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UWB PULSE TIMING TRACKING BASED ON FEEDBACK CONTROL PARTICLE FILTERING

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Abstract. *Timing tracking of ultra-wideband pulse which narrower than 1ns is a difficult problem. In existing timing technology, the timing range is narrow, and due to noise or effect of timing jitter, the timing precision becomes low and the timing stability deteriorates. In this scheme, a state space model for this problem is established and a novel timing tracking loop based on particle filtering is proposed. This scheme uses particle filtering algorithm to estimate the timing error and control the timing pulse. Simulation and experimental results show that the proposed method which utilizes the nonlinear processing ability of particle filtering has higher tracking precision and wider timing range compared with traditional digital timing loop.*

Keywords: Ultra-wideband, Particle filtering, Timing tracking, Feedback control, Time-locked loop

1. **Introduction.** For the good performance and high speed, the ultra-wideband (UWB) communication systems using narrow pulse have been the research focus in wireless communication area. Ultra wideband communication system has great commercial and military application. It not only meets the requirements of traditional communication system, but also has the characteristics of secrecy communication and low interception rate. Due to the flexible working environment, such as indoor or outdoor, it must against the multipath propagation and interference from other devices effectively. An IR-UWB radio for realizing an accurate synchronization system for wireless sensors by a very simple hardware was proposed in [1]. UWB communication systems can also be used in scheduling system, [2] proposed a method of fast scheduling for delay minimization in UWB wireless networks. Moreover, many researchers designed codes, receivers, etc., for different applications of UWB communication systems [3,4]. Usually, UWB pulse duration time is less than 1ns. Using current technology, it is difficult to sample the signal in such a short time. Moreover, timing tracking error will greatly decline the system performance [5,6]. Therefore, narrow pulse technology has also brought the design of the receiver with new problems – the pulse timing acquisition and tracking difficulty. In the UWB timing tracking, the early – late gate tracking technology formed by matched filters is used firstly in [5]. However, it points out that the early – late gate tracking technology is not optimal under the maximum likelihood criterion, and the best local reference signal should be derivative of the received signal and time-locked loop (TLL) is proposed combined with second-order digital phase-locked loop in [6]. The anti-multipath fading performance of the TLL in IEEE 802.15 multipath channel model is analyzed in [7]. The results show that the multipath effects of the TLL can be ignored. A hybrid synchronous sampling TLL is proposed in [8]. In IEEE 802.15 Multi-path Channels, the TLL improves system

bit error rate performance. However, the capture ranges of these TLLs are small; these TLLs are more sensitive to the observation noise and easily lose lock in low SNR because of the linearization of correlation function.

Particle filter technology is the major concern in recent years. Based on Bayesian theory and statistical sampling signal processing, it is mainly used in signal detection and tracking in the non-linear and non-Gaussian environment [9,10]. It describes particle filter algorithm for accurate indoor localization using an UWB signal [11,12]. It makes a detailed comparison of particle filtering, decision feedback loop and Costas loop in the phase tracking performance for the first time in [13]. The results show that the particle filter has a faster convergence rate and higher stability, and it uneasily causes cycle slip to lead to lose lock in low SNR. It quantitatively compares the particle filter's superiority on the mean time to lose lock (MTLL) in [14]. Without regard to the closed-loop tracking, the above phase-based particle filter tracking method is based on the open-loop estimation. The closed-loop tracking is only using particle filter's prediction function on the base of open-loop tracking in [15].

Combined digital phase-locked loop technology with the particle filter, a scheme based on feedback control of the particle filter time tracking is proposed in this paper. Timing error is modeled as a random walk and the parameters of the random walk are determined by Bayesian forecasting techniques. Because of random search and nonlinear processing ability of particle filter, simulation results show that the proposed method can obtain large capture range, reduce measurement noise effects and improve timing accuracy.

The paper is organized as follows. Section 2 gives a detailed overview of the UWB pulse digital timing loop. In Section 3 we describe our design of the particle filter timing tracking loop. Simulation and experimental results of the traditional digital timing loop and the proposed method are described in Section 4. In Section 5 we draw some conclusions.

2. **Problem Descriptions.**

2.1. **System model.**

UWB pulse digital timing loop is shown in diagram, and input signal is:

$$y(t) = \sum\nolimits_k s(t - k\Omega - \xi(t)) + n(t) \tag{1}$$

where $n(t)$ is additive white Gaussian noise with zero mean and power spectral density σ_n^2, $\xi(t)$ is the unknown time delay in transmitter and receiver, the pulse repetition period of transmitter is Ω, and the received monocycle waveform with unit energy is denoted as $s(t)$. Without loss of generality, we assume $s(t)$ is the 2nd order derivative Gaussian pulse $s(t) = \left(1 - 4\pi\left(\frac{t}{\tau}\right)\right)\exp\left(-2\pi\left(\frac{t}{\tau}\right)^2\right)$. It proves that the optimal local reference waveforms $r(t)$ are the three order derivative Gaussian pulses in [5].

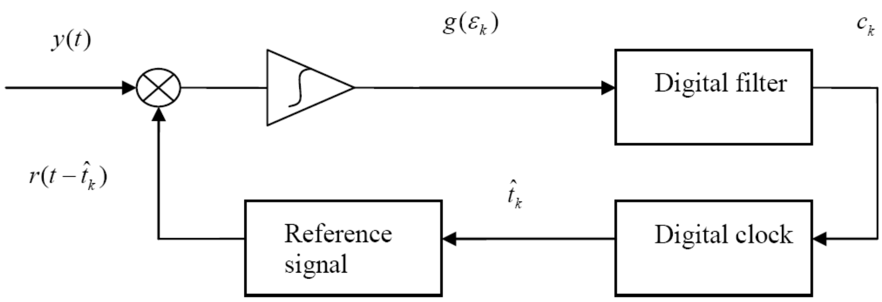

FIGURE 1. Timing structure of receiver

Digital clock determinates delay related time $\hat{t}_k$ of local reference waveforms. Assumed that $s(t) = 0$ and $r(t) = 0$, and $2T_D$ is the duration of the finite integration when $|t| > T_D$. The output of the integrator is:

$$e_k = g(\varepsilon_k) + n_k \tag{2}$$

$$g(\varepsilon_k) = \int_0^{2T_D} s(t + \varepsilon_k) r(t) dt \tag{3}$$

$$n_k = \int_0^{2T_D} n(t + \varepsilon_k) r(t) dt \tag{4}$$

where $\varepsilon_k = t_k - \hat{t}_k$ is timing error, $t_k = k\Omega - \xi_k$ is ideal delay time of the k^{th} reference waveform, the timing jitter ξ_k may be modeled as a random walk:

$$\xi_k = \xi_{k-1} + \nu_k \tag{5}$$

where ν_k is Gaussian driving noise with zero mean, and its power spectral density σ_n^2 is related to specific physical environment.

Through digital filter, sequence $\{e_k\}$ obtains c_k to control the cycles T_{k+1} of the digital clock. T_{k+1} is delay interval of the k^{th} reference waveform and the $k + 1^{\text{th}}$ reference waveform:

$$T_{k+1} = t_{k+1} - t_k = T - c_k \tag{6}$$

where the pulse repetition period of receiver is T. As can be seen from the diagram, the filter plays a decisive role in the performance of timing because it controls local reference pulse's delay time. We will discuss design problem of the filter as follows.

2.2. **Filter design.** Due to the very short duration of Gaussian pulse (when $\tau = 0.2877$ns, Quadratic Gaussian pulse duration is about 0.7ns), it is very difficult to sample in such a short pulse duration. At the same time, the effects caused by timing error on system capacity are analyzed in [5]. Particularly if the root mean square of timing error is over 40ps, the system's capacity will decline by about a half. It demands better timing performance of the receiver. This paper focuses on how to design the digital filters with larger timing range and lower timing error.

Combined with second-order digital phase-locked loop, it proposes second-order digital time-locked loop and makes a detailed analysis about the order of Gaussian pulse's impact on the variance of the timing error in [6]. However, the digital timing loop is based on linearization of correlation function $g(\varepsilon_k)$ and can only capture smaller timing error. The larger measurement noise and disturbance may cause the loss of lock. Particularly, it cannot lock when the pulse repetition cycle deviation θ is larger [6]. $\theta = \Omega - T$ represents the fixed difference in pulse repetition period between the transmitter and receiver. This timing loop has weak filtering effect on the time jitter and Gaussian observation noise, then the root mean square of timing jitter is larger. Through the above analysis, we consider a new particle filter technology, using its random search and nonlinear signal processing ability.

The key of particle filter is the state space model. The timing loop contains two unknown variables: one is the timing jitter ξ_k with time; the other is a fixed pulse repetition cycle deviation θ. The traditional approach is establishing the system equation of the timing jitter ξ_k and pulse repetition cycle deviation θ [13]. Due to the feedback of timing loop, we establish the system equation of timing error ε_k and model it as a random walk.

$$\varepsilon_k = \varepsilon_{k-1} + w_k \tag{7}$$

where w_k is Gaussian driving noise whose mean is zero and variance is σ_w^2. Forgetting factor has strong capacity on tracking. The fluctuation is relatively small in random input function. About parameter estimation, it can strengthen the role of the current observational data and weaken the impact of previous observations. Due to the effect of timing jitter and the control of feedback, there are more complex changes in the variance of timing error. We can use forgetting factor to determinate the changes of driving noise variance. If the timing error ε_{k-1} obeys Gaussian distribution with zero mean and power spectral density $\sigma^2_{\varepsilon_{(k-1)}}$ in time $k-1$, then $\sigma_w^2 = \sigma^2_{\varepsilon_{(k-1)}} \frac{1-\lambda}{\lambda}$, λ is the forgetting factor.

3. Particle Filter Timing Tracking Loop.

3.1. Description of particle filter. Particle filter is a statistical simulation method based on Bayesian sequential importance sampling and resampling. Its main ideal is that experience estimation of expectation's posterior distribution $p(\varepsilon_{0:k}|e_{1:k})$ can be obtained by sampling enough samples from importance function $q(\varepsilon_{0:k}|e_{1:k})$ [9,10]. It proves that posterior distribution of expectation can be simulated by a set of particles and its weight $\left\{\varepsilon_{0:k}^{(i)}, \varpi_k^{(i)}\right\}$, $i = 1, \cdots N$ approximately in [9]. N is the number of particles.

$$\varpi_k^{(i)} = \frac{\tilde{\varpi}_k^{(i)}}{\sum\limits_{i=1}^{N} \tilde{\varpi}_k^{(i)}}, \quad \tilde{\varpi}_k^{(i)} = \frac{p\left(\varepsilon_{0:k}^{(i)}|e_{1:k}\right)}{q\left(\varepsilon_{0:k}^{(i)}|e_{1:k}\right)} \tag{8}$$

In order to obtain particle sampling and recursive form of estimation of weight, we need to select importance function as follows:

$$q(\varepsilon_{0:k}|e_{1:k}) = q(\varepsilon_0) \prod_{j=1}^{k} q(\varepsilon_j|\varepsilon_{1:j-1}, e_{1:j}) \tag{9}$$

Then we can get weight's recursive:

$$\tilde{\varpi}_k^{(i)} = \tilde{\varpi}_{k-1}^{(i)} \times \frac{p\left(e_k|\varepsilon_k^{(i)}\right) \times p\left(\varepsilon_k^{(i)}|\varepsilon_{k-1}^{(i)}\right)}{q\left(\varepsilon_k^{(i)}|\varepsilon_{k-1}^{(i)}, e_k\right)} \tag{10}$$

The choice of importance function has great influence on algorithm, so we select prior distribution to form importance function generally

$$q\left(\varepsilon_k^{(i)}|\varepsilon_{k-1}^{(i)}, e_k\right) = p\left(\varepsilon_k^{(i)}|\varepsilon_{k-1}^{(i)}\right) \tag{11}$$

Then, we get the real-time estimation of state ε_k:

$$\hat{\varepsilon}_k = \sum_{i=1}^{N} \varepsilon_k^{(i)} \times \varpi_k^{(i)} \tag{12}$$

3.2. Particle filter timing tracking loop design. When the real-time estimation $\hat{\varepsilon}_k$ of state ε_k is obtained, $\hat{\varepsilon}_k$ is transformed to get c_k to control the delay time of next local pulse. Without pulse repetition cycle deviation θ, timing error c_k can be obtained through the following equation by first-order digital phase-locked loop [16].

$$c_k = \alpha_1 \hat{\varepsilon}_k \tag{13}$$

where coefficient α_1 is determined by first-order digital phase-locked loop. When pulse repetition cycle deviation θ exists, timing error c_k can be obtained through the following equation by second-order digital phase-locked loop [16].

$$c_k = \alpha_1 \hat{\varepsilon}_k + \alpha_2 \sum_{j=1}^{K} \hat{\varepsilon}_j \tag{14}$$

where coefficients α_1 and α_2 are determined by second-order digital phase-locked loop.

In summary, basic process of particle filter is as follows:

a) Initialization: extract the initial state from the prior distribution $\varepsilon_0^{(j)}$ and initialize weight $\varpi_0^{(j)} = 1$, $j = 1, \cdots N$. When time is k, the following steps are performed.

b) Prediction by one step:

$$\varepsilon_k^{(j)} = \varepsilon_{k-1}^{(j)} + w_k^{(j)} \tag{15}$$

Weight calculation:

$$\varpi^{(j)} = p\left(e_k | \varepsilon_k^{(j)}\right) \tag{16}$$

c) Resampling.

d) Update: count $\sigma^2_{\varepsilon(k-1)}$ and update driving noise variance σ_w^2.

e) $k \to k+1$. Go to step (b).

Then the estimation of timing error $\hat{\varepsilon}_k$ can be obtained from (12) and adjustment volume of receiver pulse repetition cycle deviation can be obtained from (13) or (14). Equation (6) controls the delay time of next reference waveform.

From the above analysis we can see that as long as it meets the following two conditions, the particle filter can be used:

a) Easy to complete the evolution of particle (15). It is related to the establishment of system equation.

b) Easy to count weight. It is related to the probability distribution of observation noise. As long as likelihood function is easy to count, the measurement noise do not need restrict Gaussian white noise. So the timing loop can be extended to the condition of colored noise.

4. **Simulation and Experiment.** We compare the performance of timing loop based on particle filter with second-order digital time-locked loop when there is pulse repetition cycle deviation θ. Considering the smaller timing jitter $\sigma_v^2 = 10^{-6}$, $\xi(0) = 0.01$, $\sigma_n^2 = 10^{-2}$ and $\theta = 0.3\tau$, the timing errors produced by the two filters in an experiment are shown in Figure 2. It is clear that the timing errors of timing loop based on particle filter are smaller than second-order digital time-locked loop.

Then we discuss the capture range of timing loop based on particle filter and second-order digital time-locked loop. The curve of correlation function is show in Figure 3. Through many repeated experiments, second-order digital time-locked loop based on linearization of correlation function needs to restrict $|\xi(0) + \theta| < 0.15$. The timing loop based on particle filter may expand $|\xi(0) + \theta| < 0.3$ because of random search and nonlinear processing ability of particle filter. We find that the variance of observation noise is close to 0.1, and that second-order digital time-locked loop which has reached steady state is easy to lose lock. It is shown in Figure 4 in an experiment. The probability of losing lock is becoming larger with the increase of the variance of timing jitter σ_v^2. However, the timing loop based on particle filter does not lose lock and has stronger stability.

When there is no timing jitter, the Cramer-Rao lower bound $E(|\varepsilon_k|^2) \geq \sigma_n^2 \times \tau^2/(10 \times \pi)$ of timing mean square error of 2nd order derivative Gaussian pulse and three order local references pulse can be obtained from [17]. In this paper, we use the FPGA platform

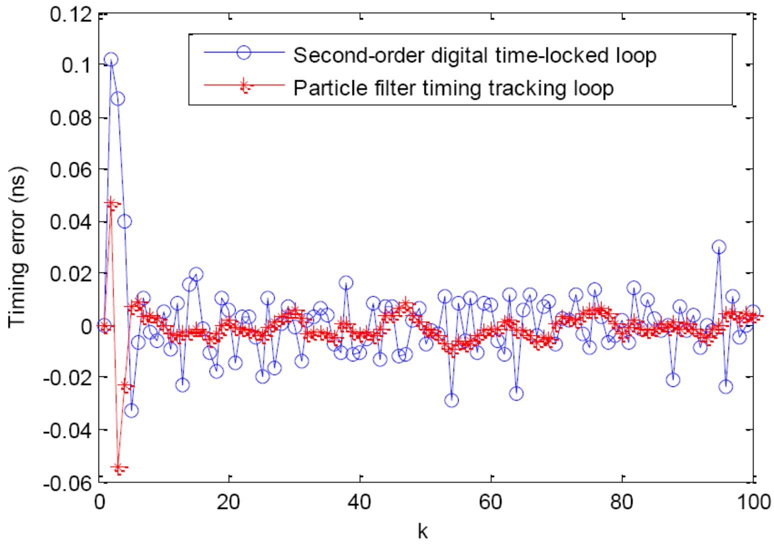

FIGURE 2. The timing error in an experiment

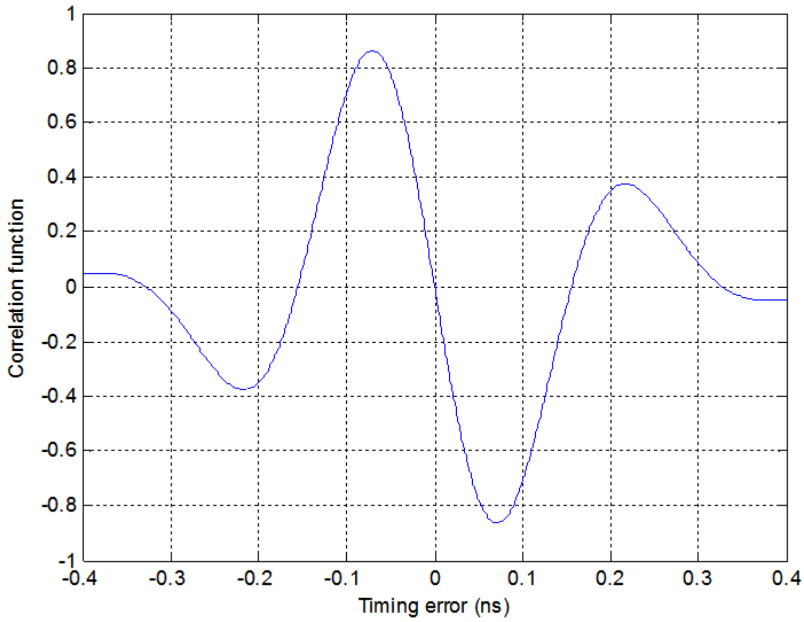

FIGURE 3. Correlation function curve

to design the particle filter timing loop and second-order digital time-locked loop, after many repeated experiments in average, the two filter's timing mean square error and Cramer-Rao lower bound in different observation noise variance are shown in Figure 5. Simulation and experimental results show that the timing mean square error of timing loop based on particle filter is smaller than second-order digital time-locked loop about an order of magnitude, and is close to the Cramer-Rao lower bound. When the observation noise variance is $\sigma_n^2 = 10^{-1}$, in particular, the larger deviation of second-order digital time-locked loop is due to the observation noise and occasional losing lock. When there is timing jitter, we can extend the lower bound to the $E(|\varepsilon_k|^2) \geq \sigma_n^2 \times \tau^2/(10 \times \pi) + \sigma_v^2$. When timing jitter is $\sigma_v^2 = 10^{-6}$, after several repeated experiments in average, the two filter's timing mean square error and Cramer-Rao Lower bound in different observation

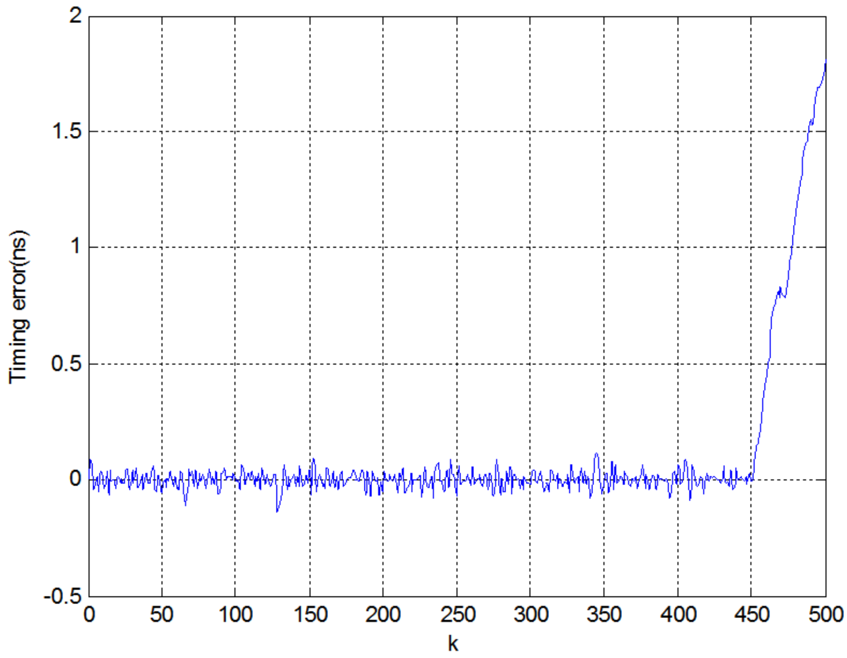

FIGURE 4. The phenomenon of losing lock about second-order digital time-locked loop in an experiment

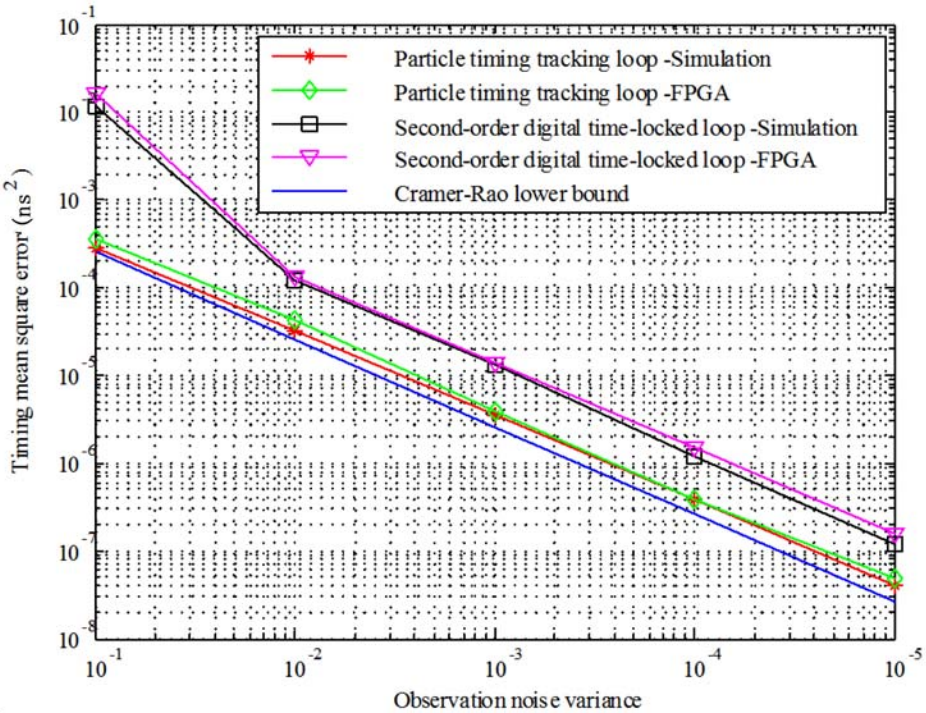

FIGURE 5. The timing mean square error in different observation noise variance without timing jitter

noise variance are shown in Figure 6. When the observation noise is larger, the timing error due to observation noise plays a dominant role; while it is smaller, the timing error due to timing jitter plays a dominant role.

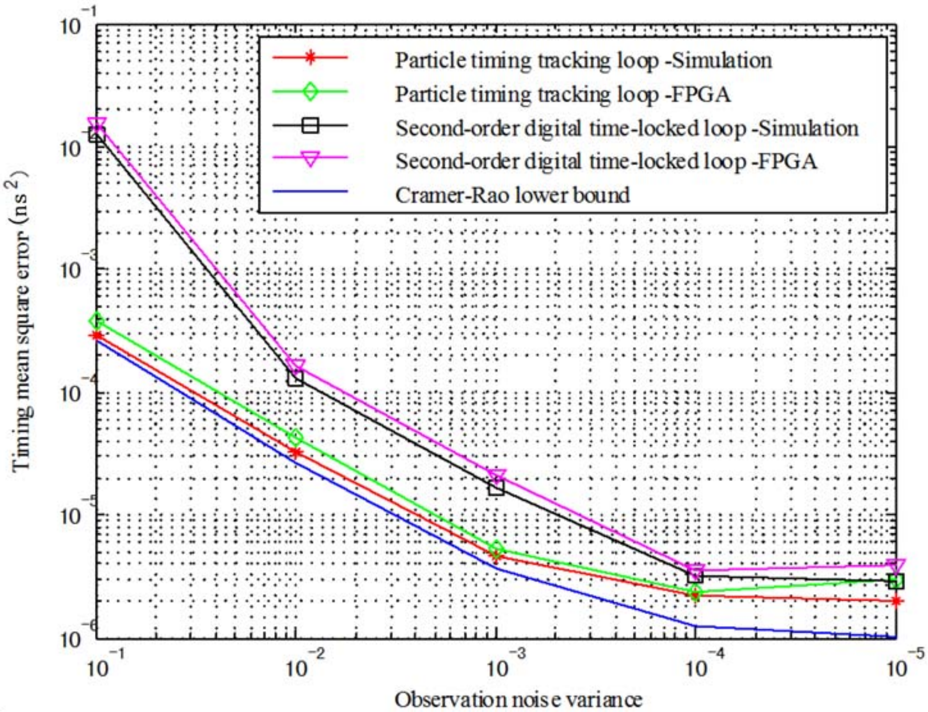

FIGURE 6. The timing mean square error in different observation noise variance with timing jitter

5. **Conclusions.** The timing loop based on particle filter is proposed in this paper. Compared with the second-order digital time-locked loop, it has a wider timing capture range and stronger stability when the observation noise is large. It can increase the timing accuracy about an order of magnitude and is close to Cramer-Rao lower bound. Due to the introduction of feedback, the timing tracking method provides a new solution to the application of particle filter in the time tracking.

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