Synchronization for VHF Data Exchange System

Shijie Rong *, Huiyuan Li, Qian Xiang, Zhe Zhang, Huihui Yin
Shanghai Academy of Spaceflight Technology Shanghai, China

* rong_shijie@njust.edu.cn

Abstract. In wireless communications, rapid acquisition of synchronization parameters is essential. Very High Frequency (VHF) Data Exchange System (VDES), a new maritime communication system developed on the basis of traditional Automatic Identification System (AIS), uses time division multiple access (TDMA) and belongs to burst communication. Therefore, synchronization is the top priority of VDES research. VDES includes the terrestrial part and satellite part, named as VDE-TER and VDE-SAT, and the two parts have different channel conditions. This paper studies synchronization algorithms for VDE-TER and VDE-SAT respectively on the basis of different channel conditions and focuses on the derivation, the theoretic analysis and performance simulation of the algorithms.

Keywords: Maritime communication; VDES; synchronization; satellite channel; simulation.

1. Introduction

Very High Frequency (VHF) Data Exchange System (VDES) is developed on the basis of traditional maritime Automatic Identification System (AIS) and integrates AIS, Application Specific Message (ASM) and VHF Data Exchange (VDE), of which VDE is divided into terrestrial and satellite part, i.e., VDE-TER and VDE-SAT [1][2]. Under this framework, AIS has the highest priority for transmitting safety-related messages including ship identification, location reporting and tracking, search and rescue [3]. Some application specific messages such as meteorology and hydrology are transferred from AIS channels to new ASM channels to protect AIS from heavy load pressure to ensure its normal operation. As the core of VDES, VDE has larger bandwidth, supports information that is richer in content and more flexible in format and makes adjustments in frame structure and modem technology for terrestrial and satellite communication scenarios. VDE-TER provides greater communication capabilities for ships in the nearshore zone and VDE-SAT uses satellites to provide data exchange service for ships outside the coverage of shore stations, and even allows ships in the polar region to access VDES channels. In summary, VDES is a globally maritime space-ground communication system. The system architecture and of VDES is shown in Figure 1.
VDES belongs to burst communication and thus synchronization is one of the most important research issues. Moreover, terrestrial and satellite part have different channel conditions. This paper studies the applicable synchronization algorithms for VDE-TER and VDE-SAT, respectively. The following of this paper is organized as follows. Firstly, section II derives the double barker synchronization algorithm for VDE-TER, focuses on the frequency offset estimation and analyzes its performance using MATLAB. Secondly, section III proposes the differential detection algorithm for VDE-SAT scenario with large delay and frequency offset, optimizes the algorithms and simulates its performance. Finally, section IV concludes the paper.

2. VDE-TER synchronization

In VDES, data is transferred using a transmission packet as shown in [4], in which Sync word (training sequence) is fixed for all transmissions and known to the transceivers and used for timing and carrier frequency synchronization, thereby preparing for decoding and demodulation of data symbols. The Sync word for VDE-TER is

\[ 1 + 111110110101 + 000001001010. \]  (1)

This training sequence is called double barker codes, as it is the combination of a 1 and 13-bit barker codes and its inverted codes. The sequence has nice autocorrelation features, furthermore, frequency offset can be obtained on the basis of phase difference between barker codes and its inverted codes. The reminder of this section focuses on its frequency offset estimation algorithms and performance.

At the transmitter side, training sequence applies following mapping: 1 maps to \( \pi/4QPSK \) symbol 3 (1,1), 0 maps to \( \pi/4QPSK \) symbol 0 (0,0), as shown in Figure II. And The first symbol of the training sequence is mapped to the constellation defined by points \((1+j)/\sqrt{2}, (-1+j)/\sqrt{2}, (-1-j)/\sqrt{2}, (1-j)/\sqrt{2}\) (constellation 1); the next symbol is mapped to the constellation defined by points \(1+0j, 0+j, -1+0j, 0-j\) (constellation 2); and so on.

At the receiver side, the training sequence symbols received can be expressed as [5]

\[ r(k) = s(k)e^{j2\pi(k-\phi)} + n(k), 1 \leq k \leq L, \]  (2)

2. VDE-TER synchronization

In VDES, data is transferred using a transmission packet as shown in [4], in which Sync word (training sequence) is fixed for all transmissions and known to the transceivers and used for timing and carrier frequency synchronization, thereby preparing for decoding and demodulation of data symbols. The Sync word for VDE-TER is

\[ 1 + 111110110101 + 000001001010. \]  (1)

This training sequence is called double barker codes, as it is the combination of a 1 and 13-bit barker codes and its inverted codes. The sequence has nice autocorrelation features, furthermore, frequency offset can be obtained on the basis of phase difference between barker codes and its inverted codes. The reminder of this section focuses on its frequency offset estimation algorithms and performance.

At the transmitter side, training sequence applies following mapping: 1 maps to \( \pi/4QPSK \) symbol 3 (1,1), 0 maps to \( \pi/4QPSK \) symbol 0 (0,0), as shown in Figure II. And The first symbol of the training sequence is mapped to the constellation defined by points \((1+j)/\sqrt{2}, (-1+j)/\sqrt{2}, (-1-j)/\sqrt{2}, (1-j)/\sqrt{2}\) (constellation 1); the next symbol is mapped to the constellation defined by points \(1+0j, 0+j, -1+0j, 0-j\) (constellation 2); and so on.

At the receiver side, the training sequence symbols received can be expressed as [5]

\[ r(k) = s(k)e^{j2\pi(k-\phi)} + n(k), 1 \leq k \leq L, \]  (2)
is the local training sequence, \( f_d \) is frequency offset, \( \phi \) is phase offset, \( T \) is symbol period, \( n(k) \) is the noise, \( L = 27 \) is the length of training sequence. We convert the received sequences into a new sequences by

\[
\hat{r}(k) = r(k) \times e^{-j\frac{\pi}{4}(k \mod 2)},
\]

phase difference of barker code and its inverted codes is then

\[
\Delta \phi(k) = \arg \left\{ \frac{\hat{r}(k+13)}{\hat{r}(k)} \right\}
\]

\[
= \arg \left\{ \frac{s(k+13) \cdot e^{j\left(\frac{2\pi}{T}(k+13) + \phi\right)} \cdot e^{-j\frac{\pi}{4} + n(k+13)}}{s(k) \cdot e^{j\left(\frac{2\pi}{T}k + \phi\right)} + n(k)} \right\}, \quad k \text{ is even}
\]

\[
= \arg \left\{ \frac{s(k+13) \cdot e^{j\left(\frac{2\pi}{T}(k+13) + \phi\right)} + n(k+13)}{s(k) \cdot e^{j\left(\frac{2\pi}{T}k + \phi\right)} \cdot e^{-j\frac{\pi}{4}} + n(k)} \right\}, \quad k \text{ is odd}
\]

here \( 2 \leq k \leq 14 \). Given

\[
\left\{ \begin{array}{l}
s(k+13) \cdot e^{-j\frac{\pi}{4}} = -s(k), \quad \text{k is even} \\
s(k+13) \cdot e^{j\frac{\pi}{4}} = -s(k), \quad \text{k is odd}
\end{array} \right.
\]

Substituting (5) into (4), we obtain

\[
\Delta \phi(k) = \arg \left\{ \frac{\hat{r}(k+13)}{\hat{r}(k)} \right\}
\]

\[
= \arg \left\{ \frac{e^{j\left(\frac{2\pi}{T}k + \phi\right) + n(k+13)}}{1 + \frac{n(k)}{e^{j\left(\frac{2\pi}{T}k + \phi\right)}}} \right\}, \quad 2 \leq k \leq 14.
\]

When the noise can be neglected, (6) is simplified as

\[
\Delta \phi(k) = \arg \left\{ -e^{j\left(\frac{2\pi}{T}k + \phi\right)} \right\}, \quad 2 \leq k \leq 14.
\]

By averaging the phase differences of 13 bits barker codes and its inverted codes, the frequency offset estimation formula can be deduced as

\[
\hat{f}_d = \frac{1}{338\pi T} \sum_{k=2}^{14} (\Delta \phi(k) + \pi) e^{-j\frac{\pi}{4}},
\]

**Fig.3** Frequency offset estimation range of algorithm
In order to verify the effectiveness and study the performance of the algorithm, we carry on the simulation by MATLAB, observe its frequency offset estimation range and performance under various SNR. The simulation parameters are set to as follows: channel bandwidth is 25 kHz with a roll-off factor of 0.3, sampling rate is 19200 samples per second [4].

Figure III shows the frequency offset estimation range under 10 dB Es/N0 (the energy per symbol to noise power spectral density ratio), in which the normalized frequency offset refers to the offset normalized to sampling rate. According to [4](7), the theoretical estimation range is \((-738,738)\) Hz, i.e., \((-0.0385,0.0385)\) normalized values. Simulation results are consistent with theoretical results. Furthermore, we simulates the mean-square error (MSE) of frequency offset estimates under various SNR, assuming the normalized frequency offset of received signal is 0.03. Simulation results are shown in Figure IV, it can be seen that even under low SNR, the double barker algorithm gets small MSE of normalized frequency error estimates.

According to [6], ships reach an average speed of 23 nautical miles per hour, i.e., 11.8 meters per second, Doppler shift is no more than 10 Hz. With the addition of 3 ppm transmitter frequency error, overall frequency error is lower than 500 Hz. Therefore, the estimation range meets actual demand. Moreover, the algorithm shows high estimation accuracy, in combination with its low computing complexity and no strict need of coherent carrier, the double barker synchronization algorithm can be used in VDE-TER scenario.

### 3. VDE-SAT Synchronization

VDE-SAT communication has characteristics of low SNR, large delay, large Doppler shift, fading, etc., nevertheless, traditional correlation method for synchronization is susceptible to large frequency offset. Differential is a mainstream technology for eliminating the effect of large frequency offset. This section studies the differential detection synchronization algorithm for VDE-SAT and focuses on the formula derivation and performance simulation.

There are two kinds of training sequences under consideration for VDE-SAT, one of which has length of 27 bits and is modulated by \(\pi/4\)QPSK, the other has a length of 48 bits and is modulated by BPSK and CDMA, as shown in Table I. Both have best autocorrelation for differential detection. Since there are much difference between them, it is necessary to study separately.

| Symbol size | Sequence |
|-------------|----------|
| 27          | 01000101001010000001110011 (sequence 1) |
| 48          | 00010001111001101000001011101101101010000 (sequence 2) |
3.1. Sequence 1
Based on differential detection, by correlating the received samples from the local sequences, the correlation function is then

\[ y_r = \sum_{n=1}^{M-1} (r_{s,n+1} r_{s,n}^*) (s_{n+1}^* s_n^*), \]  

(9)

* is conjugate operation, \( \tau \) indicates different delays, \( r_s \) is the received samples, \( s_i \) is the local training sequence, and \( M = 27 \) is the length of training sequence. When frequency offset \( f_d \) exists, the correlation function is

\[ y_r = \sum_{n=1}^{26} (r_{s,n+1} e^{j\frac{2\pi}{f_s} (r+\tau)}) (r_{s,n} e^{j\frac{2\pi}{f_s} (-r+\tau)}) (s_{n+1} e^{j\frac{2\pi}{f_s} (s+\tau)})^*, \]  

(10)

is sampling rate, and \( r_s = r_{s,n} e^{j\frac{2\pi}{f_s} r} \). In the absence of noise, the correlation value at correct timing is

| Es/N0 (dB) | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|-----------|----|----|----|----|----|----|----|
| Accuracy rate (%) | 62.8 | 77.8 | 88.1 | 95.1 | 98.1 | 99.5 | 99.9 |

Table 2. Accuracy rate of timing estimation

Fig.5 CDF of frequency estimation error

\[ y_{max} = \sum_{n=1}^{26} (s_{n+1} e^{j\frac{2\pi}{f_s} (m+1)}) (s_n e^{j\frac{2\pi}{f_s} (-m)})^* (s_{n+1} e^{j\frac{2\pi}{f_s} (m)})^*, \]  

(11)

The above equation reflects that the maximum correlation value is not affected by frequency offset. Furthermore, after locating the starting position of received training sequence, considering the Doppler shift in the range of \(-4 \text{ kHz} \) to \(4 \text{ kHz} \) [1], we obtain the coarse frequency offset estimate \( \hat{f}_{d1} \) by

\[ A = \sum_{n=1}^{26} (r_{s,n} r_{s,n+2}^*) (s_n^* s_{n+2}), \]  

(12)

and

\[ \hat{f}_{d1} = \frac{f_s}{4\pi} \arg(A), \]  

(13)

\( r_s \) is the received training sequence. After compensating the coarse estimate, the fine estimation \( \hat{f}_{d2} \) is achieved by

\[ B = \sum_{n=1}^{25} (r_{s,n} r_{s,n+24}^*) (s_n^* s_{n+24}), \]  

(14)

\[ \hat{f}_{d2} = \frac{f_s}{48\pi} \arg(B). \]  

(15)
The final estimate is

$$\hat{j}_s = \hat{j}_{s1} + \hat{j}_{s2}. \quad (16)$$

For a VDE-SAT satellite at the altitude of 600 km, the distance between satellite and ships is between 600 and 2830 km [1], hence the differential delay between the shortest and the longest propagation time with the coverage area is 8 ms. Given the 8ms maximum delay and $-4 \text{ kHz}$ frequency offset, we simulate the performance of differential detection in MATLAB. The simulation parameters are set to as follows: signal bandwidth is 42 kHz with a roll-off factor of 0.25 [4], sampling rate is 33600 samples per second.

The statistical results of the timing estimation accuracy rate are shown in Table II. When $\text{Es/N0}$ is less than or equal to 3dB, the differential detection algorithm has poor timing performance. When $\text{Es/N0}$ is greater than or equal to 4 dB, accuracy rate is about 95% or more. When $\text{Es/N0}$ is 5dB, the timing accuracy is 98%, which is generally consistent with the "Based on search looses 0.3% of packets at $\text{ES/N0}$ of 5 dB" in the VDES recommendation [4]. Furthermore, we simulate the frequency offset estimation performance of differential algorithm when $\text{Es/N0}$ equals to 4, 5, 6, and 7DB, and count the estimation error of 5000 sample frames [4]. Figure V shows the cumulative distribution function (CDF) of frequency offset estimation error. Obviously, the larger the SNR is, the greater the frequency error estimation performance is. When $\text{Es/N0}$ equals to 5 dB, the range of estimation error can be controlled within $\pm 200 \text{kHz}$, i.e.,, about 1 ppm.

3.2. Sequence 2

Sequence 2 has longer length and employs CDMA and BPSK modulation, having good stability against noise and used for synchronization of messages requiring high robustness, including broadcasting and control messages.

At the transmitter side, the 48 bits sequence is modulated by BPSK to generate 48 BPSK symbols $[s_0, s_1, s_2, \ldots, s_{47}]$, then the symbols are spread by 8 bit spreading code $SS0 = [c_0, c_1, c_2, c_3, c_4, c_5, c_6, c_7] = [1, 1, -1, -1, -1, -1, -1, -1]$.

At the receiver side, for every possible timing point, we take 48 sets of spread sequence to perform despread. After despreading, the correlation function of differential algorithm is

$$\gamma_s = \sum_{m=0}^{M-1} \left( \sum_{n=0}^{N-1} r_{c_n} e^{j2\pi n_c c_n} \right) \left( \sum_{n=0}^{N-1} r_{c_n} e^{j2\pi n_c c_n} \right) (s_{m} s_{m+1}), \quad (17)$$

$M = 48$ is the length of training sequence, and $N = 8$ is length of spreading codes. The correlation value at correct timing is then

$$\gamma_{max} = \sum_{n=0}^{N-1} \left( \sum_{m=0}^{M-1} s_m e^{j2\pi n_c c_m} \right) \left( \sum_{m=0}^{M-1} s_m e^{j2\pi n_c c_m} \right) (s_{m} s_{m+1})^* \quad (18)$$

and $D = 3008$ is a constant. Obviously, frequency offset estimate can be obtained by calculating the phase of correlation peak $\gamma_{max}$, i.e.,

$$\hat{f}_d = \text{arg}(\gamma_{max}) \times f_s / (16\pi). \quad (19)$$

However, in our study, we found that when the frequency offset $f_s$ exceeds 1 kHz, the correlation peak is likely to be flooded in the noise, as shown in Figure VI, thus it is difficult to recognize the timing, let alone the frequency error. In fact, large frequency offset will make the off angle of the eight vectors in the (18) large and even counteract with another, thus the absolute result of their sum may be very small. Therefore, if the frequency offset can be initially limited to 1 kHz, the accuracy of differential algorithm will be effectively improved, hence this paper proposes hypothesis estimation in advance.
Specifically, we make frequency offset hypothesis \( f_d = \{-3, -1, 1, 3\} \) kHz, add hypotheses to the received signals, then calculate the correlation function to get correlation peak. In this way, frequency offset is controlled within 1 kHz.

After optimizing the algorithm, we further simulates its performance timing and frequency offset estimation. The simulation parameters is the same as the above.

The statistical results of the timing estimation accuracy rate are shown in Table III. When Es/N0 (Es here means the energy per chip) is less than or equal to \(-10\) dB, the accuracy rate is less than 95%. When Es/N0 is greater than or equal to \(-9\) dB, its timing estimate accuracy reaches about 98% or more. Furthermore, we simulate the frequency offset estimation performance when Es/N0 equals to \(-10\), \(-9\), \(-8\) and \(-7\) dB, and count the estimation error of 5000 sample frames. Figure VII shows the CDF of frequency offset estimation error. Obviously, when Es/N0 equals to \(-8\) dB, the range of estimation error can be controlled within \(\pm 200\) kHz, i.e., about 1 ppm. This gain relative to the performance of sequence 1 is consistent with the gain brought by larger sequence length, spread and etc., which verifies the correctness of simulation.

![Normalized correlation value under various frequency offset](image6.png)

**Table 3.** Accuracy rate of timing estimation

| Es/N0 (dB) | -11 | -10 | -9 | -8 | -7 | -6 |
|------------|-----|-----|----|----|----|----|
| Accuracy rate (%) | 77.8 | 92  | 98.1| 99.7| 99.9| 99.9|
4. Summary
The above content studies the applicability of differential detection synchronization algorithm for VDE-SAT scenario. Study shows that the correlation peak of sequence 1 is not influenced by frequency offset and after finding the correct timing via correlation peak, frequency offset can be obtained through only two differential operations. In terms of the problem faced by sequence 2 that the correct correlation peak is likely flooded in the noise when the initial frequency offset is more than 1 kHz, we propose means of hypothesis estimation in advance which effectively improves algorithm performance. Simulation results show that sequence 1 has 98.1% timing accuracy rate and less than 200 Hz (1 ppm) frequency estimation error at Es/N0=5 dB, and sequence 2 has 99.7% timing accuracy rate and less than 200 Hz frequency estimation error at Es/N0= dB (Es here means the energy per chip). Therefore, the differential detection can be applied to VDE-SAT synchronization and can achieve good performance. Moreover, sequence 2 is of greater robustness and applies to lower SNR environment.

5. Conclusion
This paper studies the applicable synchronization algorithms for VDE-TER and VDE-SAT respectively. The double barker algorithm for VDE-TER relies on the training sequence structure and its specific modulation and has the advantages of sufficient estimation range, great performance and no need for strict coherent carrier information. The differential detection for VDE-SAT overcomes the non-applicability of traditional correlation detection under large frequency offset, the correlation peak is not sensitive to frequency offset, and the algorithm has great timing and frequency offset estimation performance.

References
[1] ITU, “Technical characteristics for a VHF data exchange system in the VHF maritime mobile band,” Rec. ITU-R M.2092-0, Oct. 2015.
[2] Jan Safar, “VHF data exchange system channel sounding campaign,” Report ITU-R M.2317-0, Nov. 2014.
[3] S. J. Chang. Development and analysis of AIS applications as an efficient tool for vessel traffic service[J]. IEEE Oceans, 2004(4): 2249-2253.
[4] ENAV. Technical characteristics for a VHF data exchange system in the VHF maritime mobile band. Rec. ITU-R M.2092-0+. Sep. 2017.
[5] JianLin Huang. "Research on Carrier Synchronization in VDE-TER," Dalian Maritime University, March.2018.
[6] ITU, “Technical characteristics for automatic identification system using time division multiple access in the VHF maritime mobile frequency band,” Rec. ITU-R M.1371-5, Feb. 2015.