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Threshold extension with Kalman array for synchronization of burst communication

Jeffrey Davidson[1a)] **and Ben-Zion Bobrovsky**[2]

[1] *Shiron Satellite Communications, P.O. Box 7567*
Petah-Tikva 49170, Israel

[2] *Dept. Electrical Engineering – Systems, Faculty of Engineering*
Tel-Aviv University, Ramat Aviv 67778, Israel

a) *jeffreyd@shiron.com*

Abstract: The attainable Frame Error Rate (FER) in satellite burst communication is much too high when a classical Costas Loop is used as the carrier synchronizer. This high FER is due to cycle slips and hang-up of the Costas Loop. We demonstrate the potential to achieve a FER of 3×10^{-6} using 3 parallel Kalman tracking loops with their initial frequencies spaced apart. We also propose an algorithm for selecting the correct loop for demodulation and use data aided and optimal phase detection for the preamble and payload respectively. This dramatic improvement is at a reasonable complexity.

Keywords: Carrier Synchronization, Kalman filter

Classification: Science and engineering for electronics

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1 Introduction

We consider carrier synchronization for a satellite burst data communication system, namely phase and frequency synchronization of a QPSK modulated burst with a few hundred symbols. We assume a preamble, which enables burst detection, timing estimation and initial phase and frequency estimation. The carrier synchronizer has access to matched filtered complex samples at the correct timing instants.

In this paper we demonstrate a Frame Error Rate (FER) of 3×10^{-5} -3×10^{-6}, an improvement of 3-4 orders of magnitude over a conventional Costas loop, which has a FER of 3×10^{-2}, where frame is a burst.

2 Motivation and problem statement

We would like the synchronization subsystem to attain high performance despite the fact that we are operating in the threshold region. We want a large Mean Time to Lose Lock (MTLL), good tracking of phase noise and minimum mean square error after convergence

Our motivation to use a PLL for burst communication is due to easy implementation, low complexity and its ability to track phase noise and Doppler offsets. Therefore our goal is to reduce the unacceptable FER of 3×10^{-2} at Es/No=5 dB, caused by hang up and cycle slips when using a conventional Costas loop.

3 Digital PLL with new features

In order to improve the performance of the synchronizer, we propose a number of changes to the digital form of a Costas loop:
1. Change the loop filter to a time varying Kalman filter.
2. Use an array of Kalman filters, each with different initial frequency offsets.
3. Design an algorithm for selecting the correct Kalman filter.
4. Change the type of phase detector to data aided detection for the preamble and the optimum MAP detector ("soft detector") for the payload.

3.1 Kalman filter formulation

The PLL can be formulated as a Kalman filter (with pre-computed Kalman Gains) [1-3]. There are several advantages to doing this:
1. Time dependent filter coefficients, which dynamically adjust the loop bandwidth and are well suited to short bursts.
2. Phase noise of type f^{-n}; $n = 2, 4, \ldots$ is easily incorporated into the solution.
3. Obtain minimum Mean Square Error after convergence.
4. The loop design is very simple and well suited to burst communication because the Kalman gain is determined by the input phase and frequency variance. These are known from the estimations based on the preamble.

The loop equations are given by [1]

$$\hat{p}_{n+1} = \hat{p}_n + \hat{f}_n + K_{1n}\varepsilon_n; \qquad (1.a)$$

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$$\hat{f}_{n+1} = \hat{f}_n + K_{2n}\varepsilon_n; \qquad (1.b)$$

where $\hat{p}_n$ and $\hat{f}_n$ are the phase and frequency estimates respectively, K_{1n} and K_{2n} are the time dependent Kalman gains and ε_n is the output of the phase detector. The Kalman gains can be pre-computed, so the complexity is almost the same as that of a Costas loop.

3.2 Multi-frequency hypothesis

The use of an array of n PLLs was proposed in [3]. Each one of these PLLs is actually an extended Kalman filter, which has to deal with a smaller range of frequency uncertainty. There are three steps to the procedure:
1. Set the initial center frequency and variance of each Kalman filter in the corresponding PLL in the array so that the full range of frequency uncertainty of the incoming signal is covered.
2. Run the PLLs and save a trace of the frequency state variable. A down sampled version is good enough (e.g. 10 samples out of 400).
3. Select the "best" PLL to be used for demodulation. We propose here a new algorithm for this selection.

The complexity is 3 times that of one Kalman filter with some additional memory in which the down sampled frequency variables are saved. There is also a small increase in complexity associated with the pre-computed time dependent gains of the Kalman filter.

3.3 Algorithm for selecting correct Kalman filter

In [3], considerable threshold extension was attained based on a majority vote of PLLs, but it has drawbacks that we improve here. In Fig. 1 we show two examples of traces of the frequency variable and phase error in which the majority vote fails. In Fig. 1 (a) PLL 2 and 3 have the same end frequency, yet the correct choice is PLL 1, as can be seen from the phase error in Fig. 1 (b). Note that in practice we do not have access to the true phase error. An example is shown in Fig. 1 (c) in which there is no group, hence no majority, yet PLL 3 has converged as in Fig. 1 (d). This means there is potential for a better selection method than a majority vote.

We designed a set of logical decisions based on the frequency state variables of each of the PLLs. The logic is based on the following principles:
1. Value of the frequency state variable at the end of the burst. This is used to group the PLLs.
2. Difference between initial and final frequencies. Usually a small difference is associated with smaller phase errors.
3. Slope of frequency traces at the end of the burst. Usually a small slope at the end of the burst is associated with a locked loop.

Only a brief description of our algorithm will be given here, see [4] for more details. As can be seen in Fig. 2 the initial stage is to group the PLLs according to their final frequency at the end of the burst.

There are 3 possible group formations:

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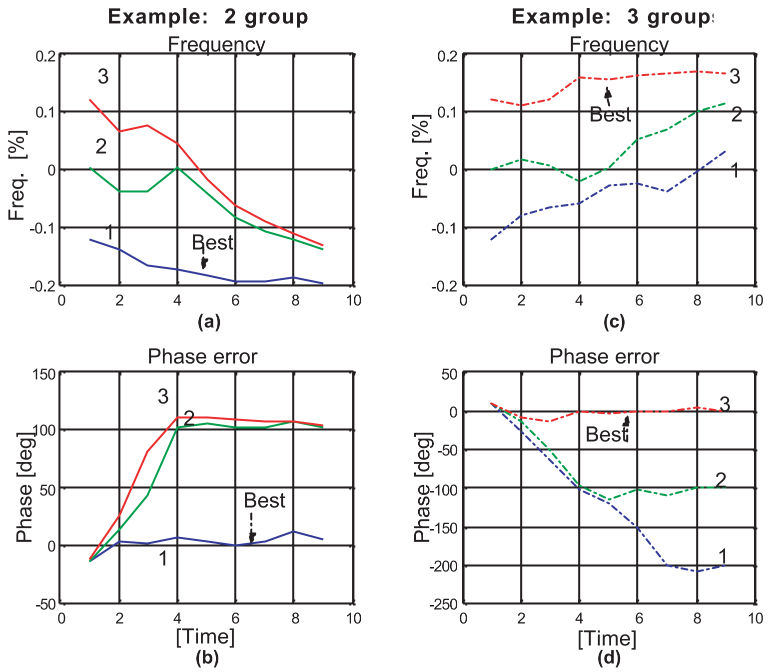

Fig. 1. Frequency and true phase error curves: (a,b) 2 groups and (c,d) 3 groups. The traces are decimated by 1:40. Frequency estimates (a,c) are given as % of symbol rate.

One Group: If all PLLs have almost the same final frequency, then the PLL with the smallest change between initial and final frequency is selected.

Two Groups: The most complicated case is of 2 PLLs with the same final frequency, different from the third, denoted "2 groups" in Fig. 2. We use a combination of frequency differences, slopes of frequency traces at the end of the burst and their averages to make a decision, see [4].

Three Groups: If none of the PLLs have the same final frequency, the decision is based on the average final frequencies and slopes, as shown for "case of 3 groups" in Fig. 2. The traces in the "if blocks" in Fig. 2 qualitatively depict the criteria. For example if the top and bottom traces are diverging ("if" block 'a'), then choose the middle PLL. The simulation trace in Fig. 1 (c) corresponds to "if" block 'b' of Fig. 2.

3.4 Phase Detector

There are two modes of operation with reference to the phase detector:

1. For the preamble a Data Aided detector is used, thereby enhancing the initial stages of convergence.

2. For the payload, where the data is unknown, we propose using the optimal MAP phase detector [5]

$$\varepsilon_n = Q_n \tanh(\beta I_n) - I_n \tanh(BQ_n) \qquad (2)$$

where I_n and Q_n are the in phase and quadrature components of the matched filter output and β is proportional to the signal to noise ratio. Although the detector is Non Data Aided (NDA), in effect a soft decision is made.

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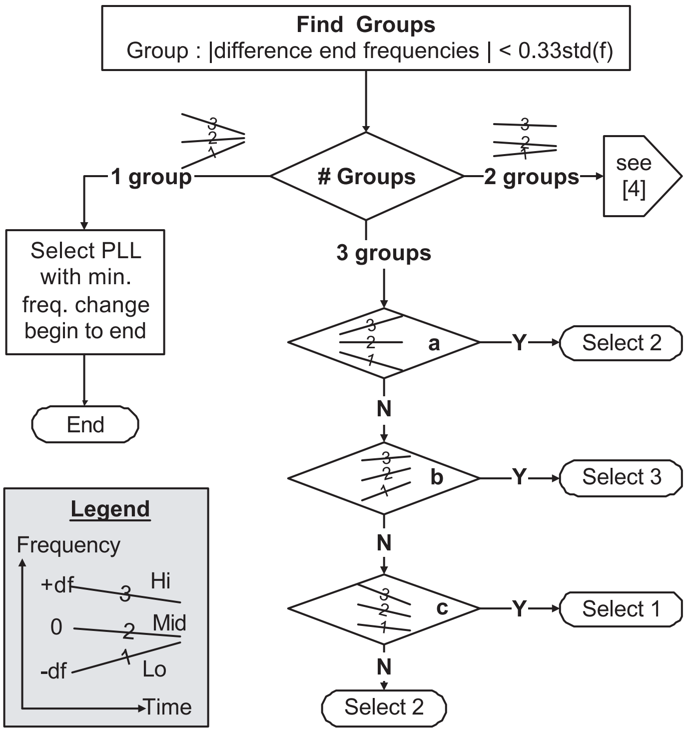

Fig. 2. Flow-chart which outlines algorithm for the selection of the best PLL. The legend defines symbolic frequency traces, which give a qualitative description of the situation

4 Performance and Simulation results

The results were obtained for a signal to noise ratio of Es/No= 5 dB, preamble length of 40 symbols, burst length of 400 QPSK symbols and $\beta = 3$. The initial phase and frequency offsets were Gaussian random variables with a standard deviation of 4 degrees and 0.06% of the symbol rate respectively (determined by estimations from preamble).

The results in Fig. 3 are for different combinations of the various improvements we propose. Each index refers to a scenario defined in terms of type of phase detector, type of loop filter and number of PLLs.

Bar 1: The base line is a single PLL Costas loop, with damping factor of 1 and natural normalized frequency of 1/200 with a burst loss probability of 3.3%.

Bar 9: Using the proposed selection algorithm we obtain a burst loss probability of 3×10^{-5}, which is 3 orders of magnitude better than the baseline system and 1 order of magnitude inferior to the genie-aided results explained below

Bar 10: The full potential of an array of 3 PLLs can be seen from the “genie” aided result. The “genie” is an idealized algorithm that identifies the correct PLL (if there is one). This ideal array has a burst loss probability of 3×10^{-6}. This performance can be attained in practice by decoding the error correcting code for each tracker output, and selecting the one with the smallest metric [6].

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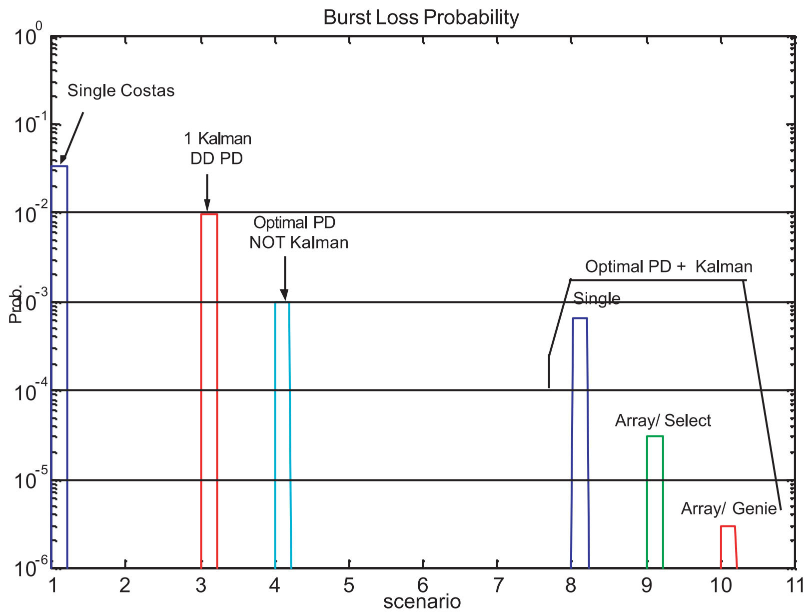

Fig. 3. Probability of burst loss for different scenarios. DD PD is decision directed with no use of preamble. Optimal PD is soft decision and data aided for payload and preamble respectively. Array/ select is an array with selection algorithm and array/genie is the "genie" aided performance.

5 Conclusion

We addressed the issue of low complexity, robust carrier synchronization for coherent burst communication. Compared to a conventional Costas loop we demonstrated the potential reduction of burst loss by 4 orders of magnitude, and managed to attain a reduction of 3 orders of magnitude in practice using our selection algorithm. This improvement was attained by using an array of 3 time varying Kalman filters, a new selection algorithm together with a data aided and optimal phase detector for the preamble and payload respectively.

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