Rake-like Receiver Structures for Unmanned Aerial Vehicle Direct Sequence Spread Spectrum PPM Control Signal

Branislav M. Todorović, Dragana B. Perić

Abstract – **Direct sequence spread spectrum (DS-SS) technique is widely used in modern telecommunications and it represents the latest advancement in radio control signal protection. One of the most widely used unmanned aerial vehicle (UAV) radio control systems is the binary pulse-position modulated (PPM) control system. In this paper, two structures of rake-like receiver for improvement of DS-SS binary PPM UAV control signal reception at low signal-to-noise ratios are proposed and analyzed. Both of them are based on the combining signals obtained from an antenna array: predetection and postdetection combiners are considered. Performance measures of the both structures are calculated. It is shown that rake-like receiver with predetection combiner is superior.**

Keywords – **Spread spectrum communication, radio control, pulse position modulation, vehicles, signal processing.**

I. INTRODUCTION

In recent years there has been rapidly increasing interest in UAVs for numerous military and civilian applications [1,2]. UAVs come in two varieties: some are controlled from a remote location while the others fly autonomously based on pre-programmed flight plans. There are several UAV radio control systems. One of the most widely used is the binary PPM control system, e.g. [3], which is suitable for low-cost UAVs remotely controlled from land. It is well known that clock recovery timing jitter impairs PPM format [4]. Besides, in a typical situation the UAV control signal receiver operates in the presence of several undesired signals that may jam desired control signal.

New binary PPM scheme that has anti-jamming protection and doesn't require clock recovery is proposed in [5] and analyzed in details [6]. That scheme is based on direct sequence spread spectrum technique and it uses $(N+1)$ pseudonoise (PN) codes: one of them (PN$_0$) is assigned to the synchronizing pulse while the each of the remaining N codes (PN$_1$, PN$_2$, ... PN$_N$) corresponds to the appropriate channel. Synchronization of PN codes is acquired by using passive correlators while tracking process is not necessary. Hence, the usage of active correlators is not necessary. Furthermore, data demodulation and, hence, clock recovery is also unnecessary. Control signal reconstruction is performed by using PN codes correlation peaks. Calculated performance measures confirm that scheme is highly reliable for moderate or high correlation peak signal-to-noise ratios (SNR), while, for low SNR scheme fails to operate properly.

The purpose of this paper is to focus on tacking the case of low SNR. In order to improve performance measures at low SNR, we combine receiver similar to rake-receiver and antenna array.

Rake-receiver is well-known structure designed to optimally detect a DS-SS signal transmitted over multipath channels [7]. In the last few years, it has been also used for reception of Ultra-Wideband (UWB) signals [8, 9]. Rake-receiver consists of M sub-receivers associated with a single antenna, where M is the number of multipath channels. In each sub-receiver, the received signal is correlated by time-shifted version of a locally generated PN code. The aim is to separate signals coming over different paths. At a later stage, this receiver optimally combines signals received over multiple paths that results in performance measures improvement. On the other hand, antenna array is also well known structure that is commonly used for jamming signal cancellation [10].

In this paper we propose the rake-like receiver, which is modified rake-receiver with M inputs, for completely different purpose: to enhance desired signal reception at low SNR. Unlike to rake receiver that receives signal from a single antenna, rake-like receiver deals with signals from an antenna array consisting of M antennas. Signals obtained from antenna array are then combined. Two structures of rake-like receiver with predetection and postdetection combiner are analyzed. It is shown that rake-like receiver with predetection combiner has better performance measures.

II. RAKE-LIKE RECEIVER STRUCTURES

Binary PPM control signal consists of data frames containing a synchronizing pulse followed by N shorter pulses (channels). The frame duration is 20ms, i.e. data is being sent at a frequency of 50Hz. 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.

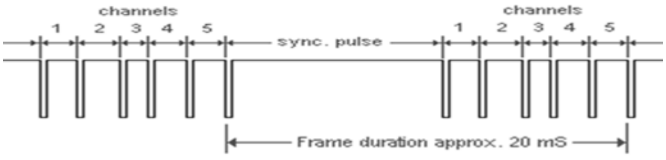

Fig. 1. Typical frame format

This work was presented at the 54. Conference ETRAN, Donji Milanovac, June 7-11, 2010.

Branislav M. Todorović is with "RT-RK d.o.o.", R&D Center for Computer Based Systems, Fruškogorska 11, 21000 Novi Sad, Serbia, E-mail: Branislav.Todorovic@rt-rk.com

Dragana B. Perić is with "IMTEL-Komunikacije a.d.", Blvd. Michael Pupin 165b, 11070 Belgrade, Serbia, E-mail: Dragana@insimtel.com.

At the beginning of any pulse is the pause, with fixed duration of T_p=0.3ms. Position of the pause is variable and it depends on duration of all pulses within a frame. 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.

According to recently proposed scheme [5], each one of ($N+1$) sections (sync pulse + N channels) in a frame is spread with its unique PN code. The same PN code is transmitted during the pause and the pulse which follows the pause. All PN codes ought to be with good autocorrelation properties, while adjacent PN codes ought to be mutually orthogonal.

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

Antenna array consists of M antennas, as shown on Fig. 2. The geometry of array and the type of antennas characterize an antenna array. Uniformly spaced linear antenna array consisting of collinear vertical electric monopoles is the most widely used in practice. Distance between adjacent antennas is denoted with d, while incident angle of received signal is θ.

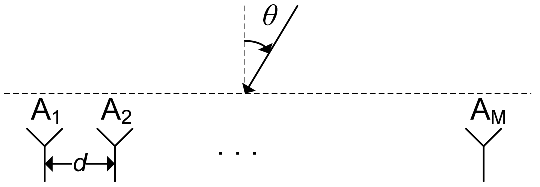

Fig. 2. Antenna array

Let us consider the relative signal delay between antennas in comparison to PN code chip duration. Signal delay between two adjacent antennas is $\tau = (d\sin\theta)/c$, where c is light velocity. Delay between two adjacent antennas has its maximal value $\tau_{\max}$ when $\theta = \pm 90^0$. If signal carrier frequency is $f_0 = 450MHz$ (i.e. wavelength $\lambda = 0.66m$) and $d = \lambda/2$, than $\tau_{\max} \cong 1.1ns$. For a common UAV wings span of two meters, a uniformly spaced linear antenna array consisting of up to $M = 7$ antennas can be mounted on wings. In that case, maximal overall delay is $\tau_{ov\max} \cong 6.6ns$. Since PN code chip duration is $T_c = 1/f_c \cong 1.2\mu s$, it means that maximal overall delay is three orders of magnitude less than PN code chip duration, so as the predetection combining can be done.

A. Rake-like receiver with predetection combiner

DS-SS/PPM rake-like receiver structure with predetection combiner is presented in Fig. 3. It is assumed that signal-to-noise ratios in each antenna are exactly the same. This assumption is justified since array is mounted on small area (UAV wings) and hence the signals are strongly correlated. So, there is just power gain, not diversity gain.

In all of ($N+1$) channels, signals received from M quadratic detectors are summed prior to comparing with threshold. It will significantly improve detection performance measures.

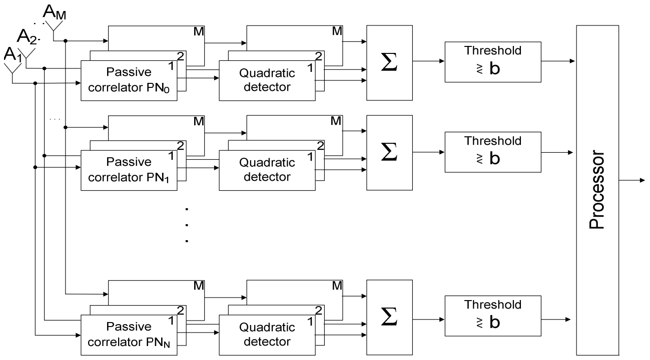

Fig. 3. Structure of the DS-SS/PPM rake-like receiver with predetection combiner

It is of high importance that first correlation peak in each channel would be detected. In order to calculate detection probability of the first correlation peak P_{d1} and false alarm probability P_{fa}, a model proposed in [11,12] is used.

Let us denote signal power at the receiver input with S and noise power density with N_0. Detection probability of the first correlation peak is given by:

$$P_{d1} = P_d \exp(-n_{fa}T_v), \qquad (1)$$

where n_{fa} denotes false alarm rate, T_v is false-alarm loss time (in our case: less than one PN code period: 0.3ms) and P_d stands for detection probability of any correlation peak

$$P_d = Q(\sqrt{2M\gamma}, \sqrt{b/ML}). \qquad (2)$$

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

$$\gamma = (2S/3)/(N_0 f_c), \qquad (3)$$

b is the normalized detection threshold $b = 2V_T^2/N_0 T_c$, where V_T denotes voltage threshold.

False alarm probability is

$$P_{fa} = Q(0, \sqrt{b/ML}). \qquad (4)$$

For analysis purposes, we assume that decision indicating the presence or absence of PN code synchronization is made at the chip rate, i.e. every T_c seconds. Since we have chosen $P_{fa} \le 10^{-8}$, it means that a false alarm will occur every 2 minutes ($n_{fa} \cong$1/120s). Corresponding detection probability of the first correlation peak versus signal-to-noise ratio at the receiver front-end ($\gamma_m = \gamma - 10\log L$), with number of antennas being parameter, is shown in Fig. 4. If detection probability of the first correlation peak $P_{d1} \geq 0.999$ is required, with increasing a number M from 1 to 7, minimal input signal-to-noise ratio at the receiver front-end γ_m is reduced from -8dB to -16.3 dB.

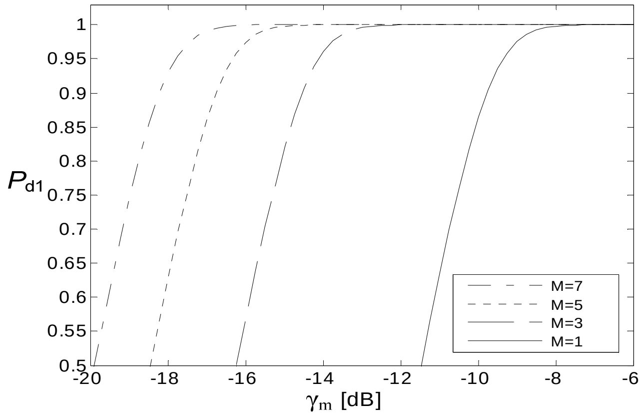

Fig. 4. Detection probability of the first correlation peak vs. SNR at receiver front-end, number of antennas is parameter (predetection combiner)

B. Rake-like receiver with postdetection combiner

Another DS-SS/PPM rake-like receiver structure that improves reception performance measures in low input signal-to-noise ratio environment is presented in Fig.5.

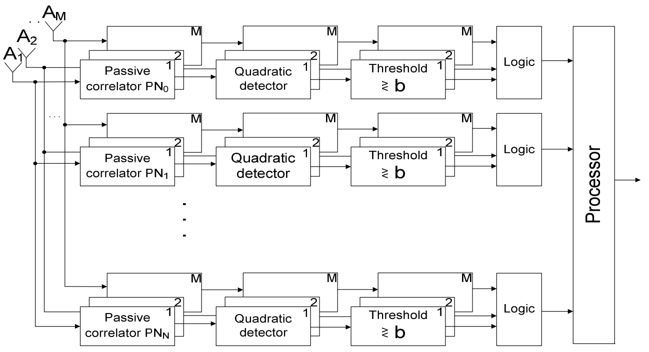

Fig. 5. Structure of the DS-SS/PPM rake-like receiver with postdetection combiner

In receiver structure with postdetection combiner, signal from each of M antennas is completely processed in M sub-receivers and, after that; some form of logic is applied to give final result to the processor. Performance measures of sub-receivers are calculated by using eqns. (1)-(4) where $M = 1$.

If majority decision logic is applied, an overall detection probability of the first correlation peak is given by:

$$P_{d1ov} = 1-(1-P_{d1})^M - \binom{M}{1}\cdot P_{d1}(1-P_{d1})^{M-1} - \ldots$$
$$\ldots - \binom{M}{(M-1)/2}\cdot P_{d1}^{\frac{M-1}{2}}(1-P_{d1})^{\frac{M+1}{2}}. \qquad (5)$$

Corresponding detection probability of the first correlation peak versus signal-to-noise ratio at the receiver front-end γ_m, with number of antennas being parameter, is shown in Fig. 6. If detection probability of the first correlation peak $P_{d1ov} \geq 0.999$ is required, with increasing a number of antennas M from 1 to 7, minimal input signal-to-noise ratio at the receiver front-end γ_m is reduced from -8dB to -9.5dB.

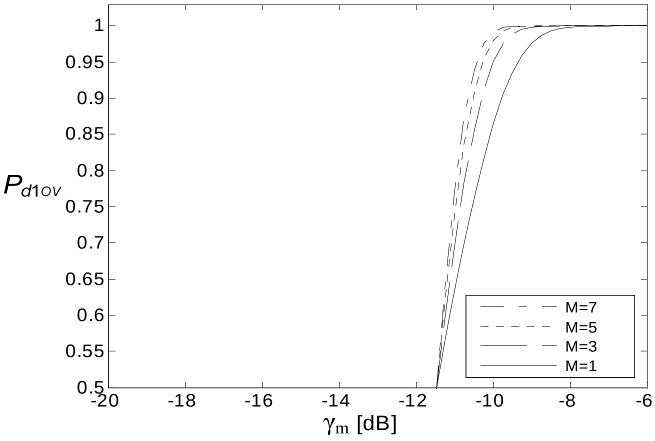

Fig. 6. Detection probability of the first correlation peak vs. SNR at receiver front-end, number of antennas is parameter (postdetection combiner – majority decision)

If “single hit” decision logic is applied, an overall detection probability of the first correlation peak is given by:

$$P_{d1ov} = 1-(1-P_{d1})^M. \qquad (6)$$

Corresponding detection probability of the first correlation peak versus signal-to-noise ratio at the receiver front-end γ_m, with number of antennas being parameter, is shown in Fig. 7. If detection probability of the first correlation peak $P_{d1ov} \geq 0.999$ is required, with increasing a number of antennas M from 1 to 7, minimal input signal-to-noise ratio at the receiver front-end γ_m is reduced from -8dB to -11dB.

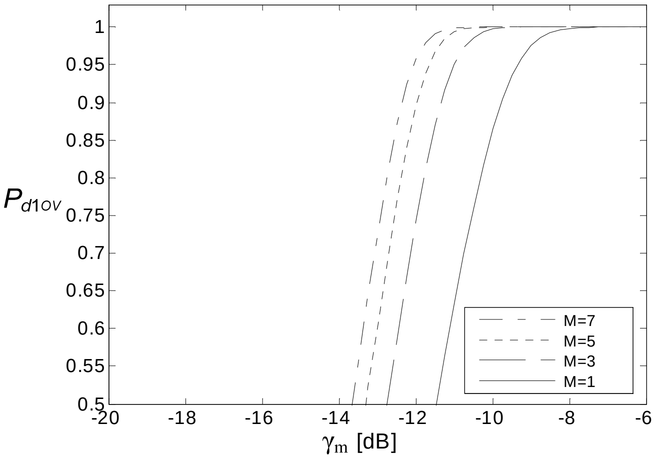

Fig. 7. Detection probability of the first correlation peak vs. SNR at receiver front-end, number of antennas is parameter (postdetection combiner – “single hit” decision)

III. CONCLUSION

Numerical results confirm that proposed DS-SS/PPM rake-like receiver structures have improved performance measures in comparison to standard scheme. Predetection combining is superior to postdetection combining. By increasing the number of antennas M from 1 to 7, for specified detection probability of the first correlation peak, it is possible to reduce minimal input signal-to-noise ratio at the receiver front-end γ_m for 8.3 dB. If postdetection combining is used, “single hit” logic is superior to majority decision logic.

ACKNOWLEDGEMENT

This work is supported by the Ministry of Science and Technological Development of the Republic of Serbia under Grant ET-11037.

REFERENCES

[1] R.Lozano (Ed.), *Unmanned Aerial Vehicles Embedded Control,* Wiley, 2009.

[2] K.P. Valavanis (Ed.), *Advances in Unmanned Aerial Vehicles,* Springer, 2008.

[3] The Model Electronics Company, *Technical Note - MTN004*, Issue 1.1, 2007.

[4] J.M.H. Elmirghani, R.A. Cryan and F.M. Clayton, “Spectral Analysis of Timing Jitter Effects on the Cyclostationary PPM Format”, *Signal Processing*, Vol.43, No.3, pp. 269-277, 1995.

[5] B.M. Todorović and V.D. Orlić: “Direct Sequence Spread Spectrum Scheme for an Unmanned Aerial Vehicle PPM Control Signal Protection”, *IEEE Communications Letters*, Vol.13, No.10, pp.727-729, October 2009.

[6] B.M. Todorović and V.D.Orlić, “Analysis and Optimization of Direct Sequence Spread Spectrum Scheme for an Unmanned Aerial Vehicle PPM Control Signal“, *Facta Universitatis (Niš), Series: Electronics and Energetics,* Vol.23, No.3, pp. 319-332, December 2010.

[7] M. Simon, J. Omura, R. Scholtz and B. Levitt, *Spread Spectrum Communications*, Computer Science Press, Rockville, 1985.

[8] H. Shao, N.C. Beaulieu, "An Analytical Method for Calculating the Bit Error Rate Performance of Rake Reception in UWB Multipath Fading Channels", *IEEE Transactions on Communications*, Vol. COM-58, No.4, pp.1112-1120, April 2010.

[9] N. Güney, H. Delic, F. Alagöz, "Achievable Information Rates of M-ary PPM Impulse Radio for UWB Channels and Rake Reception", *IEEE Transactions on Communications*, Vol. COM-58, No.5, pp.1524-1535, May 2010.

[10] R. T. Compton, Jr., “An Adaptive Array in a Spread Spectrum Communication System,” *Proc. of the IEEE,* Vol. 66, pp. 289-298, Mart 1978.

[11] M. Pandit: “Mean Acquisition Time of Active- and Passive-Correlation Acquisition Systems for Spread-Spectrum Communication Systems”, *IEE Proc. Pt. F*, Vol. 128, No. 4, pp. 211-214, August 1981.

[12] P.W. Baier, K. Dostert and M. Pandit: “A Novel Spread-Spectrum Receiver Synchronization Scheme Using a SAW-Tapped Delay Line”, *IEEE Transactions on Communications*, Vol. COM-30, No. 5, pp. 1037-1047, May 1982.