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Performance Comparison of Three Algorithms Applied to UM2000 Signal Demodulation

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ABSTRACT

UM2000 signal is a type of multi-audio frequency-modulated signal which is widely used for railway blocking. Principles of three typical demodulating algorithms are presented in details in this paper. Bit error rates of the three methods at different SNRs are achieved by Monte Carlo simulation experiments. Among the three algorithms, the quadrature demodulation has the best performance at the real working environment. However, the three methods have the same problem of phase hopping when noise is too strong.

1. Introduction

With the rapid development of high-speed railway in the world, some of the old track circuits have been unable to meet the requirements in terms of speed and safety. So the upgrading and updating of these old track circuits is getting more and more urgent. UM2000 joint-less track circuit is a new type of digital coding track circuit applying in high-speed railways. UM2000 signal is a type of multi-audio frequency modulated signal, whose modulated signal contains 28 sinusoidal waves. But the adjacent frequency interval is as small as 0.64 Hz. So its demodulation turns complicated and time-consuming. Then the research of demodulating methods plays a vital role in the railway system.

According to communication theory, coherent demodulation and non-coherent demodulation are the two traditional demodulating approaches of frequency-modulated signals. We can get the instantaneous phase of the FM signal by coherent demodulation, and directly obtain the instantaneous frequency by the non-coherent demodulation. And that is the difference of the two approaches. From this point, the performances of the following three methods are compared. The three algorithms are differential frequency detection, zero-crossing detection and the quadrature demodulation.

2. Three Demodulation Algorithms

2.1. Model of UM2000 Signal

The UM2000 signal is frequency-modulated, which can

be expressed as

$$s(t) = A\sin[2\pi f_c t + K_f \int x(t)\,\mathrm{d}\,t] \qquad (1)$$

where A is the amplitude, f_c is the carrier frequency, and $f_c \in \{1700, 2000, 2300, 2600\}$, K_f is the FM constant, $x(t)$ is the low-frequency modulating signal. $x(t)$ can be shown as

$$\begin{aligned}x(t) = \sum_{i=1}^{27} A_i \delta_i \sin(2\pi f_i t + \varphi_i) \\ + A_{28}\sin(2\pi f_{28} t + \varphi_{28})\end{aligned} \qquad (2)$$

where A_i is the amplitude of every sinusoidal wave, φ_i is the phase. The former 27 frequencies are used to transfer the corresponding information, for δ_i =0, 1. And the frequencies are f_i=0.88+0.64× (*i*-1) Hz, i=1,2,…,27; and f_{28} =25.68 Hz.

As we all know, the goal of demodulation is to obtain the modulating signal $x(t)$ from the modulated signal $s(t)$. Then we can get the 28 bits codes transmitted between the station and the cab.

2.2. Differential Frequency Detection

As is described in the "Communication Theory"[1], the algorithm of differential frequency detection is the non-coherent demodulation of FM signals. The frequency detector is the key part of this method, which is cascaded by the ideal differentiator and envelope detector. The principle of this method will be elaborated in the next paragraphs [2].

Firstly we apply differentiator to the receiving sig-

nal $s(t)$. We get its differential, $s_d(t)$, which is noted as

$$s_d(t) = A[2\pi f_c + K_f x(t)]$$
$$\times \cos[2\pi f_c t + K_f \int x(t)\mathrm{d}t] \tag{3}$$

After the differential, the FM signal turns to be the signal modulated by amplitude and frequency. From Equation (3), we can easily see that the envelope of $s_d(t)$ contains the information of $x(t)$.

Then we can get its envelope by Hilbert Transform, that is

$$\hat{s}_d(t) = A[2\pi f_c + K_f x(t)]$$
$$\times \sin[2\pi f_c t + K_f \int x(t)\mathrm{d}t] \tag{4}$$

Getting the square root of $s_d(t)$ and $\hat{s}_d(t)$ as

$$Ev = A[2\pi f_c + K_f x(t)]$$
$$= \sqrt{\hat{s}_d^2(t) + s_d^2(t)} \tag{5}$$

By removing the DC component by a filter, we get the modulating signal $x(t)$. So far, the demodulation of the UM2000 signal has been achieved according to the algorithm of differential frequency detection.

2.3. Zero-Crossing Detection

The algorithm of zero-crossing detection [3], also known as the counting method, is the easiest approach to measure the instantaneous frequency. The principle is effective for the UM2000 signal demodulation because the zero-crossing sequence directly reflects the signal's period. For the UM2000 signal, its instantaneous frequency can be noted as

$$IF = f_c + \frac{K_f}{2\pi}x(t) \tag{6}$$

The relationship of modulating signal $x(t)$ and the instantaneous frequency IF is clearly shown in Equation (6). Then we can get the instantaneous frequency by detecting the zero-crossing sequence. The specific steps are clearly elaborated below.

Firstly, get the zero-crossing sequence $zero(i)$. Then the intervals sequence can be obtained as

$$interval(i) = [zero(i+1) - zero(i)] / f_s \tag{7}$$

where f_s is the sampling frequency. Because the intervals represent the signal's half-cycle, we can get

$$IF = 1/[2 \times interval(i)] \tag{8}$$

According to Equation (6), we get

$$x(t) = (IF - f_c) \times \frac{2\pi}{K_f} \tag{9}$$

At last, filtering and interpolation are necessary to ob-

tain the real modulating signal $x(t)$. So far, the process of demodulation by the method of zero-cross detection has been completed.

2.4. Quadrature Demodulation

A common ground of the former two methods shown in section 2.2 and 2.3 is to obtain the instantaneous frequency directly. Whereas the quadrature demodulation [4], its core step is to get the signal's phase, $\varphi = K_f \int x(t)\mathrm{d}t$. The principle will be elaborated later.

We make the carrier signal and $s(t)$ to be the inputs of the multiplier. We can get

$$s_I(t) = s(t) \cdot \cos(2\pi f_c t)$$
$$= \frac{A}{2}\sin[4\pi f_c t + K_f \int x(t)\mathrm{d}t] \tag{10}$$
$$+ \frac{A}{2}\sin[K_f \int x(t)\mathrm{d}t]$$

$$s_Q(t) = s(t) \cdot \sin(2\pi f_c t)$$
$$= -\frac{A}{2}\cos[4\pi f_c t + K_f \int x(t)\mathrm{d}t] \tag{11}$$
$$+ \frac{A}{2}\cos[K_f \int x(t)\mathrm{d}t]$$

Then a low pass filter is designed to remove the high-frequency components. So we have the in-phase component and the quadrature-phase component of the phase signal as follows.

$$I(t) = \frac{A}{2}\sin[K_f \int x(t)\mathrm{d}t] \tag{12}$$

$$Q(t) = \frac{A}{2}\cos[K_f \int x(t)\mathrm{d}t] \tag{13}$$

Then we use anti-trigonometric functions to obtain the phase signal $\varphi = K_f \int x(t)\mathrm{d}t$. Thus, the modulating signal $x(t)$ can be derived as

$$x(t) = \frac{\mathrm{d}}{\mathrm{d}t}[\varphi(t)/K_f] \tag{14}$$

Therefore, the demodulating has been achieved by quadrature demodulation.

3. Simulations

In order to compare demodulation performance of the three algorithms objectively[5], we chose the same environment and parameters when simulated in MATLAB. The sampling frequency is set as $f_s = 16384\,\mathrm{Hz}$. The sampling time is $T_d = 3.125s$. The carrier frequency is $f_c = 2000\,\mathrm{Hz}$. The message matrix of UM2000 signal is **Delta**=[00111101111001111000011110]. The signal-to-noise ratio is set as SNR=20dB. Their simulation results are shown in the next parts.

In accordance with the principles described in the former part, the simulations are carried out in MATLAB. Results are shown in the three figures below, where the blue line represents the original modulating signal and the red line represents the demodulated signal. These three algorithms proved to be correct and effective.
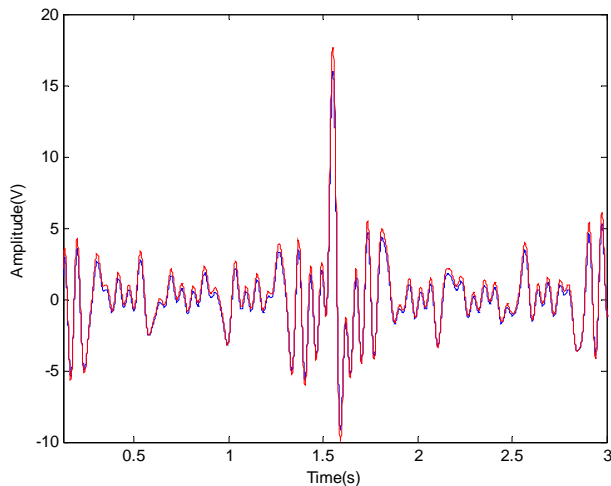

Figure 1. Differential Frequency Detection.

Figure 1 is the result of the algorithm of differential frequency detection. When the Gaussian-White-Noise is added to the signal, an amplitude limiter has to be placed before the differentiator, in order to get rid of the parasitic amplitude modulation. And the design of differential filter is also one step needed to be improved.
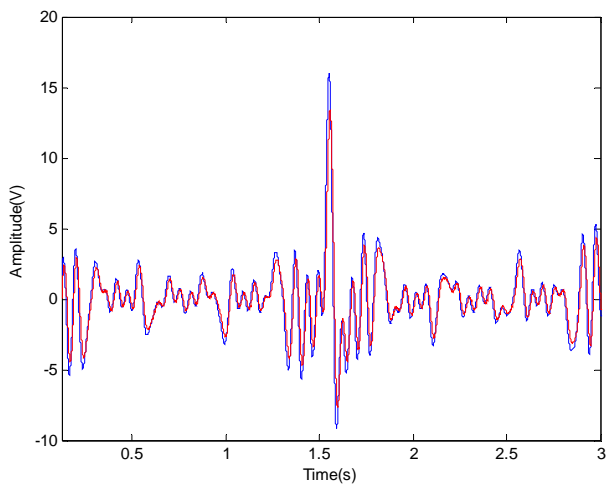

Figure 2. Zero-crossing Detection.

Figure 2 is the result of the algorithm of zero-crossing detection. The performance of this method depends largely on the sampling frequency. In order to raise the sampling frequency, we usually take measures of interpolation. However, the computing time becomes longer
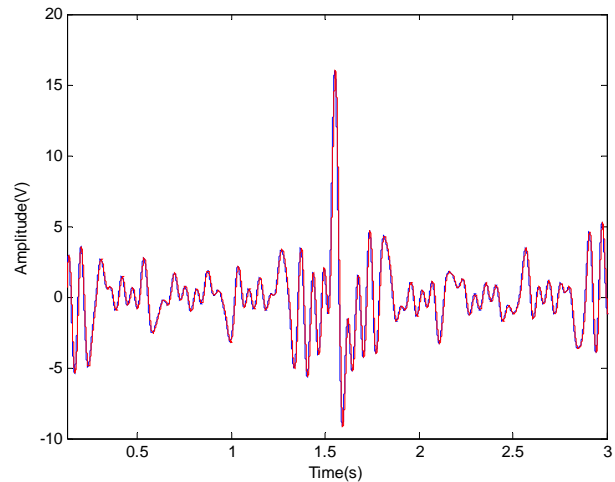
at the same time.

Figure 3. Quadrature Demodulation.

Figure 3 is the result of the algorithm of quadrature demodulation. It is a type of PM demodulation algorithm to obtain the phase information of the signals first. However, the periodic character of the phase function and the influence of phase noise, in some way, can cause the phase hopping at demodulation. Unwrapping method can remove the phase hopping caused by its periodic character.

4. Performance Comparison

The evaluation of the performance of communication receivers is most commonly used as BER (bit error rate). The transmission channel interference was simulated with additive Gaussian noise. The signal power is set as 1, and the noise was added in-band. Among the parameters, the message matrix **Delta** was generated randomly. Then the simulations were achieved through 10^4 Monte Carlo experiments. And the relationship of BER-to-SNR was shown in **Figure 4**.

As is clearly displayed in the figure, the BER of the three algorithms at high SNR was almost zero. However, with the reduction of the SNR, the BER became higher suddenly. Among the three algorithms, the quadrature demodulation has the best performance at the real working environment, i.e. at SNR > 20 dB. However, when SNR is less than 15dB, the performance of all the methods turns very bad.

In addition to the bit-error-rate, the computing time is another standard to evaluate the performance of algorithms. Due to the high demands of real-time in high-speed railway system, the decoding algorithm must respond quickly in short time. Among them, the method of zero-crossing detection takes longer time because of the applying of mathematical interpolation.
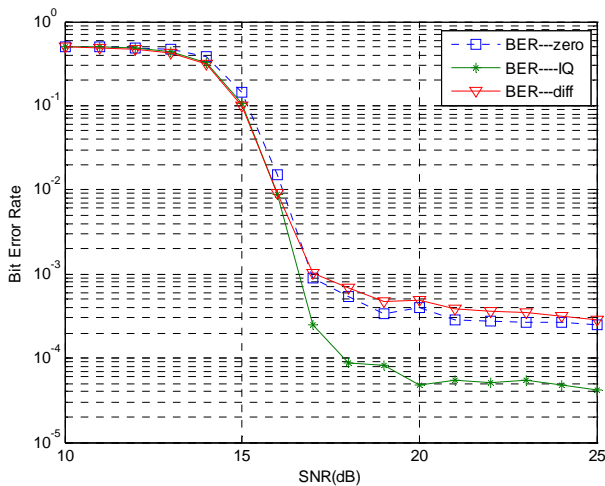
Figure 4. BER of Three algorithms.

5. Conclusions

In this paper, principles of three algorithms of demodulation were clearly elaborated and simulations were done to prove their feasibility. As UM2000 is widely used in railway system, the performances of its demodulation methods were compared. And we have some conclusions as below.

1) At real working environment (SNR > 20 dB), the Quadrature Demodulation has the best BER performance among the three demodulation algorithms. At SNR = 20 dB, its error rate is close to 10^{-5}, while the error rates of the two other methods are near 10^{-4}.

2) When the power of the noise increases (SNR < 15 dB), the performance of all the algorithms turns very bad. It is the same problem of all the demodulation algorithms. The underlying of reasons may have something to do with the phase hopping caused by the noise. The further research of phase noise is still needed in the future.

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