Preamble Design and Coarse Synchronization Using CAZAC Sequence for Uplink Cable Modem

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Abstract — In this paper, we propose a preamble structure and appropriate acquisition algorithms for the uplink cable modem. The proposed preamble consists of a serial concatenation of identical constant amplitude zero autocorrelation (CAZAC) sequences. The proposed preamble is used for the frame detection, coarse symbol timing and carrier frequency recovery for the uplink cable modem compliant to data-over-cable service interface specification (DOCSIS) 2.0. The performance of the synchronization algorithms exploiting the proposed preamble structure is evaluated with various computer simulations.

Keywords — Cable modem, Synchronization algorithms and CAZAC sequence

1. Introduction

Modern technologies promise high-speed integrated services for various kinds of applications. Hybrid fiber coax (HFC) networks, which were originally used for TV broadcast services, have recently evolved to two-way networks that provide high-speed data communications. Several critical issues must be addressed for a shared media access network to meet the service requirements. The cable modem is the key element in the cable network that will be responsible for conforming to the service requirement [1]. The cable modem systems should adopt technologies for high-speed data transmission through a band-limited channel. As modulation level and transmission data rate increase, synchronization issues become important factors of the system design.

Burst of uplink cable modem consists of preamble and data [2] and initial acquisition procedure including frame detection, symbol timing recovery and carrier frequency recovery must be accomplished by means of preamble for the successful demodulation of the remaining data in a burst. Hence, the design of an efficient preamble is crucial for the performance of uplink cable link. In this paper, we propose a serial concatenated CAZAC sequence as the preamble of uplink cable link and developed the suitable synchronization algorithms exploiting the good correlation property and rotational invariance of CAZAC sequence [3].

For frame detection, a single CAZAC sequence is used, and the missing and false-alarm probabilities of the proposed detection algorithm is investigated with extensive computer simulation. The proposed coarse timing recovery algorithm uses multiple CAZAC sequences to find the optimum timing information. In this paper, we investigate the performance of the proposed algorithm versus the number of CAZAC sequences used for coarse timing synchronization. We also developed initial carrier frequency offset estimation algorithm exploiting the structure of the proposed preamble. For the carrier phase offset recovery algorithm, we selected the algorithms proposed in [8-9].

2. System description

The system parameters of the uplink cable modem considered are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1. System parameters.</th>
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<tbody>
<tr>
<td>Modulatoin rate</td>
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<tr>
<td>Preamble length</td>
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<tr>
<td>QPSK</td>
</tr>
<tr>
<td>Roll-off factor</td>
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<tr>
<td>Number of taps for transmit filter</td>
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<tr>
<td>Root-raised cosine filter</td>
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<td>Oversampling rate</td>
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The system model considered is shown in Fig. 1. For channel model, we take only the additive white Gaussian noise (AWGN) into account.

![Fig. 1. Block diagram of cable modem system.](image)

When the signal is detected with frame detection, coarse timing synchronization algorithm is activated. After the coarse timing synchronization, the output of the matched filter is decimated according to the estimated timing information and these decimated samples are fed to the carrier frequency estimation block.

3. Coarse synchronization

Since cable modem system adopts a burst transmission, preamble plays various roles in synchronization. They are frame detection, coarse timing recovery, carrier frequency-
offset recovery, and carrier phase-offset recovery. We consider synchronization using specific preamble sequences at the receiver of cable modem. Proposed preamble consists of CAZAC and start-of-frame delimiter (SFD) sequences. The CAZAC sequence has a good autocorrelation property and SFD sequence is used for obtaining the starting point of payload.

Fig. 2. Proposed preamble structure for cable modem.

The general sixteen-symbol CAZAC sequence used in this paper reads

\[ 1, 1, 1, 1, 1, -1, -j, -1, 1, -1, 1, -1, j, -1, j. \]

We use 45-degree-rotated sixteen-symbol CAZAC sequence to fit to the cable modem specification

\[ e^{\frac{\pi i}{8}}, e^{\frac{3\pi i}{8}}, e^{\frac{\pi i}{4}}, e^{\frac{\pi i}{2}}, e^{\frac{3\pi i}{4}}, e^{\frac{\pi i}{8}}, e^{\frac{3\pi i}{8}}, e^{-\frac{\pi i}{8}}, e^{-\frac{3\pi i}{8}} \].

3.1 Frame detection

Matched filter output is given by

\[ y(n) = p(n)e^{j(2\pi f_0 T_s + \phi)} + n(n), \]  

where \( p(n) \) denotes the known CAZAC sequence at the receiver, and \( f_0, \phi, \) and \( T_s \) represents the carrier frequency, the carrier phase, and the symbol interval, respectively. Here, \( n(n) \) denotes the complex-valued independent and identically distributed Gaussian noise with zero mean.

We find the starting point of frame using the matched filter output. Since CAZAC sequence is known to have a good autocorrelation property with constant envelope [3], it is suggested to be used for this purpose especially when the data rate is high.

Frame detection algorithm uses the correlation property because CAZAC sequence has a good autocorrelation property. We compare the maximum of the correlation value with the threshold as in Eq. (2):

\[ \sum_{n=0}^{M-1} |y(n)c(n)| > \text{Threshold} \]  

If the correlation value becomes larger than the threshold, detector passes the flag information and correlation values to coarse timing recovery block. If the effect of noise is taken into account, the threshold has a signal-to-noise ratio (SNR) dependency. Thus we normalize noise to fix the threshold as shown in Eq. (3):

\[ \frac{c(n)}{\sum_{n=0}^{M-1} |y(n)|} > \text{Threshold} \]  

3.2 Coarse timing recovery

After the coarse timing recovery block receives the flag information and correlation values, this block needs more correlation values using concatenated CAZAC sequences for coarse timing recovery. Fig. 3 shows how to achieve the coarse timing synchronization.

As shown in Fig. 3, all the correlation output values are saved. The peak value and its position are determined using saved correlation values. In this way, we get the on-time samples using the coarse timing recovery block.

3.3 Carrier frequency offset recovery

Carrier frequency offset occurs because of the channel and mixer uncertainties. If carrier frequency is 60 MHz and there exists 100 parts per million (ppm) mixer offset, the offset frequency is 6 KHz. This carrier frequency offset should be eliminated.

\[ r(k) = p(k)e^{j(2\pi f_0 T_s + \phi)} + n(k), \]

This estimator uses N-symbol delay and determines the phase difference of two symbols. We estimate carrier frequency offset using the phase difference. The estimated carrier frequency \( \Delta f \) is given by [7]
\[ \Delta \hat{\gamma} = \frac{1}{2\pi T_s N} \sum_{k=0}^{N-1} \arg \left\{ r(k) r^*(k + N) \right\}. \]  

(5)

### 3.4 Carrier phase recovery

Even after the carrier frequency offset recovery, the residual frequency offset will still exist. This offset may affect the entire data packet. In this paper, we choose Cartwright’s algorithm for carrier phase (or residual frequency offset) recovery [8].

The received signal is \( Y = X e^{i\theta} + N \), and this equation can be rewritten in terms of the received in-phase and quadrature components as

\[
Y_r = X_r \cos \theta - X_i \sin \theta + N_r,
\]

and

\[
Y_i = X_r \cos \theta + X_i \sin \theta + N_i.
\]

(6)

(7)

The fourth-order cumulants across \( Y_r \) and \( Y_i \) are defined as

\[
\gamma = E\left\{ Y_r^4 \right\} + E\left\{ Y_i^4 \right\} - 6E\left\{ Y_r^2 \right\} E\left\{ Y_i^2 \right\},
\]

\[
\gamma_r = E\left\{ Y_r^4 \right\} - 3E\left\{ Y_r^2 \right\} E\left\{ Y_i^2 \right\},
\]

and

\[
\gamma_i = E\left\{ Y_i^4 \right\} - 3E\left\{ Y_r^2 \right\} E\left\{ Y_i^2 \right\}.
\]

(8)

(9)

(10)

The carrier phase recovery algorithm is based on the equation given by [8]

\[
\hat{\theta} = \frac{1}{4} \tan^{-1}\left( \frac{-4(\gamma_r - \gamma_i)}{-\gamma} \right).
\]

(11)

Note that this algorithm recovers \( \theta \) only in the range of 0° to 90°.

### 4. Numerical results

When the matched filter receives a frame, the correlation of the preamble and a known CAZAC sequence are performed to find the starting point of the frame. The missing and false-alarm probabilities using correlation in frame detection block are found through computer simulation, the results of which are shown in Fig. 5. And we choose the optimal threshold value. In the legend of Fig. 5, M and F stand for the missing and the false-alarm probability, respectively, and dB means the SNR.

After getting the on-time samples from the coarse timing recovery block, the carrier frequency offset is also be estimated using the preamble. The constellation of QPSK preamble symbols that are rotated by carrier frequency offset is shown in Fig. 8. In our simulation, carrier frequency offset of 100 ppm of the symbol rate is used. Only the AWGN but not the channel distortion is taken into account. After the carrier frequency recovery, the carrier phase offset may still exist and, as a result, the rotation of constellation can be seen as shown in Fig. 8. After applying the carrier phase recovery algorithm, recovered symbols are obtained as can be seen in Fig. 9.

![Fig. 5. Missing and false-alarm probabilities with normalized noise.](image)

![Fig. 6. BER performance of the coarse timing recovery algorithm for various lengths of CAZAC sequence.](image)

![Fig. 8. Constellation (a) before and (b) after frequency offset recovery.](image)
In Fig. 10, the residual frequency offsets are compared for different numbers of concatenated CAZAC sequences. In this simulation, $N$ equals to 16 symbols. We can see the estimation accuracy degradation when the length of concatenation decreases. Figure 11 compares the residual frequency offsets when longer than sixteen-symbol CAZAC sequences (actually $N = 32$) are used. Both results apply for 10 kHz of initial carrier frequency offset.

5. Conclusions

For synchronizations in uplink cable modem, we suggest a preamble using concatenated CAZAC sequences. The proposed preamble is used for the frame detection, coarse symbol timing and carrier frequency recovery. In our simulation, we determine the threshold value using the false-alarm and the missing probabilities for frame detection. We also choose the length of sequences which provides a good performance for coarse timing recovery. And we check the performances of the carrier frequency recovery for various lengths of CAZAC sequences. For carrier phase recovery, we choose three more concatenated CAZAC sequences. After all, the nine concatenated CAZAC sequences and the known SFD symbols are chosen for a preamble to fit to the DOCSIS 2.0 specification.

REFERENCES
