

An Alternative Carrier Frequency Synchronization Scheme for DVB-S2 Systems

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Abstract—In relating the use of consumer-grade equipment, Carrier Synchronization is a difficult task for DVB-S2 receivers, which have to operate with a large initial Carrier Frequency Offset (CFO) yet needing to achieve relatively high estimation precisions. For these reasons, conventional Carrier Frequency Recovery schemes for DVB-S2 systems need significant hardware complexity. In contrast, this paper proposes a simple and robust CFR scheme for DVB-S2 systems that is able to reduce the hardware complexity without degrading the achievable performances.

Keywords— Carrier Synchronization, DVB-S2 Systems, Carrier Frequency Recovery

I. INTRODUCTION

DVB-S2 [1], the second generation standard for broadband satellite communications, has adopted new wireless communication techniques, including low density parity checking (LDPC) codes, high order amplitude and phase shift keying (16/32APSK) to achieve a capacity gain in the order of 30% over standard DVB-S systems operating under the same transmission conditions.

In satellite transmission environments, the DVB-S2 receiver should operate at very low SNRs and consumer-type DVB-S2 receivers typically use low cost oscillators, which introduce a large initial carrier frequency offset (e.g., 5MHz at 27.5 Mbaud). Therefore, the receiver has to operate with a large initial Carrier Frequency Offset (CFO) but it has to achieve relatively high estimation precisions at very low SNRs. When the data are transmitted in the Adaptive Coding and Modulation (ACM) mode, or in the Variable Coding and Modulation (VCM) mode [1], the modulation may be changed at each frame. Thus, Data-Aided Carrier Frequency Recovery (CFR) is suitable for DVB-S2 systems, and uses 36 pilot symbols (1 pilot block) after every 16 data slots.

In [2], a two-step Carrier Frequency Recovery (CFR) scheme, combined with a coarse CFR and a fine CFR, is proposed. The coarse CFR algorithm employs a data-aided feedback loop, which uses a Delay & Multiply (D&M) [3] algorithm, and the fine CFR algorithm employs the L&R algorithm [4] by averaging the summations of the auto-correlation functions over many consecutive pilot fields

before computing the argument function for improving the precision of the estimates. The pilot-aided phase linear interpolator is used to recover any residual carrier frequency offset. Whereas the D&M algorithm for the coarse CFR is very simple, the L&R algorithm for fine CFR needs many multiplication operations and significant memory for handling the summations of the auto-correlation functions. Also, when the coarse CFR loop has converged, pilot symbols are not fed to the coarse CFR loop, and its Numerical Controlled Oscillator (NCO) keeps running with the last estimate so that only the Feed-forward fine CFR block works.

This paper proposes a simple and robust CFR scheme for DVB-S2 systems where the Fitz algorithm [5], which is a refined D&M algorithm, is used for the coarse CFR together with a simple pilot block correlation algorithm [6] for performing the fine CFR. This proposed scheme reduces the complexity and the number of multiplication operations without degrading the achievable performance.

II. CARRIER FREQUENCY RECOVERY SCHEME

A. Conventional Carrier Frequency Recovery Scheme

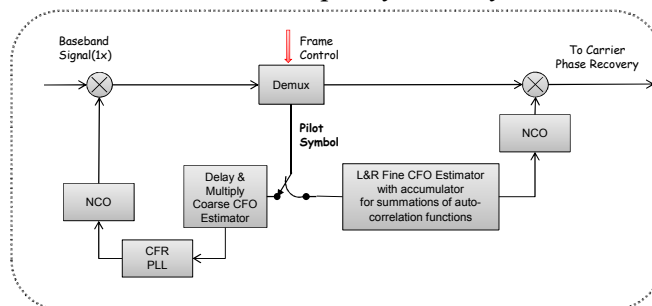


Figure 1. Conventional Carrier Frequency Recovery Scheme

In a conventional CFR scheme, as presented in [2], the simple D&M algorithm [3] is used for the coarse CFR in a feed-back loop structure, and can be written as,

$$\hat{f} = \frac{1}{D} \arg \left[\sum_{k=D}^{L_p} p(k) \cdot p^*(k-D) \right] \quad (1)$$

where L_p is the number of pilot symbols, D is a delay value, and $p(k)$ is the known pilot sequence. L_p is 36, and D is 2. The L&R algorithm [4] is employed for the fine CFR by accumulating consecutive pilot blocks. The expression of the frequency estimation is as follows:

$$R(m) = \frac{1}{L_p - m} \sum_{k=m}^{L_p-1} p(k + IL_d) \cdot p^*(k - m + IL_d) \quad (2)$$

$$\hat{f} = \frac{2}{M+1} \arg \left(\sum_{l=1}^L \sum_{k=1}^M R(k) \right)$$

where M is the number of auto-correlators, L_d is the number of data symbols (16 data slots x 90 symbols = 1,440), L is the number of summations of auto-correlations, M is 18 and L is 1,000 [2]. Whereas the D&M algorithm for performing the coarse CFR is very simple and needs only 34 multiplication operations and 1 arc-tangent operations, the fine CFR algorithm and the L&R method when M is 18, needs 477 multiplication operations, 1 arc-tangent operation, and sufficient memory for the accumulation of the summations of the auto-correlations. However when M for the L&R Method (the fine CFR) is 9 and has memory for 500 summations of auto-correlations, the BER performance is almost the same as that of the BER of ideal synchronization in computer simulation experiments.

When the coarse CFR loop has converged, the pilot symbols are not fed to the coarse CFR loop, and its Numerical Controlled Oscillator (NCO) keeps running with the previous estimate so that only the Feed-forward fine CFR block works. After the CFR block, the Pilot-aided Phase linear interpolator is also used not only for Carrier Phase Recovery but also for recovering any residual CFO [2].

B. Proposed Carrier Frequency Recovery Scheme

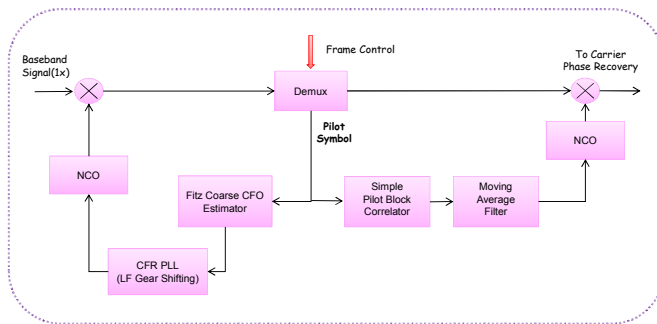


Figure 2. Proposed Carrier Frequency Recovery Scheme

Various CFO estimation algorithms can be selected for the coarse CFR but the algorithm can estimate a 20% carrier frequency offset of the symbol rate related to the use of consumer-grade equipment, and it must also have a high accuracy. Suitable algorithms that satisfy these requirements are D&M algorithms [3], the L&R algorithm [4], the Fitz algorithm [5], the M&M algorithm [7], and the Modified M&M algorithm [8].

A base function for the M&M algorithm and the Modified M&M algorithm $R(k)$ is written as,

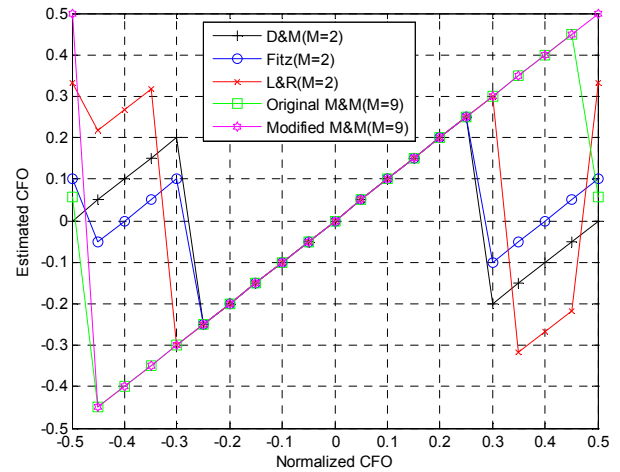


Figure 3. Estimating the Range of CFO Estimation algorithms

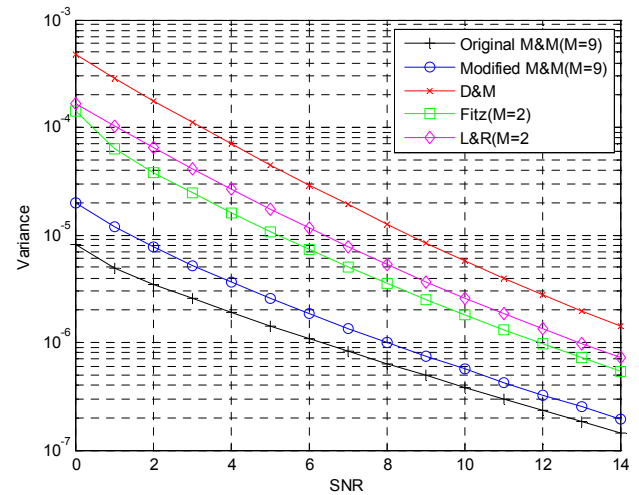


Figure 4. Variance Performanc of CFO Estimation algorithms

Table 1. Number of Operations Required

Algorithm	Multiplication	Arc-Tangent Operation
Fitz(M=2)	73	2
Original M&M(M=9)	287	8
Modified M&M(M=9)	287	1
D&M(M=2)	34	1
L&R(M=2)	73	1

$$R(k) = \frac{1}{L_p - k} \sum_{i=k}^L p(i) p^*(i-k) = \frac{1}{L_p - k} \sum_{i=k}^L e^{j\Delta f_i} + n_i. \quad (3)$$

The M&M algorithm can be written as,

$$\hat{f} = \frac{1}{2\pi T_s} \sum_{k=1}^M w_k^{(M\&M)} \arg[R(k)R^*(k-1)] \quad (4)$$

where

$$w_k^{(M\&M)} = 3 \cdot \frac{(L-k)(L-k+1) - M(L-M)}{M(4M^2 - 6ML + 3L^2 - 1)}, \quad 1 \leq k \leq M.$$

The Modified M&M algorithm can be written as,

$$\hat{f} = \frac{1}{2\pi T_s} \arg \left[\sum_{k=1}^M \{R(k)R^*(k-1)\} \right]. \quad (5)$$

The Fitz algorithm reads as,

$$\hat{f} = \frac{1}{MT_s} \sum_{k=1}^M W_k^{Fitz} \cdot \arg\{R(k)\} \quad (6)$$

$$\text{where } W_k^{Fitz} = \frac{6k}{M(M+1)(2M+1)}.$$

The L&R algorithm is written as,

$$\hat{f} = \frac{1}{\pi T_s (M+1)} \arg \left(\sum_{k=1}^M R(k) \right) \quad (7)$$

When using 36 pilot symbols, Figure 3 shows the estimation range of the algorithms, and Figure 4 shows the variance performance of the CFO estimation algorithms. Table 1 shows the number of operations of the CFO estimation algorithms. M for the Modified M&M algorithm and the Original M&M algorithm is 9. The value of M for the Fitz and L&R algorithm is 2 for estimating a 20% carrier frequency offset of the symbol rate. As shown in Figure 3, the Original M&M and Modified M&M algorithms have an almost full estimation range, and the others have less narrow estimation ranges. However, all the algorithms satisfy the ranges for estimating a 20% CFO of the symbol rate (-0.2 ~ +0.2 in the normalized CFO). The variance performance of the Original M&M algorithm is found to be the best, as shown in Figure 4 but it needs a significant number of multiplication and arc-tangent operations. The D&M algorithm needs the least number of operations but its variance performance is the worst. Note that the weighting coefficients for the Original M&M algorithm and the Fitz algorithm are a fixed when M is fixed. Thus the weighting coefficients operations can be simply implemented by performing add and subtract operations. The variance performance of the Fitz algorithm is better than that of the L&R algorithm, and needs only one more arc-tangent

operation than the L&R algorithm. The Fitz algorithm has suitable performance and needs rather simple hardware complexity compared with the other introduced algorithms.

The new proposed scheme employs the Fitz algorithm [5] to perform the coarse CFR, which can be written as follows:

$$R(m) = \frac{1}{L_p - m} \sum_{k=m}^{L_p-1} p(k) \cdot p^*(k-m)$$

$$\hat{f} = \frac{1}{M} \sum_{k=1}^M W_k^{Fitz} \cdot \arg\{R(k)\} \quad (8)$$

$$\text{where } W_k^{Fitz} = \frac{6k}{M(M+1)(2M+1)}.$$

where M is 2 for estimating a 20% carrier frequency offset of the symbol rate. When the coarse CFR loop has converged, the normalized loop noise bandwidth of the loop filter in the coarse frequency recovery phase locked loop, 0.02, is reduced to 0.0002 by the loop filter gear shifting.

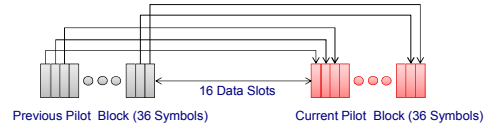


Figure 5. Simple Pilot Block Correlation Diagram

The simple pilot block correlation algorithm [6] is used for the fine CFR, as shown in Figure 5, and can be written as,

$$\hat{f} = \frac{1}{L_d + L_p} \arg \left[\sum_{k=0}^{L_p-1} P_{current}(k) \cdot P_{previous}^*(k) \right] \quad (9)$$

where $P_{current}$ is the current pilot block, and $P_{previous}$ is the previous one and the algorithm estimates the fine CFO by correlating $P_{current}$ and $P_{previous}$. Moving the average filtering with a 200 sample window for an estimated fine CFO is done to improve the precision of the estimations and Figure 6 shows the variance performance after the fine CFR.

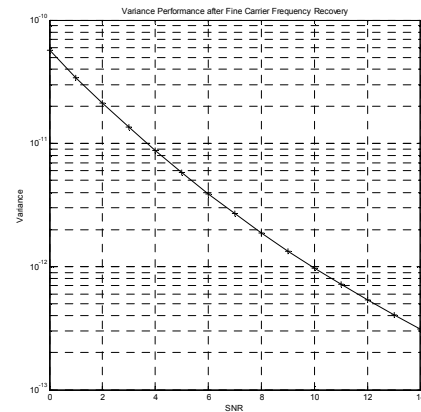


Figure 6. Simple Pilot Block Correlation Diagram

After the CFR block, a very small residual CFO exists and the Carrier Phase Offset (CPO) should also be compensated by using a Pilot-Aided (PA) Phase linear interpolator [2]. The PA interpolation techniques consist of deriving the phase trajectory over the data symbols by using only the linear interpolations of the estimates performed over two consecutive pilot fields. A Feed-Forward structure is employed in order to speed up the estimation process and Figure 7 shows the structure of the PA Phase Linear interpolator.

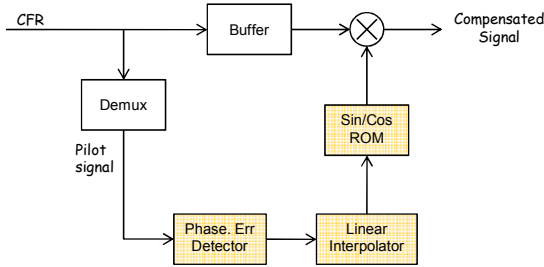


Figure 7. Structure of the PA Linear interpolations

The phase error detector estimates the CPO for one pilot block (36 pilot symbols), and can be written as,

$$\hat{\theta} = \arg \left[\sum_{n=1}^{36} x(n) \cdot p^*(n) \right]. \quad (10)$$

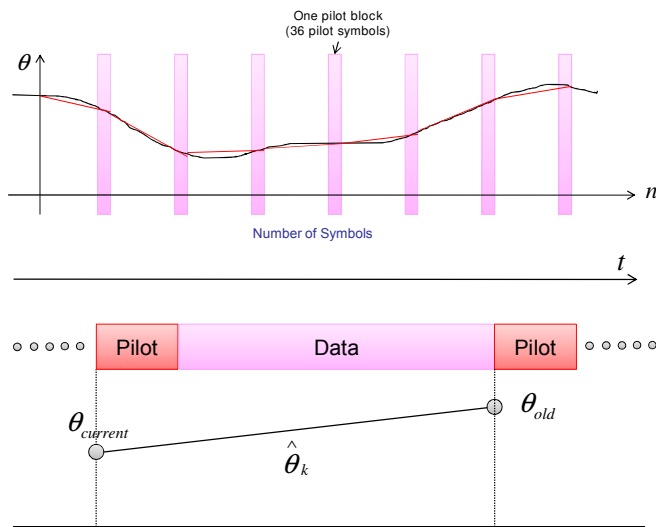


Figure 8. Pilot Aided Phase Linear Interpolation

In Figure 8, a small residual CFO exists after the CFR, and the Linear Interpolation between the phase errors of the previous pilot block and the current pilot block is achieved over the data symbols. However, the phase error detector (10) provides a phase estimate in the interval $[-\pi, +\pi]$, while the true carrier phase may grow beyond this range over a time slot period. In order to be able to consistently use the pilot-based estimates, an unwrapping technique has

to be applied [2]. The phase linear interpolation can be written as,

$$\hat{\omega} = \frac{(\theta_{current} \times k) + (\theta_{old} \times (SymSize - k))}{SymSize} \quad (11)$$

where $SymSize$ is $90 \times 16 + 36 = 1476$.

Table 2 compares the hardware complexity of the conventional CFR scheme and the new proposed CFR scheme, where the new scheme reduces the multiplication operations by 80%, as well as reducing the required memory for accumulating the summations of the auto-correlations.

III. COMPUTER SIMULATIONS

Under the assumption of ideal frame and symbol timing synchronization, computer simulations are performed in the VCM mode, and an un-coded Bit Error Rate (BER) of 16 and 32 APSK modulations, and ideal synchronization are shown in Figure 9. In 16 and 32 APSK modulations, the BERs of the conventional CFR and the new proposed CFR schemes are almost the same as those for ideal synchronization.

Table 2. Hardware Complexity Comparison

	Conventional CFR Scheme		Proposed CFR Scheme	
Coarse CFR	D&M algorithm (M=2)		Fitz algorithm (M=2)	
	Multiplication	34	Multiplication	73
	Arc-tangent operations	1	Arc-tangent operations	2
Fine CFR	L&R algorithm (M=9)		Simple Pilot Block Correlation algorithm	
	Multiplication	288	Multiplication	36
	Arc-tangent operations	1	Arc-tangent operations	1
	Memory	500 Summations of auto-correlations	Memory	200 estimated fine CFO

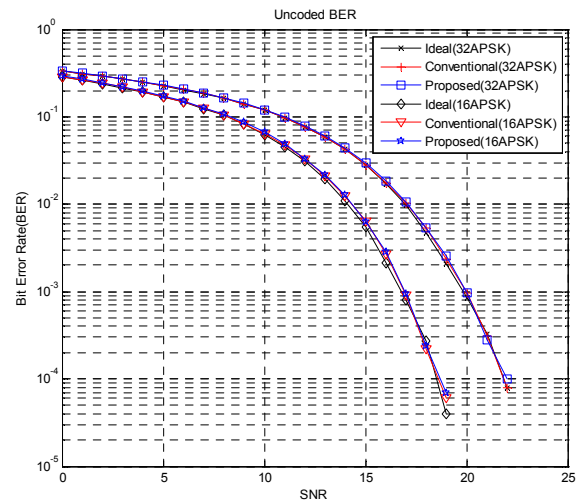


Figure 9. Uncoded BER of 16 & 32 APSK Modulation

IV. CONCLUSIONS

An alternative CFR scheme has been proposed, which is simple and reduces the hardware complexity needed without degrading the performance that is achievable. The new proposed scheme reduces the number of multiplication operations by 80% compared with the conventional scheme, and reduces the required memory for accumulating the estimated CFO's.

ACKNOWLEDGMENT

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