A Dual-Tone Radio Interferometric Tracking System

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Abstract. Localization in wireless sensors networks (WSNs) has been increasingly significant recently due to the demand of the location-aware services. The low cost and high accuracy requirements make many positioning systems adopt high-accuracy quasi-synchronization method. However it remains synchronization errors which lower positioning and tracking precision within such systems. Hence, we propose a tracking system with low-accuracy quasi-synchronization method based on dual-tone radio interferometric signals. A mobile target emits dual-tone signals whose phases contain range information. Several anchors with known positions receive the dual-tone signals and extract their phase information. We cancel the synchronization error by differentiating two phases estimated from two consecutive time instants to increase accuracy. The tracking accuracy is evaluated by simulations. The tracking system enjoys low complexity, low cost and obtains a reasonable accuracy.

Keywords: Dual-tone radio interferometric · Quasi-synchronization · Tracking · Localization · Positioning

1 Introduction

A wireless sensor network (WSN) is a distributed and self-organizing network with lots of sensor nodes deployed [1]. They are applied in many fields including military detection, intelligent traffic, hospital supervision and care [2]. All the applications are based on the awareness of sensor locations. Therefore, accurate and efficient positioning technology is very important and urgent [3]. For example, firemen rescue people's life with high risk when fiermen's locations are unknown in fire disasters. It is safer for them when their positions are located accurately within the fireplaces.

Localization has been researched for years. The Global Positioning System (GPS) offers great convenience to people's life. However, the accuracy of traditional GPS is a few meters. Newly developed differential GPS is more accurate

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but expensive [4]. Additionally, GPS does not work well indoors, in dense forest or cluttered urban environments. So it is not suitable for localization in WSNs. Radio interferometric localization satisfies three of the requirements of wireless localization applications: high precision, low cost and low power. It can achieve centimeter scale accuracy. Hence, We intend to use interferometric technology for tracking. The radio interferometric positioning system (RIPS) [5] has been proposed and developed in WSNs. The RIPS could achieve high accuracy and low cost. Then it is extended in [6,7] for a tracking system, in which Doppler shifts are adopted to estimate the positions and velocities of the motion. Besides, the RIPS is developed in [8] to combat the flat-fading channels. Furthermore, a dual-tone radio interferometric positioning system using undersampling techniques (uDRIPS) avoids amplifying the noise and simplifying the receiver structure simultaneously [9]. However, most of these approaches are in demand of high-accuracy synchronization either among anchors or between the target and anchors.

Time synchronization is still a big obstacle in WSNs, in which the resource and energy are limited. However high-accuracy synchronization system where the synchronization error is less than 10 µs consumes additional energy, bandwidth and computational resources [10]. Besides, it is difficult to implemented in practice [11]. Furthermore, it exists synchronization errors which influence the positioning and tracking accuracy. Common synchronization mechanisms have synchronization errors which are around 50 µs. The average one hop error of the TPSN synchronization method is 21.43 µs [12] and DMTS's synchronization error is 30 µs [13].

Considering these reasons, we envision an approach based on RIPS to track a mobile target and remove all the synchronization errors in order to increase tracking precision. We adopt the common synchronization method to reduce high resource cost of the high-accuracy synchronization system and lower the system cost. It has the advantage of undersampling which avoids noise amplification. We extract the TOAs accompanied by synchronization error items from the phases of the dual-tone signals in our system. For different anchors, the synchronization errors are different. Each error is fixed once the system starts to work [11]. Here we consider the motion process as a series of uniform linear motions, and each motion is a moving step. We get TDOA to eliminate the offset in two successive moving steps. Then we get the difference of random two TDOAs (DTDOA) and establish relations between DTDOAs and the velocities. And use non-linear least squares method to work out the velocity. With the known initial position of the mobile target, we acquire the position of the target at randomly time. Then we got the motion curve.

The rest of the paper is structured as follows. Section 2 introduces system model. Section 3 describes the algorithm used to estimate the velocity and position of the mobile target. We provide simulation results of this approach in Sect. 4 and evaluate our algorithm. Section 5 contains the conclusions.

2 System Model

Let us assume M anchors with known locations. The moving target moves randomly within the zone, transmitting a dual-tone signal

$$s(t) = \gamma e^{j\varphi} e^{j2\pi(f_c+f_b)t}(1 + e^{j2\pi g_b t}), \tag{1}$$

where γ is the real-valued amplitude of each components, φ is the unknown initial phase offset, f_c is the carrier frequency, and f_b is the frequency difference between the two tones and greater than zero. The frequency g_b is the frequency difference between the two tones and greater than zero as well.

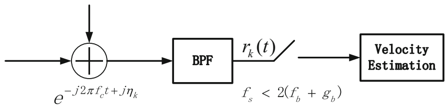

Fig. 1. The receiver structure of the tracking system

Figure 1 shows the receiver structure of the tracking system. The signal $s(t)$ goes through channels, down converted by f_c, and received by the kth anchor. We model the received signal as follows.

$$r_k(t) = \beta_k s\left(t - \tau_k - t_k\right) e^{-2\pi f_c + j\eta_k} + w_k\left(t\right), \tag{2}$$

Combining (1) and (2), we have

$$r_k(t) = \alpha_k \beta_k e^{j2\pi f_b t} e^{j\theta_k}(1 + e^{j2\pi g_b t} e^{j\phi_k}) + w_k(t), \tag{3}$$

where β_k is a complex channel coefficient attributing to the flat-fading channel effects, and can be modeled as a zero-mean complex Gaussian random variable with variance σ_k representing the average power of the flat-fading channel. The $\theta_k = -2\pi(f_c + f_b)(t_k + \tau_k), \phi_k = -2\pi g_b(t_k + \tau_k)$, and $\alpha_k = \gamma e^{j(\varphi+\eta_k)}$ are composite variables. The w_k represents the noise item. The α_k absorbs the effects of the random initial phases between the mobile target and the kth anchor. The unknown time t_k is the remaining time offset of kth anchor plus the transmission instant of the transmitter. The unknown initial phase η_k is due to the randomness of the receiver oscillator. Here ϕ_k includes the range of interest via τ_k which we are interested in. The assumptions as follows are adopted in the entire paper.

Assumption 1: The synchronization problem usually contains two elements which are time offset and skew [14]. Here we use quasi-synchronization [16] which only consider time offset. The synchronization error is t_k due to the low-accuracy synchronization between the mobile target and the kh anchor. Moreover, the synchronization errors are different to anchors according to the reality.

Assumption 2: We assume that the two tones of the dual-tone signal experience the same fading channel because the frequency difference g_b is set to be much smaller than the channel coherence bandwidth [16]. Hence in two centrosymmetric motions we will get the same measured data set and work out the same velocity. For example, when the target moves towards the x-axis positive or negative direction, the estimated velocity directions probably are all the x-axis negative directions or positive directions with the same velocity absolute value.

The received signal $r_k(t)$ is undersampled by a sampling frequency f_s ($f_s < 2(f_b + g_b)$) to lower the requirement of the equipments, at the same time to avoid amplifying the noise. After processing the sample data, we get a parameter $\phi_k = -2\pi g_b(t_k + \tau_k)$. It relates to transmission time and remaining time offset what we are interested. Next we will explain how ϕ_k can be calculated and the integer ambiguity problem. Collecting the kth anchor's samples into a vector r_k, we have

$$\mathrm{r}_k = \mathrm{A}\mathrm{x}_k,$$

where

$$\begin{aligned} \mathrm{x}_k &= [\alpha_k \beta_k e^{j\theta_k}, e^{j(\theta_k+\phi_k)}]^T \\ \mathrm{A} &= [L(f_b/f_s), L((f_b+g_b)/f]^T \\ L(f) &= [1, e^{j2\pi f}, \ldots, e^{j2\pi(L-1)f}]^T \end{aligned}$$

Finally, use the least-squares (LS) estimator to calculate x_k.

$$\hat{\mathrm{x}}_k = (\mathrm{A})^{\dagger}\mathrm{r}_k,$$

So the complex parameter ϕ_k can be estimated as

$$\hat{\phi}_k = \arg\{[\hat{\mathrm{x}}_k]_1^*[\hat{\mathrm{x}}_k]_2\} + 2\pi l,$$

where $[\mathrm{x}]_\mathrm{n}$ is the nth entry of the vector x. The integer ambiguity means the unknown integer l due to phase wrapping. We assume that the mobile positioning method is applied indoors. The target is moving in a limited space and let's assume as large as $1000\,\mathrm{m} \times 1000\,\mathrm{m}$. We could get the biggest $\phi_k = 2\pi g_b\left(\frac{1000\sqrt{2}}{3\times10^8} + t_k\right)$ where $g_b = 10\,\mathrm{kHz}$ in our system. According to the introduction, $t_k < 50\,\mu\mathrm{s}$. Hence, the $\phi_k < 2\pi$. We rewrite the formula above as

$$\hat{\phi}_k = \arg\{[\hat{\mathrm{x}}_k]_1^*[\hat{\mathrm{x}}_k]_2\} = -2\pi g_b(t_k + \tau_k),$$

This parameter is the key point to our tracking localization algorithm. The t_k here is brought about by the synchronization error between the mobile target and the kth anchor. The propagation time τ_k is the transmission time from mobile target and the k-th anchor and $d_k = \tau_k \nu$. The ν is the transmit speed of the dual-tone signal.

3 The Tracking Method

In this section, we will specifically present the steps to calculate the velocity and location of the mobile target.

3.1 The Movement Model of the Target

As we said, the mobile target moves in the interested zone in which M anchors are distributed to receive signals. Hypothesise the initial location of the mobile target is known as $[x_0, y_0]$. In order to describe conveniently later, we call the location $[x_n, y_n]$ as the nth step and denote as $T^n = [x_n, y_n]$. The ϕ_k^n means the ϕ estimated by the kth anchor when the mobile target in nth step.

$$\phi_k^n = -2\pi g_b(t_k + \tau_k^n), \tag{4}$$

The t_k is the remaining time offset, it varies only from different anchors. It does not change once the system begins to work. Then let us denote $\Delta\phi_k^n$ as the phase difference of the received signal at the kth anchor in the $(n+1)$th step and nth step.

$$\Delta\phi_k^n = \phi_k^{n+1} - \phi_k^n = -2\pi g_b(\tau_k^{n+1} - \tau_k^n), \tag{5}$$

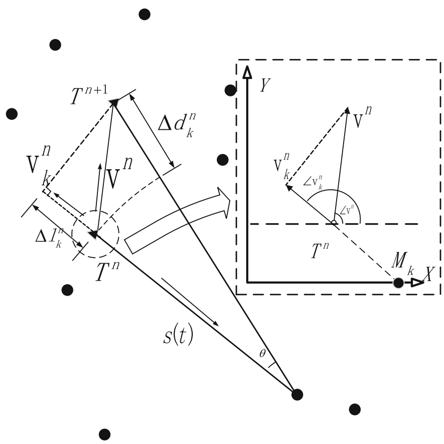

Fig. 2. The movement model of the target

Figure 2 shows the movement of the mobile target and the coordinate system we use. Let the black dots denote anchors and the black triangle indicates the mobile target. The M_k represents the kth anchor. The target moves from the nth step to the $(n+1)$th step (i.e. from T^n to T^{n+1} in Fig. 2). First we have an approximation that

$$\Delta d_k^n \approx \Delta l_k^n, \tag{6}$$

$$\Delta d_k^n = \nu(\tau_k^{n+1} - \tau_k^n), \tag{7}$$

where Δd_k^n is the distance difference of d_k in two adjacent steps (the nth step and the $(n+1)$th step), and Δl_k^n is a component of the distance $\|T^{n+1} - T^n\|$ at the radical direction (i.e. $M_k \to T^n(x_n, y_n)$). Next we will illustrate this approximate relationship. The tracking frequency can be set according to the reality. In this simulation let us hypothesis the target to be localized about 10 times per second in the tracking system. Usually the movement in such application setting is not very fast. In our movement model, we assume the mobile target moves at 5 m/s, the $\left\|T^{n+1} - T^n\right\|$ of two adjacent steps could be 0.5 m which is far less than the distance d_k between the mobile target and anchor. We have the experiment in a 1000 m × 1000 m squares, so the d_k is larger than 10 m. Hence, the $\theta \ll 5/100$ rad, then we have the last approximation. As a result, the radical component of mobile target's speed v, denoted as v_k^n, has relationship as follows:

$$\left|\mathrm{v}_k^n\right| = \frac{\Delta l_k^n}{t^{n+1} - t^n}, \angle \mathrm{v}_k^n = \angle(T^n - M_k), \tag{8}$$

where $\angle\mathrm{v}$ is the vector v's direction, defined as the angle with respect to x-axis. The $t^{n+1} - t^n$ means the time difference from nth step to $(n+1)$th step. According to the reality, decrease the positioning frequency will impair the reality of the tracking route. In this paper, we assume $t^{n+1} - t^n = 0.1$ s and we know that to decrease the parameter could increase the positioning accuracy. Combining (6), (7) and (8), we get

$$\left|\mathrm{v}_k^n\right| = \frac{\nu(\tau_k^{n+1} - \tau_k^n)}{t^{n+1} - t^n}. \tag{9}$$

We know that v_k^n is the radical velocity of v relative to the kth anchor. The ν is the transmit speed of the dual-tone signal. Therefore we get

$$\left|\mathrm{v}_k^n\right| = \left|\mathrm{v}^n\right| \cos(\angle\mathrm{v}^n - \angle\mathrm{v}_k^n). \tag{10}$$

In order to calculate the $\left|\mathrm{v}^n\right|$ and $\angle\mathrm{v}^n$ which are the moving speed and moving angle, we select any two anchors from M anchors. We might as well select the kth and jth anchors. Then we get

$$\left|\mathrm{v}_k^n\right| - \left|\mathrm{v}_j^n\right| = -2\left|\mathrm{v}^n\right| \sin\left(\frac{\angle\mathrm{v}_k^n - \angle\mathrm{v}_j^n}{2}\right) \sin\left(\frac{\angle\mathrm{v}_k^n + \angle\mathrm{v}_j^n}{2} - \angle\mathrm{v}^n\right). \tag{11}$$

$$\Delta\phi_{kj}^n = \Delta\phi_k^n - \Delta\phi_j^n = -2\pi g_b((\tau_k^{n+1} - \tau_k^n) - (\tau_j^{n+1} - \tau_j^n)),$$

Combining (9) and (11), we arrive at

$$\frac{\nu((\tau_k^{n+1} - \tau_k^n) - (\tau_k^{n+1} - \tau_k^n))}{t^{n+1} - t^n} = -2\left|\mathrm{v}^n\right| \sin\left(\frac{\angle\mathrm{v}_k^n - \angle\mathrm{v}_j^n}{2}\right) \sin\left(\frac{\angle\mathrm{v}_k^n + \angle\mathrm{v}_j^n}{2} - \angle\mathrm{v}^n\right),$$

Finally, combining the last two equations above, we obtain

$$\Delta\phi_{k,j}^n = a\left|\mathrm{v}^n\right| \sin b_{k,j} \sin(c_{k,j} - \angle\mathrm{v}^n), \tag{12}$$

where $a = \frac{4\pi g_b}{t^{n+1} - t^n}$ which is composite control variable. The parameter $b_{k,j} = \frac{\angle\mathrm{v}_k^n - \angle\mathrm{v}_j^n}{2}, c_{k,j} = \frac{\angle\mathrm{v}_k^n + \angle\mathrm{v}j^n}{2}$ which need to be calculated by (8). Equation (12) has two parameters, the target's speed magnitude $\left|\mathrm{v}^n\right|$ and direction $\angle\mathrm{v}^n$, which need to be solved.

we rewrite (12) as

$$\Delta\phi_{k,j}^n = f_{k,j}\left(\left|\mathrm{v}^n\right|, \angle\mathrm{v}^n\right). \tag{13}$$

The two parameters could be estimated only if we have two equations. As we said above, k, j is chosen arbitrarily. Generally, the system installs ($M \geq 3$) anchors, and offers $N = C_M^2 > M$ equations. Therefore, we get more information from less anchors which decrease the complexity of the system. Then we denote a matrix equation as

$$\Delta\Phi = a1_N \left|\mathrm{v}^n\right| \sin \mathrm{b} \sin(\mathrm{c} - \angle \mathrm{v}^n). \tag{14}$$

For convenience we denote Eq. 14 as $\Delta\Phi = F\left(\left|\mathrm{v}^n\right|, \angle \mathrm{v}^n\right)$, where F is the matrix form of functions $\{f_{1,2}, \ldots, f_{M-1,M}\}$. The parameter $\Delta\Phi = [\Delta\phi_{1,2}, \Delta\phi_{1,3}, \cdots, \Delta\phi_{M-1,M}]^T$ which is a measurement vector, $\mathrm{b} = [b_{1,2}, b_{1,3}, \cdots, b_{M-1,M}]^T$. Similarly, $\mathrm{c} = [c_{1,2}, c_{1,3}, \cdots, c_{M-1,M}]^T$. Due to noise influence and machine error, there is no exact $\{\left|\mathrm{v}^n\right|, \angle \mathrm{v}^n\}$ to satisfy (14). Instead, we estimate such $\{\left|\hat{\mathrm{v}}^n\right|, \angle \hat{\mathrm{v}}^n\}$ so that $\left\|F\left(\left|\mathrm{v}^n\right|, \angle \mathrm{v}^n\right) - \Delta\Phi\right\|$ is minimized.

3.2 The Tracking Algorithm

In this part we will use the theory of the non-linear least squares methods (NLS) [17] to solve the moving velocities and calculate the positions. As we need to minimized the $\left\|F\left(\left|\mathrm{v}^n\right|, \angle \mathrm{v}^n\right) - \Delta\Phi\right\|$, we use least square method to estimate. Then define a new function $\mathscr{F} : R^2 \to R$, then

$$\mathscr{F}\left(\left|\mathrm{v}^n\right|, \angle \mathrm{v}^n\right) = \sum_{k=1,j>k}^{M} \left(\Delta\phi_{k,j} - f\left(\left|\mathrm{v}^n\right|, \angle \mathrm{v}^n\right)\right)^2, \tag{15}$$

We start with an initial approximation of the estimated augment $\{\left|\hat{\mathrm{v}}^n\right|, \angle \hat{\mathrm{v}}^n\}$, linearize $\mathscr{F}$ and update the estimated augment continuously until the object function converges to its local minimum.

We can get the new location as follows

$$\hat{T}^n = HQ,$$

where $\hat{T}^n = [\hat{x}^n, \hat{y}^n]^T$, $Q = [\hat{x}^{n-1}, \hat{y}^{n-1}, \hat{\mathrm{v}}_x^n, \hat{\mathrm{v}}_y^n]$, $\hat{\mathrm{v}}_x^n = \left|\hat{\mathrm{v}}^n\right| \cos(\angle \hat{\mathrm{v}}^{\mathrm{n}}), \hat{\mathrm{v}}_{\mathrm{y}}^{\mathrm{n}} = \left|\hat{\mathrm{v}^{\mathrm{n}}}\right| \sin(\angle \hat{\mathrm{v}}^{\mathrm{n}})$. H is the state transition matrix which is modeled as

$$H = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \end{bmatrix} \tag{16}$$

where $\Delta t = t_{n+1} - t_n = 1/f$ is the reciprocal of the positioning frequency f. As long as we know the initial position $T^0 = [x^0, y^0]$, then we can get the position $\hat{T^n}$ and velocity $\{|\hat{\mathrm{v}^n}|, \angle \hat{\mathrm{v}^n}\}$ of any moment.

4 Simulation Results

In this section, we evaluate the performance of our positioning algorithm. We compare the positioning accuracy by changing the undersampling frequency f_s

and the Signal-noise ratio. We set the parameters like this: (1) We set the frequency difference $g_b = 10\,\text{kHz}$. Because the typical channel coherence bandwidth is 100 kHz which needs to be larger than the frequency difference [18]. (2) The positioning interval is set as $\Delta t = 0.1\,\text{s}$. Actually this constant could influence the simulation graphs of mobile curves. Besides, it relates closely to the energy consumption. When we decrease Δt, it means that increase positioning number per second and add energy consumption. Otherwise, the mobile model does not fit the approximation equation in (6). So we choose $\Delta t = 0.1\,\text{s}$ which is neither long nor short. We also simulated the condition when $\Delta t = 0.01\,\text{s}$. However, the simulation result is similar to this condition except consume more time and energy to over-frequent positioning. It indicates that $\Delta t = 0.01\,\text{s}$ is suitable. (3) The amplitude of the transmitted signal is $\gamma = 1$, and the carrier frequency $f_c = 2.45\,\text{GHz}$ [19]. (4) The average channel power of the flat-fading channel is set to be 1 as usual in simulation for all channels,i.e.,$\sigma_k^2 = 1, k = 1, \ldots, M$. (5) The transmission velocity of radio signal is $\nu = 3 \times 10^8\,\text{m/s}$. (6) For each estimation, operate 1000 Monte-Carlo runs to evaluate performance. (7) The positioning accuracy is evaluated with eight anchors and a mobile target. The coordinates for eight anchors are as follows like this $M_1 = [0,0]^T, M_2 = [1000,0]^T, M_3 = [1000,1000]^T, M_4 = [0,1000]^T, M_5 = [700,700]^T, M_6 = [400,800]^T, M_7 = [100,500]^T, M_8 = [600,300]^T$.

Figure 3 shows the variable motion with the speed direction and value change. It consists of three constant motion parts. The direction of arrow represents the speed direction. The dots denote the initial position of mobile target in every step. The inflection points represent the direction change of mobile target. In Fig. 3 velocity range is $2\,\text{m/s} \leq |\text{v}| \leq 7\,\text{m/s}$. The direction of speeds change is $\pi/6 \leq \angle\text{v} \leq \pi/2$. The maximum direction change is $3/\pi$. The signal-to-noise ratio (SNR) is defined as 1/s2, and SNR = 30 db. The $\Delta t = 0.1\,\text{s}$, and $f_s = 30\,\text{kHz}$. Figure 4 shows the CDF of x-axis, y-aixs and average positioning

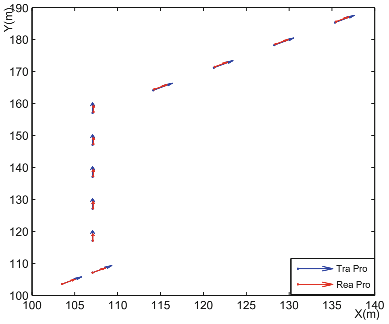

Fig. 3. The variable motion of real process and tracking process

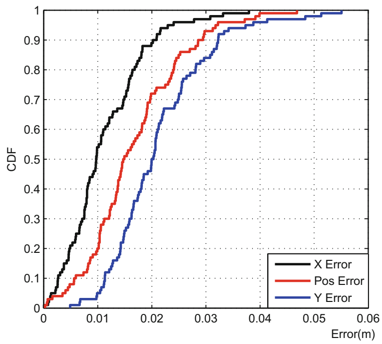

Fig. 4. The CDF of absolute positioning error at x–axis, y–axis and average in variable motion

error of variable motion. The average position error is defined as $\sqrt{\frac{\Delta x^2+\Delta y^2}{2}}$. We concluded that 90% of the average position errors are less than 3 cm, and the errors in x-axis are less than the error in y-axis. The reason is that the anchors distributed on x-axis direction is more evenly than on y-axis direction.

Furthermore, we simulate the relations among positioning accuracy, the undersampling frequency and SNR. The SNR is defined as $1/\sigma^2$. Figures 5 and 6 show the relations. The location accuracy increases when the sampling frequency increases and SNR increases. Because when the sampling frequency f_s increases, the sample information is more detailed. It helps to estimate the needed parameter exactly. As SNR increases, the dual-tone signal becomes stronger.

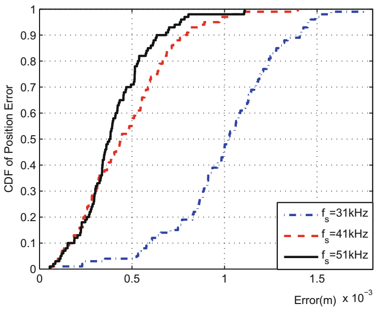

Fig. 5. The variable motion of real process and tracking process

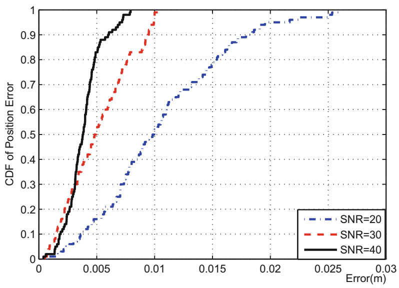

Fig. 6. The CDF position errors at different SNRs

5 Conclusion

In this paper, we propose a tracking system based on dual-tone radio interferometric signals for WSNs. Several anchors with known positions receive the dual-tone signals which are emitted by a mobile target. The key innovation in our tracking system is eliminating the remaining time offsets of the low-accuracy synchronization upon the target and anchors. By differentiating the phase estimation of two consecutive time instants, we can remove the remaining time offsets between the target and anchors. Finally, We concluded that of the average position error are less than 3 cm in viable motion tracking. The low-complexity tracking algorithm is simulated and is proved efficient in tracking.

References

1. Ma, Z., Sun, Y., Mei, T.: Survey on wireless sensors network. China Inst. Commun. **5**(4), 114–124 (2004)
2. Han, G., Xu, H., Duong, T.Q., Jiang, J., Hara, T.: Localization algorithms of wireless sensor networks: a survey. Telecommun. Syst. **52**(4), 2419–2436 (2013)

3. Wang, J., Wang, F., Duan, W.: Application of weighted least square estimates on wireless sensor network node localization. Appl. Res. Comput. **9**, 11 (2006)
4. Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J.: Global Positioning System: Theory and Practice. Springer Science Business Media, Heidelberg (2012)
5. Maróti, M., Völgyesi, P., Dóra, S., Kusý, B., Nádas, A., Lédeczi, Á., Balogh, G., Molnár, K.: Radio interferometric geolocation. In: Proceedings of ACM on Embedded Networked Sensor Systems, pp. 1–12 (2005)
6. Kusy, B., Ledeczi, A., Koutsoukos, X.: Tracking mobile nodes using RF Doppler shifts. In: Proceedings of ACM on Embedded Networked Sensor Systems, pp. 29–42 (2007)
7. Kusy, B., Sallai, J., Balogh, G., Ledeczi, A., Protopopescu, V., Tolliver, J., DeNap, F., Parang, M.: Radio interferometric tracking of mobile wireless nodes. In: Proceedings of the ACM on Mobile Systems, pp. 139–151 (2007)
8. Wang, Y., Ma, X., Chen, C., Guan, X.: Designing dual-tone radio interferometric positioning systems. IEEE Trans. Sign. Process. **63**(6), 1351–1365 (2015)
9. Wang, Y., Li, L., Ma, X., Shinotsuka, M., Chen, C., Guan, X.: Dual-tone radio interferometric positioning systems using undersampling techniques. IEEE Lett. Sig. Process. **21**(11), 1311–1315 (2014)
10. Singh, V., Sharma, S., Sharma, T.: Time synchronization in WSN: a survey. Int. J. Enhanc. Res. Sci. Technol. Eng. **2**(5), 61–67 (2013)
11. Sivrikaya, F., Yener, B.: Time synchronization in sensor networks: a survey. IEEE Network **18**(4), 45–50 (2004)
12. Ganeriwal, S., Kumar, R., Srivastava, M.B.: Timing-sync Protocol for Sensor Networks. In: Proceedings of the 1st International Conference on Embedded Networked Sensor Systems, pp. 138–149. ACM Press (2003)
13. Ping, S.: Delay measurement time synchronization for wireless sensor networks. Intel Research, Berkeley Lab (2003)
14. Noh, K.-L., Chaudhari, Q.M., Serpedin, E., Suter, B.W.: Novel clock phase offset and skew estimation using two-way timing message exchanges for wireless sensor networks. IEEE Trans. Commun. **55**(4), 766–777 (2007)
15. Schaefer, M.: Quasi-synchronization of readers and writers in a multi-level environment. Technical report TM-5407/003, System Development Corporation (1974)
16. Simon, M.K., Alouini, M.S.: Digital Communication Over Fading Channels, vol. 95. Wiley, Hoboken (2005)
17. Madsen, K., Nielsen, H.B., Tingleff, O.: Methods for non-linear least squares problems (2004)
18. Molisch, A.F., Win, M.Z., Winters, J.H.: Space-time-frequency STF coding for MIMIO-OFDM systems. IEEE Commun. Lett. **6**(9), 370372 (2002)
19. Shen, Z., Papasakellariou, A., Montojo, J., Gerstenberger, D., Xu, F.: Overview of 3GPP lte-advanced carrier aggregation for 4G wireless communications. IEEE Commun. Mag. **50**(2), 122–130 (2012)