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Study of a Pilotless Fine Frequency Estimator Algorithm in Burst-mode PSK Transmissions

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***Abstract*— This work investigates the frequency estimation method and proposed an improved pilotless fine frequency estimator (FFE) algorithm for burst-mode (PSK) transmissions. The algorithm is data-aided (DA) and has an approach based on approximated Maximum Likelihood (ML). The simulations results obtained show us its estimation accuracy is close to the Modified Cramer-Rao Bound (MCRB) for a Signal-to-Noise (SNR) as low as 0 dB. Compared with theoretical solutions and based on the results obtained here, the estimator proposed is a good candidate for implementation in hardware. The algorithm is simple and easy to be implemented in digital form. The estimator was developed targeting a digital receiver for the DVB-S2 standard, that is under development in 65nm CMOS technology, and with minor changes it can also support DVB-S2X receivers or communication system that require the same constraints for low SNR (LSNR).**

***Keywords*— DVB-S2, Synchronization, Digital Receivers, Estimation.**

I. Introduction

The demand for higher rates and reliable wireless communications have increased the need for designing more optimized devices. One device can achieve savings in the overall data rate if subsystems are further simplified. In this sense, we investigate the use of a pilotless Fine Frequency Estimator (FFE) as an alternative to improve the current standard Digital Video Broadcast Second Generation (DVB-S2) [1] receivers.

The Digital Video Broadcast group developed the DVB-S2 standard in 2003, and the European Telecommunications Standards Institute (ETSI) [2] ratified it in 2005. It was specified to cope with any existing satellite transponder characteristics, achieving about 30% of capacity gain over its predecessor standard DVB-S. DVB-S2 was defined relative to three key concepts: better transmission performance, flexibility, low complexity receiver [1]. Despite the capacity gain provided by DVB-S2, it is still not widely used worldwide, and the number of satellite broadcasters that make use of 16-APSK and 32-APSK is low [3]. Due to all previously mentioned DVB-S2 advantages and opportunities, the implementation of DVB-S2 receivers is still an area worthy of research.

The current technology of DVB-S2 uses data-aided(DA) techniques as a frequency estimation technique. Such methods include the use of training pilot sequences that contains pilot symbols embedded in the transmitting signal. The pilots reference is fundamental to allow estimation method to achieve frequency correction. On the other hand, the use of pilots reduces the throughput because it takes resources from the data payload. The demodulation using pilot symbols is the preferred method [4] - [5] due to its simplicity and robustness, but the pilotless method is less investigated, and since all requirements of the DVB-S2 standard should be supported in pilotless mode, the pilotless demodulation should be studied more than ever.

The typical demodulation chain includes a structure called Coarse Frequency Estimator (CFE), which is the early step of frequency estimation. When the system operates on a low signal-to-noise ratio (SNR) regime, the CFE can propagate high estimation error harming subsequent sub-blocks in the demodulation chain (i.e., Coarse Phase Estimator). Then, in standard systems, pilots are used to reducing the residual frequency error estimation of the first step. The focus of our investigation is to use FFE method, in the pilotless mode, to reduce the frequency error estimation instead of pilots method.

Therefore, we propose an improved algorithm for the FFE method, which is based on the [6] algorithm and derived from [7]. The transmission model of our investigation is a digital data of burst-mode phase shift keying (PSK) signals. The algorithm uses information from the header, which is the first part of the frame structure in the DVB-S2. Our simulation results demonstrate that the proposed frequency estimation method has an accuracy close to the Modified Cramer-Rao Bound (MCRB) [8] for an SNR as low as 0 dB.

We organize the remainder of this paper as follows: Section II discusses the motivation and present a briefly overview of how works the frequency estimation methods and the frame structure of the DVB-S2 standard; Section III presents a description of the signal model and describes the algorithm proposed for the FFE methods and their improvement; Section IV presents the simulations results, and Section V concludes the paper.

II. Frequency Estimation Algorithms

The evolution from DVB-S to DVB-S2 brought new algorithms that allowed the use of low-cost local oscillators without compromising the function of TV receivers. The new systems are capable of working well as low as -2.35 dB SNR. Efficient frequency estimation algorithms are essential in devices prone to a large initial frequency offset of around $\pm 5MHz$[4]. According to specifications in [1], the receiver synchronization structure has to provide a normalized residual frequency offset smaller than 5.2 x 10^{-5} to achieve Quasi Error Free (QEF)

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performance. The method includes performing coarse[9], [10], followed by fine tune frequency estimation.

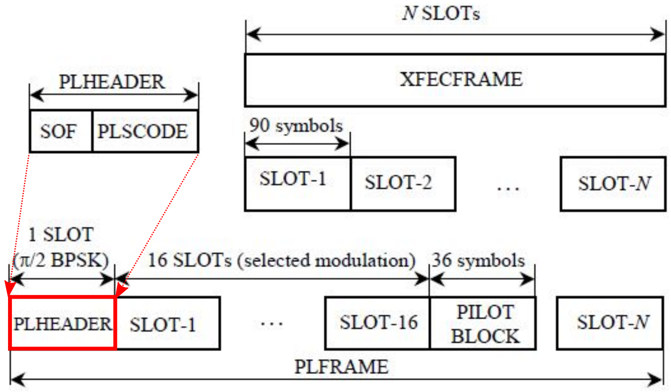

Fig. 1. *PLFRAME* structure.

Figure 1 shows the frame structure of the DVB-S2 standard. The frame splits into Physical Layer Header (PLHEADER) and XFECFRAME which comprises of 64800 bits and transmission mode configurations and payload data. The PLHEADER indicates the beginning of the frame and divides into the Start of Frame (SOF), with 26 symbols, and the Physical Layer Signaling Code (PLSCODE), with 64 symbols. This header provides information such as a synchronization sequence, pilot signals, and information on the current frame, such as modulation and coding rate. The SOF aids in the coarse carrier frequency synchronization. The XFECFRAME is composed of N slots with 90 symbols each. Finally, there is the PILOT BLOCK that can be toggled as present and comprises of 36 symbols. It goes after the first sixteen slots and repeats after every 16 slots.

The coarse frequency synchronization performs a rough first attempt to estimate the carrier frequency error. The block allows the correction of some amount of frequency deviation, but a low SNR can result in a high residual error. The DVB-S2 deals with residual errors using the information present in the PILOT BLOCK's. Furthermore, the standard allows the transmitter to operate in the pilot or pilotless mode. The pilotless mode toggle off the PILOT BLOCKS, but the sensitivity of the receiver decreases due to the deficient estimation in low SNR regime. In our approach, the transmitter toggle off the PILOT BLOCK's and FFE deal with the residual error, which recovers the sensitivity lost due to the pilotless mode. The proposed algorithm performs synchronization by using the 90 symbols present in the header.

III. Signal Model

Four important estimations happens in the reception chain: timing synchronizations, frame, frequency, and phase. If we assume that timing and frame synchronization is perfect, a certain level of carrier frequency estimation can harm the data recovery. Thus, our model considers the transmitted message with frequency offset, corrupted by noise such that,

$$x_{s,p} = c_{s,p} e^{j(2\pi k \Delta_f T + \theta)} + n_{s,p} \tag{1}$$

where s is the symbol index into the pilot slot, p pilot slot index, $c_{s,p}$ is the modulation symbol with unitary amplitude, Δf is the carrier frequency offset to be estimate, T is the symbol period, θ is an offset phase, and $n_{s,p}$ is an Additive White Gaussian Noise (AWGN) with zero mean and variance σ^2. Here, we also consider only symbols of an M-PSK constellation, but the method works for other modulation sets.

A. Current estimation approach

In general, the best performance frequency estimator are those based on Maximum Likelihood (ML). On the other hand, suboptimal approaches, such as the ones using the peak location of a periodogram [11], can present excellent performance. The main concerns of this estimation approach are the computation requirements that are usually expensive and makes implementation in hardware not viable. Therefore, more straightforward methods are desirable which balances between low estimation error and low complexity.

We based our approach on Maximum Likelihood(ML) algorithms and fit to carrier frequency recovery with linear modulations. Fundamentally, it derives an estimate of the carrier frequency offset and compensates the offset by counter-rotating the received signal [8], [12].

The algorithm requires an estimator reference and carrier phase slope track in a modulation-removed signal[7]. Thus, we obtain a continuous wave by removing modulation and making it constant and proportional to the angular frequency offset. We define $z_{s,p}$ as the result of the projection of the known symbols on the received data, such that

$$z_{s,p} = x_{s,p} \tilde{c}^*_{s,p}, \tag{2}$$

$x_{s,p}$ is the received signal, $\tilde{c}^*_{s,p}$ is the conjugate of the known pilot symbols, and $(\cdot)^*$ is the complex conjugate operator.

Jiang[6] proposed an alternative targeting DVB-S2 standard based . In the paper, the approach considers the phase error accumulation over some known symbol slot, such that

$$\phi_p = \arg\left[\sum_{s=0}^{N_s-1} z_{s,p}\right], \tag{3}$$

where N_s is the number of symbols in the pilot slot, and $arg(\cdot)$ denotes the argument function. Then, a weighted sum is performed to deal with noise and obtain the final estimation, such that

$$\Delta_{\hat{f}} = \frac{1}{2\pi(N_s + N_d)T_s}\left[\sum_{p=0}^{N_p-2} w_s \text{mod}\left(\phi_{s+1,p} - \phi_{s,p}, 2\pi\right)\right], \tag{4}$$

where N_p is the total number of available pilot slots, $N_d = N - N_s$, and w_s is a normalization factor such that

$$w_s = \frac{3\left[(2N_p-1)^2 - (2s+1)^2\right]}{\left[(2N_p-1)^2 - 1\right](2N_p-1)}. \tag{5}$$

B. Proposed solution

The *mod* operator applied in the Eq. (4) limits the estimation in the range of 0 or 2π, which severely degrades in the presence of high noise. As a result, the estimation range also decreases. One first modification is to change the phase error accumulation over some known symbol slot from (3), such that

$$\phi_s = \left[\sum_{s=0}^{N_s-1} z_{s,p}\right], \tag{6}$$

where we achieve a complex accumulation instead of just argument accumulation. Following, we can modify Eq. (4), such that

$$\Delta_{\hat{f}} = \frac{1}{2\pi(N_s + N_d)T_s} \times \bmod\left(\arg\left[\sum_{p=0}^{N_p-2} w_s \phi_{(s+1,p)}\phi^*_{s,p}\right], 2\pi\right), \tag{7}$$

where we change the order of arg and mod operator. Furthermore, we use vector projection of $\phi_{(s+1,p)}\phi^*_{s,p}$ instead of argument difference from Eq. (4). With these modifications, the error estimation decreases concideraby as it will be presented later on.

IV. Results

Computer simulations were conducted to test the algorithm described in Section III-B in every aspect of the carrier recovery algorithms based on the DVB-S2 pilotless structure with 8-PSK modulation, remembering that the method works for other modulation sets, the parameters utilized for simulations are presented in the following table.

Table I PLFRAME structure parameters of DVB-S2 for 8PSK[1].

TABLE I

	FRAME SIZE	PLHEADER	SYMBOLS	WINDOW SIZE
8PSK	64800	90	21600	21690

The Ns, Np and Nd parameters, which define the upper limits of the summations, in the Eq. (7) , are defined based on the Table I. Defined Ns=90, Np=1 and Nd=21600, the results of the simulations show that FFE model guarantees that the residual frequency error is always lower than the maximum allowed (i.e. 6×10^{-5}) of the normalized input frequency at ($\frac{E_s}{N_0}$ = -2dB). The models were quantized to depict (i.e. 10 bits), in simulations, the behavior of the hardware that will be implemented. Also, the simulations were performed, assuming perfect symbol timing synchronization.

Fig. 2 shows the performance of FFE which degrades as the frequency offset increases while keeping constant $\frac{E_s}{N_0} = -2$ dB. Results also show that the FFE meets residual requirements for frequency offsets higher than the DVB-S2 operational range, approximately at 1.2% of the input frequency, the output residual error rises to the order of 10^{-4}. During the whole simulation $\frac{E_s}{N_0}$ is kept in -2 dB.

Fig. 3 shows the result of a simulation assuming a constant frequency offset of 4×10^{-3}, which is the expected maximum error provided by a coarse frequency algorithm such as [4]. During the whole simulation, the residual frequency was lower than the target of 6×10^{-5}, and from $\frac{E_s}{N_0}$ = 7 dB and onwards, the value maintains around 1×10^{-5}.

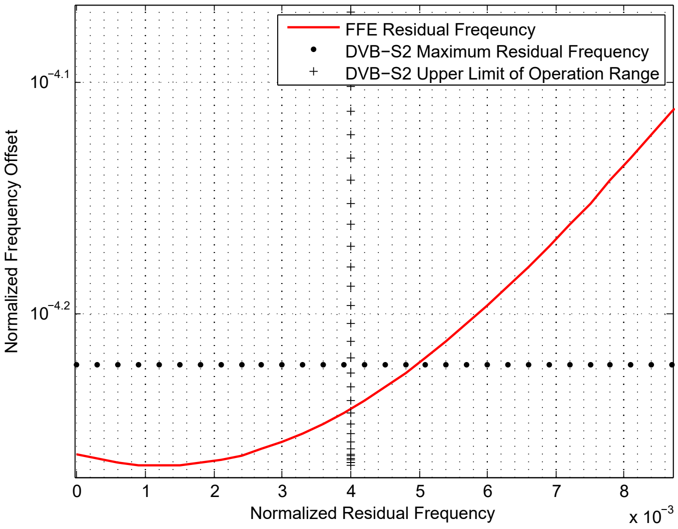

Fig. 2. FFE Residual Frequency for $\frac{E_s}{N_0} = -2$ dB

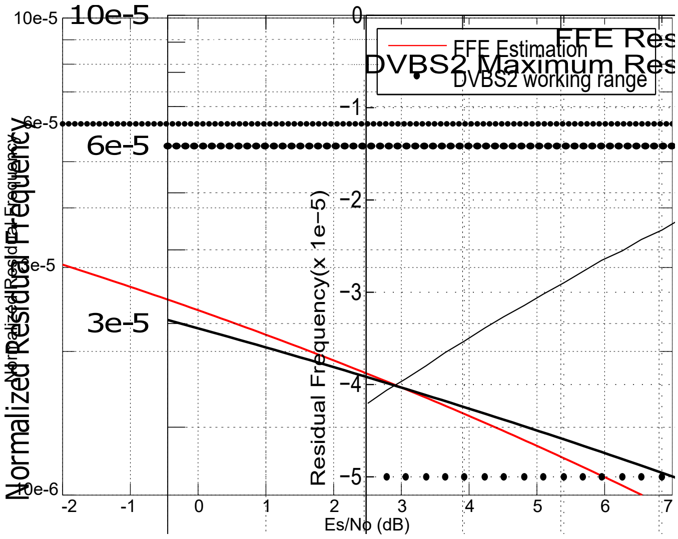

Fig. 3. FFE Residual Frequency for a Constant Frequency Offset.

Fig. 4 shows the results of our algorithm compared with other classical methods. As a reference for algorithms performance, we used the MCRB for carrier frequency estimation, which is given by [8]:

$$\text{MCRB}(\Delta f) = \left[\frac{3}{2\pi^2 N^3 T^2}\frac{1}{E_s/N_0}\right], \tag{8}$$

It is well known that the carrier phase of a modulation-removed signal (which is a continuous wave) has a constant slope proportional to its angular frequency offset. At high SNR, the frequency estimator that performs linear regression on the modulation-removed phase values is ML Kay [10] and Tretter [13]. However, like any non-linear operation, this simple algorithm has a threshold effect: When the SNR of continuous wave signal is below $\frac{E_s}{N_0}$ = 9 dB , its performance starts deteriorating very fast [12]. Then, instead of doing a linear regression directly on the modulation-removed signal itself, the frequency estimator proposed here first increase the energy of this signal by either autocorrelation over several frames or cross-correlation over a whole known symbol segment, then estimate the frequency through linear regression on the energy-enhanced modulation-removed signals.

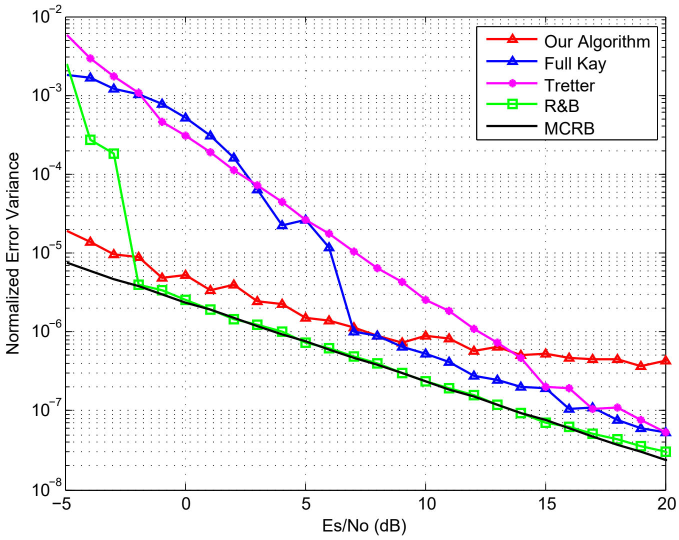

Fig. 4. Comparison with the normalized frequency estimation range of the proposed, Kay, Tretter, R&B methods and MCRB in fine frequency estimation

The result of the simulation is what can be verified in Fig. 4, the Kay and Tretter algorithms only achieve good accuracy in high SNR and our algorithm presents good accuracy for lower SNR, that its the purpose of the fine frequency estimator proposed here. For comparison, the algorithm proposed by R&B [11] was also presented in the simulation, and it can be observed that our algorithm is very close to it and the MCRB. However, the proposed estimator here is much simpler to implement in hardware and achieved the expected results.

V. CONCLUSIONS

In this paper, we have studied the frequency estimation method, which is the core part of the receiver in satellite communication, especially for the pilotless mode of DVB-S2 system.

The proposed approach is focused on the fine frequency estimation, which is based on the [6] algorithm and derived from [7]. The proposed method has advantage in terms of the estimation range and frequency offset sensitivity compared with the other methods and its validity is demonstrated by simulation results. Its estimation accuracy is close to the MCRB for a $\frac{E_s}{N_0}$ as low as 0 dB. Finally, we can derive a practical algorithm to satisfy the DVB-S2 standard that can be implemented in a real environment and with minor changes it can also support DVB-S2X receivers or with the same requisites for LSNR.

Furthermore, based on the results obtained, this algorithm will be implemented and coded using the VHDL hardware description language. In order to verify properly this implementation, this paper will serve as a golden model and the results obtained by the golden model will be adopted as reference and compared to the ones obtained by the implementation in hardware, for Register transfer level (RTL) simulations and will be implemented targeting DVB-S2 standard that is under development in 65nm CMOS technology.

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