Simulation of Direct-Sequence Spread Spectrum Data Transmission System for Reliable Underwater Acoustic Communications

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Abstract

Underwater acoustic communication (UAC) system designers tend to transmit as much information as possible, per unit of time, at as low as possible error rate. It is a particularly difficult task in a shallow underwater channel in which the signal suffers from strong time dispersion due to multipath propagation and refraction phenomena. The direct-sequence spread spectrum technique (DSSS) applied successfully in the latest standards of wireless communications, gives the chance of reliable data transmission with an acceptable error rate in a shallow underwater channel. It utilizes pseudo-random sequences to modulate data signals, and thus increases the transmitted signal resilience against the inter symbol interference (ISI) caused by multipath propagation. This paper presents the results of simulation tests of DSSS data transmission with the use of different UAC channel models using binary spreading sequences.

Keywords: underwater acoustics communication, UAC, direct-sequence spread spectrum, DSSS, PRBS

1. Introduction

Underwater acoustics communication (UAC) systems for both civil and military applications operate in tough propagation conditions, especially when the transmission is performed in shallow waters. The signal transmitted in shallow UAC channel suffers from time dispersion, caused by multipath propagation due to signal reflections from sea surface, sea bottom and other objects present in water, and by the refractions phenomenon due to the significant changes of sound velocity as a function of depth. Moreover, the signal suffers from frequency dispersion caused by the Doppler effect – much more pronounced in ultrasonic signals than in the case of electromagnetic ones [1, 2].
To ensure reliable communication in a shallow UAC channel, it is necessary to implement techniques used in modern wireless communication systems. Among them, spread spectrum (SS) techniques deserve special attention. Originally, the spread spectrum technique was used in military applications including guidance and communication systems. With the introduction and the evolution of cellular mobile radio systems, spread spectrum communications have been applied as an efficient technique in many practical systems since the late 1980s [3]. The many features of pseudo random signal processing techniques that are important for spread spectrum communications include the ability to

cope with multipath propagation, the resistance to interference, and the potential of sharing spectrum resources with other users. Spread-spectrum systems have low probability of intercept (LPI). Transmitter-receiver pairs using independent random carriers can operate in the same bandwidth with minimal co-channel interference. Moreover, a SS systems have cryptographic capabilities when the data modulation cannot be distinguished from the carrier modulation, and the carrier modulation is effectively random to an unwanted observer [4]. Among the SS systems can be distinguished: direct-sequence spread spectrum (DSSS) systems, frequency hopping spread spectrum (FHSS) systems and time hopping spread spectrum (THSS) systems. This paper focuses on DSSS systems only.

There are several reported UAC systems using DSSS technique. In [5] a DSSS signaling has been used to increase the SNR per data symbol and resolve multipath components for single-user, short range application. The system utilized 10 kHz of bandwidth and short spreading codes in order to combat multipath effects in shallow water. The research described in [6] includes discussions of multiuser access and report favorable results in the 1–2 kHz frequency band at long ranges for a single user. In [7] the authors proposed the UAC modem. Two Gold codes of length 2047 are used for spreading the differentially coded data bits. The bit rate of the system is 100 bps and the carrier frequency is set to 12 kHz. The proposed modem was tested in the Baltic sea at approximate range about 3000 m. The authors obtained error-less transmission of blocks of 200 data bits.

The DSSS-based UAC systems described in literature use specific PN sequences and a fixed transmission bandwidth. To the best of the authors' knowledge, there are no publications presenting the analysis of underwater DSSS systems performance depending on its bandwidth or PN sequence used. This paper presents a comparision of DSSS-based UAC system performance due to its bandwidth and spreading sequence. In the simulation tests performed, the bit error rate (BER) of data transmission was estimated. The channel was modeled as an additive white Gaussian noise (AWGN) channel , the Rician fading channel, and as replay channel simulated by impulse responses of UAC channel measured during the inland water experiment. The results allow for rough estimation of the transmission bandwidth and the type and the rank of the spreading sequence necessary to obtain the assumed BER.

2. Spread Spectrum technique

The foundations of spread spectrum systems are provided by the Shannon-Hartley theorem in terms of the channel capacity:

$$C = B\log_2\left(1+\frac{S}{N}\right) \tag{1}$$

Where: C denotes the capacity in bits per second of a channel pertubed by additive white Gaussian noise, S is the average received signal power, N is the average noise power, and B is the bandwidth available to the band-limited system. It can be simplified to equation:

$$C \sim 1.44B\frac{S}{N} \tag{2}$$

A reduction in the signal-to-noise ratio (SNR) can be compensated by proportionally increasing the bandwidth *B*. This is a basic rule for spread spectrum systems, which spread data signals over a much wider frequency band compared to the minimum bandwidth required to transmit the information [4].

The main idea of DSSS is to modulate data signals with a pseudo random signal called the spreading sequence. A transmit signal using BPSK modulation can be written as [4]:

$$s(t) = A_s d(t)c(t)\cos(2\pi f_0 t + \theta) \tag{3}$$

Where A_s denotes the amplitude of the signal, $d(t)$ is the data signal, $c(t)$ is the spreading sequence, f_0 is the carrier frequency, and θ is the carrier phase.

3. Spreading sequences

For simulation tests of the DSSS system, three types of speading sequences were chosen, namely m-sequences, Gold codes and Kasami codes.

M-sequences or maximal length sequences are one of the most important classes of pseudo random sequences. They have good pseudo randomness properties and can be generated by a linear feedback shift register. Its name corresponds to the fact, that they are the maximal length sequence that can be generated by a shift register of a given length [4].

Gold codes and Kasami codes are both derived from m-sequences. These codes have good cross-correlation properties and thus are useful for multi-user ranging systems, such as GPS system. Gold codes are formed by combining two specific m-sequences of the same length $2^{\mathrm{n}} - 1$ such that their absolute cross-correlation is less than or equal to $2^{(\mathrm{n}+2)/2}$, where n is the size of the linear feedback shift register used to generate the m-sequence. They are combinded this way, that one m-sequence is added with all shifts of other sequence using modulo two addition.

Kasami codes are formed by decimating an m-sequence by taking every $2^{\mathrm{n}/2} + 1$ bit from the periodic sequence. Combining the cyclic decimated sequence with all shifts of the original one, a set of n sequences with good cross-correlation properties is created.

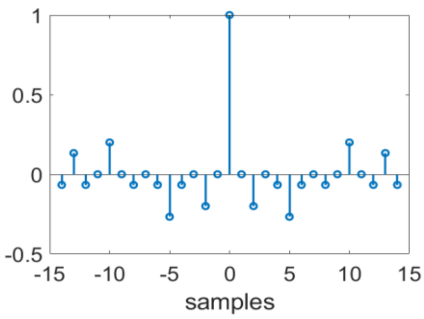

Figure 1. Autocorrelation function of m-sequence of rank L = 4

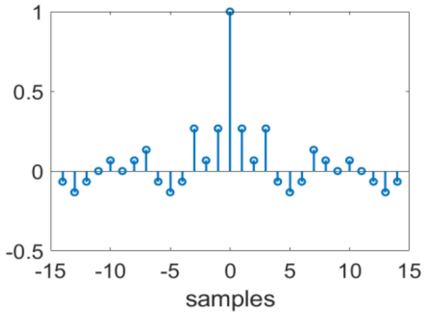

Figure 2. Autocorrelation function of Gold code of rank L = 4

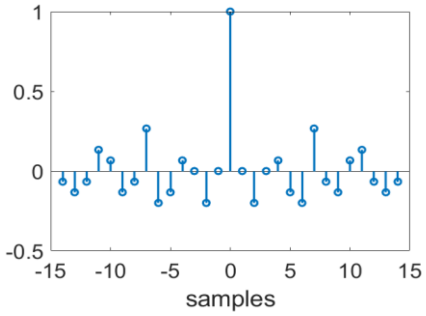

Figure 3. Autocorrelation function of Kasami code of rank L = 4

Fig. 1-3 show autocorrelation functions of m-sequences, Gold codes, and Kasami codes. It is clearly seen that the autocorrelation properties of Kasami codes and Gold codes are worse than the autocorrelation property of m-sequency of the same length. On the other hand, there are very few m-sequences of any given length with good cross-correlation properties. Gold codes and Kasami codes extend the set of binary PN sequences that have controlled cross-correlation properties, and thus are suitable for wireless communication systems with code-division multiple access (CDMA) [4].

3. Simulation of DSSS data transmission

DSSS data transmission simulations were performed in the Matlab environment to estimate the bit error rate (BER) in the propagation conditions similar to those in stationary UAC channel. Fig. 4 shows a block diagram of DSSS modulator. Each of the data bits is multiplied with PN sequence. The product is upsampled by a factor of $R = f_s/B$, where f_s is the sampling frequency and B denotes the system bandwidth. Next, the signal is passed through the binary phase shift keying (BPSK) block and the pulse shaping filter. The output is complex-value digital signal that is used for simulation of baseband transmission in UAC channel. At the receiver side (Fig. 5), the input signal is again filtered by the pulse shaping filter and passed through the BPSK demodulator. Next, the real-value digital signal is downsampled and the matched filtration is performed by a filter with coefficients corresponding to the PN code used in the transmitter. Information detection is performed by summing up the amplitudes of samples from the range corresponding to the length of a single PN sequence and checking if the result is a positive (1) or negative (0) value.

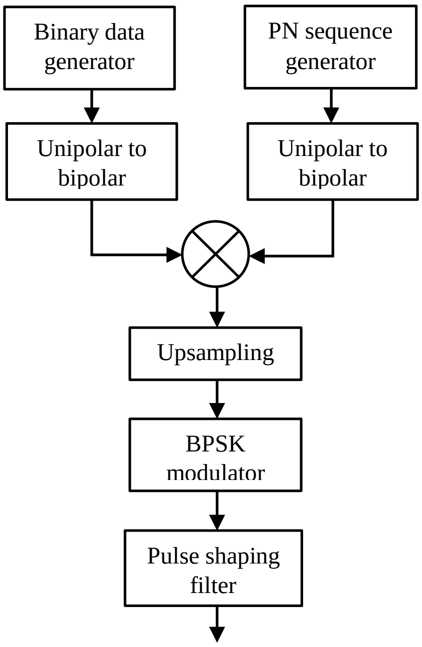

Figure 4. DSSS transmitter block diagram

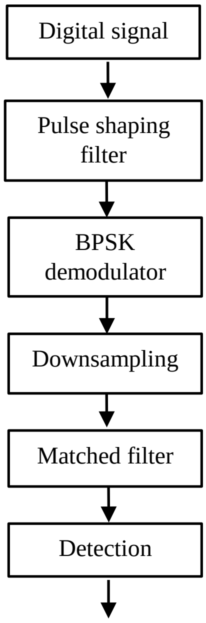

Figure 5. DSSS receiver block diagram

Three kinds of channel models were used, namely the AWGN channel model with varying signal-to-noise ratio (SNR), the Rician fading model, and UAC channel impulse responses measured during the inland water experiment. In each case, the sampling rate was $f_s = 200$ kHz and the signal bandwidth was in the range from 2 kHz to 10 kHz. M-sequences, Gold codes and Kasami codes with lengths in the range of $2^3 - 1$ to $2^{10} - 1$ were used as spreading sequences. In each communication test 20 kbits were transmitted, which allowed to estimate the bit error rate at the level of 10^{-3}. For each spreading sequence length a maximum bandwidth was found for which BER $< 10^{-3}$ was obtained.

During the tests using AWGN channel the SNR was varying from -10 dB to -30 dB. Fig. 6 shows the results obtained for the values of SNR: -12 dB, -18 dB, -24 dB and -30 dB. In case of SNR = -12 dB all spreading sequences of rank equal or higher than 5 allow for reliable transmission in the maximum tested band (10 kHz). Tests performed for SNR = -18 dB and SNR = -24 dB have shown, that using m-sequences and Kasami codes give better results than Gold codes. In case of SNR = -30 dB the reliable transmission is possible only for Kasami codes and m-sequences of rank 9 or 10.

Real impulse responses (IR) gather during the inland water experiment were used as another channel model in simulation tests. The impulse response were measured in May, 2017 in Wdzydze Lake. The detailed description of the experiment can be found in [8, 9]. The impulse responses were measured at the distances of 300 m and 500 m. The exemplary IRs are presented in Fig. 7. Fig. 8 shows the rank of spreading sequences and signal bandwidth for which BER $< 10^{-3}$ was obtained during the simulation tests. It is clearly seen that increasing the signal bandwidth means that a higher-order spreading sequence must be used to obtain the same BER. In the case of an impulse response with a larger number of multi-path reflections (Fig. 8b), the reliable transmission (BER $< 10^{-3}$) is possible using at least the spreading sequence of rank 5 (if the signal bandwidth is equal to 3 kHz). In case of impulse response with less multipath reflections, the same BER can be obtain in 2 kHz bandwidth with the use of spreading sequence of length $2^3 - 1$.

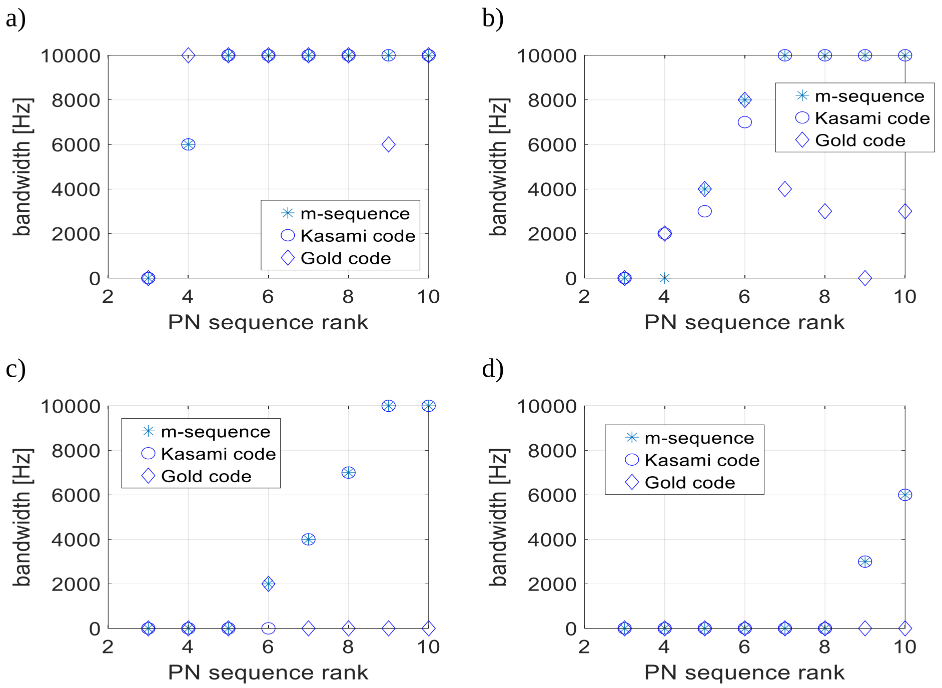

Figure 6. Maximum transmission bandwidth for which BER $< 10^{-3}$, as a function of PN sequence rank; AWGN channel model with SNR = -12 dB (a), -18 dB (b), -24 dB (c), and -30 dB (d)

The third channel model was Rician fading channel in two configurations: with 3 and 5 signals paths. The calculations were performed for rank of spreading sequences up to 9 due to the limited computational capabilities of the computer hardware used for simulations. The results tests are shown in Fig. 9. In case of 3 signal paths the data transmission with BER $< 10^{-3}$ was possible for spreading sequence of rank 5 or higher, except for rank 8, in the case of which the transmission with BER $< 10^{-3}$ could not be obtained. Surprisingly for the PN sequence of rank 5 and 6, the Gold's codes and the Kasami codes proved to be much more effective than m-sequences. In case of 5 signal paths no reliable data transmission was possible, except for m-sequence of rank 10 and signal bandwidth equal to 2 kHz.

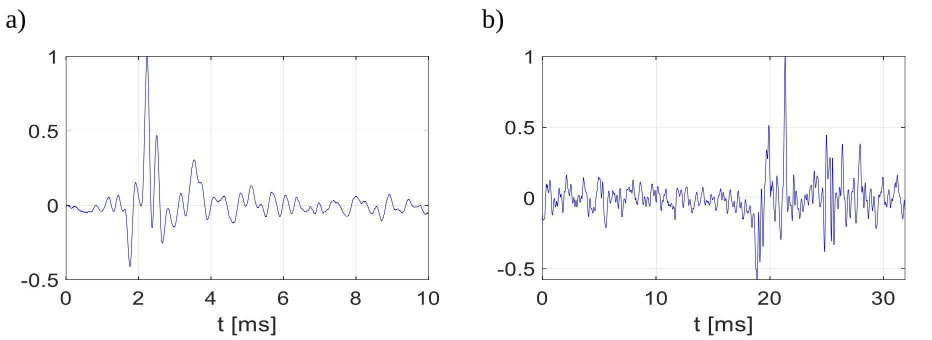

Figure 7. Impulse response of UAC channel at a distance *d* = 300 m (a), *d* = 500 m (b)

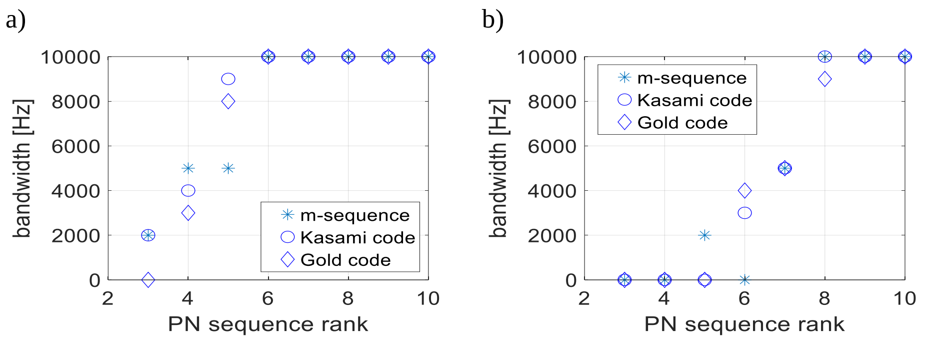

Figure 8. Maximum transmission bandwidth for which BER $< 10^{-3}$, as a function of PN sequence rank; IR of UAC channel at a distance *d* = 300 m (a) and *d* = 500 m (b)

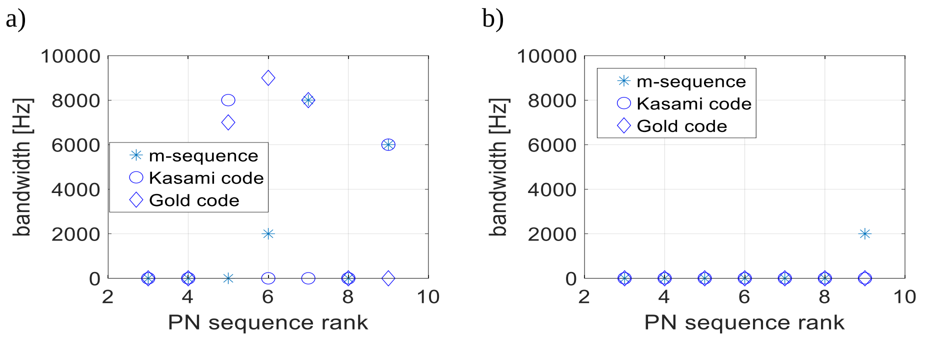

Figure 9. Maximum transmission bandwidth for which BER $< 10^{-3}$, as a function of PN sequence rank; Rician fading channel model with 3 (a) and 5 (b) reflections

4. Conclusions

The simulation tests of DSSS data transmission with the use of three UAC channel models were performed. M-sequences, Kasami codes, and Gold codes of rank varying from 3 to 10 were used as spreading sequences. For all channel models increasing the signal bandwidth means that a higher-order spreading sequence must be used to obtain the same data transmission quality. Although Kasami codes and Gold codes have worse autocorrelation properties than m-sequences, their application allowed to achieve reliability similar to that obtained in the system using m-sequences. In tests with the AWGN channel m-sequences and Kasami codes ensured better performance than Gold codes. Reliable transmission was possible even for SNR = -30 dB in the 2 kHz band and using a spreading sequence of rank 9. In tests with the Rician channel, the transmission was successful if 3 signal paths were simmulated. Increasing the number of fading paths makes it impossible to obtain the BER $< 10^{-3}$.

The results of simulation tests performer allow for rough estimation of the transmission bandwidth and the spreading sequence necessary to obtain the desired BER in DSSS-based UAC system.

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