Proceedings of Cryptography and Coding, 5th IMA Conference, Cirencester, UK,* pp. 282-291, 1995.

[14] C. Lamy and J. Paccaut, "Optimised construction for variable length error correcting codes," *Information Theory Workshop,* 2003.

[15] Y. Takishima, M. Wada and H. Murakami, "Reversible variable length codes," *IEEE Transactions on Communications,* vol. 43, pp. 158-162, Feb. 1995..

[16] I. Moccagatta, S. Soudagar, J. Liang and H. Chen, "Error resilient coding in JPEG-2000 and MPEG-4," *IEEE Journal in Selected Areas in Communications,* vol. 18, no. 6, pp. 899-914, 2000.

[17] H. Wang, "Application of reversible variable length codes in robust speech coding," *IEE Proceedings in Communications,* vol. 152, no. 3, pp. 272-276, 2005.

[18] B. Yan and K. Wing, "An Efficient Error Detection Technique for MPEG-4 Video Streams," Department of Computer Science and Engineering, Chinese University of Hong Kong, 2010.

[19] W. Hartnett, Foundations of Coding Theory, Dordietcht, Holland: D. Reidling Publishing Co., 1974.

[20] M. Bernard and B. Sharma, "Some Combinatorial Results on Variable Length Error-correcting Codes," *ARS Combinatoria,* vol. 25B, pp. 181-194, 1988.

[21] M. Bernard, Some Combinatorial Results on Variable Length Error-correcting Codes, Vols. , University of Lonsdon, England, 1987., England: University of London, 1987..

[22] M. Bernard, "Error-correcting codes with variable lengths and non-uniform errors," Ph.D Thesis, University of the West Indies , Department of Mathematics, St. Augustine, 1987.

[23] M. Bernard and B. Sharma, "A Lower Bound on Average Code word Length of Variable Length Error correcting Codes," *IEEE Transactions on Information Theory,* vol. Vol. 36,

no. No. 6, pp. 1474-1475, 1990.

[24] F. MacWilliams and N. Stoane, The Theory of Error Correcting Codes, North Holland Publishing Co., 1977.

[25] R. Hamming, "Error detecting and correcting codes," *Bell System Technical Journal,* vol. 29, pp. 147-160, 1950.

[26] M. Ashourian, A. Afzal and P. Moallem, "Usinf Reversible Variable Length Codes for JPEG image transmission in a noisy channel," *Analog Integrated Circuits and Signal Processing,* vol. 71, no. 2, pp. 337-341, 2012.

[27] H. J. Yan, C. Lin and H. M.L., "On constructing symmetrical reversible variable length code independent of the Huffman code," *Journal of Zhejiang University Science,* 2007.

[28] C. W. J. Tsai, "On constructing the Huffman code based reversible variable length codes," *IEEE Transactions on Communication,* vol. 49, pp. 1506-1509, 2001.

[29] W. H. Jeong and Y. S. Ho, "Design of Symmetrical Reversible Variable Length Codes from the Huffman Code," *Picture Coding Symposium,* pp. 135-138, 2003.

[30] C. Tsai and J. Wu, "Modified symmetrical reversible variable length code and its theoritical bounds," *IEEE Transactions of Information Theory,* vol. 47, no. 6, pp. 2543-2548, 2001.

[31] S. Golomb, "Run Length Encodings," *IEEE Transactions on Information Theory,* vol. 12, no. 3, pp. 399-401, 1966.

[32] A. G. Konheim, One Gram Probability Distribution, Third edition: John Wiley , 1981.

[33] B. Sharma and B. M.A., "Some Combinatorial Results on Variable Length Error-correcting Codes," *Ars Combinatoria,* vol. Vol25B, pp. 181-194, 1988.

[34] S. G. 16-Contributions, Draft for H.263++, Annexes U, V and W ro recommendation H.263, 1997-2000.

[35] M. Jeanne, J. Carlach and P. Siohan, "Joint Source Channel decoding of variable length codes for convolutional codes and turbo codes," *IEEE Transactions on Communications,*

vol. 53, pp. 10-15, 2005.

[36] S. Madhu, "Coding Theory: Tutorial and Survey," *Proceedings of the 42nd IEEE Symposium on FOundations of Computer Science,* vol. 42, pp. 1-18, 2001.

[37] L. C. Perros-Meilhac, "Huffman tree based metric deviation for a low-complexity sequential soft VLC decoding," *Proceedings of ICC,* pp. 783-787, 2002.

[38] M. Park and D. Miller, "Joint source-channel decoding for variable length encoded data by exact and approximate MAP sequence estimation," *IEEE Transactions on Communications,* vol. 48, no. 1, pp. 1-6, 2000.

[39] R. Roth and G. Ruckenstein, "Efficient decoding of Reed-Solomon codes beyond half the minimum deistance," *IEEE Transactions on Information Theory,* vol. 46, no. 1, pp. 246-257, 2000.

[40] C. B. Alan, Handbook of Image and Video Processing, Second edition: Elsevier Academic Press, 2005.

[41] A. J. Viterbi and J. K. Omura, Principle of digital communication and coding, New York: McGraw Hill, 1979.

[42] W. Thomas and J. S. Gray, "Overview of the H.264/AVC video coding standard," *IEEE transactions on circuits ad systems for video technology,* vol. 13, no. 7, 2003.

[43] Y. Te-Chung, "Robust coding of images using EBCOT and RVLC," *IEEE 3rd Workshop on Multimedia Signal Processing,* pp. 395-400, 1999.

[44] K. M. Rose, "Enhancement of one-dimensional variable length DPCM images corrupted by transmission errors," *IEEE Transactions on Communications,* Vols. COM-37, no. 4, pp. 373-370, 1989.