A Power and Bandwidth Efficient Remote Wireless Video Surveillance System Using Joint Source-Channel Coding

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Abstraction: A novel wireless remote video surveillance system based on joint source-channel coding is proposed in this paper. The proposed system exhibits superior bandwidth and power efficiency thanks to the adoption of the proposed iteratively decodable variable-length codes (IDVLCs). An experimental platform was built and simulation results were shown to demonstrate the superior performance of the proposed video surveillance system in terms of both objective and subjective measurements.

1 Introduction

Advanced wireless technologies have helped transform traditional video surveillance techniques. There has been growing demand on remote video surveillance systems using latest wireless techniques. Power and bandwidth have always been two constraints for developing such wireless remote video surveillance systems. As the available radio spectrum is limited, such systems can only be achieved through advanced source coding and powerful channel error control coding techniques.

From the perspective of information theory, source coding aims to remove unwanted redundancy from uncompressed source signals, whereas channel coding adds deliberate redundancy into compressed source signals. For the past decades, Shannon's classic separation theorem [1] motivated a separate source and channel coding approach, which states that the end-to-end system performance can be optimised by separately optimising source and channel coding. This theorem is, however, constrained by two hypothetical assumptions, namely perfect source codes that remove all source redundancy and perfect channel codes that guarantee error-free transmission. The two hypotheses have proved unrealistic for practical video communications systems. This fact justifies a joint source and channel coding approach that may achieve better performance for practical video communications systems.

This paper proposes a novel wireless remote video surveillance system based on the joint source-channel coding approach. The joint approach is able to improve significantly the power and bandwidth efficiency for transmitting image and video signals over noisy wireless channels compared to conventional video surveillance systems. The novel approach can find its ways in a wide range of machine vision applications including remote surveillance and visual remote control. In this paper, we aims to describe a novel power and bandwidth efficient remote video surveillance based on the proposed joint source-channel coding approach.

The remainder of the paper is organised as follows. Section 2 briefly presents wireless remote video surveillance system design overview. The technique for soft-output decoding of source codes is reviewed briefly in Section 3. Section 4 proposes IDVLCs and their design criteria, whereas Section 5 presents the system architecture of the wireless video surveillance system. Experimental results are presented in Section 6 and conclusions are drawn in Section 7.

2 Wireless Remote Video Surveillance Systems Design Overview

The wireless remote video surveillance system we consider in this paper is contingent on error resilient image and video signals transmission over highly corrupted wireless channels. Advanced source compression and channel error control mechanisms are imperative to design such systems. As mentioned in the previous section, we are only able to achieve the design goals through jointly designing source and channel coding due to the two unrealistic hypothetical assumptions imposed by Shannon's classic 'separation' theorem.

For conventional remote video surveillance systems, source coding and channel coding are done in a separate way. That is, source coding tries to compress source signals as much as possible to reduce channel bandwidth consumption, whereas channel coding utilises all available channel bandwidth to add error control redundancies. The system is not optimised in terms of bandwidth and power use from a global point of view. The essence of the novel wireless remote video surveillance system proposed in this paper is the so called joint source-channel coding approach [2], which allocates bandwidth and power resources between source and channel coding from a global optimisation perspective.

To achieve best source compression performance, most source entropy codes adopt variable-length coding. The resulting variable-length codes (VLCs) have the advantage of being able to represent most frequent source symbols with short codewords and less frequent source symbols with long codewords. Whilst it achieves nearly optimal performance solely from the source coding perspective, however, the variable length coding strategy presents a big challenge to VLC decoding. This is due to the error propagation property of VLCs. The variable length coded signals are very prone to channel noise. Even a single bit error could destroy the whole coded bitstream if no other error control schemes are adopted.

To circumvent the VLC decoding challenge, we can extend the well-known "turbo principle" [3] in channel coding to joint iterative source-channel decoding (ISCD). Iterative decoding between the source and channel decoders enables the two decoders to exchange soft *a priori* and *a posteriori* decoding information with each other, and thus significantly improve the overall decoding performance.

Huffman codes [4] are the most popular VLCs that are typically employed in international image and video coding standards. The codes are optimal in terms of minimising source redundancy. Huffman codes have little redundancy and thus small free distance from the channel coding perspective. While Huffman codes exhibit superior source compression performance, their small free distance prohibits iterative decoding between the source and channel decoders, which could yield potentially much more coding gain using a joint source-channel coding approach. In this paper, we show how VLCs like Huffman codes can be reconstructed into powerful iteratively decodable variable-length codes (IDVLCs). The proposed IDVLCs can be utilised in the remote video surveillance system to significantly improve system performance as opposed to conventional systems.

3 Soft-output decoding of source codes

To implement the ISCD algorithm stated in Section 2, both source and channel decoders of the video surveillance system need to generate soft-output information. This is not a problem for the channel decoder that employs the *a posteriori* probability (APP) decoding algorithm. However, conventional VLC source decoders are not able to generate soft-output information. We need to modify VLC decoders to yield soft-output information as the first step toward joint iterative source-channel decoding.

A variable-length coded sequence can be regarded as a sequence of bits instead of concatenated variable-length codewords. Thus, the variable length coded sequence can be represented by a simple but effective trellis structure proposed in [5]. As shown in [6], a bit-level soft-in/soft-out (SISO) decoding module for VLCs was derived by applying the BCJR algorithm [7] to such a VLC-trellis. Therefore, an APP VLC source decoder can be implemented to yield soft outputs, and exchange extrinsic information with the channel APP decoder.

For a variable length-coded sequence, the source symbol or codeword probabilities are usually assumed to be known. The *a priori* bit probabilities can be derived directly from the tree representation of VLCs using the symbol probabilities of the codes, and then be used in a joint source-channel decoding process. We proposed a method to derive the state transition probabilities (STPs) [8], based on the bit-level trellis representation of variable length codes.

Fig. 1 shows the tree representation and the bit-level trellis of an example variable-length code C = {00, 01, 10, 110, 111} with the corresponding codeword probabilities P = {p_1, p_2, p_3, p_4, p_5}. The nodes in the tree are subdivided into a root-node (R), internal nodes (I) and terminal nodes (T). We can treat the VLC-trellis as an irregular trellis in comparison to the trellis of a recursive systematic convolutional (RSC) code. The trellis of an RSC code has nice systematic properties. Each state has two paths emanating and two paths merging with the same probabilities. In contrast to the systematic trellis of an RSC code, each state in the VLC-trellis might have an arbitrary number of emanating or merging paths or even have parallel paths emanating and merging between states. Moreover, different paths might emanate or merge to a state with different probabilities from each other because the codeword probabilities of VLCs are in general different. We can utilise the codeword probabilities of VLCs to derive the STPs which are used as *a priori* information to facilitate ISCD.

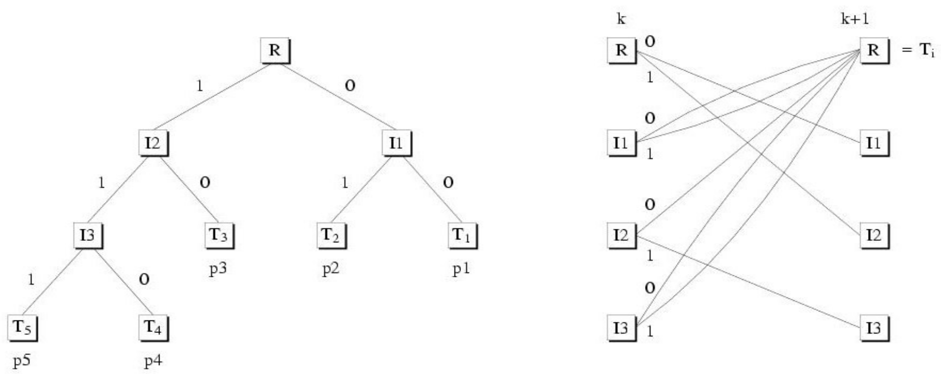

Fig. 1. Tree representation and VLC-trellis with parallel transitions

For a generic trellis, we formulise the state transition probabilities between two adjacent states associated with an input bit i as

$$P_s(S_{k+1} = m', d_k = i \mid S_k = m) = \frac{\sum_{\alpha \in f(S_{k+1}, i)} p_\alpha}{\sum_{\beta \in g(S_k)} p_\beta} \quad (1)$$

where $f(S_k, i)$ are all the forward nodes indices connected to S_k with the input bit i and $g(S_k)$ are all the forward nodes indices connected to S_k .

For the purpose of ISCD, we need a source decoder that produces soft outputs. The soft output Viterbi algorithm or the BCJR algorithm [9] can be applied to the VLC-trellis to decode variable length codes. We modified the well-known BCJR algorithm for the soft decoding of VLCs. The forward state metric α_k^m and backward state metric β_k^m are calcualted in a similar way as in [10]. However, the branch metric $\delta_k^{i,m,m'}$ is expressed as

$$\delta_k^{i,m,m'} = \chi_k \exp(L_c r_k i) \Pr(S_{k+1} = m', d_k = i \mid S_k = m) \tag{2}$$

where χ_k is a constant and $L_c = 2/\sigma^2$. σ^2 is the variance of the AWGN noisy channel. The last term in (2) is the STP which can be obtained from the VLC-trellis from (1). Note that the recursive calculation of both the forward state metric α_k^m and reverse state metric β_k^m use the same STPs.

4 Iteratively decodable variable-length codes

By employing the soft decoding techniques for source codes presented in Section 3, one can transform a conventional VLC source decoder into an APP VLC decoder, which is capable of producing soft outputs, and exchange the soft information with a channel APP decoder. For the best known source codes, *i.e.*, Huffman codes, however, iterative source-channel decoding performs rather poorly. This is because of the small free distance of Huffman codes (d_f#I #f). It is well known that the free distance of the codes used in an iterative decoding system dictates the performance of iterative decoding. In this section, we discuss the construction of the so-called iteratively decodable variable-length codes (IDVLCs) which have large free distance (d_f ≥#Q) with minimally increased redundancy.

The free distance metric d_f#plays an important role in soft VLC decoding. Due to the nonlinearity of VLCs, direct evaluation of d_f #is relatively complicated. However, other distance metrics such as minimum block distance d_b, minimum prefix distance d_p and minimum suffix distance d_s can be utilised to reduce the evaluation complexity of d_f. We therefore give the following two theorems regarding the upper bound and lower bound of the free distance d_f:

Theorem 1. The lower bound of the free distance d_f of a VLC C is

$$d_f \geq \min(d_b, d_p + d_s) \tag{3}$$

Theorem 2. The upper bound of the free distance d_f of a VLC C is

$$d_f \leq d_b \tag{4}$$

The significance of evaluating d_f of a VLC C is to understand its iterative decoeding performance. For Huffman codes, their d_f of 1 means that the codes are virtually hopeless when applied to ISCD. As a result, based on an existing Huffman codes, we can construct the corresponding IDVLC with d_f ≥#Q to realize the powerfulness of ISCD. To design good IDVLCs, our aim is to increase d_f as much as possible but minising the increase of source reduancy. In essence, the design principle for IDVLCs is to trade off source redundancy again larger free distance. IDVLCs with d_f #I #Q#and d_f #I #–#are of particular interests because of the appropriate trade-off between redundancy and good iterative decoding capability. To design IDVLCs with large free distance metric, we give the following lemmas as guidelines.

Lemma 1. A necessary condition for a variable-length code C #with a prefix distance of one to have a free distance d_f ≥#Q is to satisfy the suffix-free condition, *i.e.*, no codeword is the suffix of another codeword.

Lemma 1 indicates that C is a reversible variable-length code (RVLC) [11] which satisfies both prefix-free and suffix free conditions.

Lemma 2. For a variable-length code C with $d_b \geq 2$, either $d_p \geq 1$ and $d_s \geq 1$ or $d_p \geq 2$ can guaranty $d_f \geq 2$.

Lemma 3. For a variable-length code C with $d_b \geq 3$, either $d_p \geq 1$ and $d_s \geq 2$ or $d_p \geq 2$ and $d_s \geq 1$ can guaranty $d_f \geq 3$.

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The above theorems and lemmas are given without mathematic proofs. Refer to [12] for more details. These theorems and lemmas provide useful design criteria and insightful thoughts on constructing the proposed IDVLCs. In the next section, we will present three example IDVLCs constructed using the given guidelines.

5 Architecture of the Wireless Remote Video Surveillance System Based on Joint Iterative Source-Channel Coding

In this section, we present the system architecture of the proposed wireless remote video surveillance system. In order for the system to be more bandwidth and power efficient as opposed to conventional systems, the core part of the system, which is made up of a transmitter and receiver, will adopt the joint source-channel coding paradigm discussed in the previous chapters.

The transmitter of the video surveillance system consists of a source encoder serially concatenated with a recursive systematic convolutional (RSC) channel encoder. The receiver performs iterative decoding between the source and channel APP decoders. The two decoders are separated by a pseudo-random interleaver.

The coded bit-stream is sent through a highly corrupted wireless noisy channel. The iterative receiver of the serial concatenated system is depicted in Fig. 2. It consists of an inner channel APP decoder and an outer source APP decoder. The two source and channel APP decoders exchange soft reliability decoding information at every iteration, except for the initial iteration when the *a priori* soft input to the source APP decoder is set to zero. The iterative decoding system will exhibit significant bandwidth and power gain provided that the VLC source code used has a large free distance. However, if Huffman codes with $d_f = 1$ are used in the system, the performance gain will be minimal as explained in the previous section. Therefore, in order to exploit the potential gain of the proposed system, it is essential to construct good IDVLCs with larger free distance based on the original Huffman codes.

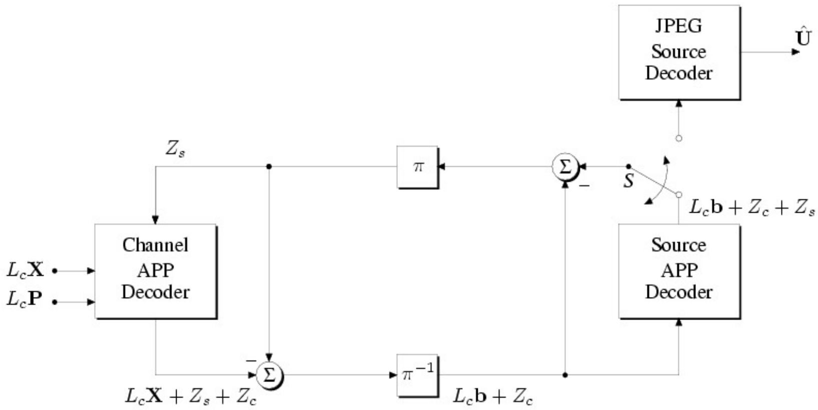

Fig. 2. Joint iterative receiver of the wireless video remote surveillance system

We evaluate the performance of the proposed system architecture on JPEG coded image and video sequences. The JPEG standard adopts Huffman codes as its entropy source code. The DC luminance components of a JPEG image are coded using a 12-entry Huffman DC table. The original JPEG DC Huffman code C_H does not exhibit good convergence behaviour in iterative source-channel decoding due to its poor free distance $d_f = 1$. Using the code design criteria presented in Section 4, we construct three IDVLCs based on the existing Huffman code C_H. Table 1 presents such three codes, *i.e.*, a symmetric RVLC C_1 ($d_b = 1, d_p = 1, d_s = 1$), an asymmetric RVLC C_2 ($d_b = 2, d_p = 1, d_s = 1$), and an asymmetric VLC C_3 ($d_b = 2, d_p = 2, d_s = 3$). Note the probability distribution $\mathcal{P}$ of DC symbols in Table 1 was obtained by training several typical JPEG images. Code C_1 is symmetric that means that it has the nice property of needing only one code table for both forward and backward decoding, which is an advantage from the viewpoint of memory usage and simplicity. Code C_2 and C_3 have $d_f = 2$ at the expense of modestly increased average codeword length.

Table 1. JPEG DC Huffman Code C_H and constructed IDVLC C_1, C_2 and C_3

DC Symbol	Occurrence Probability $\mathcal{P}$	JPEG Lumin. DC Huffman Code C_H	Symmetric RVLC C_1	Asym. RVLC C_2 with $d_f = 2$	Asym. VLC C_3 with PfxDist = 2
0	0.371745	00	00	00	000
1	0.071615	010	111	111	011
2	0.102214	011	010	010	1 0100
3	0.147135	100	101	1101	1 1000
4	0.132812	101	0110	1011	101 1100
5	0.124349	110	1001	0110	110 1100
6	0.049479	1110	1 1011	1 0101	101 1111
7	0.000651	1 1110	0 1110	1 1001	110 1111
8	0.0	11 1110	1 0001	11 0001	
9	0.0	111 1110	01 1110	100 1001	
10	0.0	1111 1110	10 0001	1010 0101	
11	0.0	1 1111 1110	11 0011	1 0011 0011	
Average codeword length		2.6790	2.9857	3.1228	4.7279

6 Experimental platform and results

In this section, we present the experimental platform and simulation results to demonstrate the superior performance of the proposed wireless remote video surveillance system. Fig. 3 illustrates the experimental platform that we developed for the video surveillance system. In Fig. 3, a video camera acts as the video source capture device. The joint iterative source-channel transceiver shown in the figure is the core part of the wireless remote surveillance system, which is made up of two functional blocks, *i.e.*, joint source-channel coding/decoding and modulation/demodulation. The first functional block is implemented via computer software program, whereas the second block is implemented via hardware.

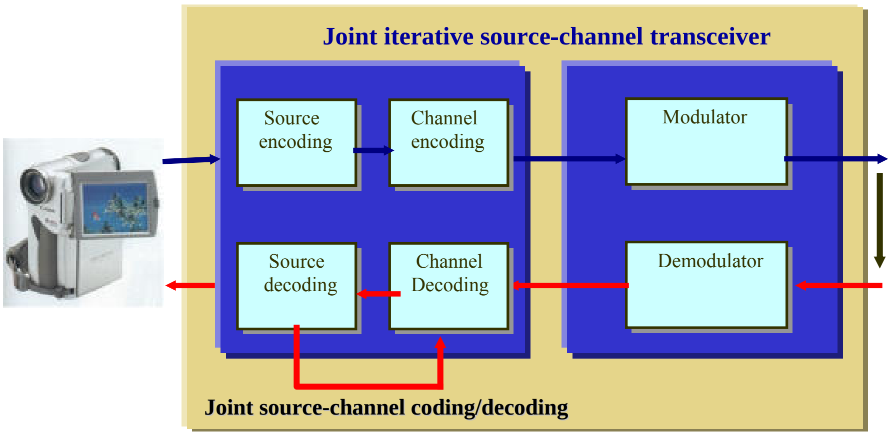

Fig. 3. Experimental platform for wireless remote video surveillance system

For the purpose of demonstrating the performance of the proposed system as opposed to conventional systems, a standard JPEG coded "Lena" 256×256 image is transmitted over a noisy channel. Assume only the DC components of the image are affected by channel noise, and the AC components are transmitted error-free. The 2000 coded DC symbols of the image are protected by a 16-state inner channel code with code polynomials 35/23 in octal notation. The channel coding rate using the reference Huffman code F_K is 1/2. S-random interleavers are used [13]. The interleaver sizes for F_K, C_1, C_2 and C_3#are 5335, 5899, 6221, 9290 with c# #..[#¯ #m#and 71, respectively. We puncture the coded bitstreams so that the overall coding rate is one half for all system configurations.

The objective simulation results regarding the bit error rate (BER) are presented in Fig. 4. As can be seen from the figure, iterative decoding using the proposed iteratively decodable VLC FQ#remarkably outperforms the original JPEG Huffman code F_K. A coding gain of 4 dB is obtained at a BER around e# #ƒH. It is also observed that iterative decoding of the Huffman code F_K#does not yield additional coding gain with increasing number of iterations. The performance improvement nearly stops after two iterations. This observation is consistent with the fact that Huffman codes have very little source redundancy, and a small free distance q_w# #ƒ.

The subjective simulation results regarding the reconstructed images at the receiver using F_Q#at a † ky} H#of 1.5 dB are presented in Fig. 5. It is evident that iterative decoding using F_Q#improves swiftly the quality of the reconstructed images with increasing number of iterations.

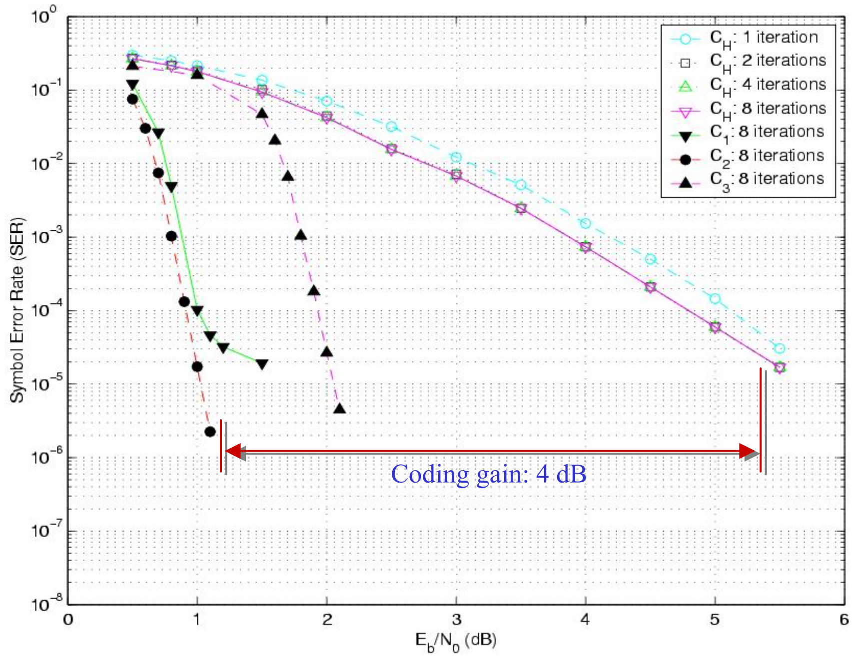

Fig. 4. BER results for iterative decoding using F_K, C_1, C_2 and C_3

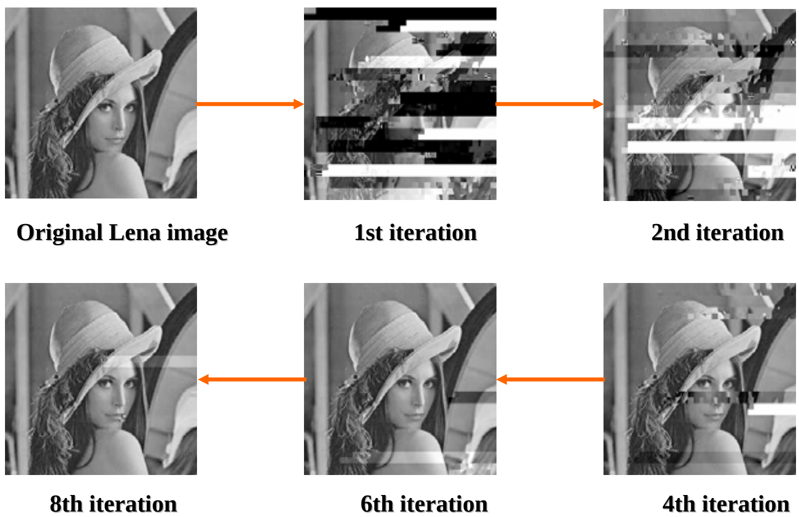

Fig. 5. Lena image decoded by iteration with F_c at a † $_k$y} $_{Hm}$ of 1.5 dB

Both subjective and objective results are in good agreement to confirm the outstanding performance of the proposed system. The 4 dB coding gain observed can be transformed into great power and bandwidth efficiency to outperform considerably conventional systems.

7 Concluding remarks

In this paper, we proposed an innovative wireless remote video surveillance system based on joint source-channel coding using IDVLCs. The proposed video surveillance system exhibits superior bandwidth and power efficiency thanks to the adoption of IDVLCs. The IDVLCs have larger free distance relative to Huffman codes with slightly increased average codeword length.

An experimental platform was built and results were shown to demonstrate the performance of the proposed wireless surveillance system. The objective simulation results in terms of the BER showed a remarkable 4 dB coding gain as opposed to conventional systems, whereas the subject simulation results in terms of reconstructed images were considerably better than those of conventional systems.

8 References

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