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RESEARCH ARTICLE

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Positioning models and systems based on digital television broadcasting signals

Abstract The requirement and feasibility of the positioning system using digital television (DTV) broadcasting signals are analyzed. The principle of DTV positioning on the basis of frame synchronization is brought forward and the ranging characteristic is studied that the observables are asynchronously measured during the same epoch interval. The models of the pseudo-range observation and Doppler carrier phase integral are researched. The system observation and state equations are presented on the basis of the above models. The simulation results showed that DTV positioning technology could remarkably improve the precision of system state estimates using smoothing methods for positioning systems or integrated navigation systems. The DTV positioning that has a sub-meter level ranging error and meter level positioning accuracy can parallel with and even taken as a beneficial substitute for the tradition positioning technology.

Keywords positioning, digital television (DTV), frame synchronization, integrated navigation, broadcasting, ranging, time of arrival (TOA), orthogonal frequency division multiplexing (OFDM)

1 Introduction

Using signals transmitted by spaced radio sources, the user location can be estimated with the time bases and coordinates of transmitters. When these radio sources are distributed on satellites, positioning systems on the basis of satellites can be established, such as the global positioning system (GPS) in USA, Galileo in Europe, the global navigation satellite system (GLONASS) in Russian and Beidou navigation system in China. By virtue of possessing a wide coverage area, these positioning systems are evolved into global navigation satellite system (GNSS). However, the existing technology, such as GPS has the following four limitations [1].

1) Because of the long range of the satellite from the user, which is about 20 000 km, the positioning accuracy will be degraded by the computing error of satellite orbits, ionosphere interference and multipath disturbance, etc.

2) The satellite signals cannot be validly received in indoor environment and the probability of successful location decreases in urban environment.

3) The initial searching satellite task costs much time before the positioning system can provide reliable location information.

4) The effects of selective availability (SA) clock dithering can reduce the location precision under special conditions.

Meanwhile, digital television (DTV) networks that provide terrestrial broadcasting services of digital video and audio have been deployed around the world. In addition to digital multimedia information, the user can measure the carrier and data code stream of DTV signals, and then estimate the distances from transmitters to receivers. Based on these distances, a type of positioning technologies emerges. For example, a positioning technology using the advanced television systems committee (ATSC) signals that can achieve 1 m of positioning accuracy was presented [2]. It should be noted that any of the digital broadcasting signals can be used for positioning purposes.

However, terrestrial DTV positioning systems cannot serve for users where the DTV terrestrial signals are not able to cover, such as the sea, the desert and island areas. Nonetheless, the integrated positioning systems, which fuse DTV broadcasting terrestrial and satellite signals or GPS, are robust solutions for these users.

2 Principles of positioning

2.1 Ranging techniques

The ranging techniques have been researched again when the location-aware applications, such as wireless networks, are deployed widely. Reference [3] used a correlation filter

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combined with a delay-lock loop (DLL) on the basis of an early-late gate to measure the time delay and obtain the distance estimation between both ultra-wide band (UWB) ends. This ranging capability is particularly attractive as a support for location-aware applications in Ad-hoc and sensor networks. Reference [4] proposed a method that modulated one or multiple subcarriers with a low-frequency ranging signal at the transmitter and by sampling the received signals at a high sampling rate at the receiver to estimate the time of arrival (TOA) of the ranging signal. This method needs both ends to transmit the ranging signals to each other. Therefore, only distances shorter than around 300 m can be accurately estimated via using this method.

The coverage and geometry are important characteristics for a positioning system. The positioning system ranging DTV broadcasting signals well conforms to this criterion. This positioning technology can be widely deployed to wireless networks and navigation systems, and employed to construct integrated navigation systems with other positioning technologies.

In order to successively demodulate and decode with high data rate and low bit error rate at the reception end, the stream of audio, video and multimedia data must be coded and packaged before being transmitted through the channel. In this way, DTV broadcasting system provides reliable reception of real-time stream when the duration of packaged block is less than hundred microseconds or under millisecond level [5].

In this paper, a new ranging method was proposed on the basis of DTV frame synchronization, which can be performed on orthogonal carriers. The synchronization algorithms can correct the timing errors and acquire high resolution in the domains of time and frequency [6–9].

The synchronization symbols are inserted into it and even the power levels are increased in order to identify the frame header [5,10]. The receiver can detect the beginning and estimate the arrival time for the header utilizing synchronization algorithms. The estimation is affected by the channel interference, the clock error and the receiver noise, etc. Meanwhile, the transmitting time instant of the header can be deduced from its frame index. By using computed transmitting time and estimated arrival time, the propagation time and the ranging measurement, namely pseudo-range, are obtained.

Imagine that just now data frames are broadcast at the beginning of an observation epoch from all transmitters in a DTV network. A DTV positioning receiver will receive the frame header corresponding to one transmitter after some delay. The value of the delay varies according to the distance between the transmitter and the receiver. Therefore, DTV positioning systems is an asynchronously sequential observation system while the traditional position technology simultaneously measures the ranging measurements.

2.2 Pseudo-range models

The positioning system based on digital broadcasting signals measures the line of sight (LOS) between the transmitter and the receiver by estimating the TOA of successive broadcasting frames. The LOS observable is the so-called pseudo-range measurement ρ that is affected by the clock drift and multipath disturb and other system errors. The differential value of two pseudo-range observables is called delta pseudo-range $\Delta\rho$.

Suppose that a data frame is transmitted at a ideal system time $t_{\mathrm{T}}^{\mathrm{ideal}}$, it will be received at a ideal system time $t_{\mathrm{R}}^{\mathrm{ideal}}$. Without any channel interference, the transmission delay τ is

$$\tau = t_{\mathrm{R}}^{\mathrm{ideal}} - t_{\mathrm{T}}^{\mathrm{ideal}} \tag{1}$$

In practice some items that represent the measurement errors must be added to modify Eq. (1). The transmission delay can be described as

$$\tau + \delta t_{\mathrm{D}} = \left(t_{\mathrm{R}} - \delta t_{\mathrm{R}}\right) - \left(t_{\mathrm{T}} - \delta t_{\mathrm{T}}\right) \tag{2}$$

where t_{R}, δt_{R}, t_{T}, δt_{T}, δt_{D} are the reception time, the bias of the receiver's clock, the transmission time, the bias of the transmitter's clock and the equal quantity of other system errors respectively.

After multiplying Eq. (2) by the speed of light c, the expression of the pseudo-range is obtained

$$\rho = c\left(t_{\mathrm{R}} - t_{\mathrm{T}}\right) = c\tau + c\left(\delta t_{\mathrm{R}} - \delta t_{\mathrm{T}} + \delta t_{\mathrm{D}}\right) = r + c\delta t_{\mathrm{R}} + \delta r \tag{3}$$

where r is the distance between the transmitter and the receiver and δr is the equal distance value of errors.

2.3 Positioning systems

The DTV positioning measurement system is shown in Fig. 1. The receiver measures the pseudo-range to every visible DTV transmitters, which includes the distance between the transmitter and the user and other system measurement errors.

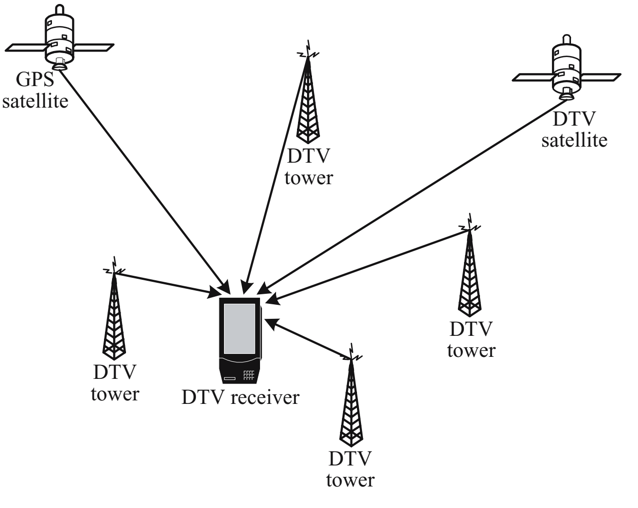

Fig. 1 A positioning system based on DTV signals

The location calculation can be implemented at the DTV user end. In order to compute an accurate location of the receiver, the precise timing of DTV signals must be completed by the frame synchronization. Pseudo-range measurements to three spatially separated DTV transmitters are sufficient to triangulate the user's position and to resolve the user's latitude, longitude and clock bias. Unlike the case of a satellite-based positioning technology, the location of the transmitter is unchanging and needs no continual updating. DTV transmitter positioning data may be stored at the receiver or broadcasted by the network of DTV transmitters.

3 Models of positioning

After coding the digital video and audio and controlling information, DTV signals are usually modulated and broadcasted by orthogonal frequency division multiplexing (OFDM) scheme [11]. On one hand, unlike the GPS receiver, which employs the scheme of single carrier and cyclic code to perform carrier tracking and code searching, the multi-carrier signal structure of DTV is not designed for ranging purpose. On the other hand, the scheme of high code rate and frame-based coding can help synchronization modules to easily catch and track signals and extract the transmission delay for DTV positioning systems.

3.1 Observation equations

The pseudo-range equation has been presented in Section 2.2. In this subsection, the delta pseudo-range is researched. Because the pseudo-range measurements have observation errors, which incompletely correlate with each other, and this will definitely results in more errors in the direct differencing pseudo-range. However, the delta pseudo-range is defined as the difference of the two pseudo-ranges, the actual observable is measured by calculating the integral of the carrier Doppler during an observation interval. This integral value reflects the dynamics of the receiver indirectly. It is defined as

$$\phi_{\mathrm{D}} = \int_{t_{\mathrm{R}_1}^{\mathrm{ideal}}}^{t_{\mathrm{R}_2}^{\mathrm{ideal}}} \left[f_{\mathrm{Rlo}}(t) - f_{\mathrm{R}}(t) \right] \mathrm{d}t \tag{4}$$

where ϕ_{D}, $t_{\mathrm{R}_1}^{\mathrm{ideal}}$, $t_{\mathrm{R}_2}^{\mathrm{ideal}}$, $f_{\mathrm{Rlo}}(t)$, $f_{\mathrm{R}}(t)$ are Doppler integral, the integral start time, the integral end time, the receiver's clock frequency and the reception carrier frequency respectively.

Separately calculating the integrals in Eq. (4), it is obtained that

$$\begin{aligned}\phi_{\mathrm{D}} &= \int_{t_{\mathrm{R}_1}^{\mathrm{ideal}}}^{t_{\mathrm{R}_2}^{\mathrm{ideal}}} f_{\mathrm{Rlo}}(t)\,\mathrm{d}t - \int_{t_{\mathrm{R}_1}^{\mathrm{ideal}}}^{t_{\mathrm{R}_2}^{\mathrm{ideal}}} f_{\mathrm{R}}(t)\,\mathrm{d}t \\ &= \int_{t_{\mathrm{R}_1}^{\mathrm{ideal}}}^{t_{\mathrm{R}_2}^{\mathrm{ideal}}} f_{\mathrm{Rlo}}(t)\,\mathrm{d}t - \int_{t_{\mathrm{T}_1}^{\mathrm{ideal}}}^{t_{\mathrm{T}_2}^{\mathrm{ideal}}} f_{\mathrm{T}}(t)\,\mathrm{d}t\end{aligned} \tag{5}$$

where $t_{\mathrm{T}_1}^{\mathrm{ideal}}$ is the corresponding transmission time of $t_{\mathrm{R}_1}^{\mathrm{ideal}}$, $t_{\mathrm{T}_2}^{\mathrm{ideal}}$ is the corresponding transmission time $t_{\mathrm{R}_2}^{\mathrm{ideal}}$ and $f_{\mathrm{T}}(t)$ is the transmitter carrier frequency.

Because the duration of Doppler integral is small, it is now assumed that the transmitter's clock and receiver's clock are relatively stable. Both clocks can be modeled by the linear summation of the system carrier frequency f_{c} and the frequency bias, as

$$\begin{aligned}f_{\mathrm{Rlo}}(t) &= f_{\mathrm{c}} + \delta f_{\mathrm{Rlo}} \\ f_{\mathrm{T}}(t) &= f_{\mathrm{c}} + \delta f_{\mathrm{T}}\end{aligned} \tag{6}$$

where δf_{Rlo} is the receiver's frequency bias, δf_{T} is the transmitter's frequency bias.

Substituting Eqs. (1) and (6) into (5), it is obtained that

$$\phi_{\mathrm{D}} = f_{\mathrm{c}}(\tau_2 - \tau_1) + \delta f_{\mathrm{Rlo}}\left(t_{\mathrm{R}_2}^{\mathrm{ideal}} - t_{\mathrm{R}_1}^{\mathrm{ideal}}\right) - \delta f_{\mathrm{T}}\left(t_{\mathrm{T}_2}^{\mathrm{ideal}} - t_{\mathrm{T}_1}^{\mathrm{ideal}}\right) \tag{7}$$

Because the transmitter's clock drift is smaller than the receiver's or it can be corrected, the last product item of the right of Eq. (7) will be neglected and then it is obtained that

$$\phi_{\mathrm{D}} = \frac{f_{\mathrm{c}}(r_2 - r_1)}{c} + \delta f_{\mathrm{Rlo}}\left(t_{\mathrm{R}_2}^{\mathrm{ideal}} - t_{\mathrm{R}_1}^{\mathrm{ideal}}\right) = \frac{\Delta r}{\lambda_{\mathrm{c}}} + \delta f_{\mathrm{Rlo}} \Delta t_{\mathrm{R}}^{\mathrm{ideal}} \tag{8}$$

where Δr is the difference of two distances, λ_{c} is the wavelength of the carrier and $\Delta t_{\mathrm{R}}^{\mathrm{ideal}}$ is the interval between the integral start time and end time.

Using the receiver time to substitute the ideal system time, Eq. (8) becomes

$$\begin{aligned}\phi_{\mathrm{D}} &= \frac{\Delta r}{\lambda_{\mathrm{c}}} + \delta f_{\mathrm{Rlo}}\left(t_{\mathrm{R}_2} - t_{\mathrm{R}_1}\right) - \delta f_{\mathrm{Rlo}}\left(\delta t_{\mathrm{R}_2} - \delta t_{\mathrm{R}_1}\right) \\ &= \frac{\Delta r}{\lambda_{\mathrm{c}}} + \delta f_{\mathrm{Rlo}} \Delta t_{\mathrm{R}} - \delta f_{\mathrm{Rlo}} \Delta \delta t_{\mathrm{R}}\end{aligned} \tag{9}$$

where δt_{R} is the receiver's clock bias from the ideal system time t_{R}, $\Delta t_{\mathrm{R}} = t_{\mathrm{R2}} - t_{\mathrm{R1}}$ is the integral period in the receiver. The last product item that is the product of $(\delta f_{\mathrm{Rlo}})^2$ and $\Delta t_{\mathrm{R}}^{\mathrm{ideal}}$, which can be neglected or treated as the measurement noise in Eq. (9).

3.2 State equations

The system state is composed of system dynamics, including the space coordinate, velocity and acceleration and the clock's bias and drift in a positioning system. The system state is represented as

$$\begin{bmatrix} \dot{\boldsymbol{P}}_{\mathrm{R}} \\ \dot{\boldsymbol{V}}_{\mathrm{R}} \\ \dot{\boldsymbol{A}}_{\mathrm{R}} \end{bmatrix} = \begin{bmatrix} 0 & \boldsymbol{I} & 0 \\ 0 & 0 & \boldsymbol{I} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{P}_{\mathrm{R}} \\ \boldsymbol{V}_{\mathrm{R}} \\ \boldsymbol{A}_{\mathrm{R}} \end{bmatrix} \tag{10a}$$

$$\begin{bmatrix} \dot{\delta} t_{\mathrm{R}} \\ \ddot{\delta} t_{\mathrm{R}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta t_{\mathrm{R}} \\ \dot{\delta} t_{\mathrm{R}} \end{bmatrix} \tag{10b}$$

where $\boldsymbol{P}_{\mathrm{R}}$, $\boldsymbol{V}_{\mathrm{R}}$ and $\boldsymbol{A}_{\mathrm{R}}$ are the vectors of the position, velocity and acceleration respectively; $\dot{\delta} t_{\mathrm{R}}$ and $\ddot{\delta} t_{\mathrm{R}}$ are the bias and drift of the receiver's clock respectively.

System dynamics and clock characteristics can be estimated by utilizing the observation expressions, namely Eqs. (3) and (9), and the state Eq. (10). The calculation approaches contain the closed-form solution, the linear iterative estimation and Kalman filtering which have been explored in Ref. [1].

4 Simulation results

Because DTV systems on the basis of DVB-T are widely employed for digital terrestrial television broadcasting, a DVB-T network possessing coverage radius 100 km is used to construct the simulation parameters. Table 1 shows the values of the transmission parameters in DVB-T [5].

Table 1 OFDM parameters of DVB-T under the 8 K mode for 8 MHz channels

Parameter	Value
Number of carriers	6 817
Duration /10^{-6} s	896
Carrier spacing /Hz	1 116
Elementary period /10^{-6} s	7/64

For the sake of clarity and simplicity, the dynamical performance of a fixed speed system is only analyzed at one dimension, and the signals are free of multipath components. The observables suffer from the channel interference of additive white Gaussian noise (AWGN). In addition, the bias and the drift in the receiver characterize the linear model of the clock error.

Using pseudo-range measurements, the extended observation equation can be presented as

$$\delta\rho = \left[-b_{x_2} \;\; 0 \;\; 1 \;\; 0\right]\delta\boldsymbol{X} + \delta r \tag{11}$$

If the system dynamics is limited at one dimension, the following formula will be obtained

$$\delta\rho = \left[-1 \;\; 0 \;\; 1 \;\; 0\right]\delta\boldsymbol{X} + \delta r \tag{12}$$

Table 2 shows the input state values at the initial time of the observation epoch. These initial values can be the prediction of the system state of the last epoch or the estimation from other positioning systems, such as GPS.

Table 2 Initial state values for the observation epoch

Parameter	Standard deviation
Position /m	10
Velocity /(m·s^{-1})	1.0
Clock bias /10^{-6} s	0.5
Clock drift /10^{-6}	1.0

The ranging error is less than 10% elementary period of DVB-T in this simulation. The error covariance of measurements is $R = \sigma_\rho^2$, namely

$$\sigma_\rho = 0.1\times\left(3\times10^8\,\mathrm{m/s}\right)\times\left(7/64\times10^{-6}\,\mathrm{s}\right) = 3.281\ \mathrm{m}$$

The system state is estimated using observables during the same epoch by Kalman filtering, which are sequentially measured from transmitters in a DTV network. The initial state is update by the smoothed estimation [12]. From Figs. 2 and 3, it can be observed that the error variance of the position decreases from 100 to 99.57 m^2 when using Kalman filtering. Meanwhile, the error variance of the position decreases from 100 to 19.91 m^2 when applying the smoothing algorithm to these Kalman estimates. The standard deviation of the position decreases from 10 to 4.46 m at the initial time for the observation epoch.

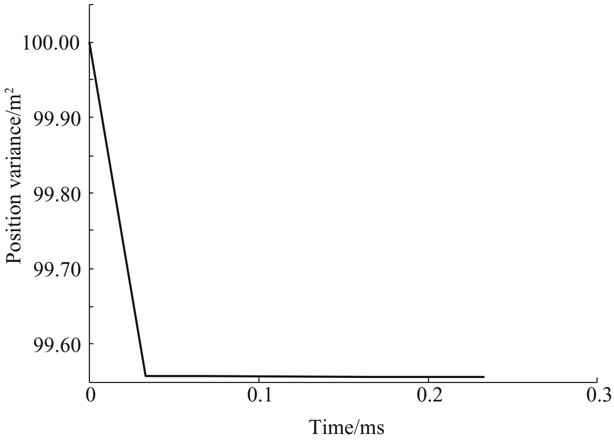

Fig. 2 Position error variance (Kalman filtering)

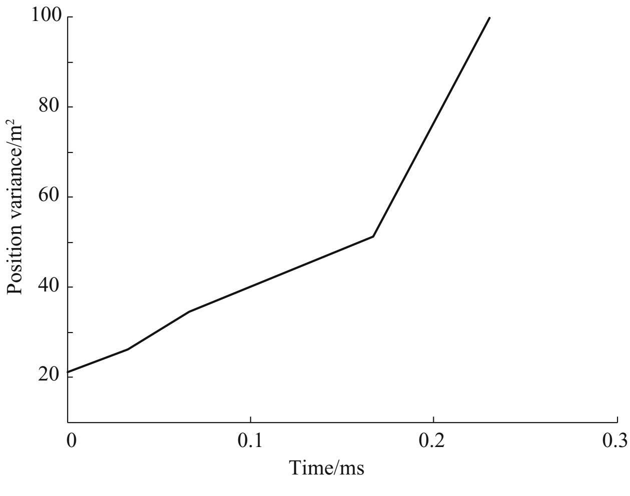

Fig. 3 Position error variance (smoothing)

5 Conclusions

The models of the pseudo-range observation and Doppler carrier phase integral are studied for positioning systems on the basis of DTV signals in this paper.

Because of the high code rate in DTV systems, the pseudo-range observables possess outstanding ranging accuracy. For instance, the code's length is 33 m in DVB-T 8 MHz channels, which is smaller compared with 293 m of GPS C/A code's length and is close to GPS P code's length. Using accurate frame synchronization algorithm by which the observable error is less than 1% code's length, the system can achieve sub-meter level ranging and meter level positioning.

Another characteristic is that asynchronously sequential observables of DTV ranging can not only be used in single positioning systems but also be applied in integrated navigation systems (INS) to compute the optimal estimate of system dynamics by filtering or smoothing algorithms. There are some INS combinations:

1) terrestrial DTV-based positioning system and GPS;

2) terrestrial DTV-based positioning system and DTV satellite-based positioning system;

3) terrestrial DTV-based positioning system and DTV satellite-based positioning system and GPS.

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