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Progressive transmission of digital diagnostic images

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Abstract

Progressive transmission of digital pictures permits the receiver to reconstruct an approximate picture first, then gradually improves the quality of image reconstruction. A performance criterion is formulated for the evaluation of alternative schemes. The use of transform coding techniques to achieve progressive transmission is discussed. Application of the concept of progressive transmission to electronic radiology is introduced, and simulation results for individual images and panels of digital diagnostic images are presented. The relative quality of intermediate image reconstruction seems to be superior to that of other progressive transmission techniques.

Introduction

Progressive transmission of digital pictures permits the initial reconstruction of an approximate picture followed by a gradual improvement in the quality of image reconstruction.¹⁻⁶ The technique is useful for the transmission of pictures over low-bandwidth channels such as telephone lines. Teleconferencing and telebrowsing are good examples of prospective applications. The concept of progressive transmission is of particular importance in an electronic radiology environment. A radiologist browsing through many remotely stored pictures of a patient may need to quickly abort transmission of one or more unwanted pictures as soon as they are recognized. Once the desired picture is identified, more information can be transmitted thereby improving the subjective quality of the received picture until a clinical diagnosis is possible.

In order to evaluate the performance of progressive transmission techniques, we assume that the image has already been digitized into an $N \times N$ array of picture elements with L bits per pixel. The performance criterion is as follows:

For X bits transmitted, such that $X < N^2L$, the best progressive transmission system will give the best quality of intermediate image approximations within some complexity limit.

It is worth noting that, by the above criterion, we evaluate the performance of progressive image transmission from the standpoint of data compression. The goal is to use the transmitted information in the most efficient way independent of bit rate. In this paper we discuss the use of transform coding techniques to achieve progressive transmission of digital pictures. In particular, we use the discrete cosine transform, which results in virtually the same energy compaction performance as does the Karhunen-Loeve transform, known to be the best in the sense of minimizing the mean squared error.⁷ Application of the concept of progressive transmission to electronic radiology is introduced, and simulation results for individual images and panels of digital diagnostic images are presented.

Transform coding for progressive transmission

In transform coding of digital pictures,^{8,9} the input image is divided into subblocks, $u_{n,m}$, $n, m = 1, 2, \dots, N/M$, where a subblock is an array of $M \times M$ picture elements. Each subblock $u_{n,m}$ is transformed into $U_{n,m}$ by the linear transformation T , as shown in Figure 1. In the transform domain, $U_{n,m}$ is quantized into $U_{n,m}^d$ by the quantizer Q . Then, the quantized subblock $U_{n,m}^d$ is encoded into $U_{n,m}^{de}$ by the entropy encoder E , and transmitted over the channel. At the receiver end, $U_{n,m}^{de}$ is entropy decoded into $U_{n,m}^d$, dequantized into $\hat{U}_{n,m}$, and inverse-transformed into the reconstruction $\hat{u}_{n,m}$. Transform coding is suitable for progressive transmission of pictures in the sense that an initial subset of transform domain samples yields an approximate picture, while the latter ones add detail. For the purpose of progressive transmission, we define $S_i[U_{n,m}^{de}]$ to be the size, in bits, of the portion of $U_{n,m}^{de}$ transmitted to produce the i th intermediate reconstruction. We note that:

$$S_i[U_{n,m}^{de}] = S_{i-1}[U_{n,m}^{de}] + d_{n,m,i} \quad (1)$$

where $d_{n,m,i}$ is the number of bits transmitted during the i th step in the progression, $i = 1, 2, 3, \dots$, and $S_0[U_{n,m}^{de}] = 0$. At the decoding end, the recently received $d_{n,m,i}$ bits are combined with the previously received $S_{i-1}[U_{n,m}^{de}]$ bits to achieve the i th intermediate reconstruction of $U_{n,m}$. Now, with X_i denoting the accumulated number of transmitted bits to achieve the i th intermediate reconstruction of the entire image, we have:

$$X_i = \sum_{n=1}^{N/M} \sum_{m=1}^{N/M} S_i[U_{n,m}^{de}] \leq N^2L \quad (2)$$

Figure 1. Transform coding.

where equality occurs when all of the transform domain samples are quantized at L bits per pixel and transmitted over the channel.

The question now is how to choose the subsets of transform domain samples and $d_{n,m,i}$ for all n , m , and i . Two points are important here. First, the order in which the transform domain samples are transmitted should be known by both the encoder and decoder such that the decoder can properly accumulate the progressively transmitted data to obtain the intermediate picture approximations. Second, some quality measure for picture reconstruction should be directly or indirectly involved in choosing the progressive subsets of transform domain samples. Chen and Smith⁷ have proposed an adaptive transform coding system for the compression of monochrome and color images. The adaptive system uses a fast discrete cosine transform to provide high energy compaction and to simplify implementation. Elnahas¹⁰ has demonstrated the suitability of this system for the compression of digital diagnostic images from the modalities of computed tomography (CT) and magnetic resonance imaging (MRI). In this paper we discuss how the adaptive approach can be modified to achieve progressive transmission of digital pictures. First, we briefly describe the adaptive system of Chen and Smith.

The activity level of pictures is proportional to the transform domain energy within the pictures. The energy can be associated with image detail. Each dc sample in the transform domain is excluded since it determines only the brightness level. All transform subblocks can then be classified into various groups according to the energy $E_{n,m}$ inside the subblocks, where:

$$E_{n,m} = \sum_{i=1}^M \sum_{j=1}^M [U_{n,m}(i,j)]^2 - [U_{n,m}(1,1)]^2. \quad (3)$$

Adaptivity is achieved by assigning more bits to the subblocks with higher energy levels and fewer bits to the subblocks with lower energy levels. This provides a good quality reconstruction for the high-activity regions and achieves an efficient coding for the low-activity regions. The span of adaptivity must be sufficiently large to draw statistically significant parameters from the image data. Coding in small subblocks meets this requirement and is computationally efficient. For $N = 256$ and $M = 16$, the entire digital image is divided into 256 subblocks, and a two-dimensional fast discrete cosine transform¹¹⁻¹³ is performed on each subblock. A list of subblock energy is then formed and sorted in decreasing order. Next, transform subblocks are classified into four equally populated groups according to the energy levels, and a subblock classification map is constructed. Note that each of the four classification groups will contain 64 subblocks. For each classification group, we next form two 16×16 matrices, a variance matrix v_k and a bit-assignment matrix N_k , where $k = 1, 2, 3, 4$ are the subblock classifications. Using v_k and N_k , the transform domain samples are then normalized, quantized, and entropy encoded. For more details and simulation results, refer to Chen and Smith⁷ or Elnahas.¹⁰

Let us now consider possible modifications suitable for progressive transmission. For example, one might ideally transmit the transform samples $U_{n,m}(i,j)$ in the order of their magnitudes; for all n , m , i , and j . However, this order is not known by the decoder. Transmitting the magnitude order would require a very large amount of side information. Another approach is to transmit the transform samples in the order of the zig-zag sampled pattern.^{14-15,28} This pattern determines the order of transmitting elements from a given subblock. The order of subblocks is not well-defined for achieving reasonable gradual improvements in the quality of progressively reconstructed images. The bit-assignment matrices N_k of the adaptive approach can provide a practical solution to this problem. The details of this solution will be discussed in the following paragraph. First, for practical considerations, we have chosen the segments of progressive data to be of fixed length, that is, we have:

$$\sum_{n=1}^{N/M} \sum_{m=1}^{N/M} d_{n,m,i} = NL \quad (4)$$

for all i . We note that, for $i = N$, $X_N = N^2L$. Therefore, N transform elements, quantized at L bits per pixel, are transmitted at each intermediate step. The final step is the N th step, and the accumulated number of transmitted bits X_N to achieve the final image reconstruction is N^2L . We emphasize that we progressively transmit the transform samples quantized at the full resolution of L bits per pixel. The bit-assignment matrices N_k are used only to tell in what order we transmit the transform samples.

Figure 2. Bit-assignment matrices. (Numbers at the upper-right corners of some locations indicate the order of transmission for Step 1 through Step 5 in the progression.)

The mechanism of using the bit-assignment matrices for determining the order of transmission is best illustrated by an example. Consider the 4x4 low-frequency portions of the 16x16 bit-assignment matrices (see Figure 2). Here, N_1 corresponds to the highest activity level, and N_4 corresponds to the lowest activity level. The full resolution L is assumed to be 8 bits per pixel. In the first step of the progression, all of the dc samples, at location (1,1), are transmitted. In the second step, all elements at locations (1,2), (2,1), and (2,2) are transmitted from the highest activity level, and all elements at location (1,2) are transmitted from the second activity level. In the third step, all elements at location (2,1) are transmitted from the second level, and all elements at locations (1,3), (2,3), and (3,1) are transmitted from the highest activity level. In the fourth step, all elements at location (3,2) from the highest activity level, all elements at location (2,2) from the second level, and all elements at locations (1,2) and (2,2) from the third level are transmitted. In the fifth step, all elements at locations (1,4), (3,3), and (4,2) from the highest activity level, and all elements at location (1,3) from the second level are transmitted. The process is continued in the obvious manner for the rest of the steps in the progression. Therefore, for $N = 256$ and $M = 16$, the four bit-assignment matrices can be used to control the progressive transmission as follows. For each intermediate step, a combination of four entries is chosen from the bit-assignment matrices. Each entry will determine the transmission of 64 transform domain samples from one of the four classification groups of transform subblocks. Entries from the bit-assignment matrices are chosen as the largest entries at the i th step for all i .

A tie-breaking rule is needed in the case of equality of two (or more) largest entries from two (or more) different matrices. As an example, consider the different possibilities of choosing a combination of four entries for the third step from the matrices given in Figure 2. The entry at location (2,1) of N_2 has the largest value of "7," and, therefore, it is one of the four needed entries. For the remaining three entries, we have different possibilities since there are seven largest entries at this point—namely, entries at locations (1,3), (2,3), (3,1), and (3,2) from N_1 ; an entry at location (2,2) from N_2 ; and entries at locations (1,2) and (2,2) from N_3 . All of these entries have the largest value of "6." Our tie-breaking rule was to choose entries at locations (1,3), (2,3), and (3,1) from N_1 as the remaining three entries for the third step in the progression. In other words, we gave the priority of transmission to elements from high-activity regions. By this tie-breaking rule, the quality of reconstruction of the high-activity regions will be improved in the early steps of the progression. Details of the low-activity regions will be added in later steps.

Figure 3 demonstrates the simulation results of the above progressive transmission scheme when applied to the chest CT image of Figure 4(d). The first 48 picture approximations are shown in Figure 3 with the first reconstruction at the upper-left corner. The quality is gradually improved from top to bottom in the first column of picture approximations. The progression is continued at the bottom picture of the second column and is improved from bottom to top in this case. The cycle is repeated every two columns of picture approximations in a cosine-like form. The relative quality of intermediate image approximations can be compared, and recognized as superior, to that of Knowlton,² Burt and Adelson,³ or Takikawa.⁴ The compared image reconstructions should be at the same compression factor. For example, the relative quality of Knowlton's 9th approximation (compression factor of 64:1) should be compared to that of the bottom approximation of the first column in Figure 3, Knowlton's 10th approximation (32:1) should be compared to the top picture approximation of the second column, and so on.

Quantization of the transform coefficients prevents the perfect reconstruction of the transformed images. However, since the transform domain samples are quantized at L bits per pixel, the same intensity resolution as that of the input image, we can expect the sequence

Figure 3. Low-order approximations: (a) 1st through 16th, (b) 17th through 32nd, and (c) 33rd through 48th.

of intermediate image approximations to converge into an almost perfect reconstruction of the input image. In other words, we claim that the subjective quality of the high-order image approximations will be the same as that of the input image, as shown in Figure 4. Quantitatively, Figure 5 shows how the signal-to-noise ratio (SNR) converges reasonably into a high value of 56.5 dB as a function of the order of image approximation. The signal-to-noise ratio for the i th intermediate reconstruction is defined as follows:

$$\begin{aligned} \text{SNR} &= 10 \log_{10} \frac{(\text{peak-to-peak value})^2}{\text{mean square error}} \\ &= 10 \log_{10} \frac{(2L)^2}{\frac{1}{N^2} \sum_{x=1}^N \sum_{y=1}^N [u(x,y) - \hat{u}_i(x,y)]^2} \end{aligned} \quad (5)$$

Figure 4. High-order approximations: (a) 50th, (b) 125th, (c) 225th, and (d) original.

Figure 5. Objective quality of reconstructed images.

Figure 6. Knowlton's approximations vs transform approximations.

where $u(x,y)$ are elements of the input image, and $\hat{u}_i(x,y)$ are elements of the i th intermediate reconstruction. In Figure 6, we compare the SNR values of our intermediate image approximations to those of Knowlton's approximations. An improvement of about 10 dB is achieved for a compression factor of 256:1. The improvement is as high as 17.5 dB for a compression factor of 8:1. We point out that no quality measure has yet been directly involved in choosing the progressive subsets of transform domain samples. Tzou and Elnahas⁶ have included the mean squared error as a quality measure and discussed an optimal progressive quantization scheme. The ability to optimize the different modules of the system is actually why transform coding techniques have a potential promise in achieving more efficient schemes for the progressive transmission of pictures. We conjecture that including a more sophisticated quality measure, based on mathematical models of the human visual system,¹⁶ will considerably improve the subjective quality of intermediate image approximations.

Application to electronic radiology

In radiology, as a result of the increased utilization of digital imaging modalities, such as CT and MRI, over a third of the images produced in a typical radiology department are currently in digital form, and this percentage is steadily increasing.¹⁷ New commercial offerings make it possible to routinely digitize film images for clinical use,¹⁸ and radiology equipment manufacturers are developing products that will produce "standard" examinations, such as chest and bone images, in digital form.¹⁹ This infusion of digital image sources is occurring at a time when significant new technical developments in the field of digital storage and transmission are close at hand, and this has stimulated planning for the development of picture archiving and communication systems (PACS), which are capable of transmitting, storing, processing, and displaying radiologic image data.^{20,21} There are important economic and medical reasons for this trend. Studies show that significant cost benefits can result from electronic storage of medical images,¹⁹ and it is anticipated that the instantaneous, reliable electronic distribution of radiology images to the appropriate clinical decision-making area will expedite the delivery of quality medical care.

The problem of storage cost has impeded the development of a comprehensive electronic image archive. New developments in storage technology, both optical²² and magnetic,²³ promise a potential solution. It has been estimated²⁴ that a large radiology department requires an archive capacity of no more than 0.5 to 2×10^{13} bits per year, a requirement that could be reduced through data compression.^{10,25,26}

Figure 7. Original picture panel of 16 CT images.

Image presentation is an important aspect in electronic radiology. Traditionally, films for critical care patients are kept in the radiology department on one of several multiviewers with rotating panels. Electronic multiviewers have been developed²⁷ to electronically simulate traditional multiviewing environments. Progressive transmission of digital pictures can play a key role in developing efficient schemes of image transmission and presentation. A radiologist will have a means to quickly browse through many remotely stored picture panels. As soon as the desired picture panel is recognized, more panel detail can be progressively transmitted until a particular image within the panel is determined. Next, more details of this particular image can be progressively transmitted such that a clinical diagnosis can be made. We have applied our progressive transmission technique to the panel of 16 CT images shown in Figure 7. The first three approximations are depicted in Figure 8. At this level of picture detail, it could be possible to make a decision on which particular images, within the panel, should be transmitted with sufficient fidelity to make diagnosis possible.

Figure 8. Progressive approximations of picture panels: (a) First, (b) Second, and (c) Third approximations.

Discussion

Progressive transmission of digital pictures is suitable for developing efficient schemes of image transmission and presentation in an electronic radiology environment. The greatest value will be in situations where the picture panels are displayed at remote workstations after transmission over low-bandwidth channels such as telephone lines. Transform coding techniques provide an efficient means for achieving progressive transmission of digital pictures. The relative quality of intermediate image approximations from transform domain coding is superior to that of spatial domain coding. An improvement of about 10 dB is achieved for a compression factor of 256:1. The improvement is as high as 17.5 dB for a compression factor of 8:1. The signal-to-noise ratio converges reasonably into a high value of 56.5 dB as a function of the order of image approximation. This assures that the sequence of intermediate image approximations converges into an almost perfect reconstruction of the input image.

The ability to optimize the different modules of a coding system is actually why transform coding techniques have a potential promise in achieving more efficient schemes for the progressive transmission of pictures. Tzou and Elnahas⁶ have recently proposed an optimal progressive quantization scheme that improves the efficiency of progressive transmission by a factor of two, and it is suitable for hardware implementation. Points for future investigation include optimal entropy coding, incorporating fidelity measures based on models of the human visual system, and developing algorithms for efficient inverse transform of the sparse matrices corresponding to the progressive reconstructions of pictures.

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$$X_i = \sum_{n=1}^{N/M} \sum_{m=1}^{N/M} S_i[\underline{U}_{n,m}^{de}] \leq N^2 L \quad (2)$$

where equality occurs when all of the transform domain samples are quantized at L bits per pixel and transmitted over the channel.

The question now is how to choose the subsets of transform domain samples and $d_{n,m,i}$ for all n , m , and i . Two points are important here. First, the order in which the transform domain samples are transmitted should be known by both the encoder and decoder such that the decoder can properly accumulate the progressively transmitted data to obtain the intermediate picture approximations. Second, some quality measure for picture reconstruction should be directly or indirectly involved in choosing the progressive subsets of transform domain samples. Chen and Smith⁷ have proposed an adaptive transform coding system for the compression of monochrome and color images. The adaptive system uses a fast discrete cosine transform to provide high energy compaction and to simplify implementation. Elnahas¹⁰ has demonstrated the suitability of this system for the compression of digital diagnostic images from the modalities of computed tomography (CT) and magnetic resonance imaging (MRI). In this paper we discuss how the adaptive approach can be modified to achieve progressive transmission of digital pictures. First, we briefly describe the adaptive system of Chen and Smith.

The activity level of pictures is proportional to the transform domain energy within the pictures. The energy can be associated with image detail. Each dc sample in the transform domain is excluded since it determines only the brightness level. All transform subblocks can then be classified into various groups according to the energy $E_{n,m}$ inside the subblocks, where:

$$E_{n,m} = \sum_{i=1}^M \sum_{j=1}^M [U_{n,m}(i,j)]^2 - [U_{n,m}(1,1)]^2 \quad (3)$$

Adaptivity is achieved by assigning more bits to the subblocks with higher energy levels and fewer bits to the subblocks with lower energy levels. This provides a good quality reconstruction for the high-activity regions and achieves an efficient coding for the low-activity regions. The span of adaptivity must be sufficiently large to draw statistically significant parameters from the image data. Coding in small subblocks meets this requirement and is computationally efficient. For $N = 256$ and $M = 16$, the entire digital image is

divided into 256 subblocks, and a two-dimensional fast discrete cosine transform¹¹⁻¹³ is performed on each subblock. A list of subblock energy is then formed and sorted in decreasing order. Next, transform subblocks are classified into four equally populated groups according to the energy levels, and a subblock classification map is constructed. Note that each of the four classification groups will contain 64 subblocks. For each classification group, we next form two 16x16 matrices, a variance matrix v_k and a bit-assignment matrix N_k , where $k = 1, 2, 3, 4$ are the subblock classifications. Using v_k and N_k , the transform domain samples are then normalized, quantized, and entropy encoded. For more details and simulation results, refer to Chen and Smith⁷ or Elnahas¹⁰.

Let us now consider possible modifications suitable for progressive transmission. For example, one might ideally transmit the transform samples $U_{n,m}(i,j)$ in the order of their magnitudes; for all n, m, i , and j . However, this order is not known by the decoder. Transmitting the magnitude order would require a very large amount of side information. Another approach is to transmit the transform samples in the order of the zig-zag sampled pattern^{14,15,28}. This pattern determines the order of transmitting elements from a given subblock. The order of subblocks is not well-defined for achieving reasonable gradual improvements in the quality of progressively reconstructed images. The bit-assignment matrices N_k of the adaptive approach can provide a practical solution to this problem. The details of this solution will be discussed in the following paragraph. First, for practical considerations, we have chosen the segments of progressive data to be of fixed length, that is, we have:

$$\sum_{n=1}^{N/M} \sum_{m=1}^{N/M} d_{n,m,i} = NL \quad (4)$$

for all i . We note that, for $i = N$, $X_N = N^2L$. Therefore, N transform elements, quantized at L bits per pixel, are transmitted at each intermediate step. The final step is the N th step, and the accumulated number of trans-

mitted bits X_N to achieve the final image reconstruction is N^2L . We emphasize that we progressively transmit the transform samples quantized at the full resolution of L bits per pixel. The bit-assignment matrices N_k are used only to tell in what order we transmit the transform samples.

The mechanism of using the bit-assignment matrices for determining the order of transmission is best illustrated by an example. Consider the 4×4 low-frequency portions of the 16×16 bit-assignment matrices (see Figure 2). Here, N_1 corresponds to the highest activity level, and N_4 corresponds to the lowest activity level. The full resolution L is assumed to be 8 bits per pixel. In the first step of the progression, all of the dc samples, at location (1,1), are transmitted. In the second step, all elements at locations (1,2), (2,1), and (2,2) are transmitted from the highest activity level, and all elements at location (1,2) are transmitted from the second activity level. In the third step, all elements at location (2,1) are transmitted from the second level, and all elements at locations (1,3), (2,3), and (3,1) are transmitted from the highest activity level. In the fourth step, all elements at location (3,2) from the highest activity level, all elements at location (2,2) from the second level, and all elements at locations (1,2) and (2,2) from the third level are transmitted. In the fifth step, all elements at locations (1,4), (3,3), and (4,2) from the highest activity level, and all elements at location (1,3) from the second level are transmitted. The process is continued in the obvious manner for the rest of the steps in the progression. Therefore, for $N = 256$ and $M = 16$, the four bit-assignment matrices can be used to control the progressive transmission as follows. For each intermediate step, a combination of four entries is chosen from the bit-assignment matrices. Each entry will determine the transmission of 64 transform domain samples from one of the four classification groups of transform subblocks. Entries from the bit-assignment matrices are chosen as the largest entries at the i th step for all i .

A tie-breaking rule is needed in the case of equality of two (or more) largest entries from two (or more) different matrices. As an example, con-

sider the different possibilities of choosing a combination of four entries for the third step from the matrices given in Figure 2. The entry at location (2,1) of N_2 has the largest value of "7," and, therefore, it is one of the four needed entries. For the remaining three entries, we have different possibilities since there are seven largest entries at this point--namely, entries at locations (1,3), (2,3), (3,1), and (3,2) from N_1 ; an entry at location (2,2) from N_2 ; and entries at locations (1,2) and (2,2) from N_3 . All of these entries have the largest value of "6." Our tie-breaking rule was to choose entries at locations (1,3), (2,3), and (3,1) from N_1 as the remaining three entries for the third step in the progression. In other words, we gave the priority of transmission to elements from high-activity regions. By this tie-breaking rule, the quality of reconstruction of the high-activity regions will be improved in the early steps of the progression. Details of the low-activity regions will be added in later steps.

Figure 3 demonstrates the simulation results of the above progressive transmission scheme when applied to the chest CT image of Figure 4.d. The first 48 picture approximations are shown in Figure 3 with the first reconstruction at the upper-left corner. The quality is gradually improved from top to bottom in the first column of picture approximations. The progression is continued at the bottom picture of the second column and is improved from bottom to top in this case. The cycle is repeated every two columns of picture approximations in a cosine-like form. The relative quality of intermediate image approximations can be compared, and recognized as superior, to that of Knowlton², Burt and Adelson³, or Takikawa⁴. The compared image reconstructions should be at the same compression factor. For example, the relative quality of Knowlton's 9th approximation (compression factor of 64:1) should be compared to that of the bottom approximation of the first column in Figure 3, Knowlton's 10th approximation (32:1) should be compared to the top picture approximation of the second column, and so on.

Quantization of the transform coefficients prevents the perfect reconstruction of the transformed images. However, since the transform domain samples are quantized at L bits per pixel, the same intensity resolution as that of the input image, we can expect the sequence of intermediate image approximations to converge into an almost perfect reconstruction of the input image. In other words, we claim that the subjective quality of the high-order image approximations will be the same as that of the input image, as shown in Figure 4. Quantitatively, Figure 5 shows how the signal-to-noise ratio (SNR) converges reasonably into a high value of 56.5 dB as a function of the order of image approximation. The signal-to-noise ratio for the i th intermediate reconstruction is defined as follows:

$$\begin{aligned} \text{SNR} &= 10 \log_{10} \frac{(\text{peak-to-peak value})^2}{\text{mean square error}} \\ &= 10 \log_{10} \frac{(2^L)^2}{\frac{1}{N^2} \sum_{x=1}^N \sum_{y=1}^N [u(x,y) - \hat{u}_i(x,y)]^2} \end{aligned} \quad (5)$$

where $u(x,y)$ are elements of the input image, and $\hat{u}_i(x,y)$ are elements of the i th intermediate reconstruction. In Figure 6, we compare the SNR values of our intermediate image approximations to those of Knowlton's approximations. An improvement of about 10 dB is achieved for a compression factor of 256:1. The improvement is as high as 17.5 dB for a compression factor of 8:1. We point out that no quality measure has yet been directly involved in choosing the progressive subsets of transform domain samples. Tzou and Elnahas⁶ have included the mean squared error as a quality measure and discussed an optimal progressive quantization scheme. The ability to optimize the different modules of the system is actually why transform coding techniques have a potential promise in achieving more efficient schemes for the progressive transmission of pictures. We conjecture that including a more sophisticated quality measure, based on mathematical models of the human vis-

ual system¹⁶, will considerably improve the subjective quality of intermediate image approximations.

Application to electronic radiology

In radiology, as a result of the increased utilization of digital imaging modalities, such as CT and MRI, over a third of the images produced in a typical radiology department are currently in digital form, and this percentage is steadily increasing¹⁷. New commercial offerings make it possible to routinely digitize film images for clinical use¹⁸, and radiology equipment manufacturers are developing products that will produce "standard" examinations, such as chest and bone images, in digital form¹⁹. This infusion of digital image sources is occurring at a time when significant new technical developments in the field of digital storage and transmission are close at hand, and this has stimulated planning for the development of picture archiving and communication systems (PACS), which are capable of transmitting, storing, processing, and displaying radiologic image data^{20,21}. There are important economic and medical reasons for this trend. Studies show that significant cost benefits can result from electronic storage of medical images¹⁹, and it is anticipated that the instantaneous, reliable electronic distribution of radiology images to the appropriate clinical decision-making area will expedite the delivery of quality medical care.

The problem of storage cost has impeded the development of a comprehensive electronic image archive. New developments in storage technology, both optical²² and magnetic²³, promise a potential solution. It has been estimated²⁴ that a large radiology department requires an archive capacity of no more than $.5 \text{ to } 2 \times 10^{13}$ bits per year, a requirement that could be reduced through data compression^{10,25,26}.

Image presentation is an important aspect in electronic radiology. Traditionally, films for critical care patients are kept in the radiology department on one of several multiviewers with rotating panels. Electronic multiviewers have been developed²⁷ to electronically simulate traditional multiviewing environments. Progressive transmission of digital pictures can play a key role in developing efficient schemes of image transmission and presentation. The greatest value will be in situations where the image panels are displayed at remote workstations after transmission over low-bandwidth channels such as telephone lines. A radiologist will have a means to quickly browse through many remotely stored picture panels. As soon as the desired picture panel is recognized, more panel detail can be progressively transmitted until a particular image within the panel is determined. Next, more details of this particular image can be progressively transmitted such that a clinical diagnosis can be made. We have applied our progressive transmission technique to the panel of 16 CT images shown in Figure 7. The first three approximations are depicted in Figure 8. At this level of picture detail, it could be possible to make a decision on which particular images, within the panel, should be transmitted with sufficient fidelity to make diagnosis possible.

Discussion

Progressive transmission of digital pictures can play a key role in developing efficient schemes of image transmission and presentation in an electronic radiology environment. The greatest value will be in situations where the picture panels are displayed at remote workstations after transmission over low-bandwidth channels such as telephone lines. Transform coding techniques provide an efficient means for achieving progressive transmission of digital pictures. The relative quality of intermediate image approximations from transform domain coding is superior to that of spatial domain coding. An improvement of about 10 dB is achieved for a compression factor of 256:1. The improvement is as high as 17.5 dB for a compression factor of 8:1. The signal-to-noise ratio converges reasonably into a high value of 56.5 dB as a

function of the order of image approximation. This assures that the sequence of intermediate image approximations converges into an almost perfect reconstruction of the input image.

The ability to optimize the different modules of a coding system is actually why transform coding techniques have a potential promise in achieving more efficient schemes for the progressive transmission of pictures. Tzou and Elnahas⁶ have recently proposed an optimal progressive quantization scheme that improves the efficiency of progressive transmission by a factor of two, and it is suitable for hardware implementation. Points for future investigation include optimal entropy coding, incorporating fidelity measures based on models of the human visual system, and developing algorithms for efficient inverse transform of the sparse matrices corresponding to the progressive reconstructions of pictures.

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Figure 1: Transform Coding

8	¹	7	²	6	³	5	⁵
7	²	7	²	6	³	4	
6	³	6	⁴	5	⁵	3	
4		5	⁵	3		3	

N_1

8	¹	7	²	5	⁵	4	
7	³	6	⁴	5		4	
5		5		5		3	
3		3		3		3	

N_2

8	¹	6	⁴	4		2	
5		6	⁴	4		2	
3		3		3		1	
1		1		1		0	

N_3

8	¹	4		2		1	
4		3		2		1	
1		1		2		0	
1		1		0		0	

N_4

Figure 2: Bit-assignment Matrices.
 (Numbers at the upper-right corners of some locations indicate the order of transmission for Step 1 through Step 5 in the progression.)

(a)

(b)

(c)

Figure 3: Low-order Approximations;
 (a) 1st through 16th,
 (b) 17th through 32nd, and
 (c) 33rd through 48th

(a)

(b)

(c)

(d)

Figure 4: High-order Approximations;
(a) 50th, (b) 125th,
(c) 225th, and (d) original

Figure 5: Objective Quality of Reconstructed Images

Figure 6: Knowlton's Approximations vs. Transform Approximations

Figure 7 : Original Picture Panel of 16 CT Images

(a)

(b)

(c)

Figure 8 : Progressive Approximations of Picture Panels;
 (a) First, (b) Second, and (c) Third Approximations