Eight-channel Transmultiplexer with Binary Matrix Sequences
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Abstract

The duals of finite impulse response filters constructed of binary matrix sequences are used to design an eight-channel transmultiplexer. The binary matrix sequences of analysis and synthesis filters are obtained from corresponding complementary sequences which satisfy the conditions for perfect reconstruction. The distortions of eight transmultiplexed images in the presence of channel noise are studied for the case of a simulated transmission over a Digital Video Broadcasting - Satellite - Second Generation (DVB-S2) system.

Keywords: Transmultiplexer, dual, binary matrix sequences, complementary sequences, DVB-S2.

Introduction

Transmultiplexing is a convenient and efficient method to pass over numerous information sources through a common channel. Transmultiplexers are playing a significant role in digital communications. The demand for an efficient transmultiplexer (TM) in digital communication systems has been radically increased. Transmultiplexers are developed on the basis of the infrastructure of multirate filter banks. A filter bank (FB) is an arrangement of filters applied to decompose input signals into a set of subband signals occupying portions of the original frequency spectrum and combine the subband signals back into composite signals. A filter bank can be transformed to a transmultiplexer by simply interchanging composition and decomposition processes (Eghbali 2006). A transmultiplexer combines several signals into a single composite signal by applying simple digital processing procedures at the transmitter: upsampling, filtering and summing. The composite signal is then transmitted over one single channel and decomposed into many signals by filtering and downsampling at the receiver.

The main task of such systems is preventing image distortions caused by the change of amplitude and phase as well as image leakage from one channel into another (Vaidyanathan 1992). Accomplishing a perfect reconstruction (PR) in transmultiplexing systems is a complicated problem. The challenging tasks in a transmultiplexer are to develop the required filters that ensure the perfect reconstruction and to reach a sub-optimal performance in the presence of noise. Polynomial techniques are usually implemented to design proper filters being able to reconstruct the original signals at the receiver in transmultiplexing systems. Also, transmultiplexers with integer filter coefficients have been constructed recently (Sypka and Ziöłko 2007).

This paper describes a new method to design a fully operational transmultiplexer with binary coefficients based on a dual of a binary matrix finite impulse response (FIR) filter, which simultaneously transmits 8 images over a single communication channel, eliminates unwanted aliasing and ensures the image
reconstruction at the receiver end.

FIR filters, also known as convolutional filters, have the advantage of exhibiting no phase distortion (Vaidyanathan 1992). A standard FIR digital filter consists of two subsystems: analysis system and synthesis system. Analysis is a single-input, multi-output subsystem consisting of the analysis (separation) filters and downsamplers. Synthesis is another subsystem which synthesizes a single signal from multiple input signals. A synthesis subsystem contains the interpolators (upsamplers) and synthesis (combining) filters. Upsampling and downsampling allow changes in the effective sample rate of a sequence, and also allow matching of sample rates of analog-to-digital, digital-to-analog and digital processes. Analysis and synthesis subsystems are duals of one another (Eghbali 2006). The synthesis system performs the complementary operation to that of the analysis system, and vice versa. A subband system and transmultiplexer are related to each other since both systems use multirate filter banks. A transposition of the same dual subsystems (analysis and synthesis) of the subband system results in a transmultiplexer (Eghbali 2006). The roles of the inputs and the outputs of the subband system are interchanged in a transmultiplexing system. This paper exploits further the perfect reconstruction properties of the obtained filters with a primary objective to analyze the average reconstructing performance of the transmultiplexing system in the presence of channel noise.

**Analytic Model**

The primary concerns in multirate FB are distortion and aliasing. If the combining filters and the separation filters are not appropriately developed, the quality of the output signals could deteriorate dramatically. Selecting appropriate filters means designing such transmit/receive filters in every branch that completely remove the effects of aliasing and distortion, i.e., fulfill the conditions of PR. The input-output relationship of a two-channel critically sampled PR filter bank can be written as (Vaidyanathan 1992; Cooklev 1995; Cooklev et al. 1996; Cooklev and Nishihara 2006):

\[
\hat{X}(z) = \frac{1}{2} [H_0(z)G_0(z) + H_1(z)G_1(z)]X(z) + \frac{1}{2} [H_0(-z)G_0(z) + H_1(-z)G_1(z)]X(-z).
\]

The first term represents the distortion transfer function and the second one represents the aliasing transfer function. One can design a perfect reconstruction (PR) filter bank by determining the coefficients of analysis filters \(H_k(z)\) and synthesis filters \(G_k(z), k = 0, 1\), such that the input is a delayed copy of the output. For PR, the distortion function should be a pure delay and the aliasing function must be zero.

Orthogonality of filter banks is an important property for many applications of digital signal and image processing. Orthogonal filter banks (also called paraunitary FB) are special critically sampled perfect reconstruction filter banks where the synthesis filters are time-reversals of the analysis filters. Therefore, knowing the analysis filters, one can easily obtain the synthesis filters. The orthogonality conditions of filter banks are given, as follows (Cooklev et al. 1996):

\[
H_0(z)\tilde{H}_0(-z) + H_0(-z)\tilde{H}_0(z) = 1, \quad (2)
\]

\[
H_1(z)\tilde{H}_1(-z) + H_1(-z)\tilde{H}_1(z) = 1, \quad (3)
\]

\[
H_0(z)\tilde{H}_1(-z) + H_0(-z)\tilde{H}_1(z) = 0, \quad (4)
\]

\[
H_1(z)\tilde{H}_0(-z) + H_1(-z)\tilde{H}_0(z) = 0, \quad (5)
\]

where \(\tilde{\cdot}\) means transposition, conjugation of the coefficients and replacing \(z\) with \(z^{-1}\).

The matrix form:

\[
H_m(z) = \begin{pmatrix} H_0(z) & H_0(-z) \\ H_1(z) & H_1(-z) \end{pmatrix}, \quad (6)
\]
is called alias component (AC) matrix or modulation matrix (Cooklev et al. 1996). Filter banks are orthogonal if the modulation matrix \( H_m(z) \) is orthogonal:

\[
H_m(z)\tilde{H}_m(z) = \tilde{H}_m(z)H_m(z) = cI. \tag{7}
\]

The dual nature between FB and TM relates the aliasing cancellation (Eghbali 2006) and makes it feasible to design multichannel transmultiplexers with matrix FIR filters and eventually obtain filters with binary coefficients which completely eliminate the aliasing and fulfill the conditions to achieve perfect reconstruction.

### Methodology

The design of transmultiplexing systems can be simplified by introducing binary matrix filters where the filter coefficients of each binary filter belong to the set \{-1,+1\}. For example, let us consider a digital model of an eight-channel binary transmultiplexing system consisting of three-stage transmit and receive configurations (8-4-2-1 and 1-2-4-8) based on standard two-channel FIR digital filters, where the filters are binary matrix polynomials. The filter length of the binary matrix polynomials used for the performance evaluation equals four bits, although longer filter lengths can also be obtained (Hossain 2010). The infrastructure of the transmultiplexer is based on the dual of standard multirate digital filter banks (Eghbali 2006). A standard digital FB comprises of two subsystems, analysis and synthesis. The analysis subsystem produces multiple signals from a single signal by performing upsampling and filtering by two simultaneous analysis filters. The synthesis subsystem generates a single output by interpolating multiple inputs and performing downsampling. One can say that a standard multirate digital FB is a two-filter approach where two splitting filters reside at the transmitter side and two combining filters reside at the receiver end. Transposition of both subsystems results in a transmultiplexer (Eghbali 2006).

The proposed TM system has the same filter configuration in every stage of transmultiplexing as the standard one but the size and the dimension of the binary matrix filters are different. The complete transmultiplexing process is done in three different stages where corresponding 4x4, 2x2 and 1x1 binary matrices are implemented as shown schematically in Fig. 1. The outer 4x4 binary FIR filters are added first to both transmitter and receiver sides in order to transmultiplex 8-images simultaneously. A dual of the standard 2x2 FIR filter is used at the outer stage but each filter component is a 4x4 matrix configuration so one can mix 8-images simultaneously, which results in a better mixing of input images compared to the eventual parallel use of four 2x2 filters.

Complementary sequences (Cooklev and Nishihara 2006) can be used to obtain the binary coefficients of the binary filters \( H(z) \) and \( G(z) \) with GENOCOP software. GENOCOP (Michalewicz 1996, 2000; Michalewicz and Janikow 1996; Michalewicz and Fogel 2004) utilizes a genetic algorithm for handling multivariate numerical optimization of problems with linear and non-linear constraints. It is also possible to extend the open source GENOCOP system for handling Boolean zero-autocorrelation problems (Htut 2008).

Two complementary matrices, \( A(z) \) and \( B(z) \), can be obtained with the GENOCOP software and the said matrices of this complementary matrix pair are then combined as first and second polyphase components, as follows (Cooklev and Nishihara 2006):

\[
H_i(z) = A_i(z^2) + z^{-1}B_i(z^2). \tag{8}
\]

The said concept of complementary matrix polynomials is used so that one can reduce twice the number of Boolean variables for the optimization problem in obtaining zero-autocorrelation solutions for the desired PR.
Computational Experiments

In obtaining the binary coefficients of the complementary pair of matrix sequences, $A(z)$ and $B(z)$, the genetic algorithm of GENOCOP performs a multi-directional search by maintaining a population of potential solutions and encouraging information formation and exchange between the said solutions. GENOCOP allows the user to provide the desirable number of iterations which influences the precision of the results. An initial study (Htut 2008) considered the existence of 2x2 binary matrix complementary sequences and used the properties of 2x2 matrix complementary sequences to construct multiple-input multiple-output MIMO FIR filter banks. Htut (2008) used custom Boolean-based functions with the GENOCOP software to find 2x2 binary matrix pairs of various filter lengths.

Let us consider a modification of the previous computational work (Htut 2008) by extending the matrix dimensions and verify the eventual existence of 4x4 binary matrix complementary sequences. This requires the definition of extended Boolean-based functions for constrained optimization of 4x4 matrices (Hossain 2010). The number of Boolean variables in 4x4 matrices increases four-fold as compared to the smaller 2x2 matrices. There are four binary polynomials in each 2x2 matrix. However, there are sixteen binary polynomials in each 4x4 matrix. The number of polynomials is to be multiplied by the filter length to obtain the number of Boolean variables per matrix. The desired solution for so many Boolean variables cannot be obtained with a single execution of the GENOCOP software and numerous consecutive trials of the multivariate Boolean optimization are needed to obtain an exact solution with zero auto-correlation. The sample solutions obtained become a basis for the implementation of empirical rules in modifying the optimization function in an effort to reduce the computational complexity.
Due to the lack of a systematic theoretical knowledge as to how such binary configurations could possibly be obtained, the solutions must be obtained computationally. The sample 4x4 matrix complementary sequences $A(z)$ and $B(z)$ obtained with the GENOCOP software are further combined to find the binary coefficients $\{-1,+1\}$ of both synthesis and analysis binary filters, $G(z)$ and $H(z)$. Given a matrix complementary pair $A(z)$ and $B(z)$ of length $l$, one can construct $G(z)$ and $H(z)$ of length $2l$ using Eq. (8) (Cooklev and Nishihara 2006). For $l = 2$, such sample 4-bit binary coefficients of 4x4 binary matrix polynomials $G(z)$ and $H(z)$ are shown in Tables 1 and 2.

Table 1. Binary coefficients of 4x4 TM synthesis filter $G$ (4 bits).

<table>
<thead>
<tr>
<th>$G_{00}$</th>
<th>$G_{01}$</th>
<th>$G_{02}$</th>
<th>$G_{03}$</th>
<th>$G_{10}$</th>
<th>$G_{11}$</th>
<th>$G_{12}$</th>
<th>$G_{13}$</th>
<th>$G_{20}$</th>
<th>$G_{21}$</th>
<th>$G_{22}$</th>
<th>$G_{23}$</th>
<th>$G_{30}$</th>
<th>$G_{31}$</th>
<th>$G_{32}$</th>
<th>$G_{33}$</th>
</tr>
</thead>
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<tr>
<td>1 1 1 1</td>
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<td>1 1 1 1</td>
<td>1 1 1 1</td>
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</tr>
</tbody>
</table>

Table 2. Binary coefficients of 4x4 TM analysis filter $H$ (4 bits).

<table>
<thead>
<tr>
<th>$H_{00}$</th>
<th>$H_{01}$</th>
<th>$H_{02}$</th>
<th>$H_{03}$</th>
<th>$H_{10}$</th>
<th>$H_{11}$</th>
<th>$H_{12}$</th>
<th>$H_{13}$</th>
<th>$H_{20}$</th>
<th>$H_{21}$</th>
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<th>$H_{23}$</th>
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<th>$H_{31}$</th>
<th>$H_{32}$</th>
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<td>1 1 1 1</td>
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<td>1 1 1 1</td>
<td>1 1 1 1</td>
<td>1 1 1 1</td>
<td></td>
</tr>
</tbody>
</table>

The duals of the obtained 4x4 binary matrix polynomials, $G(z)$ and $H(z)$, are used for the first (outer) stage of transmultiplexing. For the two internal stages, the duals of 2x2 and 1x1 binary filter configurations obtained earlier by Htut (2008) are implemented. As a result, operational three-stage transmit and receive configurations (8-4-2-1 and 1-2-4-8) can be constructed.

**Communication Model**

To verify the performance of binary matrix filters, the proposed TM system is integrated with Digital Video Broadcasting - Satellite - Second Generation (DVB-S2), a standard communication model for satellite transmission which is available in Simulink for Matlab as provided by MathWorks (2008). DVB-S2 (Morello and Mignone 2006) is an enhanced specification ratified by ETSI in March 2005 (ETSI 2005, 2009) to replace the previous DVB-S standard developed in 2003.

DVB-S2 is the most advanced digital satellite broadcasting system at present, where all the digital inputs are processed by a powerful forward error correction (FEC) encoding system. The FEC system is based on an advanced concatenation of Bose-Chaudhuri-Hocquenghem (BCH) outer code and low-density parity-check (LDPC) inner code (ETSI 2005, 2009). After modulation, the signal is transmitted through a satellite channel. The received signal is demodulated and then processed by the FEC decoding system.

DVB-S2 supports very large LDPC code block lengths (64,800 bits for the normal frame, and 16,200 bits for the short frame). Also, DVB-S2 provides techniques such as adaptive coding to optimize the usage of valuable satellite transponder resources. Adaptive coding and modulation (ACM) in DVB-S2 systems allows the transmission parameters to be changed on a frame-by-frame basis depending on the particular conditions of the delivery path for each individual user. There are four digital modulation modes (QPSK, 8PSK, 16APSK and 32APSK). Code rates of 1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9 and 9/10 are available depending on the selected modulation and the system requirements (ETSI 2005, 2009). For the intended computer simulations, the default
code rate of 0.5 is chosen. The binary signal is modulated/demodulated by using the quadrature phase shift keying (QPSK) method.

### Uniform Encoding and Decoding

In the proposed TM system, initially eight arbitrary images (USC-SIPI 2010) are loaded at the transmitter side, all the inputs are multiplexed into a single composite signal with the three-stage (8-4-2-1) multiplexer, the signal is transmitted over the single communication channel, then demultiplexed with the three-stage (1-2-4-8) demultiplexer and as a result eight images are reconstructed at the receiver end.

However, the output of the binary filters produces integer values. Therefore, the composite digital signal then passes through an uniform encoder as a part of the procedure to transform the said integer output into a serial binary stream suitable for transmission. All the integer values of the input signal are uniformly encoded into bits. After the integer-to-binary conversion, all the data is processed through the DVB-S2 communication module. Figure 2 shows the Simulink block diagram of integer-to-binary conversion before transmission. After the transmission, the estimated binary signal at the output of the DVB-S2 communication module is converted back to integer values using a binary-to-integer conversion. The resultant integers are fed to the input of the demultiplexer to obtain the estimates of the reconstructed eight images. Figure 3 shows the Simulink block diagram of binary-to-integer conversion after transmission.

![Fig. 2. Block diagram of integer-to-binary conversion before transmission.](image)

![Fig. 3. Block diagram of binary-to-integer conversion after transmission.](image)

### Analysis and Discussion

The performance of the image reconstruction is evaluated by comparing the plain scheme (serial transmission of individual images without transmultiplexing) with the proposed transmultiplexer in the presence of additive white Gaussian noise (AWGN). AWGN is the default assumption for satellite communications. Results are obtained for consecutive values of the signal-energy-per-bit-to-noise-power-density ratio $E_b/N_0$. In the plain scheme, eight arbitrary images are consecutively loaded in series at the transmitter side, processed through the communication model and relayed one by one to the receiver side. In TM, the said eight images are simultaneously loaded in parallel at the transmitter side, all the inputs are multiplexed into a single composite signal, the signal is transmitted over the single communication channel, then demultiplexed and estimates of the eight images are obtained at the receiver end. A statistical analysis of the differences between the original images and the reconstructed images after transmission is used for the performance evaluation of the proposed TM as compared to the plain scheme.

To verify the performance of the transmultiplexer, tests are carried out for various values of $E_s/N_0$. Subsequently, $E_s/N_0$ is converted to $E_b/N_0$ by implementing the formula: $E_b/N_0 = E_s/N_0 - 10\log(k) - 10\log(r)$, where: $k$ = number of bits per modulation symbol; and $r$ = coding rate (ETSI 2005, 2009).

For the default case considered in this study, with 2 bits per symbol for QPSK and $r = 1/2$, it follows that $E_b/N_0 = E_s/N_0$.

The digital video broadcasting (DVB-S2) transmission system employs BCH-LDPC error control coding on the basis of large encoded blocks for data transmission which provides a bit error rate (BER) performance in AWGN channels being very near to the Shannon limit. There exists a threshold point for $E_b/N_0$, below which the bit error rate exceeds but remains close to $10^{-1}$, in contrast to the frame error rate (FER) which approaches unity (Morello and Mignone 2006). The ‘waterfall’ curve of the BER vs. $E_b/N_0$ graph can be obtained for both

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plain and TM schemes. Both curves must be identical to ensure that the communication model is operating properly and a further comparison between the two schemes can take place (Hossain 2010).

Several tests are conducted for a typical range of $E_b/N_0$ from 0.5 dB to 0.85 dB and an inventory of data of all the reconstructed images is made for each $E_b/N_0$. The performance of the binary filters implemented in the proposed TM system is evaluated on the basis of the statistical analysis of the data obtained from the estimates of the reconstructed images. The data is used to compute the following two statistical parameters for each image: mean value and standard deviation. The value of the first statistical moment (mean) of a given image is calculated from the difference of integer pixel values between the input image and the reconstructed output image. The mean value indicates the overall increase or decrease of the brightness of an image after reconstruction. Most of the mean values oscillate within the range of five intensity units, which resembles fluctuations around zero. With the decrease of $E_b/N_0$, the mean values of the TM images increase, but also the mean values of some images remain close to zero.

The standard deviation (or the square root of the second central moment) is used for the evaluation of the level of image distortion. The graphs of standard deviation vs. $E_b/N_0$ for both the plain scheme and the TM are shown in Fig. 4. With the decrease of $E_b/N_0$, the standard deviations steadily increase.

The reconstructed images are also analyzed according to the sensitivity of visual perception and the image qualities are compared. It is observed that for $E_b/N_0$ greater than 0.80 dB, the quality of the reconstructed images is acceptable. The image distortion becomes noticeable at 0.75 dB and with the decrease of $E_b/N_0$, the image quality degrades.

At 0.50 dB, the predominant “salt and pepper” noise is observed in the reconstructed images (see the Appendix). However, even at very low $E_b/N_0$ the content of the images shown in the Appendix is still recognizable. When $E_b/N_0 = 0.5$ dB, the corresponding BER $\approx 10^{-1}$ (Morello and Mignone 2006). This means that every one in ten bits is in error, but the majority of the bits are correctly estimated. The subsequent uniform decoding and demultiplexing after error correction can split the composite signal into eight distinct images which still contain recognizable patterns. In contrast to the data transmission, when an entire frame is rendered unusable if some of its bits are in error, the image transmission is less vulnerable to bit errors.

Figure 4 illustrates the comparison of standard deviations between the plain scheme and the TM. It can be seen that the standard deviations of TM are almost twice higher compared to the ones of the plain scheme.

In general, it is to be expected that the quality of the reconstructed images after transmultiplexing would be worse than the quality of individually transmitted images of the plain scheme. However, the advantage of TM is that the composite signal can be considered as encrypted data and only a legitimate receiver would know how to demultiplex and split the images. Though the standard deviation increases almost twice after transmultiplexing, the visual quality of the reconstructed images is not affected substantially. Thus the mixed images can be transmitted for multimedia purposes even though the plain scheme is always better in terms of standard deviation. Although the quality of mixed images is worse compared to the plain scheme, the purpose of this study is to observe whether the reconstructed images can still have an acceptable visual quality after the transmultiplexing of 8 images. It is convenient to determine some ranges for the standard deviation in evaluating the visual quality, so that one can compare the plain scheme and the mixed images and if they belong to the same acceptable range of visual quality, then the proposed transmultiplexing could be used for the practice.

Table 3 presents approximate ranges for the standard deviation and the visual quality of reconstructed images for each range. For standard deviations within the range 0-20 intensity units, the visual quality of the transmitted images is almost identical to the
original input images. No significant differences are visible in the images at the receiver side. When the standard deviation exceeds 60 intensity units, the image distortion is quite substantial as shown in the Appendix. Note that the maximum intensity level for the grayscale images is 255 intensity units.

![Comparison of standard deviation (S.D.) between plain scheme and TM.](image)

**Fig. 4.** Comparison of standard deviation (S.D.) between plain scheme and TM.

**Table 3.** Approximate quality ranges for the standard deviation (S.D.) in intensity units.

<table>
<thead>
<tr>
<th>S.D. Range</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>Acceptable</td>
</tr>
<tr>
<td>10-20</td>
<td>Minor distortion</td>
</tr>
<tr>
<td>20-40</td>
<td>Noticeable noise</td>
</tr>
<tr>
<td>40-60</td>
<td>Substantial noise</td>
</tr>
<tr>
<td>Above 60</td>
<td>Predominant noise</td>
</tr>
</tbody>
</table>

**Conclusion**

The development of a dual of a binary matrix finite impulse response (FIR) filter is considered. The dual is constructed of 4x4 binary matrix polynomials. The emphasis is on the binary filters as such filters are much easier to design from hardware point of view. The concept of complementary matrix polynomials (Cooklev and Nishihara 2006) is used to reduce twice the number of variables of the optimization problem and obtain zero-autocorrelation solutions for the desired PR. The existence of binary matrix polynomials for a perfect reconstruction with the proposed multistage transmultiplexer is proven using series of exhaustive computational experiments with the GENOCOP software. Such binary solutions of four-bit matrix polynomials for the transmultiplexing of eight images are obtained for the first time. With binary filters, if the input signal consists of bits or integers and the filter coefficients are binary, the output would consist of integers. Nevertheless, binary filters can work with any input data. No matter whether the information-bearing signal is discrete or continuous, the corresponding binary filters can successfully reconstruct it at the receiver.

The following aspects of binary transmultiplexing deserve a further investigation:

- The presented initial study proves the existence of sample 4x4 matrix binary polynomials of four-bit length for transmultiplexing purposes. However, proper criteria for the selection of the most suitable binary filters from a set of known numerical solutions are yet to be obtained.

- The transmultiplexer generates output values far exceeding the range of the input ones. For example, if the pixels of the grayscale images are limited from 0 to 255 intensity levels, the output could be greater than 255 and also negative, which requires the use of uniform encoder/decoder. Thus, an optimization of the TM output is needed.

- The existence of arbitrary $k \times k$ matrix binary polynomials, $k = 2, 3, 4, 5,...$, of even and odd polynomial lengths, $l = 2, 3, 4, 5,...$, is to be tested.

- Transmultiplexing of color images could also be carried out with the developed Simulink model.

- Finally, MPEG video transmissions could be transmultiplexed to study the level of distortion in compressed video streams, where the salt and pepper noise is replaced by distortion of entire segments of the individual frames.
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Appendix

Reconstructed Noisy Images after Transmultiplexing, $E_b/N_0 = 0.50$ dB

Image 1

Image 2

Image 3

Image 4

Image 5

Image 6

Image 7

Image 8