Journal of Computer Science
https://dergipark.org.tr/en/pub/bbd
https://doi.org/10.53070/bbd.990807

Journal of Computer Science
ISSN: 2548-1304
Volume: IDAP-2021, Issue: Special, pp: 26-34
@Anatolian Science

A Comparative Study of SC and MC Underwater Acoustic Communication Systems

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Received: Sep.3, 2021 Accepted: Sep.16, 2021 Published: Oct.20, 2021

Abstract— In this study, comparative performance analyzes of single carrier (SC) and multi carrier (MC) underwater acoustic communication (UWAC) schemes are performed in underwater acoustic channel environments. Computer simulation studies are carried out to compare SC and MC UWAC communication systems in multi-path underwater acoustic channel environments based on bit error rate (BER) and mean square error (MSE) accomplishment benchmarks. From the acquired outcomes, it is perceived that the MC-UWAC communication scheme has approximately 3 dB better achievement than the SC-UWAC communication scheme.

Keywords: *underwater acoustic communications; channel equalization; underwater acoustic channel; SC-UWAC; MC-UWAC.*

1. Introduction

Underwater wireless communication has gained increasing attention in recent years. High speed and reliable wireless connectivity are critical for many underwater applications such as offshore oil exploration/drilling, underwater life data collection, submarine archeology, seismic observations, environmental protection, port and border security. Underwater wireless communication can be carried out by radio, optical, or acoustic waves. Among the existing methods, acoustic communication is the most suitable for underwater propagation environment and preferred in practical systems, and research activities are concentrated on this subject.

Underwater wireless communication technologies are very important for implementations as an example of remote control in the offshore oil industry, pollution monitoring in environmental schemes, collection of scientific data recorded with underwater sensors, un-manned underwater vehicles, speech communication between divers and mapping the ocean floor for object detection and rescue. Wireless underwater communication is based on the transmission of acoustic waves. Radio waves are less used in wireless underwater communication. Because, depending on the ambient conditions, radio waves are severely weakened. Underwater acoustic telecommunication channels are far from ideal. These channels have very restricted bandwidth and generally cause serious signal scattering in both time and frequency dimensions (Kuzlu, 2010).

The main reason for the short range (several kilometers) of the acoustic carrier is that its high communication speed (a few kbytes/sec) is less absorbed underwater than electromagnetic energy. For example, the absorption of energy at a frequency of 10 kHz is 3000 dB/km for electromagnetic waves, while it is 1 dB/km for acoustic waves. Therefore, the use of acoustic carrier is a much more effective solution than the use of electromagnetic propagation (Zielinski, 2004). Electromagnetic waves cannot spread underwater for long distances, so the acoustic waves used are very important for underwater communication (Baggeroer, 1984). The available bandwidth in the underwater acoustic communication channel is significantly restricted by the increase in transmission loss with both frequency and distance (Kuzlu, 2010). In the underwater acoustic communication channel, the loss due to the path relies not only on the transmission distance but also on the signal frequency. Therefore, the applicable bandwidth relies on the transmission distance, which is an attribute that recognizes the underwater acoustic scheme from the terrestrial radio communication system (Stojanovic, 2006). Although traditional communication techniques are quite advanced today, they are not very developed for underwater communication (Kuzlu, 2010; Zielinski, 2004; Baggeroer, 1984; Stojanovic, 2006).

Underwater acoustic communication is a communication system that provides voice and data communication underwater by using the sound wave as a carrier (Yılmaz et al., 2008). The underwater telephone, one of the first modern underwater telecommunication schemes, was improved in the 1940s by the USA in World War II to communicate with submarines (Quazi et al., 1982). This device uses carrier-suppressed single sideband modulation (SSB) with a frequency ranging from 8 to 11 kHz and is a design capable of transmitting acoustic signals up to a distance of several km. Over the past few years, important progress has been made in underwater acoustic telecommunication schemes in terms of transmission distance and data processing. Acoustically controlled robots were employed instead of divers for the repair of underwater platforms (Kaya et al., 1989), high-quality video communication was installed from the ocean bottoms to the surface (Suzuki et al., 1992) and data telemetry application was carried out at a horizontal distance of more than 200 km (Stojanovic et al., 1994).

One of the main disruptive factors encountered in underwater acoustic channels is fading. The fading in underwater channels is frequency selective and the delay propagation can be up to 50-100 msec. The basic assumption in most of the studies in the literature is that the channel information is perfectly known at the receiver side. In practice, in coherent detection systems, the fading channel coefficients should be estimated very accurately in the training phase and they should be used in the detection metric at the receiver side. A point to be considered especially in the estimation of underwater channels is the sparse structure of the channel with long delay spread. In sparse structured channels, there are too many zeros in the impulse response because the energy is concentrated in certain regions. Since classical channel estimation methods do not consider this sparse structure and try to estimate along the entire channel determined by delay propagation, their use in underwater channels cannot be an effective solution. For underwater applications, considering the sparse structure of these channels, it is appropriate to determine the points where the energy is concentrated and to decrease the number of coefficients to be estimated (Erdoğan et al., 2012). One of the most effective methods to mitigate inter-symbol interference (ISI) caused by fading is to use orthogonal frequency division multiplexing (OFDM). OFDM is employed in many wired and wireless telecommunication standards today.

In this study, the accomplishments of single carrier underwater acoustic communication (SC-UWAC) and multi carrier UWAC (MC-UWAC) systems in underwater acoustic communication channels are analyzed comparatively. SC-UWAC and MC-UWAC systems are tested over 3 taps underwater acoustic channels using bit error rate (BER) and mean square error (MSE) achievement benchmark. From the obtained results, it is understood that MC-UWAC systems are 3 dB better than SC-UWAC systems.

The remaining of the paper is planned as following: In Stage 2, the SC and MC underwater acoustic communication systems are introduced in detail. The simulation studies of computer are illustrated in Section 3. Discussions and remarks are evaluated in the last Stage.

2. SC and MC Underwater Acoustic Communication Systems

The transmitter and receiver unit scheme of the SC and MC UWAC system operating in the multi-path underwater acoustic channel environment is shown in Figure 1 (Besceli, 2021).

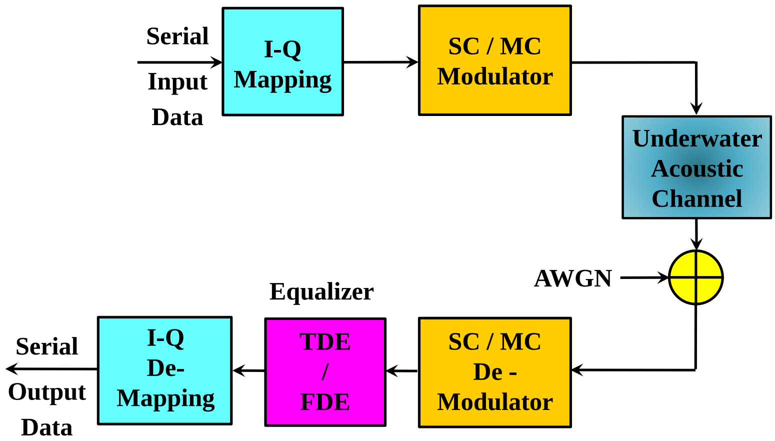

Figure 1. The block scheme of the SC and MC UWAC systems in multipath underwater acoustic channel environments (Besceli, 2021).

The randomly generated serial input information bits, on the sender part of the SC and MC UWAC system operating in the underwater acoustic channel environment in Figure 1, are modulated with one of the requested modulation methods in the I-Q Mapping Block. Then SC and MC data packets are generated in the SC/MC Modulator Block. The produced SC and MC information frames are transmitted over the multi-path underwater acoustic channel through Projectors and received by Hydrophones at the receiver part, and are deformed by additive white Gaussian noise (AWGN).

Multipath underwater acoustic channel impulse responses are calculated using the equations given in reference (Mahmutoğlu, 2013).

The resolved signals at the output of the SC/MC De-Modulator Unit are corrected by using the appropriate time domain equalizer (TDE) and frequency domain equalizer (FDE) equalization methods by inverting the operations on the sender side at the receiver side. In this study, decision feedback equalizer (DFE) channel equalizer is used to repair distorted information signals in SC-UWAC systems. The underlying rationale of the DFE channel equalizer is based on estimating the interference of previously decided symbols with the symbols after them, before the decision is made. DFE consists of two parts, a feed forward filter (FFF) and a feedback filter (FBF). The first part is the feed forward filter, which has a linear transversal channel equalizer structure and whose input is applied the signal from the output of the channel. The second part is the feedback filter, whose input is applied with previously decided symbols. The task of this filter is to eliminate the interference that previously decided symbols create on the symbol to be decided. FDE channel equalizer is used in MC-UWAC systems.

The best known in the literature is the least mean squares (LMS) and recursive least squares (RLS) algorithms to estimate the coefficients of the DFE equalizer used to equalize the multipath fading underwater acoustic channel. The LMS algorithm is a linear algorithm and the RLS algorithm is a nonlinear algorithm. Because of its simplicity and easy realization, the step size parameter used in the preferred LMS algorithm to estimate or equalize the channel is constant and when it is small, the algorithm reaches steady state more slowly, and when it is large, it may cause instability. Although the LMS algorithm is simple and easy to implement, the convergence speed is very low. The RLS algorithm, also known as the Kalman algorithm, has a very common usage area. It is used for parameter estimation in applications where high convergence speed is required. Since both high accuracy and fast convergence are required in communication systems, channel equalizer is frequently used in estimating filter coefficients (Yaşar et al., 2020).

The equalized data in the TDE/FDE Block is demodulated in the I-Q De-Mapping Block. Then, utilizing the acquired data at the output, requested accomplishment benchmarks as an example of MSE and BER can be computed. In this study, the performance of SC and MC UWAC systems is compared over the MSE and BER criteria in the multi-path underwater acoustic channel environment.

3. Computer Simulation Studies

The simulation studies of computer are composed of two parts. In the first part, MSE simulations in 3-taps underwater acoustic channels and in the second part, BER simulations in 3-taps underwater acoustic channels are made. In all simulations, SC-UWAC and MC-UWAC systems using BPSK, 4-QAM, 16-QAM and 64-QAM modulated signals are compared. OFDM data packets in MC-UWAC systems have been prepared in accordance with IEEE 802.11a Standard using 64-point FFT process. In addition, 9 taps DFE consisting of 5 taps FFF and 4 taps FBF are used in SC-UWAC systems and MSE simulations of MC-UWAC systems. The parameters used to obtain multi-path underwater acoustic channel impulse responses using Reference (Mahmutoğlu, 2013) are given in Table 1. All simulation works were performed in MATLAB surrounding.

Table 1. UWAC parameters (Mahmutoğlu, 2013).

Parameters	Values
Distance between Transmitter and Receiver (R)	1 (km)
Salinity (S)	30%
Bandwidth (f)	34.2kHZ
Depth of receiver (h)	20 (m)
Depth of transmitter (d)	20 (m)
Height of the transmitter from the seabed (a)	5 (m)
Height of the receiver from the seabed (b)	10 (m)
pH value of sea water (pH)	7
Temperature (T)	30 ° C
Sea water density	1000 g/m
Water density at the bottom of sea	1800 g/m
Sound speed at the bottom of sea	1300 m/sec
Sound speed in sea	1500 m/sec

3.1. Mean Square Error Simulation Results

In the first stage of the work, the MSE-Iteration Number accomplishments of SC-UWAC and MC-UWAC systems are compared in 3-taps underwater acoustic channels. In order to obtain the MSE performances of the channel equalizers used to equalize 3 taps UWAC channels, simulations were made by taking the length of the training sequence 900 in SC-UWAC systems and the length of the training sequence 320 in MC-UWAC systems. LMS-DFE and RLS-DFE are used as channel equalizers. Simulations were made by taking the parameter of step size of the LMS algorithm for both UWAC systems 0.0045 and the parameter of forgetting factor of the RLS algorithm as 0.999 for both UWAC systems. Simulations have been obtained over 1000 Monte Carlo cycles with related communication systems using BPSK, 4-QAM, 16-QAM and 64-QAM modulated signals.

Figure 2 illustrates the evaluation of the MSE-Iteration Number performances at 25 dB with LMS / RLS-DFE equalizers in SC-UWAC and MC-UWAC systems for BPSK modulation.

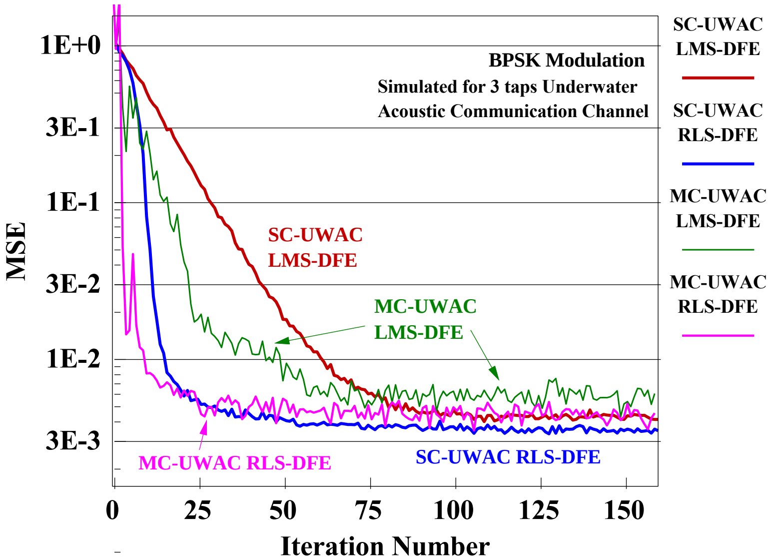

Figure 2. MSE performance comparison of SC and MC-UWAC systems over 3 taps underwater acoustic channel for BPSK modulation.

When Figure 2, where MSE performances are given in 3-taps underwater acoustic channel for BPSK modulation, is evaluated, it is perceived that the fastest convergence is achieved with the MC-UWAC scheme. It is understood that the obtained performances with RLS-DFE exceed the obtained performances with LMS-DFE in both communication systems.

In Figure 3, evaluation of MSE-Iteration Number accomplishments of BPSK, 4-QAM, 16-QAM and 64-QAM modulated MC-UWAC systems are provided with the obtained LMS-DFE and RLS-DFE equalizers for 3-taps underwater acoustic channels at 25 dB.

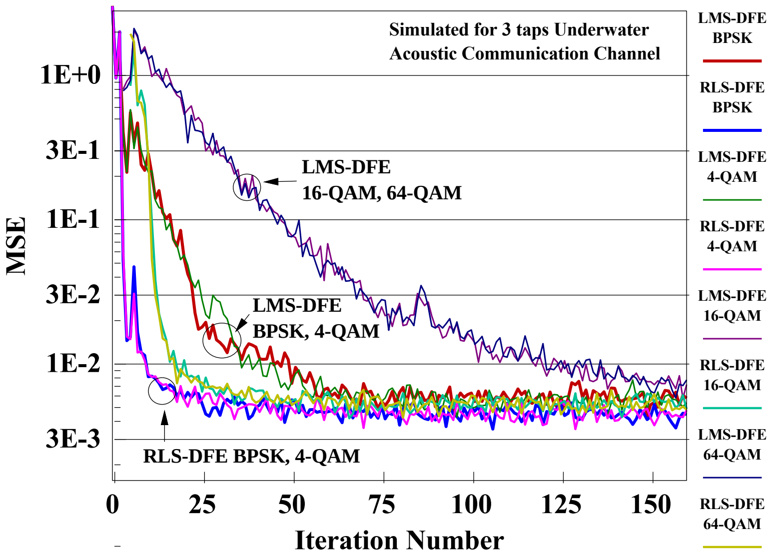

Figure 3. MSE performance comparison of MC-UWAC systems over 3 taps underwater acoustic channel for all modulation.

As Figure 3 is evaluated, it is perceived that similar to the previous performances, the acquired performances with the RLS-DFE exceed the obtained performances with the LMS-DFE. However, it is understood that the obtained performances with BPSK and 4-QAM modulated signals are very close to each other. The same results are observed in 16-QAM and 64-QAM modulated signals. The reason for this can be explained by the sparse structure of the underwater acoustic channel. It is understood from Figure 3 that the accomplishments worsen as the modulation depth raises.

3.2. Bit Error Rate Simulation Results

In the second phase of the work, the achievements of BER-SNR of SC-UWAC and MC-UWAC systems are compared in 3-taps underwater acoustic channels. 3-taps underwater acoustic channel impulse response values are calculated using reference (Mahmutoğlu, 2013). In the SC-UWAC system, simulations are obtained with 100 packets of SC information signals after the 900-length training phase to equalize 3 taps underwater acoustic channels. Simulations are made by taking the parameter of step size of the LMS algorithm as 0.0085 for both equalizers and the parameter of forgetting factor of the RLS algorithm as 0.999 for both equalizers. In the MC-UWAC system, simulations are carried out with 100 packets of MC (OFDM) information signals after the 320-length training phase to equalize 3-taps underwater acoustic channels. Simulations have been acquired via 1000 Monte Carlo loops with related communication systems using BPSK, 4-QAM, 16-QAM and 64-QAM modulated signals.

Figure 4 depicts the evaluation of BER-SNR achievements of BPSK modulated SC-UWAC and MC-UWAC systems for 3-taps underwater acoustic channels.

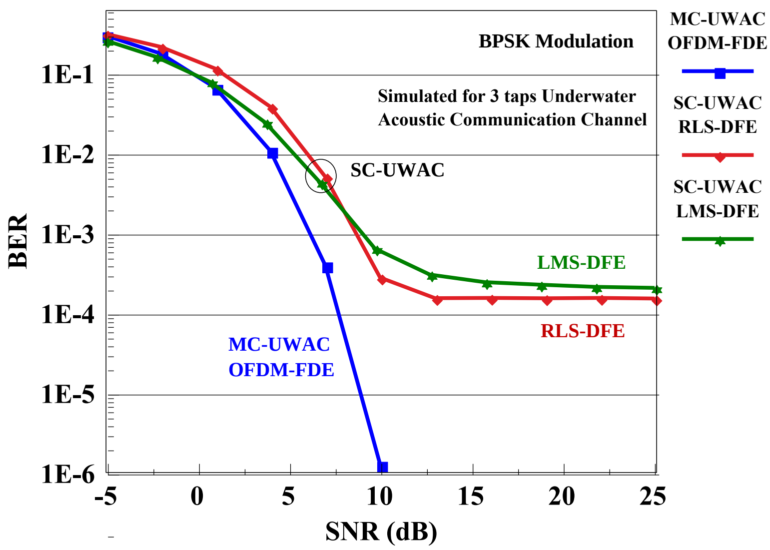

Figure 4. BER-SNR performance comparison of SC and MC-UWAC systems over 3 taps underwater acoustic channel for BPSK modulation.

When Figure 4, where BER-SNR performances are given in 3-taps underwater acoustic channel for BPSK modulation, is evaluated, it is observed that the obtained achievement with the SC-UWAC scheme converges to the 2E-4 error base after approximately 10 dB SNR value. It is understood that the obtained performance with RLS-DFE is better than the obtained performance with LMS-DFE. However, it is perceived that the best performance is achieved by eliminating the error base with the FDE used in the MC-UWAC system. In addition, it is understood from the Figure 4 that approximately 3 dB of SNR development is provided for 1E-3 BER value with MC-UWAC system against SC-UWAC system.

In Figure 5, the evaluation of BER-SNR accomplishments of BPSK, 4-QAM, 16-QAM and 64-QAM modulated MC-UWAC system is given for 3-taps underwater acoustic channels.

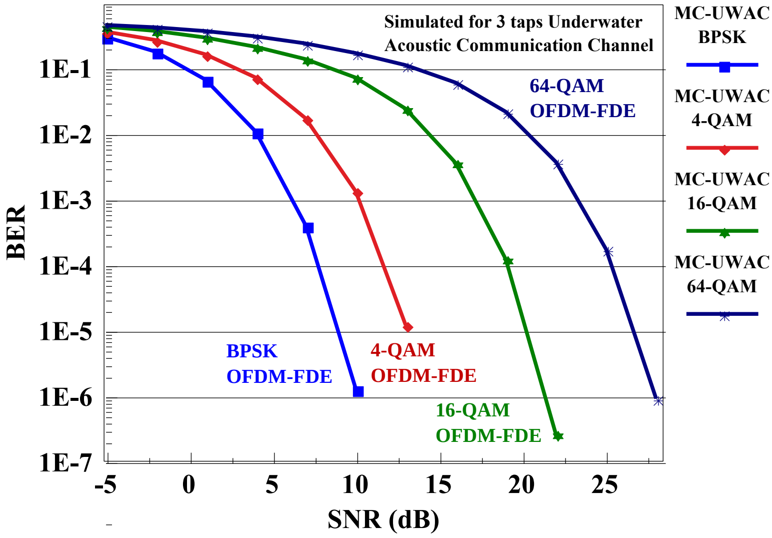

Figure 5. BER-SNR achievement evaluation of MC-UWAC systems over 3 taps underwater acoustic channel for all modulated signals.

As Figure 5 is evaluated, it is understood that the obtained performances with the FDE utilized in the MC-UWAC system are highly satisfactory in all modulation types evaluated in this study. In addition, it is perceived from Figure 5 that the accomplishments are continued as the modulation depth increases, but the SNR value increases.

4. Conclusion

In this study, the performance of SC and MC underwater acoustic wireless communication systems is analyzed in multi-path underwater acoustic channel environment. SC-UWAC and MC-UWAC systems using BPSK, 4-QAM, 16-QAM and 64-QAM modulation are compared in 3-taps underwater acoustic channel environments based on MSE-Iteration Number and BER-SNR performance criteria. In MC-UWAC systems, obtaining approximately 3 dB SNR improvement for 1E-3 BER level versus SC-UWAC systems made the study very interesting. In the light of these results, it is understood that MC-UWAC communication systems in the multi-path underwater acoustic channel environment can be one of the indispensable techniques for underwater acoustic wireless telecommunication schemes that can be utilized for future beyond 6G implementations.

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