Unequal Error Protected Bitplanes Improve the Robustness of Wireless Holographic Image Communications

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Abstract: Digital holograms are partitioned into multiple bitplanes that are independently encoded by a forward error correction code for transmission over wireless channels. PSNR improvements of 12.5 dB are achieved with a recursive systematic convolutional code.

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1. Introduction

Holography [1] constitutes a sophisticated technique of recording and reconstructing both the amplitude and phase of an optical wavefront relying on the interference and diffraction imposed by an object on visible light. Optical holography allows the holographic images to be recorded and reconstructed using a white-light illumination source [2] or a illuminating laser [3]. Digital holography (DH) [4, 5] refers to the class of techniques that records an optical hologram digitally and reconstruct the image using numerical manipulations.

Digital holograms may be widely utilized in future applications. However, apart from [6], the transmission of digital holograms has rarely been researched. We propose an optimized unequal error protection based forward error correction (Opt-UEP-FEC) coded system, where the holograms will be transmitted bitplane by bitplane after forward error correction (FEC).

2. System Architecture

We introduce the proposed unequal error protection (UEP) based FEC coded (Opt-UEP-FEC) system conceived for holographic communications, whose system model is detailed in Fig. 1.

At the transmitter, the original hologram U (for example, as shown in Fig. 2) is de-multiplexed into the classic bitplanes $u_0, \cdots, u_{m-1}$ by the *DEMUX* block, where u_0/u_{m-1} represents the most/least significant bitplane. Meanwhile, the original hologram U is input to the "Code Rate Optimization" block, which will generate the optimized coding rates $r_0, \cdots, r_{m-1}$ for the bitplanes $u_0, \cdots, u_{m-1}$, respectively. Afterwards, each bitplane u_i $(0 \leq i < m)$ is encoded as follows:

1. The bitplane u_i will be linearly indexed to generate the sequence $\overline{u}_i$ by the block L.
2. The resultant sequence $\overline{u}_i$ is then encoded by the FEC encoder i, which generates the encoded bit sequence x_i.

Finally, the bit sequences $x_0, \cdots, x_{m-1}$ are concatenated into a joint bitstream for transmission.

The receiver structure generates the soft information $y_0, \cdots, y_{m-1}$ for the bitplanes $u_0, \cdots, u_{m-1}$, respectively. Then each bitplane u_i $(0 \leq i < m)$ is estimated as follows:

1. The soft information y_i is decoded by the FEC decoder i generating the bit sequence $\hat{\overline{u}}_i$, which is the estimated version of bit sequence $\overline{u}_i$.
2. The sequence $\hat{\overline{u}}_i$ will then be reformatted to the bitplane $\hat{u}_i$ by the the block L^{-1}, where $\hat{u}_i$ is the estimated version of the bitplane u_i.

Finally, the estimated bitplanes $\hat{u}_0, \cdots, \hat{u}_{m-1}$ are reconstructed into the final estimated hologram $\hat{U}$ by the "MUX" block.

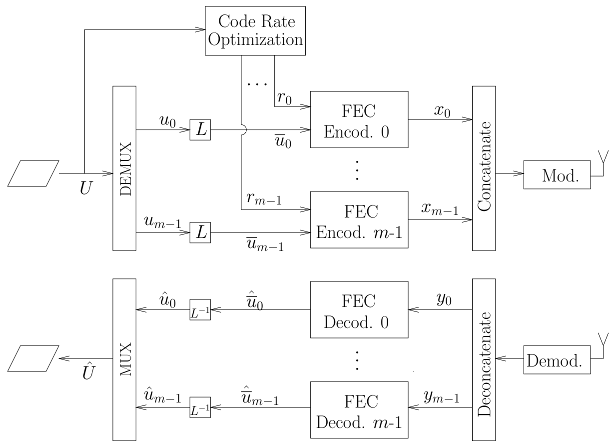


Fig. 1: Block diagram of the proposed Opt-UEP-FEC system.

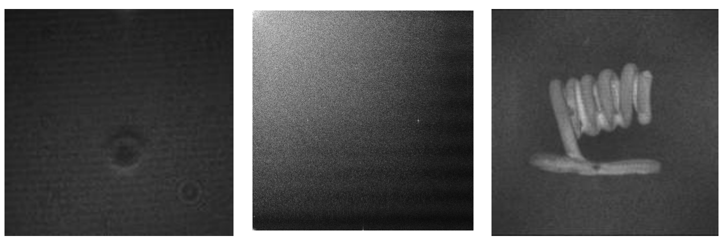
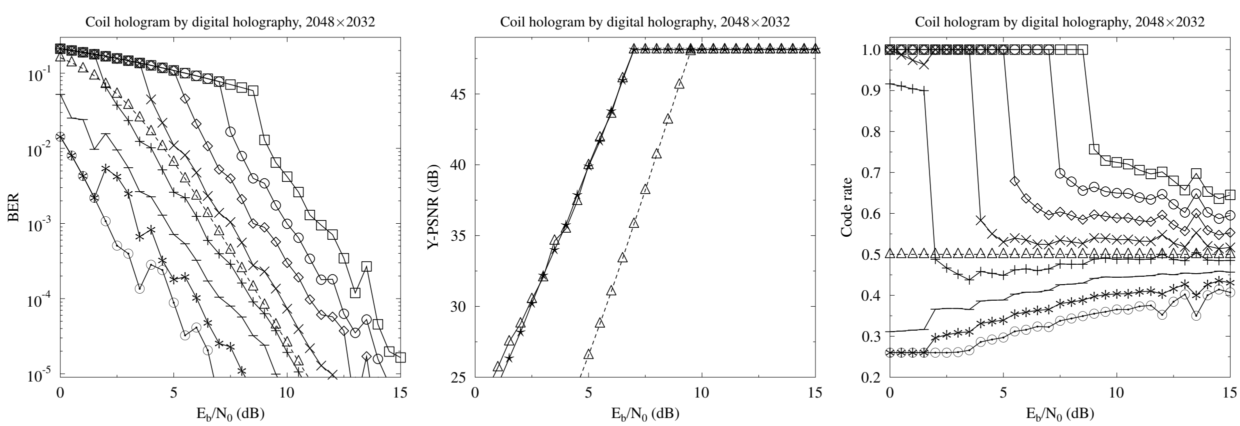


Fig. 2: Example hologram used in the simulations (L-R): hologram of a coil, DCT domain from this *Coil* hologram, reconstructed image from this *Coil* hologram



(a) BER vs E_b/N_0 - *Coil* (b) PSNR vs E_b/N_0 - *Coil* (c) Code rate vs E_b/N_0 - *Coil*

Fig. 3: BER, PSNR, Code rate versus E_b/N_0 performance comparison of the proposed system and the benchmarkers, namely the EEP-RSC scheme, the Opt-UEP-RSC scheme and the Opt-UEP-RSC-Est scheme for the *Coil* hologram.

The "Code Rate Optimization" block of Fig. 1 has the task of finding the specific FEC coding rates $r_0, \cdots, r_{m-1}$ required for encoding the different-significance bitplanes $u_0, \cdots, u_{m-1}$. We denote the position of a specific pixel by $\rho = (w, h)$ in the intensity hologram frame for notational simplicity.

The coding rates $r_0, \cdots, r_{m-1}$ of Fig. 1 aim for maximizing the quality of the image reconstructed from the estimated hologram $\hat{U}$ at the receiver. In this paper, our objective is to maximize the peak signal-to-noise ratio (PSNR) of the estimated hologram $\hat{U}$, which represents the most popular objective video quality metric of the reconstructed image [7]. Defining the PSNR of the estimated hologram $\hat{U}$ as $PSNR_U$, our objective function (OF) invoked for maximizing the quality of this hologram may be formulated as

$$\underset{r_0,\cdots,r_{m-1}}{\arg} \max \left\{ E\left(PSNR_U\right) \right\}, \tag{1}$$

where the $PSNR_U$ of the reconstructed hologram $\hat{U}$ may be calculated as

$$PSNR_U = 10 \cdot \log_{10} \left\{ \frac{(2^m - 1)^2}{MSE} \right\} dB \quad , \quad MSE = \frac{1}{W \cdot H} \sum_{w=0}^{H-1} \sum_{h=0}^{W-1} \left[U(\rho) - \hat{U}(\rho) \right]^2, \tag{2}$$

where the MSE is calculated based on the original hologram U and the reconstructed hologram $\hat{U}$.

3. Simulations

We benchmark our Opt-UEP-RSC system against the traditional EEP-RSC system. The BER versus E_b/N_0 curves of the eight bitplanes of the Coil hologram are displayed in Fig. 3a. As expected, the BER of the bitplanes $u_4, \cdots, u_7$ of the Opt-UEP-RSC system is always better than that of the EEP-RSC system, while the BER of the bitplanes $u_0, \cdots, u_3$ is worse than that of the EEP-RSC system owing to the specific code rates.

The PSNR versus E_b/N_0 performance recorded for the Coil hologram is displayed in Fig. 3b, where the PSNR is also provided by the curve Opt-UEP-RSC-Est. We observe that the Opt-UEP-RSC scheme substantially outperforms the EEP-RSC system, while it has similar performance to the theoretical curve Opt-UEP-RSC-Est. Specifically, the Opt-UEP-RSC scheme achieves an E_b/N_0 reduction of about 2.6 dB compared to the EEP-RSC scheme at a PSNR of 48 dB. Alternatively, about 12.5 dB of PSNR hologram quality improvement is observed at an E_b/N_0 of 7 dB. The optimized coding rates found by our proposed regime for the Coil holograms are shown in Fig. 3c.

4. Conclusions

We proposed a UEP-FEC technique for the bitplane based transmission of digital holograms over wireless channels, where the coding rates of different bitplanes were optimized to improve hologram quality. We solved the resultant multi-dimensional optimization problem of generating the optimal coding rates for the m bitplanes. Our numerical simulations show that the proposed Opt-UEP-FEC system outperforms the traditional UEP-FEC system by up to 2.6 dB of E_b/N_0 or 12.5 dB of PSNR, when employing a RSC code.

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