RELIABLE UNDERWATER COMMUNICATION SYSTEM
FOR SHALLOW COASTAL WATERS

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This paper presents a reliable and robust low data rate spread spectrum approach which is implemented in the acoustic underwater communication system for shallow coastal waters. It shows operation assumptions of spread spectrum techniques based on the well-known Shannon equation. It describes two methods of spread spectrum: frequency hopping spread spectrum and direct sequence spread spectrum; their block diagram and their characteristics are then listed to make comparisons. In short, adverse channel effect is analyzed on the expected operation of the system. I present the platform for the target implementation of the acoustic underwater communication system, which now has to allow continuous and easy development of stable algorithms.

INTRODUCTION

Any underwater acoustic communication system whose most important task is the reliable operation in shallow coastal waters (assuming a very low rate of transmission errors) must overcome a number of limitations. The first dominant factors are spreading in time domain (multipath delay spread) and in frequency domain (Doppler spread), which are characteristic of the horizontal channel [1]. The multipath propagation is the result of reflections from the surface, bottom and any obstacles in the water. In addition, wave refraction can be dispersed in the heterogeneity of the water medium. As a result, intersymbol interferences occur which are undesirable in such communication systems. The Doppler effect is related to the movement of the transmitter and receiver in relation to one another. These negative factors are also present in other communication systems, which are implemented using different transmission mediums, but it is in a water environment and when using the acoustic wave that they are particularly emphasized.

For example, due to the fact that the velocity of acoustic wave propagation in the water is about two hundred thousand times smaller than the speed of propagation of electromagnetic waves, the Doppler effect has a greater impact on acoustic underwater communication systems. This is due to the fact that the relative Doppler deviation of these systems is two hundred thousand times greater than in systems with electromagnetic waves. Others problems are low speed of sound in water and comparatively limited bandwidth caused by the phenomenon of absorption, which increases with both frequency and range. Developed and used commercially, modems typically use a bandwidth from a few kHz to 100 kHz. Taken together, all the constraints are the cause of complications in the built receiver, whose function is to decode the symbol based on the received signal. Generally it is a known fact that an underwater acoustic channel is one of the most challenging channels for modern digital communication. This particularly applies to transmission over horizontal channels in coastal waters.

Underwater acoustic communication systems are commonly used to transmit control information, telemetry data, speech and image signals. For the transmission of speech and image signals a transmission rate of a few kbps is required, while BER (bit error rate) is tolerated at a level of 10^{-2} to 10^{-3}. It establishes the use of a generally vertical channel which is not dominated by the multipath phenomenon. On the other hand, due to the required high reliability of the transmitted telemetry and control data, the communication system has BER at level 10^{-3} to 10^{-4} and performs with a rate from several hundred bps to 1kbps. It works in both the shallow horizontal channel and vertical channel.

To achieve wireless underwater communication, a modem which transmits a tone or carrier is used, which carries the data through amplitude, frequency or phase modulation. Most of the available acoustic modems can work using a few selected methods of modulation. Noncoherent FSK modulation (Frequency Shift Keying) and MFSK modulation (Multiple Frequency Shift Keying) are able to overcome undesirable effects of multipath and Doppler spread, where multipath occurs strongly in water medium - especially in the horizontal transmission channels with relatively low bit error rates. To avoid the intersymbol interference, the modem must be inserted in the guard time between successively transmitted symbols. The guard time has a length at least equal to the multipath spread [2][3]. These modulations are most often successful in devices which are long-life battery-powered. In the case of deep water, as well as vertical channels, modems commonly use different versions of coherent modulations, such as BPSK, QPSK, 8-PSK (Phase Shift Keying). Coherent modulations are more bandwidth-efficient, but they require a more complex receiver having phase recovery and adaptive equalization, as well as requiring a greater SNR (signal to noise ratio) for correct operation. Equalizers, especially in the stationary and stable configurations of transmitter-receiver systems, work very well and can partially eliminate the reflected signals.

Additionally, application of the channel coding and interleaving affect can significantly reduce the error bit rate [4]. The problem of random error detection is solved by channel coding. Most commonly used are block codes, convolutional codes, turbo codes and low-density parity-check codes. Turbo codes and LDPC codes are the most efficient coding, however these methods are very complex, requiring significant computational power. Channel interleaving can effectively exclude burst error.

The realization of an efficient underwater communication network must be based on the physical layer providing an efficient and reliable acoustic communication link. In these systems, a reliable low data rate signaling mode is utilized to establish and reestablish communication links, even if we have the ability to work under high data rate mode. In the

case of the deterioration of propagation conditions or increase in the noise level, the system returns to the mode with a lower transmission rate, because high data rate coherent techniques sill remain less robust and reliable as desired.

I have been involved in the development of a wireless underwater communication system based on non-coherent MFSK modulation [2] [3]. The essence of its actions was the transmission of control signals to numerous objects, and the receipt of confirmation from the execution of a specific command.

Presented in this article is an approach which will ultimately result in the implementation of spread spectrum technique for underwater communication systems. The current work will lead to the evaluation of the possibilities of the implementation of this communication technique in the underwater telephone. In design of the underwater telephone I was responsible for the hardware and software parts. In fact, it is a device of software-defined type and therefore allows one to realize a number of independent modulation techniques and protocols without specific restrictions.

To overcome all of the complications and to build a reliable working system with low data rate for shallow coastal water, I am going to use the following spread spectrum technique; the basics of operation and the anticipated implementation are presented below.

The efficient development of such systems is still a big scientific and engineering challenge.

1. SPREAD SPECTRUM TECHNIQUE

The spread spectrum techniques were originally developed for use in military systems on account of their low probability of interception (LPI) and resistance to jamming signals. Because it is difficult for adversaries to listen, the transmission and unauthorized sources cannot transmit false information to disrupt the communication by confusing the receiver system. Additionally, it is possible to share by using the frequency band with many types of conventional modulations with minimal or no interference.

The conception of spread spectrum systems is due to the well-known Shannon equation (1) to channel capacity, with the specified bandwidth B and the power signal to noise ratio (SNR):

$$C = B \, log_2 \; (1 + SNR) \tag{1}$$

It specifies that a wider range and better signal to noise ratio provides more capacity within the communication system. On the other hand, the transformation of the equation of the form (1) into (2), means it can be concluded that the more noise that dominates the signal, the wider the bandwidth signal must be to receive it correctly.

$$\frac{C}{B} \cong 1.44 \, SNR \tag{2}$$

In this case, we seek to significantly expand the bandwidth used, allowing at the same time a much lower power signal to noise ratio.

This technique transforms an information signal into a transmission signal with a much wider bandwidth [5][6]. This is achieved by spreading the data signal with a pseudorandom code signal (PN). PN code is independent of the data signal and has wider spectral width. Consequently, the data spreads the information signal power over a much broader bandwidth with lower spectral power density than the narrowband transmitter. In the receiver, a despreading operation restores the information signal into its original bandwidth. Therefore,

the exact same PN code must be known to the receiver, which was used in the transmitter. Figure 1 shows a model of the typical spread spectrum digital communication system.
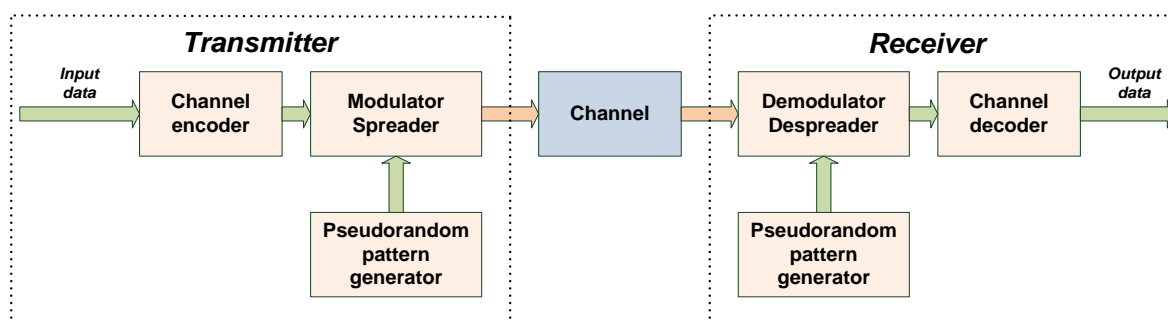

Fig. 1. Model of spread spectrum digital communication system.

The characteristic parameter for the spread spectrum system is *gain processing*, which expresses the bandwidth expansion factor:

$$G_p = \frac{B_{SS}}{B_{US}} = \frac{T_b}{T_c} \tag{3}$$

Where:

B_{SS} - *bandwidth of spreaded signal,*
B_{US} - *bandwidth of unspreaded signal (input data signal),*
T_b - *bit interval,*
T_c - *dwell time, chip interval.*

There are many types of spread spectrum systems, of which the most common are: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), Time Hopping Spread Spectrum (THSS) and Chirp Spread Spectrum (CSS). In the circle of my interests are the first two systems, which will be discussed shortly, as they are the fundamental types of spread spectrum system.

1.1 FREQUENCY HOPPING SPREAD SPECTRUM TECHNIQUE

Communication systems with a frequency hopping spread spectrum technique most commonly use binary or M-ary frequency shift keying with non-coherent detection. The block diagram of the transmitter and receiver in a typical FH/FSK system is shown in figure 2. In a system with conventional FSK modulation, the data signal modulates a fixed frequency carrier. However, in the FHSS technique, all the available channel bandwidth is divided into adjacent frequency subchannels. The carrier among frequency subchannels is switching by using a pseudorandom sequence, which is known to both the transmitter and receiver. Pseudorandom sequence controls the frequency synthesizer in every signaling interval. In a transmitter, the data signal is subjected to pre-encoding, and then goes to the FSK modulator. The modulator assigns to sending bit with duration T_b and the corresponding frequency. And so the signal produced is then placed in the appropriate frequency slot for the time equal to T_c - termed as dwell time. Then, after amplification the signal travels through the transducer to the channel, which in our case is water medium. On the receiving side, the amplified signal in the preamplifier goes to the receiver. At the receiver it is dehopped by mixing the synthesizer

output with the received signal. Next, the resulting signal is demodulated in the FSK modulator. A synchronization signal for keeping synchronism of the pseudorandom generator with a frequency hopping received signal is extracted from the received signal. The time during a hop when signal cannot be transmitted or received is termed the blanking interval.

When changes of the carrier frequency occur many times during a particular data bit T_b, then we have to deal with a fast frequency hopping system (FFH). Figure 3 shows an example of FH pattern for FFH system, where $T_b=7T_c$. In a situation when carrier frequency changes occur, every data bits have to deal with the slow frequency hopping system (SFH).
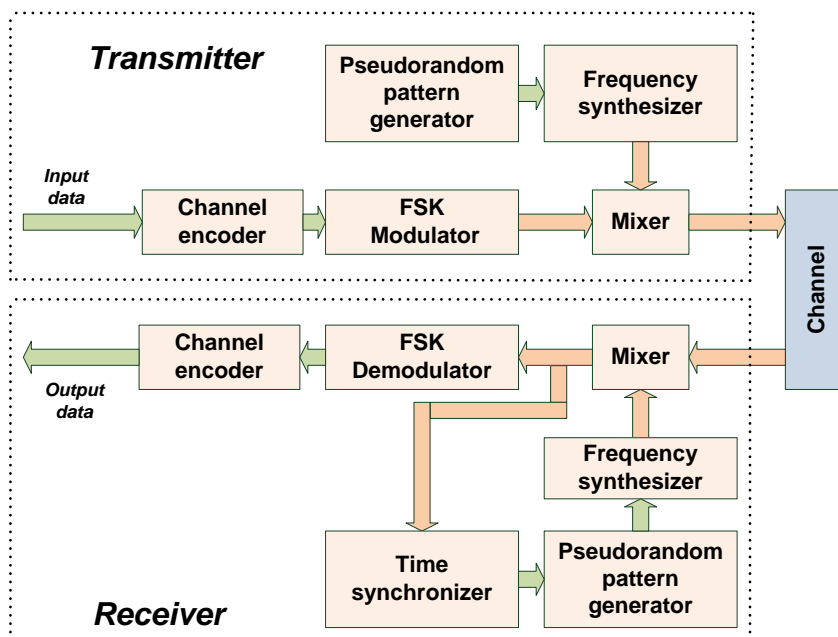

Fig. 2. Block diagram of frequency hopping spread spectrum system.

This technique is usually employed in BFSK or MFSK modulation with non-coherent demodulation. In the use of coherent modulations, it is difficult to keep phase coherence in the hopping pattern's generated signal.

The mechanism of the suppression of an interfering signal is due to the fact that the useful signal is transmitted in a specific moment of time in a single narrowband channel. Assuming that we are working with the system FFH, the interfering signal will coincide with the spectrum of the useful signal only for a small duration.
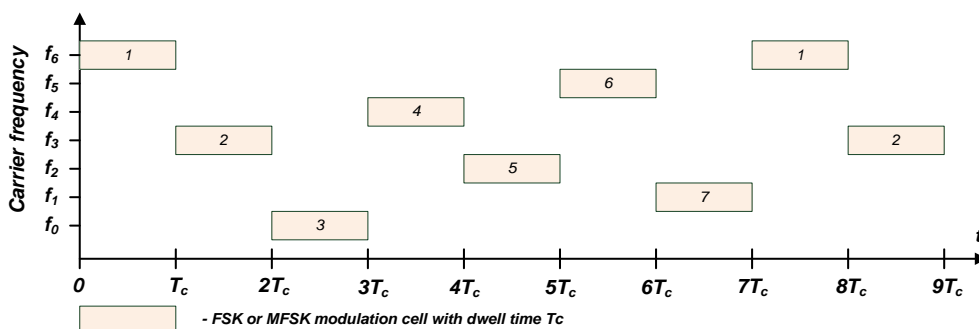

Fig. 3. Example of frequency hopping pattern in FFH system.

1.2 DIRECT SEQUENCE SPREAD SPECTRUM TECHNIQUE

Direct sequence spread spectrum technique performs the spectral spreading of signal through modulating each bit of the input data stream d(t) by pseudorandom sequence p(t). Assuming that the data stream and a pseudorandom sequence p(t) are stored in the form of NRZ(-1,+1), then the spreading of a spectrum signal consists of multiplying the data stream and a stream of pseudorandom. As a result, the spreading produced spread signal s(t). This principle is illustrated in figure 4, as an example of a spreading stream with a length of 7 bits.
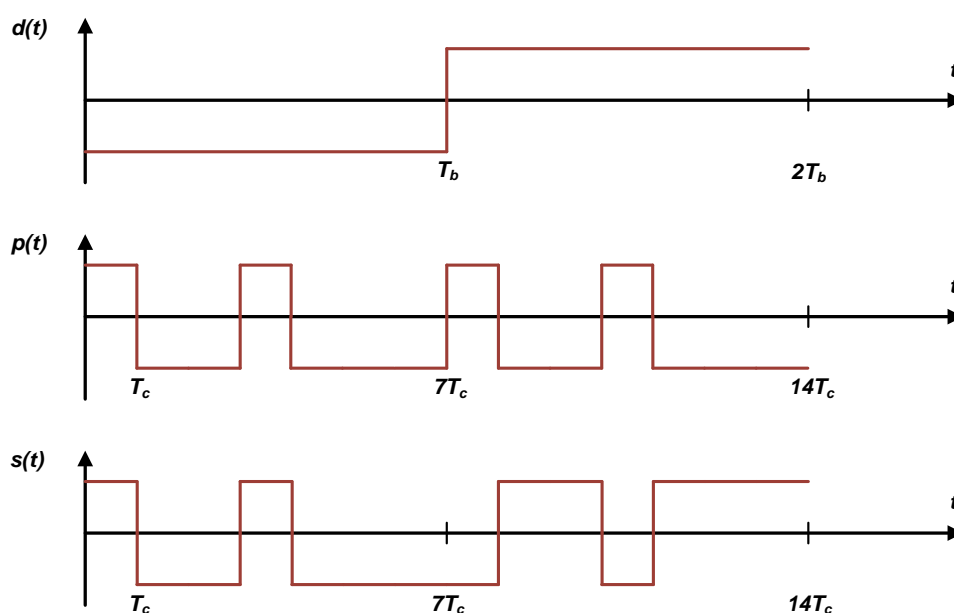
Fig. 4. Generation of a direct sequence spread spectrum signal.

When the duration of one data bit is T_b and the duration of one speading sequence bit is T_c, it must always be fulfilled with the condition $T_c \ll T_b$. The transmitted signal bandwidth is wider when it is greater than the number of bits within the spreading stream per one bit of data. In addition, so the resulting signal has a greater resistance to interference and gives greater security of transmission. Spread signal s(t) is then transferred to the modulator of one of the classic modulations, e.g. PSK family modulation – see figure 5.
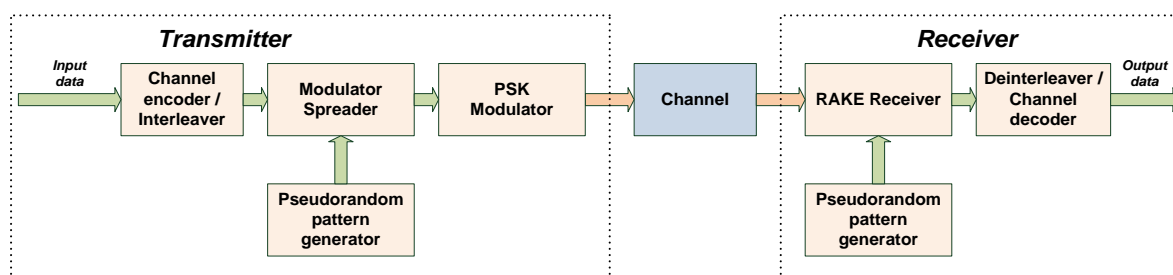
Fig. 5. Block diagram of direct sequence spread spectrum system.

After this, the modulation signal is transmitted via a transmission channel to a receiver.

At the receiver the received signal is subjected to quadrature sampling, which aims to bring the signal from bandpass to baseband. Then the signal goes to the RAKE receiver, which effectively reduces the effect of multipath on the received signal, acting on the basis of the correlation method. Different paths are used to reach the receiver; they use the same information, but convey when signals have a different delay, amplitude and phase. Disruptions occurring in the transmission channel are not correlated with the sequence of the spreading code used and therefore they are effectively dispersed. The suppression of undesirable signals is done so by spreading their spectrum, and the strength of disruptions suppression determines processing gain G_p. It identifies the suppression times of undesirable signals. Also, at the same time the SNR is improved as a result of the spectrum despreading.

Compassion of two methods leads to the following conclusions. The bit error rate for FHSS is higher than for DSSS, and the same as SNR. The frequency hopping technique is very simple to implement and therefore is more suitable for battery-powered solutions. It is also less sensitive to the near-far effect, i.e. when the interference is caused by other active transmitters located close to the target receiver. In DSSS, the energy distribution is much more uniform and a pseudorandom sequence has much more rigorous requirements to qualify as a PN code, among others orthogonality.

Another important issue is the choice of the periodic spreading code for the transmitter and receiver of spread spectrum systems. Accordingly selected code should have an autocorrelation function, which gives a maximum at any single phase compliance, and takes a value of zero for the other phases. Typically, these pseudorandom sequences are used: m-sequences, Gold codes, Walsh codes, Barker codes and Kasami sequences [4].

In my test of the underwater communication system, the structure of the transmitted signals packet includes first the pilot signal, which is followed by the data signal. The pilot signal consists of several signal pulses of linear frequency modulation (LFM) or hyperbolic frequency modulation (HFM) signals, with gaps between them. The signal pulses such as HFM or LFM, are used for a synchronization purpose and the estimation of the channel impulse response functions. The length of each signal pulse is adjusted to the desired length.

Presented here are spread spectrum techniques which are able to work with small values of SNR and are well-placed to be implemented in systems belonging to the group of covert communications systems - especially for military and security solutions.

2. THE PLATFORM FOR THE IMPLEMENTATION OF THE ACOUSTIC UNDERWATER COMMUNICATION SYSTEM

Underwater telephone HTL-10 is a device designed to carry out underwater communication using analog modulation (SSB), as well as digital modulation. The method of generation of the transmitted signals and analysis of the received signals is always performed digitally. It is an open system, designed as a software-defined communication system. Structure of digital signal processing modules used in the underwater telephone is shown in figure 6. Its design ensures an optimal flow of signals and computational performance.

The processor responsible for managing the flow of all analogue signals, the forcing of digital signal processing tasks and communication with the master computer visualization, has been implemented based on a 16-bit microprocessor MSP430F149 from Texas Instruments (TI). Performing complex digital signal processing tasks take two computational paths. The first of these contains a 16 bit fixed point DSP, TI's TMS320VC5416, clocked at 160MHz. Its main function is the modulation and demodulation of signals using a DDS modulator circuit (Direct Digital Synthesis), which includes the structure of the multiplier IQ. In contrast, the second path is arranged to perform complex computational algorithms.

It includes a digital signal processor TMS320C6713B from TI, clocked at 300MHz. It has a 256k x 32 bit internal fast static memory, 2M x 16 bit flash memory and a 128MB dynamic memory. The processor's peak performance is 1800 MFLOPS, but it can only be used fully if the program uses all of the available eight streams in the processor. This usually implies arduous optimization of the program code. Each of the computational paths includes a 16 -bit multi-channel analog-to-digital converter and a single-channel digital-to-analog converter to achieve efficient cooperation with the module of analog processing.

This flexible module structure is convenient for the implementation of an underwater acoustic communication system.
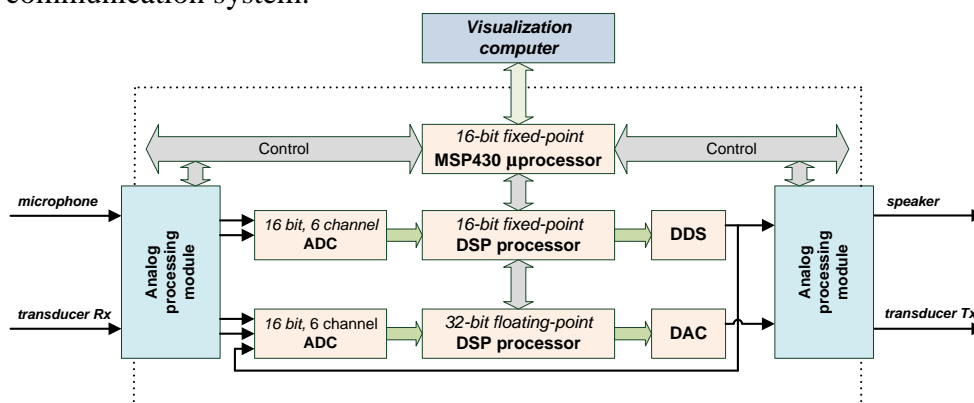

Fig. 6. General block diagram of the digital part in the underwater telephone HTL-10.

3. CONCLUSION

A low data rate spread spectrum approach is a promising direction to take in the development for physical layers in the underwater modem. Presented are two methods of spread spectrum techniques, which belong to the group of modulation used in order to realize the concept of reliable underwater communication. These modulation techniques should soon create the base for underwater communication standards, with the methods based on FSK modulation, which still determine the core of commercial modems' underwater communication. This technique, in combination with suitable channel coding, can provide reliable, robust and covert data transmission, but still requires the continuous development of reception algorithms on which I am currently working intensively.

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