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RESEARCH ARTICLE

Efficient image transmission in high-degradation scenarios

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Abstract Nowadays, it is required to transmit images and videos underwater with high speed and good quality. Many applications and activities in underwater environments need modern and modified techniques. Moreover, robots with macro size underwater and with micro size inside the body need high-speed communication with the control station. In this paper, we survey some of the available tools for underwater acoustic communication, the trends and difficulties in this area. We survey the characteristics of Orthogonal Frequency Division Multiplexing (OFDM) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in underwater acoustic image communication. In addition, a model for image compression to increase the data rate of transmission under water is presented. It achieves a Compression Ratio (CR) of about 14 and gives better-decoded images with a Peak Signal-to-Noise Ratio (PSNR) up to 34 dB. A comparison between Zero-Forcing (ZF) and pre-ZF equalization formats for Multi-Input Multi-Output (MIMO) OFDM used for image transmission is presented with some results. Below a Signal-to-Noise Ratio (SNR) of 5 dB over the communication channel, the Bit Error Rate (BER) difference between the MIMO OFDM with ZF equalization and the MIMO OFDM with ZF pre-equalization is not high. At an SNR of more than 10 dB, the difference is very high. The ZF pre-equalization for MIMO OFDM improves the system performance compared to the case of ZF post-equalization due to the elimination of noise enhancement.

Keywords Image compression · OFDM · SC-FDMA

Introduction

In recent years, both academia and industry have shown a considerable interest in underwater activities and their associated wireless communication. A great deal of work has been devoted to developing hardware and communication methods that may be used to perform numerous activities such as seafloor surveys, environmental monitoring, offshore oil exploration, ocean seismic monitoring, pollution management, and harbor monitoring. The most popular option for underwater communication (UWC) is through acoustic waves, because they can travel many kilometers in water. An acoustic communication system can only transmit data at a rate of few kilobits per second, which is insufficient for many potential applications.

The roles of UWC in maritime activities are environmental monitoring, collecting sensitive information in military activities, and exploring the ocean below. Although still quite new, UWC is complicated from the modeling perspective because of the ruthless circumstances that characterize underwater channels.

Cables can be used only in few applications such as Internet communication between countries. Optical and electromagnetic waves are used in UWC, but they suffer very high absorption. On the other hand, acoustic waves propagate tens of kilometers with relatively low absorption. Unfortunately, acoustic waves suffer some other problems because of the anisotropic nature of the underwater environment [1, 2].

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Doppler effect is a big problem for acoustic waves in underwater propagation. It comes from the change of the propagation velocity of acoustic waves due to the variability of characteristics such as salinity, temperature, and pressure, in addition to transmitter and receiver relative motion. This effect is a limiting factor for acoustic wave propagation in UWC. OFDM has been adopted for underwater communication to solve the problems of high channel degradations.

Subcarriers are chosen to be orthogonal to the others in OFDM multicarrier systems. OFDM is recommended to achieve good spectral efficiency in underwater acoustic image transmission. With OFDM, we can get a suitable data rate that is reasonable to transmit images with good quality. Unfortunately, the large Peak-to-Average Power Ratio (PAPR) and the sensitivity to subcarrier frequency drift are the drawbacks of OFDM. On the other hand, the SC-FDMA signals have lower PAPR, which makes SC-FDMA a good candidate for UWC. The paper is organized as follows. "Survey" section is a survey of the image transmission underwater. "The proposed system" section presents a description of the proposed system. "Simulation results" section presents the simulation results. The final section is the conclusion.

Survey

In this section, we introduce a survey of the new trends in image transmission underwater.

Multi-carrier and single-carrier modulation

Relevant analysis and simulation results of Frequency Shift Keying (FSK), OFDM, and SC-FDMA systems are discussed for narrow-band UWC. Frequency-Shift Keying (FSK) as a simple system is compared to OFDM and SC-FDM. The OFDM and SC-FDM are more sensitive to the Doppler effect than the FSK. The Doppler effect also degrades the BER performance. Without any Doppler effect correction, the BER is degraded and the channel effects disrupt the orthogonality among the sub-carriers in SC-FDMA and OFDM. In both cases, to avoid performance degradation, we need to introduce some Doppler effect correction for the transmitter–receiver relative velocities of about 3 m/s and 5 m/s, respectively. For low-data-rate applications, FSK can be used as a simple solution for transmission. If the carrier separation in SC-FDMA and OFDM systems is less than that of the FSK system, then in the presence of Doppler effect, the FSK system will be more efficient. For high-data-rate applications such as underwater image and video transmission, SC-FDMA reveals potential advantages. The harmful effects of the communication channel can be mitigated by modern signal processing techniques in the transceiver design, especially with SC-FDMA.

Advanced multi-band modulation technology for UWC systems

In [3], it is considered that image transmission is a critical task for underwater acoustic communication systems in the next generation. To ensure efficient image transmission over an acoustic underwater channel for effective ocean exploration, sophisticated solutions are needed.

Interference reduction methods for multicarrier systems have been tested to reduce inter-carrier interference in UWC systems. Their objectives are related to image transmission over underwater acoustic channels, efficiently.

Achieving a wide bandwidth with a low BER, and saving energy for image transmission are discussed. The OFDM technology is based on the time reversal communication scheme that is recommended for use in UWC. The network lifetime underwater can be increased, and the energy efficiency and bandwidth can be enhanced by controlling the OFDM guard interval.

An optimum bit rate can be achieved over an underwater acoustic channel for image transmission through the utilization of a rate allocation scheme. The PSNR of the reconstructed images can be improved using Single-Input Multiple-Output OFDM (SIMO-OFDM) combined with the time reversal technique.

A receiver design was also introduced for UWC based on a training sequence and a preamble signal. This study results show that the conventional OFDM systems are outperformed by these recommendations in terms of energy and spectrum efficiency as well as received image quality. In these recommendations, the training sequence and the preamble are used to update the estimated Doppler scaling factor and UWA channel parameters. The estimated parameters are used in a feedback framework to reduce the multipath effect. In this process, the receiver records a probe symbol sequence, which was transmitted at the very beginning by the transmitter. This probe sequence is transmitted back to the transmitter after the time reversal operation to serve as channel information.

Fading channels with dispersive nature can be made impulse-like, by using the time reversal technique. So, in UWC with a long tap delay, and without introducing much inter-block interference, a moderate guard interval length can be used. In addition, the guard interval can be made shorter than the maximum channel tap delay with a significant bandwidth efficiency [4]. In [4], a progressive image transmission scheme that considers a passive time reversal system was presented to compensate for the significant delays of multipath UWC channels.

It was reported that image compression is necessary for communication over limited bandwidth channels. Different image compression schemes have been presented for efficient image communication. In one of such schemes, four different groups of bit streams are generated based on their significance, namely the significant bits, the sign bits, the set bits, and the refinement bits. This coding scheme is called Modified Set Partitioning In Hierarchical Trees (M-SPIHT). It is used as an image coder, and the Hierarchical Quadrature Amplitude Modulation (HQAM) is used to provide error protection based on the modulation technique. In addition, to reduce the total distortion of the reconstructed image, the bits are transmitted in four different groups with different protection levels [5, 6].

For efficient image communication under water, less transmission power consumption is required. Hence, the Zero Padding OFDM (ZP-OFDM) is preferred. Moreover, it is required that the overall PSNR of the received images is maximized under channel bit rate and BER constraints. These requirements contribute mainly to the selection of modulation schemes and equalization formats.

Efficient real-time image transmission over underwater acoustic channel

A UWC system for efficient real-time image transmission was proposed in [7]. To improve the bandwidth utilization of the UWC channels, the Set Partitioning in Hierarchical Trees (SPIHT) coder is exploited to compress images in order to cope with the underwater channel bandwidth limitations. In addition, the Reed Solomon encoder is used to reduce the BER over the UWC channel. According to the results, the quality of the reconstructed image is improved in terms of PSNR with both SPIHT and Reed Solomon coding. In this paper, we also introduce improvements in the underwater image transmission with the help of fractal image compression. The proposed system for real-time image transmission over UWC channel is effective as shown by the simulation results. According to these results, an improvement of about 25 dB in the reconstructed image quality is achieved compared to the conventional UWC system without compression.

Underwater robotic applications and wireless image compression and transmission

The necessity of image compression for UWC and the problem of robotic control have been discussed in [8]. Image compression is necessary to reduce the time delay of transmission between the robot and the control station. Several techniques of transmission and progressive image compression have been tested for robot control and communication.

A developed low-cost UWC prototype based on UHF and progressive image compression algorithms has been proposed. The results show that in fresh water, visual compressed data transmission could be viable in a range of, at least, 6 m by an underwater communication system based on radio frequency.

Borowski [9] offered another study on the acoustic characterization of a shallow channel. By employing a simulation software, acoustic channel modeling for the coastal environment and estuaries has been performed, along with bandpass testing. Jeongwoo, et al. established a paradigm for high-speed image transmission [10]. Using OFDM, the image was communicated through underwater acoustic channels. Close-range OFDM testing was continued, and the outcomes were compared to those of single-carrier Quadrature Phase Shift Keying (QPSK) modulation. Jordi et al. [11] introduced a feasibility study of the video transmission through the deep ocean acoustic channel for offshore oil drilling applications.

The proposed system

Fractal model for image compression

The main advantage of the proposed fractal model for image compression for UWC is that fractal coding is popular for its fast decoding and resolution-independent features, thereby enhancing the performance of the communication system.

Fractal geometry can produce an iterative shape that is unachievable with regular geometry. Fractal compression is based on the idea that most natural and artificial objects have self-similarity redundancy at various scales. Self-similarity refers to the aspects of a part relationship with the whole image. The proposed compression approach is based on exploiting the redundancy that fractal image coding algorithms detect.

Fractal image compression is a technique that uses an Iterated Function System (IFS) to mathematically represent an image according to similarity considerations [12]. The coding method is based on the collage theorem, which establishes a bound on the distance between the original image and the decompressed image in terms of the distance between the image transform and the image itself.

The image is partitioned into two sorts of blocks in the proposed model, and we seek a mapping between the larger and smaller blocks. The smaller blocks are recognized as range blocks of size $R \times R$, whereas the larger blocks are recognized as domain blocks of size $2R \times 2R$.

Fractal image compression depends on a search process to approximate the image to be encoded as:

Fig. 1 Original images: **a** Lena, **b** Cameraman, and **c** Pepper

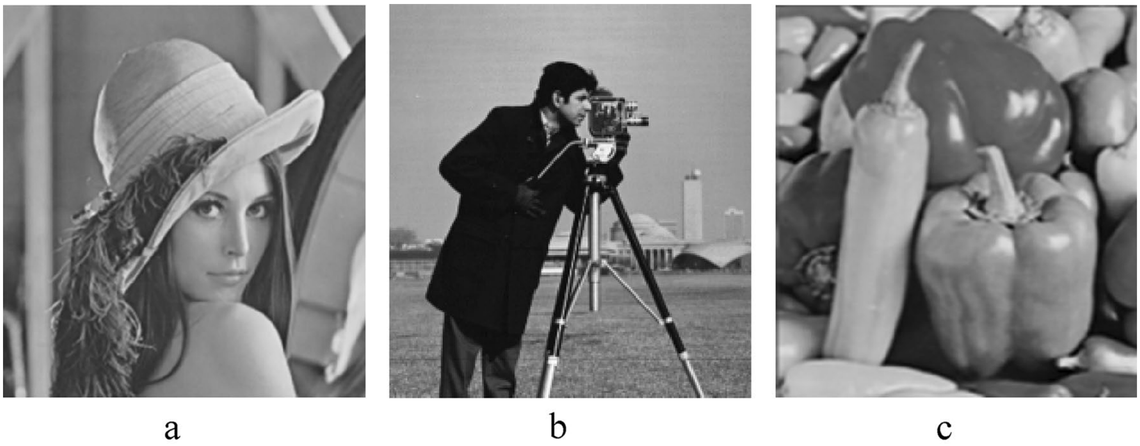

Fig. 2 Decoded images: **a** Lena, **b** Cameraman, and **c** Pepper

Table 1 Performance metrics

	CR	PSNR (dB)	Encoding time (s)
Lena	14.1	34.4	16.8
Cameraman	13.8	32.1	16.9
Pepper	11.2	33.6	16.4

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = w_i \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & 0 \\ k_{21} & k_{22} & 0 \\ 0 & 0 & s_i \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} D_x \\ D_y \\ o_i \end{bmatrix} \tag{1}$$

where x and y are the spatial coordinates of the range block, z is the pixel intensity, k_{11}, k_{12}, k_{21} and k_{22} denote the isometric symmetrical transformations. s_i is a contrast scaling, $0 \leq s_i < 1$, o_i is the brightness offset, and (D_x, D_y) are the contracted domain block spatial coordinates.

We look for the contracted domain in the domain pool that has the best representation of the range by deciding which transformed domain blocks have the least distortion compared to each range block, as follows:

$$E\left(r_i, d_i\right) = \frac{1}{n} \sum_{i=1}^{n} (s.d_i + o_i - r_i)^2 \tag{2}$$

where s_i and o_i are calculated using the following relations:

$$s_i = \frac{n \sum_{i=1}^{n} d_i r_i - \sum_{i=1}^{n} d_i \sum_{i=1}^{n} r_i}{n \sum_{i=1}^{n} d_i^2 - \left(\sum_{i=1}^{n} d_i\right)^2} \tag{3}$$

$$o_i = \frac{1}{n}\left(\sum_{i=1}^{n} r_i - c \sum_{i=1}^{n} d_i\right) \tag{4}$$

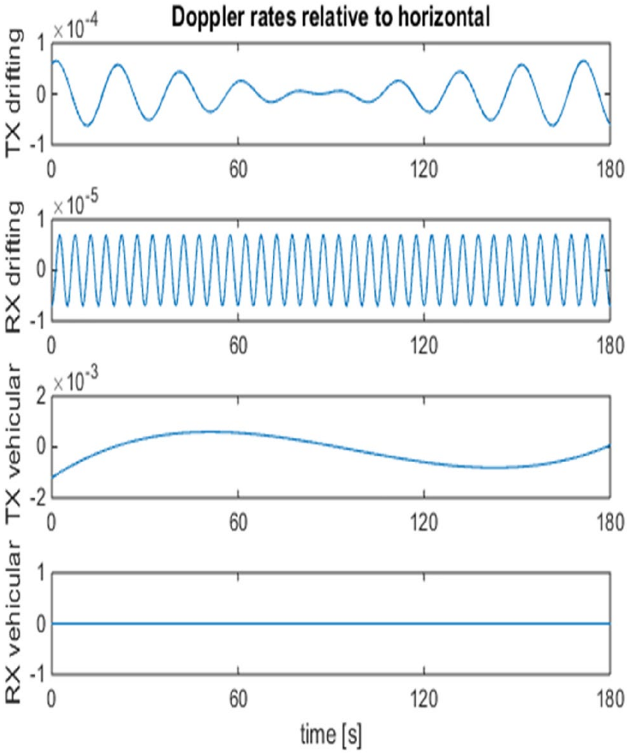

Fig. 3 Channel modelling

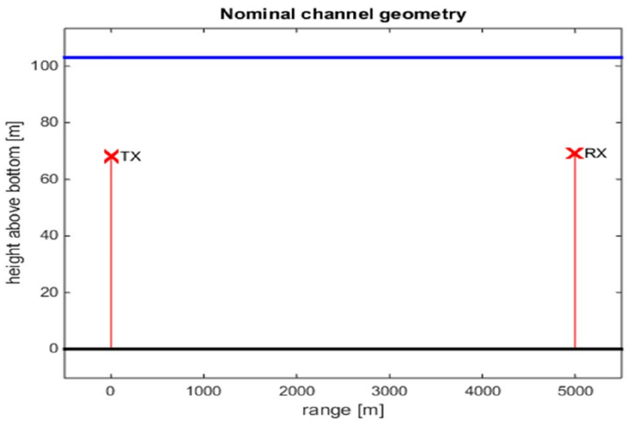

Fig. 4 Channel geometry

Equalization and carrier frequency offset for UWC at different channel conditions

To improve the system performance for image transmission underwater, equalization is one of the requirements. Minimum Mean Square Error (MMSE) equalizer, Matched Filter (MF), and ZF equalizer are appropriate for UWC [13]. Estimating the operating SNR is required for the MMSE equalizer to work, properly. Unfortunately, the MIMO configurations destroy the performance of the matched filter.

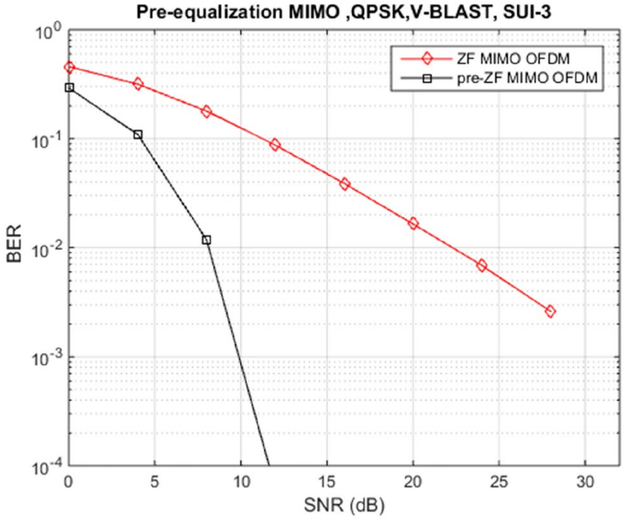

Fig. 5 BER versus SNR of the proposed UWC system

Moreover, the direct matrix inversion tends to induce noise enhancement problems for the ZF equalizer.

In this paper, we study the ZF equalizer to deal with these problems. The proposed equalization algorithm mitigates the noise enhancement problem for image transmission in UWC.

The Frequency-Domain Equalizers (FDE) are used to improve the system performance and mitigate the Inter-Symbol-Interference (ISI), as the UWC channel causes a large delay spread and results in ISI. Generally, the post-equalization and the pre-equalization are two possible formats that can be used in Frequency-Domain Equalization (FDE). In this paper, we are concerned with the comparison between ZF and pre-ZF MIMO OFDM equalization formats in the case of image transmission.

Simulation results

Firstly, the images chosen for testing of the compression model are Lena, Cameraman, and Pepper of size 512×512. The operating system is Windows with 4 GB RAM along with MATLAB R14. Three metrics, namely CR, PSNR, and encoding time, are used to evaluate the compression process.

The main goal of the proposed compression system is to speed up processing by grouping blocks into smaller different sets, where matching is done on range and domain blocks from the same set.

The encoder first divides the size $L \times L$ image into two sorts of blocks in the proposed model, and we seek for a mapping between the larger and smaller blocks. The smaller blocks are recognized as range blocks of size $R \times R$, whereas the larger blocks are recognized as domain blocks of size $2R \times 2R$ with an integer step B, in vertical and horizontal directions. The minimum value for B is 1, which makes the domain set with the maximum size.

Figure 1 shows the three original gray-scale images (Lena, Cameraman, and Pepper). Typical results representing the three reconstructed images with remarkable visual quality are shown in Fig. 2. Table 1 shows that the compression model successfully achieves a high CR, while sustaining the quality of the decoded images in terms of PSNR. For Lena image, the PSNR and CR values are significantly greater than those of images with large smooth regions, such as Cameraman and Pepper.

We tested the performance of the proposed system by sending the images at different channel conditions. The data is divided into vectors that are given in parallel to the OFDM system. We simulated the transmitter and receiver operations with drifting effect as shown in Figs. 3 and 4. The channel geometry is as shown in Fig. 4, and the channel model is the Bellhop. The modulation is QPSK with a spreading factor of 5, a sound speed of 1500 m/s, and a minimum frequency F_{min} of 10 kHz. The bandwidth B is 10 kHz, and the maximum frequency F_{max} is equal to $F_{\min}+B$.

Figure 5 shows the BER versus the SNR of the proposed UWC system with ZF and pre-ZF MIMO OFDM equalizers in the case of Cameraman image transmission. From these results, we conclude that the pre-ZF equalizer outperforms the post-ZF equalizer.

Below $\text{SNR}=5$ dB, the BER difference between the two systems is not high. At a BER larger than 10 dB, the difference is very high. The pre-ZF equalization improves the system performance very well compared to the post-ZF equalization.

Conclusion

We introduced in this paper a survey of image transmission in UWC. We covered the problems related to the channels under water and how we to react with them. The equalization in UWC is introduced and studied also in this paper. The fractal model for image compression in UWC increases the data rate of transmission. The comparison between the post-ZF and pre-ZF MIMO OFDM shows that the pre-ZF equalization outperforms the post-ZF equalization due to elimination of the noise enhancement problem. The future work is to study several different techniques for transmission and progressive image compression for UWC to increase the data rate of transmission and cope with the underwater channel bandwidth limitations.

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