Analysis on the TOA Tracking With DVB-T Signals for Positioning

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***Abstract*—The digital television signal is a promising signal of opportunity for ubiquitous wireless positioning. This letter analyzes the time of arrival (TOA) tracking errors of the European standard digital video broadcasting-terrestrial (DVB-T) signals in the context of positioning. The Cramér–Rao lower bound on the unsmoothed TOA estimation is derived and an information-theoretic lower bound (ITLB) is further computed on the smoothed TOA tracking errors in delay locked loop (DLL). Theoretical analysis shows that, the increase of the bandwidth of the equivalent loop filter will lead to larger DLL tracking errors. Despite different bandwidth of the loop filters, the tracking errors derived in theory are asymptotic to ITLB with the increase of signal-noise ratio. Comparatively, the theoretical results of the DLL tracking errors are slightly larger than the ITLB, which is due to the inequality and nonlinear approximation used in the analysis. Theoretical analysis has also verified the effectiveness of the DVB-T signals to be able to achieve high accuracy in positioning.**

***Index Terms*—Digital TV, wireless positioning, orthogonal frequency division multiplexing (OFDM), time of arrival, delay locked loop, Cramér-Rao lower bound.**

I. Introduction

GLOBAL Navigation Satellite Systems (GNSS) have been put into use in mass-market applications in recent years. However, as it is well known, the signal availability and the positioning accuracy dramatically deteriorate when these systems are operated in challenging environments, such as indoors and urban canyons [1]. Recently, digital broadcasting systems, such as Digital Video Broadcasting (DVB), Digital Audio Broadcasting (DAB), and the Advanced Television Systems Committee(ATSC) standards, have been widely used as an alternative information transmission technique [2]. It has been recognized that novel wireless location methods can be designed by utilizing the terrestrial digital broadcasting signals [3]–[9]. Compared with the GNSS, wireless positioning based on the digital broadcasting has potential advantages: the signal transmission power is stronger and the frequency band is within $300 - 900$ MHz, which contribute to better diffraction performance than the currently used GPS L1 or Galileo E1 of around 1.5 GHz. Therefore, a better receiving quality indoors is expected [10]. The nominal signal bandwidth of the terrestrial digital TV (DTV) broadcasting is designed between $6 - 8$ MHz, which is much larger than the chipping rate of GPS L1 or Galileo E1 signals. This will improve the precision of timing. In contrast to the GNSS, the location of the DTV transmitters are fixed and the range between the DTV transmitters and the receivers changes very slowly. As a consequence, the DTV signal does not experience significantly the Doppler effects nor the impairment caused by the delay of ionosphere propagation, which will lead to easier signal acquisition and the possibility of integration over a longer period of time [3]. As a signal of opportunity (SoO) for positioning, the DTV facilities have already been in use and no more infrastructure investment is required, except the positioning devices [11].

Among all the terrestrial DTV standards, the European standard DVB-T [12] has been applied most widely in the world [2]. It is therefore reasonable to predict that the wireless position based on DVB-T system might have massive potential users in the future. The DVB-T uses the OFDM (orthogonal frequency division multiplexing) modulation to achieve robust transmission in multipath scenarios. From the perspective of wireless positioning, the following properties in DVB-T system can be utilized [4]. Firstly, DVB-T signals are continuously transmitted and each OFDM symbol is transmitted within a fixed duration, which enables the receiver to continuously track the arrival of signal and thus improve the accuracy of the timing-based estimation for positioning. Secondly, the pilot subcarriers in each OFDM symbol are given by a known Pseudo-Random Binary Sequence (PRBS) and the amplitudes are boosted. Therefore, by exploiting the autocorrelation property of the PRBS in the pilots, it is promising to achieve the accurate delay estimation for positioning. Lastly, multiple emitters are suggested in [12] to transmit the same signals in the same frequency simultaneously, which is called single frequency network (SFN) transmission. The network synchronization among the multiple emitters makes the timing-based estimation (TOA/TDOA) available.

Research interest in positioning using OFDM based DVB-T signals has grown rapidly. For the purpose of high accuracy positioning and navigation with the OFDM signals, there are several methods to determine the time of arrival (TOA) proposed in the literature. To enumerate a few, one method is based on a sliding correlator for the coarse timing acquisition by using the property of OFDM cyclic prefix [13]. Another method is to use Delay-locked loop (DLL) or early-minus-late (EML) loop for a finer timing tracking [14]. Scatter pilots [5], [15], [16] or the full OFDM symbols demodulated from the receiver [6] have been used as the local template in the DLL. A complete software defined radio (SDR) based DVB-T receiver is developed to estimate the time of arrival (TOA) for positioning in [4]. Outdoor field tests showed that, the achieved 2-σ error intervals are about 1 - 4 meters depending on different signal-noise ratio (SNR) conditions.

In this paper, we will focus on the theoretical analysis on the time of arrival (TOA) tracking errors of DVB-T signals. The results we derive could be used as the theoretical basis for evaluating the accuracy of the practical TOA based ranging method with DVB-T signals. In addition, the methodology is completely general, which will be useful in predicting the performance for TOA ranging method with other OFDM based signals. The paper is organized as follows: Section II briefly describes TOA estimation and tracking method of the DVB-T signals. Section III derives DLL tracking errors of DVB-T signals. Section IV presents the Cramér-Rao lower bound (CRLB) on

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the unsmoothed TOA estimate and the information-theoretic lower bound (ITLB) on the DLL tracking errors. The theoretical tracking errors are compared with the ITLB. Finally, in Section V, conclusions are summarized.

II. The TOA Tracking of DVB-T Signals for Positioning

A whole scheme of the SDR DVB-T receiver for TOA estimation is presented in [4]. In principle, the TOA estimation is to find the start instant of the OFDM symbols as accurately as possible. As a typical wireless transmission system, DVB-T signals usually travel along multiple paths, arising from reflection, scattering and diffraction, which are due to numerous obstacles in the propagation environment. At the receiver, there generally exist symbol-timing offset (STO), carrier-frequency offset (CFO), and sampling clock offset (SCO) [17]. Therefore, to track the first arrival path, three steps are carried out. The first step is coarse synchronization, which is to find the start of OFDM symbol in the accuracy of one sample period. Due to the various offsets and the multipath, the estimated timing errors in coarse synchronization could be as large as tens of samples. Then a second step called acquisition is carried out, which aims to detect the multipath and acquire the first path of arrival within a fraction of a sample period. By applying the above synchronization steps, the residual timing and frequency errors are small enough for the data demodulation. However, for the purpose of positioning and navigation, further refinement steps that aim to find more accurate symbol timing are necessary. Therefore, after the first path is acquired and as the third step, DLL tracking loops are then implemented to filter the time delay and to achieve even more accurate TOA estimation.

To analyze the tracking errors of the DLL output, the operation of the DLL is formulated as follows. Let us assume that after the acquisition step, the time delay of the first path arrival τ is estimated as $\hat{\tau}$, and the received signal sampled at time k is defined as $r(k)$. By taking advantage of the time shift property of the N-point discrete Fourier transform, i.e., $\mathcal{F}\{r(k \pm \tau)\} = d(n) \cdot \exp(\pm j\frac{2\pi n\tau}{N})$, which transforms the time delay estimation to the problem of phase estimate in frequency domain, we can write the phase adjusted received pilots as

$$\hat{d}_i(p) = e^{-j\frac{2\pi p\hat{\tau}}{N}} d_i(p), p \in \mathcal{P}_s \tag{1}$$

where $d_i(p)$ denotes the received pth scattered pilot subcarrier in ith symbol, $\mathcal{P}_s$ the set of index sequences of all the scattered pilot subcarriers. The received pilots are then cross-correlated with the locally generated early and late reference pilots. The locally generated early and late reference pilots are given by

$$\begin{aligned} c_{i,e}(p) &= e^{+j\frac{2\pi p\xi}{N}} c_i(p) \\ c_{i,l}(p) &= e^{-j\frac{2\pi p\xi}{N}} c_i(p) \end{aligned} \tag{2}$$

where $c_i(p)$ is the local replica of the scattered pilots in the ith symbol, and $\xi (0 < \xi < 1/2)$ is the advanced (and retarded) interval which is normalized to the OFDM sample interval. Let us define a modified cross-correlation function of the received scattered pilots with its replica as

$$R_i(\epsilon) = \frac{1}{N_p} \sum_{p\in\mathcal{P}_s} \hat{d}_i(p) \cdot c_i^*(p) \tag{3}$$

where $\epsilon = \tau - \hat{\tau}$, N_p is the number of the scattered pilot subcarriers in ith OFDM symbol. Accordingly, we can write the early and the late cross-correlation branch output as

$$\begin{aligned} R_{i,e}(\epsilon) &= \frac{1}{N_p} \sum_{p\in\mathcal{P}_s} \hat{d}_i(p) \cdot c_{i,e}^*(p) \\ R_{i,l}(\epsilon) &= \frac{1}{N_p} \sum_{p\in\mathcal{P}_s} \hat{d}_i(p) \cdot c_{i,l}^*(p) \end{aligned} \tag{4}$$

We apply the Early-Minus-Late Power (EMLP) discriminator for DLL tracking. The normalized discriminator is expressed as:

$$a_i(\epsilon) = \frac{1}{k_d}\left(|R_{i,e}(\epsilon)|^2 - |R_{i,l}(\epsilon)|^2\right) \tag{5}$$

where the normalization factor k_d is to keep $a_i(\epsilon) \approx \epsilon$ when $\epsilon \to 0$. By smoothing the discriminator $a_i(\epsilon)$ with a loop filter, the delay estimate of the $(i+1)$th OFDM symbol is updated by

$$\hat{\tau}_{i+1} = \hat{\tau}_i + \tilde{\epsilon}_i \tag{6}$$

where $\tilde{\epsilon}_i$ is the output from the loop filter of the ith symbol.

III. Theoretic Analysis on DLL Tracking Errors

A. Ideal Autocorrelation Function (ACF) of Pilot Signals

We start the theoretic analysis from the ideal autocorrelation function of the pilots. Without the noise, the normalized ideal ACF of pilot sequence is calculated as

$$\begin{aligned} R_i^o(\epsilon) &= \frac{1}{N_p} \sum_{p\in\mathcal{P}_s} c_i(p) \cdot \left(c_i(p) \cdot e^{-j\frac{2\pi p\epsilon}{N}}\right)^* \\ &= \frac{1}{N_p} \sum_{p\in\mathcal{P}_s} c_i(p) \cdot c_i^*(p) \cdot e^{j\frac{2\pi p\epsilon}{N}} \end{aligned} \tag{7}$$

In DVB-T, the pilots are inserted every 12 subcarriers. Denote $\mathrm{E}[c_i(p) \cdot c_i^*(p)] = A$, where $\mathrm{E}[\cdot]$ denotes statistical expectation. Thus (7) is equal to

$$R_i^o(\epsilon) = \frac{1}{N_p} A e^{\frac{j\pi[2p_i(0)+12(N_p-1)]\tau}{N}} \frac{\sin \pi 12 N_p \epsilon/N}{\sin \pi 12\epsilon/N} \tag{8}$$

where $p_i(0)$ is the index of the first scattered pilot in ith symbol. Furthermore, since $N \gg 1$ (for a commonly used 8k mode in DVB-T, $N = 8196$) and for small values of τ within several samples, the following approximations validate: $[2p(0) + 12(N_p - 1)]/N \approx 1$ and $\sin\frac{\pi 12\epsilon}{N} \approx \frac{\pi 12\epsilon}{N} \to 0$. Therefore, the correlation function (8) can be simplified as

$$R_i^o(\epsilon) = Ae^{j\pi\epsilon}\mathrm{sinc}(\pi\beta\epsilon) \tag{9}$$

where $\beta = \frac{12N_p}{N} \approx 0.832$ [4].

The ideal ACF is shown in Figure 1. Reference [4] compares the ACF of DVB-T signals with the GPS C/A code and the Galileo E1 code and evaluates the DLL sensitivity to multipath with the multipath error envelop (MEE).

B. Analysis on TOA Tracking Error

We consider an AWGN channel with a high enough SNR. The early cross-correlation branch output in such scenarios can be written as

$$R_{i,e}(\epsilon) = Ae^{j\pi\epsilon}\mathrm{sinc}(\pi\beta(\epsilon - \xi))) + n_e \tag{10}$$

where

$$n_e = \frac{1}{N_p} \sum_{p\in\mathcal{P}_s} c_i(p) \cdot e^{j\frac{2\pi p\xi}{N}} n_i(p) \tag{11}$$

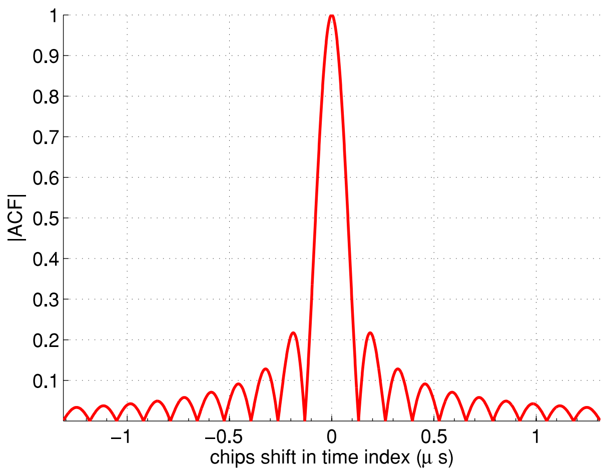

Fig. 1. Ideal ACF of DVB-T signal with 8K mode (the signal bandwidth is 9.14 MHz).

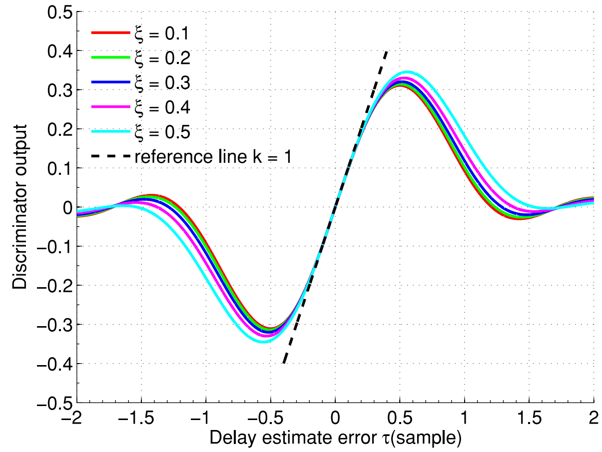

Fig. 2. DLL S curve.

where $n_i(p)$ is a white complex Gaussian noise with variance $\frac{\sigma^2}{N}$. It can be derived that in (11), n_e is a discrete-time independent identically distributed (i.i.d) complex Gaussian process with zero mean and the variance $\sigma_{n_e}^2 = \frac{A\sigma^2}{N_p \cdot N}$.

The mean of $|R_{i,e}(\epsilon)|^2$ is

$$\mathrm{E}\Big[|R_{i,e}(\epsilon)|^2\Big] = A^2 \mathrm{sinc}^2(\pi\beta(\epsilon - \xi))) + \sigma_{n_e}^2 \tag{12}$$

The variance of $|R_{i,e}(\epsilon)|^2$ is

$$\begin{aligned} \mathrm{var}\Big[\big|R_{i,e}(\epsilon)\big|^2\Big] &= A^2 \mathrm{sinc}^2(\pi\beta(\epsilon - \xi))\sigma_{n_e}^2 + \left(\sigma_{n_e}^2\right)^2 \\ &= \frac{A^2\sigma^4}{N_p^2 N^2} + \frac{2A^3\sigma^2}{N_p N}\mathrm{sinc}^2(\pi\beta(\epsilon - \xi)) \\ &= \frac{A^2\sigma^4}{N_p^2 N^2}\Big(1 + 2N_p \cdot \mathrm{SNR} \cdot \mathrm{sinc}^2(\pi\beta(\epsilon - \xi))\Big) \end{aligned} \tag{13}$$

where var[·] is the variance and SNR $\triangleq A/(\sigma^2/N)$.

Similarly, by replacing ξ with $-\xi$ in (10)-(13), the output of the late cross-correlation $R_{i,l}(\epsilon)$, the mean and variance of $|R_{i,l}(\epsilon)|^2$ can also be derived.

Therefore, the unnormalized tracking errors are generated as:

$$a_i'(\epsilon) = \big|R_{i,e}(\epsilon)\big|^2 - \big|R_{i,l}(\epsilon)\big|^2 \tag{14}$$

1) The Calculation of k_d: Define S-curve $S(\epsilon, \xi)$ as the mean of $a_i'(\epsilon)$, i.e.,

$$S(\epsilon, \xi) = \mathrm{E}\big[a_i'(\epsilon)\big] = A^2\Big(\mathrm{sinc}^2(\pi\beta(\epsilon - \xi)) - \mathrm{sinc}^2(\pi\beta(\epsilon + \xi))\Big) \tag{15}$$

To get a normalized S-curve, the normalization factor k_d in (5) is derived as:

$$\begin{aligned} k_d &= \frac{\partial S(\epsilon, \xi)}{\partial \epsilon}\Big|_{\epsilon=0} \\ &= \frac{2A^2}{\pi^2\beta^2\xi^3}[\pi\beta\xi\sin(2\pi\beta\xi) + \cos(2\pi\beta\xi) - 1] \end{aligned} \tag{16}$$

Figure 2 illustrate the normalized S curve when the value of ξ is chosen from 0.1 to 0.5.

2) The Variance of the Tracking Errors: the variance of the loop noise in (14) is

$$\begin{aligned} \mathrm{var}\big[a_i'(\epsilon)\big] &= \mathrm{var}\Big[\big|R_{i,e}(\epsilon)\big|^2\Big] + \mathrm{var}\Big[\big|R_{i,l}(\epsilon)\big|^2\Big] \\ &\quad - 2\mathrm{cov}\Big[\big|R_{i,e}(\epsilon)\big|^2, \big|R_{i,l}(\epsilon)\big|^2\Big] \\ &\le \mathrm{var}\Big[\big|R_{i,e}(\epsilon)\big|^2\Big] + \mathrm{var}\Big[\big|R_{i,l}(\epsilon)\big|^2\Big] \\ &= \frac{2A^2\sigma^4}{N_p^2 N^2}\Big(1 + 2N_p \cdot \mathrm{SNR} \cdot \mathrm{sinc}^2(\pi\beta\xi)\Big) \\ \epsilon &= 0,\ 0 < \xi \le 1/2 \end{aligned} \tag{17}$$

where cov[·] is the covariance. The inequality in (17) has been proved in [14]. Consequently, the variance of the normalized loop noise in (5) is

$$\begin{aligned} \mathrm{var}[a_i(\epsilon)] &= \frac{\mathrm{var}\big[a_i'(\epsilon)\big]}{k_d^2} \\ &\le \frac{2}{k_c^2 N_p^2}\frac{1}{\mathrm{SNR}}\left(\frac{1}{\mathrm{SNR}} + 2N_p \mathrm{sinc}^2(\pi\beta\xi)\right) \end{aligned} \tag{18}$$

where $k_c = k_d/A^2$.

Suppose B_l be the one-sided loop bandwidth and the loop is updated every T_s second. Therefore, the smoothed variance at the output of the loop filter can be approximated using a result of [18]:

$$\begin{aligned} \mathrm{var}[\bar{\epsilon}] &\approx 2B_l \cdot T_s \cdot (1 - 0.5B_l \cdot T_s) \cdot \mathrm{var}[a_i(\epsilon)] \\ &\approx 2B_l \cdot T_s \cdot \mathrm{var}[a_i(\epsilon)] \end{aligned} \tag{19}$$

where the second approximation is valid when $B_l \cdot T_s$ is small. In our case, (19) is further calculated as

$$\begin{aligned} \mathrm{var}[\bar{\epsilon}] &\le \frac{4B_l \cdot T_s}{k_c^2 \cdot N_p^2}\frac{1}{\mathrm{SNR}}\left(\frac{1}{\mathrm{SNR}} + 2N_p \mathrm{sinc}^2(\pi\beta\xi)\right) \\ &\overset{0<<\mathrm{SNR}}{\approx} \frac{8B_l \cdot T_s}{k_c^2 \cdot N_p}\frac{\mathrm{sinc}^2(\pi\beta\xi)}{\mathrm{SNR}} \end{aligned} \tag{20}$$

Equation (20) suggests that, other than the parameters B_l and T_s that affect the variance of the output of loop filter, var[$\bar{\epsilon}$] is also related to the normalized coefficient k_c and the autocorrelation function sinc($\pi\beta\xi$). Besides, by increasing the SNR and allocating more pilots N_p in the signal, the tracking errors will decrease, which is reasonable.

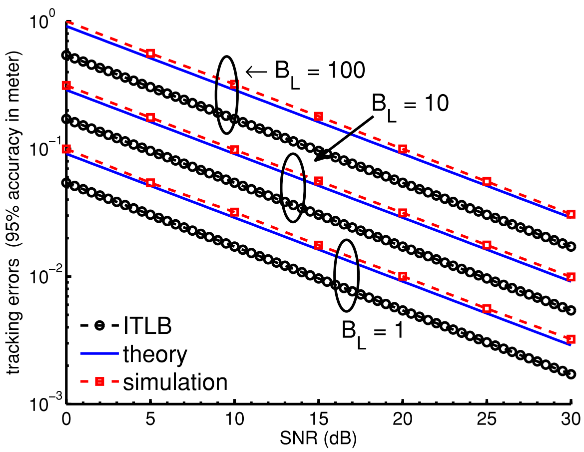

Fig. 3. Ranging accuracy performance.

IV. Information-Theoretic Lower Bound on the Tracking Errors

We first derive the CRLB on the unsmoothed TOA estimation, and then the ITLB on the variance of the DLL tracking errors is computed. The ITLB is related to the CRLB of the unsmoothed TOA estimate by a scale factor that indicates the bandwidth of the smoothing loop filter B_l and the updated symbol time T_s [18].

A. CRLB on the Unsmoothed TOA Estimate

CRLB is the most common lower bound and describes the maximum achievable accuracy of any unbiased estimator in the moderate- to high- SNR region. Since the time delay is estimated with pilot sequence, the CRLB can be analytically computed. According to [19], the CRLB for the unsmoothed TOA estimation ϵ' can be derived from the general definition given by Kay [20]

$$\mathrm{var}(\epsilon') \geq \mathrm{CRLB}(\epsilon') = \frac{1}{\frac{E_s}{N_0/2}\bar{F}^2} \tag{21}$$

where $E_s = P_x \cdot T_s$, P_x is the defined as the power of the band-pass signal. $\mathrm{SNR} = (C/N_0)/B$, being C/N_0 the carrier-to-noise-density ratio and B the bandwidth of the signal. The mean square bandwidth (MSB) of the DVB-T signal, $\bar{F}^2$, defined by

$$\bar{F}^2 = \frac{\int_{-\infty}^{+\infty}(2\pi f)^2)|X(f)|^2 df}{\int_{-\infty}^{+\infty}|X(f)|^2 df} \tag{22}$$

can be approximated as follows,

$$\begin{aligned}\bar{F}^2 &\approx \frac{\Delta f \cdot \sum_{p\in\mathcal{P}_s}(2\pi p \cdot \Delta f)^2 |X(p\cdot\Delta f)|^2}{\Delta f \sum_{p\in\mathcal{P}_s}|X(p\cdot\Delta f)|^2} \\ &= \frac{4\pi^2\cdot\Delta f^2}{N_p}\sum_{p\in\mathcal{P}_s} p^2\end{aligned} \tag{23}$$

where Δf is the subcarrier spacing. It also has to be noticed that the OFDM symbol duration T_s is determined by the duration of the chip T_c and the number of subcarriers N or the subcarrier spacing Δf, i.e., $T_s = T_c \cdot N = 1/\Delta f$.

By considering a rectangular power spectral density (PSD). Thus, the CRLB for the DVB-T signal pilots is

$$\mathrm{CRLB}(\epsilon') = \frac{T_s^2}{8\pi^2 \cdot \mathrm{SNR} \cdot \frac{N}{N_p} \cdot \sum_{\mathcal{P}_s} p^2} \tag{24}$$

B. ITLB of the Smoothed Tracking Errors

Substituting (24) into (19), we get the ITLB on the performance of a DLL for a given bandwidth of the equivalent loop filter and the update symbol time, i.e.,

$$\mathrm{var}_{\mathrm{ITLB}}(\epsilon) \approx 2B_l \cdot T_s \cdot (1 - 0.5B_l \cdot T_s) \cdot \mathrm{CRLB}(\epsilon') \tag{25}$$

Figure 3 shows TOA tracking errors as a function of SNR with different loop bandwidths. The tracking errors in simulations are in 95% confidence interval of the output from the normalized delay locked loop in the AWGN channel, which in equivalence, is calculated as the interval of $\pm 2\sqrt{\mathrm{var}[\bar{\epsilon}]}$. The ITLB is also included for comparison. From Figure 3, the simulation results of the tracking errors coincide with the theoretical results derived in (20). It is also clear that, with the increase of the bandwidth of the equivalent loop filter, since the signals get more noisy, the tracking errors of the DLL get larger, which is reasonable. Despite different bandwidth of the loop filters, the tracking errors derived in theory are all asymptotic to ITLB with the increase of SNR. By further comparison with ITLB, the theoretical tracking errors are slightly larger, which is caused by the inequality introduced in (17) and the approximation of the non-linear discriminator output in (16). However, as is shown in Figure 3, the difference between ITLB and the theoretic tracking errors is only several decimeters or centimeters even in low SNR, which is fairly small. It is also noticed in Figure 3 that, in general, the TOA tracking errors are small. Even when $B_L = 100$ and SNR = 0 dB, the error interval with 95% accuracy are only within 1 meter, which verifies that the DVB-T signal is promising for positioning related applications.

V. Conclusion

In this work, the DLL tracking errors of DVB-T signals are derived and the information theoretic lower bound on TOA tracking errors is also presented. By comparison, it is concluded that the theoretical tracking errors of the DLL asymptotically approach the ITLB of the TOA estimation and theoretical analysis has verified that it is able to achieve high accuracy in positioning with DVB-T signals. The theoretical analysis in this work will be useful for evaluating new TOA based ranging method with DVB-T signals. Moreover, the methodology, which is completely general, could be used to predict the performance for TOA ranging method with other OFDM based signals.

References

[1] E. D. Kaplan, Ed., *Understanding GPS: Principles and Applications*. Norwood, MA, USA: Artech House, 1996.

[2] Y. Wu, S. Hirakawa, U. H. Reimers, and J. Whitaker, "Overview of digital television development worldwide," *Proc. IEEE*, vol. 94, no. 1, pp. 8–21, Jan. 2006.

[3] M. Rabinowitz and J. J. Spilker, "A new positioning system using television synchronization signals," *IEEE Trans. Broadcast.*, vol. 51, no. 1, pp. 51–61, Mar. 2005.

[4] L. Chen *et al.*, "TOA estimation for positioning with DVB-T signals in outdoor static tests," *IEEE Trans. Broadcast.*, vol. 61, no. 4, pp. 625–638, Dec. 2015.

[5] D. Serant *et al.*, "Positioning using OFDM-based digital TV: New algorithms and tests with real signals," in *Proc. 24th Int. Tech. Meeting Satellite Divis. Inst. Navig.*, Portland, OR, USA, Sep. 2011, pp. 3451–3460.

[6] L. Chen, L.-L. Yang, and R. Chen, "Time delay tracking for positioning in DTV networks," in *Proc. Ubiquitous Positioning Indoor Navig. Location Based Service (UPINLBS)*, Helsinki, Finland, Oct. 2012, pp. 1–4.

[7] L. Chen, R. Piché, H. Kuusniemi, and R. Chen, "Adaptive mobile tracking in unknown non-line-of-sight conditions with application to digital TV networks," *EURASIP J. Adv. Signal Process.*, vol. 2014, no. 22, pp. 1–10, 2014. [Online]. Available: http://asp.eurasipjournals.com/content/2014/1/22

[8] J. Yang *et al.*, "A new positioning system using DVB-T2 transmitter signature waveforms in single frequency networks," *IEEE Trans. Broadcast.*, vol. 58, no. 3, pp. 347–359, Sep. 2012.

[9] J. Yan and L. Wu, "A passive location system for single frequency networks using digital terrestrial TV signals," *Eur. Trans. Telecommun.*, vol. 22, no. 8, pp. 487–499, 2011.

[10] J. T. Ong, H. Yan, S. V. B. Rao, and G. Shanmugam, "Indoor DTV reception: Measurement techniques," *IEEE Trans. Broadcast.*, vol. 50, no. 2, pp. 192–199, Jun. 2004.

[11] L. Chen *et al.*, "Delay estimation for DVB-T signals in adverse multipath scenarios," in *Proc. Int. Conf. Localization GNSS (ICL-GNSS)*, Helsinki, Finland, Jun. 2014, pp. 1–6.

[12] Framing Structure, *Channel Coding and Modulation for Digital Terrestrial Television, Digital Video Broadcasting (DVB)*, ETSI Standard EN 300 744, ver. 1.5.1., Nov. 2004.

[13] J. J. van de Beek, M. Sandell, and P. O. Börjesson, "ML estimation of time and frequency offset in OFDM systems," *IEEE Trans. Signal Process.*, vol. 45, no. 7, pp. 1800–1805, Jul. 1997.

[14] B. Yang, K. B. Lataief, R. S. Cheng, and Z. Cao, "Timing recovery for OFDM transmission," *IEEE J. Sel. Area Commun.*, vol. 18, no. 11, pp. 2278–2291, Nov. 2000.

[15] P. Thevenon *et al.*, "Positioning principles with a mobile TV system using DVB-SH signals and a single frequency network," in *Proc. Digit. Signal Process. (DSP)*, Santorini, Greece, Jul. 2009, pp. 1121–1128.

[16] D. Serant *et al.*, "Development and validation of an OFDM/DVB-T sensor for positioning," in *Proc. IEEE/ION Position Location Navig. Symp. (PLANs)*, Indian Wells, CA, USA, May 2010, pp. 998–1001.

[17] T.-D. Chiueh and P.-Y. Tsai, *OFDM Baseband Receiver Design for Wireless Communications*, 1st ed. Singapore: Wiley, Dec. 2007.

[18] J. W. Betz and K. R. Kolodziejski, "Generalized theory of code tracking with an early-late discriminator part I: Lower bound and coherent processing," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 45, no. 4, pp. 1538–1550, Oct. 2009.

[19] H. L. van Trees, *Detection, Estimation and Modulation Theory*, vol. 1. New York, NY, USA: Wiley, 1968.

[20] S. M. Kay, *Fundamentals of Statistical Signal Processing: Estimation Theory*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1993.