

¹SYNCHRONIZATION FOR A DVB-T RECEIVER IN PRESENCE OF CO-CHANNEL INTERFERENCE

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Abstract - This paper deals with the synchronization of a multi-antenna receiver for terrestrial digital video broadcasting (DVB-T) in the presence of strong co-channel interference. Two algorithms are proposed which exploit different features of the DVB-T signal. Both algorithms take advantage from the spatial diversity provided by the antenna array. The first algorithm uses the presence of pilot carriers within the DVB-T signal. The second algorithm uses the cyclic prefix property of the DVB-T signal. By simulations we demonstrate that the proposed algorithms show promising performance even in strong co-channel interference.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has generated considerable interest as a highly suitable technique for high-bit-rate transmission. It has been adopted for the European standard for digital video broadcasting for terrestrial systems (DVB-T) [1]. In the context of future deployment of the DVB-T networks, some co-channel interference problems between different transmitters may appear. Broadcasting operators will need a tool that permits to identify all the transmitters that interfere at a measurement point.

The first task to achieve this identification is the temporal and frequency synchronization of the receiver to all the transmitters. This synchronization is more difficult in this interference context than for a classical DVB-T receiver because the useful signal to interference ratio can be very low.

Symbol time and carrier frequency offset estimation methods for OFDM transmission systems have been addressed in many contributions. Most of these offset

estimators rely on the cyclic prefix property of the OFDM signal. They use it either to maximize a correlation criterion [3], to minimize a quadratic error criterion [3] or to maximize a likelihood function [2]. One paper presents an algorithm which takes profit of the pilot carriers transmitted in an OFDM symbol to make the time synchronization [4]. All these algorithms concern mono-sensor OFDM receivers which are not adapted to deal with interference.

An algorithm dealing with the synchronization of a multi-sensor OFDM receiver is presented in [5]. The proposed antenna diversity permits to reduce the effect of fading of a mobile radio channel but it doesn't allow to deal with interference. This algorithm will be considered in this paper as a reference algorithm which will allow to evaluate the performances improvement achieved by the proposed new algorithms.

The paper is organized as follows. In Section II we introduce the system model, in Section III we devise the proposed algorithms, and in Section IV we present the simulation results.

II. SYSTEM MODEL

We consider a system of T interfering DVB-T transmitters. The transmission frame is that fixed by the DVB-T standard [1]. Each transmitted signal is OFDM modulated with N subcarriers by means of an inverse discrete Fourier transform. Among these carriers, some are used for data signaling and synchronization purposes. These pilot carriers are modulated with reference information whose transmitted values are known to the receiver. These pilots are of two kinds : continual pilots and scattered pilots. The continual pilot carriers occur on all symbols at the same frequency location fixed by the DVB-T standard [1]. The location of the scattered pilot carriers is varying from one

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symbol to another but is the same every four OFDM symbols.

In order to avoid intersymbol interference, the last G samples of the body of the OFDM symbol are copied and appended as a preamble to form the complete OFDM symbol. This is called the cyclic prefix of an OFDM signal.

The resulting OFDM symbols are transmitted over a multipath propagation channel and received on a multi-sensor antenna at the receiver. We assume that the channel is modeled by a Clarke model [6]. At the propagation channel output, the base-band received signal for one DVB-T transmitter is given by

$$\mathbf{x}(t) = \sum_{p=1}^P a_p d(t - \tau_p) \cdot \left[\sum_{n=1}^{N_p} c_{n,p} \exp\left(j2\pi \frac{v}{\lambda} \cos(\theta_{n,p} - \gamma) + \varphi_{n,p}\right) \mathbf{s}_{n,p} \right] \quad (1)$$

where $d(t)$ is the transmitted DVB-T signal, $\mathbf{x}(t)$ is the received signal vector of size M (the number of antennas), P is the number of paths, a_p is the attenuation of the p^{th} path, τ_p is the delay of the p^{th} path, N_p is the number of elementary sub-paths associated to the p^{th} path, $c_{n,p}$ is the attenuation of the n^{th} sub-path associated to the p^{th} path, v is the mobile speed, γ is the angle between the mobile speed and the North (randomly uniformly distributed in $[0, 2\pi]$), λ is the wavelength, $\theta_{n,p}$ is the azimuth of the n^{th} sub-path associated to the p^{th} path, $\varphi_{n,p}$ is the phase of the n^{th} sub-path associated to the p^{th} path (randomly uniformly distributed in $[0, 2\pi]$), $\mathbf{s}_{n,p}$ is the steering vector of the n^{th} sub-path associated to the p^{th} path.

In order to demodulate the data of each transmitter, the first task of the multi-sensor receiver is to detect all the present transmitters and to synchronize temporally and in frequency on each of them, allowing thus to suppress the cyclic prefix and to do the OFDM demodulation (FFT). This synchronization step is the issue of the next section.

III. SYNCHRONIZATION ALGORITHMS

The time synchronization aims at detecting the number of DVB-T signals and at determining the position of the useful part of the OFDM symbols. It is composed of two stages.

The first stage consists in computing a criterion for each sample. The value of this criterion is compared to a threshold in order to decide which samples may correspond to the beginning of the useful part of the OFDM symbols.

The second stage consists in identifying among the samples selected during the first stage those which really correspond to the beginning of the OFDM symbols and those which correspond to a false alarm. This is done easily by using the periodicity property of the detection and it won't be presented in this paper.

The frequency synchronization compensates the frequency offset due to the offset between the oscillator of a DVB-T transmitter (modulator part) and the local oscillator of the DVB-T receiver. In this contribution, the frequency synchronization method is directly deduced from the time synchronization algorithms.

The algorithms presented in this section are used for the first stage of the synchronization procedure. They exploit the multi-sensors availability in the receiver. The underlying idea is to implement a spatial filter (or a space-time filter) and to compute a synchronization criterion using the output of this filter. The value of this synchronization criterion is then compared to a threshold to validate the presence of one or several DVB-T signals.

The first algorithm (section A) is an adaptation of the synchronization principles used in smart adaptive antennas in GSM [7] to the DVB-T case.

The second algorithm (section B) is more specific of the OFDM nature of the DVB-T signal. It is an adaptation of the algorithms used in the classical mono-sensor receivers to the constraints of strong interference.

A. Correlation with a Known Sequence

This first algorithm relies on the detection of a known reference sequence $d(k)$ of length N_d emitted by each DVB-T transmitter.

We consider the following hypotheses test:

$$H_1: \mathbf{x}(n+k) = \mathbf{h}d(k) + \mathbf{w}(n+k) \quad (2)$$

$$H_0: \mathbf{x}(n+k) = \mathbf{w}(n+k) \quad (3)$$

for $n = 0, 1, \dots, N_r - 1$ and $k = 0, 1, \dots, N_d - 1$, where $\mathbf{w}(n)$ is spatially correlated and temporally white interference and noise. We assume that the channel consists of a single path only, N_r is the length of the received sequence, and N_d is the length of the reference sequence. We propose to use as test statistics the maximum likelihood ratio.

We can show that the maximum likelihood ratio is

$$c(n) = \frac{1}{\|d\|^2} \hat{\mathbf{r}}_{xd}^H(n) \hat{\mathbf{R}}_{xx}^{-1}(n) \hat{\mathbf{r}}_{xd}(n) \quad (4)$$

where

$$\|d\|^2 = \sum_{k=0}^{N_d-1} |d(k)|^2 \quad (5)$$

$$\hat{\mathbf{r}}_{xd}(n) = \sum_{k=0}^{N_d-1} \mathbf{x}(n+k) d^*(k) \quad (6)$$

$$\hat{\mathbf{R}}_{xx}(n) = \sum_{k=0}^{N_d-1} \mathbf{x}(n+k) \mathbf{x}^H(n+k). \quad (7)$$

The expression (4) can be interpreted as the correlation of the reference sequence with the spatially filtered received signal. The spatial filter is matched to the reference

sequence. The detection statistics (4) has a dominant peak at the synchronization position n_0 .

As reference sequence we use either the temporal signal associated to the continual pilots over one OFDM symbol duration, or the temporal signal associated to the scattered pilots over four OFDM symbols duration.

B. Use of the Cyclic Prefix Property

This second algorithm is an adaptation of the algorithms used in a classical mono-sensor DVB-T receiver [3] to the multi-sensor case. Under some constraint, we calculate a spatial filter $\mathbf{g}(n)$ that maximizes the correlation with the cyclic prefix at its output. The test statistics is

$$c(n) = \max_{\mathbf{g}(n)} \left| \sum_{i=0}^{G-1} \left(\mathbf{g}(n)^H \mathbf{x}(n+i) \right) \left(\mathbf{g}(n)^H \mathbf{x}(n+i+N) \right)^* \right|^2, \quad (8)$$

where the maximization is carried out either under the constraint

$$\mathbf{g}(n)^H \mathbf{g}(n) = 1, \quad (9)$$

or the constraint

$$\sum_{i=0}^{G-1} \left(\left| \mathbf{g}(n)^H \mathbf{x}(n+i) \right|^2 + \left| \mathbf{g}(n)^H \mathbf{x}(n+i+N) \right|^2 \right) = 1. \quad (10)$$

It can be shown that the equivalent formulation of the test statistic (8) and the constraint (9) or (10) is

$$c(n) = \max_{\mathbf{g}(n)} \frac{\left| \mathbf{g}(n)^H \mathbf{R}_{CP}(n) \mathbf{g}(n) \right|^2}{\left| \mathbf{g}(n)^H \mathbf{R}_{xx}(n) \mathbf{g}(n) \right|^2} \quad (11)$$

where

$$\mathbf{R}_{CP}(n) = \sum_{i=0}^{G-1} \mathbf{x}(n+i) \mathbf{x}^H(n+i+N), \quad (12)$$

for the constraint (9)

$$\mathbf{R}_{xx}(n) = \mathbf{I}_M, \quad (13)$$

and for the constraint (10)

$$\mathbf{R}_{xx}(n) = \sum_{i=0}^{G-1} \left(\mathbf{x}(n+i) \mathbf{x}^H(n+i) + \mathbf{x}(n+i+N) \mathbf{x}^H(n+i+N) \right) \quad (14)$$

An exact solution of (11) is difficult to evaluate since the matrix $\mathbf{R}_{CP}(n)$ in the numerator of (11) is not hermitian. However, we can show that an approximate solution to (11) is obtained by taking the eigenvector for $\mathbf{g}(n)$ that corresponds to the maximum eigenvalue of the matrix

$$\mathbf{A}(n) = \mathbf{R}_{xx}^{-1}(n) \left(\mathbf{R}_{CP}(n) + \mathbf{R}_{CP}^H(n) \right) + \left(\mathbf{R}_{xx}^{-1}(n) \left(\mathbf{R}_{CP}(n) + \mathbf{R}_{CP}^H(n) \right) \right)^H. \quad (15)$$

Then the test statistics (11) is the maximum eigenvalue of (15) (in the following, we term this as synchronization criterion 1). Alternatively, we will consider the following

test statistics (in the following referred to as synchronization criterion 2)

$$c(n) = \left| \mathbf{g}(n)^H \mathbf{R}_{xx}^{-1}(n) \mathbf{R}_{CP}(n) \mathbf{g}(n) \right|^2, \quad (16)$$

where $\mathbf{g}(n)$ is again the eigenvector associated to the dominant eigenvalue of (15).

C. Integration of the criteria

For the synchronization algorithm (4), we can derive a criterion taking into account the periodicity T_{sp} of the reference sequence using the hypotheses test:

$$\mathbf{H}_1 : \mathbf{x}(n + mT_{sp}) = \mathbf{h}d(n) + \mathbf{w}(n + mT_{sp}), \quad (17)$$

$$\mathbf{H}_0 : \mathbf{x}(n + mT_{sp}) = \mathbf{w}(n + mT_{sp}), \quad (18)$$

for $m=0, \dots, N_{sp}-1$, where N_{sp} is the number of observed synchronization periods and assuming that r_{xd} and \mathbf{R}_{xx} are a function of m . It can be shown that the test statistics for a maximum likelihood ratio test is

$$\tilde{c}(n) = \frac{1}{N_{sp}} \sum_{m=0}^{N_{sp}-1} -\ln(1 - c(n + mT_{sp})). \quad (19)$$

with $c(n)$ given by (4).

If all the terms $c(n + mT_{sp})$ in (19) are small compared to 1, the test statistics (19) is well approximated by

$$\bar{c}(n) = \frac{1}{N_{sp}} \sum_{m=0}^{N_{sp}-1} c(n + mT_{sp}). \quad (20)$$

It is seen that (20) is an averaging of the synchronization criterion (4) over several periods. This will improve the detection probability while reducing the false alarm probability.

The same kind of averaging can be used with the second algorithm (8).

D. Frequency synchronization

The frequency synchronization can either be done jointly with the time synchronization or once the time synchronization is done.

For the first algorithm, the synchronization criterion is computed at one given sample time with $\mathbf{x}(n) \rightarrow \mathbf{x}(n) e^{j2\pi\Delta f n T_s}$ for Δf varying from $-\Delta f_{\max}$ to Δf_{\max} with the required resolution and where T_s is the sampling period. The maximum of the criterion is obtained for Δf being the searched frequency offset.

For the second algorithm, the time synchronization criterion is computed at one given sample time with $\mathbf{R}_{CP} \rightarrow \mathbf{R}_{CP} e^{j2\pi\Delta f N T_s}$ for Δf varying from $-\Delta f_{\max}$ to Δf_{\max} with the required resolution and where T_s is the sampling

period. The maximum of the criterion is obtained for Δf being the searched frequency offset.

The jointly time and frequency offset search consists in doing this for each sample and in searching for the maximum in the "time offset-frequency offset" plan, while the other solution consists in doing this only for the sample corresponding to the synchronization. We can also combine the methods by first doing a coarse synchronization by searching for the maximum in the "time offset-frequency offset" plan and then by tracking more accurately the frequency offset at the synchronization sample.

IV. SIMULATIONS

A. Simulations environment

The DVB-T standard specifies several values for the signal bandwidth, as well as many configuration parameters. This allows DVB-T to cope with more or less severe propagation channels by adapting the useful bitrate, the robustness of the modulation and the error protection level. We simulated the configuration that will be used in France. For this configuration, we have the parameters $N = 8192$ and $G = 256$. As a consequence, the length of the reference sequence used for the first algorithm (4) can either be $N_d = 8448$, if we use the continual pilots, or $N_d = 4 * 8448$, if we use the scattered pilots.

The receiver has a circular antenna array with $M = 5$ sensors.

For the simulations, we considered two scenarios. The first scenario consists of two co-channel DVB-T transmitters. One of them is transmitted over channel 2 (Table 1). The other (interfering) DVB-T transmitter is sent over channel 1 (Table 1) and has a relative delay of $(109 + n * 924) \mu s$, where n is an integer.

The second scenario consists of three co-channel DVB-T transmitters. One DVB-T transmitter is sent over channel 4 (Table 1). The dominant interfering DVB-T transmitter is sent over channel 3 with an additional delay of $(328 + n_1 * 924) \mu s$, where n_1 is an integer. The other interfering DVB-T transmitter is sent over channel 1 with a relative delay of $(109 + n_2 * 924) \mu s$, where n_2 is an integer, and its power is 10 dB lower than the power of the main interfering DVB-T transmitter.

The channels used in the simulations are Rayleigh multi-path channels with different gains applied to the different paths. The number of paths and the maximum delay for the different channels are summarized in Table 1.

Table 1
Channels characteristics used in the simulations

Channel	Number of paths	Maximum delay in μs
Channel 1	6	5
Channel 2	6	3.25
Channel 3	17	5.42
Channel 4	19	5.43

Further, for all channels and all paths we used 10 sub-paths with equal power. Phases and angles of arrival were randomly chosen in $[0, 2\pi]$ from an uniform distribution. With C/N , C/I , and I/N we denote the signal to noise ratio, the signal to interference ratio, and the interference to noise ratio, respectively.

The present simulations study the performances of both synchronization algorithms in terms of detection probability for a certain tolerable false alarm probability. Firstly, we evaluate the false alarm probability versus the threshold. Secondly, we evaluate the detection probability versus the false alarm probability.

The performances of the proposed algorithms will also be compared to the performances of the algorithm presented in [5].

B. Simulations Description

In order to evaluate the false alarm probabilities versus the thresholds we generate DVB-T signals with the following characteristics depending on the algorithm used :

- For the first synchronization algorithm, the signal has no continual and no scattered pilots.
- For the second synchronization algorithm, the signal has no cyclic prefix.

For the first scenario, signals with these characteristics are used with $C/I = 0$ dB and $C/N = 30$ dB. For the second scenario, all three DVB-T transmitters have the same power and $C/N = 30$ dB.

For each algorithm, we compute 5 times the corresponding criterion for a signal with length $12 * 8448$ samples long, in order to average the influence of the channel parameters (angles of arrival, phase differences, etc.). For a predetermined list of thresholds, we count how often the criterion is greater than the threshold. Thus we have a relation $P_{fa} = f(\text{threshold})$.

In order to evaluate the detection probability, we generate signals corresponding to each scenario. The channels are generated 14 times with different values for the angles of arrival and phases. The total duration corresponds to about 100 synchronization periods for each configuration. For each generation, we evaluate the values of the synchronization criterion at the positions of all the paths of the useful transmitter. For all studied scenarios, the I/N level was 20 dB and the C/I level was varied.

This information allows to evaluate the detection probabilities by comparing the values of the synchronization criteria to the thresholds.

C. Simulations Results

The Figure 1 and Figure 2 represent the detection probability versus the false alarm probability by using the different algorithms for both scenarios 1 and 2 for $C/I = -20$ dB and a speed of 20 m/s. All the criteria were integrated over 6 synchronization periods except for the algorithm 1 using the scattered pilots which was integrated over 2 synchronization periods. In each case, the detection probability is that of the path that is most often received.

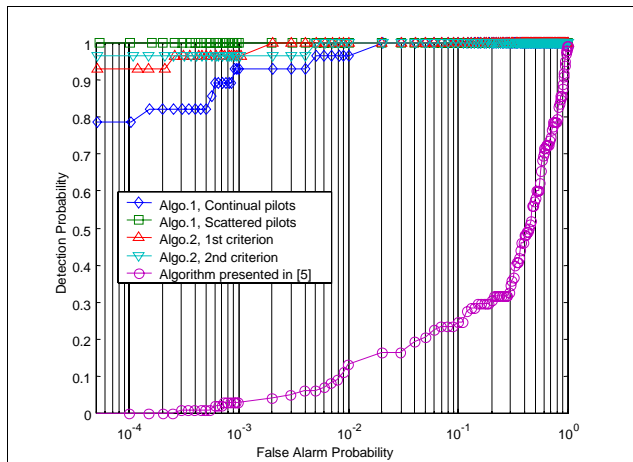


Figure 1 : Detection probabilities for scenario 1,
 $C/I = -20$ dB, $v = 20$ m/s

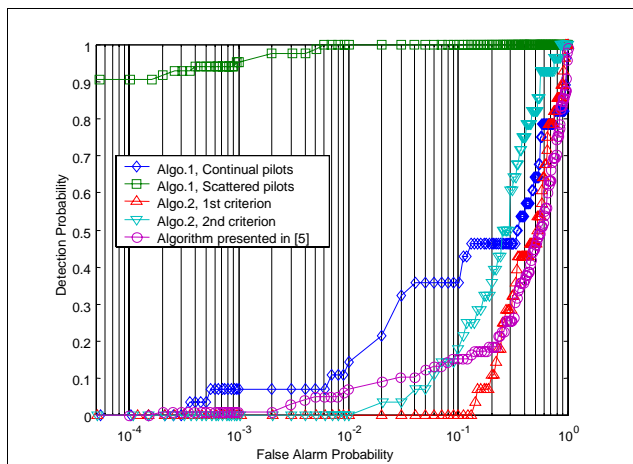


Figure 2 : Detection probabilities for scenario 2,
 $C/I = -20$ dB, $v = 20$ m/s

The simulation results show that the first algorithm (4) which uses the scattered pilots as reference sequence is the most reliable. For scenario 1, detection is always achieved using this algorithm. For the second scenario, it is also always achieved if we consider the detection of one of two neighboring paths (not presented in Figure 2).

The second algorithm (8) shows satisfying performance only for the first scenario. However, increasing the number of interferers negatively affects the performance. The algorithm presented in [5] has very poor performances for both scenarios. This confirms that it is not adapted for dealing with interference.

V. CONCLUSION

The proposed synchronization method based on a known reference sequence shows satisfying performance and outperforms the synchronization method based on the cyclic-prefix in presence of strong interference. The performances can further be improved by a spatio-temporal extension of the algorithm taking into account not only the present samples but also the past samples of the received signals to exploit the channel's multipath diversity. However, this would increase the computational complexity.

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