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Multimedia Communication Over OFDM Mobile Wireless Networks: A Cross-Layer Diversity Approach

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Abstract— **Diversity can be used to combat multipath fading and improve the performance of mobile wireless multimedia communication systems. In this work, by considering transmission of an embedded bitstream over a slow varying Rayleigh faded environment, we develop a cross-layer diversity technique which takes advantage of both multiple description source coding and frequency diversity techniques. More specifically, assuming a frequency-selective channel, we study the packet loss behavior of an OFDM system and construct multiple independent descriptions using an FEC-based strategy. We demonstrate the superior performance of this approach using the Set Partitioning in Hierarchical Trees (SPIHT) coder.**

I. INTRODUCTION

Diversity is an important technique to improve the performance of mobile wireless systems over fading channels. Diversity can be exploited through channel coding across parallel fading components at the physical layer. Diversity can also be exploited through source coding techniques, specifically multiple description coding. Analogous to the physical layer diversity techniques offered by channel coding, this has sometimes been referred to as *application layer diversity* [1].

A multiple description source coder generates multiple independent bitstreams of the source such that each description individually describes the source with a certain level of fidelity. Due to the individually decodable nature of the multiple descriptions, the loss of some of the descriptions will not jeopardize the decoding of correctly received descriptions, while the fidelity of the received information improves as the number of received descriptions increases.

Most research has focused on either physical layer or application layer diversity. In this paper, we investigate physical layer diversity and application layer diversity simultaneously. In particular, by considering transmission of a progressive bitstream using an orthogonal frequency division multiplexing (OFDM) system, we develop a cross-layer diversity technique which takes advantage of both the application layer and the physical layer diversities. More specifically, based on the order of diversity, we combine the concept of frequency diversity with the construction of multiple independent descriptions using an FEC-based strategy [2], [3], [4].

The remainder of this paper is organized as follows: In Section II, we describe the channel model. In Section III, we provide an overview of FEC-based multiple description source coding. In Section IV, we describe the proposed cross-layer diversity approach and discuss some of the associated tradeoff issues. In Section V, we study the packet loss probability mass function associated with multimedia transmission over a frequency-selective fading channel. In Section VI, we provide some simulation results and discussion. Finally, Section VII gives a summary and conclusions.

II. CHANNEL MODEL

In this work, we assume a frequency-selective environment and use a block fading channel model to simulate the frequency selectivity [5]. In this model, the spectrum is divided into blocks whose size equals the coherence bandwidth (Δf_c). Subcarriers in different blocks are considered to be independent; subcarriers in the same block experience identical fades. We assume an OFDM system with an overall system bandwidth W_T such that we can define N independent channels. Each of the N independent channels consists of M correlated subcarriers spanning a total bandwidth approximately equal to Δf_c. As a result, the total number of subcarriers in the OFDM system is equal to $N_t = N \times M$. In the time domain, we assume the channel experiences slow Rayleigh fading.

Due to the frequency-selectivity of the multiple parallel channels, frequency diversity can be applied to combat channel errors. This can be achieved, for example, by sending signals that carry the same information through different channels so that multiple independently faded replicas of the information symbol can be obtained and a more reliable reception can be achieved. However, in essence, this comes at the expense of a reduced information rate. On the other hand, by transmitting independent data streams in parallel through the independent spectral channels, the information rate can be increased at a price of sacrificing frequency diversity. Hence, there is a tradeoff between the information rate and the diversity gain, which is essentially a tradeoff between the error probability and the data rate of the system.

III. FEC-BASED MULTIPLE DESCRIPTION CODING

We first provide a brief overview of FEC-based multiple description coding [4], [2], [3] in which maximum distance sep-

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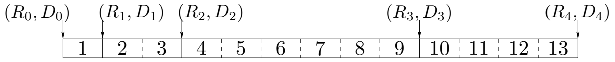
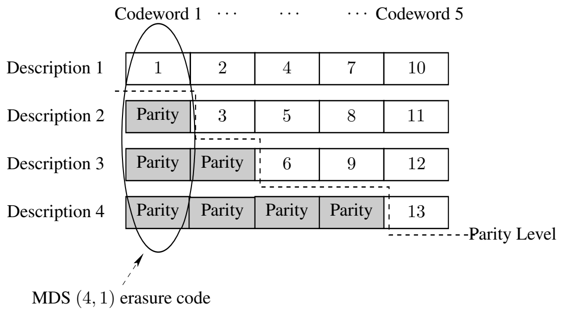


(a) An embedded description from the source coder partitioned into 5 quality levels of Rate R_g and distortion $D(R_g) = D_g, g = 0, 1, \ldots, 4$.



(b) $n = 4$ independent and equally important descriptions.

Fig. 1. Illustration of the FEC-based multiple description coding technique for an embedded bitstream with $n = 4$ descriptions.

arable (MDS) (n, k) erasure codes are used to construct multiple independent bitstreams under a joint source-channel coding framework. Fig. 1(a) shows a typical embedded bitstream, in which the source can be reconstructed progressively from the prefixes of the bitstream, while an error generally renders the subsequent bits useless. In Fig. 1(b), we illustrate the general mechanism for converting an embedded bitstream from a source encoder into multiple descriptions in which contiguous information symbols are spread across the multiple descriptions. The information symbols are protected against channel errors using systematic $(n = 4, k)$ MDS codes, with the level of protection depending on the relative importance of the information symbols. An (n, k) MDS erasure code can correct up to $n - k$ erasures. Hence, if *any* g out of n descriptions are received, those codewords with minimum distance $d_{min} \geq n - g + 1$ can be decoded. As a result, decoding is guaranteed at least up to distortion $D(R_g)$, where $D(R_g)$ refers to the distortion achieved with R_g information symbols. For example, in Fig. 1(b), we show the construction of a $(4, 1)$ systematic MDS code (codeword 1) in which erasure of any three descriptions still allows us to reconstruct information symbol 1 and achieve a delivered quality at least equal to $D(R_1)$.

IV. A CROSS-LAYER DIVERSITY TECHNIQUE AND SOME TRADEOFF ISSUES

A. *System Description and Problem Formulation*

In this section, we describe the proposed coding scheme using the cross-layer approach combining application layer and physical layer diversity techniques. In order to illustrate the basic ideas, we only consider frequency diversity techniques achieved by coding across the subcarriers using the class of MDS Reed-Solomon (RS) codes, without considering either time diversity or space diversity techniques.

As illustrated in Fig. 2, based on the total number of subcarriers (N_t) of an OFDM system, an embedded bitstream is first converted into $N_t = N \times M$ approximately[1] equally important descriptions using the FEC-based multiple description coder. The multiple description source encoder chooses unequal error protection (UEP) using the class of RS codes based on the rate-distortion curve of the source, the channel conditions, and the degree of diversity available at the physical layer. In this work, each code symbol consists of 8 bits, or equivalently 4 QPSK symbols. Two bytes of a cyclic redundancy check (CRC) code are appended to each description for error detection. The N_t individual descriptions are then mapped to the N_t subcarriers and transmitted through the OFDM system. If any of the subcarriers/channels experience deep fades and are lost, the source can still be recovered from other correctly received subcarriers with a fidelity depending on the number of correctly received descriptions.

Given N i.i.d. channels, each with M subcarriers and packet size equal to L code symbols[2], we assume that for codeword l, c_l code symbols are information data symbols. Hence, the number of parity symbols assigned to codeword l is

$$f_l = N_t - c_l \qquad l \in [1, L]. \tag{1}$$

Let ϕ_{th} be the minimum number of descriptions that a decoder needs to reconstruct the source and g be the number of correctly received packets. The reception of any number of packets $g \geq \phi_{th}$ leads to improving image/video quality $D(R_g)$, where R_g, the information rate, in terms of the number of MDS symbols, is given by

$$R_g = \sum_{\{l: c_l \leq g\}} c_l. \tag{2}$$

Hence the overall channel coding rate equals $R_c = (R_{N_t} + R_{CRC})/(N_t \times L)$, where R_{CRC} is the bit budget for CRC codes. Given the source coding rate-distortion curve $D(R_g)$ and the packet loss probability mass function $P_{\mathcal{J}}(j)$, where j is the number of lost packets such that $j = N_t - g$, we can then minimize the expected distortion

$$E^*[D] = \min_{\{c_l\}} \left\{ \sum_{j=0}^{N_t - \phi_{th}} P_{\mathcal{J}}(j) D(R_{N_t - j}) + \sum_{j=N_t-\phi_{th}+1}^{N_t} P_{\mathcal{J}}(j) D_0 \right\}, \tag{3}$$

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[1] In Fig. 1(b), lower-numbered descriptions are slightly more important than higher-numbered ones. For example, if only description 1 is received, the decoder knows the first two information symbols, whereas any other single description being the unique one received would provide only one information symbol. This effect is trivial, however, and the descriptions are considered to be equally important.

[2] Since each code symbol contains 4 modulated symbols, the packet size in terms of modulated symbols is $V = 4 \times L$.

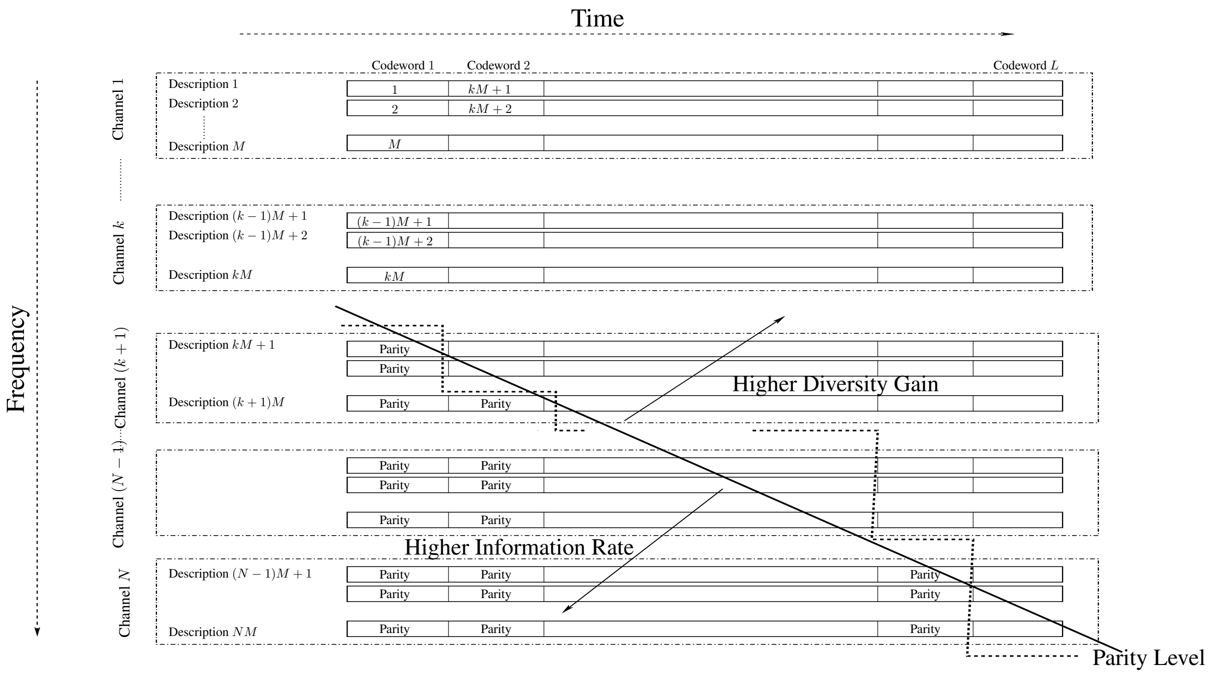
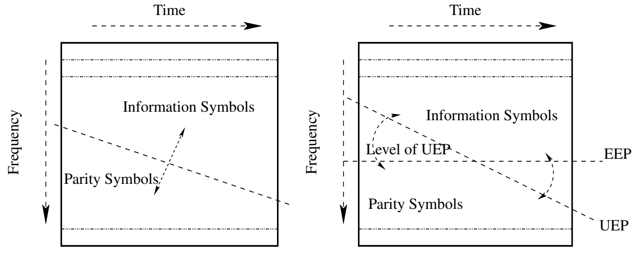


Fig. 2. The proposed cross-layer diversity coding scheme.



(a) Parity Level

(b) Degree of UEP

Fig. 3. Tradeoff issues associated with the cross-layer diversity technique.

where D_0 corresponds to the distortion when less than ϕ_{th} descriptions are received and so the decoder reconstructs the source without using any of the transmitted information. Different optimization algorithms can be used to find the optimal allocation [6]. We use the iterative procedure described in [3].

B. Some Tradeoff Issues

For an OFDM system employing frequency diversity techniques, there is a tradeoff between the information rate and the diversity gain. In essence, this is the tradeoff between the error probability and the data rate of the system. As illustrated in Fig. 3(a), symbols above the boundary (dashed line) are information symbols while those below the boundary are parity symbols. The boundary corresponds to the level of parity symbols. By moving the boundary upwards, more redundancy is added across the subcarriers. As a result, a higher diversity gain and hence smaller error probability is achieved at a reduced information rate. This tradeoff is particularly important for certain image/video transmission methods, as the output bitstream after compression may be extremely sensitive to channel errors and sometimes a single bit error may render the entire source unrecoverable.

In addition to the tradeoff between information rate and diversity gain, the degree of UEP is another important issue associated with multimedia transmission over the OFDM system. Generally, as the compressed bitstream from an image/video encoder has different sensitivities to channel errors, it is expected that the performance can be significantly improved by employing UEP techniques. In particular, by adding additional redundancy to the more important bits and less redundancy to the less important bits, subject to a constraint on the overall bit budget, the performance of the system can be greatly enhanced. For the system considered here, since the relative importance of an embedded bitstream is strictly decreasing, this results in a tilted boundary across the subcarriers, as illustrated in Fig. 3(b), which corresponds to a decreasing level of protection for the codewords on the right. The gradient of the boundary indicates the degree of UEP which can be adjusted to achieve optimal performance. A horizontal boundary represents an equal error protection (EEP) strategy.

It should be noted that, for an EEP transmission scheme, we can also optimize the amount of parity by raising or lowering the horizontal boundary. Regardless of what level one picks, however, the EEP transmission scheme can be considered to correspond to the transmission of a *single description* over an OFDM system. If (n, k) MDS erasure codes are used, the reception of any $g \geq k$ out of n packets allows the decoder to reconstruct the source at the same particular distortion level D', while the reception of $g < k$ packets renders the entire source unrecoverable (distortion D_0). As there is only one possible distortion level that can be achieved (other than the zero-information quality level D_0), we do not consider this as multiple description coding. Hence, our study of the EEP transmission is useful from two points of view. First of all, it is of interest to optimally trade off diversity gain and information rate by choosing the level of EEP coding. Secondly, our UEP approach is a cross-layer diversity scheme in which both the physical layer diversity and application level diversity (multiple description coding) are being jointly exploited. The EEP system serves as a comparison system in which the physical layer diversity is still being exploited, but the application layer diversity (multiple description coding) has been removed.

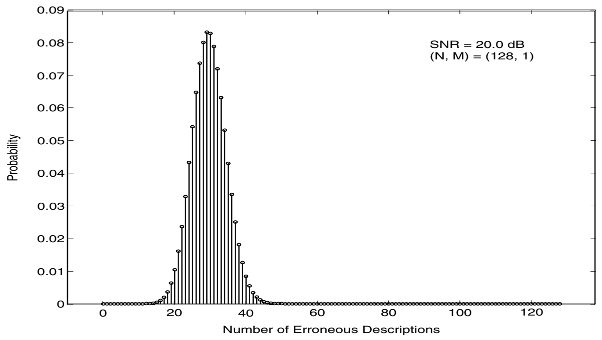
V. PACKET LOSS PROBABILITY MASS FUNCTION

As indicated in (3), the optimal allocation of the c_l and $f_l, l \in [1, L]$, and hence the delivered image/video quality, depends on the packet loss probability mass function (PMF) $P_{\mathcal{J}}(j)$, where $j \in [0, N_t]$ is the number of packets lost. Although the PMF can be found analytically for uncorrelated fading channels, due to the correlated fading in both the time and frequency domains of the wireless environment considered here, we use simulation to find the packet loss PMF. Specifically, we use the modified Jakes' model [7] to simulate the fading coefficients. We assume ideal coherent detection in our simulations.

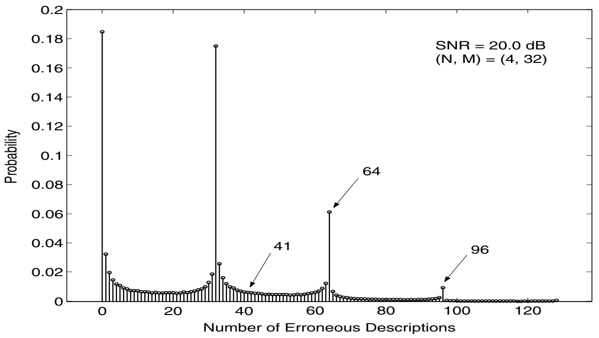
In Fig. 4, we show the packet loss probability $P_{\mathcal{J}}(j)$ of an OFDM system with different coherence bandwidths. The total number of subcarriers is $N_t = N \times M = 128$. The normalized Doppler spread is set to be $f_{nd} = 10^{-3}$. Figs. 4(a)-4(b) show $P_{\mathcal{J}}(j)$ for systems with $(N,\ M) = (128,\ 1)$ and $(4,\ 32)$, respectively. Due to the effect of correlated fading across the subcarriers, the PMF shows local maxima at integer multiples of M when the number of independent channels is relatively small. For example, in Fig. 4(b), we show a system with $N = 4$ and $M = 32$. As can be seen, $P_{\mathcal{J}}(j)$ is relatively high at $j = 0,\ 32,\ 64,\ 96$ and 128. It can also be noticed that the variance of the number of packet losses decreases as N increases. In particular, the packet loss PMF $P_{\mathcal{J}}(j)$ for the system $N = 128$ (Fig. 4(a)), having the largest number of independent channels, has the smallest variance. We see that the physical layer diversity has a tremendous impact on the PMF $P_{\mathcal{J}}(j)$. Hence, an efficient coding scheme should take it into consideration for optimal system performance.

VI. RESULTS AND DISCUSSION

We carried out simulations on the 512×512 gray-scale images Lena, Peppers and Goldhill. Similar results were obtained for all three. Hence, we only present the results using the Lena image. The image was encoded using SPIHT [8] to produce an embedded bitstream. The serial bitstream was converted to 128 parallel bitstreams using the FEC-based multiple description encoder. The 128 descriptions were mapped to the OFDM system with 128 subcarriers.



(a) $N = 128$, $M = 1$



(b) $N = 4$, $M = 32$

Fig. 4. The packet loss PMF for the OFDM system ($N_t = 128$) with different coherence bandwidths and hence different numbers of independent channels N and correlated carriers M.

In Fig. 5(a), we illustrate the importance of the information rate and diversity gain tradeoff. In particular, we show the optimal peak-signal-to-noise ratio[3] (PSNR) performance vs. the number of independent channels, N, employing the adaptive EEP techniques. The performance is optimized by raising or lowering the parity line based on N. We show results for SNR $= 16.0,\ 20.0,\ 24.0,\ 28.0$ dB. As expected, for a fixed $N_t = 128$, as N increases, there is a significant improvement in overall system performance measured in terms of PSNR, even though the average packet loss rates are the same. Note that the PSNR increases monotonically as N increases. Note also the relatively poor performance in a flat-fading environment ($N = 1$). In Fig. 5(a) we also plot the PSNR performance for systems without employing the adaptive strategy. In particular, we fix the coding levels at $f_l = 64$ and $f_l = 86$, $\forall l \in [1, L]$, corresponding to overall channel coding rates $R_c = 1/2$ and $R_c = 1/3$, without taking into consideration the number of independent channels available in the physical layer. It can be noticed that the PSNR performances of both systems improve as the number of independent channels increases due to higher

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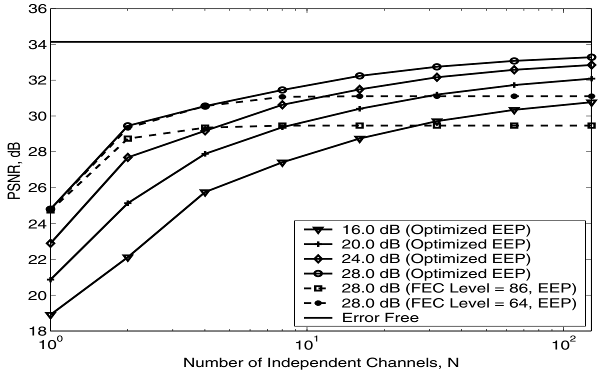
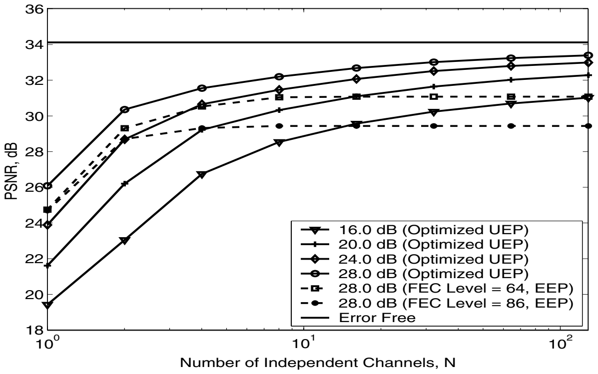
[3] PSNR $\overset{\triangle}{=} 10 \log \frac{255^2}{MSE_{avg}}$.



(a) EEP



(b) UEP

Fig. 5. Optimized PSNR vs. Number of independent channels (N) for the adaptive cross-layer OFDM system employing EEP and UEP technques under different SNRs, respectively.

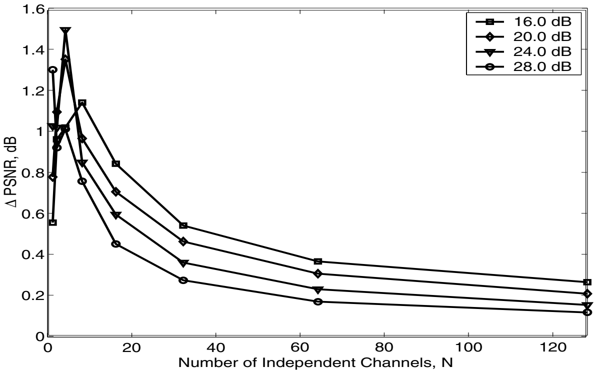


Fig. 6. Difference in optimized PSNR performance between UEP and EEP vs. the number of independent channels, N.

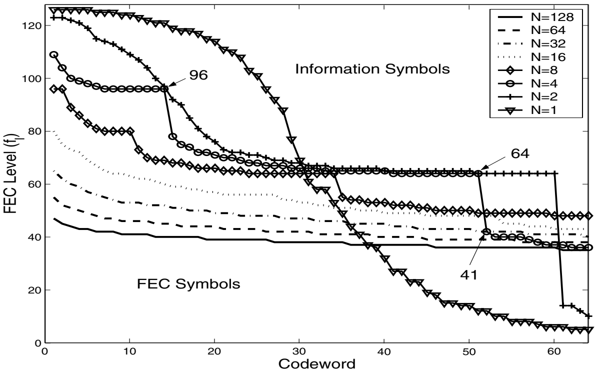


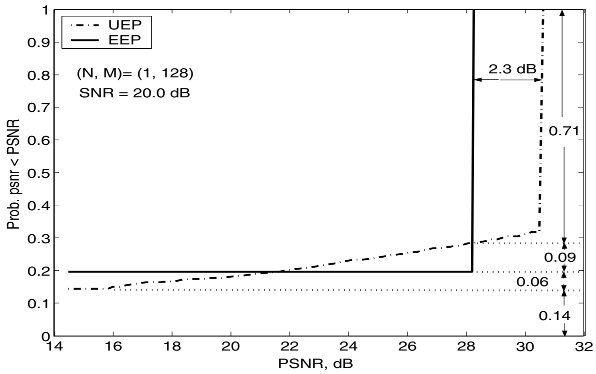
Fig. 7. Profiles showing the optimal allocation of source and channel symbols for systems with different numbers of independent channels, N.

diversity gains. However, the rate of improvement diminishes quickly. As shown in the figure, only marginal improvement can be achieved beyond $N = 4$ for $f_l = 64$, while no further practical gain can be obtained for $f_l = 86$ beyond $N = 4$. For the purpose of comparison, we also include a plot of the PSNR performance for error free channel conditions.

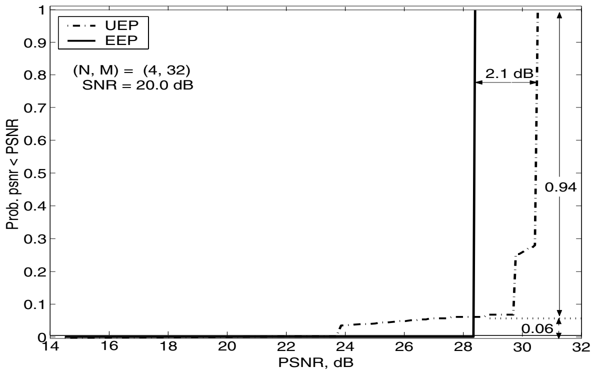
In Fig. 5(b), we show the optimal PSNR vs. the number of independent channels, N, for the adaptive cross-layer diversity approach employing UEP techniques for different SNRs. Again, we show results for SNR = 16.0, 20.0, 24.0, 28.0 dB. Similar to the systems of Fig. 5(a), for a fixed $N_t = 128$, the overall system performance measured in terms of PSNR improves monotonically as N increases. For comparison, we also include plots of the PSNR performance for error free channel conditions as well as for the systems using fixed parity levels with $f_l = 64$ and $f_l = 86$.

In Fig. 6, we show the difference in the PSNR performance between the optimized UEP and optimized EEP strategies vs. N. As can be seen, there is a significant improvement in the PSNR performance by employing the optimized UEP technique, in particular when N is small. Generally, a larger performance gain is achieved at the lower SNRs, corresponding to poorer channel conditions. Note that the advantage of the optimized UEP strategy relative to EEP diminishes with increasing N. As discussed previously, the variance of packet losses decreases with increasing N, thus reducing the need and hence the relative advantages of the UEP techniques. Nevertheless, in some OFDM systems, the number of independent channels is limited. Hence, there is a significant advantage in employing the proposed cross-layer diversity and UEP techniques.

In Fig. 7, we show the optimal allocation of the source symbols and parity symbols for SNR = 20.0 dB. In particular, we present the boundaries, given by f_l in (1), for systems with different numbers of independent channels, N, and hence different potential diversity gains. The symbols above the boundaries are information symbols while those below are RS parity symbols. As can be seen, since the relative importance of an embedded bitstream is strictly decreasing, less redundancy is added across the subcarriers as we move to the right. Moreover, the degree of UEP, represented by the tilt of the boundary, increases as N increases. As indicated in the plots and discussions for the packet loss PMF, $P_{\mathcal{J}}(j)$, in the previous section, as N increases, the variance of the number of packet losses decreases and thus reduces the degree of UEP. It can also be noticed that the boundary exhibits a stepwise behavior when N is



(a) $N = 1$, $M = 128$, $SNR = 20.0$ dB



(b) $N = 4$, $M = 32$, $SNR = 20.0$ dB

Fig. 8. The cumulative distributions of the optimized PSNR performance for the systems employing UEP and EEP techniques, respectively.

small. This is mainly due to the highly correlated fading within a channel, which results in the loss of the correlated subcarriers simultaneously when a channel is under a deep fade. For example, consider the case when $(N, M) = (4,\ 32)$. The corresponding $P_J(j)$ is shown in Fig. 4(b), and exhibits local maxima at integer multiples of $M = 32$, i.e., $j = 0,\ 32,\ 64,\ 96$. From the plot of the boundary in Fig. 7 for $N = 4$, we notice that the most important information symbols are protected against $j = 96$ descriptions lost with $f_l \geq 96$. The relatively less important information symbols are protected against $j = 32$ and $j = 64$, with $f_l \geq 64$ and $f_l \geq 32$, respectively.

To further illustrate the advantages of this cross-layer diversity technique, in Fig. 8 we plot the cumulative distribution functions (CDF) of the PSNR performance for systems with different N using both the optimized UEP and the optimized EEP approaches. In Figs. 8(a)-8(b), we show the CDFs for systems with SNR $= 20.0$ dB and $(N, M) = (1, 128)$, $(4, 32)$, respectively. To provide a specific performance comparison, consider, for example, Fig. 8(a). It can be noticed that the UEP approach provides approximately a 2.3 dB gain over the optimized EEP approach with a probability equal to 0.71. Although there are regions over which the UEP approach performs worse than the optimized EEP approach, the probability of these events is relatively small (about 0.09). The UEP technique also enables the source to be reconstructed under noisier channel conditions than the EEP technique, although at a low fidelity. From the figure, it can be noticed that the probability that the source cannot be recovered is 0.20 by employing the optimized EEP technique, while the corresponding probability is only 0.14 using the UEP approach. Similar observations can be found in other systems. Consider, for example, Fig. 8(b), where we illustrate the CDF of a system with $(N, M) = (4, 32)$ at SNR $= 20.0$ dB. As can be seen, a performance gain of about 2.1 dB can be achieved 94% of the time, while sacrificing only a small performance loss 6% of the time.

VII. CONCLUSION

We studied an OFDM system supporting multimedia communications. In particular, assuming a slow varying Rayleigh fading environment, we investigated the packet loss PMF for an OFDM system with different coherence bandwidths, and hence different numbers of correlated subcarriers. We then proposed a cross-layer diversity transmission scheme incorporating both physical layer and application layer diversities. More specifically, based on the frequency selectivity of an OFDM system, we constructed multiple descriptions employing an FEC-based approach. We demonstrated the superior performance of this adaptive cross-layer approach using the SPIHT coder. We also compared the performance against an OFDM system that does not use multiple description coding. Results indicate improvement can be achieved by constructing multiple independent bitstreams using UEP techniques.

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