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Comparative Analysis of Phase-lock Control System Algorithms for Spread-spectrum Signal Receiver

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This paper investigates noise-immunity of phase-lock control system for spread-spectrum minimum shift keying signal receiver in case of adjacent channel interference influence. Four algorithms of phase-lock control system are suggested and described. Statistic simulations of signal processing in involved system are given.

Keywords: Spread-spectrum signal, minimum shift keying, signal from adjacent channel, phase synchronization system, statistical modeling, comparative analysis.

Introduction

Spread spectrum signals with minimum shift keying (MSK) are widely used in modern radio navigation systems (RNS). Serviceability on long distances $D_{\max} \approx 1000\,km$ makes a demand to RNS, to have rather large value of receiver's dynamic range (more than $80\,dB$). High accuracy of coordinate measuring in all working area of RNS, requires investigating algorithms of phase-lock control system of MSK-signal receiver, which provides phase shift measurements with root-mean-square (RMS) error $\sigma_\varphi \le 3^\circ$, then signal-to-noise ratio threshold equals to $-40\,dB$ (in the band of MSK-signal) and in case of adjacent channel interference influence (disturbing signal from another radio-range beacon) [1].

The aim of this article: noise-immunity investigation for suggested algorithms of phase-lock control system for MSK-signal receiver in case of adjacent channel interference influence.

Describing and comparative analysis of phase-lock control system algorithms results

Total realization of MSK-signal, signal from adjacent channel (SAC) and additive white Gaussian noise (AWGN) can be described as [2, 3]:

$$y(t) = s(t-\tau_s) + \gamma s'(t-\tau_s') + \xi(t),$$
$$s(t-\tau_s) = \mathrm{Re}\left\{\dot{S}(t-\tau_s)\exp\left[j\left(2\pi(f_0 \pm F_d)t - \varphi_s\right)\right]\right\}, \qquad (1)$$

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here $s(t-\tau_s)$ and $s^{/}(t-\tau_s^{/})$ are MSK-signal and SAC with delays τ_s and $\tau_s^{/}$ accordingly; $\gamma = \sqrt{P_s^{/}/P_s}$ – ratio «SAC/signal», P_s and $P_s^{/}$ – powers of signal and SAC accordingly; $\xi(t)$ – AWGN; f_0 – carrier frequency; F_d – frequency Doppler shift; φ_s – starting phase of signal; $\dot{S}(t-\tau_s)$ – complex envelope of MSK-signal:

$$\dot{S}(t-\tau_s) = D(t-\tau_s)\sqrt{2P_s}\exp\left[j\theta(t-\tau_s)\right], \tag{2}$$

where $D(t-\tau_s) = \pm 1$ – the information signal imposed on navigation signals for information transfer about differential corrections for GNSS users; $\theta(t) = \frac{\pi}{2T}\int_0^t d(t')dt'$ – function, which determines angle modulation, $d(t) = \sum_{i=0}^{N-1} d_i \,\mathrm{rect}(t-iT)$, $\{d_i\}$ – pseudorandom sequence (PRS) of *N*-length, *T* – one's bit PRS duration, $\mathrm{rect}(t)$ – square pulse with *T* duration. Disturbing signal from adjacent channel has similarly mathematics description, and different parameters (including information signal $D^{/}(t-\tau_s^{/})$).

Digital phase-lock control system (PLCS) structure chart of MSK-signal receiver is presented on Fig. 1. Values $y_i = y(t_i)$ ($t_i = i\Delta t$, $i = 0,1,...$, Δt – sampling interval) are incoming observations to digital phase-shift discriminator (DPD), which comes from an exit of analog-digital converter (ADC) [1, 4].

Reference signals of carrier frequency is $\cos\hat{\Phi}_i(k) = \cos(2\pi(f_0 \pm \hat{F}_d(k))t_i)$ and $\sin\hat{\Phi}_i(k) = \cos(2\pi(f_0 \pm \hat{F}_d(k))t_i)$ come into supporting inputs of DPD. These signals are formed by digital synthesizer (DS) and based on frequency Doppler shift estimation $\hat{F}_d(k)$ in each *k*-period of filtering. Reference signals $Q_i = \sin\theta_i$ and $I_i = \cos\theta_i$, which are synchronous with quadrature components of MSK-signal, formed by delay lock system. Quadrature components of bandwidth compressing signal (after MSK-detection) are formed by summarizing of multiplications of quadrature components of realization (1) and reference signals I_i, Q_i and integration on intervals $t \in [kT_p,(k+1)T_p]$, $k = 0,1,...$, (T_p – MSK-signal's period). Time of one cycle radio-range beacon transmition equals $T_c = 25T_p$. Error signal which is proportion to phase mismatch forms in compliance with algorithm:

$$Z_d(k) = \mathrm{sign}(z_1(k))z_2(k) = \hat{D}(k)z_2(k), \tag{3}$$

where $\mathrm{sign}(x)$ – sign function, $\hat{D}(k)$ – estimation of information signal $D(t-\tau_s)$ on *k*-period of filtering, $z_1(k)$ and $z_2(k)$ – quadrature components of correlation, computing on interval $t \in [kT_p,(k+1)T_p]$. Error signal $Z_d(k)$ comes into digital filter (DF). Output signal of DF used to control signals $\cos\hat{\Phi}_i(k)$ and $\sin\hat{\Phi}_i(k)$ frequencies.

Model of PLCS is presented on Fig. 2, where $Z_d(\varphi)$ – discrimination characteristic of DPD; T_i – time constant of integrator; $K = K_F K_S$ – instantaneous element, taking account of transfer constants of digital filter K_F and digital synthesizer K_S.

Frequency Doppler shift estimation on *k*-period of filtering is forming in compliance with algorithm [1]:

$$\hat{F}_d'(k) = K\left(Z_d(k) + x(k-1) + \frac{T_p}{T_i}Z_d(k-1)\right). \tag{4}$$

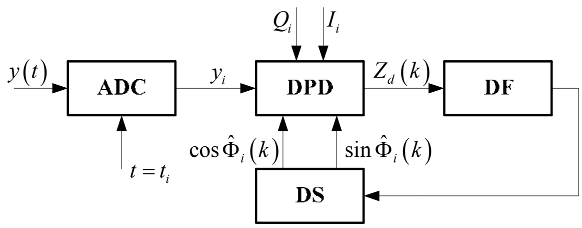

Fig. 1

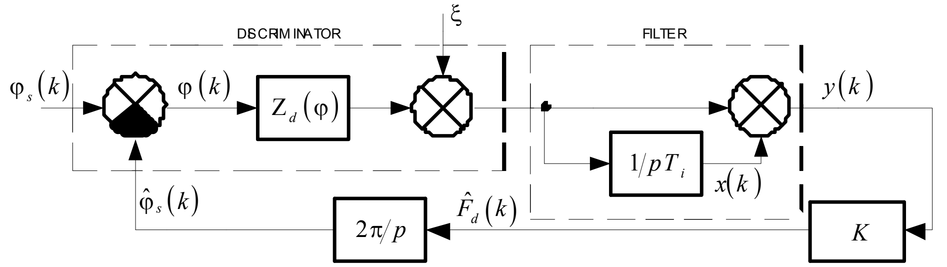

Fig. 2

Analysis of statistic simulation data of PLCS (Fig. 2) shows, that algorithm (3) is well-behaved if rated value $\gamma_{\max} = 40\,dB$, on the assumption of user's top speed equals $V_{\max} = 100\,km/h$ (peak level of frequency Doppler shift $F_{d\max} = 0{,}2\,Hz$), signal-to-noise ratio threshold $q = -40\,dB$ and capture probability $P_c \to 1$. Noise-immunity increase of PLCS ($\gamma_{\max} > 40\,dB$) can be achieved by using a separate channel for an information signal. In this case the algorithm (3) can be simplified and written as $Z_d(k) = z_2(k)$. Consequently, there are the following ways of frequency Doppler shift estimation:

$$\hat{F}''_d(k) = \begin{cases} K\left(Z_d(k) + x(k-1) + \dfrac{T_p}{T_i} Z_d(k-1)\right), M^* = \dfrac{1}{2}, \\ \hat{F}_d\left(\dfrac{T_c}{T_p}(M-1)\right), M^* = 0, \end{cases} \tag{5}$$

$$\hat{F}'''_d(k) = \begin{cases} K\left(Z_d(k) + x(k-1) + \dfrac{T_p}{T_i} Z_d(k-1)\right), M^* = \dfrac{1}{2}, \\ \dfrac{\hat{\varphi}_s\left(\dfrac{T_c}{T_p}(M-1)\right) - \hat{\varphi}_s\left(\dfrac{T_c}{T_p}(M-1) - \dfrac{T_c}{T_p}\right)}{2\pi T_c}, M^* = 0, \end{cases} \tag{6}$$

where $M^* = (M/2) -]M/2[$, $][$ – integer part separation operation, $M = 1 +]T_p(k-1)/T_c[$ – MSK-signal cycle number.

Statistic simulation results of PLCS in case of adjacent channel interference and AWGN influence are presented in table 1. Results are the following: average and RMS values of phase and frequency errors of tracing in steady-state regime (SR). Number of statistical examination equals to 10^3.

Table 1. PLCS statistic simulation results

$Z_d(k)$	$\text{sign}(z_1(k))z_2(k)$	$Z_d(k)=z_2(k)$	$Z_d(k)=z_2(k)$	$Z_d(k)=z_2(k)$
$\hat{F}_d(k)$	$\hat{F}'_d(k)$	$\hat{F}'_d(k)$	$\hat{F}''_d(k)$	$\hat{F}'''_d(k)$
$\overline{\varphi}_{sr}, rad$	0	0	0	0
$\sigma_{\varphi sr}, rad$	0,09	0,09	0,45	0,08
$\overline{F}_{sr}, Hz$	0	0	0	0
$\sigma_{F sr}, Hz$	0,035	0,035	0,039	0,028
γ_{max}, dB	40	75,6	54	80

Conclusion

The best for PLCS in case of adjacent channel interference influence is algorithm (6), which provides phase error of tracing RMS $\sigma_{\varphi sr} \approx 0,08\,rad$ with capture probability $P_c \to 1$, $F_{d\max} = 0,2\,Hz$, signal-to-noise ratio threshold $q = -40\,dB$ and $\gamma_{\max} = 80\,dB$.

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Сравнительный анализ алгоритмов слежения за фазой шумоподобного сигнала

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В статье исследуется помехоустойчивость системы фазовой синхронизации приёмника шумоподобного сигнала с минимальной частотной манипуляцией при воздействии структурно-подобной помехи. Предложены и описаны четыре алгоритма слежения за фазой шумоподобного сигнала с минимальной частотной манипуляцией. Представлены результаты статистического моделирования рассматриваемой системы.

Ключевые слова: шумоподобный сигнал, минимальная частотная манипуляция, фазовая синхронизация, статистическое моделирование.