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A Modified Modulation Recognition Method against Doppler Effects

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Abstract: In this study, we present a modified modulation recognition method- the way to seek the slope (TW-STS), based on decision theory, which can classify 7 kinds of basic digital modulation signals well under the influence of Doppler Effect. The proposed scheme is obtained by analyzing the influence to instantaneous amplitude, instantaneous phase and instantaneous frequency caused by Doppler Effect and modifying the original modulation recognition model. It can retrain the influence well and then we can get high recognition rate. In actual band-limited channel, the Doppler Effect to the modulation recognition is more complex.

Key words: Modulation recognition, instantaneous character, TW-STS, band-limited channel

INTRODUCTION

In order to recognize the modulation of the received signal, a basic method based on decision theory is proposed (Nandi and Azzouz, 1998; Zorlu *et al.*, 2004; Wong and Nandi, 2001). Decision tree is an important method based on decision theory, which is widely applied in classification (Ali *et al.*, 2009a). On the basis of decision tree, K-means clustering is applied and has good capability (Ali *et al.*, 2009b). The result of the recognition depends on the extraction of the instantaneous characters, referring to the works (Harris *et al.*, 2003; Iwabuchi *et al.*, 2008). In this way we can get high recognition rate in Additive White Gaussian Noise (AWGN) channel. By studying the signals from a moving source, we can find that the instantaneous characters of transmitted signal vary with the speed. The work (Abolfazl and Shahosseini, 2009) has shown that, when the source moves slowly, the influence to the recognition at the receiver is minor. But as the speed increasing gradually, this factor should be considered so as to guarantee the accuracy.

In this study we propose the way to seek the slope (TW-STS) by studying the influence to the decision threshold. Based on the original algorithm, this method can recognize automatically when the speed is under a value.

Doppler effect: The method based on decision theory is divided into 3 steps, the extraction of instantaneous characters, the extraction of parameters and classification by the parameters. Doppler effect influences the extraction of instantaneous characters mainly. We use the classic poly-phase filter to analyze the effects. The narrowband signal transmitted is:

$$x(t) = a(t) \cdot \cos[2\pi f_0 t + \varphi(t)] \quad (1)$$

where a (t) is the instantaneous amplitude, f_0 is the carrier frequency, φ (t) is the instantaneous phase and x (t) is the transmitted narrowband signal.

Because of doppler effect, the spectrum moves and the signal turns into:

$$x(t) = a(t) \cdot \cos[(2\pi f_0 + \frac{2\pi v}{\lambda})t + \varphi(t)]$$
$$= a(t) \cos[2\pi f_0 t + \varphi'(t)] \quad (2)$$

where, v is the relative speed between target and receiver, λ is the wavelength, f'(t) is the phase influenced by doppler effect and it is written as:

$$\varphi'(t) = \varphi(t) + \frac{2\pi v}{\lambda} t \quad (3)$$

From the of work (Harris *et al.*, 2003) the instantaneous characters treated by the poly-phase filter are:

$$A(n) = a(n) \quad (4)$$

$$\phi(n) = \varphi'(n) = \varphi(n) + \frac{2\pi v \cdot 2n}{\lambda \cdot f_s} \quad (5)$$

$$F(n) = \phi(n) - \phi(n-1) = \varphi(n) - \varphi(n-1) + \frac{2\pi v \cdot 2}{\lambda \cdot f_s} \quad (6)$$

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where, A (n), φ(n) and F (n) are the discrete express of instantaneous characters, which are obtained by the poly-phase filter. f_s is the sampling frequency.

The results show that a fixed component is added to the instantaneous frequency caused by the effect and a linear component is added to the instantaneous phase, but the amplitude is unchanged. For the phase, the slope of the component is related to the speed of the source. In this paper we adopt five parameters (Nandi and Azzouz, 1998) to distinguish 2ASK, 4ASK, 2PSK, 4PSK, 2FSK, 4FSK and 16QAM. The parameters are amplitude parameters, which contain γ_{max} and σ_{aa}, frequency parameter, which contains σ_{af} and phase parameters, which contain σ_{dp} and σ_{ap}. The function of this parameter is expressed in the work of Nandi and Azzouz (1998).

Because of the doppler effect to the phase, the amplitude parameter and the center normalized frequency parameter do not change, but the phase parameter changes, which distinguishes ASK with other signals and 2 with 4PSK signal. Then the rate of recognition drops.

MATERIALS AND METHODS

The way to improve the threshold: Because of the linear component, the phase parameters σ_{ap} and σ_{dp} increase, so we should improve the decision thresholds so as to raise the recognition rate. The parameter σ_{dp} is used to distinguish the phase information. The parameter of ASK signal is low, yet the parameter of other signals is high. Because the phase of signals is center normalized, this parameter is easily distinguished and then the effect is relatively not serious. The parameter σ_{ap} is used to identify the signals with multi-phase modulation, so the effect is relatively serious. When the speed of source is low, we should regulate the threshold continuously so as to keep the recognition rate. When the source moves fast, this method may become invalid.

This method is simple, because we just improve the threshold based on existing recognition process. However, it does not modify the phase information and the selection of threshold is difficult. Only after we know the speed of the source, we can set the threshold. When the speed reaches a value, the phase of one signal mainly depends on the doppler effect, not the signal itself. Especially when speed of source is variable or unknown, this method is invalid, so this approach has limitations.

The way to seek the slope: In order to clear up the influence caused by moving source, the speed of which is unknown, this method is proposed. The gist is to estimate the speed of the source from the statistics and then use the value to modify the phase information.

For PSK and 16QAM signals, in one symbol period the value of phase is fixed and only for different symbol the value is different. Similarly the phase value of ASK signals is fixed all the time. We can subtract sampling point one by one and the result is constant, unless the symbol changes. After dealing with these results by a threshold, we can estimate the speed by the statistical mean.

Under the influence of Doppler Effect the phase of ASK, PSK, FSK, 16QAM signals is:

$$\varphi(n) = 2\pi v \cdot \frac{2n\cos\theta}{\lambda \cdot f_s} + \varphi_0(n) \tag{7}$$

The Eq. 7 is similar to Eq. 5 and φ (n) is the phase of signal obtained by the receiver, φ_0 (n) is the phase of signal produced by the emitter. v is the speed of target and θ is the angle between the direction of target speed and the direction to the receiver. where:

$$\varphi_0(n) = \begin{cases} 0 & \text{ASK} \\ a_k\pi & \text{PSK} \\ a_k \, 2n/f_s & \text{FSK} \\ \arctan(b_k/a_k) & \text{16QAM} \end{cases} \tag{8}$$

In the Eq. 8 a_k and b_k are the parameters which control the signals.

Subtract phase information one by one and the result is:

$$\Delta\varphi'(n) = \varphi(n) - \varphi(n-1) = 2\pi v \cdot \frac{2\cos\theta}{\lambda \cdot f_s} + \theta(n) \tag{9}$$

where,

$$\theta(n) = \varphi_0(n) - \varphi_0(n-1) = \begin{cases} 0 & \text{ASK} \\ \begin{cases} 0 \\ (a_k - a_{k-1})\pi \end{cases} & \text{PSK} \\ \begin{cases} a_k \times 2/f_s \\ a_k \times 2n/f_s - a_{k-1} \times 2(n-1)/f_s \end{cases} & \text{FSK} \\ \begin{cases} 0 \\ \arctan(b_k/a_k) - \arctan(b_{k-1}/a_{k-1}) \end{cases} & \text{16QAM} \end{cases} \tag{10}$$

From the Eq. 10, we can find that for ASK, PSK and 16QAM signals, the θ (n) is zero expect some point which caused by the change of parameter a_k and b_k. But for FSK the θ (n) is nonzero.

Firstly, we analyze the ASK, PSK and 16QAM signals. After dealing with these results by a threshold, the phase information θ (n) becomes zero. This process is equal to filter and the mean is similar to zero:

$$E[\theta(n)*h(n)] \approx 0 \tag{11}$$

From Eq. 10 and 11, we obtain:

$$\Delta\varphi(n) = E\{[\varphi(n) - \varphi(n-1)] * h(n)\} \approx 2\pi v \cdot \frac{2\cos\theta}{\lambda \cdot f_s} \qquad (12)$$

The result is the Doppler effect. So we can use Eq. 12 to modify the phase:

$$\varphi_0(n) = \varphi(n) - \Delta\varphi(n) \cdot n = \varphi(n) - E\{[\varphi(n) - \varphi(n-1)] * h(n)\} \cdot n$$

$$(13)$$

The threshold should be decided by the test of experimental signals and in different environments the selected results for different types of signals are different. We can use optimization algorithm to choose the threshold, but in this paper it is decided from experiment.

From the mathematical analysis, we know that this method can clear up Doppler Effect theoretically. The process is shown in Fig. 1.

For FSK signals, the results of seeking the slope include component of themselves. So the results are beyond the threshold all the time. The estimation of the speed is zero and it means that the phase of FSK signals is not modified, so the effect to FSK signals still exists and the parameter σ_{dp} becomes bigger. Because in original method this parameter is bigger than the threshold, the recognition is not influenced.

Above all, this method can clear up Doppler effect effectively and the speed is allowed to reach very high, under which the type of modulation can be recognized. The advantage of this method is that we need to set only one threshold for different speed, so it has higher applicability.

Verifying the feasibility of methods: Here, simulation of the recognition results about these two methods are showed so as to verify the feasibility. Earlier, we have obtained the way to improve the threshold. Based on the right selection of the threshold we propose the way to seek the slope. So first of all we should choose the threshold reasonably. Firstly, we present the adjustment of five parameters as the speed is 1km s^{-1}, as shown in Fig. 2. We add AWGN to the channel and the Signal to Noise Ratio (SNR) is 8dB. The center frequency of carrier is 525 kHz and the rate of symbol is 12.5 kHz.

Where '-' represents 2ASK signals, '.' represents 4ASK signals, '*' represents 2PSK signals, '+' represents 4PSK signals, '<' represents 2FSK signals, '>' represents 4FSK signals, 'o' represents 16QAM signals, '-.' represents the original threshold and '--' represents the current threshold modified with the speed. From the Fig. 2 a-c, we can see the effects to the parameters γ_{max}, σ_{aa} and σ_{af} are tiny and we can use the threshold which is selected when the target is immobile to distinguish the signals.
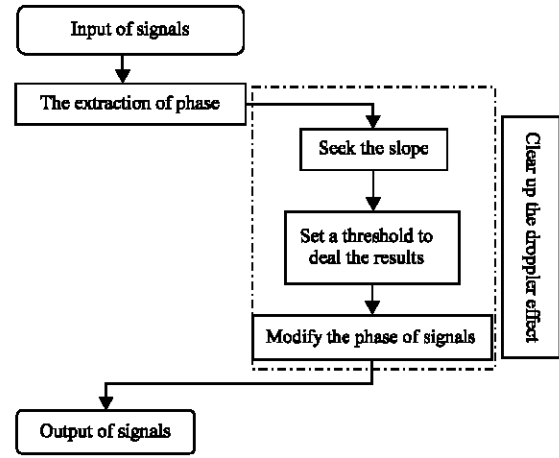

Fig. 1: Process of modifying the phase of signals

From the Fig. 2d-e, we can see the threshold of parameter σ_{dp} is unchanged, however the threshold of σ_{ap} should be improved, which is used to distinguish 2 and 4PSK signals. The amount increased is decided by the speed and we need to know the speed firstly.

From the above result, we see that the doppler effect mainly influences the recognition of 2 and 4PSK signals. In the original method we should choose different threshold with different speed and it is inapplicable when the speed is unknown. The way to seek the slope is based on the way to improve threshold, in this section we only need to recognize 2 and 4PSK signals so as to verify the feasibility of this method. In order to show the function of this method, we present the results of the modified phase of 4PSK signals, as shown in Fig. 3 with v = 10, 100 and 200 km sec^{-1}.

As seen in Fig. 3, a linear component is added to the phase and the slope of this component is related to the speed, as shown in the Fig. 1. As the speed increases, the slop of the linear component increases. With the method presented, the slope is reduced, as shown in the Fig. 2. The phase may lack fidelity, but it can still be recognized. We can recognize 2 and 4PSK signals with one threshold when the speeds are different. The Fig. 4 shows the threshold of parameter σ_{ap} with v = 0 m sec^{-1}, 1, 10 km sec^{-1}.

From the Fig. 4, we can use one fixed threshold to distinguish 2 and 4PSK signals with different speed. Considering both the effect of SNR and the effect of speed, we simulate the results of recognition with different SNR and different speeds, as shown in Fig. 5.

From the Fig. 5, we can see that this method is feasible. When the SNR is high the rate of recognition is high and the effect of speed is inessential. When the SNR drops, the effect of speed becomes obvious and the rate
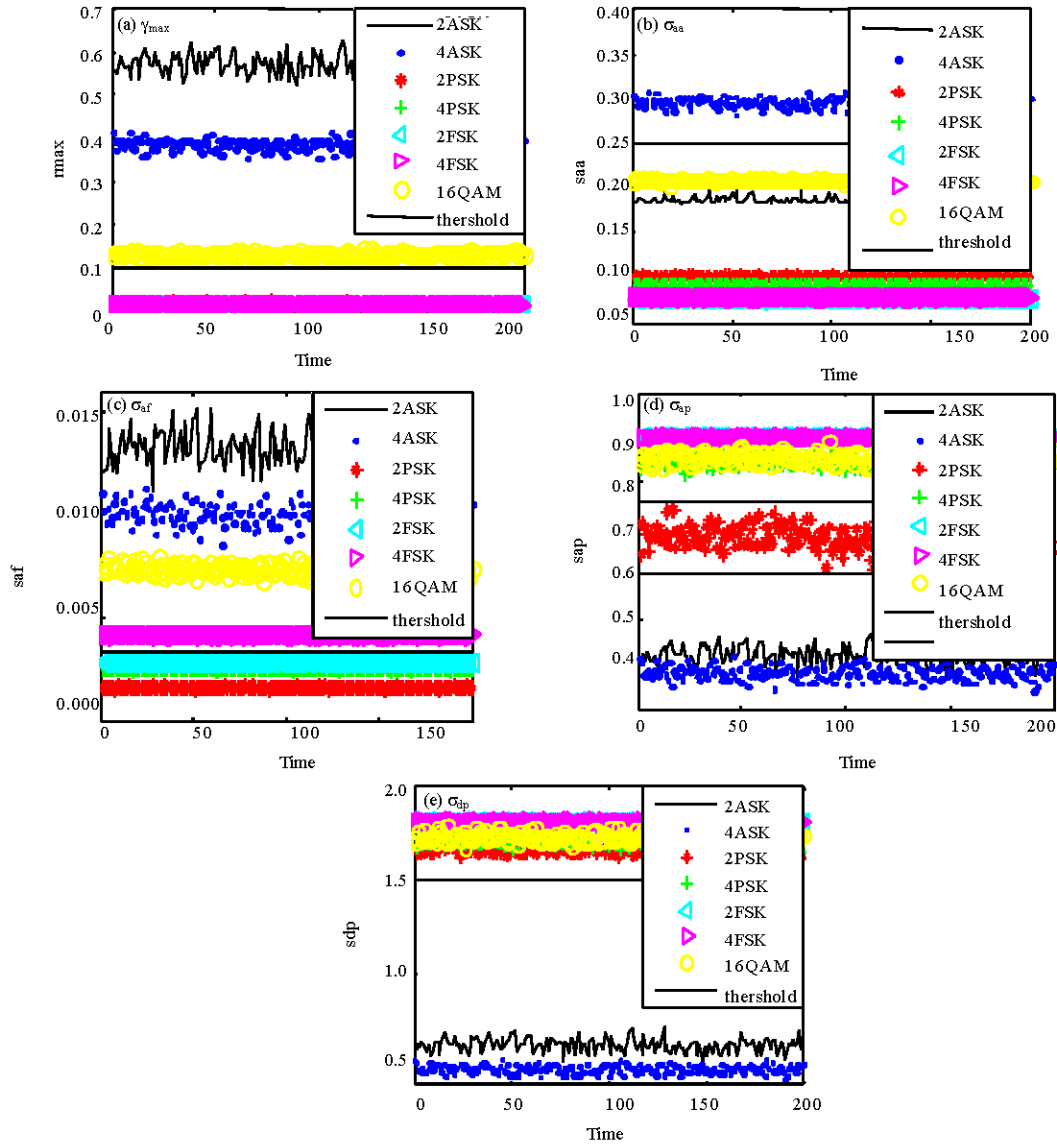
Fig. 2: Adjustment of the threshold pf five parameters

of recognition drops as the speed increases. When the SNR drops to a certain value, we can not recognize the modulation, because the method presented in this study is based on the instantaneous characters which are sensitive to noise.

Above all, these two methods are useful to resist the Doppler effect, but their performances are different, as shown in Table 1.

From the Table 1, we can see that though the way to seek the slop is complex, but this method can use one fixed threshold to recognize signals with different speed. We should choose different methods in different situation. The way to seek the slope is used more widely.

Effects in actual channel: In actual transmission channel, some relay systems are added in order to keep the quality of signals. Because of the existing of the filters in front of the relay systems, the whole channel is band-limited. In this kind of channel the frequency of carrier should be considered. We divide the channel into two kinds, one has absolutely unchanged bandwidth and the other has relatively unchanged bandwidth. The effects in two kinds of channels are different, so we should analyze and compare them.

One constant $2\pi\upsilon\cdot2\cos\theta/\lambda\cdot f_s$ is added to the frequency character because of doppler effect. The
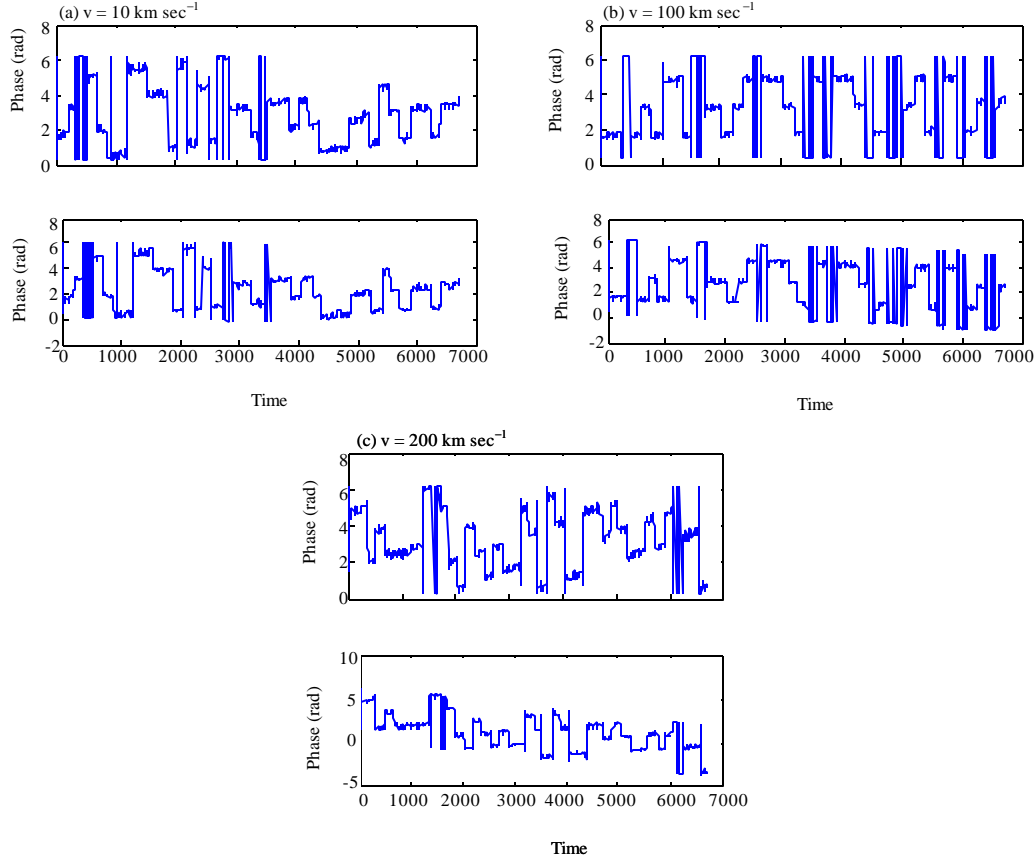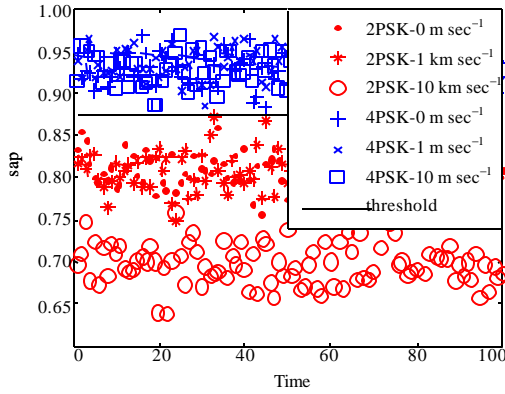
Fig. 3: The instantaneous phase of 4PSK signals by the way of seeking the slope

Fig. 4: The threshold of parameter σ_{ap} with different speed

parameters σ_{af} and σ_{df} are calculated from the frequency character. In ideal situations they are not influenced.

Effects to absolutely unchanged bandwidth channel: With the frequency of carrier increasing, the sampling frequency increases. For FSK signals the frequency is $2a_k/f_s$, so it decreases as f_s increases and the parameters σ_{af}

and σ_{df} decrease. When the frequency of carrier reaches one value, the effect of noise becomes serious and then we cannot distinguish 2 and 4FSK signals at high rate.

Because of Doppler Effect, the carrier frequency f_c turns into $f_c+v\cos\theta/\lambda$ and the offset is related to speed of source. For narrowband signals, the bandwidth is far less than carrier frequency and the wavelength $\lambda = c/f_c$, so the carrier frequency turns into $f_c+v\cos\theta/\lambda = f_c(1+v\cos\theta/\lambda)$. At the same speed, as the carrier frequency increases, the offset increases and then in the band-limited channel signals will be influenced. In other words, in the band-limited channel, in order to keep the signals out of distortion, as the carrier frequency increases, the speed limit decreases.

In this section, FSK signals are researched. The channel bandwidth is B and carrier frequency is f_c, so the signals frequency is between $f_c-\Delta f$ and $f_c+\Delta f$. Because of Doppler effect, signals frequency becomes $f_c(1+v\cos\theta/c)-\Delta f$ to $f_c(1+v\cos\theta/c)+\Delta f$ and the channel is between $f_c-B/2$ and $f_c+B/2$. We should ensure that:

$$f_c(1+\frac{v}{c}\cos\theta)+\Delta f < f_c+\frac{1}{2}B \qquad (14)$$

Table 1: Performances of two methods

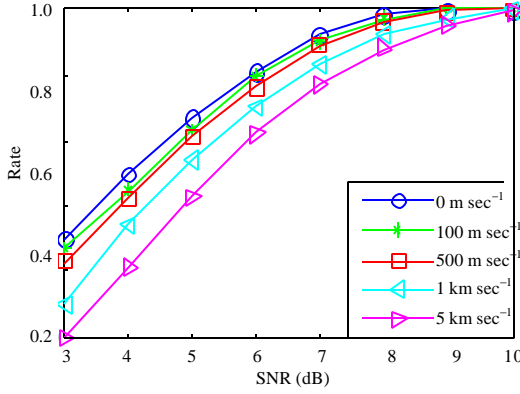| Method	Complexity	Decision of threshold	Know the speed first	Recognize when the speed varies	Demand of the memory
The way to improve threshold	Easy	Changed	Need	No	Few
The way to seek the slope	Complex	Unchanged	No need	Yes	Many

Fig. 5: The recognition rates with different SNR and speeds

We obtain:

$$v < \frac{\frac{1}{2}B - \Delta f}{f_c \cos\theta} \cdot c \qquad (15)$$

Effects to relatively unchanged bandwidth channel: In this kind of channel, the carrier frequency is f_c, the bandwidth of signals is $f_c \cdot r$ and the channel bandwidth is $f_c \cdot q$. In the frequency $2a_k/f_s$, a_k is proportional to the carrier frequency interval f_{cp}, so it is proportional to signals bandwidth $f_c \cdot r$. We can see in this kind of channel, the received frequency is independent with carrier frequency. This is different from absolutely unchanged bandwidth channel. Similarly the speed should be under one value and it satisfies:

$$f_c(1 + \frac{v}{c}\cos\theta) + \frac{1}{2}f_c \cdot r < f_c + \frac{1}{2}f_c \cdot q \qquad (16)$$

We can obtain:

$$v < \frac{1}{2\cos\theta}(q - r) \cdot c \qquad (17)$$

The speed limit does not change with the carrier frequency.

SIMULATION RESULTS AND DISCUSSION

Extraction of frequency character: Firstly, we simulate the diversification of received frequency characters with

Table 2: Results of recognition of FSK signals with different carrier frequency

Carrier frequency	525	2625	3150	3675	4200	5250
	----------------------- kHz (%)----------------------------					
2FSK	97.57	60.68	55.34	41.75	26.7	16.99
4FSK	98.54	67.96	47.57	28.16	26.21	21.84
Average rate	98.06	64.32	51.46	34.96	26.46	19.42

Table 3: Location of spectrum under different conditions in absolutely unchanged bandwidth channel

	525 Khz				3 MHz			
	--				--			
	0	1000	5000	6000	0	500	1000	2000
	m sec⁻¹ ----- km sec⁻¹---------				m sec⁻¹ ------- km sec⁻¹-----------			
a_1	1554	1560	1586	1584	9477	9493	9514	9535
a_2	1806	1814	1836	1843	9725	9741	9754	9799
a_3	4916	4908	4886	4879	28677	28611	28648	28603
a_4	5172	5162	5136	5138	28925	28909	28888	28867

the carrier frequency in absolutely unchanged bandwidth channel. The bandwidth is 100 kHz, for 2FSK signals the frequency interval is 80 kHz and for 4FSK signals the interval is 30 kHz. The results are shown in Fig.6 and Fig.7, with f_c = 525 kHz and f_c = 5250 kHz.

As seen in Fig. 6 and 7, the frequency of FSK signals decreases as carrier frequency decreases. When the carrier frequency reaches 5250 kHz, the noise effect to the signals is so serious that we cannot distinguish 2 and 4FSK signals. The results of recognition of 2 and 4FSK signals are shown in Table 2. When the carrier frequency reaches 2625 kHz, this kind of effect becomes obvious and the recognition rate decreases. These results are in accordance with the results in Fig. 6 and 7.

In relatively unchanged bandwidth channel, the received frequency of FSK signals is shown as Fig. 8, where the carrier frequency is 5250 kHz.

Compare Fig. 7 and 8 and then we can see in relatively unchanged bandwidth channel, the frequency is unchanged with the increasing carrier frequency. We can use the parameter σ_{af} to distinguish 2FSK and 4FSK signals.

Determination of speed limit: In this section we analyze carrier frequency and Doppler effect together in actual band-limited channel. In order to reduce the effects from other factors, this section only simulates the spectrum of signals under the influence of Doppler effect.

In absolutely unchanged bandwidth channel, the frequency intervals are 80 kHz for 2FSK signals and 30 kHz for 4FSK signals. The carrier frequency are 525 kHz and 3 MHz and the channel is ideal band-limited channel with B = 100 kHz. We find the speed limit by experiment.
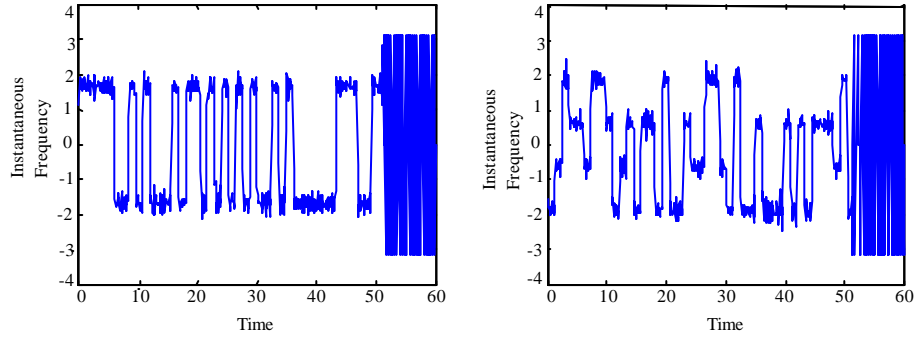
Fig. 6: Instantaneous frequency with f_c = 525 kHz (a) Instantaneous frequency of 2FSK; (b) Instantaneous frequency of 4FSK
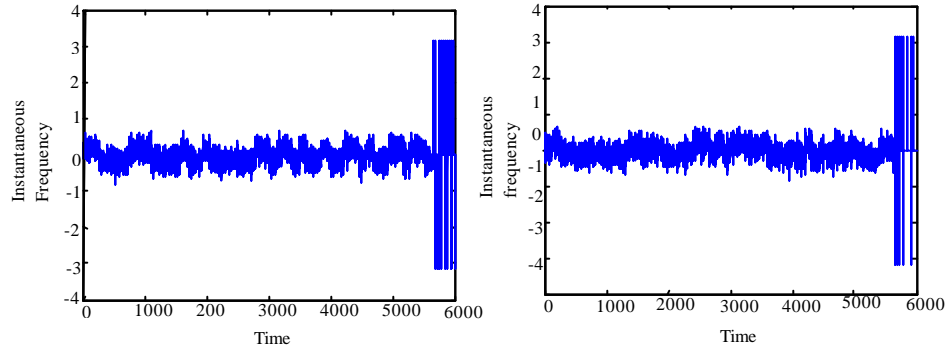

Fig. 7: Instantaneous frequency with f_c = 5250 kHz (a) Instantaneous frequency of 2FSK; (b) Instantaneous frequency of 4FSK
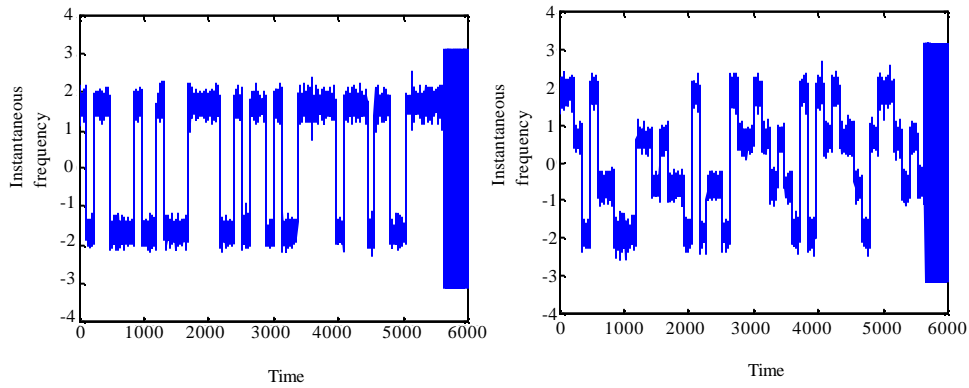

Fig. 8: Instantaneous frequency extracted in relatively unchanged bandwidth channel

Table 4: Location of spectrum under different conditions in relatively unchanged bandwidth channel

	5250 KHz			
	0	5000	5714	6500
	m sec^{-1}	km sec^{-1}		
a_1	19401	19751	19801	19856
a_2	22601	22951	23001	23056
a_3	61401	61051	61001	60946
a_4	64601	62451	64201	64146

Here we only simulate 2FSK signals and there are four lines in the frequency spectrum. Each line represents one kind of frequency and they are expressed by a_1, a_2, a_3 and a_4, separately. The results are shown as Table 3.

From Eq. 15 we can get the speed limit. For 525 kHz it is 6700 km sec^{-1} and for 3 MHz it is 1000 km sec^{-1}. From the spectrum of stationary source we can calculate the value of a_3 and a_4, when the source reaches the speed

limit. For 525 kHz $a_3 = 4885$, $a_4 = 5203$ and for 3 MHz $a_3 = 28646$, $a_4 = 28956$. From the Table 3 we can obtain the speed limit are 5000 km sec^{-1} for 525 kHz and 1000 km sec^{-1} for 3 MHz. The speed limit decreases as carrier frequency increases.

For the purpose of comparison, we simulate 2FSK signals in relatively unchanged bandwidth channel with $f_c = 5250$ kHz. The results are shown as Table 4.

When the source reaches the speed limit, the spectrum $a_3 = 61001$, $a_4 = 65001$. From the table we get the speed limit and it is 5714 km sec^{-1}. Compare it with the speed limit in absolutely unchanged bandwidth channel, we know that in relatively unchanged bandwidth channel the speed limit is independent with carrier frequency.

Above all we can obtain that, in order to transmit signals in high quality we should improve the carrier frequency interval as much as possible.

CONCLUSION

In this study, we mainly research on Doppler effect. The analysis shows that because of Doppler effect a linear component is added to the phase and a fixed component is added to frequency, so the extraction of parameters and classification are influenced. We can improve the threshold to resist the effect. Based on this method, we propose the way to seek the slope. With this method we use one fixed threshold to identify in the case of different speeds and this method has good applicability. Then we analyze the effect in band-limited channels including absolutely unchanged bandwidth channel and relatively unchanged bandwidth channel. In the absolutely unchanged bandwidth channel, the frequency information changes with the carrier frequency. When the carrier frequency reaches one value, we cannot recognize the FSK signals. The speed limit decreases as the carrier frequency increases. In relatively unchanged bandwidth channel, the frequency information and speed limit are independent with carrier frequency. It can clearly be seen that the relatively unchanged bandwidth channel ensure the correctness of the transmission at the expense of bandwidth.

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