Channel Coding for Progressive Multimedia in a 2-D Time-Frequency Block of an OFDM System[†]

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***Abstract*—Coding and diversity are very effective techniques for improving transmission reliability in a mobile wireless environment. The use of diversity is particularly important for multimedia communications over fading channels. In this work, we study the transmission of progressive image bitstreams using channel coding in a 2-D time-frequency resource block in an OFDM network, employing time and frequency diversities simultaneously. In particular, in the frequency domain, based on the order of diversity and the correlation of individual subcarriers, we construct symmetric n-channel FEC-based multiple descriptions using channel erasure codes combined with embedded image coding. In the time domain, a concatenation of RCPC codes and CRC codes is employed to protect individual descriptions. We consider the physical channel conditions arising from various different coherence bandwidths and coherence times, leading to various orders of diversities available in the time and frequency domains. We also study the tradeoffs and the relative effectiveness associated with the use of erasure codes in the frequency domain and convolutional codes in the time domain under different physical environments.**

I. INTRODUCTION

Embedded source coding, allowing partial decoding at various resolution and quality levels from a single compressed bitstream, is widely considered as a promising and efficient technology for signal representation for multimedia communications in heterogeneous environments. In [1], the authors considered using a concatenation of outer cyclic redundancy check (CRC) codes for error detection and inner rate-compatible punctured convolutional (RCPC) codes for error correction for the transmission of an embedded bitstream employing the Set Partitioning in Hierarchical Trees (SPIHT) source coder [2]. The joint source-channel image coder was shown to outperform previously reported techniques at that time. Unfortunately, the performance of this scheme was not satisfactory for certain physical channels such as slow fading channels commonly observed in a wireless environment.

Coding and diversity are very effective techniques for improving the transmission reliability in a mobile wireless environment. The use of diversity is particularly important for communications over fading channels. However, time diversity achieved by channel coding plus intra-packet interleaving in a single carrier (SC) communication system becomes less effective in a slow fading environment where correlated and prolonged deep fades often result in the erasure of the whole packet or even several contiguous packets. Hence, although improvement could still be achieved due to the coding gain associated with the use of RCPC codes, the performance is not satisfactory [3].

In order to improve the performance against deep fades in a wireless environment, two different approaches have been proposed in the literature. Both approaches were designed to exploit diversity in the time domain at the physical layer for SC communication systems. One was to add systematic Reed-Solomon (RS) codes across multiple packets [4]. With the addition of RS codes across multiple packets, if some of the packets were lost, the information might still be recoverable due to the possibility of transmitting the multiple packets over independently faded time slots. Owing to the possibility of achieving a higher diversity gain, the system was shown to perform well in a slow fading environment [4].

Besides employing channel coding across multiple packets, another approach uses source coding techniques, specifically multiple description (MD) coding, to achieve possible diversity gain. An example is the symmetric n-channel FEC-based MD coding proposed in [5]. Due to the individually decodable nature of the multiple packets, if some of the packets are corrupted during transmission, the source can still be recoverable, although at a lower fidelity that depends on the particular set of successfully transmitted packets.

While both approaches perform well in the designated channel conditions, the order of diversity of the physical channel is vital to the selection of system parameters (e.g., the choice of channel codes and the corresponding coding rates) and the ultimate success of these transmission strategies, as shown in a related study in [6]. Despite their importance, such factors are usually overlooked or ill-treated in the literature.

On the other hand, in recent years, due to the shifting of narrowband SC systems toward broadband communication systems supporting high-data-rate transmission, a multicarrier modulation scheme, specifically orthogonal frequency division multiplexing (OFDM), has drawn intense interest. For broadband transmission over wireless multipath channels, OFDM offers certain advantages over conventional SC communication systems, such as robustness against frequency-selective fading.

Moreover, due to the frequency-selectivity of the multiple parallel channels, frequency diversity by adding redundancy across the subcarriers can be achieved to combat channel errors due to multipath fading and achieve a more reliable overall

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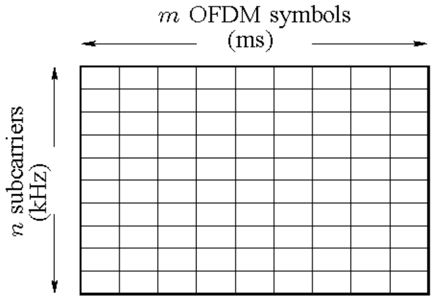

Fig. 1. A 2D time-frequency resource block of an OFDM system consisting of m OFDM symbols and n subcarriers.

system performance.

In this work, we study the transmission of progressively coded image bitstreams using channel coding in a 2-D time-frequency resource block (RB) in an OFDM network, employing time and frequency diversities simultaneously. In particular, in the frequency domain, based on the order of diversity, we construct FEC-based MD using channel erasure codes combined with embedded source coding. In the time domain, a concatenation of RCPC codes and CRC codes is employed to protect individual descriptions. We consider the physical channel conditions arising from various different coherence bandwidths and coherence times, leading to various orders of diversities available in the time and frequency domains.

The remainder of this paper is organized as follows: In Section II, we give a description of the OFDM system and the channel model. In Section III, we describe the proposed transmission system and discuss some of the issues associated with the use of channel coding in a time-frequency block. In Section IV, we describe the optimization problem. In Section V, we provide some simulation results and discussion.

II. SYSTEM DESCRIPTIONS AND CHANNEL MODEL

The basic principle of OFDM is to split a high-rate data stream into a number of lower rate streams that are transmitted over overlapped but orthogonal subcarriers. Since the symbol duration increases for the lower rate parallel subcarriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. In Fig. 1, we illustrate a typical 2D time-frequency RB of an OFDM system. In the figure, the horizontal axis represents the time domain while the vertical axis represents the frequency domain.

Depending on the propagation environment and the channel characteristics, the RB in an OFDM system can be designed to exploit time and/or frequency diversities through channel coding. For time diversity, channel coding plus interleaving can be used in the time domain. However, for the technique to be effective, the time frame has to be greater than the channel coherence time $(\Delta t)_c$. The maximum time-diversity gain $\mathcal{D}_t$ is given by the ratio between the duration of a time frame and $(\Delta t)_c$.

In additional to time diversity, frequency diversity by adding redundancy across the subcarriers can also be applied to combat channel errors. Generally, the maximum achievable frequency diversity $\mathcal{D}_f$ is given by the ratio between the overall system bandwidth W_T and the coherence bandwidth $(\Delta f)_c$.

In this work, we consider a frequency-selective environment and use a block fading channel model to simulate the frequency selectivity [7]. In this model, the spectrum is divided into blocks whose size equals $(\Delta f)_c$. Subcarriers in different blocks are considered to fade independently; 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 subbands. Each of the N independent subbands consists of M correlated subcarriers spanning a total bandwidth of $(\Delta f)_c$. The total number of subcarriers in the OFDM system is equal to $N \times M$. In the time domain, we assume the channel experiences Rayleigh fading. We use the modified Jakes' model [8] to simulate different fading speeds, resulting in different time diversity orders.

III. TRANSMISSION SCHEME: CHANNEL CODING FOR THE 2D TIME-FREQUENCY BLOCK

We construct the 2D RB taking into consideration the diversity opportunities in both the frequency domain and time domain, as well as the use of application layer diversity techniques, specifically n-channel FEC-based multiple description coding.

Fig. 2 illustrates the proposed scheme for the construction of the 2D resource block for transmission of an embedded bitstream over mobile wireless characterized by a doubly selective environment. In the frequency domain, $S_{tot} = N \times M$ symmetric descriptions of approximately equal importance are constructed in which contiguous information from the embedded bitstream is spread across the multiple descriptions/packets [5], [9]. The information symbols are protected against channel errors using systematic (n, k) RS codes, with the level of protection depending on the relative importance of the information symbols as well as the order of diversity available in the frequency domain. Generally, 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.

The individual descriptions are then mapped to the $S_{tot} = N \times M$ subcarriers through a concatenation of CRC codes and RCPC codes, for possible diversity and coding gains in the time domain. Since the descriptions are approximately equally important, RCPC codes with the same coding rate can be applied to protect each individual description. This results in a vertical boundary (RCPC coding line), as illustrated in Fig. 2. The symbols on the left of the boundary are the multiple description RS symbols, while those on the right are CRC/RCPC parity symbols. It should be noted that the multiple description RS symbols and RCPC parity symbols are interleaved in the real system. However, for the sake of illustration here, we show the de-interleaved version throughout the paper so that the relative amounts of RCPC parity symbols and RS symbols can be clearly indicated.

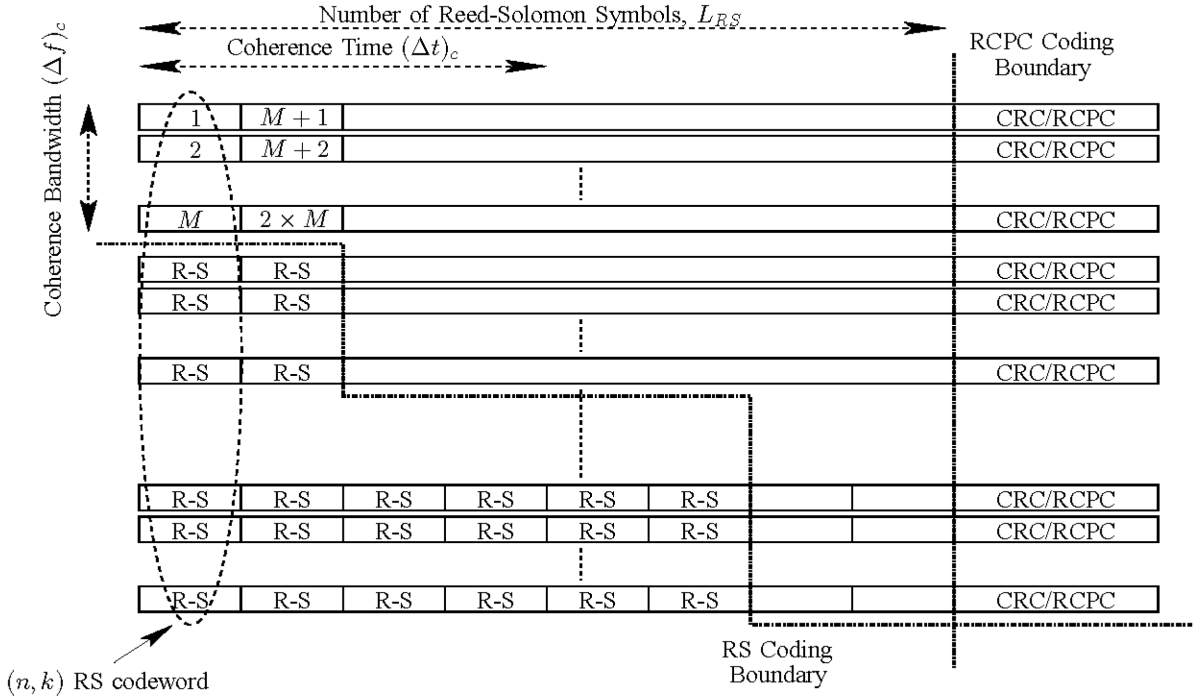

Fig. 2. The construction of the RB for transmission of embedded bitstreams over OFDM mobile wireless networks; note that the CRC/RCPC parity symbols are interleaved with the RS symbols in the actual system.

Hence, for the system considered here, coding and diversity gains are exploited through the use of RS codes in the frequency domain and RCPC codes in the time domain. It should be noted that due to the individually decodable nature of multiple description coding techniques, if any of the sub-carriers/descriptions are lost during transmission, the source can still be recovered from other correctly received subcarriers with a fidelity depending on the number of correctly received descriptions.

Since both forms of diversity are not necessarily simultaneously available at any given instant of time, the channel coding scheme should be designed to synergistically exploit the available diversity. For example, in a slow fading environment, channel coding plus interleaving is usually ineffective, especially for delay-sensitive applications such as real-time multimedia services. Hence, in this case, frequency diversity techniques may be more effective than time diversity techniques.

IV. PROBLEM FORMULATION

Given the channel model in Section II and the coding scheme in Section III, in this section, we describe the optimization problem to be solved. Consider N i.i.d. subbands, each with M subcarriers and packet size equal to L_{RS} code symbols before channel coding using RCPC/CRC codes. Since each vertical column corresponds to one RS codeword, there are altogether L_{RS} RS codewords. The constraint on the bit budget/packet can then be written

$$(L_{RS} \times B_{RS} + B_{CRC})/R_{rcpc} \leq B_{tot}, \qquad (1)$$

where B_{CRC} is the bit budget allocated for the CRC codes and R_{rcpc} is the channel coding rate of the RCPC codes. B_{RS} is the number of bits per RS symbol and B_{tot} is the total bit budget of the RB.

We assume that for RS codeword l, where $l \in [1, L_{RS}]$, c_l code symbols are assigned to information data symbols. Hence, the number of RS parity symbols assigned to codeword l is

$$f_l = S_{tot} - c_l \qquad l \in [1, L_{RS}]. \qquad (2)$$

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 quality $D(R_g)$, where R_g is the allocated bit budget for the information symbols,

$$R_g = \sum_{\{l: c_l \leq g\}} c_l \times B_{RS}. \qquad (3)$$

Hence the overall RS channel coding rate equals $R_{rs} = R_{S_{tot}}/(S_{tot} \times L_{RS} \times B_{RS})$. 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 $j = S_{tot} - g$, we can minimize the expected distortion as follows:

$$E^*[D] = \min_{\{c_l, R_{rcpc}\}} \left\{ \sum_{j=0}^{S_{tot}-\phi_{th}} P_{\mathcal{J}}(j) D(R_{S_{tot}-j}) + \sum_{j=S_{tot}-\phi_{th}+1}^{S_{tot}} P_{\mathcal{J}}(j) D_0 \right\}, \qquad (4)$$

subject to the constraint on the overall bit budget

$$\frac{R_{S_{tot}}/R_{rs} + B_{CRC}}{R_{rcpc}} \leq B_{tot} \tag{5}$$

where D_0 corresponds to the distortion when fewer than ϕ_{th} descriptions are received and so the decoder must reconstruct the source without being able to use any of the transmitted information. For a still image, this typically means reconstructing the entire image at the mean pixel value.

The packet loss probability mass function $P_{\mathcal{J}}(j)$ depends on the $(\Delta f)_c$, $(\Delta t)_c$ and R_{rcpc} used. Although $P_{\mathcal{J}}(j)$ can be found analytically for uncorrelated fading channels, due to the correlated fading in both time and frequency domains of the mobile environment considered here, we use simulations to find $P_{\mathcal{J}}(j)$. In this work, we use the iterative procedure described in [5] to solve the optimization problem (4).

V. RESULTS AND DISCUSSION

We carried out simulations on the 512×512 gray-scale image Lena. The image was encoded using the SPIHT [2] algorithm to produce an embedded bitstream. The serial bitstream was converted into 128 parallel bitstreams using the FEC-based multiple description encoder. The 128 descriptions were mapped to the OFDM system with 128 subcarriers. We used RS codes in the frequency domain and there were 8 bits per RS symbol. The packet size was set equal to 512 bits. We used QPSK modulation and assumed perfect channel state (CSI) information. The set of RCPC codes of rates, $R_{rcpc} = \frac{8}{9}, \frac{8}{10}, \ldots, \frac{8}{24}$, are obtained by puncturing an $R_c = 1/3$ mother code with $K = 7$, $p = 8$ and the generator polynomials $(133, 165, 171)_{octal}$ with the puncturing table given in [10].

In Fig. 3, we illustrate the optimized constructions of RS information symbols, RS parity symbols and RCPC parity symbols for different R_{rcpc}'s for $(N, M) = (4, 32)$ and normalized Doppler spread $f_{nd} = 10^{-4}$ at SNR = 16.0 dB with perfect CSI. The diversity order in the frequency domain is $\mathcal{D}_f \approx 4$, while the diversity order in the time domain is $\mathcal{D}_t \approx 1$. In other words, no diversity can be exploited by using RCPC codes although coding gain can still be obtained. From the figure, we notice that as more redundancy is added in the time domain, the number of RS parity symbols is reduced accordingly, due to the improved packet loss performance as a result of the coding gains associated with the use of RCPC codes. This is indicated in Fig. 3 by the lower RS coding boundaries. The tradeoff between RCPC codes and RS codes is further illustrated in Fig. 4, where we plot the (R_{rs}) for minimizing the expected distortion $E[D]$ with different R_{rcpc} subject to the constraint (5). As can be seen, when R_{rcpc} moves to the left, more channel redundancy has to be added across the subcarriers so as to optimize the system performance. It is worth noting that the RS coding boundaries exhibit similar stepwise behaviors for all R_{rcpc}. This is mainly due to the perfectly correlated fading within a subband in the frequency domain, which results in, with high probability, the simultaneous loss of the correlated subcarriers when a subband is under a deep fade.

Fig. 5 shows the optimized PSNR performance vs. R_{rcpc} for systems with N ranging over $N = 1, 2, 4, \ldots, 128$. f_{nd} is set to 10^{-3} and SNR is set to 16.0 dB. As mentioned previously, due to higher order achievable diversity gains in the frequency domain, channel coding across subcarriers using RS codes, which simultaneously provides coding and diversity gain becomes more effective than channel coding in the time domain using RCPC codes. Hence, optimal system performances are generally achieved using relatively low channel coding rates in the frequency domain and high channel coding rates in the time domain. Observe, for the cases $N = 64$ and $N = 128$, a high rate $R_{rcpc} = 8/9$ is employed for optimal performance. Also note the relatively poor performance for $N = 1$, which corresponds to a flat fading environment. For a flat fading environment, channel coding across subcarriers becomes less effective due to lack of achievable frequency diversity. Without any possible diversity gain, low channel coding rates in both the frequency and time domains are employed so as to provide higher coding gains, as indicated in the figure. For example, the optimal R_{rcpc} for $N = 2$ is $8/15$.

In Fig. 6, we provide the optimized PSNR performance vs. R_{rcpc} with $f_{nd} = 10^{-1}$ for different frequency diversity orders N. The SNR is set to be 16.0 dB. As can be seen from the figure, the diversity in the time domain has greatly improved the performance of using RCPC codes plus intra-packet interleaving. In the systems considered here, optimal system performances can be achieved by using RCPC codes with high coding rates of $R_{rcpc} = 8/9$ and $8/10$.

In Fig. 7, we compare the performance for systems with different normalized Doppler spreads. In particular, we plot the PSNR performance versus R_{rcpc} for a system with $(N, M) = (4, 32)$ and SNR = 16.0 dB. Note that there are crossovers among the curves with different fading rates. Specifically, for systems without channel coding in the time domain, systems with slower fading rates provide a better overall performance. Due to the bursty nature of the errors associated with slow multipath fading, most bit errors occur within a packet smaller than the average fading duration, hence for the same bit error rates, the packet loss rate is smaller. In contrast, a faster fading rate generally delivers a better end-user QoS due to higher diversity. These observations explain the crossovers among the different curves.

Conclusion: We studied the channel coding in a 2D time-frequency resource block in an OFDM system. In particular, we proposed the symmetric n-channel FEC-based multiple descriptions based on the diversity order in the frequency domain. In the time domain, a concatenation of RCPC codes and CRC codes was employed to protect individual descriptions. The proposed approach allows one to trade off and take advantage of both time and frequency diversity opportunities that may appear in different physical environments.

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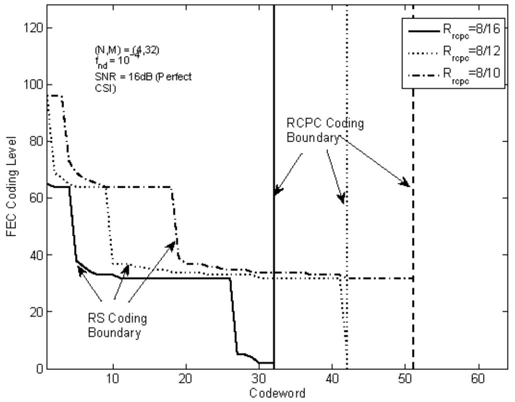

Fig. 3. Profiles showing the optimal allocation of source and channel symbols for systems with $(N, M) = (4, 32)$, $f_{nd} = 10^{-4}$ and SNR $= 16.0$ dB with three different choices of RCPC coding rates.

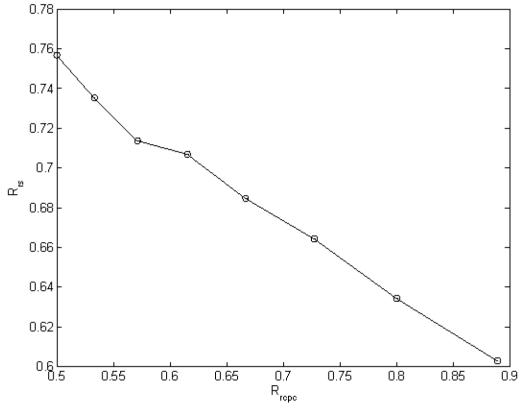

Fig. 4. R_{rs} vs. R_{rcpc} for optimized performance with $(N, M) = (4, 32)$, $f_{nd} = 10^{-4}$ and SNR $= 16.0$ dB.

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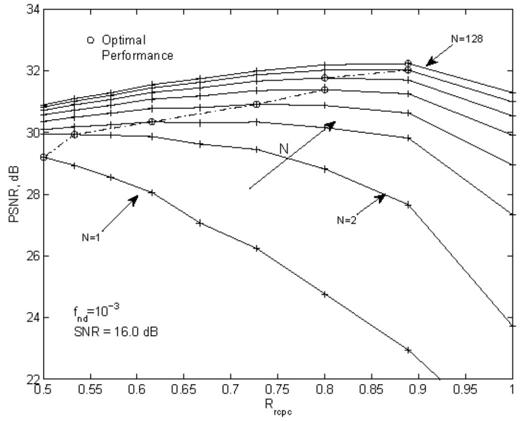

Fig. 5. Optimal PSNR performance vs. R_{rcpc} for systems with $f_{nd} = 10^{-3}$, SNR $= 16.0$ dB for different N in the frequency domain.

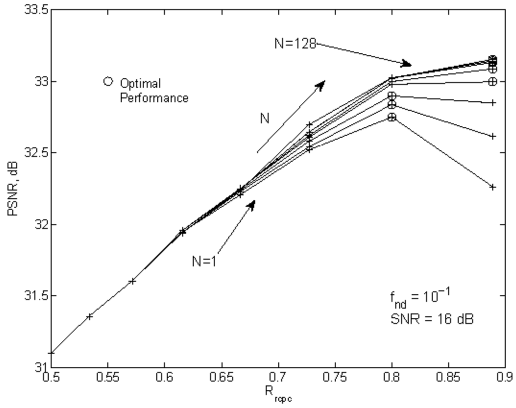

Fig. 6. Optimal PSNR performance vs. R_{rcpc} for systems with $f_{nd} = 10^{-1}$, SNR $= 16.0$ dB for different N in the frequency domain.

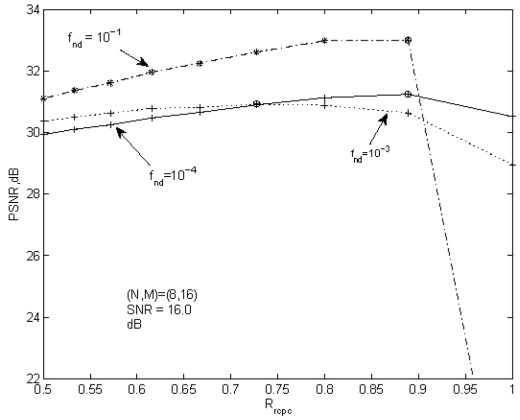

Fig. 7. Optimal PSNR performance vs. R_{rcpc} for systems with different normalized Doppler spreads; SNR $= 16.0$ dB and $(N, M) = (8, 16)$.