# One Joint Demodulation and Despreading Algorithm for MOD5

Li Huan*, Zhao Feng, Li Yu Bai and Wang Jian

*University of Electronic Science and Technology of China, Chengdu, Sichuan, 611731, P.R. China*

**Abstract:** IFF determines the response properties of the target to identify friend or foe through question and answer mechanism, and nowadays it plays an important role in the modern information warfare. This paper introduces the transponder digital processing system in the new type of IFF, specially including the processing method of receiving and transmitting in MOD5 and the theory of basic MSK modulation, maximum likelihood Viterbi demodulation and Walsh spreading and despreading, discussing the shortage of maximum likelihood Viterbi demodulation, then proposing the weighted MSK demodulation and despreading algorithm and joint demodulation and despreading algorithm based on the improved maximum likelihood Viterbi demodulation algorithm. The joint demodulation algorithm is more outstanding than the maximum likelihood Viterbi demodulation algorithm according to simulation.

**Keywords:** MOD5, Walsh, Maximum likelihood Viterbi demodulation algorithm, Joint demodulation and despread.

## 1. INTRODUCTION

### 1.1. IFF Technology

IFF (Identification Friend or Foe) technique is used for determining the enemy property. As an important part, it appears to significantly enhance the joint nature of each combat troops on the battlefield, reducing the probability of accidental injury. The requirements of IFF are increasing with modern high-precision weapons and destructive war growing. Fig. (**1**) shows the scenarios of IFF application.

IFF works as follows: when the fire control radar on the carrier A detects suspicious target B, interrogator on A immediately sends an interrogation signal to the target B, and opens a time window to wait for a response. Transponder on target B receives the interrogation signal, and returns the corresponding response signal after decoding. This response signal is received within the time window, then the expected response code is compared with the code which is decoded. If they are the same, B can be judged to be a friendly target, if no response signal is received, or the response code is error, target B will be judged as an enemy [1].

### 1.2. IFF Technology

Some years before, IFF used the radar reflect signal for target recognition. Until after World War II the United States developed the Mark-X type IFF and introduced PPM modulation technology, using "Question and Answer" signal to target recognition, also proposed three kind of operating modes, called MOD1, MOD2 and MOD3(M1/M2/M3). The appearance of side lobe suppression inquiry solved the effects of spatial asynchronous interference and improved the capacity of the IFF system [2].

At first, the IFF which had encryption capability is the type Mark-XII, it used encryption technology called MOD4 (M4). Aim at eliminating the randomly response guessed by enemy target, it will ask a series of encrypted signals from binary coding composition, the starting position of the response signal is random. And the encryption and decryption is independently completed by the encrypted computer.

At the end of 20th century, technical standard of MOD5 (M5) which had the more powerful encryption performance was proposed by NATO. Compared to M4, the more complexity of signal processing techniques, such as using MSK modulation technique, Walsh spread spectrum technology, RS coding technology, more powerful encryption technologies made M5 signal not only more confidential, higher recognition probability, but also a stronger data transmission capability, realizing information fusion and interacting data link level. The IFF using the M5 called Mark-XII [3].

## 2. BASIC METHOD OF DEMODULATION AND DESPREADING

This paper will focus on MSK demodulation and despreading, because the performance will be affected by some key parameters, such as sensitivity and error rate, which depend on the performance of demodulation and despreading. MOD5 baseband signal processing is the core technology. Therefore, the signal transmitting and receiving process of MOD5 can be simplified as Fig. (**2**).

### 2.1. MSK Modulation

MSK is a frequency modulation technique and the signal modulated by MSK modulation can be expressed as [4]:

1874-4443/15 2015 Bentham Open

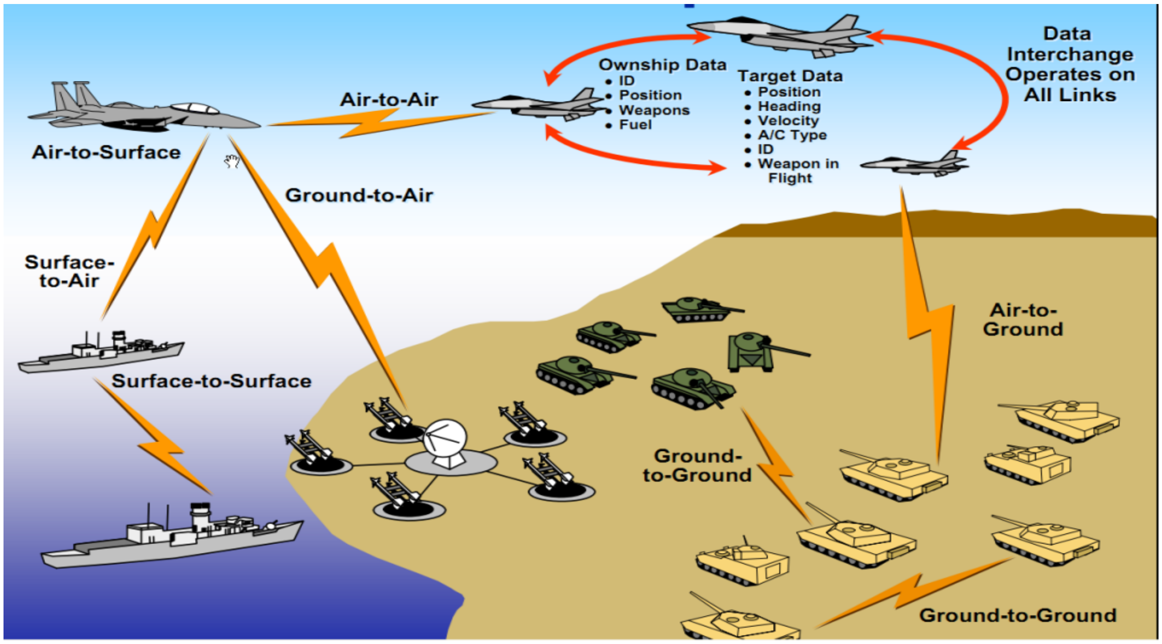


**Fig. (1).** Computer support of hand-painted ceramic pattern sketches technology framework.

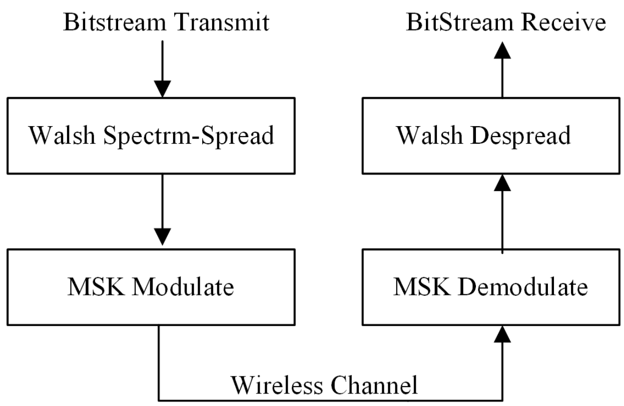


**Fig. (2).** MOD-5 signal process flow.

$$S_k(t)=\begin{cases}S_1(t)=A\cos(w_1t+\theta_1), \ send\ 1\\ S_2(t)=A\cos(w_0t+\theta_0), send\ 0\end{cases} \quad (1)$$
$$(k-1)T\le t\le kT$$

Because MSK signal is orthogonal and independent, according to the digital modulation index definition of the FSK signal $h=2f_dT$, Since the minimum modulation index is used, the h is equal to 1/2. MSK can be considered an continuous phase modulation signal(CPM) with h=1/2, it can be expressed as [5]:

$$S(t)=A\cos[2\pi f_c t+4\pi f_d T\int_0^t m(\tau)d\tau+\varphi_0] \quad (2)$$

Where, $f_c$ is the carrier frequency, $\varphi_0$ is the initial phase, $m(t)=\sum a_n g(t-nT)$ is the baseband signal and *g(t)* is a rectangular shaped pulse with the width being *T*, the amplitude being *1/2T*.

The additional phase after deducting the phase of the carrier frequency is as follow:

$$\begin{aligned}\theta(t,a_k)&=2\pi f_d T\sum_{j=1}^{k-1}a_j+4\pi f_d T a_k\frac{t-(k-1)T}{2T}\\ &=\pi h\sum_{j=1}^{k-1}a_j+2\pi h a_k\frac{t-(k-1)T}{2}\\ &=\frac{\pi}{2}\sum_{j=1}^{k-1}a_j+\frac{\pi t}{2T}a_k-\frac{(k-1)\pi}{2}a_k\end{aligned} \quad (3)$$

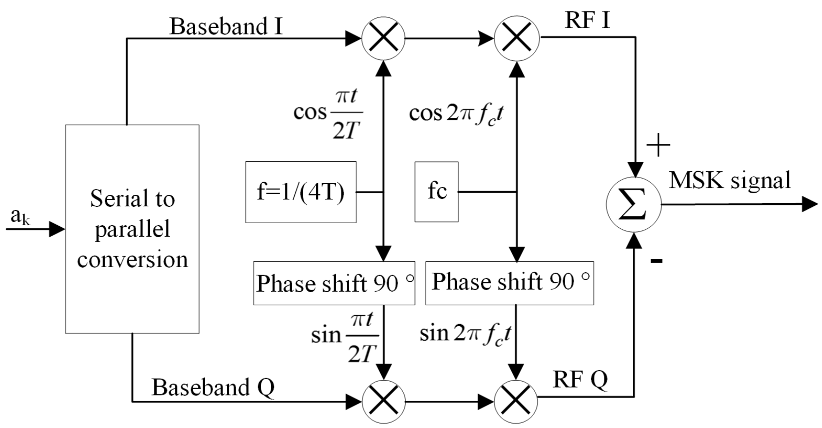


**Fig. (3).** MSK Modulation.

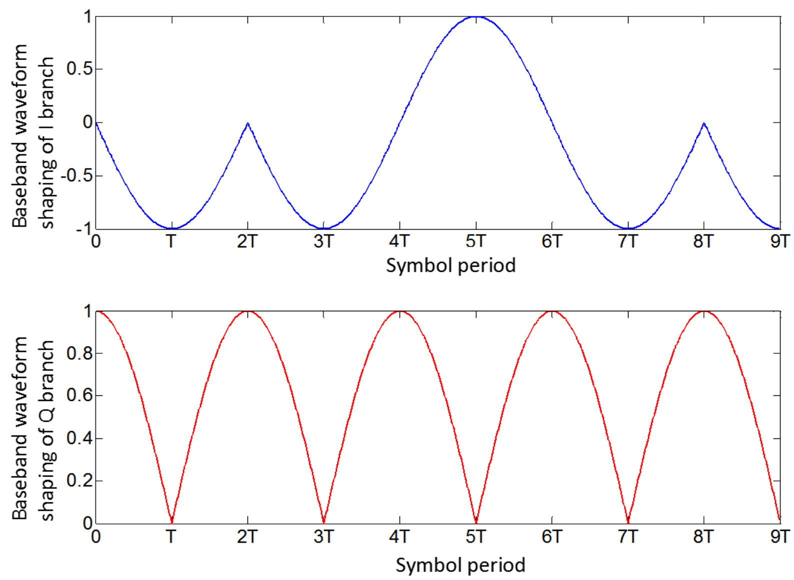


**Fig. (4).** Example of MSK modulation IQ waveform.

Make $\varphi_k = \frac{\pi}{2}\sum_{j=1}^{k-1} a_j - \frac{(k-1)\pi}{2} a_k$, obtained by the recurrence relations:

$$\varphi_k - \varphi_{k-1} = \frac{(k-1)\pi}{2}(a_{k-1} - a_k) \quad (4)$$

So, phase change of per symbol is:

$$\varphi_k = \varphi_{k-1} + \frac{(k-1)\pi}{2}(a_{k-1} - a_k) = \begin{cases} \varphi_{k-1} & a_k = a_{k-1} \\ \varphi_{k-1} \pm (k-1)\pi, a_k \neq a_{k-1} \end{cases} \quad (5)$$

According to the formula (2), normalizing amplitude A, MSK Signal can be express as below:

$$S_k(t) = \cos(2\pi f_c t + \frac{\pi t}{2T} a_k + \varphi_k) \quad (6)$$

When $a_k = 1$, carrier frequency becomes $(f_c + 1/(4T))$;

When $a_k = -1$, Carrier frequency becomes $(f_c - 1/(4T))$;

According to (6), the simplified formula can be expressed as:

$$S_k = \cos\varphi_k \cos\frac{\pi t}{2T}\cos 2\pi f_c t - a_k \cos\varphi_k \sin\frac{\pi t}{2T}\sin 2\pi f_c t \quad (7)$$

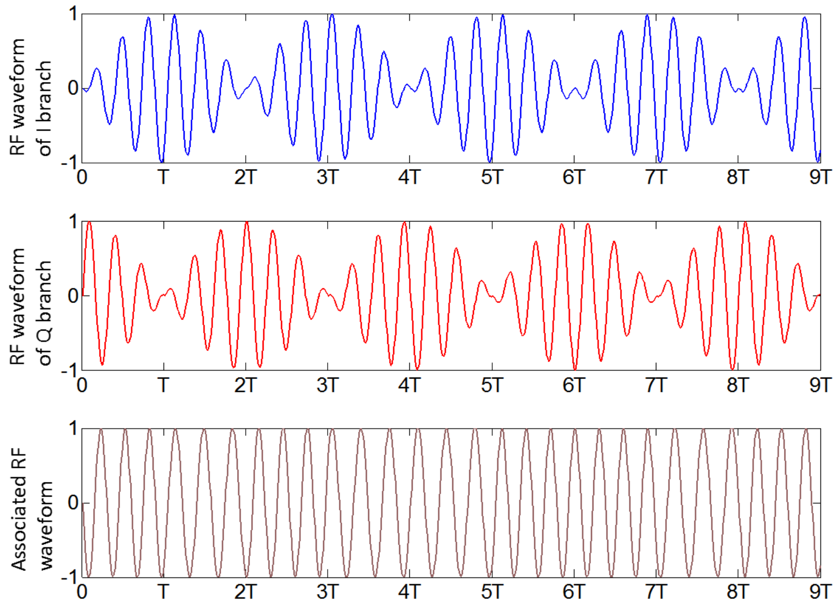


**Fig. (5).** MSK RF waveform.

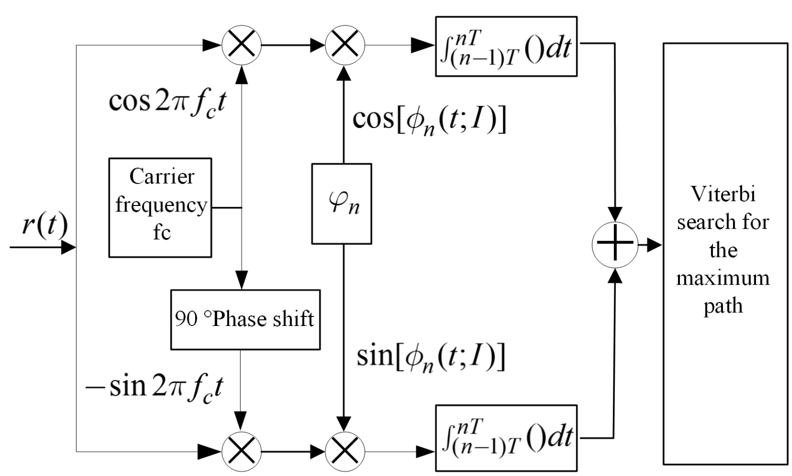


**Fig. (6).** The diagram of ML-Viterbi demodulation.

So, the procedure of MSK modulation can be shown as Fig. (**3**).

Figs. (**4**) and (**5**) give an example of MSK IQ waveform in the case of the input symbol in binary being [1 0 1 0 0 1 1 0 1], the carrier frequency being 50Hz. And the symbol rate being 16bit/s.

## 2.2. Maximum Likelihood Demodulation Algorithm

The differential MSK modulation signal can be demodulated using the maximum likelihood thoughts. Assuming symbol $I$ means transmission sequence, the likelihood function of the received signal *r(t)* is as follows [6]:

$$P(r(t)\,|\,I) = F\exp\{-\frac{1}{N_0}\int_0^{(n-1)T}[r(t)-\cos(2\pi f_c t+\phi(t;I))]^2\,dt\} \quad (8)$$

The log likelihood ratio of the observed signal $r(t)$ under known the particular transmitted bit sequence $I$ (the length is n) is proportional [7] to the following cross-correlation measure if unfolding the formula and removal of items independent of $I$.

$$CM_n = \int_0^{(n-1)T} r(t)\cos[2\pi f_c t+\phi(t:I)]dt \quad (9)$$

So, MSK demodulation based on the maximum likelihood is to find the sequence $I$ which makes the likelihood

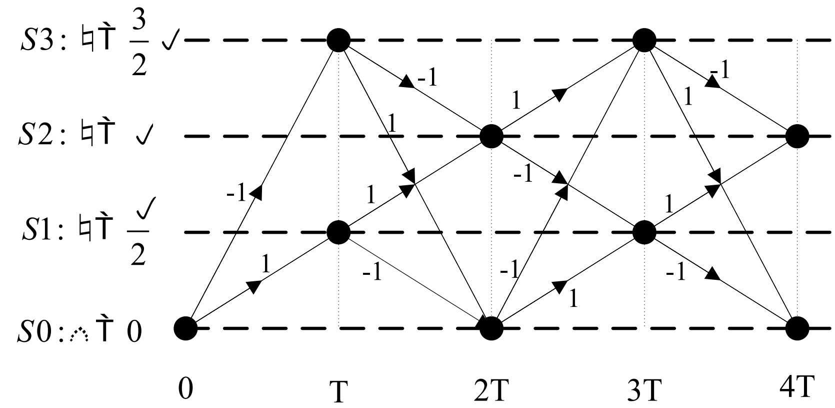


**Fig. (7).** Phase change trellis of MSK signal.

ratio *p(r(t)|I)* the largest, that means regarding the sequence making cross-correlation metrics $CM_n$ the largest as demodulation sequence. $CM_n$ can be calculated by the following formula:

Where is the associated phase information with symbol sequence *I*:

$$\phi_n(t;I) = \frac{\pi}{2}\sum_{k=0}^{n-2} a_k + \pi a_{n-1} q\left(t-(n-1)T\right) = \frac{\pi}{2}\sum_{k=0}^{n-2} a_k + \frac{\pi}{2} a_{n-1}\left(\frac{t-(n-1)T}{T}\right) \quad (10)$$

Splitting the measure into the term which has the integral length $T$, the additional incremental of each *[(k-1)T, kT]* is as follows:

$$V_k(I) = \int_{(k-1)T}^{kT} r(t)\cos[2\pi f_c t + \phi_k(t;I)]dt \quad (11)$$

The demodulation diagram of maximum likelihood estimation is shown in Fig. (**6**).

Fig. (**7**) shows phase change trellis of MSK signal in which the initial phase is assumed to be 0, it can be noted that: the phase state of the signal at each time has only two choices. Four phase states could not occur at a moment. Therefore the increment of measurement in one interval only has two available values. So, in *[(k-1)T, kT]*, additional increment for each state node has only two kinds of metrics [8]. For binary MSK signal, the phase changes over symbols sequence. As shown in Fig. (**7**), the four phase states in MSK signals are S0, S1, S2 and S3.

ML demodulation algorithm can be descripted as below:

1. Choose the moment $t = 2T$ as the search beginning. To get into the state S0 and S2, each state has two paths. Choose a larger cumulative metric value as the survivor path survivor$_0$ and survivor$_2$, and record the current metric values $CM_{2T(S0)}$ and $CM_{2T(S2)}$.
2. Enter the search process, at the moment $t = kT$ calculate the incremental metric of the entered current two states. For example: current status are S1 and S3, the incremental metric for S1 are $V_{kT(01)}$ and $V_{kT(21)}$, the incremental metric for S3 are $V_{kT(03)}$ and $V_{kT(23)}$.
3. Accumulate the metric values, then delete the eliminated path. For example:

$$CM_{kT(S1)} = \max(CM_{(k-1)T(S0)} + V_{kT(01)}, CM_{(k-1)T(S2)} + V_{kT(21)}) \quad (12)$$

4. Then, record the corresponding path as survivor$_1$. The same operation for state S3 to get $CM_{kT(S3)}$ and survivor$_3$.
5. Determining *k=16*, if the result is true, enter 5, (otherwise enter 2) and continue operating ACS operation [9].
6. At this time, S0 and S2 should be the final phase states, compare their cumulative metric $CM_{16T(S0)}$ and $CM_{16T(S2)}$, Choosing the survivor path corresponding the greater of output as the demodulated data *I*.

The responder obtain the 0/1 hard-determination after demodulated the signal, then use Walsh despreading algorithm to solve the received symbol.

### 2.3. Basic Method of Walsh Spreading and Despreading

MOD5 spreading solution uses the fixed Walsh code map. The Walsh spreading module in Fig. (**2**) maps the input symbol (4bits) to the output extended 16bits. The spreading mappings in the following table:

As shown, the Walsh functions are mutually orthogonal, i.e. satisfy:

$$\langle wi, wj \rangle = \begin{matrix} 16, i=j \\ 0, i \pi j \end{matrix} \quad (13)$$

Formula (13) shows that the correlation value is the maximum value when Walsh codes are the same, or else, the correlation value equal 0, so the Walsh code is distinguishable [10].

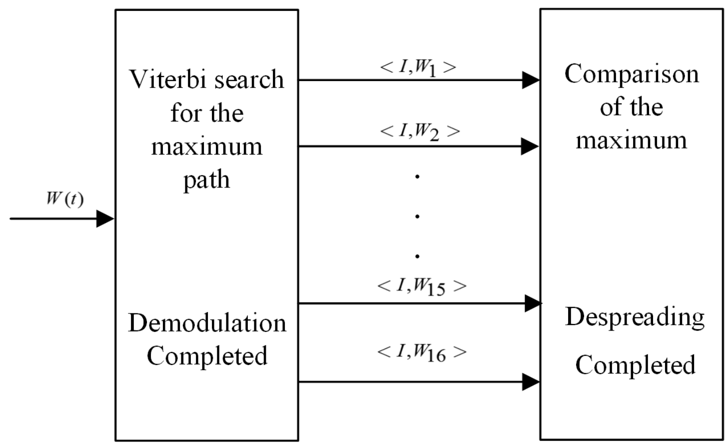


**Fig. (8).** The block diagram of Walsh despreading.

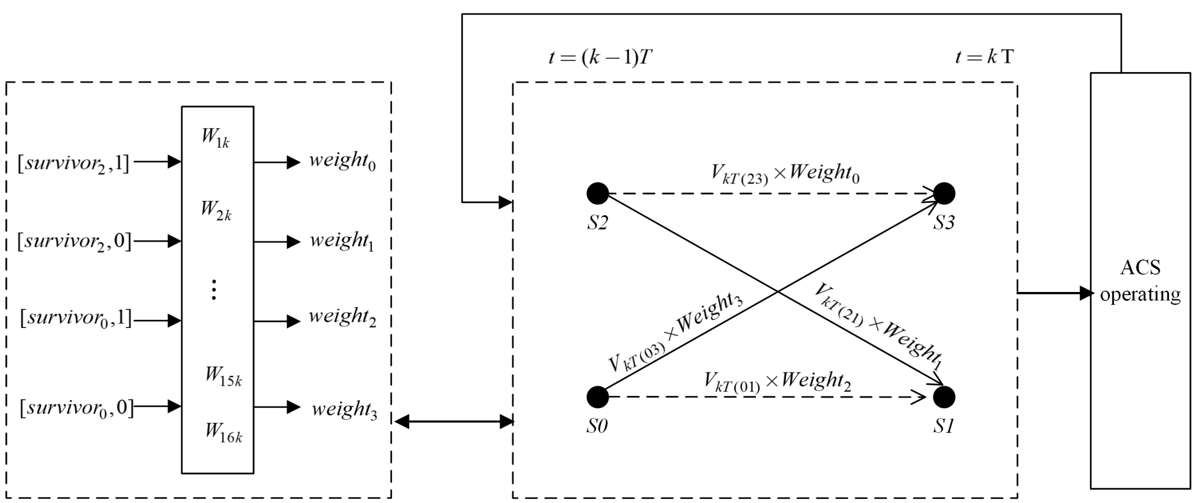


**Fig. (9).** Calculation of the additional increment in Weight-ML-Viterbi algorithm.

Basic Walsh despreading method utilizes its orthogonal properties. Use the received Walsh symbol (16 bits) and the local 16 kinds of all possible Walsh functions as the maximum inner product and identify its index look-up table to obtain the corresponding symbol, the following formula:

$$R = i\left|\max_{i=0,\mathrm{L}\ ,15}\left\langle W_R, W_i\right\rangle\right. \qquad (14)$$

In which, is the 16 bits of demodulated data. $R$ is the symbol after despreading. The process is shown as Fig. (**8**).

## 3. THE WEIGHTED ML-VITERBI DEMODULATION

The basic idea of ML-Viterbi demodulation algorithm is to obtain data *via* Comparing 0/1 bit and matching the data with the known Walsh functions to judging which function arrivals. But in the case where the SNR is very low, it is possible that the demodulated 16-bit will not completely correspond to any Walsh code, at this time the right despreading result will not be reached [11]. If we can restrict the Viterbi sequence "trend" on the survivors, maybe it can improve performance. Ideas go as follows:

1. Create the weight value to the incremental metric on each loop of the Viterbi algorithm. This value reflects the similarity of current survivor and the Walsh code.
2. Use the ideology of "Soft Decision", restrict the additional increment of each level via Walsh code restricting survivor series.

Now what we need is only changing the second step of the ML-algorithm. Multiply each incremental metric value with the weight value, so the path can be constrained by the finite 16 kinds of Walsh code.

$$Weight_{k,I_k} = \frac{\max\left\{\left\langle I_k, Walsh_{k,j}\right\rangle\right\}}{k} \quad k,j=1,2\mathrm{L}\ 16 \qquad (15)$$

Among equation (15), $I_k$ is the survivor after the moment $kT$, it will be bring for the inner product operation respectively with sequences generated from the first k bits of each Walsh code, then choose the max value to normalization. As shown, the max value of numerator is k, which indicates the first k bits of this survivor match one Walsh function at least, the weight is 1 in this case. The ACS operation is as same as the basic ML-Viterbi demodulation. The additional incre-

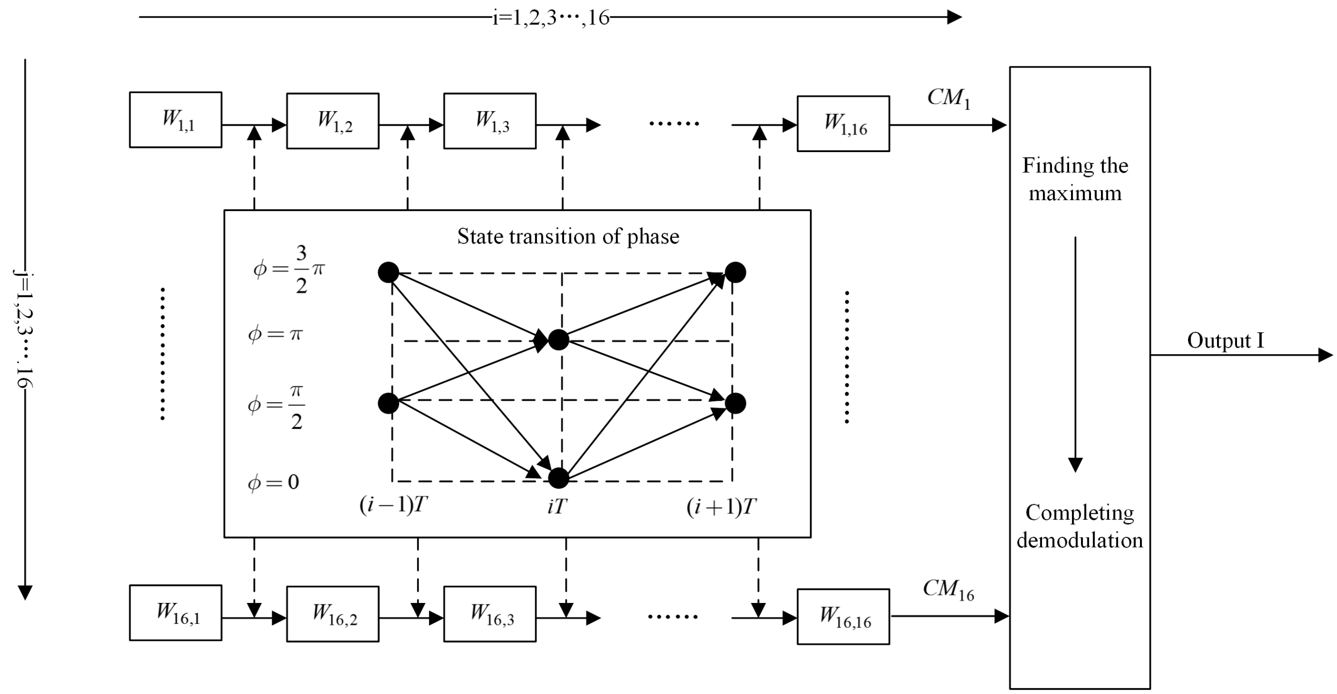


**Fig. (10).** Schematic diagram of joint algorithm.

ment calculate method of weighted ML-Viterbi demodulation is given by Fig. (**9**).

## 4. JOINT DEMODULATION AND DESPREADING ALGORITHM

In order to obtain the theoretical gain (6dB) of Walsh spreading for MSK demodulation brought, we need to optimize for the phase grid of ML-Viterbi algorithm, excavate Walsh spreading performance. Based on the theory on maximum likelihood demodulation, to improve on the original ML algorithm.

Demodulate operation should be done on one Walsh code frame unit, i.e. It is known that, in condition of sending sequence *I*, the logarithmic probability of received *r(t)* is proportional to the cross-correlation metrics $CM_n$, based on considering Walsh spreading, setting the length of integral as 16*T* for single frame. It is shown in below equation:

$$CM_I = \int_0^{16T} r(t)\cos[2\pi f_c t + \phi(t;I)]dt \tag{16}$$

The demodulation and despreading can be express in Fig. (**10**).

As mentioned above the sending sequence *I* has only 16 kinds of possibilities as shown in Table **1** because of joining Walsh functions to encode. The direct method is to generate the sending sequence *I* from each Walsh sequence, and making integration by the 16*T*, then getting the 16 cross-correlation metrics, then picking the max value and choosing the respond data (4bit) in index as demodulation result.

### 4.1. Definition of Algorithm

Now in order to reduce the reference demodulation sample value corresponding 16 kinds of Walsh sequence when operating the method introduced above, propose a method to equivalent achievement. It can reduce the complexity of long time integration and the storage consumption.

Construct the phase matrix by 16 rows and 16 columns by the phase states, which are decided by the Walsh sequence.

1. Split the correlation integration on 16*T* into 16 sections integration of the period *T*.
2. Take advantage of the particularity of phase state of MSK (There are only 2 states can exist in any state point). During the process of one period, the start point is the end point of last state changed, i.e. 0, π, π/2 or π/3. By the condition of current input value “1” or “-1”, define the local demodulation reference sampling value as below:

$$S_k(t) = \cos(2p f_c t + j_{k-1} + a_k \frac{t - (k-1)T}{2T}) \tag{17}$$

3. Use the each possible $S_k(t)$ to correlate with the receive signal $r(t)$, then obtained the incremental metric $V_k(I)$.
4. Match the input parameter $(\varphi_{k-1}, a_k)$ of incremental metric and the Walsh sequence matrix mentioned in 1). Accumulate $V_k(I)$ into the corresponding metric value $(CM_1, CM_2 \text{L } CM_{16})$, which was matched successful with Walsh sequence.
5. Come back to step 3), continue calculating and matching with the incremental metrics, until the 16 symbol had all been counted.

**Table 1. Walsh Spectrum-Spread function.**

| $i$ | **Input** $S_i$ **MSB LSB** | **Output** $W_i$ **MSB LSB** |
|---|---|---|
| 0 | 0000 | 1111 1111 1111 1111 |
| 1 | 0001 | 1111 1111 0000 0000 |
| 2 | 0010 | 1111 0000 0000 1111 |
| 3 | 0011 | 1111 0000 1111 0000 |
| 4 | 0100 | 1100 0011 1100 0011 |
| 5 | 0101 | 1100 0011 0011 1100 |
| 6 | 0110 | 1100 1100 0011 0011 |
| 7 | 0111 | 1100 1100 1100 1100 |
| 8 | 1000 | 1001 1001 1001 1001 |
| 9 | 1001 | 1001 1001 0110 0110 |
| 10 | 1010 | 1001 0110 0110 1001 |
| 11 | 1011 | 1001 0110 1001 0110 |
| 12 | 1100 | 1010 0101 1010 0101 |
| 13 | 1101 | 1010 0101 0101 1010 |
| 14 | 1110 | 1010 1010 0101 0101 |
| 15 | 1111 | 1010 1010 1010 1010 |

**Table 2 Parameter settings of demodulation algorithm performance simulation (MATLAB).**

| **# Simulation Parameters** | |
|---|---|
| IF Sampling | 30MHz |
| Sampling rate | 160MHz |
| Symbol rate | 16Mbps |
| The initial phase | 0 |
| Simulation SNR range | [0dB, 8dB] |
| Test times with single SNR point | 10000 |

6. Find the max value in $(CM_1, CM_2 \text{L } CM_{16})$, choose the index of it as the demodulated result.

Within this algorithm, the long integration was split to short integration in one period. It follows the grid of ML-Viterbi to calculate the incremental metrics, just add the process of matching and the storage consumption of survivors.

## 4.2. Algorithm Optimization

Without affecting the performance of the joint demodulation and despreading algorithm, taking into account needing too much storage resource, propose the optimization approach. In this algorithm, need to storage the metrics for 16 paths of Walsh sequences, aim at final determination of the maximum metric. But it can be found through the simulation that at the halfway of integration, the metric of the 16 paths has appeared less than zero. The reason is that: the influence caused by noise had been so small after the long time integration.

According to this feature mentioned above, the algorithm can be optimized, that is truncating Walsh sequence at the special time node. The process is as follows:

a. Discard the Walsh sequence which has the Smaller 8 cumulative metric after Integration within 8 Symbol period;

b. Discard the Walsh sequence which has the Smaller 4 cumulative metric after Integration within 12 Symbol period;

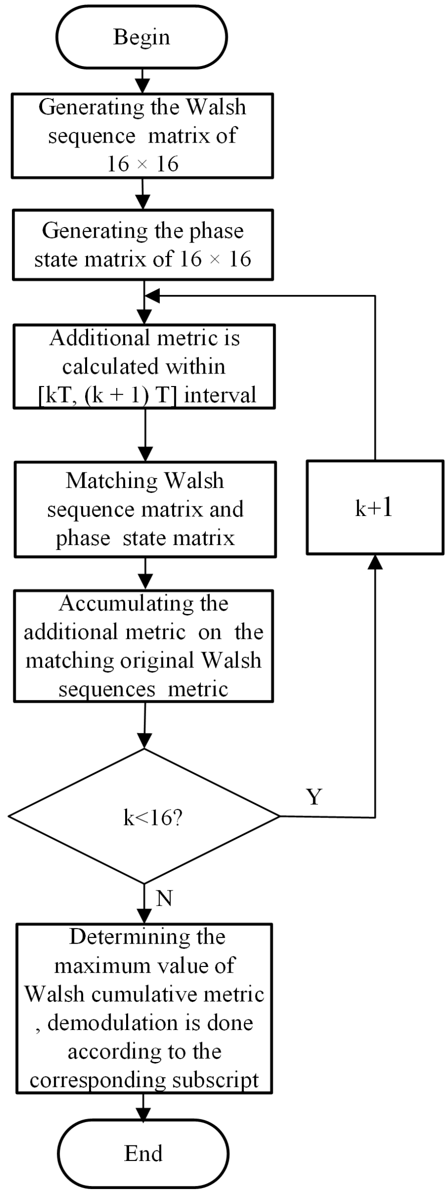


**Fig. (11).** Flow of joint demodulation and despreading algorithm.

c. Discard the Walsh sequence which has the Smaller 2 cumulative metric after Integration within 14 Symbol period;

d. Completing integration. Determine the greater value in remaining two cumulative measure to complete the final demodulation.

Flowcharts based on maximum likelihood joint demodulation and despreading algorithm is as Fig. (**11**). In this flowchart, additional metric calculation is consistent with what is introduced in Fig. (**9**).

This algorithm splitting the long period of integration into each period, and adopting the grid structure of ML-Viterbi demodulation to calculate the additional metric greatly reduces the amount of multiplications with only increasing the additional metrics matching process and storage capacity of the possible paths. The algorithm will fundamentally limit the path of the Viterbi search in the 16 kinds of Walsh codeword values to advantage Walsh spreading gain.

## 5. SIMULATION

For basic ML-Viterbi demodulation, weighted ML-Viterbi demodulation and joint demodulation, Matlab simulation diagram of BER is showed in Fig. (**12**).

Table **2** shows the parameter settings of performance simulation.

Figs. (**13** to **15**) show BER curves and comparison results of Basic ML-Viterbi demodulation, Weighted ML-Viterbi demodulation and joint demodulation and despreading by simulation algorithm.

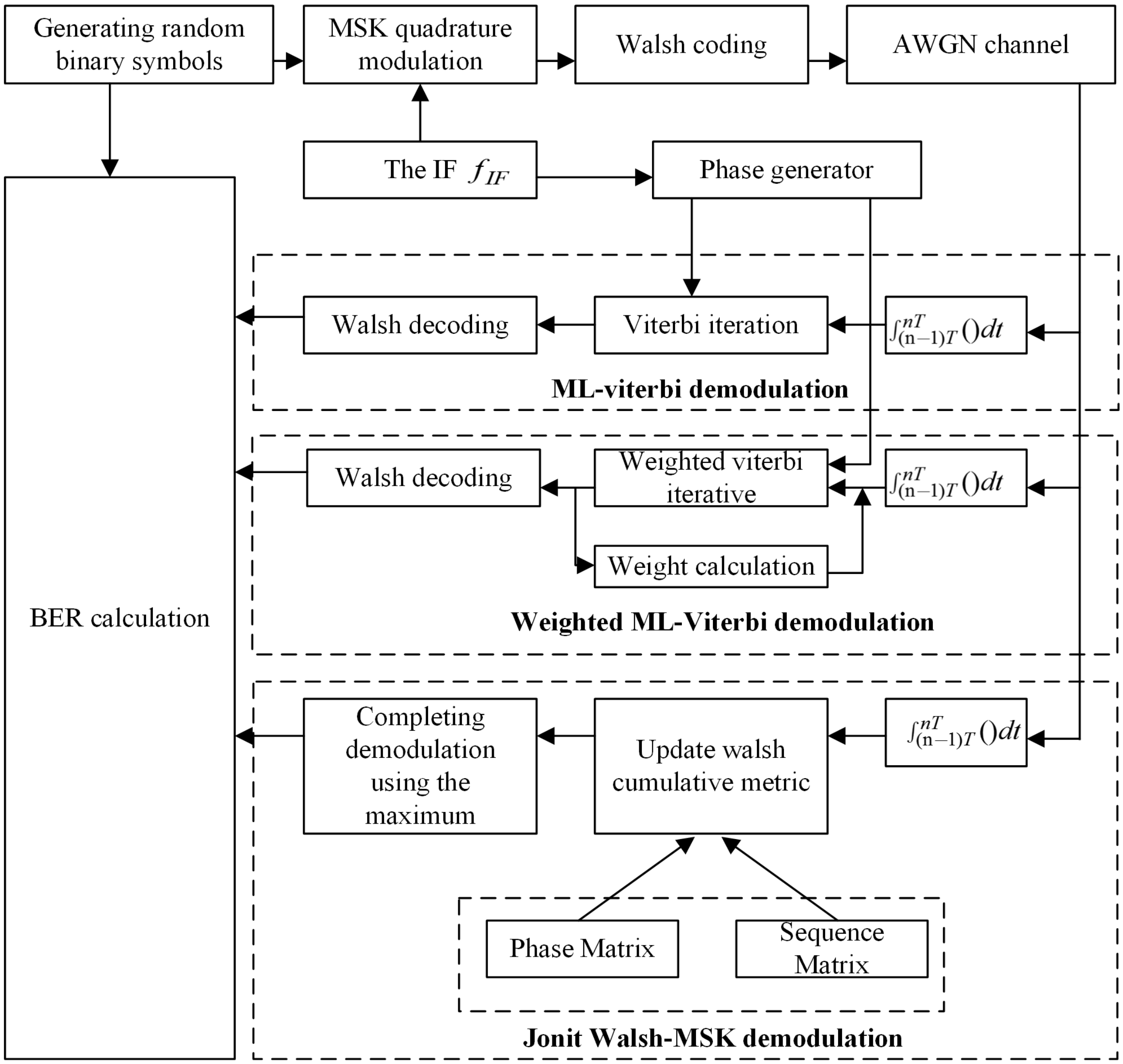


**Fig. (12).** The flow of joint demodulation and despreading algorithm.

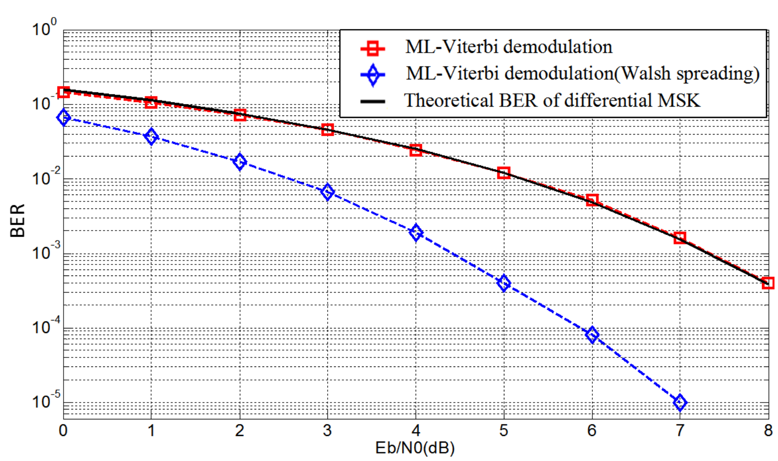


**Fig. (13).** BER curves of basic ML-Viterbi demodulation algorithm.

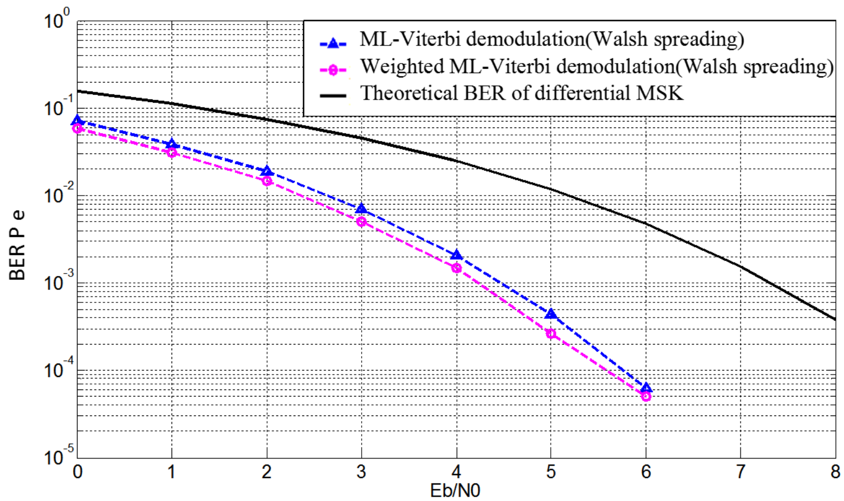


**Fig. (14).** BER curves of weighted ML-Viterbi demodulation algorithm.

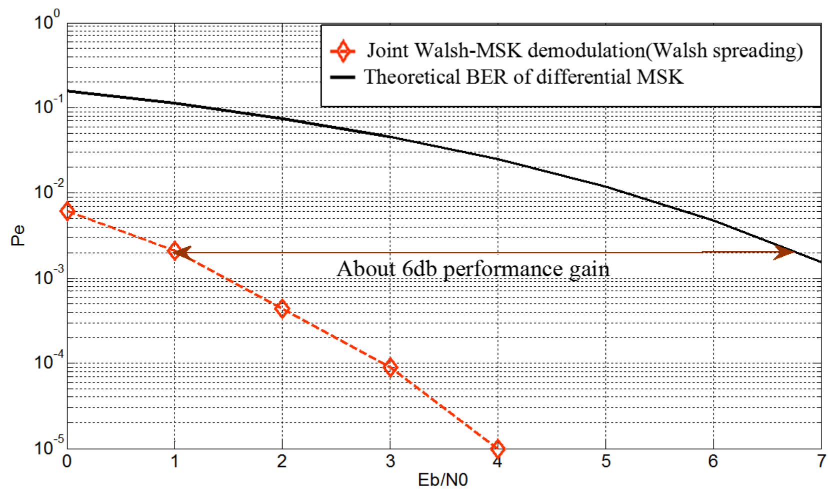


**Fig. (15).** BER curves of joint demodulation and despreading algorithm.

## CONCLUSION

Fig. (**13**) shows that the disparity of BER performance between ML-Viterbi and MSK coherent demodulation is obvious, it is caused by the reason that the data needing demodulated is modulated by differential MSK modulation, which will introduce 2-fold BER attenuation when demodulation; and with joining Walsh spreading, BER performance gain is only 2 ~ 3dB, which could not meet the theoretical gain of 6dB.

Fig. (**14**) shows that the performance of weighted ML-Viterbi demodulation is better (about 0.3 dB) than what of basic ML-Viterbi demodulation under the low SNR situation, even joining Walsh spreading, BER performance gain still could not meet the theoretical gain of 6dB.

Fig. (**15**) shows that joint demodulation algorithm has about 6dB of performance gain compared with the basic ML-Viterbi demodulation algorithm, as SNR increasing, the performance gain should be kept at 6dB.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

## ACKNOWLEDGEMENTS

The authors thank the support of the National Natural Science Funds [grant number 61201005]; Sichuan Province Science and Technology Support Program [grant number 2014SZ0093]; China Postdoctoral Science Foundation [grant number 2014M562303].

## REFERENCES

[1] C. F. Huang, and L. M. He, “IFF MK XIIA Analysis”, *Telecommunications Technology*, vol. 47, no. 4, pp. 66-71, Aug. 2007.

[2] W. M. Yang, “The development of IFF and technology”, *Shipboard Electronic Warfare*, vol. 26, no. 5, pp. 10-12, Oct. 2003.

[3] F. F. Chen, "The situation and development trend of foreign IFF and technology", *Telecommunications Technology*, vol. 41, no. 2, pp. 5-10, 2001.

[4] X. F. Li, *Communication Theory*, National Defence Industry Press: Beijing, pp. 319-336, 2008.

[5] C. X. Fan, *Communication Theory*, National Defence Industry Press: Beijing, 2000, pp. 242-250.

[6] J. G. Proakis, *Digital Communications*, McGraw Hill; New York, 2011, pp.198-222.

[7] T. Aulin, "Continuous phase modulation--Part II: partial response signaling", *IEEE Transactions on*, vol. 29, no. 3, pp. 210-225, Jan. 1981.

[8] S. J. Xuan, "Implement of Viterbi algorithm of maximum likelihood sequence detection", *University of Yun Nan Nation*, vol. 48, no. 50, pp. 48-50, 2005.

[9] J. S. Yuan, "*Viterbi algorithm: Analysis and implementation*", *M.S. thesis*, University of National Defense Technology, ON, China, 2004.

[10] K.G. Beauchamp, *Walsh Function And their Application*, Academic press: London, 2004, pp. 9-15.

[11] J. X. Zhou, "Non-coherent demodulation with composite grid algorithm of continuous phase modulation", *Electronics & Information Technology*, vol. 31, no. 9, pp. 2137-2142, 2009.

Received: October 16, 2014 Revised: December 23, 2014 Accepted: December 31, 2014