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Analysis and Optimization of Direct Sequence Spread Spectrum Scheme for an Unmanned Aerial Vehicle PPM Control Signal

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Abstract: Binary pulse-position modulated (PPM) control signal is widely used in remotely controlled unmanned aerial vehicles. It consists of data frames, which contain a synchronizing pulse followed by a number of shorter pulses equal to the number of channels N. In this paper we present analysis and optimization of direct sequence spread spectrum (DS-SS) scheme for PPM control signal protection. That scheme uses (N+1) pseudonoise (PN) sequences: one of them (PN_0) is assigned to the synchronizing pulse while the each of the remaining N sequences ($PN_1, PN_2, \ldots, PN_N$) corresponds to the appropriate channel. At the receiving side, the set of (N+1) passive correlators is used to detect respective PN sequences and to reconstruct data. One-level and two-level detection are considered. Threshold settings optimization is based on the Neyman-Pearson procedure. As an additional performance measure we introduce probability of corruptive false alarms. Numerical results are presented.

Keywords: Spread spectrum communication, unmanned aerial vehicle, pulse position modulation.

1 Introduction

UNMANNED aerial vehicle (UAV) is an aircraft that flies without a human crew on board the aircraft. In last few years UAVs are widely used in diverse military and civilian application domains [1]. They come in two varieties: some

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are controlled from a remote location while the others fly autonomously based on pre-programmed flight plans. There are several UAV remote control systems. One of the most widely used is the binary PPM control system, e.g. [2], which is suitable for low-cost UAVs remotely controlled from land. It is well known that clock recovery timing jitter impairs PPM format [3]. Besides, in a typical situation the UAV control signal receiver operates in the presence of several undesired signals that may jam desired control signal. A new binary PPM scheme, based on direct sequence spread spectrum technique, which has anti-jamming protection and doesn't require clock recovery is recently proposed in [4].

Spread spectrum techniques have been used in modern radio communications for a variety of reasons including, but not limited to: low detectability and anti-jamming protection. Two the most prevalent forms of spread spectrum techniques are: frequency hopping and direct sequence, both of which utilize PN sequences for spreading the spectrum. Aiming to despread the spectrum at the receiving side, it is necessary to generate a local replica of the PN sequence in the receiver and to synchronize it to the one superimposed on the received waveform. The received signal is either correlated by a locally generated PN sequence or filtered by a matched filter. The former is called the active correlator technique, and the latter the passive correlator (matched filter) technique. In general, the synchronization process is accomplished in two steps: code acquisition, which is a coarse alignment process bringing the two PN sequences within one chip interval, and code tracking, which is a fine tuning and synchronization maintaining process [5].

In this paper we present analysis and optimization of the recently proposed scheme [4], which is suitable for application since doesn't require clock recovery. Hence, the scheme is not impaired by timing jitter. We propose how to improve performance measures of the scheme by applying two-level detection procedure. As performance measures we use miss probability and false start probability. Threshold settings calculation is based on the Neyman-Pearson procedure. Since the scheme is robust on false alarm occurrence owing to its ability of tracking regularity in correlation peaks appearances, as an additional performance measure we introduce probability of corruptive false alarms. Numerical results are presented.

2 Model of DS-SS Scheme for UAV PPM Control Signal

2.1 Structure of the UAV PPM control signal

Binary PPM control signal consists of data frames containing a synchronizing pulse followed by *N* shorter pulses (channels). Number *N* corresponds to the number of controlled surfaces of the UAV and it varies from four to eight, but typically is equal to five. Typical frame format is presented in Fig. 1. The frame duration is 20ms, i.e. data is being sent at a frequency of 50Hz. At the beginning of any pulse is the pause, with fixed duration of $T_p = 0.3$ms. Position of the pause is variable and it depends on duration of all pulses within a frame.

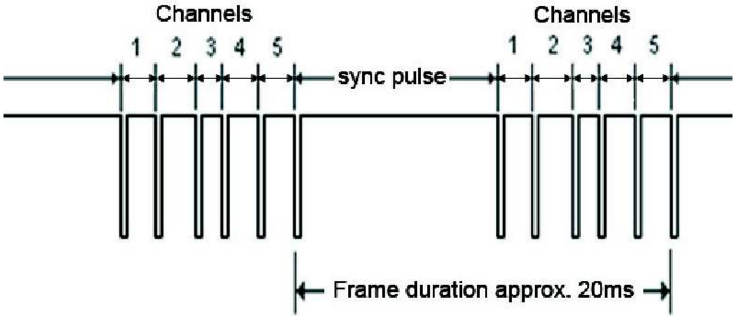

Fig. 1. Typical frame format.

The transmitter encoder circuit reads each control potentiometer's value and switch's position sequentially, converting each value to a channel pulse duration which corresponds to the respective controlled surface position. A control potentiometer in neutral position gives a pulse of 1.5ms and in the end positions may be either 1ms or 2ms depending on which way the control potentiometer has been moved.

2.2 Transmitter structure

Each one of (N+1) sections (sync pulse + N channels) in a frame is spread with its unique PN sequence. The same PN sequence is transmitted during the pause and the pulse which follows the pause. All PN sequences ought to be with good autocorrelation properties, while adjacent PN sequences ought to be mutually orthogonal.

Let us suppose that length of any PN sequence is the same and let L denotes the length of PN sequence. Since we have chosen that entire period of PN sequence is equal to the duration of a pause, generation of any PN sequence is performed at $f_c = L/T_p$ clock. In our realization we have used PN sequences of length $L = 255$, so is $f_c \cong 0.85$MHz. Since the DS/BPSK modulation is applied, the occupied bandwidth is $B_{DS} \cong 1.7$MHz. Spreading is performed prior to RF modulation and all PN generators are operating from their initial state synchronously with a start of corresponding frame section.

2.3 Receiver structure

At the receiving side we have a priori information about all (N+1) spreading PN sequences and its arrangement, but we don't know when each of them will begin: that has to be determined from the transmission itself. The structure of the receiver is presented in Fig. 2.

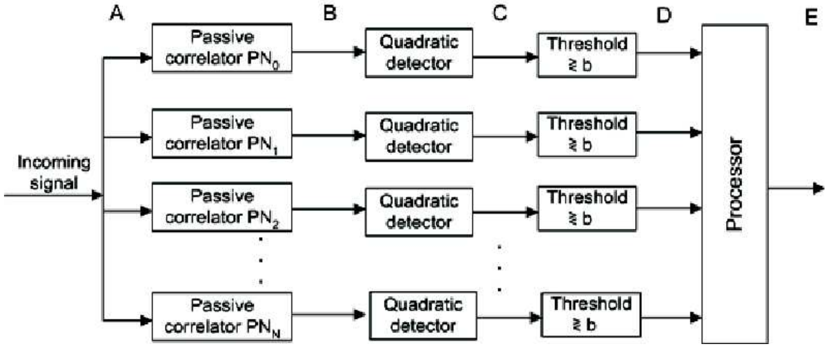

Fig. 2. Structure of the receiver.

Receiver consists of (N+1) branches containing (N+1) passive correlators; each of them is matched to one of (N+1) spreading PN sequences. Quadratic detector and a threshold comparator follow each one of passive correlators. Based on pulses generated at the outputs of (N+1) threshold comparators, processor reconstructs the UAV control signal.

2.4 Detection procedure

(a) One-level detection. When pause that precedes pulse (either sync or channel) arrives to receiver, peak signal of autocorrelation function is generated at the output of the respective passive correlator. After passing through quadratic detector, that signal is compared to threshold.

Outlet of comparison of the signal level at the output of quadratic detector to threshold can be characterized in probabilistic sense by: probability of detection P_d and probability of false alarm P_{fa} that can be defined as follows:

1. Probability of detection represents the probability that threshold comparator correctly detects an in-sync position when it is present,
2. Probability of false alarm represents the probability that the threshold comparator falsely detects an in-sync position when in fact it is not present.

Probability of detection and probability of false alarm may be described as [6]:

$$P_d = Q(\sqrt{2\gamma}, \sqrt{b}), \tag{1}$$

$$P_{fa} = Q(0, \sqrt{b}), \tag{2}$$

where $Q(\alpha, \beta)$ is Marcum's Q-function, γ is the correlation peak signal-to-noise ratio at the input of quadratic detector

$$\gamma = L\frac{E_c}{N_0} = L\frac{ST_c}{N_0}, \tag{3}$$

and b is the normalized detection threshold

$$b = V_t^2/\sigma^2, \tag{4}$$

where E_c denotes chip (PN sequence symbol) energy, N_0 denotes noise power spectral density, S denotes received signal power, T_c is chip duration and V_t denotes voltage threshold. σ is the equivalent noise that is a sum of the thermal noise σ_n^2 and the correlator self-noise σ_i^2 [7, 8]:

$$\sigma^2 = \sigma_n^2 + \sigma_i^2, \tag{5}$$

where

$$\sigma_n^2 = \frac{N_0 L T_c}{2} \tag{6}$$

and

$$\sigma_i^2 = \frac{E_c L T_c}{2}. \tag{7}$$

Since the threshold level should be set above the noise level, noise power that prevails just before threshold comparator has to be estimated. For low signal-to-noise ratios $E_c/N_0 \ll 1$, correlator self-noise may be neglected, i.e. $\sigma^2 \cong \sigma_n^2$.

Detection and hence reconstruction of one frame starts with the first correlation peak at the output of passive correlator corresponding to sync pulse (more precisely, this correlation peak appears at the end of the pause that precedes sync pulse), and it represents the start of sync pulse length. Since the length of sync pulse is varied from 6.8ms to 11.8ms, and bearing in mind that PN sequence period is 0.3ms, the first correlation peak is followed with minimum 27 and maximum 44 more correlation peaks. All these peaks, after compared to threshold, are being transferred to processor that uses them for signal reconstruction and system monitoring.

An example of signal waveforms, considering a segment of incoming signal: end of sync pulse, channel 1 and beginning of channel 2 (corresponding to sequences PN_0, PN_1 and PN_2, respectively) is presented in Fig. 3.

After detection of the first peak in channel 1, processor sets the indication that activity in channel 1 has started, and then counts the number of chip intervals until another peak in same channel is detected: if this number equals to L, system is working properly. Since pulse duration in the channel is varied from 1ms to

2ms, the first correlation peak is followed with minimum 3 and maximum 6 more correlation peaks. At the same time, processor is analyzing the output of passive correlator in channel 2: the first correlation peak represents the start of activity. Since the first correlation peak in channel 2 is generated at the end of pause in this channel (when L^{th} chip within pause arrives to correlator), to ensure that pulse length in channel 1 would be measured with its true value, it is necessary to shorten the pulse length of the previous pulse for pause interval of 0.3ms. This causes delay in UAV control signal for one PN sequence period, i.e. for pause duration of 0.3ms.

This process repeats for channels from 2 to N and for sync pulse, and is always performed in strictly defined order: only correlation peak in channel 1 can be correctly detected after correlation peak in sync pulse, ..., only correlation peak in channel N can be correctly detected after correlation peak in channel (N-1) and only correlation peak in sync pulse can be correctly detected after correlation peak in channel N. Thus, correlation peak detection within a channel that disturbs this order is clearly a false alarm, and is being automatically removed by processor.

Only false alarms that occur within the ”first following” channel during pulse length measurement corrupt receiver performances. Under assumption that false alarms occur within a frame with equal probability and are uniformly distributed over time, we calculate that no more than 5.95% of false alarms are potentially corruptive [9] (see Appendix). This fact makes proposed scheme being extremely robust on false alarm occurrence.

One-level detection procedure assumes delay of pause duration ($T_p = 0.3$ms) in forwarding data. For common UAV speed of 100km/h, this delay interval corresponds to 0.83cm in path length.

(b) Two-level detection. Presence of more than one correlation peak within each pulse gives an opportunity of making two-level detection at the output of any passive correlator.

Let b_1 denotes the first normalized detection threshold level, while b_2 denotes the second normalized detection threshold level.

Let P_{d1} and P_{d2} be the probability of detection of the first and of the second correlator peak, respectively. Similarly, let P_{fa1} and P_{fa2} be the probability of false alarm of the first and of the second normalized detection threshold level, respectively.

If the first correlation peak was correctly detected, the second peak appears exactly L chip periods later. Processor can check out whether the second peak, which serves for confirmation, appears at this known position or not. If the first correlation peak was falsely detected (false alarm), there is very low probability that next false alarm will appear exactly L chip periods later. In the case when only

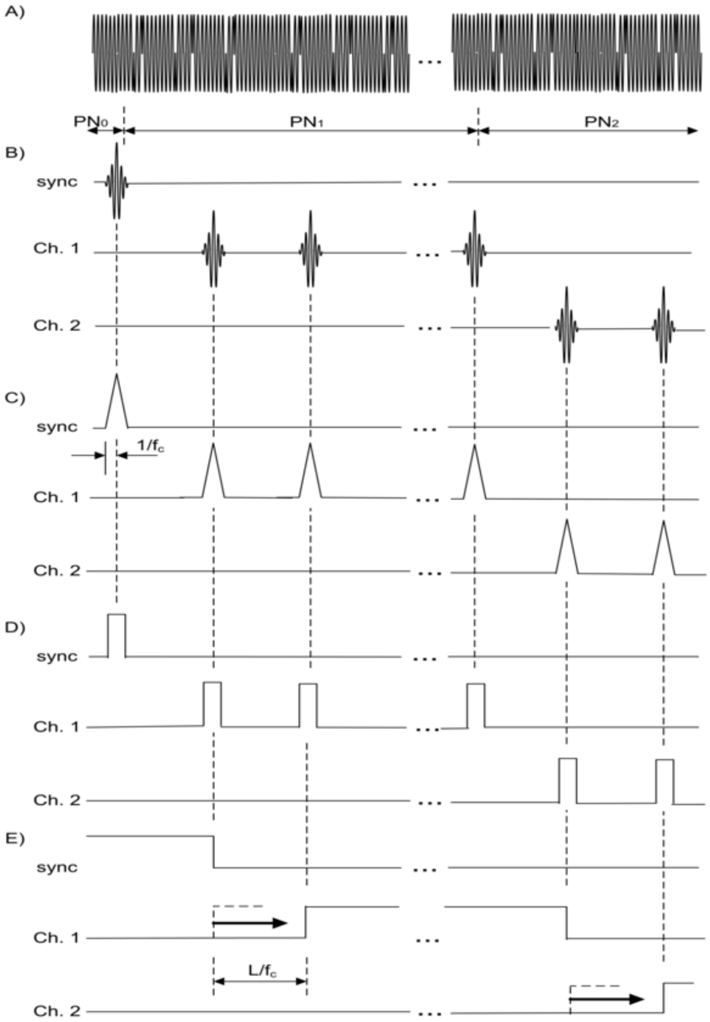

Fig. 3. Signal waveforms in sync pulse, channel 1 and channel 2 branch within receiver: A) signal at receiver front-end; B) signals at passive correlators' outputs; C) signals at quadratic detectors' outputs; D) signals at comparators' outputs and E) UAV control pulses reconstructed by processor.

one correlation peak is detected, processor considers that false alarm has occurred and removes it without interrupting current pulse length measurement.

Two-level detection procedure allows an additional improvement of performance measures by using two-level threshold setting. After detection of the first correlation peak, *a priori* information on the position of the second correlation peak is available. Hence, threshold levels may be different. Within time interval where pulse may start and thus the first correlation peak may appear, threshold level may be set to one level, while within time interval where the second correlation peak may appear, threshold level may be set to another level.

Two-level detection procedure assumes same delay as in the case of one-level detection, i.e. it doesn't imply any additional delay.

2.5 Choice of suitable set of PN sequences

For the realization of the scheme, set of (N+1) pseudonoise sequences of length $L = 255$ is used. It is of high importance to use PN sequences with autocorrelation properties as good as possible, in order to achieve high detection probability, while keeping low probability of false alarm. On the other hand, within long time interval correlator contains segments of two adjacent PN sequences. Hence, good crosscorrelation properties of adjacent PN sequences are also important demand.

Using linear maximum-length PN sequences (m-sequences) is the optimal compromise. All of them have ideal autocorrelation properties, while it is possible to choose (N+1) of them with crosscorrelation properties as good as those of Gold sequences [10].

3 Performance Measures

We use miss probability and false start probability as performance measures. In text which follows performance measures analysis for one-level and two-level detection procedures are presented.

(a) One-level detection. In one level detection procedure, miss is the situation when processor indicates that pulse (either sync or channel) has not started, but in fact in-sync situation is present. False start is the situation when processor indicates that pulse (either sync or channel) is started, but in fact in-sync situation is not present.

Therefore, the probability of missing the pulse start in one-level detection can be expressed by:

$$P_{miss}^{(1)} = 1 - P_d. \tag{8}$$

Similarly, probability of false start can be expressed by:

$$P_{fs}^{(1)} = P_{fa}. \tag{9}$$

(b) Two-level detection. In two-level detection procedure, miss happens if any of two the following mutually exclusive events occur:

1. At the output of respective passive correlator in-sync situation is not detected, and thus pulse length measurement doesn't start,
2. At the output of respective passive correlator in-sync situation is detected, leading to pulse length measurement, but after time interval of L chips, another hit is not detected.

Therefore, the probability of missing the pulse start in two-level detection can be expressed by:

$$P_{miss}^{(2)} = (1 - P_{d1}) + P_{d1}(1 - P_{d2}) = 1 - P_{d1}P_{d2}. \tag{10}$$

False start happens if two consecutive false alarms, time displaced for L chips, happen:

$$P_{fs}^{(2)} = P_{fa1}P_{fa2}. \tag{11}$$

Within time interval in branch where pulse (either sync or channel) may start and thus the first correlation peak may appear, normalized detection threshold level b_1 is set to one value, while within time interval during confirmation process one can set the normalized detection threshold level b_2 to another value. Let us denote thresholds level ratio:

$$k = \frac{V_{t1}}{V_{t2}} = \sqrt{\frac{b_1}{b_2}}. \tag{12}$$

Two-level threshold settings optimization based on the Neyman-Pearson procedure assumes to find values of b_1 and b_2 that result in miss probability as low as possible, while probability of false alarm (in our case: false start signal) is kept at some specified value.

4 Numerical Results

In numerical calculations we assume that decision indicating the presence or absence of a PN sequence synchronization is made at the chip rate, i.e. every $T_p/L = 0.3 \cdot 10^{-3}/255 \cong 1.2 \cdot 10^{-6}$s .We chose to keep $P_{fs} \cong 10^{-8}$, so as one false alarm will occur every 120s.

Miss probability versus threshold settings ratio for different signal-to-noise ratios is presented in Fig. 4. From this Figure one can see that $k_{opt} = 1$ for any signal-to-noise ratio.

Miss probabilities for one-level and two-level detection procedures versus signal-to-noise ratio, for $k = k_{opt}$, are presented on Figure 5. From this Figure it can be

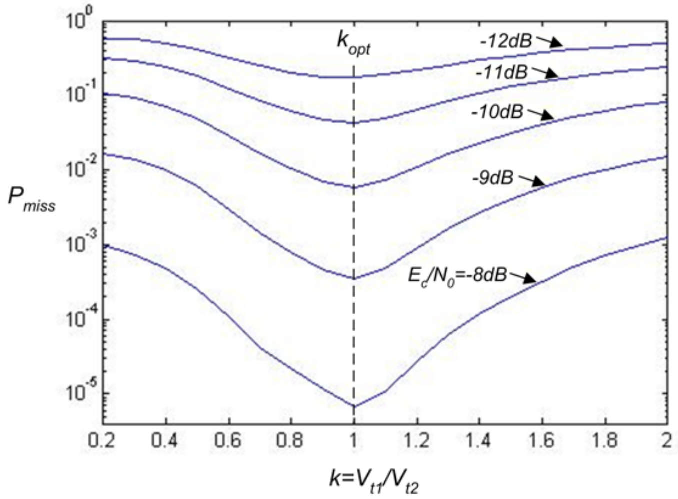

Fig. 4. Miss probability versus thresholds ratio for different signal-to-noise ratios.

noticed that improvement in performance measures achieved by using two-level detection is significant. Robustness of the scheme to noise is increased for approximately 2dB, since the same value of miss probability in the case of two-level detection is achieved for approximately 2dB lower signal-to-noise ratio than in the case of one-level detection.

5 Conclusion

In this paper we present analysis and optimization of DS-SS PPM scheme for UAV control signal protection. This scheme is suitable for implementation since it doesn't require clock recovery. Structure of the scheme is simple and complete realization can be performed with passive correlators only and small amount of digital logic, while signal processing can be done via single μC/FPGA chip. Calculated performance measures confirm that proposed scheme is robust on false alarm occurrence owing to its ability of tracking regularity in correlation peaks appearances. Numerical results show that no more than 5.95% of false alarms are potentially corruptive. We propose how to further improve performance measures by applying two-level detection for data reconstruction at receiver. On that way robustness of the scheme to noise is increased for 2dB in comparison to one-level detection. It should be noticed that properties of proposed scheme for UAV control signal protection give an opportunity of making decision on basis of even more than two consecutive correlation peaks. Since minimum number of correlation peaks in

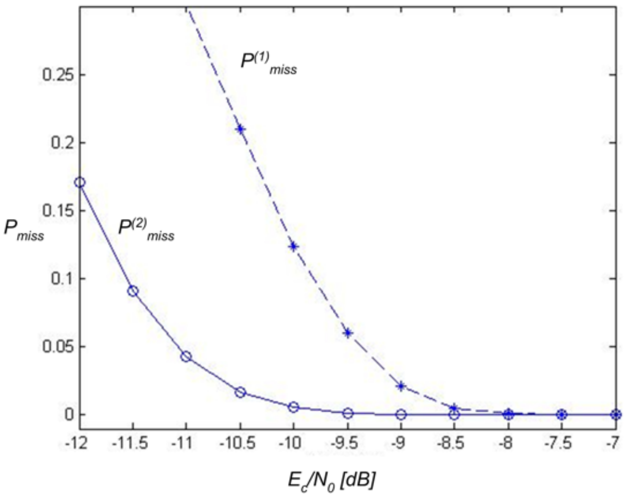

Fig. 5. Miss probability for one-level (dotted line) and two-level detection for k_{opt} (solid line) versus signal-to-noise ratio.

every channel pulse length measurement is 3, it is possible to achieve even better performance measures by checking the presence of two successive correlation peaks after the first one, at their known positions. Necessary delay in forwarding data is then doubled and equals to $2T_p = 0.6$ms. However, reported delay is negligible in both cases: (1) when vehicle is remote controlled by human operator in comparison with response time of a man, and (2) when control is computer-aided since common speed of 100km/h for UAV corresponds to 1.66cm in path length for delay interval. Analysis and optimization in that case can be done in manner proposed in this paper, but may consider three-level threshold settings.

Appendix

Probability of corruptive false alarms

Let us assume that false alarms occur within a frame with equal probability and are uniformly distributed over time. We denote: T_{SYNmax} - maximum duration of sync pulse, T_{SYNmin} - minimum duration of sync pulse, T_{CHmax} - maximum duration of channel pulse and T_{CHmin} - minimum duration of channel pulse. Bearing in mind the structure of the frame, we shall calculate probability that the false alarm is potentially corruptive. In order to do this let us consider possible scenarios. First, let's assume that sync pulse is successfully detected and that measurement of its length is in progress. Correlation peaks appear at the output of threshold comparator following the passive correlator PN_0 and, according to previous observations, only false alarms that occur at the output of threshold comparator following the passive correlator PN_1 are potentially corruptive, since they may represent the beginning of pulse in channel 1. Having in mind that the length of sync pulse T_{SYN} is varied from $T_{SYNmin} = 8.2$ms to $T_{SYNmax} = 13.2$ms, all peaks that appear in channel 1 during the time shorter than 8.2ms from the beginning of sync pulse are recognized as false alarms and removed by processor. It means that only

$$p_{SYN} = \frac{(T_{SYN} - T_{SYNmin}) + T_p}{T_f} \cdot \frac{1}{N+1} \tag{A1}$$

of false alarms that occur in receiver are potentially corruptive for sync pulse measurement. For maximum possible length of sync pulse within a frame ($T_{SYN} = T_{SYNmax}$) we get upper bound of $p_{SYN}|_{N=5} \approx 4.417\%$. Similarly, since the length of channel's pulse T_{CH} is varied from $T_{CHmin} = 1$ms to $T_{CHmax} = 2$ms, during the measurement of pulse length in any channel (1 to N) processor monitors only the "first following" channel and removes all peaks that appear within it during the time shorter than 1ms from the beginning of pulse under measurement. For maximum possible length of (any) channel pulse within a frame, only

$$p_{CH} = \frac{(T_{CH} - T_{CHmin}) + T_p}{T_f} \cdot \frac{1}{N+1} \tag{A2}$$

of false alarms that occur in receiver are potentially corruptive for measurement of particular channel. For maximum possible length of channel pulse within a frame ($T_{CH} = T_{CHmax}$) we get upper bound of $p_{CH}|_{N=5} \approx 1.083\%$. Maximum lengths of sync pulse and channel pulses can not appear within the same frame, so it is of interest to calculate the overall probability of corruptive false alarms. Corresponding to previous calculations, false alarms are potentially corruptive only if appear in "first following" channel after T_{SYNmin} from the beginning of sync pulse (i.e. after T_{CHmin} from the beginning of channel pulse), so we calculate:

$$p_{OV} = \frac{(T_f - T_{SYNmin} - NT_{CHmin})}{T_f} \cdot \frac{1}{N+1}. \tag{A3}$$

Since T_{SYNmin} can be expressed as function of number of channels N, one can write:

$$T_{SYNmin} = T_f - NT_{CHmax} - (N+1)T_p. \tag{A4}$$

From previous two equations we get the following expression for overall probability of corruptive false alarms p_{OV} as function of N:

$$p_{OV} = \frac{N(T_{CHmax} - T_{CHmin} + T_p) + T_p}{T_f} \cdot \frac{1}{N+1}. \tag{A5}$$

Overall probability of corruptive false alarms versus number of channels is presented on Figure 6. Its value varies between 5.5% and 5.95%, when number of channels N is varied from 4 to 8. For typical frame consisting of 5 channels, $p_{OV}|_{N=5} \approx 5.67\%$.

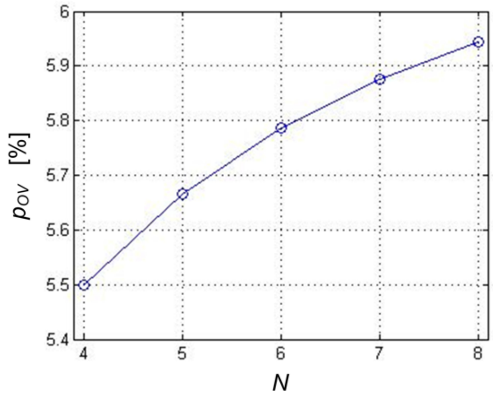

Fig. 6. Overall probability of corruptive false alarms versus number of channels.

Acknowledgments

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