Design and Implementation of Multi-channel Burst Frame Detector

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Abstract. In order to realize the frame detection of signals which have different unique word (UW) lengths in multi-channel receiver, multiple UWs correlation detection algorithm is proposed. The algorithm judges whether the decision variable is greater than the threshold according to the UW length, from large to small, to determine whether a valid header is presented. Monte Carlo simulation is used to analyze the feasibility of the algorithm. In addition, a barrel shift register bank structure is adopted in hardware implementation, which can reuse multipliers to calculate the square magnitude of the correlation value and the energy of differential signal while traversing UWs. Simulations show that the proposed algorithm improves the detection performance and results in an easy-to-implement and resources saving structure.

Keywords: Frame detection · Barrel shift register bank

1 Introduction

Burst communication has the advantages of anti-interference, low intercept, etc., which is widely used in frequency hopping communication and time division multiple access (TDMA) communication, and has become an important way of digital communication. Burst transmission signals usually have characteristics of short-term and burst, so the receiving equipment requires the ability to synchronize and capture quickly, and frame detection is the premise of other synchronization.

Although the commonly used algorithm of frame detection can detect the frame head, there still exists the problems in terms of accuracy or the range of application. Delay and correlate algorithm in [1–3] can detect the signal quickly, but it is not accurate due to the flat correlation peak. The algorithm in [4, 5] improves the performance of the delay and correlate algorithm. However, it improves the complexity and can not realize the frame detection quickly. In [6], the hard decision is adopted, but frame detection can not be realized with this method in low signal-to-noise ratio (SNR). The differential correlation detection algorithm in reference [7] is advantageous to the selection and judgement of the frame head because of the sharp output peak. None of the above methods has considered frame detection problems in the case of multiple UW lengths, so there is an urgent need for a highly scalable and highly practical frame detection method.

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In multi-channel burst receivers, signal frames of different channels may have different lengths of UW for different application conditions (such as SNR, frame length, modulation scheme, etc.). These UWs may have some of the same characteristics, the uniform use of the same UW length for detection will inevitably lead to the difference between detection length and UW length of some frame, and there will be two cases:

(i) If UW length is longer than the detection length, the UW is not fully utilized and the detection accuracy may be reduced.
(ii) UW length is less than the detection length which will introduce a certain interference and seriously affect the detection performance.

This paper proposes a correlation detection method for multiple UW lengths. The algorithm can adapt to the frame detection with different UW lengths, which provides accurate and reliable frame detection result for subsequent demodulation.

In addition, UW which is in different channels with the same length may also be different, and needs to be detected at the same time. The use of multiple correlators to detect different kinds of UWs will inevitably cause the multiplier resource waste. The structure of a barrel shift register group is adopted in this paper, which reduces the resource consumption and improves the versatility.

2 The UW Structure

Supposing that there are P kinds of UWs, and the length of each UW can be $L_1, L_{2,} \cdots L_N (L_1 < L_2 < \cdots < L_N)$. The structure of any kind of UWs is shown in Fig. 1, and the short UW is the interception of long UW.

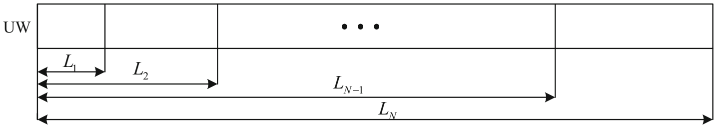

Fig. 1. UW structure of different lengths

3 Frame Detection Algorithm

3.1 Differential Correlation Detection Algorithm

Since the frequency and phase of the transmitter and the receiver are not the same, thereceived signal has a frequency and phase offset. In this regard, the effects of frequency offset and phase offset can be reduced by differential correlation. Assuming that the current received signal with ideal sampling is r_n, then r_n can be expressed as

$$\mathrm{r}_n = a_n e^{j(2\pi n \Delta f T_{sam} + \Delta\theta)} \quad (1)$$

Where a_n is the signal transmitted, and $\Delta\theta$ is the phase offset. $\Delta f T_{sam}$ represents the normalized frequency offset. After differential operation, the differential signal can be written as

$$Y_n = r_n^* r_{n+q} = a_n^* a_{n+q} e^{j(2\pi q \Delta f T_{sam})} \tag{2}$$

Where q is the sampling ratio. We can see that the influence of $\Delta\theta$ is eliminated, and the phase deflection caused by the frequency offset is limited to $2\pi q \Delta f T_{sam}$. Similarly, do differential operation with UW b_n,

$$\alpha_n = b_n^* b_{n+1} \tag{3}$$

The decision variable of differential correlation detection algorithm can be expressed as

$$\Omega_n = \frac{|C_n|^2}{W_n} \tag{4}$$

where

$$C_n = \sum_{k=0}^{L-1} \alpha_k^* Y_{k+n} \tag{5}$$

and

$$W_n = \sum_{k=0}^{L-1} r_{n+q+k}^* r_{n+q+k} = \sum_{k=0}^{L-1} |r_{n+q+k}|^2 \tag{6}$$

The L in formula (5) and (6) is the UW length. Finally, if Ω_n is larger than the corresponding threshold ξ, output the frame head. Otherwise, repeat the above operation when the new data comes.

3.2 Multiple UWs Correlation Detection Algorithm

The correlation detection algorithm adopts one of the detection lengths uniformly,the algorithm proposed in this paper can adopt multiple detection lengths to detect from large to small, the algorithm implementation structure is shown in Fig. 2.

The UW structure is shown in Fig. 1, and the procedure of multiple UW correlation detection algorithm is summarized as follows :

step 1: calculate the decision variables $\Omega_{N,n}, \Omega_{N-1,n}, \cdots \Omega_{2,n}, \Omega_{1,n}$ with N kinds of UW lengths respectively according to the UW length from large to small by formula (4), and the corresponding threshold are $\xi_N, \xi_{N-1}, \cdots \xi_2, \xi_1$.

step 2: If $\Omega_{N,n}$ is larger than ξ_N, output the frame head; otherwise, go to the step 3;

step 3: If $\Omega_{N-1,n}$ is larger than ξ_{N-1}, output the frame head; otherwise, go to step 4;

⋮

step N: If $\Omega_{2,n}$ is larger than ξ_2, output the frame head; otherwise, go to step N + 1;
step N + 1: If $\Omega_{1,n}$ is larger than ξ_1, go to step N + 2; otherwise, wait for the new data and go to step 1;
step N + 2: If $\Omega_{1,n}$ is larger than $\max\{\Omega_{1,n-1}, \Omega_{1,n+1}\}$, output the frame head; otherwise, wait the new data and go to step 1.

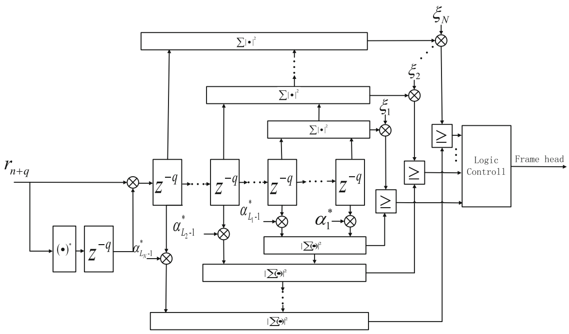

Fig. 2. The multiple UWs correlation algorithm implementation structure

4 Simulation Analysis

4.1 Theoretical Analysis

Based on the structure of the differential detector, we can sum up the frame detection into a binary hypothesis testing problem [8]. Suppose that the decision variable of the detector is Ω, we define H_1 when Ω is larger than the threshold ξ, otherwise H_0. And the probability density functions (PDF) of Ω can be expressed as $p_{\Omega|H_1}(\Omega)$ and $p_{\Omega|H_0}(\Omega)$. Therefore, the probability of correct detection P_d is

$$P_d = \int_{\xi}^{\infty} p_{\Omega|H_1}(\Omega) d\Omega \tag{7}$$

and the false alarm probability $P_{f\text{u}}$ is

$$P_{f\text{u}} = \int_{\xi}^{\infty} p_{\Omega|H_0}(\Omega) d\Omega \tag{8}$$

We can give the expression of Ω, but calculating the PDF of Ω is very difficult. Hence, Monte Carlo simulation is adopted to observe P_d and $P_{f\text{u}}$. Figures 3 and 4 show the PDFs of Ω when UW length is 20 and 40, respectively.

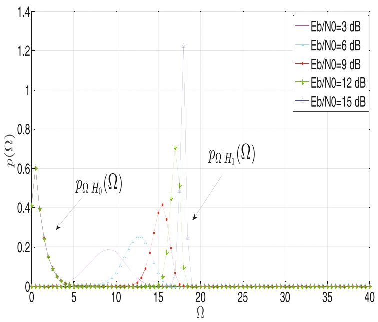

Fig. 3. The PDF of Ω (UW length = 20)

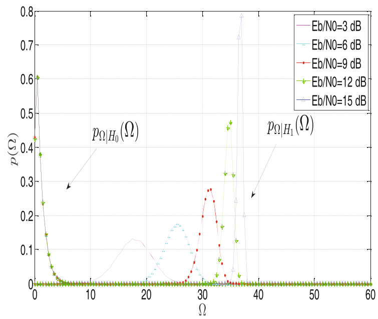

Fig. 4. The PDF of Ω (UW = 40)

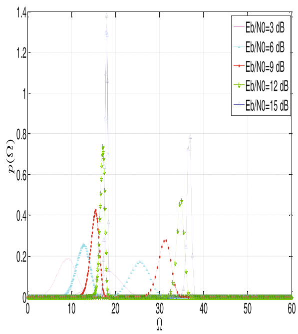

Fig. 5. $p_{\Omega|H_1}(\Omega)$ (UW length = 20 and 40)

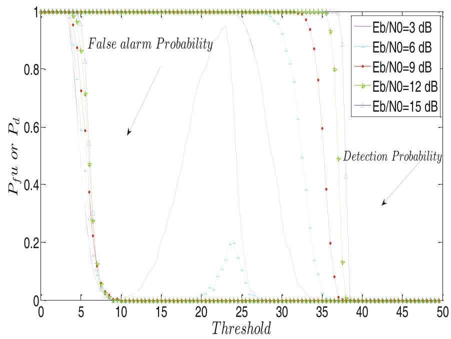

Fig. 6. The P_d and P_{fu} versus threshold

Figure 5 shows the $p_{\Omega|H_1}(\Omega)$ while detecting UW length of 20 and 40. From the results shown in Fig. 5, $p_{\Omega|H_1}(\Omega)$ in the case of length 20 and 40 can be well distinguished, so it is reasonable to detect the higher threshold first and then detect the lower threshold. With the simulation in Fig. 4 and formulas (7) and (8), we can get the P_d and P_{fu} as shown in Fig. 6. The threshold of the choice should ensure P_d is high while P_{fu} is low as far as possible which can refer to Fig. 6.

4.2 Simulation

To verify the effectiveness of the algorithm proposed, the two kinds of signals with UW length of 20 and 40 are simulated respectively. Both adopt QPSK modulation, oversampling ratio is 4, SNR is 8 dB, the frequency offset is 7% and phase offset is $\pi/4$. Simulate the detection rate of 10000 frames sent, and compare with the differential correlation detection algorithm, the result is shown in Table 1. Besides, the threshold is selected by the simulation of the local optimal.

Referring to Table 1, using the detection length of 20 to detect signals with UW length of 40 will lead to a decline in frame detection rate. And using the detection

Table 1. Frame detection performance comparison.

Detection length	UW length	Threshold	Frame detection rate
20	20	10	0.9997
20	40	10	0.9993
40	40	18	1
40	20	18	0.2204
Algorithm proposed	20	10	0.9998
Algorithm proposed	40	18	1

length of 40 to detect signals with UW length of 20 will lead to frame head missed, which caused by a higher threshold. However, the multiple UWs correlation detection algorithm proposed in this paper can achieve the optimal detection at the same time.

5 Hardware Implementation

5.1 Barrel Shift Structure

In order to obtain the cross-correlation values with UWs of P kinds, the conventional parallel frame detector simultaneously instantiates P structures, which is complicated and resource consuming. In order to save the corresponding resources, we use a barrel shift register bank which is shown in Fig. 7. Suppose that UWs need to be cross-correlated are $\alpha_1, \alpha_2, \cdots \alpha_P$ of P kinds after the differential operation, and the length is L.

The register RAM_I and RAM_Q in Fig. 7 control the outputs of the real parts Yre and imaginary parts Yim of the differential signal Y_n respectively, and then do cross correlation calculation for the P kinds of UWs. Do correlation operation with α_1

Real part:

$$reg_{\alpha_1,I} = \sum_{k=0}^{L-1} Yre_{k+n}\alpha_{1,k}^{*} \tag{9}$$

Imaginary part:

$$reg_{\alpha_1,Q} = \sum_{k=0}^{L-1} Yim_{k+n}\alpha_{1,k}^{*} \tag{10}$$

Similarly do correlation operation with other kinds of UWs, the corresponding value $reg_{\alpha_2,I}, \cdots reg_{\alpha_P,I}$ and $reg_{\alpha_2,Q}, \cdots reg_{\alpha_P,Q}$ are obtained. The input ports of the multiplier M are $reg_{\alpha_1,I}$ and $reg_{\alpha_1,Q}$, the multiplication results can be expressed as :

$$M_1 = \left(reg_{\alpha_1,I} + jreg_{\alpha_{1,Q}}\right)\left(reg_{\alpha_1,I} - jreg_{\alpha_{1,Q}}\right) = \left|\sum_{k=0}^{L-1} \alpha_{1,k}^{*} Y_{k+n}\right|^2 \tag{11}$$

When the first barrel shift is performed after the complex multiplication operation, we do the complex multiplication operation again. Since the data in the register which connected to M has changed, M_1 will be the square magnitude of cross correlation value between data and α_2. Repeat the barrel shift and multiplication P times, all of the square magnitudes of cross correlation value between data and UWs can be obtained. Then the energy of Y_n. is obtained by controlling the input port of M according to (6). Using the energy of Y_n and the maximum value of P square magnitudes to calculate the decision variable according to (7). For multi-channel cases, the corresponding resource reuse can be accomplished by calculating corresponding values of different channels at different time periods. The only difference between the multi-channel implementation structure and Fig. 7 is that the front register will double.

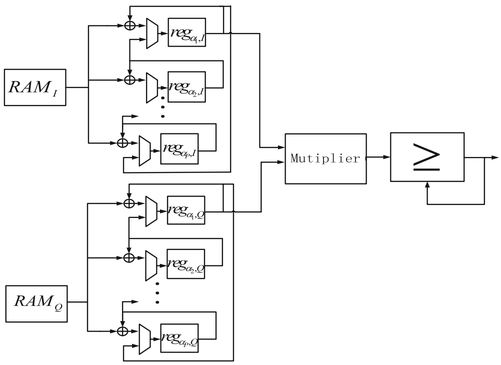

Fig. 7. Barrel shift register groups of single channel

5.2 Resource Evaluation

A burst frame detector for multi-channel is implemented in this paper. The related parameters are as follows: 15 channels, 4 different symbol rates, two kinds of UW lengths, and 17 types of UWs. Through the QUARTUS software synthesization, the resource usage of the module which calculates correlation value and energy value is shown in Table 2, where f represents the symbol rate, and the N means the number of channels. Referring to Table 2, only one multiplier is used in each case, that is, two $DSP36 \times 36$.

Table 2. Resource usage.

f/kBaud	N	$DSP36 \times 36$	ALMs	M4Ks	Combinational ALUTs
16.8	1	2	1013	4	1264
33.6	2	2	1257	9	1305
67.2	4	2	1829	18	1344
151.2	*8*	2	2888	29	1572

6 Conclusion

Aiming at the specific application environment of multi-channel burst frame detection, multiple UWs correlation detection algorithm and a barrel shift register bank structure are proposed in this paper to realize the frame detection. The simulation shows that the algorithm can improve the detector performance, and the structure can greatly save the multiplier and other resources to facilitate the realization of hardware circuits.

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