UDC 621.396 DOI: 10.18698/0236-3933-2019-4-62-70

METHODS OF FREQUENCY SYNCHRONIZATION OF OFDM SIGNALS IN AN UNDERWATER ACOUSTIC CHANNEL

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Abstract

Application of signals with orthogonal frequency division multiplexing in underwater communication systems allows efficient use of the information transfer channel bandwidth and thereby increase the carrying capacity of the system. Among the main distinguishing features of the underwater channel there are the relatively low speed of sound propagation in water, multiple reflections from the water surface and the bottom of the reservoir and the Doppler effect, which leads to compression / stretching of the signal in time. The model of the underwater acoustic channel was developed on the assumption that the signal at the receiver input is a superposition of the signals which are copies of the transmitted signal, but passed through different paths from the transmitter. Each signal has its own amplitude, time delay and degree of compression / stretching in time. For correct demodulation of the orthogonal frequency division of the channel-signal, the receiver must first perform time and frequency synchronization. Time synchronization is performed to determine the beginning of the packet and the symbols' boundaries, and frequency synchronization is necessary for matching the receiver and transmitter sampling frequency to eliminate interchannel interference. For frequency synchronization in a hydroacoustic channel of orthogonal frequency division type, either the preambles invariant to Doppler effect or pilot components of the channel of the orthogonal frequency division type are used. The method based on the synchronization preamble and on a bank of matched filters uses a non-invariant to the Doppler effect preamble at the beginning of the packet. Each

Keywords

Underwater communication systems, Orthogonal Frequency Division Multiplexing (OFDM), frequency synchronization, hydroacoustic channel

filter is matched with a preamble having compression / stretching in time. The autocorrelation method assumes that two identical symbols are included in the transmitted data block for signals with orthogonal frequency division multiplexing, which are used to estimate the scale of signal stretching / compression. The conclusions on the advantages of using orthogonal frequency division multiplexing in an underwater acoustic channel are given

Received 24.01.2019

Introduction. Application of signals with orthogonal frequency division multiplexing (OFDM) in underwater communication systems allows more efficient use of the information transfer channel bandwidth and thereby increase the carrying capacity of the system. In addition to high spectral efficiency, this type of signal modulation has a low level of inter-symbol and inter-channel interference. In contrast to radio frequency, underwater communication systems with OFDM modulation must take into account the features of signal propagation in the hydroacoustic channel.

The relatively low speed of sound propagation in water, depending on various physical parameters, as well as multiple reflections from the water surface and the bottom of the reservoir, the Doppler effect, which leads to compression / stretching of the signal in time, are the main distinguishing features of the underwater channel [1]. In this case, the time and frequency synchronization algorithms used in radio frequency systems with orthogonal frequency division multiplexing become inefficient and other approaches are required to implement these operations in the underwater transmit/receive equipment.

Underwater acoustic channel model. The signal at the receiver input is a superposition of the signals which are copies of the transmitted signal, but passed through different paths from the transmitter. Each signal will have its own amplitude, time delay and degree of compression / stretching in time.

The transmitted signal $x(t)$ passing through the hydroacoustic channel with the impulse response $h(t, \tau)$, at the receiver input can be represented as [2]

$$y(t) = x(t) \otimes h(t, \tau) + n(t) = \sum_{p=1}^{N_p} A_p x((1 + a_p)t) + n(t),$$

where A_p, a_p, τ_p are attenuation coefficient, Doppler scale factor and time delay for path p, respectively; N_p is number of signal propagation paths; n_p is additive white Gaussian noise.

This model is a simplified one, since in the general case both the attenuation coefficient and the time delay are non-linearly dependent on time.

Methods of frequency synchronization of OFDM systems in an underwater acoustic channel. For correct demodulation of the OFMD signal, the receiver must first perform time and frequency synchronization. Time synchronization is performed to determine the beginning of the packet and the symbols' boundaries, and frequency synchronization is necessary for matching the receiver and transmitter sampling frequency to eliminate interchannel interference. To provide both time and frequency synchronization, service components are added to the transmitted signal and they are searched during the reception process or components of the OFDM symbol itself are used, for example, cyclic extension.

In underwater acoustic systems, due to the greater influence of the Doppler effect, it is necessary to take into account the compression / stretching of the signal in the time domain, estimate the scale factor of this effect at the frequency synchronization stage, and perform appropriate compensation [3].

For frequency synchronization in a hydroacoustic OFDM, either the preambles invariant to Doppler effect or pilot elements of the OFDM-type are used. The following are the main approaches used in synchronization algorithms in underwater OFDM communication systems.

Method 1. The preambles invariant to Doppler effect. One of the synchronization methods is the use of invariant to the Doppler effect signals with linear frequency modulation (LFM), or with hyperbolic frequency modulation (HFM).

To ensure time and frequency synchronization, a preamble and a postamble of this type are added to the beginning and end of each transmitted data packet, respectively. The structure of such packet is shown in Fig. 1.

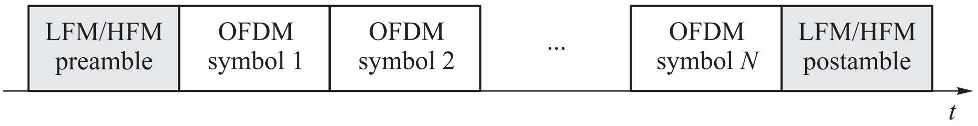

Fig. 1. The structure of a packet with LFM/HFM preamble and postamble

The beginning of the packet is determined by the preamble detection, and to estimate the degree of compression / stretching of the signal, it is enough to find the time difference of preamble and postamble arrival in the received signal, and compare it with the same time in the transmitted signal. The latter is known from the length of the OFDM symbol and total number of them.

The time of preamble and postamble arrival is usually registered using matched filters (MF) [4]:

$$\tau_{pre} = \arg\max_{\tau} \left| \int_{0}^{T_0} y(t+\tau) x_{pre}^{*}(t)\, dt \right|;$$

$$\tau_{post} = \arg\max_{\tau}\left|\int_0^{T_0} y(t+\tau)x^*_{post}(t)dt\right|,$$

then the Doppler scale factor is estimated as follows:

$$\hat{a} = \frac{T_{tp}}{\hat{T}_{rp}} - 1,$$

where $\hat{T}_{rp} = \hat{\tau}_{post} - \hat{\tau}_{pre}$ is the time difference between the preamble and postamble registrations in the received signal, T_{tp} is in the transmitted signal.

Despite the seeming implementation simplicity of this method, it has a significant drawback: in order to estimate the scaling effect and the subsequent demodulation of the OFDM block, the receiver must write the entire data packet into memory. This means that information at the demodulator output will be put out with a delay equal to the length of the information packet.

Method 2. Synchronization preambles and matched filter bank. This method uses a non-invariant Doppler preamble at the beginning of the packet. It can be a pseudorandom sequence or an OFDM-type preamble. The time of the packet arrival and the Doppler coefficient is defined as follows:

$$\left(\hat{a}, \hat{\tau}\right) = \arg\max_{a,\, \tau}\left|\int_0^{T_0} y\left(t+\tau\right)x^*\left(\left(1+a\right)t\right)dt\right|,$$

where f_c is center frequency; a is scale factor; T_0 is preamble duration.

In practice, this method is implemented using a bank of cross-correlators or MF, as shown in Fig. 2.

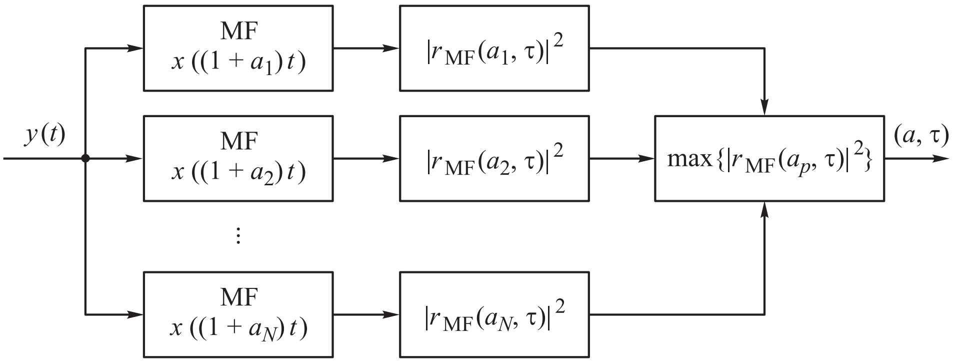

Fig. 2. MF bank

Each filter is matched with a preamble having compression / stretching in time a_p. At the output of the MF bank, there is a comparison device that selects the branch with the highest MF output power. The branch number in this case corresponds to the scale factor a_p. The estimation accuracy of the latter depends on the number of MF in the bank [5].

Method 3. Autocorrelation. This method assumes that two identical OFDM symbols are included at the beginning of the transmitted data block, which are used to estimate the scale of signal stretching / compression. The packet structure is shown in Fig. 3.

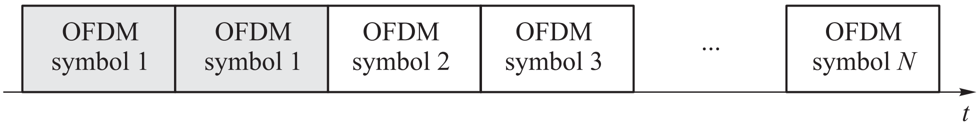

Fig. 3. Packet structure with two repeated symbols at the beginning of the packet

The Doppler effect will cause the two received first symbols to not be identical and their correlation is defined as follows [6]:

$$r_{cp}(a,\tau)=\int_{0}^{T_0/(1+a)} y(t+\tau)\,y^{*}\left(t+\tau+\frac{T_0}{1+a}\right)dt.$$

To estimate the factor a, it is necessary to correlate a symbol with its compressed / stretched copy. This can be done by analogy with the previous method: using the bank of autocorrelators [7].

Method 4. Estimation by each OFDM symbol. The considered methods have a common drawback — they are ineffective for a rapidly changing channel, when its properties may change during the reception of a data packet. For a more accurate and continuous estimation, service subcarriers — zero or pilot — are included in each OFDM symbol [5].

When using zero subcarriers, the minimum signal power at the frequencies corresponding to these subcarriers is used as an estimation criterion, and for the case of using pilot subcarriers, the signal maximum corresponding to a compressed / stretched pilots signal is used. The estimation operation can be performed using the considered banks of MF or correlators [8].

For weakly changing channel parameters during the data packet, the Decision aided method can be applied, which involves inserting special synchronization symbols in the information packet; these symbols allow to more accurately estimate the Doppler scale factor.

Simulation. The simulation was carried out to estimate the effectiveness of the described methods of frequency synchronization. The efficiency criterion is the standard deviation of the Doppler scale estimate in terms of the speed of sound propagation in the channel (residual error) [9, 10]:

$$\varepsilon = \sqrt{E\left((\hat{v}-v)^2\right)} = \sqrt{E\left(\left((\hat{a}-a)c\right)^2\right)},$$

where c is speed of sound propagation in the hydroacoustic channel.

System parameters

Dimension of the discrete Fourier transform	2048
Number of used subcarriers	512
Subcarrier modulation type	QPSK
Sampling frequency, Hz	44100
Upsampling rate	5
Average speed of sound in the channel, m/s	1500
RMS error of sound speed through various paths, m/s	4,5
Number of paths	15

Fig. 4 shows the graphs of the scale factor estimation error versus signal-to-noise ratio (SNR). Dependencies are presented for methods with LFM and HFM preambles / postambles, cross-correlation and autocorrelation methods.

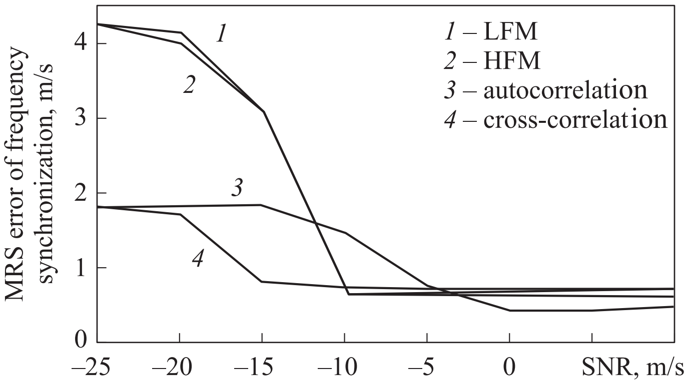

Fig. 4. RMS error of frequency synchronization by preamble

The most stable characteristics on the entire SNR range has a method that uses cross-correlation [11]. The autocorrelation method is comparable to it in performance when SNR is higher, and can be used as a way to reduce residual error after coarse synchronization. As for the method with preambles/postambles invariant to the Doppler effect, using them is possible only at high SNR values [12–15].

Fig. 5 shows the residual error versus SNR at synchronization by each symbol.

As can be seen, the estimates for pilot and zero subcarriers give a similar result. The Decision aided method is different for the better, but it uses a separate symbol for synchronization and subsequent estimation by the symbols.

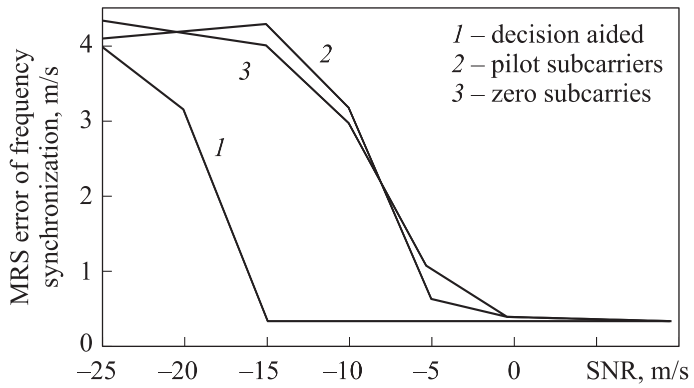

Fig. 5. RMS error of frequency synchronization by each symbol

Of particular interest in the method using the service subcarriers to synchronize by each symbol is the density of their distribution within the OFDM symbol. Fig. 6 shows the synchronization error versus SNR for two methods (pilot / zero subcarriers) with different distribution density of service subcarriers.

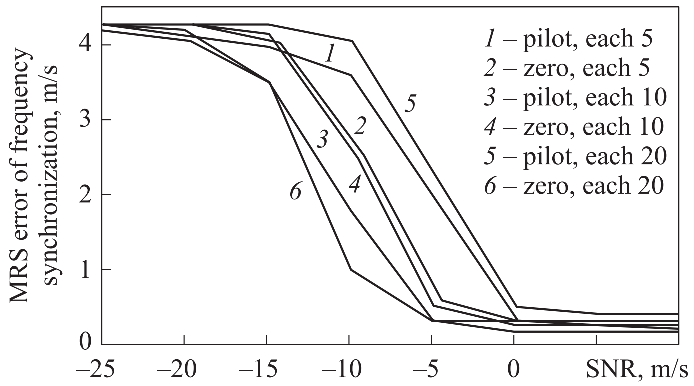

Fig. 6. RMS error of frequency synchronization depending on the distribution density of service subcarriers

It should be noted that with frequent use of service components, the pilot subcarriers method is more advantageous. For a low distribution density, the zero subcarriers method shows itself better.

Conclusions. The use of OFDM in an underwater acoustic channel provides certain advantages, but leads to the complication of frequency synchronization circuits. This forces developers to seek a compromise between the effectiveness of the methods and the possibility of their implementation. However, this choice should be made in the presence of knowledge about the use conditions of data transmission systems. The simulation performed has shown that the most advantageous methods (autocorrelation and cross-correlation) require large computational costs, but if the conditions are such that one can neglect the delay in obtaining data, then the preambles invariant to the Doppler shift should be used. Frequency synchronization in a rapidly changing channel was also investigated, i.e., provided that the Doppler scale changes during the data packet. In this case, if it is necessary to work in a wide range of SNR, the method of inserting the service synchronization symbol into the packet should be chosen, but with strong Doppler scale changes from one symbol to another, it may be more feasible to estimate each symbol by introducing pilot or zero subcarriers. In addition, the pilot subcarriers work more effectively at greater density of service subcarriers, and the zero subcarriers — at lower one.

Translated by K. Zykova

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DOI: 10.18698/0236-3933-2018-3-4-16

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Please cite this article as:

Shakhtarin B.I., Chudnikov V.V., Dyabirov R.M. Methods of frequency synchronization of OFDM signals in an underwater acoustic channel. *Herald of the Bauman Moscow State Technical University, Series Instrument Engineering*, 2019, no. 4, pp. 62–70.
DOI: 10.18698/0236-3933-2019-4-62-70