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DVB-T Positioning with a One Shot Receiver

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Abstract—In this paper a one shot receiver for DVB-T positioning is presented. DVB-T SFN signals can be used as Signals-of-Opportunity in urban environment to assist GNSS in case the GNSS-only positioning shows degraded performance. The normal mechanism of DVB-T positioning involves a tracking stage to refine the coarse delay estimation obtained by the acquisition stage. However due to the high SNR of DVB-T signals, the delay estimation can be refined by some simple interpolation methods with lower complexity and power consumption. Two different interpolation methods, linear interpolation and sinc interpolation, are analysed in the paper. Simulation results show that the one shot receiver proposed in this paper behaves as a tracking-based receiver, but exhibits a lower complexity.

I. INTRODUCTION

Global Navigation Satellite Systems (GNSSs) based positioning provides a good performance in terms of availability and accuracy in rural and suburban environments. However, in dense urban and indoor environments, GNSSs usually show degraded performance due to the low number of satellites in view and the great attenuation of signal power. Fortunately, many local wireless networks are implemented. These networks are not developed for positioning originally, but some of them can be used as Signals-of-Opportunity (SoO) due to some good properties (i.e. wide bandwidth, high Signal to Noise Ratio (SNR)). In this paper, we use signals transmitted from DVB-T (Terrestrial Digital Video Broadcasting) as SoOs for positioning, especially from a Single Frequency Network (SFN). DVB-T is an European digital TV standard, but it is used worldwide. DVB-T signals adopt Orthogonal Frequency Division Multiplexing (OFDM) technique, which is a good candidate for positioning purpose. Besides this, in DVB-T SFN all the emitters are synchronized by some professional GPS receivers, which simplify the positioning methods.

In the literature, some papers based on DVB-T positioning can be found. In [1], [2], the authors use the scattered pilots to calculate the pseudo-ranges with a mechanism similar to the one used by conventional GNSS receivers, which use acquisition systems for a preliminary coarse delay estimation and refine the estimated delay by means of a tracking stage [3]. In [4] a similar mechanism is presented to calculate the pseudo-ranges based on the transmitted DVB-T data. Some other papers can be found, all of which use the tracking stage to refine the delay estimation.

In this paper we present a one shot receiver to calculate the position based on DVB-T signals. This receiver achieves

the coarse delay estimation by acquisition. After that some interpolation methods are used to refine the delay estimation thanks to the good SNR of DVB-T signals. The receiver just processes the data when the position is requested instead of continuously tracking the signals. This reduces the receiver complexity and power consumption which is important for the mobile devices. Since all the emitters in a SFN transmit the same signals on the same frequency simultaneously, the initial phase presented in [5] is also used to distinguish the signals from different emitters.

The rest of this paper is organized as follows: section II describes the DVB-T system and summarizes the positioning method with tracking stage. Section III describes the novel positioning mechanism which skips the tracking stage. Section IV presents the simulation results. Finally conclusions are drawn.

II. DVB-T DESCRIPTION AND RANGING WITH TRACKING

DVB-T sub-carriers are categorized into four types: Null, Data, Transmission Parameter Signalling (TPS) and Pilot sub-carriers [6]. The pilot sub-carriers are used for channel estimation and equalization. They are modulated by a known Pseudo-Random Binary Sequence (PRBS) with a 4/3 boosted signal amplitude compared to data and TPS sub-carriers. The PRBS has a good auto-correlation property. Therefore it can be used for delay estimation by correlating the incoming signals with some local generated replicas. Based on [6], the pilot sub-carriers are divided into two groups: the continuous pilots and the scattered pilots sub-carriers (SPS). The continuous pilots are placed on the same location in all OFDM symbols, while the scattered pilots are inserted every 12 sub-carriers with an initial position chosen from the set $\{3, 6, 9, 12\}$, depending on the index of the OFDM symbol. In this paper, we are interested in the SPS for positioning. This ranging method with tracking has been presented in [1], [2], [5], and it is summarized hereafter.

In the ideal case of a noise-free channel each received SPS p of the k -th OFDM symbol generates, after FFT demodulation, a value

$$d_p^k(n) = c_p^k \alpha e^{-j2\pi \frac{pn}{N_{FFT}}} \quad (1)$$

where c_p^k is the transmitted value of SPS p of the k -th OFDM symbol, α is the attenuation introduced by the channel and it is a real number, and n is the unknown delay to be

estimated, normalized with respect to T_{samp} , which is the OFDM sampling period. N_{FFT} is the FFT number. In the presence of noise, the received value will be

$$d_p^k(n) = d_p^k(n) + w_k \quad (2)$$

where w_k is the noise contribution.

It is well known that in a Gaussian channel, the delay can be detected by Maximum Likelihood (ML) estimation through correlation [7]. Since the positions of SPS in different OFDM symbols are different, before generating a local replica, the algorithm introduced in [8] is used to detect the SPS position of the current OFDM symbol. Once the SPS position is known, a local replica of d_p^k , with a variable delay \tilde{n} ,

$$P_p^k(\tilde{n}) = c_p^k e^{-j2\pi \frac{p\tilde{n}}{N_{FFT}}} \quad (3)$$

is generated and correlated with d_p^k . This correlation can be performed in the frequency domain, as described in [1], as

$$R(m) = \frac{1}{N_p} \sum_{p \in p_s(k)} d_p^k(n) P_p^{k*}(\tilde{n}) \quad (4)$$

where N_p is the number of SPSs in the OFDM symbol, $(\cdot)^*$ denotes complex conjugate, $m = n - \tilde{n}$ is the delay offset between the received signal and the local replica, and $p_s(k)$ is the index set of the SPSs of the k -th OFDM symbol.

By substituting $d_p^k(n) = d_p^k(n)$ in (4) it is possible to show [5] that the absolute value of $R(m)$ is

$$|R(m)| = \frac{16}{9} \sigma_p^2 \alpha \left| \frac{\sin(\pi B m)}{\sin\left(\frac{\pi B m}{N_p}\right)} \right| \quad (5)$$

where σ_p^2 is the power of the data and TPS subcarriers, and B is defined as

$$B = \frac{P_I N_p}{N_{FFT}} \quad (6)$$

where P_I is the interval between two adjacent SPSs, which is equal to 12 in DVB-T signals.

The coarse delay estimation is obtained by simply searching the maximum of this correlation function or by the match pursuit algorithm [9]. Then the coarse delay estimation is refined by a tracking stage, which is similar to the one used in GNSS receivers [3]. An Early-Late delay lock loop (DLL) is used. A difference between this DLL and the one used in GNSS receivers is the re-acquisition stage, which is implemented to overcome the delay jump during the user's motion [5].

III. RANGING WITHOUT TRACKING

In this section the novel receiver mechanism is presented. This mechanism adopts only the acquisition stage together with some interpolation methods for delay estimation thanks to the high SNR and negligible Doppler effect [10] of DVB-T signals.

The pseudoranges are calculated only when the position is requested. So the receiver is in hibernation between these requests. The flow chart of this positioning mode is schematically illustrated in Figure 1.

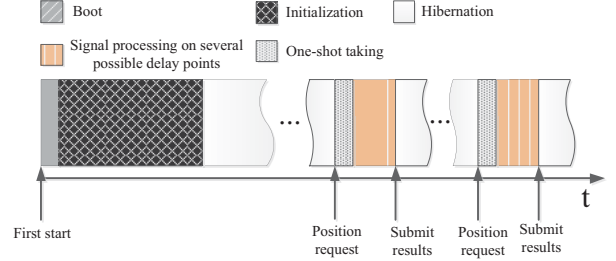


Fig. 1. One shot positioning mode

As shown in Figure 1, when the receiver starts for the first time, it needs the initialization to obtain some information, like the DVB-T signal association. In this initialization, the receiver acquires all the DVB-T signals on all delay points. Therefore the ranges can be calculated for all the visible DVB-T emitters. In this paper, the initial phase described in [5] is also used. In this way, the DVB-T signals can be correctly associated to the emitters on the basis of different propagation delays. The initial position and velocity are also known by the receiver. Based on this information, the receiver can predict the possible delay for each emitter in the following position fix point. Therefore after the initialization, the receiver can compute the correlation only on several possible delay points to simplify the complexity.

The correlation function without noise is shown in Figure 2. The y axis represents the normalized correlation amplitude and the x axis is the delay to be estimated, normalized with respect to the sampling frequency. While the green star in Figure 2 is the true maximum $\{t_r, R_r\}$ and the blue square is the estimated delay \hat{t} by the linear interpolation method. The distance between the two measured points is δt . Therefore the three measured points shown in red nodes are:

$$\begin{aligned} |R_A| &= \frac{16}{9} \sigma_p^2 \alpha \left| \frac{\sin(\pi B t_A)}{\sin\left(\frac{\pi B t_A}{N_p}\right)} \right| \\ |R_B| &= \frac{16}{9} \sigma_p^2 \alpha \left| \frac{\sin(\pi B (t_A + \delta t))}{\sin\left(\frac{\pi B (t_A + \delta t)}{N_p}\right)} \right| \\ |R_C| &= \frac{16}{9} \sigma_p^2 \alpha \left| \frac{\sin(\pi B (t_A - \delta t))}{\sin\left(\frac{\pi B (t_A - \delta t)}{N_p}\right)} \right| \end{aligned} \quad (7)$$

Based on these three measurements, two different interpolation methods are used to refine the delay estimation, instead of tracking which is used in normal receivers. These two interpolation methods are presented in the following sections.

A. Linear interpolation

In this part, a simple linear interpolation method is presented. This method is based on the three points in the main lobe containing the maximum correlation point, $A\{R_A, t_A\}$, $B\{R_B, t_B\}$ and $C\{R_C, t_C\}$, as shown in Figure 2. Suppose R_C is smaller than R_B , therefore we can draw a line through

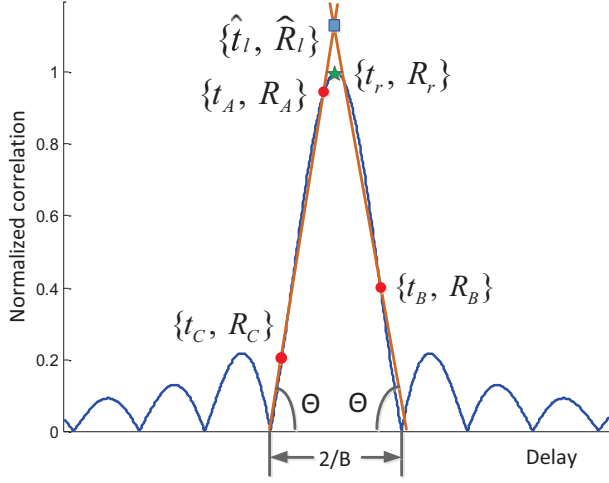


Fig. 2. Interpolation

points A and C, which is:

$$y(t) - R_C = \frac{R_A - R_C}{t_A - t_C}(t - t_C) \quad (8)$$

In the remaining point B we draw a line with a slope opposite to the one of the straight line in (8) and passing through B:

$$y(t) - R_B = -\frac{R_A - R_C}{t_A - t_C}(t - t_B) \quad (9)$$

By intersecting these two lines, and observing that $2t_A = t_B + t_C$, we can write the abscissa of the intersection point as

$$\hat{t} = t_A + \frac{R_B - R_C}{2(R_A - R_C)}(t_A - t_C) \quad (10)$$

An example is shown in Figure 2. In this method we don't exploit the shape of the correlation, as done in the sinc interpolation method.

B. Sinc interpolation

In the ideal case with no noise, the correlation can be expressed as in (5). We can exploit the knowledge of this expression, by adopting a method similar to the one proposed in [11] for the fine estimation of the Doppler frequency in GNSS applications. We show here that a similar approach can be adopted for the delay estimation in an OFDM system.

The width of the main lobe of the correlation in (5) is $2/B$. Therefore if we choose $\delta t = 2/(3B)$, the points A, B and C will be located in the main lobe, and then we can write:

$$\left| \frac{\sin(\pi Bm)}{\sin\left(\frac{\pi Bm}{N_p}\right)} \right| = \frac{\sin(\pi Bm)}{\sin\left(\frac{\pi Bm}{N_p}\right)} \quad (11)$$

where $m = t_r - t$, and t_r is the abscissa of the maximum, as shown in figure 2. We observe that the point A is located in a point $t' = t_r - t_A$ very close to zero, and then, since N_p is a large number (it is 142 in 2K mode), since:

$$\sin\left(\frac{\pi Bt'}{N_p}\right) \approx \frac{\pi Bt'}{N_p}$$

Then for a generic t close to the maximum, we can write

$$\begin{aligned} t|R| &= (t_r - t')|R| \\ &= t_r|R| - \frac{16}{9}t'\sigma_p^2\alpha \frac{\sin(\pi Bt')}{\sin\left(\frac{\pi Bt'}{N_p}\right)} \\ &\approx t_r|R_M| - \frac{16}{9}t'\sigma_p^2\alpha \frac{\sin(\pi Bt')}{\frac{\pi Bt'}{N_p}} \\ &= t_r|R| - K \sin(\pi Bt') \end{aligned} \quad (12)$$

where K is expressed by the following equation:

$$K = \frac{16}{9}\sigma_p^2\alpha \frac{N_p}{\pi B}$$

In our case, with the choice $\delta t = 2/(3B)$, the abscissas of the three points A, B, and C can be written as:

$$\begin{aligned} t_C &= t_A - \frac{2}{3B} \Rightarrow t'_C = t'_A - \frac{2}{3B} \\ t_B &= t_A + \frac{2}{3B} \Rightarrow t'_B = t'_A + \frac{2}{3B} \end{aligned} \quad (13)$$

With these values it is possible to show that

$$\begin{aligned} &\sin(\pi Bt'_A) + \sin(\pi Bt'_B) + \sin(\pi Bt'_C) \\ &= \sin(\pi Bt'_A) + \sin[\pi B(t'_A + \frac{2}{3B})] \\ &\quad + \sin[\pi B(t'_A - \frac{2}{3B})] \\ &= 0 \end{aligned} \quad (14)$$

and combining (12) and (14), we finally obtain:

$$\begin{aligned} &t_A|R_A| + t_B|R_B| + t_C|R_C| \\ &= t_r(|R_A| + |R_B| + |R_C|) \\ &\quad - K[\sin(\pi Bt'_A) + \sin(\pi Bt'_B) + \sin(\pi Bt'_C)] \\ &= t_r(|R_A| + |R_B| + |R_C|) \end{aligned} \quad (15)$$

Therefore the true delay can be obtained as

$$t_r = \frac{t_A|R_A| + t_B|R_B| + t_C|R_C|}{|R_A| + |R_B| + |R_C|} \quad (16)$$

Equation (16) represents a weighted average of the three measured samples. It gives an independent final delay estimation apart from the error t' introduced by the acquisition.

C. Complexity comparison

The computational complexity of the two methods is evaluated taking into account the multiplication operations involved in correlation. For the sake of simplicity, in this comparison we only count the number of symbol multiplication, neglecting the complexity of the discriminator and loop filter for the normal receiver and interpolation of the one shot receiver. One symbol multiplication represents all the sample multiplications included in one OFDM symbol correlation in one delay point. For the normal receiver mechanism, the receiver performs one acquisition and enters a continuous tracking for the

coming OFDM symbols. Therefore the number of symbol multiplication for a normal receiver is:

$$\frac{4N_{fft}}{P_I} + \frac{3T_p}{T_{sym}}N_p \quad (17)$$

where T_p is the update period of the position fix, T_{sym} is the OFDM symbol duration, and N_p is the number of position fix requests. The first term of the expression takes into account the operations in the acquisition stage. Since the correlation is a periodic function with a periodicity N_{fft}/P_I , by adding four successive symbols together, the periodicity is expanded to $4N_{fft}/P_I$. Each symbol multiplication is needed for each possible delay point. The second term of (17) takes into account the operations of the continuous tracking stage. Since three local replicas are generated and multiplied with the incoming signal for each OFDM symbol, the number of symbol multiplications for each position fix request is $3T_p/T_{sym}$. For example, for 2K mode N_{fft} is 2048 and T_{sym} is $280\mu s$ with a Cyclic Prefix (CP) equal to $1/4$. P_I is 12 for DVB-T signal. If T_p is chosen equal to 0.2s and $N_p = 100$, then the total number of symbol multiplications for a normal receiver is 212825.

For the one shot receiver, the receiver performs one acquisition on all delay points at the initialization stage and one acquisition on several possible delay points for each position fix. Therefore the number of symbol multiplications for the one shot receiver is:

$$\frac{4N_{fft}}{P_I} + L_s N_p \quad (18)$$

where the first term is due to the acquisition at the initialization stage, which is the same we have in a normal receiver. L_s is the search space used for the acquisition except the first one, and depends on the velocity. Normally, it is a small number. For example, let us consider a user moving with a speed of 100m/s toward to or away from a DVB-T emitter. If the period of the position fix request is 0.2s, the distance covered between two position fix requests is 20m. It is less than one delay interval, which is 32m for the 2K mode. Therefore for the same configuration considered before and with $L_s = 10$, the total number of symbol multiplications for the one shot receiver is 1683. Comparing with the normal receiver, the complexity is greatly reduced.

IV. SIMULATION RESULTS

We tested the proposed methods by simulation. The DVB-T signals are generated by Anritsu MX3700. Then the fraction delay is added according to the receiver path by shifting the FFT window. The signal parameters are summarized in Table I. We suppose that the carrier frequency offset has been corrected before the correlation and the multipath is absent.

In order to analyze the performance of the two methods presented previously, the estimated range errors obtained by these two methods are compared with those obtained by the normal tracking receiver, as shown in Figure 3. The errors are calculated by comparing the estimated range with the range added into the DVB-T signals. In this way, the error introduced

TABLE I
PARAMETERS OF DVB-T SIGNALS

Parameters	Values
FFT size N_{FFT}	2048
CP length	$\frac{1}{4}(56\mu)s$
Signal bandwidth	8 MHz
Length of simulation	100 s
Symbol duration T_{sym}	$280\mu s$
Sampling period T_{samp}	$109ns$
position updated rate	0.2 s

by the quantization has been avoided. In Figure 3, we can observe that when the SNR is low, the tracking method is much better than the linear interpolation and slightly overperforms the sinc interpolation by paying much higher computation complexity. When the SNR goes up to around -2 dB or higher, the tracking method gives the same performance of the two interpolation methods. It is worth to notice that the SNR of DVB-T signals is normally around 10dB due to the error probability requirement of TV service. So at this SNR level the one shot receiver provides the same performance of the normal receiver, but it has lower complexity which means lower power consumption.

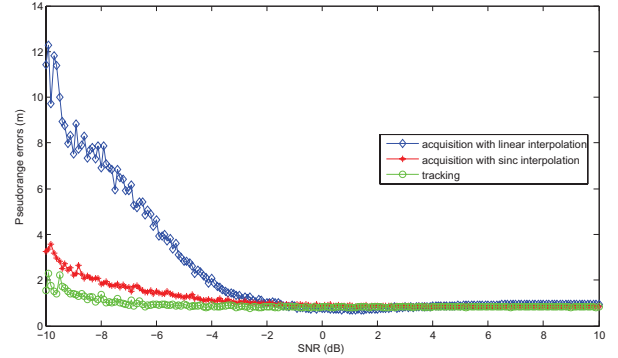


Fig. 3. Pseudorange errors of the one shot receiver and normal tracking receiver

In order to calculate the position, a scenario with 4 DVB-T emitters is considered [5]. The method works with an initialization phase necessary to identify the emitters, as described in [5], and the path ambiguity problem is solved based on the methods proposed in [12]. The Extended Kalman Filter (EKF) is used for the position calculation. In Figure 4, the path errors of the two interpolation methods and the normal receiver are plotted. It can be seen that when the SNR is low, the linear interpolation method gives the biggest position errors. The sinc interpolation and tracking method provide a similar performance. All the three methods show large variance. When the SNR increases, the position errors of the three methods converge to a similar level which is dominated by the EKF. The variance becomes smaller as well.

V. CONCLUSION

In this paper, we present a one shot receiver for positioning with DVB-T signals in one SFN. The receiver skips the track-

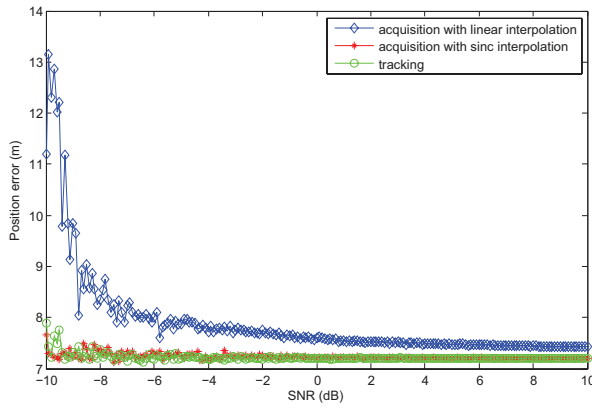


Fig. 4. Path errors of the one shot receiver and normal tracking receiver

ing stage and calculates the range by acquisition by adopting one of two different interpolation methods. These methods are described and compared with the normal tracking method. Both interpolation methods have less complexity. They provide a performance comparable with the one of the normal tracking method, thanks to the good SNR and negligible Doppler effect of DVB-T signals .

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