Efficiency Analysis of Time Synchronization and PAPR Reduction of N-OFDM Modem

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Abstract. Non-Orthogonal Frequency Division Multiplexing (N-OFDM) remains to be a promising digital modulation technique for high-data-rate wireless transmission. This research is focused on the efficiency analysis of a technique for data frames time synchronization in a white noise communication channel and an optimal demodulation in the N-OFDM system. N-OFDM signals are generated using the Hartley transform and the Cauchy method is applied for the evaluation signal amplitude the demodulation procedure. The peak-to-average power ratio (PAPR) for different frequency spacing between N-OFDM subcarriers is analyzed. As a result, the mathematical expression for the subcarrier initial phase over subcarrier frequency is derived that allows calculating initial phase with the minimum of PAPR. The paper contains experimental results confirming the operability of the proposed time synchronization scheme. In the experiment, bit error rate estimation was performed for various spacing frequencies and signal-to-noise ratio in the range from 0 to 25 dB. The experimental results have shown the opportunity of PAPR reduction through the calculation of reasonable initial phase for each subcarrier. The experiment was based on simulation in MATLAB with the use of a sound card of a personal computer.

Keywords. N-OFDM, time synchronization, Peak-to-average power ratio, Hartley transform, Cauchy method.

1. Introduction

Nowadays, signal multiplexing in multifrequency systems is considered as a challenging problem that is caused mainly by the wide and rapid expansion of digital wireless communication and as a result, continues increase of mobile users. Traditional Orthogonal Frequency Division Multiplexing (OFDM) technique has been applied for the development of wireless as well as wire communication systems such as WiMAX, power line communication (PLC), asynchronous digital subscriber line (ADSL), Long-Term Evolution (LTE) standard of GSM/UMTS systems and etc. This popularity is explained by the well-known advantages of this multi-carrier transmission technique including high spectral efficiency, robustness to channel fading and immunity to impulse interferences [1, 2]. However, in spite of these proved merits, OFDM cannot be used in the next generation of mobile communication 5G networks due to the inherent drawbacks in OFDM such as its sensitivity to frequency errors, time misalignment and high out of band emission [3]. Also, for telecommunication systems with high data rates, the spectral efficiency of OFDM system decreases as it is impossible to allocate subcarrier frequencies with shorter intervals than the intervals of orthogonality. In order to overcome the mentioned shortcomings, Non-Orthogonal Frequency Division Multiplexing (N-OFDM) represents an encouraging technology for future digital wireless communication systems with high data rates. Over
the last decade, this digital modulation technique has gained the attention of researchers focusing on the analysis of its spectral efficiency [4] and the development of efficient N-OFDM decoding schemes [5–11]. This work is devoted to the consideration of N-OFDM signals modulation process on the basis of the Hartley transform (HT), whereas the demodulation is offered to be based on the modified Cauchy method as an approach for the evaluation signal amplitude solving a set of linear algebraic equations. Some questions of demodulator efficiency analysis of the mentioned method have been considered in [12–16].

The objective of the paper is the efficiency analysis of N-OFDM data packets time synchronization that is proposed by authors, and the performance evaluation of a method for the reduction of the peak-to-average power ratio.

In order to get an adequate estimation to the efficiency of the designed time synchronization technique, series of experiments have been done using personal computer (PC) sound card containing 16-bit ADC/DAC as well as a signal amplifier stage, and MATLAB software. Using this experimental assembly, information sequences were sending with the frequency from the interval 0.3-3.4 kHz and modulated by binary phase-shift keying (BPSK) technique. Then, the signal-to-noise ratio threshold was calculated for the transmission sessions with stable time synchronization and controlling the level of bit error rate (BER).

One of the important issues while transmitting a massive number of subcarriers is the high peak-to-average power ratio (PAPR). For OFDM signals, the challenge of PAPR reduction has been investigated extensively [18-21], while especially for N-OFDM systems the problem remains to be of a great importance with few pieces of research dealing with this issue. In [22], the authors present simulation results for PAPR reduction of N-OFDM signals using clipping, partial transmit transform and selective mapping methods.

This work considers PAPR reduction through the evaluation of a phase-frequency characteristic that is optimal for signals with linear amplitude modulation. The obtained results allowed the identification of an optimal phase frequency response when the peak factor has the minimum that is related to the square law [23].

The rest of the paper is organized as follows. In Section 2, the description of an approach for optimal demodulation of N-OFDM signals is presented. Section 3 deals with the proposed technique for time synchronization and presents experimental results of signal-to-noise ratio (SNR) estimation while the obtained results of PAPR reduction analysis are demonstrated in Section 4. Finally, Section 5 is devoted to the main conclusions.

2. Modulation and demodulation technique of N-OFDM signals

As we consider a communication channel with the Additive White Gaussian Noise (AWGN), any transmitted signal can be interpreted by a vector of voltage readouts. The matrix form of such translation is defined by the expression:

\[ Q = W_{BPSK}(n,l) \cdot A_t + N_t, \]

where \( N_t = [n_1, n_2, ..., n_v]^T \) is the AWGN voltage samples grouped in a vector, \( W_{BPSK}(n,l) \) is the signal matrix with the Hartley function \( \cos(\omega t) + \sin(\omega t) \), \( A_t = [a_1, a_2, ..., a_v] \) is the BPSK signal amplitudes, \( V \) is the samples quantity of BPSK signal, \( N \) is the number of subcarrier frequencies in a group N-OFDM signal.

The next step is the estimation of subcarrier frequencies for the considered N-OFDM system with BPSK. For doing that, the interval of orthogonality, which is the minimum of frequency separation between subcarriers with keeping the signals orthogonality, was evaluated using the ratio

\[ \Delta F = \frac{1}{V \cdot \tau}, \]

where \( \tau \) is the sampling period for the selected sample rate of 8 kHz.
The number of samples for BPSK signal $V$ can be estimated as follows:

$$V = \frac{f_s}{R},$$

where $R$ is the data rate on a subcarrier ($R = 200$ bit/sec).

The period of samples generation $\tau$ can be evaluated as:

$$\tau = \frac{1}{f_d},$$

For the considered conditions, the subcarriers keep orthogonality with the frequency separation $\Delta F = 200$ Hz. Thus, using the derived estimation for $\Delta F$, the frequency separation between non-orthogonal subcarriers $\Delta f$ can be defined by:

$$\Delta f = \frac{\varepsilon}{V \cdot \tau},$$

where $\varepsilon = \Delta f / \Delta F$ is the orthogonality coefficient.

Equality to one of this coefficient corresponds to the orthogonal allocation between subcarriers. Non-orthogonal allocation defines for the values from the interval $(0, 1)$. Further, during the experiments, four values of $\varepsilon$ were specified: 1, 0.5, 0.25 and 0.1. Thus, for the frequency separation $\Delta F = 200$ Hz, the spacing frequencies equal to: 200 Hz, 100 Hz, 50 Hz and 20 Hz.

The demodulation process is based on the solving the equation set (1) through the evaluation of signal amplitudes using the Cauchy method, which is explained in [14, 24]. Consequently, the signal amplitudes estimation problem comes to the finding of the minimum of the function:

$$X = \min \sum_{l=1}^{V} \left( Q - \sum_{n=1}^{N} [a_n \cdot cas_{LN}] \right)^2,$$

Traditionally, mathematical modeling of signals with BPSK modulation can be done using the formula [25]:

$$U(t) = a \cdot \cos(\omega t + \phi(t)),$$

where $a$ is the signal amplitude, $\omega$ is the cyclic frequency and $\phi(t)$ is the initial phase of the transmitted signal.

According to the Hartley Transform (HT) the function is presented as:

$$cas\left(\omega t + \phi(t)\right) = \cos\left(\omega t + \phi(t)\right) + \sin\left(\omega t + \phi(t)\right),$$

Hence, let rewrite the expression (7) using the previously formulated Hartley function as follows:

$$U(t) = a \cdot cas\left(\omega t + \phi(t)\right),$$

The signal matrix can be written down as follows:

$$W_{BPSK} = cas_{LN}\left((\omega t + \phi(t))\right),$$

Thus, according to the signal matrix [10], let rewrite the representation of the BPSK signal [9] in matrix form:
\[ Q_{yn} = W_{bpsk} \cdot A_n, \]

where \( Q_{yn} \) is the final sequence transmitted through AWGN channel.

In accordance with the presented approach for the modulation and demodulation of N-OFDM signals, the following block structures of modulator and demodulator can be suggested with the illustrations in Fig. 1 and 2, respectively. The N-OFDM modulator is based on the real Hartley transformation, whereas the Cauchy method forms the base of the demodulator with the time synchronization block. The clock signal generating is performed in the block of signal matrix generator (Fig. 1).

3. Time Synchronization in N-OFDM modem

As it is well known, time synchronization has a significant influence on the quality of data transmission and interference immunity of the whole communication system [25]. The estimation of the phase noises influence of frequency carrier generator on the quality of the OFDM signal and the synchronization methods of OFDM signals with the cyclic prefix is demonstrated in [17, 26].

In most cases, a telecommunication system without time synchronization is inoperable. It is caused mainly by a time delay of the signal transmitted through the real communication channel. Time synchronization system does the calculations of the time delay and compensates this time shift. In Fig. 3, the proposed structure of the transmitted data frame in the N-OFDM modem is presented.
N-OFDM data frame consists of the synchronization burst that is a sequence of bits equal to 1 or -1. The length of this packet matches with the number of N-OFDM subcarrier frequencies. A copy of unbiased synchronization burst is saved in the block of time synchronization of the demodulator and it is known in transmitter and receiver. The received data frame is processed starting with the synchronization burst.

In the block of time synchronization in Fig. 2, a cyclic shift for one bit of the received sequence is performed and compared with its unbiased copy. Further, the received signal proceeds to the block of amplitudes estimation by the Cauchy method and comes in the thresholder. After, the signal is processed for BER estimation and its comparison with the threshold level. The estimated BER aims to the threshold level when the estimations are minimal or ideally aimed to zero. Zero or near zero BER value is possible if there is the maximum correlation between the received clock signal shifted in time and its copy stored in the block of time synchronization. This block captures the time delay value from the bit counter when BER equals to zero. In this case, the delay is measured in the number of samples that corresponds to the shift of the received clock signal in order to achieve the maximum of correlation with its biased copy.

After the measurements of time delay, the obtained values are used for the synchronization and receiving of the rest five information packets IP1-IP5. Further synchronization of IP1-IP5 packets is performed for one cycle by means of the shift of the initial IP for already identified time delay occurred in the communication channel.

In order to check the feasibility of the proposed time synchronization technique for N-OFDM demodulation, series of experiments have been carried out on the basis of the designed experimental prototype of the N-OFDM modem. Block scheme of the prototype is depicted in Fig. 4.

![Figure 4. An experimental prototype of the N-OFDM modem.](image-url)

The experimental assembly consists of two principal parts. The first is the software that is responsible for the process of modulation and demodulation presented in Section 2 of the paper. These functions are realized using the MATLAB instruments. The second part corresponds to the hardware of the prototype, which includes sound card PCA-Audio-HDA1E, 16-bit DA/AD converters, and amplifier circuits.

Thus, the experiment was in the transmission of a signal generated in MATLAB through the sound card, and its optimal demodulation. For this purpose, the generated signal was transmitted to the liner input that is connected with output by a coaxial cable.

During the experiments we were considering four values of spacing frequencies: 200 Hz, 100 Hz, 50 Hz, and 20 Hz, with the following number of subcarriers 16, 31, 62 and 155, respectively. The N-
OFDM MATLAB-based modulator was preparing BPSK sequence $Q_{VN}$ without coding, as has been presented by expression (11). For each spacing frequency, one hundred signal sequences from the frequency range 0.3-3.4 kHz with AWGN were sent. In order to compensate time delays in the experimental communication channel, the previously offered time synchronization technique was applied with the meander signal as a synchronization sequence.

After the signal transmission, in the demodulator side, the BER measure was evaluated for various levels of AWGN. And in this, as it was mentioned in Section 2, the time synchronization is correct when BER is equal to zero that can be considered as a criterion of operable synchronization. Therefore, the signal-to-noise ratio (SNR) have been evaluated for the moments when the obtained BER estimations have a null value.

As a result, for the mentioned number of subcarriers and spacing frequencies, the estimations of SNR threshold were calculated that have a non-linear and decreasing tendency, as it is shown in Fig. 5.

![Figure 5. Experimental estimations of SNR threshold for operable time synchronization.](image-url)

Thus, the obtained results mean that, for example, if SNR is lower than 14 dB in the system with 100 Hz frequency spacing between 31 subcarriers, consequently, such system will be inoperable due to the lack of synchronization with BER > 0.

4. Analysis of PAPR of N-OFDM signal

One of the significant drawbacks of OFDM signals is a high value of peak-to-average power ratio (PAPR) that is given as a ratio $\frac{\text{MAX}(S_i^2)}{\sum_i S_i^2}$. For OFDM signals, $\text{MAX}(S_i^2)$ is determined as a sum of all subcarriers amplitudes, and $\sum_i S_i^2$ equals to statistical average over the amplitudes of the same subcarriers. Consequently, for systems with a high number of subcarriers, PAPR can be numbered in the hundreds. Besides this, the peak-to-average power ratio serves as a condition of channels linearity in analog systems, as well as this measure has an impact on the digital capacity of DA/AD converters. Hence, high PAPR values result in the more complicated design of such systems.

There are several algorithms for peak-to-average power ratio reduction [18-21, 25]. However, the clipping algorithm leads to distortions in the spectrum of a signal with an increase of out-of-band emissions. Dynamical changing of modulated constellations is more effective, nevertheless, it requires routine calculations that makes it quite complicated to apply it for constellations over QAM-16. The iterative methods also are used that imply rotation of the subcarriers on a random angle with the PAPR estimation. After that, it is performed one more rotation if the peak-to-average power ratio did not take place. These methods are complicated to be realized in real time. One more method is to add a subcarrier signal that is intended for the generation of a guard interval. The disadvantage of this method is the significant increase of the calculations caused by the amplitude and phase selection of subcarriers, as well as the disruption of the signal spectrum mask. Thus, at least there are methods to solve the problem of high PAPR, however, these approaches have some drawbacks.
As a technique for PAPR decreasing in reference [23], it is suggested and explained how to find an optimal phase-frequency variation for a channel with linear amplitude modulated signals. It was derived that for this conditions the phase-frequency characteristic changes according to the square law:

\[ \varphi(k) = \frac{\pi k^2}{2 \cdot N}, \]  

(12)

where \( k \) is the actual number of the signal subcarrier of the OFDM signal and \( N \) is the total number of subcarriers in OFDM signal spectrum.

Thus, the initial phase \( \varphi \) of each signal subcarrier can be estimated easily using the abovementioned analytical expression (12).

In order to make the estimation of PAPR for N-OFDM signals, series of experiments were performed using the previously described prototype of the N-OFDM modem in Section 3. The same conditions have met regarding the spacing frequencies and the number of subcarriers, as well as for the parameters of the transmitted sequences generation. The peak-to-average power ratio was evaluated for five information packets and one clock burst that was generated as a meander with amplitude 1 and -1. The structure of data frames is the same as it is depicted in Fig. 3. Two kinds of calculations were done, for null initial phase \( \varphi = 0 \) and for the values of the phase evaluated by means of an experimentally derived analytical function that is given by:

\[ \varphi(k) = \frac{3\pi k^2}{2 \cdot N}, \]  

(13)

As it could be easily noticed, the only difference between expression (12) and (13) lies in factor 3. However, during the experiment, it was discovered that for this multiplier it was possible to achieve an optimal decreasing of PAPR for N-OFDM signals.

Table I contains the summary information regarding the experimental PAPR estimation. The results are divided into two groups when the initial phase is equal to zero and the values \( \varphi(k) \), calculated using the experimentally derived expression (13).

**Table 1. Experimental Results of PAPR Analysis**

| Number of subcarriers \( N \) | SB      | IP1     | IP2     | IP3     | IP4     | IP5     |
|------------------------------|---------|---------|---------|---------|---------|---------|
| PAPR, dB, for \( \varphi = 0 \) |
| 16                           | 15.0514 | 9.9781  | 10.2729 | 9.7523  | 10.9691 | 9.5424  |
| 31                           | 17.8824 | 11.6109 | 11.4300 | 10.1516 | 11.1438 | 10.3292 |
| 62                           | 20.7973 | 11.4527 | 12.4579 | 13.1530 | 11.2064 | 11.5526 |
| 155                          | 24.8695 | 13.9698 | 13.1524 | 13.8157 | 12.4449 | 13.2032 |
| PAPR, dB, for \( \varphi(k) = \frac{3\pi k^2}{2 \cdot N} \) |
| 16                           | 9.9589  | 12.4304 | 10.7969 | 11.1571 | 11.3599 | 10.1327 |
| 31                           | 11.8173 | 11.6894 | 12.3726 | 11.5265 | 11.9194 | 12.1752 |
| 62                           | 12.1422 | 11.8240 | 12.4385 | 11.7182 | 12.9965 | 13.0689 |
| 155                          | 12.9166 | 13.3724 | 13.5333 | 11.6590 | 12.4830 | 13.1892 |

As it can be seen in Table I, for the initial phase \( \varphi = 0 \), peak-to-average power ratio has the value close to \( \text{PAPR}_p = 10 \log_{10}(2 \cdot N) \) with the transmission of the periodical synchronize sequence in the communication channel. The information packets have a random initial phase and, in this case, PAPR remains constant both when the phase equals to zero and its value is calculated by the expression (13).
At a high quantity of subcarriers and zero initial phase, PAPR for clock sequence can achieve high value equal to $2 \cdot N$. For example, for $N=155$, $PAPR_{sp}=2 \cdot 155$ or 15 dB. The calculation of the initial phase on the basis of the experimentally derived expression (13) provides an opportunity to decrease PAPR for 12 dB that is a reasonable reduction.

5. Conclusions

The interest of researches in the field of performance assessment of N-OFDM systems keeps on the high level due to attractive advantages of this technology. In the work, it was demonstrated and proved the operability of N-OFDM modem on the basis of the obtained results of a physical experiment with the designed N-OFDM modem prototype. Two kinds of experiments were carried out, for the evaluation of signal-to-noise ratio (SNR) threshold with stable time synchronization, and for the efficiency analysis of an approach for peak-to-average power ratio (PAPR) reduction especially for N-OFDM signals.

The performed experiments for the SNR threshold estimation have demonstrated that it is necessary to specify a higher threshold with the application of more subcarriers, at the average 4 dB more for an approximately two-fold increase of subcarriers quantity. With regard to the PAPR analysis, the conducted experiments have made it possible to derive an analytical expression, which allows calculating an optimal initial phase and, consequently, achieving PAPR reduction at the average for 12 dB transmitting periodic signals with 155 subcarriers.

References

[1] Gangwar A Bhardwaj M 2012 An Overview: Peak to Average Power Ratio in OFDM system & its Effect International Journal of Communication and Computer Technologies vol 1 pp 22–25
[2] Saad W El-Fishawy N EL-Rabaie S Shokair M 2010 An Efficient Technique for OFDM System Using Discrete Wavelet Transform. Advances in Grid and Pervasive Computing. Lecture Notes in Computer Science vol 6104 pp 533-541 DOI: https://doi.org/10.1007/978-3-642-13067-0_55
[3] Honggui Deng Shuang Ren Yan Liu Chengying Tang 2017 Modified PTS-based PAPR Reduction for FBMC-OQAM Systems Journal of Physics: Conference Series. IOP Publishing vol 910 (1) p 012057 DOI: 10.1088/1742-6596/910/1/012057
[4] Kanaras I et al. 2009 Spectrally efficient FDM signals: Bandwidth gain at the expense of receiver complexity Communications IEEE International Conference pp 1–6 DOI: 10.1109/ICC.2009.5199477
[5] Xing Yang Wenbao Ai Tianping Shuai Daoben Li 2007 A fast decoding algorithm for non-orthogonal frequency division multiplexing signals Second International Conference on Communications and Networking in China pp 595-598 DOI: 10.1109/CHINACOM.2007.4469461
[6] Kanaras I Chorti A Rodrigues M R D Darwazeh I 2009 Spectrally Efficient FDM Signals: Bandwidth Gain at the Expense of Receiver Complexity IEEE International Conference on Communications pp 1-6 DOI: 10.1109/ICC.2009.5199477
[7] Kanaras I et al. 2008 A combined MMSE-ML detection for a spectrally efficient non orthogonal FDM signal Broadband Communications, Networks and Systems 5th International Conference pp 421-425 DOI: 10.1109/BROADNETS.2008.4769119
[8] Bharadwaj S et al. 2011 Low complexity detection scheme for NOFDM systems based on ML detection over hyperspheres Devices and Communications International Conference pp 1–5 DOI: 10.1109/ICDECOM.2011.5738467
[9] Guo M et al. 2017 Simplified Maximum Likelihood Detection for FTN Non-Orthogonal FDM System IEEE Photonics Technology Letters vol 29 (19) pp 1687–1690 DOI: 10.1109/LPT.2017.2743244
[10] Kai-rui F U 2014 Study on Non-orthogonal frequency division multiplexing technology Journal of Qiqihar University (Natural Science Edition) vol 6 p 013
[11] Fagorusi T Feng Y Bajcsy J 2017 An architecture for non-orthogonal multi-carrier faster-than-nyquist transmission Information Theory (CWIT) 15th Canadian Workshop pp 1–5 DOI: 10.1109/CWIT.2017.7994837

[12] Slusar V I Smolyar V G Utkin Yu V 2006 The research of capabilities of frequency division multiplexing of N-OFDM signals on the base of the Hartley function Radio electronic and computer systems vol 6 pp 215–218

[13] Slusar V I 2008 The method of nonorthogonal frequency discrete modulation on the base of the Hartley transformation with quadrature amplitude modulation of frequency carriers Information processing system vol 2 pp 102–104

[14] Maystrenko V V 2011 The method of the data transmission in the short-wave communication channel with nonorthogonal N-OFDM modulation on the base of the Hartley transformation with quadrature amplitude modulation of stand-alone carriers International scientific and technical conference Radioolocation, navigation, communication vol 2 pp 903–914

[15] Bakulin M G Krejndelin V B Shloma A M Shumov A P 2016 OFDM technology. Manual for High School (Moscow: Goryachaya liniya Telekom) p 352

[16] Maystrenko V A Maystrenko V V Lyubchenko A 2016 Distortion effect analysis of N-OFDM signal with frequency drifts of the carrier wave 13th International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering pp 82–86 DOI: 10.1109/APEIE.2016.7806417

[17] Batyrev I A 2018 OFDM-signal synchronization technique based on the training symbol Tehnika radiosvjazi JSC «Omskiy Nauchno Issledovatelskiy Institut Priborostroeniya» vol 1(36) pp 90–102

[18] Pradhan P K Yadav S S Patra S K 2014 PAPR Reduction in OFDM systems India Conference (INDICON) pp 1-5 DOI: 10.1109/INDICON.2014.7030615

[19] Xin Y Fair I J 2003 Peak-to-average power ratio reduction of an OFDM signal using guided scrambling coding Global Telecommunications Conference vol 4 pp 2390–2394 DOI: 10.1109/GLOCOM.2003.1258663

[20] Mukunthan P Dananjayan P 2012 PAPR reduction by modified PTS combined with interleaving technique for OFDM system with QPSK subcarriers Advances in Engineering, Science and Management (ICAESM) International Conference pp 410-415

[21] Deng H et al. 2017 PAPR Reduction in OFDM-based Visible Light Communication Systems Using a Combination of Novel Peak-value Feedback Algorithm and Genetic Algorithm Journal of Physics: Conference Series. IOP Publishing vol 910 (1) p 012058

[22] Mokhtar I M et al. 2018 PAPR Reduction Techniques in Generalized Inverse Discrete Fourier Transform Non-Orthogonal Frequency Division Multiplexing System Indonesian Journal of Electrical Engineering and Computer Science vol 10 (3) pp 1045–1052 DOI: http://doi.org/10.11591/ijeecs.v10.i3.pp1045–1052

[23] Ruhlin S N 2013 Questions of generation and application of OFDM signals in modern telecommunication systems 3d Russian Armadovskie chterniya pp. 201–207

[24] Svetlakov A A 2007 The traditional and nontraditional evaluation of unknown values. Study guide. (Tomsk: TUSUR) p 522

[25] Kalashnikov K S Shahtarin B I 2011 OFDM signal synchronization in time and frequency range Herald of the Bauman Moscow State Technical University. Series Instrument Engineering. Bauman Moscow State Technical University vol 1 pp 18–27

[26] Batyrev I A Semenov A M 2016 Estimation of the influence of phase noise of carrier frequency oscillator on quality of received OFDM signal Tehnika radiosvjazi JSC «Omskiy Nauchno Issledovatelskiy Institut Priborostroeniya» vol 3(30) pp 68–79