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Structural Processing for Wireless Communications

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Recommended by Sherman Shen

Foreword

As wireless communication systems continue to grow, their designs are becoming increasingly complex, whereas the problem of identifying better system designs is posing severe challenges not only to the academia but also to the industry. Specifically, as the number of mobile subscribers has been increasing at an incredible speed in recent years, services have rapidly diversified to meet widely divergent user needs and a variety of stringent requirements. This exacerbates the difficulty of the problem, since analyzing the complexity of systems where various services are involved is very difficult, as such systems cannot be decomposed into sub-systems that exhibit linear properties. Likewise, interferences caused by the coexistence of different elements in the same physical channel makes the wireless environment harsher than ever, highlighting the uncertainty issues in wireless transmission. As a result, the classic communication theory has reached its limits.

This brief presents an alternative viewpoint on processing technologies for wireless communications based on recent findings. The structure perspective presented acts as a lever in enabling emerging processing technologies and helps to cope with the aforementioned challenges. Unlike classic processing methods that are mainly element based (they operate on elements such as bits or samples), in this brief, wireless multimedia communication, channel coding and pre-coding methods are designed with different structures as intermediate processing units. Based upon mathematical analysis and simulation results, the proposed technologies are convincingly shown with promising performance in broadband wireless multimedia systems. I personally believe that the idea of structural processing is unique and innovative and hope this brief may boost the development of new theories and technologies with this perspective, which would likely open up a new trend in wireless communications research.

With a great pleasure, I highly recommend this brief to everyone in the area of information and communication technology.

Hong Kong, China Khaled B. Letaief

Preface

In the early twentieth century, the revolution in wireless communication began with the pioneering attempt of long-distance radio communications by Guglielmo Marconi, who performed the famous *transatlantic* transmissions in 1901 from Newfoundland, Canada, to Cornwall, Britain. Other great pioneers include Samuel Morse (telegraph), Alexander G. Bell (telephone), as well as Edwin Armstrong (radio).

The greatest breakthrough in theory emerged with the publication of Claude Shannon's theorems in 1948. These theorems underlay the performance limits in encoded transmission, which catalyzed the development of a new area in science currently known as *information theory*. Under the effective guidance from Shannon's theorems, processing technologies have been designed for compressing data, increasing link speed, reducing transmission errors and so on. There have been much efforts to push the performance closer to the Shannon limit, but challenges continue to exist when facing the ever-growing complexity of systems. Indeed, one necessary prerequisite of applying Shannon's theorems is that the source and the channel models should both possess independent identical distributions (*i.i.d.*). When the complexity and uncertainty issues in wireless systems get so severe that this assumption deviates too greatly from the truth, the classic processing technologies will meet difficulties in achieving high transmission performance.

To address the problems caused by complexity and uncertainty, we hereby attempt to develop an alternative processing method called *structural processing*. Instead of operating on bits or samples based on the *i.i.d.* model, structural processing tries to handle grouped bits or samples, namely, structures. The study of structural processing should be traced back to 18 years ago when I started my research as a PhD student, under the supervision of Prof. Khaled Ben Letaief and Prof. Ming L. Liou at The Hong Kong University of Science and Technology in 1996. At the very beginning, we found that the impact on the perceptive image quality caused by bit errors with a fixed error rate in the transmission of JPEG files varied greatly across different trial runs. The uncertainty of the effect of the errors was mainly due to the complexity of the underlying data structure being corrupted by the errors. By learning the data structure of the JPEG format, the concept called *minimum data unit (MDU)* was proposed, which grouped the related encoded bits representing an image block. Once MDU is transmitted as an entity, its error rate, i.e., $E_r(MDU)$, may act as a bridge between received image quality and bit error rate, or, BER, performance. This is in fact an initiation to have the idea of structural processing. In the meantime, a block shuffling scheme was proposed, together by Mr. I. P. Chan, Prof. J. C.-I. Chuang and myself, as a structural processing method in order to enhance the error resilience of image transmission. Part of this work is introduced in Chap. 3.

Later on, Prof. Ning Ge, Dr. Liuguo Yin, Dr. Yukui Pei and Dr. Xiaoming Tao joined our group in Tsinghua University, continuing the research on structural processing. It was noted that IP over SDH and IP over ATM faced a similar issue regarding the high variability of the effect of errors as that which MDU was proposed to solve in data communications. We studied the framing procedure on the data link layer which prevented IP structure corruption from transmission errors to protect the integrity of variable-length IP packets. This further generalized our research on wireless transmission based on structures. Some important ideas are included in Chap. 2.

Channel coding is an important part of a communication system to combat errors in transmission. It is well known that conventional LDPC code design is usually a bit-based random search for a coding matrix, where the number of bit-element combinations is usually huge. To address this complicated matrix optimization problem, we proposed a structured method based on Galois field sub-matrices, which decomposed the huge matrix design problem into a succession of sub-matrix design problems. This structured coding design is another demonstration of structural processing, which is introduced in Chap. 4.

In 2007, Mr. Weiliang Zeng started his study in our group. We carried on a collaborative research on pre-coding design together with Prof. Chengshan Xiao from Missouri University. Although classic pre-coding design may achieve optimal system capacity, yet it is nearly infeasible for practical implementations, for its derivation is based on the assumption of Gaussian signals, which are both unbounded and undetectable. Considering a finite-alphabet constellation structure of the modulation signal, we proposed a structured pre-coding design with a two-step iterative optimization algorithm. Benefiting from the merit of structural processing, the developed algorithm may provide a performance gain that brings the system capacity close to the optimum with acceptable computing complexity. Part of this work is presented in Chap. 5.

Since 2010, Mr. Yang Li, Mr. Yipeng Sun and Mr. Shaoyang Li have joined us to conduct research of structural processing towards their respective PhDs. Instead of finding and utilizing structures constructed by correlated bits, we have then focused on a structural perspective inspired by the cognition of human brains. Specifically, images and videos are modeled based on high-level perceptions and represented with structural decomposition. Consequently, dictionary learning methods for image representation and model-based approaches for face video communications are studied with improved transmission efficiency and perceptive quality. As a matter of fact, these technologies deal with the non-i.i.d. sources and channels without simple transformation or approximation to i.i.d. ones. Some interesting results are briefly presented in Chap. 6.

In this brief, we have therefore assembled exemplar works from our 18 years of team research, where methods of source coding, channel coding and pre-coding are presented with structure perspectives. Specifically, the concept of MDU is introduced to help redesign the compressed wireless multimedia data, so as to significantly curb the impact of both random and burst errors. Likewise, a gradual construction scheme of structured LDPC codes is found, having near-optimal error-correction performance but much lower complexity than the conventional LDPC coding. Moreover, pre-coding for high-dimension constellation consisting of the basic QPSK structure is designed, achieving near-optimal capacity in harsh wireless environments. Further studies on information representation, such as dictionary learning and model-based video coding, are introduced as potential interesting areas to the development of advanced structural processing technologies for future wireless communications.

This brief only showcases some recent processing technologies with structural perspective. Hence, more research work is encouraged to follow up. Although the introduced technologies belong to different parts of the wireless system, the theme is unified: *structure*. It is the structure that enables the processing complexity of non-i.i.d. systems may be decomposed, facilitating further studies on more general methods to tackle the complexity and uncertainty issues in modern wireless communication systems. We hope that this brief may provide alternative ideas to the researchers and also be used as a reference for both post and undergraduate students who major in wireless communication, information theory or related areas. Our research thus far constitutes preliminary explorations into their respective topics, with inevitable flaws and limitations. Much work remains to be done toward the eventual formulation of a comprehensive theoretical framework.

In the meantime of writing this brief, some members in our group in Tsinghua University participated in preparing the materials and provided valuable assistance. Specifically, Dr. Linhao Dong assisted in editing Chap. 1; Dr. Yukui Pei provided simulation results and helped edit Chap. 4; Mr. Shaoyang Li prepared part of Chap. 2 and helped edit Chap. 6; Dr. Rui Shi helped edit Chap. 3 and part of Chap. 4; Mr. Hongliang Mao helped complete Chap. 5; and Mr. Yang Li helped improve the quality of presentation of the brief. We highly appreciate their excellent work.

Beijing, China — Jianhua Lu
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Contents

Acronyms

AWGN	additive white Gaussian noise
BER	bit error rate
bpp	bit per pixel
BPSK	binary phase-shift keying
CSCC	combined source-channel coding
CSI	channel state information
DCT	discrete cosine transform
DPC	dirty paper coding
DPCM	differential pulse-code modulation
EM	electromagnetic (wave/field)
FEC	forward error correction
GF	Galois field
HEVC	high efficiency video coding
i.i.d.	independent identical distribution
IP	Internet protocol
JPEG	joint picture expert group
LDPC	low-density parity-check (code)
MBVC	model-based video coding
MDU	minimum data unit
MIMO	multiple-input and multiple-output
MMSE	minimum mean square error
MSR	multi-sample sparse representation
OFDM	orthogonal frequency-division multiplexing
PB	picture block
PCA	principal component analysis
PSNR	peak signal-to-noise ratio
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying
R-D	rate-distortion
ROI	region-of-interest
RTP	real time transport protocol

SER	symbol error rate
SNR	signal-to-noise ratio
SSIM	structural similarity index measure
SVD	singular value decomposition
VLC	variable length coding
WER	word error rate