**FRAME SYNCHRONIZATION OF DIGITAL TELEMETRY INFORMATION**

**I.M. Sidyakin**, **M.A. Elshafey**

Bauman Moscow State Technical University, Moscow, Russian Federation
e-mail: ivan.sidyakin@bmstu.ru; elshafey.m@gmail.com

*Frame synchronization algorithm plays an important role in the recovery process of telemetry data transmitted over a communication channel with noise, and it significantly affects the entire process efficiency. In particular, frame synchronization is important in the case when the nature of noise in the communication channel and methods of processing the transmitted information allow for both omission of the reliable messages and insertion of the false ones into the telemetry data stream, as well as interruption and resuming transmission at irregular intervals. In general, the frame synchronization process provides a decommutation ability of telemetry information parameters in the stream. A necessary theoretical description of the frame synchronization system model is given, as well as techniques for selecting basic parameters of the synchronizer. The selection criteria for these parameters are defined. In the experiments with real telemetry data of IRIG-106 format, the model of a communication channel with noise allowing for both inversion and bit omissions is used. The obtained experimental results are compared with theoretical estimations of the synchronizer parameters.*

***Keywords*:** telemetry information, frame synchronization, synchronization code, synchronization threshold, Search mode, Test mode, Capture modes, IRIG-106 standard, symmetric binary channel with missing bits.

Data synchronization is a detection of a cycling group of characters in a stream of digital telemetry information (TMI). A synchronizer can be represented as a finite state machine with three modes [1–4]:

- “Search” mode — is a state in which the synchronizer scans the entire input data stream to detect a synchronization code;
- “Test” mode — is a state in which the synchronizer confirms the initial detection of the synchronization code using a predetermined number of successful checking detections of the synchronization code;
- “Capture” mode — is a synchronizer operation condition in which the synchronization code is detected with a high degree of accuracy based on the initial detection and a sufficient number of checks.

Theoretical calculation of the frame synchronization system parameters introduced in well-known publications [1–7] is based on the fact that an information component of the frames is filled with random values distributed according to the normal law. The frames in the stream are divided by bit sequences of the synchronization codes. Transmission of TMI stream through a signal channel distorts both the information component of the frame and the synchronization codes due to noise. In general, this leads to a loss of the real synchronization codes and emerging of the false ones in the stream. The probability of the false synchronization codes occurrence depends on the structure and the content of an information part of the frame and it may differ from the one theoretically calculated. This paper

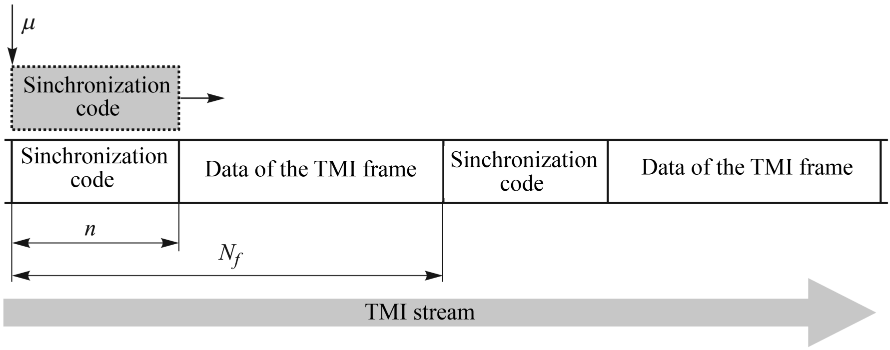


**Fig. 1. The structure of the synchronized TMI frame**

presents the results of the research into the frame synchronization recovery system in the TMI stream of IRIG-106 standard filled with information from sensors. Parameters of the synchronization system are chosen based on experimental data and they are compared with the theoretically obtained values.

In all operational modes the synchronization code detection is typically performed using a correlation process in which an input message is being continuously compared with the synchronization code known by the correlation algorithm. With a relatively high correlation between the synchronization code and the messages symbols, the code is considered to be detected.

The task of the synchronization code detection is to determine the location of the synchronization code in each TMI frame (Fig. 1) in the received bitstream:

$$\mu_{s,l} = \underset{\mu_l \in [(l-1)N_f+1; lN_f]}{\operatorname{argmax}} L(\mu), \tag{1}$$

where $\mu$ is the location of the detected synchronization code in the bitstream $d = \{d_1, d_2, d_3, \ldots\}$; $S = \{s_1, s_2, \ldots, s_n\}$ — is $n$-bit synchronization code being used; $l$ — is a serial number of the detected frame in the stream $d$; $N_f$ — is the TMI frame length; $L(\mu)$ — is a correlation process described in [5–7], which is defined by the formula

$$L(\mu) = \sum_{k=1}^{n} s_k d_{k+\mu}. \tag{2}$$

The correlation coefficient in each state of the synchronizer is continuously compared with a predetermined threshold $\varepsilon$ for each state. While this value does not exceed the threshold value, the synchronizer remains in its current state, but when the threshold is exceeded, the synchronizer proceeds to the previous one.

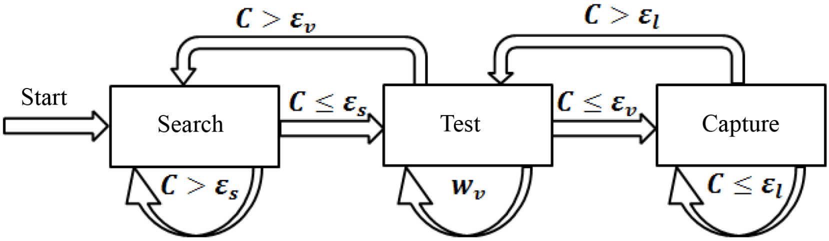


**Fig. 2. Transition between the TMI stream frame synchronizer states**

Fig. 2 shows transitions between the synchronizer states: "Search", "Test" and "Capture", where $\varepsilon_l$ is the synchronizer threshold in the "Search" mode, $\varepsilon_v$ — in the "Test " mode, and $\varepsilon_l$ — in the "Capture" mode; $C$ is a correlation coefficient, equal to the value $L(\mu)$ calculated based on formula (2). In each state, if the value of the correlation coefficient $C$ is either less than or equal to the threshold of the current state, the synchronization code is considered to be detected and vice versa.

At the beginning of its operation, the synchronizer is in the "Search" state. If the synchronizer detects the synchronization code ($C \le \varepsilon_s$), it proceeds to the "Test" state. If in the "Test" state the number of detected consecutive synchronization codes ($C \le \varepsilon_v$) reaches a predetermined value $w_v$, the synchronization system proceeds to the "Capture" state, otherwise, the system returns to the "Search" mode. In the "Capture" mode the frame synchronization is provided. When the synchronization code exceeds the threshold $\varepsilon_l$, the synchronizer returns to the "Test" mode. In the "Search" mode the synchronizer reads bits until it detects the synchronization code in a stream, and then in the "Test" and "Capture" modes it shifts in the stream to a step length. A step length is equal to the TMI frame length, as it is shown in Fig. 3.

The purpose of this work is to develop methods of calculation and selection of frame synchronizer parameters, including thresholds $\varepsilon_s$ for the "Search" state, $\varepsilon_v$ — for the "Test" state and $\varepsilon_l$ — for the "Capture" state, as well as the avarage synchronizer latency $w_v$ in the "Test" mode, where the value $w_v$ is represented by the average number of frames. The synchronization system parameters are selected for the telemetry frame of

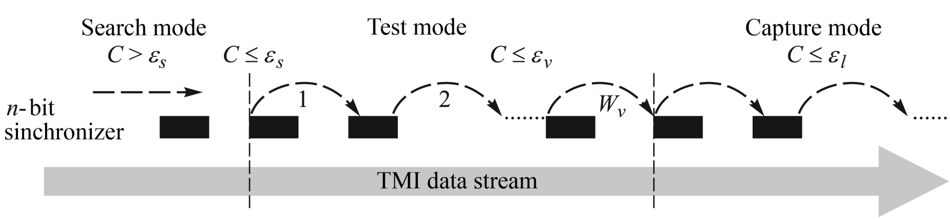


**Fig. 3. Shift of the synchronizer in telemetry data stream in various operating modes**

the $N_f$-bit length generated by the switching system on an telemetry object with a predetermined synchronization code of the $n$-bit length.

This article presents the algorithm for frame synchronization and the equations describing the operating states of the synchronizer [1, 2], with regard to the problem of frame synchronization in a stream of TMI.

The performance of the frame synchronization system in the “Search” and “Test” states is determined by the probability of correct detection of both the synchronization code and the average time required for the procedure. In the “Capture” state the performance is determined by the average time of false synchronization detection after the transition to the “Capture” mode.

The selection of low thresholds for the state transitions increases the likelihood of correct detection of the synchronization code. However, this increases the synchronization recovery time. Methods of synchronization parameter selection are based on the analysis of correlation of these two indicators.

TMI synchronization systems are described in such works as [1–4]. They are based on transmission of the telemetry stream as random data over the communication channel with noise, model of which allows for only the occasional inversions. This paper describes the experiments carried out by transmitting the telemetry stream containing the real telemetry data, generated in the IRIG-106 standard [8], over the communication channel with noise, the model of which allows for not only the occasional inversions, but also for the occasional missing bits [9]. This kind of errors significantly affects the quality of the frame synchronization in the TMI stream. Usefulness of the IRIG-106 standard is proved by its wide use in the aerospace industry.

Due to the fact that the actual telemetry data used in the experiments can affect the quality of solving the proper detection problem of the synchronization code in the stream, the experimental results may differ from those obtained theoretically, but it is shown that the best results are obtained in the experiments with the same selection of synchronizer parameters as for the best theoretical results.

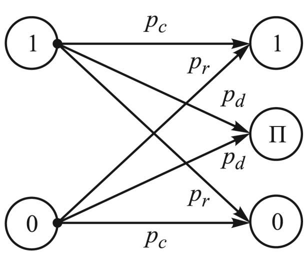


**Рис. 4. Model of symmetrical binary channel with missing bits ($p_c + p_r + p_d = 1$)**

Fig. 4 shows a model of the communication channel, allowing for random inversion and missing bits: $p_c$ — is the probability of correct bit transmission (0 or 1), $p_r$ — is the probability of bit inversion during transmission ($0 \to 1, 1 \to 0$), $p_d$ — is the possibility of missing the current bit (loss of bit 0 or 1).

To ensure the frame synchronization, one of 18 markers listed in the IRIG-106 standard is selected. The selected marker is used as the synchronization code and is added to each frame [8]. The list of markers is shown in Table 1.

Table 1

**Standard synchronization codes of TMI in the IRIG-106 standard**

| Optimal frame synchronization codes of TMI in the IRIG-106 standard | |
|---|---|
| Code length | Code format |
| 16 | 111 0101110010000 |
| 17 | 111 10011010100000 |
| 18 | 111 100110101000000 |
| 19 | 111 1100110010100000 |
| 20 | 111 01101111000100000 |
| 21 | 111 011101001011000000 |
| 22 | 111 1001101101010000000 |
| 23 | 111 10101110011010000000 |
| 24 | 111 110101111001100100000 |
| 25 | 111 1100101101110001000000 |
| 26 | 111 11010011010110011000000 |
| 27 | 111 110101101001100110000000 |
| 28 | 111 1010111100101100110000000 |
| 29 | 111 10101111001100110100000000 |
| 30 | 111 110101111001100110100000000 |
| 31 | 111 1111001101111101010000100000 |
| 32 | 111 11110011010110010100001000000 |
| 33 | 111 110111010011101001010010011000 |

**Preparing data for the experiments.** Digitized analog sensory data were included in the frame of telemetry data. The sensors measured typical parameters for the telemetry system: temperature, pressure, positional values. These parameters were obtained in the laboratory, examples of the signals are shown in Fig. 5, *a*. The frame structure shown in Fig. 5, *b* was developed for the experiments, the test telemetry data bitstream was formed on its basis.

A frame contains 14 channels. Digitized analog sensor readings are transmitted over each channel. The frame also contains service information, which provides frame synchronization in the telemetry stream. The service information of the frame is composed of the selected synchronization code (the marker), and the registration time in the IRIG-106 standard [8]. The frame stream to be used in the experiments was formed with the help of a telemetry data simulator [10].

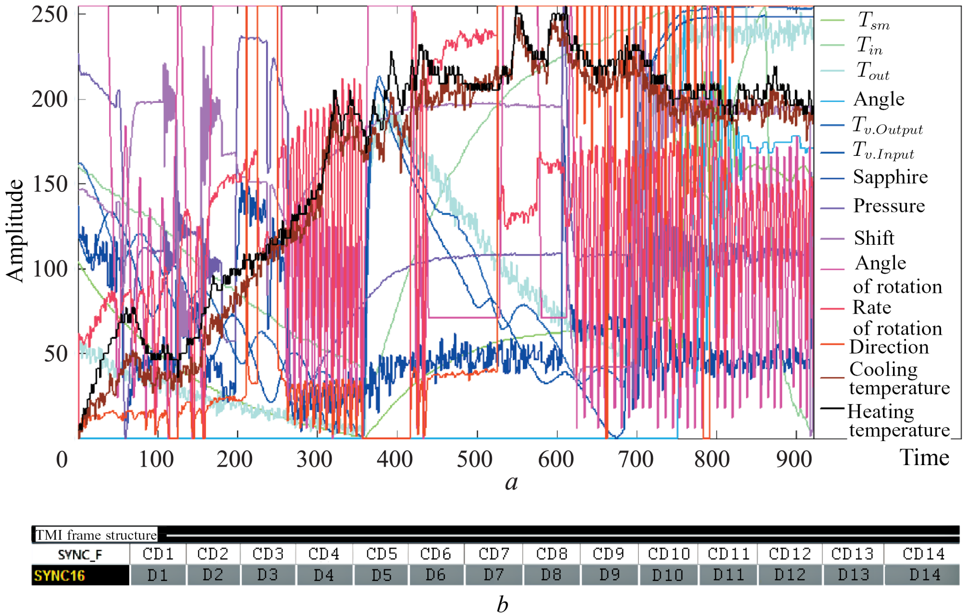


**Fig. 5. Telemetry parameters (*a*) and telemetry frame structure (*б*):**
D.W. — is a data word, D1:D14 — are samples of the signals shown in figure (*a*)

The telemetry word length of a frame is 8 bits. A quantized sensor sample in the range of 0...255 is stored in the word. The service information consists of the marker and 48 bits being used to store the time in the IRIG-106 standard. The total length of the reduced frame (see. Fig. 5, *b*) is 176 bits.

**Analysis of the synchronizer in the "Search" mode.** In the "Search" mode, the synchronization code is considered to be detected, if comparing $n$ successive message symbols with the known synchronization code, the number of mismatches doesn't exceed a threshold value $\varepsilon_s$. The probability of correct detection of the synchronization code in the "Search" mode at an acceptable threshold $\varepsilon_s$ in the presence of noise $p_r \neq 0$ can be written as

$$p_{cs} = \sum_{i=0}^{\varepsilon_s} \binom{n}{i} (1 - p_r)^{n-i} \, p_r^i, \tag{3}$$

where $n$ is the length of the synchronization code; $\binom{n}{i} = \dfrac{n!}{i!\,(n-i)!}$;

$$p_{fs} = \frac{\sum_{i=0}^{\varepsilon_s} \binom{n}{i}}{2^n} \tag{4}$$

is the probability of the false synchronization code emerging among the message characters in the "Search" mode with an acceptable number of errors $\varepsilon_s$.

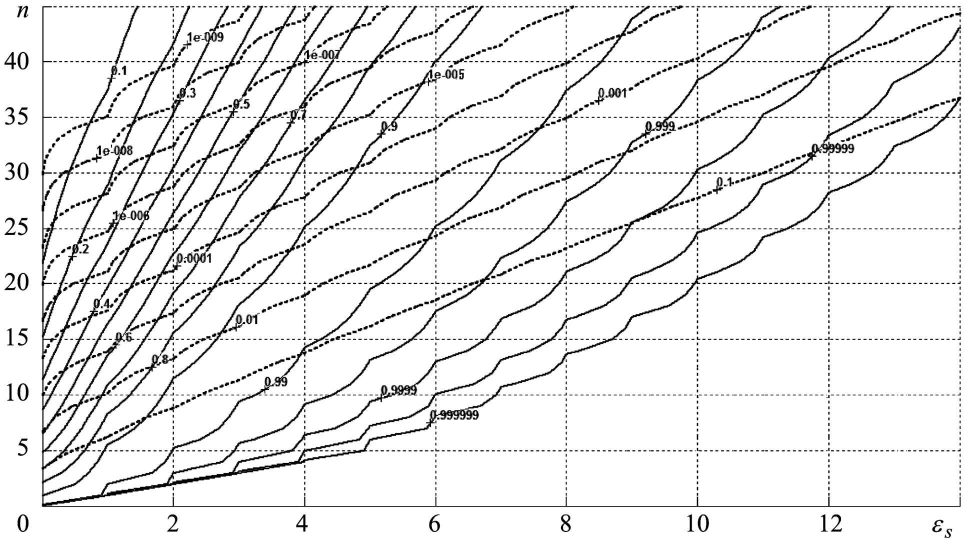


**Fig. 6. Values $p_{cs}$ and $p_{fs}$ at $p_r = 0,1$ and at different values of $n$ and $\varepsilon_s$**

In Fig. 6 the curves intersect at certain values of $n$ and $\varepsilon_s$. Thus, the selection of $n$ and $\varepsilon_s$ affects the values $p_{cs}$ and $p_{fs}$. In case of false detection of $n$-bit sequence of the synchronization code in the data frame space, the length of which is $b$bits, the probability of false synchronization is calculated by the formula

$$F = 1 - (1 - p_{fs})^b, \tag{5}$$

where

$$b = N_f - (n) - (n - 1), \tag{6}$$

$N_f$ is the total length of the frame, $n$ — is the length of the synchronization code (Fig. 7).

The probability of making the right decision in the "Search" mode can be written as:

$$T = \frac{p_{cs}(1 - F)}{F + p_{cs}(1 - F)}; \tag{7}$$

the probability of making a wrong decision in the "Search" mode has the following form

$$W = \frac{F}{F + p_{cs}(1 - F)}, \tag{8}$$

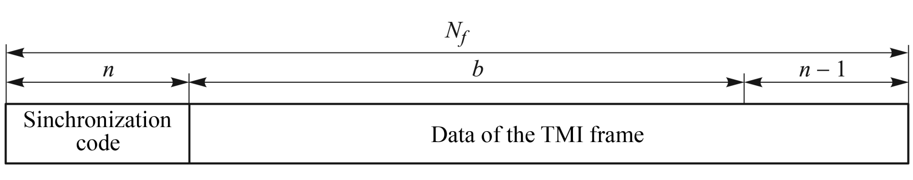


**Fig. 7. TMI frame structure**

where

$$W + T = 1. \tag{9}$$

The average number of frames required for making the right decision in the “Search” mode is

$$w_s = \frac{1}{p_{cs}\,(1 - F)}, \tag{10}$$

where a value $w_s$ should be as small as possible.

Table 2 shows values $w_s$ when $p_r = 0{,}1$, $n = 16$, $b = 145$ and at different values $\varepsilon_s$.

Table 2

**Values $w_s$ in the “Search” mode for $p_r = 0.1$**

| $p_r$ | $n$ | $\varepsilon_s$ | $b$ | $p_{cs}$ | $p_{fs}$ | $F$ | $T$ | $W$ | $w_s$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.1 | 16 | 0 | 145 | 0.185 | $1.53\cdot10^{-5}$ | 0.002 | 0.988 | 0.011 | 5.408 |
| 0.1 | 16 | 1 | 145 | 0.514 | 0.0002 | 0.036 | 0.930 | 0.069 | 2.017 |
| 0.1 | 16 | 2 | 145 | 0.789 | 0.002 | 0.261 | 0.690 | 0.309 | 1.716 |
| 0.1 | 16 | 3 | 145 | 0.931 | 0.010 | 0.787 | 0.200 | 0.799 | 5.059 |
| 0.1 | 16 | 4 | 145 | 0.982 | 0.038 | 0.996 | 0.003 | 0.996 | 297.625 |
| 0.1 | 16 | 5 | 145 | 0.996 | 0.105 | 1 | $1.02\cdot10^{-7}$ | 1 | 9796884 |
| 0.1 | 16 | 6 | 145 | 0.999 | 0.227 | 1 | $1.11\cdot10^{-16}$ | 1 | $9.01\cdot10^{15}$ |

From these data it follows that for $\varepsilon_s = 0$ the value $T$ is maximum, but $w_s$ is also of great importance. Therefore, it is required to select a set $ST$ consisting of some values $T$ close to the maximum value, in this case it is $ST = \{0.988; 0.930\}$ when $\varepsilon_s = \{0, 1\}$, and then to select the value $\varepsilon_s$ for which $w_s$ is minimal. In the above example $\varepsilon_s = 1$ is selected, for which $T = 0.930$ and $w_s = 2.017$.

The criterion for the selection of the parameter $\varepsilon_s$ in the “Search” mode is:

$$\varepsilon_s = \arg\max_{\varepsilon_s}\{T\,(\varepsilon_s) = \max\,(T)\,,\;\; w_s(\varepsilon_s) = \min\,(w_s)\}. \tag{11}$$

In Table 3. values $w_s$ with $p_r = 10^{-2}$and $p_r = 10^{-3}$ are given additionally to illustrate the dependencies of the parameters.

The results of the experiments with telemetry data in the IRIG-106 format are shown in Table 4. The experiments were performed for $p_r = 0.1$ and for different probability values of bit missing $p_d = \{0, 10^{-4}, 10^{-3}, 10^{-2}\}$. The synchronization code of the IRIG-106 standard with the 16-bit length was used.

Table 3

**Values $w_s$ in the "Search" mode at $p_r = 10^{-2}$ and $p_r = 10^{-3}$**

| $n$ | $\varepsilon_s$ | $b$ | $p_{cs}$ | $p_{fs}$ | $F$ | $T$ | $W$ | $w_s$ |
|---|---|---|---|---|---|---|---|---|
| $p_r = 10^{-2}$ | | | | | | | | |
| 16 | 0 | 145 | 0.851 | $1.53{\cdot}10^{-5}$ | 0.002 | 0.997 | 0.002 | 1.177 |
| 16 | 1 | 145 | 0.989 | 0.0002 | 0.036 | 0.962 | 0.037 | 1.049 |
| 16 | 2 | 145 | 0.999 | 0.002 | 0.261 | 0.738 | 0.261 | 1.355 |
| 16 | 3 | 145 | 0.999 | 0.010 | 0.787 | 0.212 | 0.787 | 4.713 |
| 16 | 4 | 145 | 1 | 0.0384 | 0.996 | 0.003 | 0.996 | 292.564 |
| 16 | 5 | 145 | 1 | 0.105 | 1 | $1.02{\cdot}10^{-7}$ | 1 | 9764587 |
| 16 | 6 | 145 | 1 | 0.227 | 1 | $1.11{\cdot}10^{-16}$ | 1 | $9.01{\cdot}10^{15}$ |
| $p_r = 10^{-3}$ | | | | | | | | |
| 16 | 0 | 145 | 0.9849 | $1.53{\cdot}10^{-5}$ | 0.002 | 0.997 | 0.002 | 1.018 |
| 16 | 1 | 145 | 0.999 | 0.0002 | 0.036 | 0.963 | 0.036 | 1.038 |
| 16 | 2 | 145 | 0.999 | 0.002 | 0.261 | 0.738 | 0.261 | 1.354 |
| 16 | 3 | 145 | 1 | 0.010 | 0.787 | 0.212 | 0.787 | 4.713 |
| 16 | 4 | 145 | 1 | 0.038 | 0.996 | 0.003 | 0.996 | 292.564 |
| 16 | 5 | 145 | 1 | 0.105 | 1 | $1.02{\cdot}10^{-7}$ | 1 | 9764587 |
| 16 | 6 | 145 | 1 | 0.227 | 1 | $1.11{\cdot}10^{-16}$ | 1 | $9.01{\cdot}10^{15}$ |

Table 4

**Value $w_s$ in the "Search" state**

<table>
<tr><td rowspan="4">$p_r = 0.1$</td><td rowspan="2">$\varepsilon_s$</td><td>Theoretical values $w_s$</td><td colspan="4">Experimental values $w_s$</td></tr>
<tr><td>$p_d = 0$</td><td>$p_d = 0$</td><td>$p_d = 10^{-4}$</td><td>$p_d = 10^{-3}$</td><td>$p_d = 10^{-2}$</td></tr>
<tr><td>0</td><td>5.408549</td><td>5.15</td><td>5.4</td><td>4.4</td><td>5</td></tr>
<tr><td>1</td><td>2.017249</td><td>1.69</td><td>2.12</td><td>1.76</td><td>1.84</td></tr>
</table>

It should be noted that the parameters of the synchronizer calculated from the experimental data match the theoretical ones.

For the considered case in the "Search" mode it is recommended to select $\varepsilon_s = 1$.

**Analysis of the synchronizer in the "Test" mode.** Upon detecting the synchronization code in the "Search" mode, the synchronizer enters the "Test" mode. If the number of the detected successive markers reaches a predetermined value in the "Test" mode, the system switches to the "Capture" mode.

Let

$$R = \frac{\textit{probability of exitting the "Search" and "Test" modes with the false synchronization decision after } \omega_v \textit{ frames}}{\textit{"Search" and "Test" modes with the correct synchronization decision after } \omega_v \textit{ frames}},$$

$$R = \frac{W}{T} \left( \frac{p_{fv}}{p_{cv}} \right)^{w_v}, \tag{12}$$

where $p_{cv}$ — is the probability of correct detection of the synchronization code in the "Test" mode at the threshold value $\varepsilon_v$, and $p_{fv}$ — is the probability of false detection of the synchronization code in the message symbols in the "Test" mode at $\varepsilon_v$. The value $R$ should be as small as possible.

Table 5 shows the values $R$ at the selected value $\varepsilon_s$ and at different $\varepsilon_v$ and $w_v$.

Table 5

**Values *R* in the "Test" mode**

| Values $R$ at $p_r = 0.1$, $n = 16$, $b = 145$ and $\varepsilon_s = 1$ | | | | | |
|---|---|---|---|---|---|
| $\varepsilon_v$ | $w_v = 1$ | $w_v = 2$ | $w_v = 3$ | $w_v = 4$ | $w_v = 5$ |
| 0 | $6.13 \cdot 10^{-6}$ | $5.05 \cdot 10^{-10}$ | $4.158 \cdot 10^{-14}$ | $3.424 \cdot 10^{-18}$ | $2.819 \cdot 10^{-22}$ |
| 1 | $3.75 \cdot 10^{-5}$ | $1.89 \cdot 10^{-8}$ | $9.532 \cdot 10^{-12}$ | $4.803 \cdot 10^{-15}$ | $2.420 \cdot 10^{-18}$ |
| 2 | 0.000197 | $5.22 \cdot 10^{-7}$ | $1.383 \cdot 10^{-9}$ | $3.665 \cdot 10^{-12}$ | $9.708 \cdot 10^{-15}$ |
| 3 | 0.00085 | $9.71 \cdot 10^{-6}$ | $1.108 \cdot 10^{-7}$ | $1.265 \cdot 10^{-9}$ | $1.444 \cdot 10^{-11}$ |
| 4 | 0.00291 | 0.000114 | $4.441 \cdot 10^{-6}$ | $1.735 \cdot 10^{-7}$ | $6.780 \cdot 10^{-9}$ |
| 5 | 0.00785 | 0.000827 | $8.721 \cdot 10^{-5}$ | $9.192 \cdot 10^{-6}$ | $9.689 \cdot 10^{-7}$ |
| 6 | 0.016933 | 0.00385 | 0.000875 | 0.000199 | $4.524 \cdot 10^{-5}$ |

In Table 5, for example, the pairs $(\varepsilon_v, w_v)$ are selected for the synchronization system in such a way that at the required value $R_T$ the value $R$ does not exceed the predetermined $R_T$ ($R \le R_T$).

In this example, at the given acceptable probability value $R_T = 10^{-6}$, $R = \{5.22 \cdot 10^{-7}; 1.108 \cdot 10^{-7}; 1.735 \cdot 10^{-7}; 9.689 \times 10^{-7}\}$ are selected for the pair values $(\varepsilon_v, w_v) = \{(2,2), (3,3), (4,4), (5,5)\}$, respectively.

The probability of outcoming from the states "Search" and "Test" in the case of correct detection of the synchronization code is as follows:

$$p_{tc} = \left( p_{cs} (1 - F) \frac{(1 - q^{w_s})}{(1 - q)} \right) (p_{cv})^{w_v}, \tag{13}$$

where

$$q = (1 - p_{cs})(1 - F). \tag{14}$$

Table 6 shows the values $p_{tc}$ for the chosen value $\varepsilon_s$ and different $\varepsilon_v$ and $w_v$.

The values $p_{tc} = \{0.454; 0.602; 0.681; 0.718\}$ correspond to the selected values $R$. It should be noted that while increasing the value of the pair $(\varepsilon_v, w_v)$ from $(2,2)$ to $(3,3)$ it increases $p_{tc}$ (from 0.602 to 0.454) by 0.148, but while increasing it from the value $(3,3)$ to $(4,4)$, it increases $p_{tc}$ only

Table 6

**Values $p_{tc}$ in the "Test" mode**

| Values $p_{tc}$ at $p_r = 0.1$, $n = 16$, $b = 145$ и $\varepsilon_s = 1$ | | | | | |
|---|---|---|---|---|---|
| $\varepsilon_v$ | $w_v = 1$ | $w_v = 2$ | $w_v = 3$ | $w_v = 4$ | $w_v = 5$ |
| 0 | 0.135 | 0.025 | 0.004 | 0.0008 | 0.0001 |
| 1 | 0.375 | 0.193 | 0.099 | 0.051 | 0.026 |
| 2 | 0.576 | 0.454 | 0.358 | 0.283 | 0.223 |
| 3 | 0.680 | 0.633 | 0.602 | 0.549 | 0.512 |
| 4 | 0.717 | 0.705 | 0.693 | 0.681 | 0.670 |
| 5 | 0.727 | 0.725 | 0.722 | 0.720 | 0.718 |
| 6 | 0.729 | 0.729 | 0.728 | 0.728 | 0.728 |

by 0.079, and the increase from the value $(4, 4)$ to $(5, 5)$, it increases $p_{tc}$ by 0.038, etc. Based on this, we selected $(\varepsilon_v, w_v) = (3,\ 3)$.

Thus, the selection of parameters $(\varepsilon_v, w_v)$ for "Test" mode consists of two steps. First, the required value $R_T$ is given and two sets $m_1, m_2$ are selected according the following conditions:

$$m_1 = \{(\varepsilon_v, w_v) : R\,(\varepsilon_v, w_v) \le R_T\}; \tag{15}$$

$$m_2 = \{p_{tc}\,\{m_1\}\} = \{p_{tc1}\,(m_1\,\{1\})\,,\ p_{tc2}\,(m_1\,\{2\})\,, \ldots, p_{tcl}\,(m_1\,\{l\})\}\,, \tag{16}$$

where $l$ is the number of elements $m_1$.

Then, parameters $(\varepsilon_v, w_v)$ for the "Test" mode are calculated by the formula

$$(\varepsilon_v, w_v) = \arg\max_p\{d_p : p_{tc}(\varepsilon_v, w_v) \in m_2, \varepsilon_v > \varepsilon_s\}, \tag{17}$$

where $d_p = p_{tci} - p_{tci-1},\ \ i = 2, \ldots, l$.

The results of the experiments with telemetry data are shown in Table 7. The experiments were performed at $p_r = 0.1$, the selected value $\varepsilon_s$, and for different values of the probability of bit missing $p_d = \{0, 10^{-4}, 10^{-3}, 10^{-2}\}$ and for different values $\varepsilon_v$ and $w_v$.

Table 7

**Parameters $\varepsilon_v$ and $w_v$ in the "Test" state**

| Parameters | Theoretical values $p_{tc}$ | Experimental values $p_{tc}$ | | | |
|---|---|---|---|---|---|
| | $p_d = 0$ | $p_d = 0$ | $p_d = 10^{-4}$ | $p_d = 10^{-3}$ | $p_d = 10^{-2}$ |
| $\varepsilon_v = 2, w_v = 2$ | 0.454762 | 0.7972 | 0.7777 | 0.6613 | 0.1203 |
| $\varepsilon_v = 3, w_v = 3$ | 0.60248714 | 0.9308 | 0.923 | 0.7916 | 0.124 |
| $\varepsilon_v = 4, w_v = 4$ | 0.68165127 | 0.9876 | 0.967 | 0.8112 | — |
| $\varepsilon_v = 5, w_v = 5$ | 0.718099482 | 0.9900 | 0.9752 | 0.838 | — |

The experimental values of the synchronizer parameters $(\varepsilon_v, w_v)$ also match the theoretical ones.

For the case under consideration, in the "Test" mode, it is recommended to select the parameter values $\varepsilon_v = 3$ and $w_v = 3$.

**Analysis of the synchronizer in the "Capture" mode.** In the "Capture" state, the synchronizer controls only the group of $n$ characters in the position where the synchronization code should be placed. If the number of errors in code checking exceeds the threshold $\varepsilon_l$, the synchronizer returns to the "Test" state.

The performance of the synchronizer in the "Capture" mode is estimated by the relative value of information loss $DL$ caused by any synchronization failure in the presence of noise. The value $DL$ is calculated using the formula

$$DL = \frac{L}{L+K}\,\%, \tag{18}$$

where

$$L = \left(\frac{1/(1-q)+w_v}{p_{tc}}\right) + (JR) \tag{19}$$

— is the average time required for correct detection of the synchronization code;

$$J = \frac{1}{1-p_{fl}} \tag{20}$$

— is the average number of synchronization codes necessary for making a decision on erroneous detection of the synchronization code in false synchronization ($p_{fl}$ — is the probability of the false synchronization code in the "Capture" mode at the threshold value $\varepsilon_l$); $q, R, w_v$ and $p_{tc}$ are calculated in the "Test" mode;

$$K = \frac{1}{1-p_{cl}} \tag{21}$$

Table 8

**Values $DL$, % in the "Capture" synchronization state**

| Values $DL$, %, at $p_r = 0{,}1$, $n = 16$, $b = 145$, $\varepsilon_s = 1$, $\varepsilon_v = 3$ и $w_v = 3$ | | | | |
|---|---|---|---|---|
| $\varepsilon_l$ | $J$ | $K$ | $L$ | $DL$, % |
| 0 | 1.000015 | 1.227 | 8.263 | 87.066 |
| 1 | 1.000259 | 2.060 | 8.263 | 80.039 |
| 2 | 1.002095 | 4.744 | 8.263 | 63.523 |
| 3 | 1.01075 | 14.618 | 8.263 | 36.113 |
| 4 | 1.03994 | 58.809 | 8.263 | 12.319 |
| 5 | 1.117389 | 303.328 | 8.263 | 2.651 |
| 6 | 1.294078 | 1982.025 | 8.263 | 0.415 |

Table 9

**Values $DL$, % in the "Capture" mode**

| $\varepsilon_l$ | Values $DL$ at $p_r = 0, 1$, $n = 16$, $\varepsilon_s = 1$, $\varepsilon_v = 3$ and $w_v = 3$ | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Theoretical values | | | Theoretical values | | | | | | | | | | | |
| | $p_d = 0$ | | | $p_d = 0$ | | | $p_d = 10^{-4}$ | | | $p_d = 10^{-3}$ | | | $p_d = 10^{-2}$ | | |
| | $K$ | $L$ | $DL$ | $K$ | $L$ | $DL$ | $K$ | $L$ | $DL$ | $K$ | $L$ | $DL$ | $K$ | $L$ | $DL$ |
| 3 | 14.618 | 8.263 | 36.11 | 60.687 | 5.8 | 8.723 | 24.44 | 6.8 | 21.76 | 8.6 | 9.2 | 51.69 | 307.4 | 295 | 48.97 |
| 4 | 58.80 | 8.263 | 12.319 | 357.75 | 5.8 | 1.595 | 28.8 | 6.8 | 19.1 | 8.84 | 9.2 | 51 | 307.48 | 295 | 48.96 |
| 5 | 303.32 | 8.263 | 2.6519 | 643.5 | 5.8 | 0.893 | 29.04 | 6.8 | 18.97 | 8.92 | 9.2 | 50.77 | 307.48 | 295 | 48.96 |
| 6 | 1982.02 | 8.263 | 0.415 | 881.602 | 5.8 | 0.653 | 29.24 | 6.8 | 18.86 | 9.04 | 9.2 | 50.44 | 307.68 | 295 | 48.95 |

— is the average number of synchronization codes required to make a decision about the absence of the synchronization code ($p_{cl}$ — is the probability of correct detection of the synchronization code in the "Capture" state at the threshold value $\varepsilon_l$).

From Table 8 it is possible to select the value $\varepsilon_l$ at which the calculated value $DL \le DL_{\text{T}}$. For example, if the desired value is $DL_{\text{T}} = 1\,\%$, then $DL = 0.415$ can be selected and the threshold value $\varepsilon_l = 6$ is considered to be the best one.

Therefore, the criterion for selecting $\varepsilon_l$ of the "Capture" mode is as follows:

$$\varepsilon_l = \arg\max_{\varepsilon_l}\{DL : DL(\varepsilon_l) \le DL_{\text{T}}\}, \tag{22}$$

where $DL_{\text{T}}$ is the required minimum value of the information loss.

The results of the experiments with telemetry data (IRIG-106) are shown in Table 9. The experiments were performed at $p_r = 0.1$, the selected values $\varepsilon_s, \varepsilon_v, w_v$ and for different values of the probability of bit missing $p_d = \{0, 10^{-4}, 10^{-3}, 10^{-2}\}$ and $\varepsilon_l$.

In the case under consideration, it is recommended to select the parameter value $\varepsilon_l = 6$ for the "Capture" synchronization mode.

**Conclusions.** The theoretical model of the frame synchronization of the digital telemetry data stream is considered. The system is represented as a final state machine with three states. The basic model parameters determining the conditions of transition between the synchronizer states are given. The methods of selecting such synchronizer parameters are specified. The experiments with real telemetry data of the IRIG-106 format are carried out. A comparative analysis of the obtained results with theoretical estimates of the parameters of the synchronization system is performed. It shows that the proposed method of selecting synchronizator parameters leads to the same results both for the theoretical TMI stream model and for the real telemetry data, despite the difference in quantitative estimates of the intermediate results.

## REFERENCES


[1] Vil'yard M.V. Russ. ed.: Nekotorye voprosy sinkhronizatsii v tsifrovykh sistemakh: Dostizhenie v oblasti telemetrii [Some issues of synchronization in digital systems (translated by L.S. Gelbershteyn): Achievement in the field of telemetry]. Moscow, Mir Publ., 1970, pp. 58–73.

[2] Techniques for Synchronizing Pulse-Code-Modulated Telemetry. *Report the theoretical and experimental investigation of synchronization methods for PCM telemetry*. California: naval ordnance laboratory corona. 1963. 111 p.

[3] Prasad G., Vasantha N. Design and implementation of multi-channel frame synchronization in FPGA. *International journal of electronics and communication engineering & technology* (*IJECET*), 2013, vol. 4, pp. 189–199.

[4] Introduction to PCM Telemetering Systems. 2nd Edition. Stephen Horan, ed. CRC Press LLC, 2002. 446 p.
[5] Massey J.L. Optimum frame synchronization. *IEEE transactions on communications*, 1972, vol. 20, no. 2 pp. 115–119.
[6] Stiffler Jack J. Self-synchronizing binary telemetry codes: PhD Dissertation. California, Institute of technology, 1962, 156 p.
[7] Chiani M., Martini M.G. Analysis of Optimum Frame Synchronization Based on Periodically Embedded Sync Words. *IEEE transactions on communications*, 2007, vol. 55, no. 11, pp. 2056–2060.
[8] Telemetry Standards, IRIG Standard 106-13. New Mexico, Secretariat Range Commanders Council US Army White Sand Missile Range, 2013. Availlable at: http://www.irig106.org/docs/106-13/ (accessed 10.12.2013).
[9] El'shafei M.A. Method of antinoise coding telemetry information correcting bit inversion and omissions. *Jelektr. Nauchno-Tehn. izd "Nauka i obrazovanie"* [El. Sc.-Tech. Publ. "Science and Education"], 2014, no. 10, pp. 328–346 (in Russ.).
[10] El'shafei M.A., Sidyakin I.M. Simulation of telemetering data transmission in the noisy channel. *Jelektr. nauchno-tehn. izd. "Inzhenernyy vestnik"* [El. Sc.-Techn. Publ. Eng. bulletin], 2014, no. 1, pp. 38–51 (in Russ.).

## Contributors

Sidyakin I.M. — Ph.D. (Eng.), Associate Professor, Department of Information Systems and Telecommunications, Bauman Moscow State Technical University, author of over 10 research publications in the field of systems of telemetry data recording.
Bauman Moscow State Technical University, 2-ya Baumanskaya ul. 5, Moscow, 105005 Russian Federation.

Elshafey Mohamed Abdelmoneim Taha — Ph.D. student, Department of Information Systems and Telecommunications, Bauman Moscow State Technical University, author of 4 research publications in the field of systems of telemetry data processing.
Bauman Moscow State Technical University, 2-ya Baumanskaya ul. 5, Moscow, 105005 Russian Federation.

***The translation of this article from Russian into English is done by E.A. Yudacheva, senior lecturer, Linguistics Department, Bauman Moscow State Technical University under the general editorship of N.N. Nikolaeva, Ph.D. (Philol.), Associate Professor, Linguistics Department, Bauman Moscow State Technical University.***