Method of processing a distorted signal of a MODE-S format from an airplane transponder

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Abstract. The article describes a rather efficient method for processing a signal of the MODE-S format, which has distortions in amplitude and timing parameters. Distortion can be caused by various factors, such as the presence of interference in the air and the reflection of the signal, the impact of various electromagnetic fields. Receiving and further processing of the signal with distortion can not be performed correctly using simple algorithms that do not take into account these features. The method described below allows processing part of the distorted signals correctly and increasing the total number of decoded signals. MODE-S is part of a large air traffic processing and monitoring system. Today, a large number of civil aircraft are equipped with receivers and transponders of signal in MODE-S format. This system allows identifying aircraft and obtaining the necessary information about the flight in a simple way. MODE-S works on the question-answer principle. The so-called “question” is sent to the aircraft in order to obtain specific information about the flight. The aircraft accepts this “question”, analyzes its format and, depending on it, sends an “answer” back. It is very important to process correctly as many signals as possible, because the information in them is important and must be received on time.

1. Introduction

Currently, it is obvious that aircraft are equipped with a large number of electronic equipment [1]. These can be flight control systems, stabilization of the aircraft, pilot assistance systems, and many others. Also there presents the aircraft identification system. This system allows identifying the aircraft during the flight, which allows avoiding certain problems with flight safety. Of course, these systems operate according to international standards [2]. This allows identifying the aircraft even when the flight passes over the territories of several states.

The process of identification is not the only, but the most important function that this system performs. Obviously, some time ago there used to be a simple need to identify an aircraft by the simple principle of “friend or foe”. As time went on, systems evolved more and more. Now these systems can provide not only the identifier of an aircraft, but also the parameters of flight. The coordinates of an aircraft, its speed, ICAO address, altitude and some other information can be obtained from the aircraft thanks to the ADS-B systems and the MODE-S format. This system is the result of the development of aircraft identification systems [3].

The main principle of information sharing was not unchanged [4]. The request is sent from air traffic control centers, airports or other aircraft at a frequency of 1030 MHz. It can be of different types depending on the information is in need to get at the moment. The receiver located on board of an aircraft handles this request. Depending on its type, a transponder sends back to the Earth or other aircraft the
necessary information at a frequency of 1090 MHz. Answers can also be of different types. The two main ones differ in length and have 56 or 112 bits of information.

2. Problem statement
According to international documentation, answers are sent at a frequency of 1090 MHz. The information in them is encoded by signal drops from 0 to 1 and vice versa from 1 to 0 (Manchester coding). 1 μs is given for each bit of information (the drop) [5]. Thus, 0.5 μs is obtained at the moment of the presence of a pulse - 1 and at the time of the absence of an impulse – 0. An ADC with a frequency of 16 MHz is used to convert the signal to digital form and its further processing to the FPGA. For the moments of the presence and absence of a pulse described above, there are 8 values from the ADC for each bit [6].

Processing of a real signal arises the main problems of its decoding [7]. The first is the absence of a clear transition from one level to another (0-1; 1-0). The theoretical signal should have a strict rectangular shape with a clear transition point. The real signal looks more like a sinusoidal function, which makes it difficult to determine the transition. Accordingly, it is necessary to invent a method for determining the difference that occurred in the current signal fragment, which is responsible for the information bit.

The second problem is the presence of signal distortion in timing parameters. Described above 1 μs per bit of information does not always correspond to the actual signal parameters. Timing distortions can be up to 10% of the duration of the moment of presence and absence of a pulse can be observed. Accordingly, 8 values from the ADC (also points) may not correspond to the specified moments. Depending on the degree of distortion in reality, the number of points can be from 7 to 9. This distortion is battery-like. If a small number of bits were subjected to distortion, for example, from 1 to 4, then such time shifts will not be critical and this signal can be decoded correctly without any problems. A larger number of distorted bits will introduce serious shifts relative to the decoder grid, consisting of 8 processed points for each half of bits, which will lead to incorrect decoding of the signal (Figure 1). There is a problem of determining the attribute, by which it will be possible to split the received signal into 7, 8 or 9 points for each half of the bit, respectively.

![Figure 1. Problem of timing distortions of signal](image)

The third problem is the signal distortion in amplitude. Few number of bits contain distortion data, but they can be presented. The simplest example of this distortion is the reflection of a fragment of the signal containing 1 by the mirror method. That is, the peak of the signal fragment is not directed upwards, but downwards, which naturally leads to incorrect decoding of the message and loss of information (Figure 2). This feature must be considered when searching for a way to determine a bit of information.
3. Method of decoding distorted signal

Solving of the problems described above is not a trivial task and does not have a specific solution for each situation [8]. The search for a solution for each of the described tasks was performed heuristically based on the obtained parameters of the real signal and their analysis.

The solutions of the first and third tasks complement each other. It is necessary to find a way to determine the value of a bit of information from the corresponding signal fragment, taking into account amplitude distortion. The most appropriate method for this was chosen by summing the values of the ADC with their further comparison with each other. For each half of the current bit, the sum of its values taken from the ADC is found, and the comparison will show which of the amounts is greater, in that half of the bit the unit is contained and the difference that occurs on the signal fragment is determined:

\[ s_1 = \sum_{i=1}^{n} a_i \]
\[ s_2 = \sum_{i=1}^{n} a_i \]
\[ \text{bit} = s_1 > s_2 \]

In the process of finding a way to determine the value of the current bit, other methods were also tested, namely the comparison of the extremes of the two fragments. When comparing the maxima of the signal fragments, signals that were not decoded using the comparison of sums were decoded. A comparison of the minima was also used, which gave other results. It was decided to use all three methods to achieve the biggest possible number of decoded signals. For each signal fragment, the sum of values taken from the ADC is calculated, the maximum and minimum are found. Then the border values are calculated, with respect to which one or another method of determining the value of the bit will be used:

\[ \text{border} = (\max_1 + \min_1 + \max_2 + \min_2) \gg 3 \]
\[ \Delta max = |\max_1 - \max_2| \]
\[ \Delta min = |\min_1 - \min_2| \]

The definition of the bit value is as follows. If \( \Delta max \) and \( \Delta min \) greater then \( \text{border} \), the sums comparison will be used. Otherwise \( \Delta max \) and \( \Delta min \), are compared with each other, if \( \Delta max \) is the biggest, then the value of a bit is defined as:

\[ \text{bit} = \max_1 > \max_2 \]
Otherwise, a minimum comparison is used:

\[ bit = \min_1 > \min_2 \]  \hspace{1cm} (8)

Next, it was necessary to choose a sign by which it would be possible to divide the signal into fragments for further work with them. While analyzing the values taken from the ADC, the following feature was noted. The bigger the differential occurs, the greater the difference in values between adjacent points. Thus, an algorithm based on this feature was developed. Between the points lying on the border of half a bit, namely, 6, 7, 8, 9, the difference in their values is calculated:

\[ \Delta_{67} = |a_6 - a_7| \]  \hspace{1cm} (9)

\[ \Delta_{78} = |a_7 - a_8| \]  \hspace{1cm} (10)

\[ \Delta_{89} = |a_8 - a_9| \]  \hspace{1cm} (11)

Further, the maximum is selected from these values, on the basis of which the length of the first half of the bit was determined. If \( \Delta_{67} \) is the biggest one, then the length becomes 7, if \( \Delta_{78} \), then length turns 8 and if \( \Delta_{89} \), then length becomes 9. Obviously, the determination of the length of the second half of the bit is performed only after the length of the first half has been calculated. Calculate the difference in values between the next points: 13, 14, 15, 16, 17, 18.

\[ \Delta_{1314} = |a_{13} - a_{14}| \]  \hspace{1cm} (12)

\[ \Delta_{1415} = |a_{14} - a_{15}| \]  \hspace{1cm} (13)

\[ \Delta_{1516} = |a_{15} - a_{16}| \]  \hspace{1cm} (14)

\[ \Delta_{1617} = |a_{16} - a_{17}| \]  \hspace{1cm} (15)

\[ \Delta_{1718} = |a_{17} - a_{18}| \]  \hspace{1cm} (16)

If the length of the first half is 7, then the maximum is sought among \( \Delta_{1314}, \Delta_{1415}, \Delta_{1516}, \) and the length of the second half of the bit is also determined depending on it. If maximum \( \Delta_{1314} \), then the length is 7, if \( \Delta_{1415} \), then the length is equal 8, if \( \Delta_{1516} \), then the length is equal 9. If the length of the first half of a bit is 8 or 9, then the length of the second half is determined in a similar way, but other values are used for comparison. If the first half uses 8 points, then compare \( \Delta_{1415}, \Delta_{1516}, \Delta_{1617} \). If the length of the first half is 9, then in comparison are used \( \Delta_{1516}, \Delta_{1617}, \Delta_{1718} \).

Based on the algorithm described above, it is possible to get the following pairs of lengths: 7-7, 7-8, 7-9, 8-7, 8-8, 8-9, 9-7, 9-8, 9-9. These values fully correspond to possible temporal distortions. Using this algorithm for splitting signals allows getting into the middle of a differential, which was originally required from solving the second problem.

4. Realization and tests

The receiver of MODE-S signal is implemented on the FPGA Xilinx Spartan 6 XC6SLX150 [9]. It consists of several interconnected signal processing units; each of them performs its own function [10]. The block diagram of the device is presented in Figure 3.
Figure 3. Decoder scheme

Testing was conducted on a real broadcast. Two receivers took part in the tests; one of them used the usual decoding algorithm, which does not take into account possible signal distortions. The second receiver used the decoding algorithms described above. The test results are presented in the table below.

| Types of decoded signals | Simple decoding algorithm | Distortion tolerant algorithm | Result increase |
|--------------------------|---------------------------|-------------------------------|----------------|
| Mode S                   | 12436                     | 16580                         | 4144 (33%)     |
| Mode S 56 bit            | 4029                      | 5665                          | 1636 (40%)     |
| Mode S 112 bit           | 8407                      | 10915                         | 2508 (29%)     |
| Mode S CRC OK            | 12436                     | 16580                         | 4144 (33%)     |
| Mode S CRC bad           | 0                         | 0                             |                |

5. Conclusions

Based on the results of testing, it can be concluded that all the proposed methods for preprocessing distorted signals are quite effective and can significantly increase the number of correctly decoded signals. Approximately 25,000 gates of the Spartan 6 XC6SLX150 FPGA were required to implement the developed decoder. The implementation of the FPGA-based device allows processing signals in real time. This is extremely important for the specified subject area. Improving the transponder signal decoding subsystem is a strategic task, since the operation of all systems that ensure the safety of civil aircraft and other aircraft depends on it.

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