Mobile Image Transmission Using Combined Source and Channel Coding with Low Complexity Concealment

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Abstract: In this paper, we propose an efficient image transmission system for reliable transmission of vulnerable compressed images over mobile radio channels. The image coder is fully compatible with the JPEG baseline coding standard. Its transmission system is designed based on lossy transmission with combined source and channel coding (CSCC) and low complexity error concealment. Specifically, the proposed CSCC uses block codes which are designed to match both the coded image characteristics and wireless channel statistics, thereby accomplishing efficient transmission along with good visual quality. Together with a block-shuffling scheme [1], a simple error-concealment technique is introduced to effectively reconstruct the damaged image blocks caused by the residual errors. It is shown that the proposed techniques are applicable to mobile image transmission with different compression ratios under various mobile channel conditions. Performance results based on images “LENA” and “AIRPLANE”, which are coded at 0.85 and 0.90 bit/pixel, respectively, under the simulated GSM channel [2] with an average SNR (signal-to-noise ratio) of 18 dB and various vehicle speeds (2 - 50 miles/hour) indicate that the proposed system achieves a throughput as high as 70% with good visual quality at PSNRs (peak signal-to-noise ratio) around 30 dB for the reconstructed images.

I. INTRODUCTION

There has been considerable interest worldwide in wireless multimedia communications, of which mobile image transmission is one of the fundamental applications [1, 3-6]. The large amount of data needed for high-quality image reconstruction must be efficiently transmitted over the limited bandwidth available in wireless networks, thus requiring the use of highly compressed source coding and efficient channel coding. However, highly compressed image data, such as those generated by the JPEG coding standard [7], are extremely sensitive to channel errors, especially to bursty errors that are commonly encountered in wireless channels [8]. Therefore, a reliable image transmission requires significant error protection at the cost of reduced transmission efficiency.

Fortunately, unlike random data, image data contain a great deal of redundancy even after compression. Previous studies such as those in [6] and [9] show that image data with a small portion of information loss caused by transmission errors can be reconstructed using error concealment techniques. If some information loss is allowed, the required error protection capability can be reduced significantly, resulting in substantial improvement in transmission efficiency. In this paper, we consider image transmission with an allowable amount of information loss, which is referred to as *lossy transmission*. However, it is important to point out that lossy transmission may not be applicable to some crucial part of image data and the information loss must be well controlled so that an error concealment method can be effectively applied.

Based on the lossy transmission concept along with its design considerations, we propose an efficient mobile image transmission system. Specifically, we consider an image coder which is fully compatible with the JPEG baseline standard due to its simplicity and popularity for many applications [7]. In terms of its file structure, the coded information can be separated into two parts: overhead data and coded data. The overhead data part, which includes the quantization table and Huffman table, etc., is the essential component for guaranteeing the visual quality of the entire image. It requires high reliability in transmission and thus prohibits the use of lossy transmission. As such, a type-I hybrid ARQ (Automatic Repeat reQuest) [10] is used for its transmission. For the coded data part, due to the information redundancy remained, we adopt lossy transmission with a CSCC scheme and a low complexity concealment. In particular, the proposed CSCC, which is based on simple BCH (Bose-Chaudhuri-Hocquenghem) codes, is to control the information loss with trade-offs between transmission reliability and efficiency. Likewise, the error concealment technique is developed to trade off concealment performance and implementation complexity.

Most previously proposed CSCC schemes often ignore the effects of *bursty errors* in wireless channels [8] by assuming perfect interleaving [5, 11], which requires a prohibitively large interleaver in the slow fading environment [12]. In contrast, our proposed CSCC takes both the source coding characteristics and wireless channel statistics into account. Specifically, the image coding may include resynchronization to provide certain error-resilient capability in source coding [7, 9], thereby supporting lossy transmission with reduced error-protection. On the other hand, inserting resynchronization introduces extra bit-expansion, which in turn decreases transmission efficiency. Accordingly, our CSCC scheme is based on a joint study of source coding and channel coding in terms of their combined error-resilient capability and bit-expansion. In addition, such joint study is conducted over non-interleaved wireless channels, in which the bursty error nature is included.

Finally, to better quantify information loss, we propose using PBLR (picture-block loss rate) as the performance measure. The influence of wireless channel statistics on PBLR is thoroughly investigated under different CSCC schemes. An optimum design of CSCC is obtained by best matching the statistics of both image data and wireless channels.

Error concealment is also a key technique in supporting lossy transmission. In fact, error concealment plays a very important role in visual communications and has been the subject of various studies [6, 9, 13-16]. In [9], [14] and [15], concealment algorithms based on linear interpolation are performed in a transform domain. They are very simple but may produce severe blocking artifacts. To alleviate the blocking artifacts, more powerful algorithms are provided by [6] and [16]. However, both algorithms are very complicated. For wireless communications, low implementation complexity is desirable. Thus, by incorporating a block-shuffling scheme [1], we propose a low complexity concealment algorithm which can be implemented using simple shift registers. Simulation results show that this algorithm performs very closely to that of [16].

This paper is organized as follows. In Section II, based on the file structure of image data coded with JPEG baseline standard [7], an efficient and robust mobile image transmission system is proposed. In Section III, using the statistics of both wireless channels and image data, we investigate the effects of different CSCC schemes on transmission efficiency and PBLR. Consequently, an optimum design of CSCC for mobile image transmission is obtained. Section IV introduces a low complexity but powerful concealment algorithm. Performance of the proposed system is demonstrated in Section V based on some sample simulation results. Accordingly, a brief comparison with the error protection scheme used in GSM is given. Finally, Section VI concludes the paper.

II. PROPOSED IMAGE TRANSMISSION SYSTEM

We begin by considering the system design for efficient image transmission over wireless channels. For image coding, we wish to make the source coding fully compatible with the JPEG baseline standard due to its simplicity and popularity for many applications [7]. Fig. 1 depicts its file structure, which is segmented into *Picture Layer* and *Block Layer*. In *Picture Layer,* the *Header* includes “start of image” code, Huffman table(s), and quantization table(s), etc.. These data are non-compressed. The *Tailor* provides an “end of image” information which is also non-compressed. The *Block Data* is further referred to the *Block Layer*, where a single picture-block is its basic unit and VLC (variable length coding) is used to achieve the required compression. Note that this file structure is inclusive of the cases in a gray-level image or in a color image with multiple components

[7]. For the sake of simplicity, we consider a gray-level image in this paper. Moreover, we call the non-compressed part as "overhead" and VLC coded part simply as "coded data".

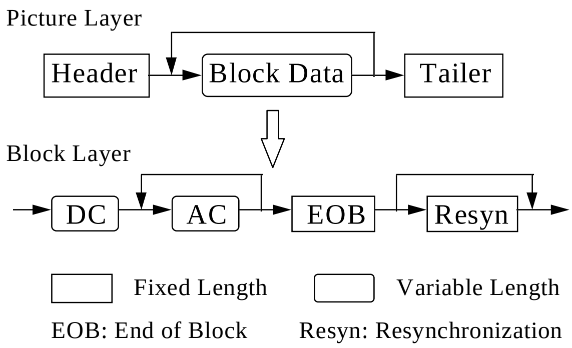
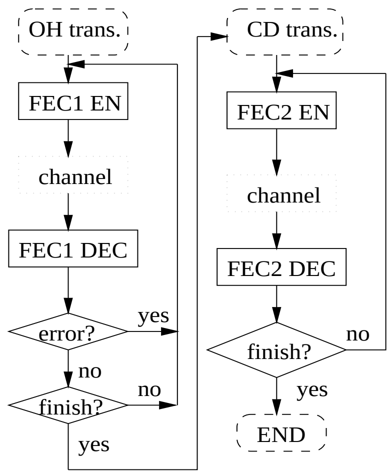


Fig. 1. *Bit-stream structure based on JPEG baseline coding standard.*

Overhead data is the essential component for guaranteeing the visual quality of the whole image. Hence, extremely high transmission reliability is required, for which either extensive channel coding or ARQ or a combination of both should be used. In [17] and [18], it has been shown that basic ARQ protocols can offer reasonable throughput in a land mobile fading channel[*]. Likewise, based on ARQ, Khansari *et al* proposed a real-time video transmission system over wireless channels in [4]. It is also noted that the type-I Hybrid ARQ, which combines error correcting and re-transmission, can achieve both reasonable throughput and less delay due to re-transmission if channel coding and ARQ are properly combined [10]. Furthermore, the overhead data is usually a small portion of the entire image data. For example, for image LENA with 256×256 pixels coded at 0.85 bit/pixel, the overhead is less than 2%. Thus, even if re-transmission is involved, the overall system throughput may not be affected much. As a result, we adopt type-I Hybrid ARQ for the overhead transmission.

Coded data are produced using the block-based image coding algorithm per JPEG standard. It follows that there is a great deal of redundancy among neighboring blocks even after compression. Thereby, suggesting that lossy transmission can be used to improve transmission efficiency. However, all the coded picture-blocks are correlated due to the DPCM (Differential Pulse Coding Modulation) being adopted for DC component compression if no resynchronization is available. Moreover, since VLC is used, any bit error can lead to loss of synchronization at the decoder, which can cause error propagation. Hence, to effectively incorporate lossy transmission, error-resilient capability must be provided to limit error propagation. In this paper, a periodic resynchronization scheme [7, 19], which is also shown in Fig. 1, is deployed to guarantee uncorrectable errors not to propagate.

[*] This paper focuses on the case of land mobile communications as well.



OH trans. : Overhead transmission
CD trans. : Coded data transmission
FEC : Forward error control coding
EN : Encoding DEC : Decoding

Fig. 2. *Proposed control flow for image transmission.*

Based on the above information segmentation, we propose in Fig. 2 an effective system control flow over a mobile channel. For overhead data transmission, type-I Hybrid ARQ is used; for coded data transmission, lossy transmission is used. Note that, in the overhead data transmission, *Header* is always transmitted ahead of the coded data, while the *Tailor* is either used as a transmission termination signal or transmitted together with next frame's *Header*. It is observed that such control flow has the features of simplicity in implementation and compatibility with JPEG standards. Nevertheless, to make the system more efficient, special attention is needed for the design of FEC1 (forward-error-control coder 1) and, more importantly, for the design of FEC2 (forward-error-control coder 2), which is the key innovation of the proposed CSCC scheme in this study. Such design will be discussed in the next section.

The block diagram of the mobile image transmission system is further developed in detail in Fig. 3. At the source coding phase, the input image will be first shuffled block by block and then encoded based on the ISO JPEG baseline coding standard [7]. Meanwhile, the resynchronization flags are periodically inserted (in terms of coded picture blocks). In particular, the reference of DPCM (for DC component compression) is set to zero after each resynchronization [19]. By doing so, the error-resilient capability of coded data is enhanced. At the transmission phase, two different transmission schemes are included. Lossy transmission with a CSCC technique, which is represented by a dashed line from the JPEG encoder to FEC coding, will be used for coded data transmission in order to improve the transmission efficiency. Re-transmission is involved in order to guarantee highly reliable transmission of overhead data ahead of the coded bit stream. Furthermore, the FEC is based on a family of BCH codec, which may be different for FEC 1 and FEC 2 as shown in Fig. 2. Finally, at the decoding phase, the decoded image will be first de-shuffled and then passed through an error concealment element to further improve the visual quality.

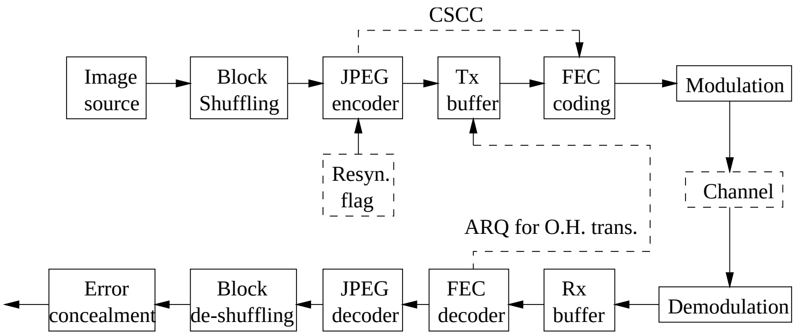


Fig. 3. *The block diagram of the mobile image transmission system.*

Note that in Fig. 3, the block-shuffling/deshuffling and proposed CSCC as well as error-concealment are key elements of the proposed system. The block shuffling technique used in this paper is originally proposed by [1] for wireless image transmission. It is evidenced that this scheme can effectively make the error blocks isolated and thus eases the error concealment at the decoder. Moreover, since the block-shuffling is performed before source encoding and de-shuffling is performed after source decoding, and shuffling is simply a reordering of the memory address of picture blocks, no extra delay and no extra hardware complexity are introduced. This is different from the case of bit-interleaving/de-interleaving. Bit-interleaving and de-interleaving elements is normally placed after channel coding and before channel decoding, respectively, if they are involved. Thus, their I/O bandwidths are limited by the transmission rate of a radio link. If the transmission rate is very low while the required interleaving depth is very large, excessive delay will be introduced while requiring extra memory. Therefore, block-shuffling is better than bit-interleaving in image transmission. It is also noted that this block-shuffling/deshuffling scheme is performed in the spatial domain in order to simplify implementation. In [15], a block-shuffling/deshuffling scheme is suggested to be performed in the transform domain for no degradation in compression ratio. However, when VLC is used, shuffling becomes more complicated. Studies in [1] show that the bit-expansion of coded image after spatially block-shuffling is very small (less than 2% usually) and thus negligible.

Finally, we note that both CSCC and a low complexity concealment techniques are the key contributions of this paper. They will be demonstrated in detail in next two sections.

III. COMBINED SOURCE AND CHANNEL CODING FOR IMAGE TRANSMISSION

A. Transmission Efficiency of the CSCC Schemes

As mentioned above, resynchronization is considered as an essential error-resilient technique in source coding. Different resynchronization schemes with different resynchronization intervals will result in different source coding schemes along with different error-resilient capabilities and different amount of extra bit-expansion, which in turn affects transmission efficiency. Let α, *Resyn*, and ρ denote the normalized bit-expansion which results from source coding, resynchronisation interval in terms of picture-blocks, and compression ratio, respectively. Specifically, α is determined as a percentage of image data expansion after resynchronization insertion with respect to the image data without resynchronization. Table I lists some values of α with different images coded at different values of ρ and *Resyn* using the JPEG coding standard.

TABLE I: Simulation results of bit-expansion α

Images	Resyn=1	Resyn=2	Resyn=4	Resyn=8
LENA (ρ = 9.41)	0.367	0.185	0.0935	0.0452
AIRPLANE (ρ = 8.86)	0.369	0.192	0.0978	0.0495
BABOON (ρ = 5.96)	0.243	0.128	0.0585	0.0284

A close observation of Table I indicates that we can approximate α in terms of *Resyn* and ρ using a single formula. Specifically, we have

$$\alpha = k\frac{\rho}{Resyn} \tag{1}$$

where k is experimentally determined as 0.04 for the JPEG coding standard. It is noted that the usefulness of this approximation has been confirmed by extensive simulations.

Another key factor which affects the overall transmission efficiency is channel coding. Different channel coding schemes with different error-correcting capabilities will result in different channel coding efficiencies. For a binary BCH code, it has the following parameters:

- Block length: $2^m - 1$;
- Number of parity-check digits: $\leq mt$;
- Minimum distance: $\geq 2t + 1$,

where m ($m \geq 3$) is a positive integer and t ($t < 2^{m-1}$) is the error-correcting capability. Let β denote the normalized bit-expansion that results from channel coding. Then,

$$\beta \le \frac{2^m - 1}{2^m - mt - 1} - 1 = \frac{mt}{2^m - mt - 1}. \qquad (2)$$

Consequently, the overall normalized bit-expansion is given by

$$(1+\alpha)\times(1+\beta) - 1 = \alpha + \beta + \alpha\beta \qquad (3)$$

and the transmission efficiency is

$$\eta \ge \frac{1}{(1+\alpha)(1+\beta)} = \frac{1}{\left(1 + k\frac{\rho}{Re\,syn}\right)\times\left(1 + \frac{mt}{2^m - mt - 1}\right)}. \qquad (4)$$

It is noted that, when t is not very large, the equalities in (2) and thus in (4) are true.

B. Effects of Different CSCC Schemes on PBLR (Picture-Block Loss Rate)

Throughout, we define a minimum data unit (MDU) as the interval between two consecutive resynchronisation flags in a compressed bit stream. Such unit will have the following features:

- Different MDUs are uncorrelated in the sense that errors do not propagate across different MDUs[†];
- A MDU is unseparable. That is, any uncorrectable errors inside a MDU may result in decoding mismatch errors and produce an annoying image with that MDU;
- The error rate of an MDU, denoted by $E_r(MDU)$, is equivalent to the PBLR due to periodic resynchronization in terms of picture blocks.

Note that the third feature is under the condition that a resynchronization interval is not very large. Otherwise, it will be shown in the following that its error-resilient capability is significantly decreased. It must be pointed out that the use of PBLR is for better quantifying the information loss of image transmission so as to ease the study of CSCC schemes. Moreover, for a particular error concealment algorithm, it will be shown in Table IV that PBLR is quite indicative of the visual quality of both damaged and reconstructed images.

We now calculate the PBLR, or $E_r(MDU)$, with block-code channel coding. Consider a practical situation of channel coding based on systematic BCH codes, which are specified as BCH(L(B), L(B'), t), where B denotes a block code, B' is the information field of B, and their lengths are represented by L(B) and L(B'), respectively. Throughout, a wireless channel is modeled as a slow Rayleigh-fading channel [8]. Note that, most of applications are likely to be in slow fading environments. Furthermore, assuming that the Rayleigh fading affects approximately equally over a codeword, then the instantaneous bit error rate at time τ, denoted by $P_e(\tau)$, is approximately the

[†] Recall that, after each resynchronization, the reference of DPCM is set to zero such that a decorrelation is achieved.

same over the codeword after demodulation. Consequently, let $P_r(\tau, B, i)$ denote the probability that i errors occur in B at time τ. Then, we have

$$P_r(\tau, B, i) = \binom{L(B)}{i} P_e(\tau)^i \left(1 - P_e(\tau)\right)^{L(B)-i}. \tag{5}$$

Next, we study the relationship between the error rate of block codes and that of MDUs. Define *L(MDU)* as the length of MDU and let $E_r(B)$ denote the error probability of B. For the case of *L(B) < L(MDU)*, it follows that

$$E_r(MDU) = 1 - (1 - E_r(B))^{L(MDU)/L(B')}. \tag{6}$$

For small $E_r(B)$, we have

$$E_r(MDU) \approx \frac{L(MDU)}{L(B')} E_r(B). \tag{7}$$

This suggests that the resynchronization interval is desirable not to be very large. Otherwise, L(MDU) tends to be very large. Due to the fact that L(B) ≤ 511 is considered more practical [10], the scaling factor L(MDU)/L(B') in (7), and thus PBLR may be very large. Therefore, the error resilient capability of resynchrionization will be reduced significantly.

We then consider the case of *L(B) > L(MDU)*. In this case,

$$\begin{aligned} E_r(MDU) &= \sum_{i=t+1}^{L(B)} E_r(MDU|\, i) P_r(\tau, B, i) \\ &\approx \sum_{i=t+1}^{L(MDU)} E_r(MDU|\, i) P_r(\tau, B, i) \\ &= \sum_{i=t+1}^{L(MDU)} \frac{i}{i + \xi - 1} P_r(\tau, B, i) \end{aligned} \tag{8}$$

where $\xi = \frac{L(B)}{L(MDU)}$ and $E_r(MDU|\, i) = \frac{i}{i+\xi-1}$ (See the proof in the appendix). To clearly understand the effect of using different block codes on PBLR in this case, consider the following numerical example. Assume that L(B)=255, ξ = 1, 2, 3, 4 (In practice, ξ should not be very large) and that different codes are constructed with different values of t. Then, a comparison in terms of PBLR is shown in Fig. 4 using two different values of instantaneous bit-error rate, $P_e(\tau)$. A close observation of this figure indicates that with different values of ξ, the PBLR is very close for the same block code. In particular, the larger the t is, the smaller the relative difference. Therefore, *for L(B) > L(MDU)* and a noisy fading channel which usually requires a large value of t, we have

$$E_r(MDU) \approx E_r(B). \tag{9}$$

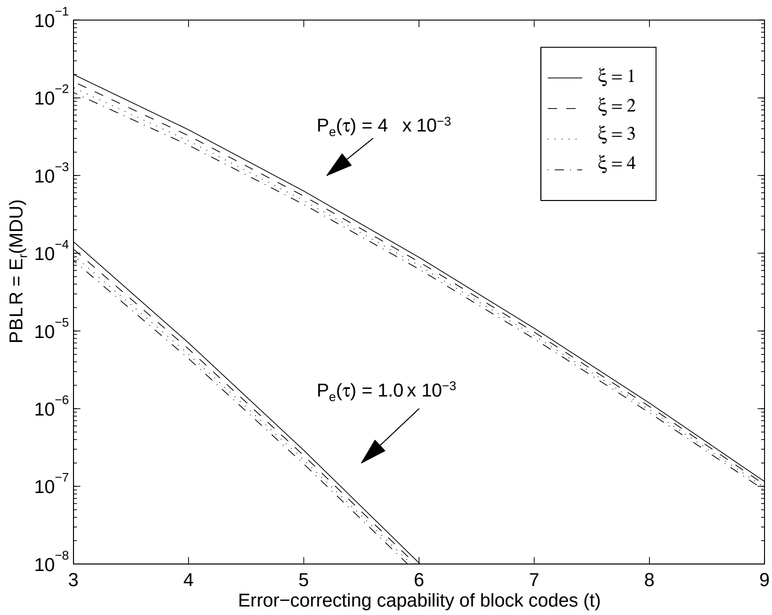


Fig. 4. *Performance comparison of different block codes in terms of PBLR in noisy channels for the case of L(MDU) < L(B). L(B) = 255 bits.*

C. Optimum Block Code Design in Time-Correlated Fading Channels

Different source coding schemes are made using different resynchronization intervals. When a resynchronization interval is not very large, the error rate of an MDU is equivalent to PBLR. In such case, PBLR is determined by a block-code channel coding design. In this subsection, we will focus on how to design a block code which matches a given source coding with resynchronizations in terms of minimized PBLR.

We begin by considering the statistics of erroneous block codes over typical time-correlated fading channels. Computer simulations are employed for the sake of more precisely describing such statistics, albeit they are sometimes very time-consuming. The parameters used in the simulations, which are based on GSM system configuration [2], are depicted in Table II. On the other hand, the GSM specified channel codec, interleaving and frequency hopping are not included. In addition, we assume vehicle speeds (*v*) of 2 and 50 miles/hour, which correspond to normalized Doppler frequencies, denoted by $f_d \times T$, of 2.0×10^{-5} and 5.0×10^{-4}, respectively, where f_d is the maximum Doppler frequency given by $v\times f/c$, $c = 3\times10^8$ m/s, and 1/T is the symbol rate which is 135 ksps for the GMSK being used. Note that, both cases refer to very slow fading conditions. Furthermore, suppose that the fading is subject to Rayleigh distribution and that the inherent equalizer in the GSM works well such that the effect of ISI (inter-symbol-interference) will be negligible. As such the wireless channels are modeled as slow flat Rayleigh fading channels in our study. Throughout, the

GSM frame structure [2] is employed and the simulations are conducted over a single user channel. In particular, to generate the channel parameters, Jakes' model [8] is used.

Table II. Some Parameters Used in Simulations.

Carrier Frequency	900 MHz
Modulation Data Rate	270.8333 kbps (one channel)
Modulation Scheme	0.3 GMSK
Maximum User Data Rate	22.8 kbps (8 users per channel)
Equalization	Included
Average Signal-to-Noise Ratio	18 dB

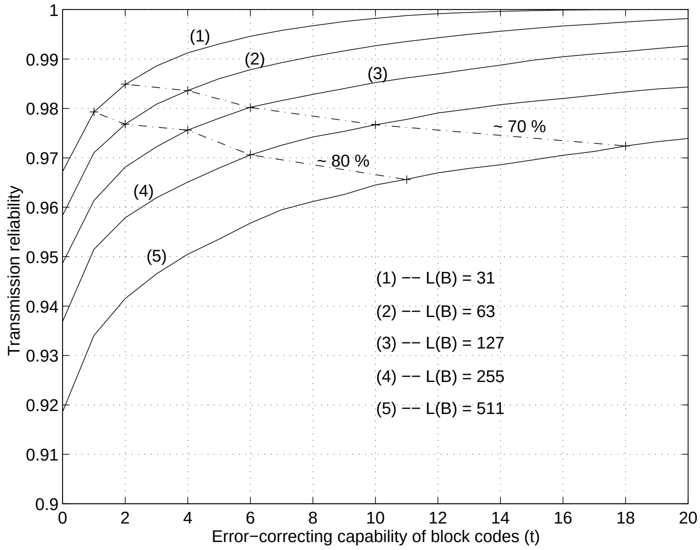


Fig. 5. *Statistics of data-block error rate versus error-correcting capability under the simulated GSM channels with average SNR of 18 dB. The vehicle speed is 2 miles/hour and channel bit rate is 22.8 kb/s. The solid lines denote transmission reliability versus t; the dash-dot lines are the "equal" channel-coding-efficiency lines.*

Figs. 5 and 6 show the transmission reliability of different BCH codes over the above specified channels. Here, the transmission reliability is defined as the percentage of successfully transmitted codewords. In particular, note that the *equal-efficiency*‡ lines along with coding efficiencies are plotted in the figures. It is shown that, in both slow fading channels, the reliability becomes worse as the block code size becomes larger at the same coding efficiency. This phenomenon becomes more explicit when the coding efficiency is higher. Such observation is quite interesting. Intuitively, without interleaving, longer codes tend to perform better due to their ability to overbridge error

‡ In this paper, those codes which have *very close* coding efficiencies are considered as having an *equal-efficiency.*

bursts. However, in a very slow fading channel with reasonable SNR, e.g., 18 dB in GSM, the error burst length tends to be very long. In addition, we wish to keep coding efficiency relatively high[§], say > 70%, thereby the error correcting capability of the code is limited. In such case, to effectively overbridge error bursts, the required code length will be extremely large. For the above specified channel conditions, simulations show that, even codes with block length ≥ 2047 bits get insignificant improvement in transmission reliability when coding efficiency is greater than 70%. In this paper, we consider a practical implementation with reasonable complexity, for which the block length is opted not to exceed 511 bits. Longer codes are considered impractical [10]. Furthermore, under this condition, simulations also show that the above observation in terms of Figs. 5 and 6 are widely valid for most of applications in practice, such as with SNR < 20 dB and vehicle speed < 60 miles/ hour.

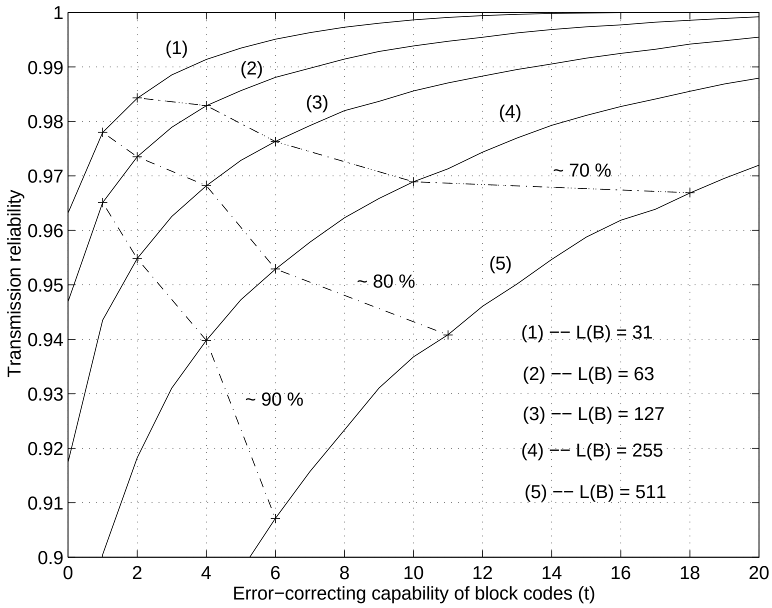


Fig. 6. *Statistics of data-block error rate versus error-correcting capability under the simulated GSM channels with average SNR of 18 dB. The vehicle speed is 50 miles/hour and channel bit rate is 22.8 kb/s. The solid lines denote transmission reliability versus t; the dash-dot lines are the equal channel-coding-efficiency lines.*

It must be pointed out that, with interleaving, the statistics of error blocks may be changed significantly, thus leading to different code design philosophy. In this paper, we will focus on the case without interleaving which is more practical in our application.

Consider a MDU with certain length. If *L(B) > L(MDU)*, then according to Eqn. (9) it is better to have a small value of L(B) if we want to achieve a small PBLR for a given channel coding efficiency or if we want to improve the coding efficiency for a given PBLR. For *L(B) < L (MDU)*, L(B) tends

[§] If the channel coding efficiency is very low, the transmission efficiency will be very low. This is likely to contradict one of our key goals, namely, enhancing the transmission efficiency.

to be larger. This can be best explained by an example. Assuming that L(MDU) = 255 and channel coding efficiency = 80%, then according to Eqn. (7) and Fig. 6 (By referring to Fig. 5, we can perform similar comparison and get the same conclusion),

$$PBLR|_{BCH(63,51,2)} \approx \frac{L(MDU)}{L(B')} E_r(B) = \frac{255}{51} \times 2.6\% = 13.0\%$$

$$PBLR|_{BCH(127,99,4)} \approx \frac{L(MDU)}{L(B')} E_r(B) = \frac{255}{99} \times 3.2\% = 8.24\%$$

$$PBLR|_{BCH(255,207,6)} \approx \frac{L(MDU)}{L(B')} E_r(B) = \frac{255}{207} \times 4.8\% = 5.9\%$$

Based on both observations, it is desirable that a block code contains exactly one MDU or

$$L(B') = L(MDU) \qquad (10)$$

to minimize PBLR for given coding efficiency or to maximize transmission efficiency under a certain PBLR.[**]

Next, consider a MDU with variable length. In such case, Eqn. (10) suggests a multiple channel coding scheme where different block codes with different L(B) may be used to match different lengths of MDU. However, this will result in a very complicated implementation. In this paper, we consider a simple case where only one BCH coder is used. Furthermore, assuming that P_r(L(MDU)=j) = P_j and χ is the maximum length of MDU, then the PBLR can be estimated as

$$PBLR \approx \sum_{j=1}^{L(B')} P_j E_r(MDU|_{L(MDU)=j}) + \sum_{j=L(B')+1}^{\chi} P_j \left(1-\left(1-E_r(B)\right)^{\frac{j}{L(B')}}\right) \qquad (11)$$

where $E_r(MDU|_{L(MDU)=j})$ is determined by Eqn. (8). In other words, given PBLR and using Eqn. (11) along with statistic curves such as those in Figs. 5 and 6, we can find the most efficient block-code as well. However, this is not straightforward. In the sequel, we propose a methodology to find the optimum code design.

We first set a threshold for PBLR, then investigate what codes can achieve high efficiency for a given source coding with certain resynchronization interval, *Resyn*. Assuming that Γ is the average length of MDUs in bits under different source coding schemes. Since each MDU contains *Resyn* 8×8 blocks and each resynchronization inserts a two-byte flag per JPEG coding, we have

$$\Gamma = 8 \times 8 \times 8 \times \frac{Resyn}{\rho} + 16. \qquad (12)$$

[**] This observation was found to be valid for different fading conditions with different vehicle speeds.

As an example, we consider image LENA with 256×256 pixels coded at 0.85 bit/pixel (ρ= 9.41). Different combinations of error-resilient source coding and channel coding, which meet a threshold with PBLR = 4%, are obtained through Eqn. (11) in a fading condition with a vehicle speed of 50 miles/hour. Thus, β and η can be both computed accordingly. Such results are listed in Table III.

It is observed that, for Resyn = 1 with Γ = 70, a good choice is to select L(B) = 63 along with an error-correcting capability of 2. Likewise, for Resyn = 2 and Γ = 125, BCH(127,99,4) has higher transmission efficiency. Finally, for Resyn = 4 with Γ = 234, a high transmission efficiency around 70% can be achieved by designing the code as BCH(255,207,8). Note that an important implication here is that a good design, which provides higher transmission throughput η whilst keeping a reasonable low PBLR, can be obtained by the following *rule of thumb*

$$L(B) \cong \Gamma \tag{13}$$

where ≅ means "*is very close to*". It is noted that Eqn. (10) is a special case of (13). In particular, this *rule of thumb* has been in fact verified through the conduction of extensive simulations with different test images under different fading conditions. Therefore, (13) can provide a *generalized method* for optimizing the channel coding design for a given image coding scheme over time-correlated wireless channels.

Table III: Combination of source and channel coding under PBLR = 4%

	L(B) = 63	L(B) = 127	L(B) = 255	L(B) = 511
Resyn = 1 Γ = 70	t = 2, β = 0.235 η = 59%	t = 4, β = 0.283 η = 57%	t = 8, β = 0.335 η = 54%	t = 16, β = 0.392 η = 52.5%
Resyn = 2 Γ = 125	t = 5, β = 0.908 η = 44%	t = 4, β = 0.283 η = 65.8%	t = 8, β = 0.335 η = 63.2%	t = 16, β = 0.392 η = 60.6%
Resyn = 4 Γ = 234	t = 6, β = 1.33 η = 39.2%	t = 7, β = 0.628 η = 56.2%	t = 8, β = 0.335 η = 68.5%	t = 16, β = 0.392 η = 65.7%

D. Optimization of CSCC for Image Transmission

In the last three subsections, we have studied the effects of different CSCC schemes on both PBLR and transmission efficiency. In particular, for given image coding, an optimal codec design is obtained. However, how to design a CSCC, which achieves both high transmission efficiency and low PBLR, remains challenging. Intuitively, by referring to Eqns. (1) and (12), the larger the values of *Resyn*, the lower the values of α and thus the larger the values of Γ are for given ρ. On the other hand, the larger the values of Γ are, the larger the L(B) is required according to Eqn. (13).

Furthermore, based on Figs. 5 and 6, for given PBLR, the larger the L(B) is, the larger the normalized bit-expansion β. Thus, by referring to (4), α and β are traded against each other in terms of the overall transmission efficiency η. Moreover, such tradeoff is subject to PBLR. If we want to keep PBLR very small, the transmission efficiency will be very low. Thereby, PBLR and transmission efficiency are traded against each other. As such, the optimal CSCC design should consider these tradeoffs. Unfortunately, this is a difficult optimization problem.

In this subsection, we develop a practical and simple procedure for an optimal design of CSCC for image transmission. Specifically, we first set certain threshold level of PBLR, at which the reconstructed image (after compression and error concealment) maintains acceptable visual quality. Then, for each image coding with certain value of *Resyn*, and thus α, we can find its matched coder which has the smallest value of β. Comparing all the possible image coding schemes, for which the values of *Resyn* are not very large, e.g., ≤ 16 in this paper, along with their matched coders in terms of the overall transmission efficiency η, the CSCC having the highest value of η, denoted by η_{max}, is obtained. Note that, if the threshold level of PBLR is selected as the highest tolerant value associated with a particular image compression and error concealment algorithm, this procedure will achieves an optimal CSCC design. In the following, we give a more detailed description of the proposed procedure.

Given an image compression ratio, ρ, and given the channel conditions which are represented by statistic curves such as in Figs. 5 and 6.

***Step 1**: Determine the highest level of PBLR at which acceptable visual quality can be guaranteed. To do so, simulations with the included error concealment algorithm are required;*

***Step 2**: Set the initial values of Resyn = 1 and η_{max} = 50%;*

***Step 3**: Compute α and Γ using Eqns. (1) and (12), respectively, then select the block code length as $L(B) \cong \Gamma$;*

***Step 4**: Find t, and thus β, for the selected block code B to meet the determined PBLR using statistic curves such as those in Fig. 6;*

***Step 5**: Compute η using Eqn. (4) and compare with η_{max} ;*

***Step 6**: If $\eta > \eta_{max}$, then let $\eta_{max} = \eta$;*

***Step 7**: Increase Resyn by 1. If Resyn ≤ 16, go to Step 3. Otherwise, go to the next step;*

***Step 8**: Select the CSCC which corresponds to η_{max} .*

As an example, consider a practical system design. By referring to Fig. 2, we use the above procedure to achieve an optimal design of FEC2 along with the selection of *Resyn*. Recall that FEC2 is for coded data transmission which is possibly lossy. Its design is crucial to trade the transmission efficiency and PBLR. We consider a compressed image data of image LENA with 256×256 pixels coded at 0.85 bit/pixel. By incorporating the proposed error concealment, which will be introduced in next section, the highest threshold level of PBLR of 4% is determined using various *uniformly distributed*[††] picture-block error patterns. Furthermore, assuming a difficult channel condition in GSM with average SNR of 18 dB and a vehicle speed of 50 miles/hour, then the block error statistics as shown in Fig. 6 can be used. As such, using the above procedure, FEC2 can be designed as BCH(255,207,8) along with *Resyn* = 4, which has a transmission efficiency as high as about 70% with a PBLR below 4%.

For the sake of completion, we now discuss the design of FEC1 in Fig. 2, although it may not be as crucial as that of FEC2 due to a small portion of the overhead data. It turns out that, since FEC1 is coupled with re-transmission, its error-correcting capability can be smaller than that of FEC2 in order to achieve higher coding efficiency. On the other hand, it is desirable that FEC1 and FEC2 have the same block size in order to simplify the system implementation. As a result, FEC1 is determined as BCH(255,231,3) for this particular example. Moreover, Go-Back-N [20] is selected as the re-transmission protocol due to its simplicity.

IV. LOW COMPLEXITY ALGORITHM FOR ERROR CONCEALMENT

Error concealment techniques are essential to recover missing blocks, which are due to lossy transmission, in the received images. In particular, lossy transmission with high transmission efficiency is only possible when an effective error concealment technique is used so that good visual quality can be achieved. In fact, as far as image communication is concerned, lossy transmission is usually inevitable. Therefore, error concealment plays a very important role in visual communications and has been the subject of various studies [6, 9, 13-16].

One of the most powerful error concealment algorithm is given in [16], In this algorithm, a multi-directional interpolation was proposed over the spatial domain. The missing blocks are reconstructed by a weighted average of interpolated results using more than one directions. By doing so, the

[††] This is desirable to effectively apply error concealment. In practice, we use blockshuffling to achieve such *uniformly distributed* picture-block error patterns in a time-correlated fading channels.

blocking artifacts are minimized. To determine a direction, the gradient in terms of variation of pixel intensity is calculated using 8 blocks surrounding the missing block. Suppose that the pixels involved in one-dimensional interpolation are $X_0 \sim X_N$ and the indices of missing pixels are in a set M, then each one-dimensional interpolation is governed by the following equation

$$X_{j:j\in M} = \frac{\sum_{i=0,i\notin M}^{N} \frac{X_i}{d_{ji}{}^w}}{\sum_{i=0,i\notin M}^{N} \frac{1}{d_{ji}{}^w}} \tag{14}$$

where d_{ji} denotes the pixel distance between X_i and X_j, and a power weighting factor of w = 2.5 is experimentally evidenced to be very good in practice.

It has been shown that the above algorithm is very powerful. For example, even if the portion of missing blocks is very high, say 10%, the reconstructed image without compression still has a reasonably good quality. However, this algorithm suffers from extremely high computational complexity due to the complicated interpolation based on the power weighting factor of w = 2.5. In fact, it is very difficult to achieve a simple implementation using this algorithm.

In wireless communication, low implementation complexity is particularly desirable. In this paper, we propose an algorithm which performs well both in concealment performance and implementation complexity. Our proposed algorithm is similar to the one in [16] in the sense that multi-directional interpolation is used to minimize the blocking artifacts. However, in contrast to [16], our one-dimensional interpolation is given as follows:

$$X_{j:j\in M} = \frac{\sum_{i=0,i\notin M}^{N} 2^{16-|i-j|} X_i}{\sum_{i=0,i\notin M}^{N} 2^{16-|i-j|}}. \tag{15}$$

Note that the key innovation in our concealment algorithm is the use of a scaling factor of power 2 in (15), for which simple shift registers can be used for its implementation. Thus, the complexity is significantly reduced compared with that of the algorithm proposed in [16]. Table IV shows a performance comparison of the proposed low complexity algorithm (LCA) and that of [16] in terms of the concealment gains in PSNR (peak signal-to-noise ratio). In this comparison, image LENA with 256×256 pixels, without compression[‡‡], is used and uniform error patterns are assumed. It can be observed that both algorithms have very close performance. This is indeed confirmed by extensive simulations which were conducted using different test images under different error conditions. Therefore, the new algorithm is also powerful but is much simpler and could be more suitable for practical visual communication over wireless channels.

[‡‡] Note that, without compression, the comparison does not lose generality.

Table IV: Comparison of the proposed error concealment with the one in [16].

PBLR	6.0%	5.1%	3.8%	2.1%
PSNR[1*] before EC[2*]	18.3 dB	19.31 dB	20.26 dB	24.13 dB
PSNR after EC by [16]	34.21 dB	35.7 dB	36.64 dB	38.51 dB
PSNR after EC by LCA	34.03 dB	35.54 dB	36.52 dB	38.45 dB

[1*] EC: Error Concealment

[2*] PSNR: Peak Signal-to-Noise Ratio

V. SIMULATION AND DISCUSSION

Simulations are performed over the channels specified in Section III.C. These channels are quite representative of most of the mobile application environments. Image LENA with 256×256 pixels coded at 0.85 bit/pixel and image AIRPLANE with 256×256 pixels coded at 0.90 bit/pixel are both used to examine the proposed system. Recall that the JPEG baseline coding standard is used in this study and the parameters of the slow Rayleigh fading channels are generated using Jakes' model [8].

Figs. 7 and 8 show the simulation results of transmitting image LENA over the proposed system with vehicle speeds of 2 and 50 miles/hour, which correspond to normalized Doppler frequencies of 2.0×10^{-5} and 5.0×10^{-4}, respectively. Using our proposed optimization procedure, BCH(255,207,8) and *Resyn* = 4, which implies a transmission efficiency as high as 70% with PBLR being below 4%, are selected. From Figs. 7(a) and 8(a), it is observed that the picture-block loss rates in both fading channels are well controlled under a predetermined threshold value of 4%. Thereby, confirming the validity of the proposed optimal design of CSCC. By incorporating random block-shuffling and the proposed LCA for error concealment, the reconstructed images in Figs. 7(b) and 8(b) presents very good visual quality with PSNR of around 30 dB[§§]. As such, the usefulness of the proposed error concealment algorithm is verified.

Similarly, Figs. 9 and 10 show the simulation results of transmitting image AIRPLANE, with 256×256 pixels coded at 0.90 bit/pixel, over the proposed system under similar fading channel conditions. After the optimization of CSCC, BCH(255,207,8) and *Resyn* = 4 are again selected with a transmission efficiency of about 70%. Figs. 9(a) and 10(a) indicate that the picture-block loss rates are 2.9% and 2.8% in both fading channels. Note that the picture-block loss rates in both fading channels are again well controlled by the design of CSCC. Likewise, the effect of random block-

[§§] Through an error free channel, the PSNR of the reconstructed image LENA is 33.6 dB.

shuffling is clearly shown. Figs. 9(b) and 10(b) give the finally reconstructed image after error concealment. Even though PSNRs in this case are lower than that of image LENA, the subjective quality of received images through both fading channels is still reasonably good and quite acceptable. Thereby, confirming again that our proposed system is robust for wireless image transmission.

In summary, even though the channel quality is poor (an average SNR of 18 dB implies an average BER of about 4×10^{-3} in a GSM channel) and the channel statistics varies between two extreme fading cases, the proposed method can achieve high image transmission efficiency along with good visual quality. More importantly, note that this is done without the use of complicated techniques such as bit-interleaving, convolutional coding and Viterbi decoding. Instead, to combat the bursty channel errors, we incorporate a low-cost random block-shuffling and a low complexity error concealment technique which will not introduce extra transmission delay while maintaining reasonable implementation complexity.

With the original error protection scheme of GSM, a rate 1/2 convolutional coder is used. After inserting resynchronization (it is also needed since there are residual errors which may cause image decoding mismatch propagation), the overall image transmission efficiency will be less than 50%. In addition, to randomize the error bursts, interleaving and frequency hopping are included [2]. Thus, extra transmission delay is introduced and the system implementation is complicated. It is true that such error protection scheme is very powerful in terms of possibly achieving less PBLR during image transmission. However, it has a very poor ability in reporting residual errors, thus helping less in indicating where the missing blocks are so that error concealment can be incorporated more effectively. Therefore, the finally reconstructed images may not get significant improvement in terms of visual quality.

It is also noted that, even though the study in this paper is based on gray-level images, the developed techniques are applicable for the mobile transmission of a color image with multiple components. Basically, the JPEG baseline coding algorithm will produce the same bit stream file structure as shown in Fig. 1 for a color image. In addition, each component is in fact coded/decoded individually. Therefore, the proposed image transmission system with CSCC and error concealment can be applied in a straightforward manner. Since each image component is made with good quality, the overall visual quality of the color image will be quite acceptable as well.

VI. CONCLUSIONS

In this paper, we propose an efficient mobile image transmission system based on the JPEG baseline coding standard, which is sufficient for many applications. Its key innovation lies in the improved transmission efficiency and implementation simplicity due to the use of *lossy transmission* with CSCC and low-complexity error concealment. In particular, the proposed CSCC with simple BCH codes are designed to match both the coded image characteristics and wireless channel statistics, thereby trading off the transmission efficiency and information loss. Meanwhile, block-shuffling and error-concealment technique are included as essential means to compensate the information loss so as to guarantee acceptable visual quality of the reconstructed images. To accomplish a simple implementation, a low-complexity concealment algorithm is introduced and shown to have excellent performance which is very close to that of [16]. The performance of the overall proposed image transmission system has been evaluated using computer simulation. Some sample results based on images "LENA" and "AIRPLANE", which are coded at 0.85 and 0.90 bit/pixel, respectively, under a simulated GSM channel with an average SNR of 18 dB and various vehicle speeds (2 - 50 miles/hour) indicate that the proposed system achieves a throughput as high as 70% with good visual quality at PSNRs around 30 dB for the reconstructed images. It is also noted that the proposed system is applicable for color image transmission with the baseline coding standard. Applications of the developed techniques to mobile video communications are being investigated.

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APPENDIX

Theorem. Let B be a block code, MDU be a minimum data unit with $L(MDU) < L(B)$. If B contains i error bits which are uniformly located in B with $i \leq min(L(MDU), L(B)-L(MDU))$, then

$$E_r(MDU|i) = \frac{i}{i + \xi - 1} \tag{16}$$

where $E_r(MDU|i)$ denotes the error probability of MDU under the condition of B containing i error bits, and $\xi = \frac{L(B)}{L(MDU)}$.

Proof. We first consider a simple case where ξ is an integer N. For the sake of simplicity, let's think of an corrupted bit as a "ball" and a MDU as a "box". Then, $E_r(MDU|i)$ is equivalent to the probability of a box containing at least one ball under an experiment of i balls being randomly placed among N boxes. Assume that an outcome of such experiment is shown in Fig. A.1. In this figure, all balls in the right side of box k and in the left side of box $k+1$ belong to box k.

Since all the boxes should not be empty, the first item in the left side of Fig. A.1 should be a box. Thus, the total number of outcomes of placing i balls among N boxes is $\binom{i+N-1}{N-1}$. Further, set a condition that a box contains at least one ball. Such experiment corresponds to Fig. A.2. Then, the number of outcomes in this case is $\binom{i-1+N-1}{N-1}$.

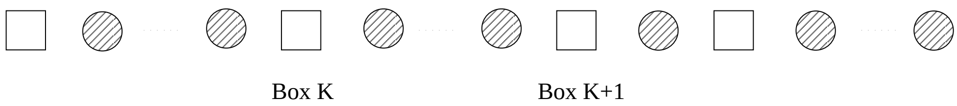

Figure A.1

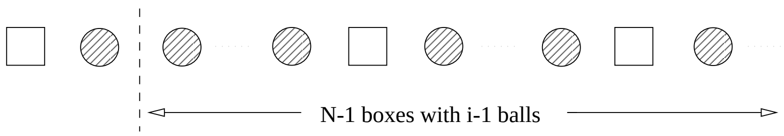

Figure A.2

Therefore,

$$E_r(MDU|\,i) = \binom{i-1+N-1}{N-1}\bigg/\binom{i+N-1}{N-1} = \frac{i}{i+N-1} = \frac{i}{i+\xi-1}. \qquad (17)$$

Next, we consider a general case where $\xi = {}^{N_1}\!/_{N_2} > 1$, N_1 and N_2 are both integers. By expanding both ξ and i by N_2 times, we then have N_1 boxes along with N_2 balls. Consequently, the experiment of placing $N_2 i$ balls among N_1 boxes randomly and the experiment that N_2 boxes contain at least one ball can be illustrated in Figs. A.3 and A.4, respectively.

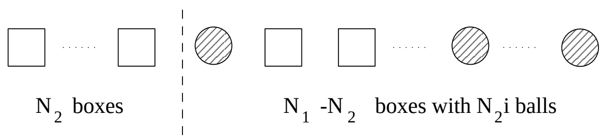

Figure A.3

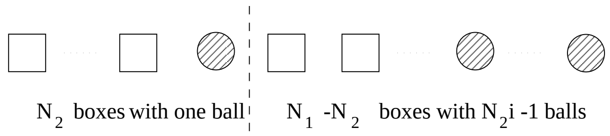

Figure A.4

Note that a MDU contains N_2 boxes and that N_1 - N_2 boxes can contain at most $N_2 i$ balls (recall that $i \leq min(L(MDU), L(B)\text{-}L(MDU))$). Hence,

$$E_r(MDU|\, i) = \binom{N_2 i - 1 + N_1 - N_2}{N_1 - N_2} \Big/ \binom{N_2 i + N_1 - N2}{N_1 - N_2} = \frac{N_2 i}{N_2 i + N_1 - N_2} = \frac{i}{i + \xi - 1}. \quad (18)$$

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