MULTIRESOLUTION BROADCAST FOR DIGITAL HDTV USING JOINT SOURCE-CHANNEL CODING

K. Ramchandran * *A. Ortega* † *K.M. Uz* ‡ *M. Vetterli* §

Department of Electrical Engineering
and Center for Telecommunications Research,
Columbia University,
New York, N.Y. 10027

ABSTRACT

In the context of digital terrestrial broadcast of High Definition Television (HDTV), the use of multiresolution joint source-channel coding is shown to provide an attractive alternative to traditional single resolution (SR) digital techniques. While SR schemes suffer from a sharp threshold effect in the fringes of the broadcast area, we show how a matched multiresolution approach to both source and channel coding can provide a stepwise graceful degradation. Furthermore, this multiresolution approach improves the behavior, in terms of coverage and robustness of the transmission scheme, over systems that are not specifically designed for broadcast situations. This paper examines the alternatives available for multiresolution transmission, through embedded modulation, possibly trellis-coded to increase coverage range. From a systems point a view, we also discuss the trade-offs involved in the choice of coverage areas for the low and high resolution signals.

1. INTRODUCTION

Recent advances in video compression techniques have spurred interest in the idea of digital HDTV. Even the most demanding delivery mechanism, namely terrestrial broadcast, might turn digital. Digital broadcast differs from digital point-to-point transmission in that different receivers have different channel capacities, i.e. channel capacity decreases with distance from the emitter. Furthermore, in a digital environment, the transition from reliable to unreliable reception is very abrupt, creating the so-called threshold effect. Hence, if digital broadcast is tackled as a single resolution (SR) problem, one would in effect be designing for the fringes of the coverage area, thus reducing the spectral efficiency in areas close to the emitter, as pointed out in [1]. In light of the current interest in digital terrestrial broadcast of HDTV in the U.S., the concern for *spectral efficiency* becomes even more pressing, especially given the conditions set by the FCC in terms of bandwidth allocation.

The approach of designing for the fringes is known from information theory to be suboptimal: when dealing with different channels, one can do better than to transmit only for the worst one, or to perform "naive" time or frequency multiplexing between the different channels. Cover [2] showed that one could trade capacity from the poor channels for more capacity in the better ones, and that the trade-off can in theory be worthwhile. These ideas point out the efficiency of using a multiresolution (MR) approach to digital broadcast. However, to the best of the authors' knowledge, no real end-to-end digital system has been designed using these results.

We approach this problem as one of joint source and channel coding in a *multiresolution (MR) framework*, extending our work of [3]. We assume a simple additive white Gaussian noise channel model, with more complicated models requiring further study. See Figure 1 for an example of a two-resolution system. We refer the reader to [4] for a more comprehensive treatment of what is summarized in this paper. In the two-resolution case, the source is split into "base" information, the coarse channel, and "refinement" information, the fine channel[5]. As in Figure 1, the idea is to match the different resolution levels to different channel capacities, thus creating a *MR channel coding scheme*, so that the receiver closer to the emitter can decode the full quality signal, while the distant receiver has access to the lower resolution quality, providing a stepwise graceful degradation. Furthermore, we show that the use of error concealment in the source decoder of a MR system improves the robustness of the full resolution signal, thus increasing the coverage of "indistinguishable quality" delivery over SR schemes.

We explore the available alternatives to an embedded transmission design and show how MR modulation schemes, combined with trellis coded modulation (TCM) techniques, can be used for this purpose. Note that Error Correcion Codes (ECC's) can be combined with modulation techniques, but their study goes beyond the scope of this paper. Refer to [4] for a detailed treatment. We consider, in our experiments, a specific high quality MR HDTV coder [5] whose coarse resolution to detail resolution bit rates are in the ratio of 1:2. We assume a spectral efficiency of 6 bits/symbol for our specific example, though, depending on

*Work supported in part by the New York State Science and Technology Foundation's CAT.

†Work supported in part by the Fulbright Commission and the Ministry of Education of Spain.

‡Work supported by the National Science Foundation under grants ECD-88-11111. K.M.Uz is now with David Sarnoff Research Center in Princeton, NJ 08543

§Work supported in part by the National Science Foundation under grants ECD-88-11111 and MIP-90-14189.

[5]Note that, throughout this paper, we use "coarse" synonymously with the lower resolution channel and "detail" or "fine" with the refinement or augmentation channel of the two-resolution hierarchy

the available broadcast bandwidth, other scenarios may use 3-4 bits/symbol. We evaluate the performance of the system in terms of both coverage area and subjective quality.

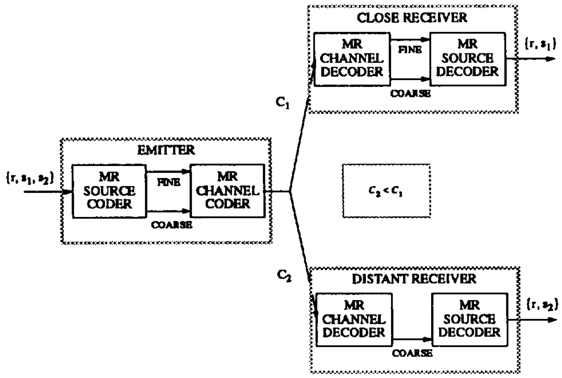

Figure 1: Block diagram of a multiresolution digital broadcasting scheme shown for two receivers with channel capacities C_1 and C_2 with $C_2 < C_1$.

2. MATCHED MR SOURCE CHANNEL CODING

For the broadcast or multichannel environment, where a source communicates with a multitude of receivers of varying strengths, Cover [2] established that optimal broadcast scenarios are multiresolution or embedded in character. This justifies the choice of a multiresolution (MR) source coding scheme to represent a source compactly in a hierarchy of resolutions, to which a "matched" MR transmission can be designed in order to produce an efficient end-to-end design.

While the problem of joint source and channel coding has been addressed previously in various coding contexts, in this paper, we propose the idea of designing an end-to-end joint MR system, i.e. *one which includes a MR channel coding scheme (an analog MR constellation), possibly using a MR Trellis Coded Modulation (TCM).*

Figure 2 outlines the importance of employing a joint design. For the different receiver Carrier-to-Noise Ratios (CNR's) throughout the broadcast area, the MR digital transmission system (see Figure 2(a)) can reliably deliver different user bit rates. The idea is to design the MR source and channel coders so that their delivered rates are efficiently matched. The channel rates correspond to the MR modulation scheme, while the source rates refer to the different resolutions of the source coder, whose characteristics are shown in Figure 2(d) [6], resulting in the broadcast characteristics of Figure 2(c).

We explain how the MR channel coder curve, which we attempt to match to the MR source coder, can be designed

[6] Note that SNR is a source quality measure, while CNR is a channel quality measure.

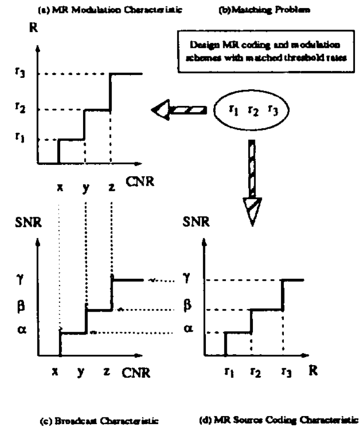

Figure 2: Matching of MR source and channel coders for desired broadcast characteristics. (a) MR channel coder characteristics (Rate vs. CNR). (b) Matching of threshold rates of channel and source coders to achieve desired broadcast characteristics. (c) Achieved broadcast characteristics. (d) MR source coder characteristics (SNR vs. Rate).

using the concept of embedded transmission, using a modulation parameter λ. Note that while embedded transmission for broadcast is efficient even for a single resolution source, it is even more natural to invoke when the source coder is hierarchical in nature. Refer to [5] for a description of our MR video coder, a three-dimensional pyramidal decomposition, based on spatiotemporal interpolation, forming a hierarchy of video signals at increasing temporal and spatial resolutions.

3. MULTIRESOLUTION TRANSMISSION: EMBEDDING

The problem of efficient communication of digital information from a single source to multiple receivers with various CNR's is key to digital broadcast of HDTV. An efficient end-to-end broadcast system should have its *transmission constellation matched to its source coding scheme,* and this is the crux of our work, which we undertake in a *multiresolution environment.*

3.1. Efficiency of using embedding for digital broadcast

Figure 1 depicts a source wishing to convey information $\{r, s_1\}$ to a stronger receiver and $\{r, s_2\}$ to a weaker one. Note that r represents the common message to be conveyed to both receivers. In [2], Cover establishes the efficiency of superimposing information, i.e. broadcasting in a multiresolution embedded fashion, where the *detailed information meant for the stronger receiver necessarily includes the coarse information meant for the noisier receiver.* The efficiency of embedded broadcast, in terms of theoretically deliverable bitrate, compared to independent sharing of the broadcast channel resources in time or frequency among the

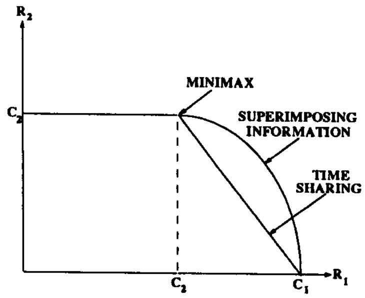

Figure 3: Set of achievable broadcast bitrates for receivers 1,2.

receivers is depicted in Figure 3, where the superior curve is obtained by superimposing the detail information within the coarse information. That is, the superior receiver 1, in an optimal scenario, necessarily has access to the information $\{r, s_2\}$ meant for the weaker receiver 2. While the plot portrays the theoretically attainable capacity due to embedding, in this work, we show a practical way of realizing this gain.

3.2. Embedding in the modulation domain

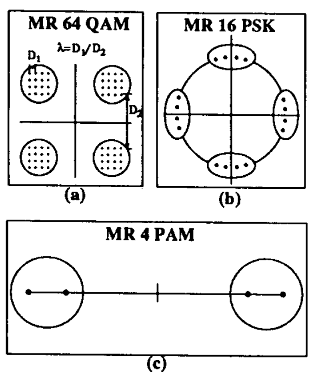

Figure 4: Some multiresolution constellations: (a) MR 64 QAM, (b) MR 16 PSK, (c) MR 4 PAM.

Cover's concept of embedding the coarse information within the detailed information is generic in scope, and places no restrictions on the domain in which the embedding should be performed. To describe the effect of an analog domain embedded modulation, we refer to Figure 4 to point out some typical MR embedded modulation constellations. The basic idea is that each constellation consists of "clouds" of mini-constellations or "satellites," where the detail information is represented in the satellites, while the coarse information is carried in the clouds. Thus, the loss of coarse information is associated with the receiver's inability to decipher correctly which cloud was transmitted, while the loss of refinement information occurs from the receiver's confusing one intracloud signal point for another. The decoder first decodes the likeliest cloud (coarse information), "subtracts" the decoded cloud value from the received point, and then decodes the likeliest satellite within the cloud (detail information). Thus, the MR 64 QAM constellation of Figure 4(a) has 6 bits/symbol, of which 2 bits are coarse (4 clouds) and 4 bits are detail (16 satellites/cloud). Similarly, the MR 16 PSK scheme has 2 coarse bits/symbol and 2 detail bits/symbol, while the 4 PAM constellation has 1 bit/symbol of each.

3.2.1. MR 64-QAM

For our specific source coder, we consider as Example A the MR 64 QAM constellation of Figure 4(a). By "matching" the relative distances between intra-cloud constellation points (D_1) and inter-cloud points (D_2), whose ratio is a design parameter λ, (see Figure 4(a)) to the relative "information contents" of the two bitstreams, one obtains an efficiently designed joint MR source/MR transmission system. One could determine an optimal "broadcast λ" if a meaningful cost function over the broadcast area (which would probably include factors like population density) is available.

In order to prevent error propagation, we packetize the source data into packets of composite length 1080 bits, with 1/3 coarse bits and 2/3 detail bits, in accordance with the 1:2 MR source stream. It must be emphasized that the topology of the equivalent perceived constellation at the broadcast receiver is a function of the CNR and λ. Qualitatively, the CNR affects the "radius" of the constellation as seen at the receiver for a fixed noise variance, while λ affects the relative distances between intercloud and intracloud points. As λ goes from 0 to 1, the intracloud and intercloud thresholds decrease and increase, respectively, for a fixed power budget. Due to favored protection of the coarse stream via the parameter λ, it is possible for the fine packet component to be corrupted, while the coarse packet component is received reliably *for the same composite packet.*

3.3. Embedded TCM constellation

In order to increase reliability of reception over the demanding broadcast channel and to increase coverage area, it may be necessary to add more redundancy to protect the broadcast information. As is well known, convolutional codes employing a Euclidean distance metric can achieve better performance for the same complexity than the more commonly used block ECC's, which use a "hard limiting" Hamming distance metric. Convolutional (trellis) codes achieve coding gain by using soft decoding with the Viterbi algorithm. It is possible to achieve almost all the coding gain theoretically possible, i.e. to approach the Shannon limit, by expanding the 2-D modulation constellation by a factor of 2, and using a redundant constellation via Trellis Coded Modulation, as established by Ungerboeck [6]. *The novelty here is that we combine the concept of multiresolution with* *the power of TCM to propose an embedded TCM modulation* for efficient broadcast of a MR source (see Figure 5). Simulations verify that a simple 4-state Ungerboeck trellis provides a coding gain of 3 dB/symbol in CNR for the fine channel, while the coarse channel performance remains unaffected. We call this Example B.

Embedded TCM 128-QAM

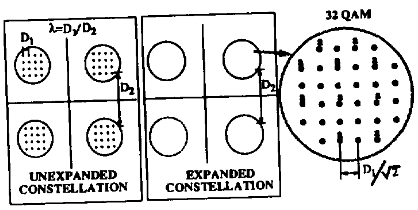

Figure 5: Example B: Expansion of MR 64 QAM into MR-TCM 128 QAM with an expansion in constellation points of each cloud from 16 to 32. Note that the coarse channel is unaffected. The first level of set partitioning is shown with the set marked "'a" and the complementary set.

4. DISCUSSION OF λ-MODULATION AND MR-TCM SCHEMES

The λ-modulation scheme of Example A might be used to provide a desired coverage range for the coarse-resolution signal, and a "basic" coverage for the fine channel, with the MR TCM scheme of Example B used to increase the full-resolution coverage area using an embedded TCM for the fine channel. An important feature of our MR system is that due to inclusion of *error concealment techniques* at the decoder, it is possible to obtain indistinguishable full-resolution quality even at a fine-channel packet loss rate exceeding 10^{-1}. As verified by simulations (see [4]) at this high detail channel loss rate, one gets marginal return from using trellises over 4 states, thus making the MR-TCM design nearly optimal with only a simple 4-state trellis! It is important to note that this scheme permits operation with *no decrease in source coding bit rate* over that of an uncoded system, but it requires an expanded modulation constellation. Thus, Example B seems like an attractive digital broadcast transmission scheme if it can meet the coverage and quality demands.

5. COMPARISON OF MR EMBEDDED, MR INDEPENDENT, AND SR CONSTELLATIONS

Simulations were carried out for an Additive White Gaussian Noise (AWGN) channel for the MR embedded, MR independent, and SR constellations. The independent case refers to separate transmission of the coarse and fine channels using "naive" independent multiplexing of the frequency spectrum. To ensure fairness of comparison, all three cases were tailored to operate under conditions of equal power and equal spectral efficiency (i.e. throughput/bandwidth).

To compare the MR vs. independent constellations, a MR 64-QAM (of free parameter λ), and a 16/256 QAM (coarse/fine) independent constellation pair were picked. The independent channels have a spectral efficiency of 4 bits/symbol and 8 bits/symbol, or an average spectral efficiency (6 bits/symbol) identical to that of the MR 64-QAM for a 1:1 multiplexing ratio between the fine and coarse symbols in either time or frequency. Simulations verify the superiority of an embedded constellation over independently multiplexed constellations for the coarse and fine information. For example, using a MR 64 QAM of Figure 4(a), for values of λ from 0.2 to about 0.4, one can obtain *superior performances for both coarse and detail channel* over those of the multiplexed case (using 16 QAM/ 256 QAM). Other multiplexed constellations can be beaten by embedding with other λ values. This is a verification of the information theoretical result that embedding outperforms multiplexing.

A comprehensive picture is provided in Figure 6(a), where a plot of received quality (SNR) vs. receiver CNR is shown, which results from using perceptually consistent thresholding at coarse and fine packet loss probabilities of 10^{-3} and 10^{-1} respectively. As seen from Figure 6 (a), the MR constellation outperforms the independent one over all ranges of CNR's for a range of λ values (e.g. λ=0.2).

In our comparison, we assume that the SR source coder is 16% more efficient than the MR coder, a "worst case" analysis from the MR point of view. Under these conditions, the SR channel could afford a 32-QAM modulation scheme for the same transmitter power as the MR 64-QAM scheme due to a source compression advantage of roughly 5/6. The results shown in Figure 6(b) indicate the tradeoffs involved. As can be seen by comparing the SR scheme with, say, the MR embedded scheme with $\lambda = 0.5$, the broadcast coverage area is much greater for the MR scheme, at the price of some mid-region suboptimality. A point to note in favor of the MR scheme is the increase in full-resolution quality coverage area made possible by performing error concealment techniques. The SR scheme loses this advantage as it has no coarse resolution channel to fall back upon.

5.1. Error concealment

The source coder we have used [5] is based on a finite memory structure, and errors would not accumulate but die out within a few time samples. This structure used in conjunction with the MR modulation also allows very successful error concealment. As verified by simulations, for typical values of λ, at the same CNR's for which the fine channel packet error rate is greater than 10^{-1}, *the coarse channel is almost perfect* (packet error rate less than 10^{-9}).

Our motion-compensated previous frame replacement concealment strategy [4] gives excellent results even in extreme cases of packet loss due to a noisy channel. Complete loss of a frame can be tolerated, and sustained 15% packet loss rate causes no visible loss in quality. Figure 7 illustrates the power of error concealment in a MR environment for the case of a 15% fine-packet loss channel (obtained for λ=0.5, CNR=25.5 dB/symbol) on the spatial residual of the sequence.

Figure 7: Effect of channel noise for λ=0.5,CNR=25.5 dB/symbol (15% fine-channel packet loss): Full resolution reconstruction after error concealment. Original image is 512x512

6. CONCLUSION

We have demonstrated a multiresolution (MR) joint source channel coding system, where using a source coder matched to an embedded trellis-coded modulation constellation has been shown to provide an efficient end-to-end MR system. The threshold effect plaguing single resolution (SR) systems is softened by a stepwise graceful degradation reminiscent of analog systems, without sacrificing the source coding advantage of digital schemes. We show the superiority of an embedded MR transmission scheme over independent transmissions of the MR source resolutions, and point out the tradeoffs in robustness and broadcast area coverage of low and high resolutions between embedded MR and SR digital systems for QAM constellations, highlighting the benefits of deploying joint MR source and channel coding.

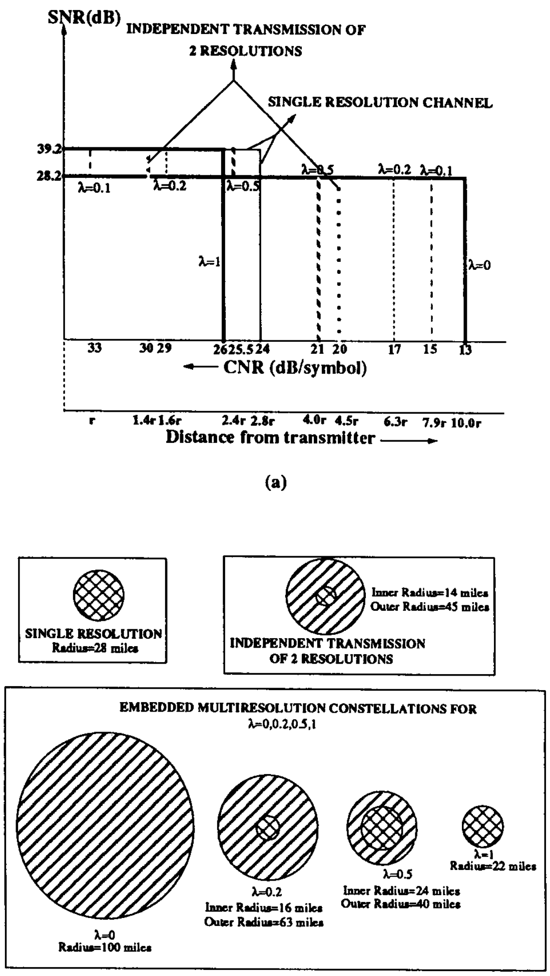

Figure 6: Typical broadcast environment (a) SNR vs. Receiver CNR. (b) Broadcast ranges for the different constellations.

REFERENCES

[1] W. F. Schreiber, "Considerations in the design of HDTV systems for terrestrial broadcasting," *Electronic Imaging*, Oct. 1990.

[2] T. Cover, "Broadcast channels," *IEEE Transactions on Information Theory*, vol. IT-18, pp. 2–14, Jan. 1972.

[3] K. M. Uz, K. Ramchandran, and M. Vetterli, "Multiresolution source and channel coding for digital broadcast of HDTV," in *Proceedings Fourth International Workshop on HDTV and beyond, Torino*, Sept. 1991.

[4] K. Ramchandran, A. Ortega, K. M. Uz, and M. Vetterli, "Multiresolution joint source and channel coding for digital broadcast of HDTV," *Submitted to IEEE Journal on Selected Areas in Communications*, 1991.

[5] K. M. Uz, M. Vetterli, and D. LeGall, "Interpolative multiresolution coding of advanced television with compatible subchannels," *IEEE Transactions on CAS for Video Technology, Special Issue on Signal Processing for Advanced Television*, vol. 1, pp. 86–99, Mar. 1991.

[6] G. Ungerboeck, "Channel coding with multilevel/phase signals," *IEEE Transactions on Information Theory*, vol. IT-28, pp. 55–67, Jan. 1982.