Accurate Position Location in TDS-OFDM Based Digital Television Broadcasting Networks

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***Abstract*—Compared with the global positioning system (GPS), the digital television (DTV) broadcasting signal is a promising candidate for position location due to low implementation cost and strong signal reception. Without changing the current infrastructure of the Chinese DTV broadcasting network, this paper proposes a novel positioning scheme using the multi-carrier pseudo-noise (PN-MC) training sequence in the guard interval of the time domain synchronous OFDM (TDS-OFDM) signal frame. Different from the existing positioning methods based on timing synchronization or super resolution algorithms, the joint time-frequency estimation utilizing the properties of the received PN-MC sequence both in the time and frequency domain with respect to transmission delay, results in the accurate time of arrival (TOA) estimation. Performance of the proposed scheme is evaluated by Monte Carlo simulations in comparison with other the-state-of-art methods. The positioning accuracy of less than 0.1 m when the signal-to-noise ratio (SNR) is greater than 15 dB is achieved, under both the additive white Gaussian noise (AWGN) and the simulated multi-path channels.**

I. Introduction

In contrast to the satellite based navigation system like global positioning system (GPS), the digital television (DTV) broadcasting signals do not suffer from the ionosphere disturbance and high Doppler effects caused by the high-speed satellites, both of which affect the performance of GPS. Working at low frequencies, the DTV signals are well-suited for urban propagation. The received GPS signal strength is relatively weak (usually in the order of -160 dBm) after transmission over long distance [1], and the DTV signal has a power advantage over GPS signal of more than 40 dB, thereby permitting position location even in the presence of blockage and indoor environments. Multi-path effect is one of the dominant sources to the time of arrival (TOA) estimation error budget for GPS [1], while the orthogonal frequency division multiplexing (OFDM) signal used by several digital television terrestrial broadcasting (DTTB) standards has intrinsic robustness to multi-path channels. Rabinowitz and Spilker proposed the position location scheme using the synchronization signals specified by the American DTTB standard set forth by the advanced television systems committee (ATSC), and the positioning accuracy was about several meters [2]. The positioning scheme based on the frequency-domain pilots was presented for the European DTTB standard called digital video broadcasting terrestrial (DVB-T), and the accuracy was in the order of decimeter [3]. To the best of the authors' knowledge, there is no literature addressing the positioning issue using the Chinese DTTB standard whose key technology is called time domain synchronous OFDM (TDS-OFDM) [4].

Regarding to positioning with OFDM signals, the state-of-the-art methods can be generally divided into two categories. The first one used the traditional or improved correlation based timing synchronization algorithms to locate the boundaries of OFDM blocks [5]–[8]. The complexity was low but the accuracy was directly limited by the sampling rate, and generally an error of several meters was expected. The second one was based on super resolution algorithms such as multiple signal classification (MUSIC) [9], maximum likelihood (ML) [10] or matrix pencil (MP) [11] derived from modern spectral estimation techniques. They had better positioning accuracy but the complexity is unacceptably high for commercial receivers.

In this paper, the navigation method using the multi-carrier pseudo-noise (PN-MC) training sequence embedded in the guard interval of the TDS-OFDM signal frame is proposed for high accuracy yet low complexity positioning in the Chinese DTTB network. The properties of the PN-MC sequence both in the time and frequency domain are jointly utilized for the accurate TOA estimation. The main contributions of this paper are listed as below: 1) The positioning scheme in the TDS-OFDM based DTV broadcasting network is proposed; 2) The positioning method with low complexity requires little modification of the current infrastructure of the broadcasting network, thus backward system compatibility can be maintained; 3) The positioning accuracy of less than 0.1 m is achieved under both AWGN and multi-path channels, higher than the state-of-the-art positioning methods using OFDM signals.

The rest of this paper is organized as follows. Section II illustrates the system model for position location in the TDS-OFDM system. In Section III, the time-frequency positioning algorithm based on the PN-MC sequence is proposed, together with the corresponding analysis of the positioning time, positioning accuracy and computational complexity. The performance evaluation of the proposed scheme is presented in Section IV. We then conclude this paper in Section V.

II. System Model

The frame structure of the transmitted signal in the TDS-OFDM system is shown in Fig. 1. Each signal frame is com-

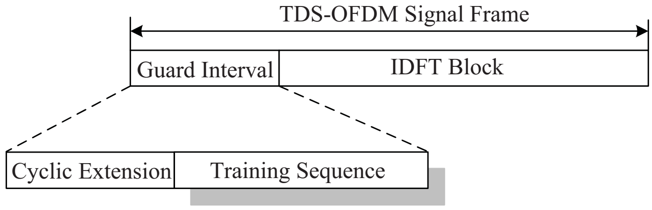

Fig. 1. Frame structure of the TDS-OFDM system.

posed of the inverse discrete Fourier transform (IDFT) block and the guard interval, which consists of the training sequence (TS) and its cyclic extension. Besides synchronization and channel estimation, the TS will be also used for positioning in this paper, without changing the digital broadcasting network infrastructure.

The continuous channel impulse response (CIR) is modeled as a finite impulse response (FIR) filter

$$h(t) = \sum_{l=0}^{L-1} h_l \delta(t - \tau_l), \tag{1}$$

where L is the total number of the paths, h_l is the amplitude and τ_l is the time delay of the lth path. Even if some time delays of the actual channel might not be integer multiple of sampling period T_s at the receiver, the discrete CIR can be modeled as [12]

$$h(n) = \sum_{l=0}^{L-1} h_l \delta(n - n_l), \tag{2}$$

where n_l is the integer delay corresponding to τ_l.

After passing through the multi-path wireless channel with the propagation delay of τ_d, the received TS is

$$\begin{aligned} r(t) &= p(t) * h(t) * \delta(t - \tau_d) + w(t) \\ &= \sum_{l=0}^{L-1} h_l p(t - \tau_l - \tau_d) + w(t), \end{aligned} \tag{3}$$

where $p(t)$ is the time-domain transmitted TS, $*$ is the linear convolution operator , and $w(t)$ is the additive white Gaussian noise (AWGN) with zero mean and the variance of σ^2.

The transmission delay normalized by the sampling period is denoted as

$$\theta = \frac{\tau_d}{T_s} = \theta_I + \theta_F, \tag{4}$$

where θ_I is the normalized integral delay, and $\theta_F \in (-0.5, +0.5]$ is the normalized fractional delay, respectively. The distance from the transmitter to the receiver is

$$D = \tau_d c = \theta T_s c, \tag{5}$$

where $c = 3 \times 10^8$ m/s is the speed of light in the free space. The method of using the training sequence to estimate the distance is the topic of the following section.

III. Positioning in the TDS-OFDM System

In this section, the PN-MC training sequence is firstly presented, and then the time-frequency positioning algorithm is addressed. The positioning time, accuracy and complexity are also analyzed in the sequel.

A. *Multi-Carrier PN (PN-MC) Sequence*

Instead of the single carrier PN sequence usually used in TDS-OFDM system, the multi-carrier PN (PN-MC) sequence can be also adopted as the TS. The time-domain PN-MC sequence $\mathbf{p} = \{p(n)\}_{n=0}^{N-1}$ is generated by

$$p(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} P(k) \exp(j\frac{2\pi}{N}nk), \tag{6}$$

where $\mathbf{P} = \{P(k)\}_{k=0}^{N-1}$ is the frequency-domain PN sequence whose elements are either +1 or -1. Compared with the traditional single carrier PN sequence, PN-MC has the following two features:

1) *Good Channel Estimation Performance*: According to [13], minimum channel estimation error could be achieved if the TS has constant envelope in the frequency domain, i.e.,

$$|P(0)| = |P(1)| = |P(2)| = ... = |P(N-1)|. \tag{7}$$

Obviously, the PN-MC sequence satisfies this rule, while the PN sequence does not.

2) *Ideal Autocorrelation for Synchronization*: Due to the constant envelope in the frequency domain, the PN-MC sequence has perfect autocorrelation function

$$R_c(\tau) = \sum_{k=0}^{N-1} p(n) p^*((n+\tau))_N = \begin{cases} N & \tau = 0 \\ 0 & \tau \neq 0 \end{cases}, \tag{8}$$

where $(\cdot)^*$ is the complex conjugation, and $((\cdot))_N$ is the modulo-N operator. However, the autocorrelation of the PN sequence is good but not ideal.

Therefore, the PN-MC sequence can be used for channel estimation and synchronization, having better performances than the PN sequence.

B. *Time-Frequency Positioning Algorithm*

The continuous time-domain PN-MC can be expressed as

$$p(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} P(k) \exp(j 2\pi f_k t), \tag{9}$$

where $f_k = k f_0$ is the frequency of the kth subcarrier, $f_0 = 1/NT_s$ is the subcarrier frequency spacing. The corresponding received signal in (3) can be rewritten as

$$r(t) = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} h_l \sum_{k=0}^{N-1} P(k) \exp\left(j2\pi \frac{k}{NT_s} (t - \tau_l - \tau_d) \right) + w(t). \tag{10}$$

Sampling the received signal with the time interval of the symbol duration T_s will generate the discrete-time samples as

$$\begin{aligned} r(n) =& \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} h_l \sum_{k=0}^{N-1} P(k) \cdot \exp\left(j\frac{2\pi}{N}k(n-n_l)\right) \cdot \\ & \exp\left(-j\frac{2\pi}{N}k\theta_I\right) \cdot \exp\left(-j\frac{2\pi}{N}k\theta_F\right) + w(n), \end{aligned} \tag{11}$$

where $w(n)$ is the noise term. The corresponding signal over the kth subcarrier is

$$\begin{aligned} R(k) =& \sum_{l=0}^{L-1} h_l \exp\left(-j\frac{2\pi}{N}kn_l\right) \\ & \left[P(k)\exp\left(-j\tfrac{2\pi}{N}k\theta_F\right)\right]\exp\left(-j\tfrac{2\pi}{N}k\theta_I\right) + W(k) \\ =& \left[H(k)P(k)\exp\left(-j\frac{2\pi}{N}k\theta_F\right)\right]\exp\left(-j\frac{2\pi}{N}k\theta_I\right) + W(k), \end{aligned} \tag{12}$$

where $W(k)$ is the DFT output of $w(n)$, $H(k)$ is the channel frequency response (CFR) of the CIR

$$H(k) = \sum_{l=0}^{L-1} h_l \exp\left(-j\frac{2\pi}{N}kn_l\right). \tag{13}$$

It is clear that the impact of the transmission delay θ on the received PN-MC sequence lies in two aspects:

1) Time shift by θ_I samples in the time domain.

2) Phase rotation by $-j\frac{2\pi}{N}k\theta_F$ in the frequency domain.

The joint time-frequency processing utilizing those properties both in the time and frequency domain will be used for high accuracy positioning.

Estimating the time shift of the received signal is equivalent to the traditional timing synchronization of the communication systems, which can be realized by correlating the local PN-MC sequence with the received signal [14]

$$\widehat{\theta}_I = \arg\max_d \left\{p((n-d))_N \cdot r^*(n)\right\}, \tag{14}$$

where $\widehat{\theta}_I$ is the estimated integral delay. Due to the perfect autocorrelation of the PN-MC sequence denoted by (8), the correlation peak is confirmed when $d = \theta_I$.

For actual communication systems, it suffices to locate the beginning of each transmission block within one sampling period for correct demodulation, since the fractional delay is inherently compensated by the one-tap frequency-domain equalization [15]. In other words, the fractional delay θ_F is usually ignored for data recovery. However, for positioning systems, it has to be exactly estimated for high positioning accuracy, because the estimation accuracy provided by the integral delay estimation is strictly limited by the sampling period. For TDS-OFDM system with the sampling rate of 7.56 MHz, the distance error turns out to be $(T_s/2)\,c$, which equals to about 20 m. Even for the over-sampling by the factor of four (e.g., the sampling rate is 30.24 MHz), the estimation error is about 5 m, which is not enough for accurate positioning.

After compensating the time-domain effect due to the integral delay $\widehat{\theta}_I$, the frequency-domain received PN-MC sequence on the kth subcarrier is

$$R(k) = H(k)P(k)\exp\left(-j\frac{2\pi}{N}k\theta_F\right) + W(k). \tag{15}$$

According to [16], under the assumption that correct channel estimation has been obtained before the fractional delay estimation, the received PN-MC sequence could be simplified as

$$C(k) = \frac{R(k)}{H(k)P(k)} = \exp\left(-j\frac{2\pi}{N}k\theta_F\right) + W'(k), \tag{16}$$

where $W'(k) = W(k)/\left(H(k)P(k)\right)$ is the noise term. For simplicity, $W'(k)$ is omitted in the following mathematical deduction.

The G-lag autocorrelation of $C(k)$ reads

$$Z(G) = \sum_{k=0}^{N-G-1} C(k) \cdot C^*(k+G) = \exp\left(j\frac{2\pi}{N}G\theta_F\right). \tag{17}$$

To avoid the phase ambiguity problem [17], the differential sequence corresponding to adjacent two elements from (17) is generated as

$$D(G) = Z^*(G)Z(G+1) = \exp\left(j\frac{2\pi}{N}\theta_F\right). \tag{18}$$

The unbiased TOA estimation can be derived by averaging the phase of the differential sequence of $D(G)$

$$\widehat{\theta}_F = \frac{N}{2\pi(N/2-1)} \sum_{G=1}^{N/2-1} \arg\left\{D(G)\right\}. \tag{19}$$

Note that the fractional delay estimation accuracy is increased by the averaging process in (19).

The transmission distance estimation for positioning is

$$\widehat{D} = \left(\widehat{\theta}_I + \widehat{\theta}_F\right) T_s c. \tag{20}$$

C. Positioning Time

It is sufficient to process snapshots lasting one TDS-OFDM signal frame to track the PN-MC sequence, thus fast positioning speed could be achieved. The average time for the first positioning of the proposed method is

$$\begin{aligned} T_p =& \int_0^{T_C} (T_C + T_{PN} - t)\frac{1}{T_F}dt + \int_{T_C}^{T_F} (T_C + T_{PN} + T_F - t)\frac{1}{T_F}dt \\ =& \frac{T_F}{2} + T_{PN}, \end{aligned} \tag{21}$$

where T_C , T_{PN} and T_F denotes the duration of the cyclic extension, the PN-MC sequence and the TDS-OFDM signal frame, respectively. For the PN420 mode of the TDS-OFDM system, the positioning time is 589.3 μs, and 692.6 μs for the PN945 mode, much shorter than the first positioning time of several minutes in GPS [1].

D. Positioning Accuracy

The theoretical Cramer-Rao lower bound (CRLB) of the unbiased parameter estimation based on a discrete-time observation model is given as [18]

$$CRLB(\frac{2\pi}{N}\widehat{\theta}_F) = \frac{6}{\gamma N^2(N-1)}, \quad (22)$$

where $\gamma = 1/\sigma^2$ is the signal-to-noise ratio (SNR). From (20), the positioning accuracy of the proposed scheme can be derived as

$$CRLB(\widehat{D}) = \frac{3T_s^2c^2}{2\pi^2\gamma(N-1)}. \quad (23)$$

E. Computational Complexity

Table I compares the computational complexity of proposed positioning scheme with other two types of methods based on conventional synchronization and super resolution algorithms.

TABLE I
COMPUTATIONAL COMPLEXITY COMPARISON.

Method	Complexity
Conventional Synchronization Based [5]-[8]	$O(N)$
Super Resolution Algorithm Based [9]-[11]	$O(N^3)$
Proposed	$O(N\log_2 N)$

The main complexity of the proposed method lies in computing of autocorrelation sequence $\{Z(G)\}_{G=1}^{N/2}$ in (17), which can be realized by M-point FFT/IFFT algorithm ($M = 2N$) after a one-step process. So the computational complexity is in the order of $O(N\log_2 N)$, much lower than that of the super resolution based methods.

IV. SIMULATION RESULTS AND DISCUSSIONS

Numerical simulations are carried out to evaluate the performance of the proposed positioning method in the TDS-OFDM based digital broadcasting networks. The main simulation parameters are configured to be consistent with the TDS-OFDM system specified in [4]. The PN-MC length is 255 for the PN420 mode with the cyclic extension length of 165, and 511 for the PN945 mode with the cyclic extension length of 434. The baseband symbol rate is 7.56 MHz, and the received PN-MC signal is over-sampled by the factor of four, thus the sampling rate is 30.24 MHz. Both the AWGN channel and two typical DTTB test multi-path channel models called Brazil A and Brazil B [19] are used.

Fig. 2 presents the positioning accuracy comparison in terms of the root mean square error (RMSE) under AWGN channel. The root of the theoretical CRLB from (23) is also included for reference. It is clear that the second category of positioning methods based on super resolution algorithms generally outperforms the first category of positioning methods, while the proposed scheme has the best positioning accuracy. For example, when the SNR is 15 dB, the distance estimation error is about 5 m for Mensing's method, 0.35 m for MP based algorithm which has the best performance of the second category methods, and 0.06 m for the proposed method. Simulation results also indicate that the positioning error of the proposed method almost reaches the CRLB when the SNR is above 10 dB, and deteriorates a little under low SNR conditions.

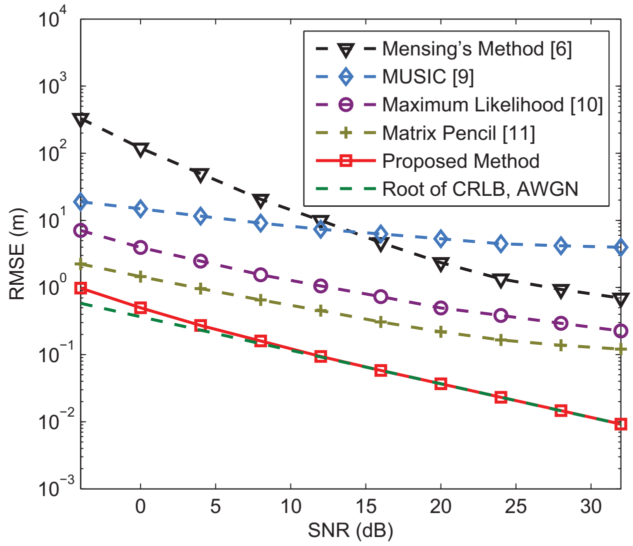

Fig. 2. Positioning accuracy comparison under AWGN channel.

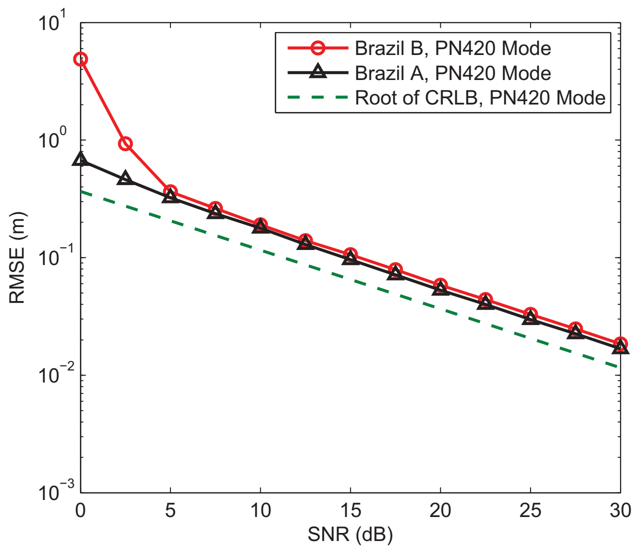

Fig. 3. Positioning accuracy for the TDS-OFDM PN420 mode under Brazil A and Brazil B channels.

Fig. 3 shows the positioning accuracy for the TDS-OFDM PN420 mode under Brazil A and Brazil B multi-path channels. Compared with the theoretical bound under AWGN channel, the positioning accuracy deteriorates a little under multi-path channels. At the SNR of 15 dB, the distance estimation error under Brazil A channel is 0.096 m, and 0.10 m for Brazil B channel.

Fig. 4 presents the positioning accuracy for the TDS-OFDM PN945 mode under Brazil A and Brazil B multi-path channels.

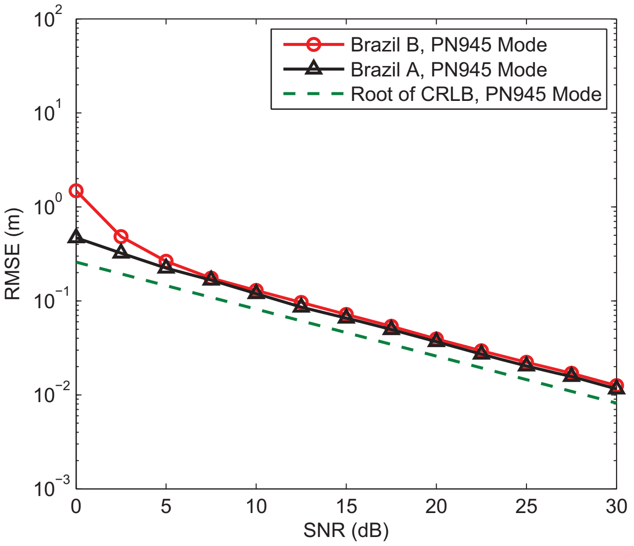

Fig. 4. Positioning accuracy for the TDS-OFDM PN945 mode under Brazil A and Brazil B channels.

The achievable estimation error is 0.066 m for Brazil A channel and 0.072 m for Brazil B channel when the SNR equals to 15 dB. Although the angular responses of Brazil A and Brazil B channels are not quasi-constant, high accurate positioning is still achieved due to the robustness of multi-carrier transmission to the multi-path effect.

V. Conclusion

This paper proposes the positioning scheme with the backward compatibility for the TDS-OFDM based Chinese digital television broadcasting network. Besides synchronization and channel estimation, the PN-MC training sequence in the TDS-OFDM signal frame is also used for accurate positioning. The proposed scheme has lower complexity than the super resolution based positioning methods. The initial positioning time is less than 0.7 ms. The positioning accuracy under AWGN channel reaches the Cramer-Rao bound, and the estimation error is less than 0.1 m under Brazil A and Brazil B multi-path channels. The concept of joint time-frequency processing of the multi-carrier signals for accurate positioning can be directly applied to other OFDM based systems.

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