The Wavelet/Scalar Quantization Compression Standard for Digital Fingerprint Images

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ABSTRACT

A new digital image compression standard has been adopted by the US Federal Bureau of Investigation for use on digitized gray-scale fingerprint images. The algorithm is based on adaptive uniform scalar quantization of a discrete wavelet transform image decomposition and is referred to as the wavelet/scalar quantization *standard. The standard produces archival quality images at compression ratios of around 20:1 and will allow the FBI to replace their current database of paper fingerprint cards with digital imagery.*

I. INTRODUCTION.

At last count, the US Federal Bureau of Investigation (FBI) had in its possession some 114 million criminal fingerprint cards representing over 29 million individuals (many of them evidently repeat customers). In response to rapidly growing demand within the criminal justice community for faster turn-around time on background checks, the FBI is converting this database from paper to a digital electronic format. Fingerprint images are digitized at a scanning resolution of 500 pixels/inch with 8 bits of gray-scale information. At this level of resolution, a single 1.5 × 1.6 inch rolled fingerprint impression yields about 600 kilobytes of digital data, and an entire card produces about 10 megabytes. Without any data compression, digitizing the FBI's current database would produce around 1,140 terabytes of image data. Besides database storage considerations, there are also significant communications costs involved in fingerprint digitization. Transmitting a single digitized fingerprint card over phone lines at 9600 baud would take almost three hours.

The FBI's Criminal Justice Information Services Division and researchers at Los Alamos National Laboratory and the National Institute of Standards and Technology have developed national standards for fingerprint digitization [1] and lossy image compression [2]. The compression algorithm described below utilizes adaptive uniform scalar quantization of a 64-subband discrete wavelet transform (DWT) image decomposition, followed by zero run-length and Huffman coding. The official specification is referred to as the *wavelet/scalar quantization* (WSQ) standard. Testing by the FBI has shown that the quality of images compressed by the WSQ algorithm is acceptable for archival use at compression ratios of around 20:1. Note that compression ratios on the order of just 2:1 or 3:1 are all that is practically attainable using most conventional lossless compression methods.

Background information on the WSQ standard can be found in [3], and the expository paper [4] contains additional information on the aspects of the standard not covered in Sections III and IV of the present paper.

II. OVERVIEW OF THE WSQ ALGORITHM.

Figure 1 gives an overview of the WSQ algorithm. The algorithm consists of three main steps: a discrete wavelet transform decomposition of the source fingerprint image, scalar quantization of the DWT coefficients, and lossless entropy coding of the quantizer indices.

The DWT in the WSQ algorithm is implemented using a two-channel perfect reconstruction linear phase filter bank [5]. Symmetric extension techniques are used to apply the filters near the image boundaries, an approach that allows transforming images with arbitrary (e.g., odd) dimensions; see [6] for details. This two-channel splitting is applied to both the image rows and columns, resulting in a four-channel, 2-D decomposition. The analysis filter bank is cascaded several times to generate the 64-subband frequency decomposition shown in Figure 2. Selection of this decomposition was based on fingerprint image power spectral estimation and on subjective evaluations of quantization artifacts resulting from various frequency splittings.

The 64 DWT subbands (indicated by parallel arrows in Figure 1) are quantized according to uniform scalar quantization characteristics. The integer indices output by the quantization encoders are entropy-encoded by run-length coding of zeros and Huffman coding. Both the scalar quantizers and Huffman coders are image-specific. The compressed data contains a table of wavelet

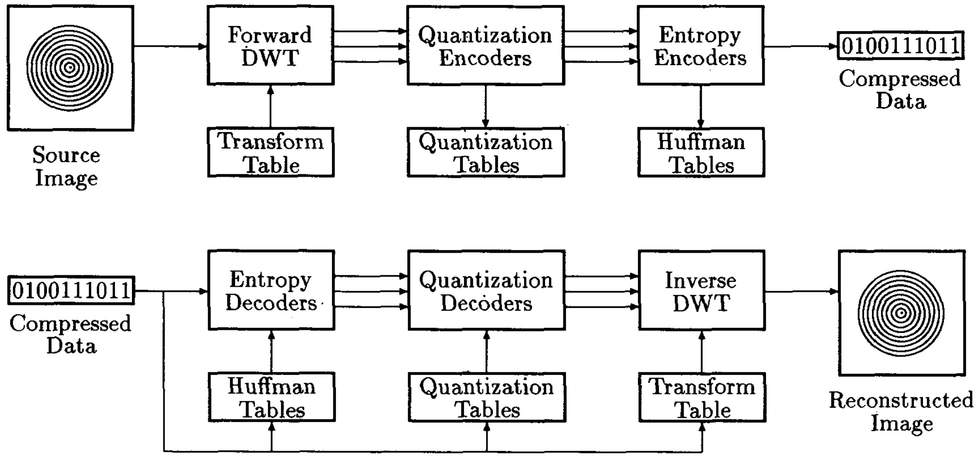

Figure 1: Simplified WSQ Encoder and Decoder Diagrams.

transform specifications and tables for the scalar quantizers and Huffman coders. The WSQ decoder parses the compressed data and extracts the tables needed in the decoding process. To produce the reconstructed image, the decoded, quantized wavelet coefficients are run through an inverse DWT.

The standard specifies a class of encoders and a single decoder with sufficient generality to decode compressed image data produced by any compliant encoder; in particular, we anticipate future refinements in the areas of filter bank and scalar quantizer design. Parameter settings for the first FBI-approved encoder, including filters, quantizer parameters, and Huffman coding specifications, are given in [2]. The FBI specification also includes compliance tests for commercial implementations.

A significant technical problem that affects any lossy data compression application is controlling the quantization process so as to ensure uniformly high reconstructed image quality. In recent work by the authors [7], a bit allocation method was developed for overcoming this problem; the algorithm is discussed in the next section.

III. OPTIMAL BIT ALLOCATION.

Thorough discussions of the problem of optimal bit allocation and its solution can be found in [8, 9]. The basic approach involves constrained optimization of high-rate distortion models, typically solved with Lagrange multiplier techniques.

The function to be minimized in the optimization problem is the mean-square distortion induced by subband quantization. This is modelled by

$$D = \sum_k \frac{1}{m_k} \sigma^2_{e,k} \quad , \tag{1}$$

where m_k is the factor by which the k^{th} subband has been downsampled and $\sigma^2_{e,k}$ is the k^{th} subband's quantization error variance. If the subband decomposition is orthogonal then D is the error variance between the original and reconstructed images. This distortion measure is often used with nonorthogonal transforms (such as the filter banks employed in the WSQ standard), although it no longer coincides exactly with overall mean-square error. However, the use of mean-square error as a distortion measure is based not on perceptual quality, but rather on the mathematical tractability of the resulting optimization problem. A more flexible distortion measure can be defined by weighting the $\sigma^2_{e,k}$ in (1), i.e.,

$$D = \sum_k \frac{1}{m_k} \alpha_k^2 \sigma^2_{e,k} \quad , \tag{2}$$

where the weights α_k are chosen by subjective criteria.

The following model is assumed for $\sigma^2_{e,k}$:

$$\sigma^2_{e,k} = c\, \sigma_k^2\, 2^{-2r_k} \quad , \tag{3}$$

where σ_k^2 is the variance of the k^{th} subband, c is a constant of the data's probability density function, and r_k is the bit rate, in bits/pixel (bpp), to be allocated for coding the k^{th} subband. This relationship assumes high-quality (i.e., high bit rate) quantization [8].

The bit allocation problem specifies that the overall quantization distortion be minimized while maintaining some user-supplied constraint, R, on the overall bit rate (i.e., the overall compression ratio). The problem is formally stated as follows: minimize

$$D = \sum_{k=1}^{M} \frac{1}{m_k} \alpha_k^2\, \sigma_k^2\, 2^{-2r_k} \tag{4}$$

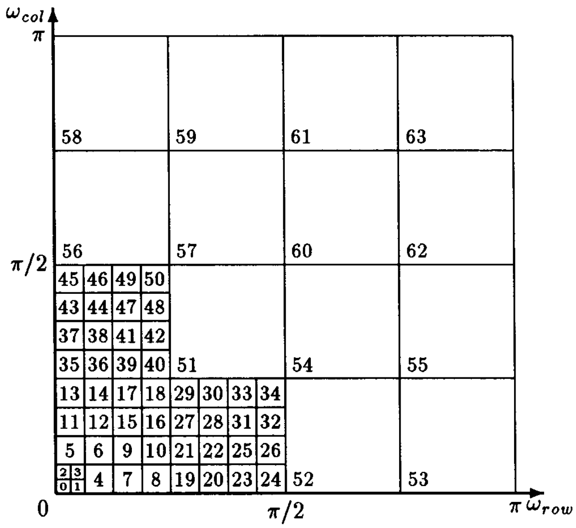

Figure 2: Frequency Support of WSQ DWT Subbands.

subject to

$$\sum_k \frac{r_k}{m_k} = R \quad . \tag{5}$$

The Lagrange multiplier solution to this problem is

$$r_k = R + \frac{1}{2}\log_2 \frac{\alpha_k^2\sigma_k^2}{\prod_i (\alpha_i^2\sigma_i^2)^{1/m_i}} \quad . \tag{6}$$

Since this expression does not ensure nonnegativity for the r_k's, the bit allocation is usually performed by setting negative r_k's to zero.

Relation (5) will not hold if some subbands are discarded (i.e., given a zero bit rate) in order to ensure nonnegativity of the r_k's. To compensate for discarded subbands, we introduce an iterative procedure for correcting the Lagrange multiplier solution when the optimization is no longer being done over the complete family of transform subbands. Let K_j be the set of indices of subbands with positive bit rates at the start of the j^{th} iteration and let S_j be the fraction of the spectrum contained in those bands:

$$S_1 \equiv 1 \quad ; \quad S_j = \sum_{k \in K_j} \frac{1}{m_k} \quad ; \quad S_j < S_{j-1} \leq 1 \quad .$$

The j^{th} iteration of the bit allocation is then given by

$$r_k = \frac{R}{S_j} + \frac{1}{2}\log_2 \frac{\alpha_k^2\sigma_k^2}{\left[\prod_{i\in K_j} (\alpha_i^2\sigma_i^2)^{1/m_i}\right]^{1/S_j}} \quad , \tag{7}$$

for $k \in K_j$. If any of these r_k's are negative, they are set equal to zero, new iterates K_{j+1} and S_{j+1} are constructed, and the r_k's are recomputed. The iteration terminates when all of the remaining r_k's are nonnegative, in which case the final bit allocation satisfies (5) and gives a constrained minimum for (4).

IV. QUANTIZER DESIGN.

We design a quantizer for the k^{th} subband to cover the interval $[\mu_k - \gamma\sigma_k, \mu_k + \gamma\sigma_k]$, where the *loading factor*, γ, is a parameter that specifies the number of standard deviations of data that are being coded (e.g., $\gamma = 2.5$). If L_k is the number of bins in the quantizer and if the bins have a uniform width, Q_k, then this implies

$$Q_k = 2\gamma\sigma_k / L_k \quad . \tag{8}$$

The prescribed transmission bit rate, r_k, determined by the bit allocation procedure can be related to L_k via

$$r_k = \log_2 L_k \quad \text{bits/sample.} \tag{9}$$

This rate (9) will only be achieved in "worst-case" scenarios in which bin indices occur with equal probabilities; if indices are not equally likely then Huffman coding will produce additional coding gain. Equating (7) with (9) and then substituting into (8) to eliminate L_k gives

$$Q_k = \frac{\gamma 2^{1-R/S}\left[\prod_{i\in K} (\alpha_i^2\sigma_i^2)^{1/m_i}\right]^{1/2S}}{\alpha_k} \quad . \tag{10}$$

S is the final fraction of coefficients and K the final set of subband indices not discarded in the iteration. Note that the overall bit rate is determined by the single parameter, R, and the relative interband distribution of resources is determined by the weights α_k and variances σ_k^2. While the selection of the α_k has so far been based on subjective tuning, we hope to relate the selection of these parameters to empirical results based on quantitative models of the human visual system.

In the bit allocation formula derived in this section, the quantity R is the bit rate for the *lossy* portion of the compression process. This neglects lossless gain from Huffman and zero run-length coding of the quantizer indices; the final compression ratio achieved will therefore also depend on the amount of blank area in the fingerprint image. For an image containing all fingerprint ridge detail, the above theory predicts that the actual bit rate achieved would be R bpp, while an image with significant blank regions would come in at a higher compression ratio. This has been confirmed by extensive empirical testing of the algorithm; see [7]. The quantity R is therefore a *quality* parameter: the quality of the compressed image is largely determined by the lossy bit rate constraint, R, rather than by the final compression ratio, which also includes varying amounts of lossless coding gain.

Figure 3: Original Fingerprint Image.

Figure 4: Image After 21:1 WSQ Compression.

Details of an original image and the same image after WSQ compression are shown in Figures 3 and 4. The latter was compressed with a bit rate constraint of $R = 0.6$ bpp, which is approximately the quality level being considered by the FBI; because of additional lossless gain, the final compression ratio came in at 21:1.

V. CONCLUSION.

The first published work on this subject [3] was presented at the 1992 IEEE Computer Society Data Compression Conference by Tom Hopper (FBI) and Fred Preston (UK Home Office). Since that work appeared, the WSQ algorithm has changed significantly in several important aspects, particularly with regard to the DWT subband decomposition and the bit allocation procedure. It is anticipated that some version of the bit allocation procedure described above will be included in future revisions of the standard. A formal specification [2] has been published by the FBI to standardize the electronic exchange of digital fingerprint information within the United States. The UK Home Office has also expressed interest in the WSQ algorithm and is comparing it to their current fingerprint image coding technology. Work is currently under way to develop compliance testing procedures for certifying commercial implementations that comply with the specification. As mentioned above, in the future we also expect to investigate refinements to the encoder design.

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