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# Proposal of New Decision Feedback Carrier Synchronization Method for Meteor Burst Communications

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***Abstract*—We have previously proposed Go-Back-i symbol automatic repeat request (GBi-ARQ) scheme appropriate to meteor burst communications. The GBi-ARQ scheme can achieve symbol-wise ARQ by using the Viterbi decoder for convolutional codes. In this paper, we propose a new carrier synchronization method appropriate to the GBi-ARQ scheme. The method can efficiently estimate carrier phase and frequency offset by using a pair of simple recursive equations for each survivor of the Viterbi algorithm.**

## I. INTRODUCTION

Space dust particles (meteors) entering the earth's atmosphere leave behind ionized trails, called meteor bursts, at the altitude of 80-120km. The meteor bursts are capable of reflecting or scattering radio waves in the low VHF band. Over-the-horizon communication systems using this phenomenon are called meteor burst communication (MBC) systems. MBC is known to have superiority over other long distance communications (e.g., HF and satellite communications) for low rate traffic applications in some aspects, such as simplicity of implementation and operation, lower initial and running costs, and reliability. Existing and proposed applications of MBC include meteorological data acquisition, remote monitoring, vehicle tracking and so on [1]-[3].

Although billions of meteors enter the earth's atmosphere each day, only a small fraction has sufficient mass and proper entry geometry to be useful for point-to-point communication. Thus, the meteor burst channel between two specific points opens randomly with typical average interval on the order of ten seconds. The channels established by meteors typically last less than one second since the ionized trails diffuse rapidly. As electron density in the trail changes, the received signal power varies with time, which mostly exhibits exponential attenuation.

Due to the rapidly attenuating signal power, a packet transmitted via MBC channel tends to have errors in its tail part. Even though in such a case, conventional automatic repeat request (ARQ) schemes inevitably discard whole of the packet. To cope with this issue, we have previously proposed a new ARQ scheme named Go-Back-i symbol ARQ (GBi-ARQ) scheme [4][5]. The GBi-ARQ scheme can achieve symbol-wise ARQ by using a convolutional encoder and a Viterbi decoder. In the GBi-ARQ scheme, the receiver decodes received symbols and simultaneously evaluates the reliability of the decoded data. Then, the receiver accepts only the reliable data and requests retransmission for the rest of the packet in the next opened channel.

As is well known, in order to attain maximum likelihood (ML) decoding, Viterbi decoder requires coherent demodulation, so that carrier synchronization is an indispensable issue in the GBi-ARQ scheme. In addition to phase uncertainty, demodulators in radio communications such as MBC generally suffer from frequency offset caused by unstable local oscillators. Received signal in MBC also undergoes Doppler frequency shift of less than few tens of hertz due to drift of meteor bursts by high-altitude winds. The radio wave occasionally experiences another Doppler shift typically ranging 50-75 Hz, so-called head echo, when it is reflected from the head of a meteor burst at its forming instant [3][6].

A new carrier synchronization method proposed in this paper is developed for the GBi-ARQ scheme. Since the GBi-ARQ scheme uses Viterbi algorithm (VA) to decode convolutionally coded phase shift keying (PSK) signal, we can take advantage of per-survivor processing (PSP) technique to the carrier synchronization [7]. PSP is known as a technique to jointly demodulate and decode convolutionally coded signal. It utilizes tentative decisions associated with each survivor in VA to remove modulation. Since the PSP performs calculations for each survivor, simple and efficient method for the estimation of carrier parameters is required.

In this paper, we describe the proposed decision feedback carrier synchronization (DFCS) method suitable to the use in PSP of the GBi-ARQ scheme as an estimating method of carrier parameters associated with each survivor. The method can accomplish efficient phase and frequency offset estimations by using a pair of simple recursive equations. The initial values of the recursive equations are assumed to be obtained from a preamble, predetermined symbols known to the receiver. Due to the bursty nature of meteor burst channels, MBC generally uses short packets, so that their preambles should be as short as possible. In this paper, we also propose two methods to obtain the initial values from the short preamble. One method can achieve ML estimation while the other gives fairly good estimation by simple calculation.

As is easily expected, the proposed DFCS method is not restricted only to the GBi-ARQ scheme in MBC systems but also applicable to other demodulation techniques in various communication systems using PSK modulation. In this paper, we thus firstly consider to apply the DFCS method to the demodulation of uncoded PSK signal in a stationary additive white gaussian noise (AWGN) channel (i.e., conventional AWGN channel) to study the fundamental performance. Then, we show that the proposed DFCS method can very efficiently estimate the carrier parameters by comparing the performance with that of a conventional method [8], which uses a pair of recursive equations derived from the theorem of Kalman filter. Efficiencies of the two method to obtain the initial values for the recursive equations are also studied in a stationary AWGN channel. Finally, we evaluate the throughput performance of the GBi-ARQ scheme using the PSP technique with the proposed DFCS method in an MBC channel.

This paper is organized as follows. In Section II, characteristics of meteor burst channels are described. Section III introduces the GBi-ARQ scheme proposed in the previous paper. In Section IV, we propose the new DFCS method. Performances of the proposed DFCS in both stationary AWGN and MBC channels are evaluated in Section V.

## II. METEOR BURST CHANNEL

By convention, meteor bursts are classified into underdense bursts and overdense bursts, depending on the electron line density. However, in most literature, only underdense bursts are considered to study the performances of MBC systems. This is because the underdense bursts largely outnumber the overdense bursts and their channel model is mathematically tractable. In this paper, we also use the channel model based on underdense bursts.

Fig. 1 shows a typical time variation of received signal power from an underdense burst, observed in our experimental MBC system. Underdense bursts are characterized by their rapid rise and exponential decay with time. Thus, the received signal power, $P(t)$, from an underdense burst can be modeled by the equation:

$$P(t) = P(0)\exp\left(-t/\tau\right) \tag{1}$$

where $t$ is elapsed time from the beginning of the meteor burst, and $\tau$ is the decay time constant. $P(0)$ represents the initial received signal power, which is a function of electron line density of the meteor burst trail and thus varies from trail to trail. $\tau$ also changes per meteor burst since it depends on the height at which the meteor burst occurs [1][2].

## III. GB$i$-ARQ SCHEME

This section briefly describes the GBi-ARQ scheme, which is a symbol-wise ARQ scheme suitable to MBC, proposed in [4][5]. In the GBi-ARQ scheme, the receiver decodes a convolutionally coded packet by using VA and simultaneously evaluates the reliability of the decoded data. If the receiver judges that the reliability is not enough to decode successfully, it stops decoding and requests retransmission of the rest of the packet in the next opened channel.

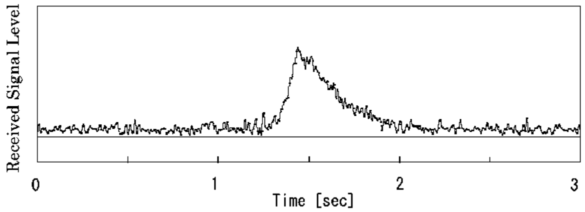

Fig. 1. A typical example of received signal from an underdense burst

### A. Method to Evaluate Reliability

The GBi-ARQ scheme uses differences between metrics of paths merging into each node in Viterbi trellis diagram to evaluate the reliability of decoded data. Fig. 2 illustrates the method by using an example. Similar to the ordinary VA, at each node on the trellis diagram, a path with the largest metric among the paths merging into the node is selected as a survivor. However, it is different from the ordinary VA that the survivor is labeled $X$ if the difference between metrics of the survivor and the others is smaller than a threshold $U$, a predetermined positive constant. The label $X$ indicates that the path is unreliable and it is not removed as long as the path survives.

In Fig. 2, $M_a(t)$ represents the path metric of the survivor to state $S_a$ at level $t$, and $m_{a,b}(t)$ is the branch metric of the branch from state $S_a$ at level $t-1$ to state $S_b$ at level $t$. For example, paths with metrics $M_1(t-1)+m_{1,2}(t)$ and $M_3(t-1)+m_{3,2}(t)$ merge into state $S_2$ at level $t$, so that the path metric of the survivor of state $S_2$, $M_2(t)$, is given by

$$M_2(t) = \max[M_1(t-1)+m_{1,2}(t), M_3(t-1)+m_{3,2}(t)]. \tag{2}$$

Then, if

$$|\{M_1(t-1)+m_{1,2}(t)\} - \{M_3(t-1)+m_{3,2}(t)\}| < U, \tag{3}$$

the survived path is labeled $X$ because its reliability is not enough. The label $X$ is not removed as long as the path survives.

### B. Method to Decide Termination Node

Fig. 3 describes the procedure to decide the termination node of VA for decoding the received data symbols in this transmission. The decoding and the reliability evaluation processes are continued until the survivor with the largest metric at the current level is labeled $X$. In the Fig. 3, the path with the largest metric is assumed to be labeled $X$ at level $t$ and thus the decoder stops VA at this level. Since the decoding is truncated on the way of the processing, the decoder needs to determine a node terminating the VA to decide the received data symbols

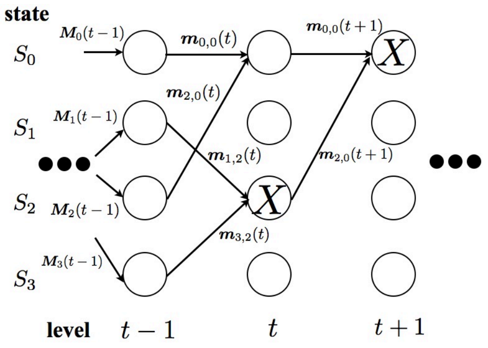

Fig. 2. Example of the reliability evaluation method

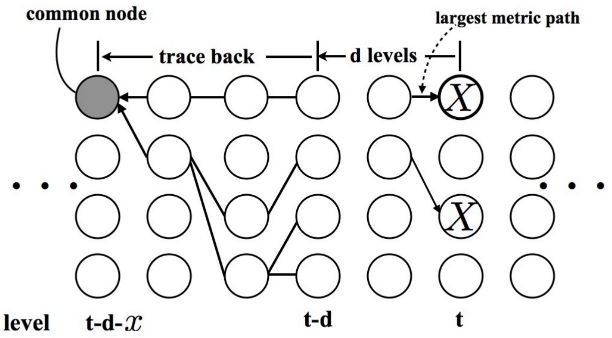

Fig. 3. Description of the method to decide the termination node

in this transmission. To determine the termination node, the decoder firstly goes back **d** levels, a fixed predetermined number of levels, and then traces back all survivors at level $t-\mathbf{d}$ to their common node. If the value of **d** is properly selected, we can expect that the correct path is survived at level $t-\mathbf{d}$. Thus, the common node can be used as the termination node of the VA in this transmission.

## IV. PROPOSAL OF THE DFCS METHOD

In this section, we firstly present outline of coherent demodulation process using the DFCS method. Secondly, we propose the DFCS method, which can accomplish efficient phase and frequency offset estimations by using a pair of recursive equations. The initial values of the recursive equations are obtained from the preamble of a packet. To obtain the initial values, we also propose two methods, named "ML estimation" and "Simple estimation". Finally, we describe PSP technique to apply the proposed DFCS method to the GBi-ARQ scheme.

### A. Outline of the Coherent Demodulation Process

Received PSK signal is firstly input to a quasi-coherent detector, composed of local oscillators with fixed frequency and matched filters [8]. The output of the quasi-coherent detector corresponding to the $i^{th}$ symbol, $r[i]$, is given by

$$r[i] = A[i]e^{j\{\phi[i]+\theta+(i-1)\Delta\}} + n[i], \tag{4}$$

where $\phi[i]$, $\theta$, $n[i]$, and $A[i]$, are modulation phase, initial carrier phase, noise, and signal amplitude, respectively. $\Delta$ represents symbol-by-symbol phase rotation caused by frequency offset $\mathit{\Delta} f$, given by $\Delta = 2\pi \mathit{\Delta} f T_s$. We assume that the noise $n[i]$ is AWGN with one-sided spectral density $N_0$. For systems with stationary AWGN channels, the amplitude $A[i]$ is assumed to be constant. For MBC systems with underdense burst channel model, $A[i]$ is expressed from (1) as

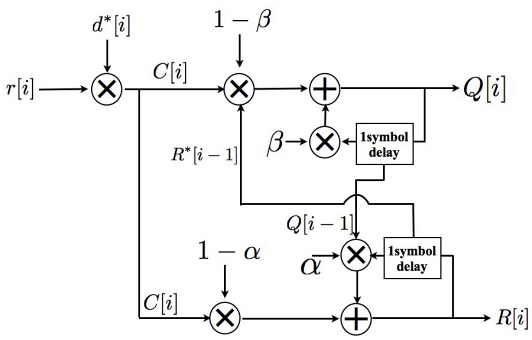

Fig. 4. Block diagram of the proposed DFCS method

$$A[i] \simeq A[0]\exp\left(\frac{-(i-1)T_s}{2\tau}\right) \tag{5}$$

where $T_s$ is the symbol interval, since amplitude is proportional to square root of power. Note that we have assumed that $\mathit{\Delta} f$ is constant in a packet and ignored inter-symbol interference caused by the frequency offset.

The proposed DFCS method uses two complex estimators, $R[i]$ and $Q[i]$, to perform coherent demodulation using the output of the quasi-coherent detector. $R[i]$ is an estimator for the carrier phase of the $i^{th}$ symbol and $Q[i]$ is an estimator for the carrier phase rotation between the $(i-1)^{th}$ and $i^{th}$ symbols. For the coherent demodulation, the receiver firstly calculates

$$w[i] = r[i](R[i-1]Q[i-1])^*, \tag{6}$$

where $()^*$ denotes complex conjugate. Then, the demodulator chooses the modulation phase $\hat{\phi}[i]$ that makes $|\hat{\phi}[i]-\arg(w[i])|$ minimum and outputs $d[i](= e^{\hat{\phi}[i]})$ as the demodulated data.

### B. the DFCS Method

In the proposed DFCS method, $R[i]$ and $Q[i]$ are generated by a pair of recursive equations:

$$R[i] = (1-\alpha)C[i] + \alpha R[i-1]\frac{Q[i-1]}{|Q[i-1]|}, \tag{7}$$

$$Q[i] = (1-\beta)C[i]\frac{R^*[i-1]}{|R[i-1]|} + \beta Q[i-1], \tag{8}$$

where $\alpha$ and $\beta$ are weighting coefficients ($0 \le \alpha \le 1$ and $0 \le \beta \le 1$) and $C[i]$ is unmodulated signal generated by $r[i]d^*[i]$. Fig. 4 shows the block diagram of the proposed DFCS method.

### C. Method to Obtain the Initial Values

In this section, we propose two methods to obtain the initial values of (7) and (8) using the preamble part of a packet. Let the length of the preamble sequence be $N$ [symbol] and the $i^{th}$ $(i = 1, 2, \cdots, N)$ matched filter output of the received preamble, $r_p[i]$, be given by (4).

*1) ML Estimation:* Denoting the phase of the $N^{th}$ symbol of the preamble by $\theta_N$ and the symbol-by-symbol phase rotation by $\Delta$, the logarithm likelihood function of $\theta_N$ and $\Delta$ is given by

$$\lambda(\theta_N, \Delta) = \sum_{i=1}^{N} \ln\{\Pr(r_p[i] \mid \theta_N, \Delta)\}, \tag{9}$$

where

$$\begin{aligned} & \ln\{\Pr(r_p[i] \mid \theta_N, \Delta)\} \\ = \quad & -\ln(\sqrt{\pi N_0}) - \frac{\mid C_p[i] - e^{j\{\theta_N - (N-i)\Delta\}} \mid^2}{N_0}. \end{aligned} \tag{10}$$

Assuming $\Delta = \hat{\Delta}$, we can derive the value which maximizes $\lambda$ by

$$\hat{\theta}_N = \arg\left(\sum_{i=1}^{N} C_p[i] e^{j(N-i)\hat{\Delta}}\right). \tag{11}$$

Therefore, we can numerically obtain the ML estimation of $\theta_N$ and $\Delta$ by varying $\Delta$ in an adequate range and thus use $D\hat{e}lta$ and $\hat{\theta}_N$ as the initial values.

*2) Simple Estimation:* The Simple estimation method utilizes the recursive equations of (7) and (8) assuming $R_p[1] = r_p[1]d_p^*[1]$ and $Q_p[1] = 1 (= e^{j0})$ as their initial values. Performing the recursive equations until $i = N$, we can obtain $R_p[N]$ and $Q_p[N]$, the initial values for the main part of the DFCS. Note that the weighting coefficients used to obtain the initial values, which we denote here $\alpha_p$ and $\beta_p$, is not necessarily the same as those used for the main part of the DFCS, denoted by $\alpha$ and $\beta$. $\alpha_p$ and $\beta_p$ should be optimized for the length of the preamble and the predicted frequency offset.

Fig. 5 shows the mean squared error of the estimated values obtained by the ML and Simple estimations in a stationary AWGN channel with $E_b/N_0 = 8$ [dB]. For the Simple estimation, we adopt $\alpha_p = 0.7$ and $\beta_p = 0.89$ for $N = 8$ and $\alpha_p = 0.7$ and $\beta_p = 0.94$ for $N = 16$, respectively.

As shown in Fig. 5, although the performance of the Simple estimation is worse than that of the ML estimation, the Simple estimation gives fairly good performance. Since the initial value $Q_p[1]$ for the Simple estimation is $e^{j0}$, the Simple estimation gives especially good performance in a low frequency range.

### D. PSP with the DFCS Method in GBi-ARQ Scheme

In the discussions so far, unmodulated signal $C[i]$ in the DFCS is assumed to be generated by $r[i]d^*[i]$ where $d[i]$ is the output of the demodulator. In the case of application to the GBi-ARQ scheme, we utilize tentative outputs corresponding to each survivor instead of the demodulated data (i.e., each survivor has its own carrier synchronization). Since only the DFCS for the correct survivor uses the correct data in this PSP, reliability of the correct survivor is highlighted. Accordingly, we can expect that the performance of the GBi-ARQ scheme is improved by the PSP.

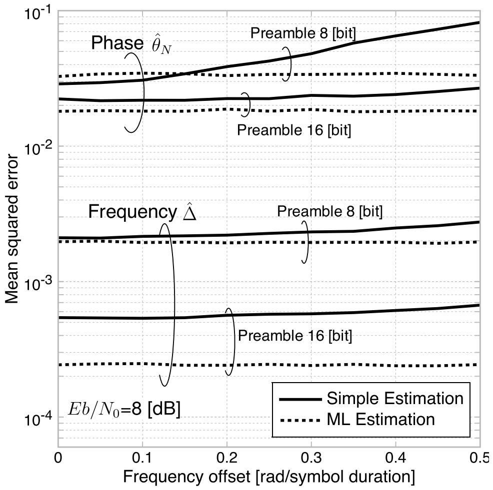

Fig. 5. Mean squared error comparison of the ML estimation and the Simple estimation

## V. PERFORMANCE EVALUATION

In this section, we investigate the performance of the proposed DFCS method by computer simulations. Performances of ideal coherent and differential detections are also presented for the sake of comparison. We firstly evaluate the demodulation performance for uncoded PSK signal in a stationary AWGN channel. Next, we show the throughput performance of the GBi-ARQ scheme using the PSP technique in an MBC channel.

For the purpose of comparison, we consider, in Subsection A, another carrier synchronization method proposed by Denno and Saito in [8] and refer to the method as D-S method. The D-S method also uses a pair of recursive equations to obtain estimators for the carrier phase and the symbol-by-symbol phase rotation, which we denote here by $R_{D-S}$ and $Q_{D-S}$, respectively. The equation for $R_{D-S}$ is the same as that for $R$ (i.e., the equation of (7)), while the equation to obtain $Q_{D-S}$ is

$$Q_{D-S}[i] = (1-\beta)C[i]\frac{C^*[i-1]}{|C[i-1]|} + \beta Q_{D-S}[i-1]. \tag{12}$$

Note that $Q_{D-S}$ in the D-S method is a weighting average of $C[i]C^*[i-1]$ whereas $Q$ in the proposed DFCS method is a weighting average of $C[i]R^*[i-1]$.

In the followings, we assume that weighting coefficients for the DFCS(ML), DFCS(Simple), and D-S methods are fixed to nearly optimal values, $\alpha = 0.9$ and $\beta = 0.99$, and for the DFCS(Simple) $\alpha_p = 0.7$ and $\beta_p = 0.89$.

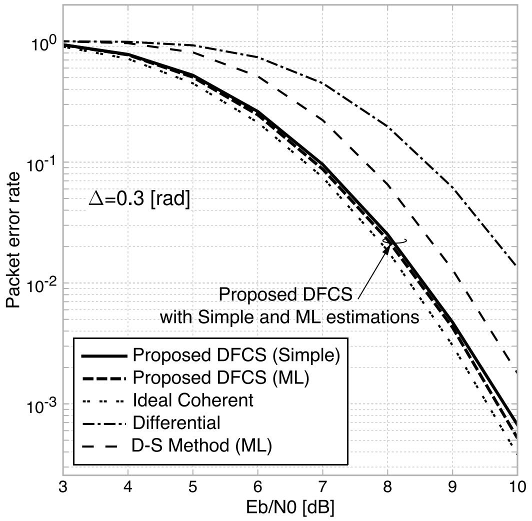

Fig. 6. PER performances in stationary AWGN channel

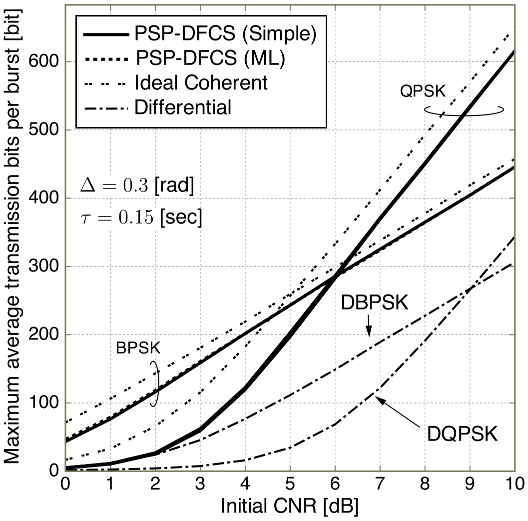

Fig. 7. Throughput performances of GBi-ARQ scheme in MBC channel

### *A. Performance Evaluation in Stationary AWGN Channel*

Fig. 6 shows packet error rate (PER) characteristics of each demodulation method for uncoded BPSK packet in a stationary AWGN channel with the frequency offset $0.3$ [rad]. The length of the data part of a packet is assumed to be $100$ [bit]. The length of the preamble part in the DFCS and D-S methods is assumed to be $8$ [bit].

In Fig. 6, the curve for the DFCS(Simple) is overlapping with that for the DFCS(ML). As shown in the figure, the proposed DFCS method is superior to the D-S method and the differential detection. The demodulators with the DFCS(Simple) and DFCS(ML) methods achieve nearly the same performance of the ideal coherent demodulator.

### *B. Throughput Performance of GBi-ARQ Scheme with PSP in MBC Channel*

Fig. 7 shows the throughput performances of the GBi-ARQ scheme with each demodulation method in an MBC channel. We assume that packets are convolutionaly coded with rate $1/2$ and constraint length $5$, and also assume that $T_s = 1/2400$ [sec], $\tau = 0.15$ [sec], and $\Delta = 0.3$ [rad]. The horizontal axis is initial CNR($= A^2[1]T_s/N_0$). The vertical axis is "maximum average transmission bits per burst" which denotes the average number of correctly received bits per one communication with the parameters of the GBi-ARQ scheme, $U$ and $\mathbf{d}$, optimized for each initial CNR. For the PSP-DFCS, it is assumed that a preamble sequence of length $8$ [symbol] is added to the head of a packet but the amount of the transmission bits excludes the number of preamble bits.

As shown in Fig. 7, the curves for PSP-DFCS(Simple) and PSP-DFCS(ML) are overlapping. For both BPSK and QPSK modulations, the GBi-ARQ scheme using the PSP-DFCS has substantially superior throughput performance to the GBi-ARQ scheme with the differential demodulation. Furthermore, in higher CNR range, the GBi-ARQ scheme using the PSP-DFCS exhibits almost the same throughput performance of the GBi-ARQ scheme with ideal coherent demodulation.

## VI. CONCLUSION

In this paper, we have proposed a new decision feedback carrier synchronization method appropriate to meteor burst communications. Performances of the proposed DFCS method are evaluated in stationary AWGN and MBC channels, comparing with the ideal coherent demodulation, the differential demodulation, and the D-S method. We have consequently shown that the demodulator using the proposed DFCS method has better performance than that using D-S method and the differential demodulator and achieves nearly the same performance of the ideal coherent demodulator.

Although the proposed DFCS method has a capability of adaptively tracking frequency variation in a packet, studies on such performances are left for the future work.

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