Abstract—Combining the single-input and multiple-output (SIMO) technology with the frequency-modulated differential chaos shift keying (FM-DCSK) modulation, a novel SIMO FM-DCSK ultra-wideband (UWB) system is proposed in this paper. Single sub-stream signal based on high order Walsh function is adopted in the transmitter and two detection schemes are presented in the receiver. Simulations and analyses show that the proposed system with differential correlation detection possesses superior performance as well as relatively low complexity, thus is particularly suitable for the low rate and low power applications in wireless personal area networks (WPANs).

I. INTRODUCTION

In recent years, several chaotic modulation schemes have been proposed as candidates of the ultra-wideband radio standards for WPAN by the IEEE 802.15.4a Task Group [1-3]. Among all the chaotic modulation schemes, FM-DCSK is proven not only having the best noise performance but also achieving an excellent anti-multipath fading capability [4-7]. Consequently, it has been attracting some researching interest to use FM-DCSK modulation for UWB transmission [8, 9].

In [8], Kolumbán has firstly determined the feasibility of an FM-DCSK UWB radio system and given an exact expression for the noise performance of generalized transmitted reference (TR) system by a comparison between the FM-DCSK and non coherent impulse radio systems. And the authors in [9] have discussed several key features and principle of operation of FM-DCSK combined with the UWB technology, and demonstrated its superiority in multipath environment. Recently, the performance of the FM-DCSK UWB system has been evaluated through the important system parameters, and its feasibility along with the promising advantages in the indoor communication have been demonstrated by a proposed optimization scheme [10]. Meanwhile, a theoretical analysis on the bit error rate (BER) performance of the FM-DCSK UWB communication system with timing error is further investigated in [11]. Those works promote its application for IEEE 802.15.4a in WPANs.

However, the performance of the FM-DCSK UWB system is still bounded since the non coherent detection method and 3dB signal power wasting to transmit the non information-bearing reference pulses. To overcome the inherent constraint, considering its own evolution of the FM-DCSK modulation, an SIMO FM-DCSK system has been proposed recently in [12], which employs high order Walsh functions with multiple sub-stream transmission in the transmitter and multiple antennas receiving at the receiver, thus achieving a obvious increase of the data rate as well as receiver diversity gain. It has been demonstrated that the performance of the proposed SIMO FM-DCSK scheme is significantly improved comparing with the original FM-DCSK.

Basing on the conclusions in [12], we introduce the SIMO architecture into the existing FM-DCSK UWB system to form a novel SIMO FM-DCSK UWB scheme in this paper. Considering its application in the IEEE 802.15.4a low rate environment, unlike the multiple sub-streams transmission to achieve increasing of the data rate in the SIMO FM-DCSK [12], the signals with single sub-stream but still based on high order Walsh function are transmitted in the proposed system. As transmitting one bit information by multi-doublets pulses, it lowers the amplitude of each pulse to accord well with the low-power spectrum requirement by the FCC regulation. In the receiver of the proposed system, multiple antennas achieve diversity gain as well as power gain to improve the BER performance as in SIMO FM-DCSK. Since using single sub-stream transmission herein, two detection schemes can be performed in the receiver of the proposed system, i.e. differential correlation (DC) detection as in the original FM-DCSK and generally maximum likelihood (GML) detection as in the SIMO FM-DCSK, respectively. The comparison of both the error performance and the complexity between the two detection schemes with different parameters will be indicated in this paper.

The rest of this paper is organized as follows. Section II describes the configuration of the proposed SIMO FM-DCSK UWB system compared with the existing FM-DCSK UWB and the existing SIMO FM-DCSK scheme. The simulation results and analyses are presented in Section III. Finally Section IV summarizes the conclusions.

II. CONFIGURATION OF THE PROPOSED SIMO FM-DCSK UWB SCHEME

A. Transmitter

As in the existing SIMO FM-DCSK system, high order Walsh function is adopted in the transmitter of the proposed SIMO FM-DCSK UWB system. Unlike two orders Walsh scheme in the existing FM-DCSK UWB system, high order...
Walsh function has more than two row vectors. Taking the order number \( M = 4 \) in (1) as an example, the four order Walsh function has four row vectors. However unlike using all the row vectors of the high order Walsh function to achieve multiple sub-streams transmission in SIMO FM-DCSK, only the first two rows (i.e., \( w_1 \) and \( w_2 \)) are assigned to form single sub-stream transmission in the proposed system. The other row vectors are useless herein, but they could be used by other users to achieve multiple access communication, which is not considered temporarily in this paper. Represented by the two basis functions \( g_1(t) \) and \( g_2(t) \) as in (2), four pulses (i.e., \( c_0(t) \), \( c_1(t) \), \( c_2(t) \), \( c_3(t) \)) will be transmitted for one information bit in this scenario. \( T_c \) is the duration of the single pulse and \( T \) is the bit duration in (2). And the amounts of pulses will be further increased with the increase of the order \( M \). Considering bit energy constant, the amplitude of each pulse is lowered in the proposed scheme.

\[
W_4 = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}
\]

(1)

\[
g_1(t) = \begin{cases} +c_0(t) & 0 \leq t < T_c \\ +c_1(t) & T/4 \leq t < T/4 + T_c \\ +c_2(t) & T/2 \leq t < T/2 + T_c \\ +c_3(t) & 3T/4 \leq t < 3T/4 + T_c \end{cases}
\]

(2)

\[
g_2(t) = \begin{cases} -c_0(t) & 0 \leq t < T_c \\ -c_1(t) & T/4 \leq t < T/4 + T_c \\ -c_2(t) & T/2 \leq t < T/2 + T_c \\ -c_3(t) & 3T/4 \leq t < 3T/4 + T_c \end{cases}
\]

(3)

It is particularly worth noting that the carriers in the FM-DCSK scheme are continuously varying chaotic waveforms, i.e. the chaotic carriers \( c(t) \) are not the same in different symbols in the two order scheme. Also they will be different in different chips of the same symbol in the high order scheme if without any necessary measures. To assure the same chaotic carriers during one symbol shown in (3), a series of delay lines are needed in the transmitter of the high order Walsh scheme. However, the issue was not clarified clearly and the block diagram of the transmitter was also not given in the SIMO FM-DCSK scheme [12]. Here, the transmitter of the proposed SIMO FM-DCSK UWB system is shown in the Fig.1, which is also applicable to the previous SIMO FM-DCSK scheme [12].

### B. Receiver

Considering the detection scheme in the receiver, the DC detection is performed in the existing FM-DCSK UWB system, whereas the GML detection is adopted in SIMO FM-DCSK. Since combining the high order Walsh scheme with single sub-stream transmission, both the two detections can be applicable in the proposed system.

The block diagrams of the two receiver schemes are shown in the Fig. 2 and Fig. 3, respectively. In the Fig. 2, differential correlation detection is performed in each antenna, then the decision vectors are combined in an equal gain way. With \( N \) antennas, it can be expressed in (4). Here, \( T \) is the bit duration, \( r_n(t) \) is the received signal in the receiver antenna \( n \). And the estimated bit will be “1” if \( E_{DC} > 0 \) or “0” if \( E_{DC} \leq 0 \).

\[
E_{DC} = \sum_{n=1}^{N} \int_{T/M}^{T} r_n(t) r_n^*(t - T/M) dt
\]

(4)

The GML detection is shown in the Fig.3. The detection process is carried out through each receiver antenna independently, with the corresponding Walsh functions (i.e., \( w_1 \) and \( w_2 \)) used in the transmitter. Then, the weighted energy calculated from each receiver antenna is combined for final decision making. The weighted energy combined with \( N \) antennas can be expressed in (5). Here, if the vector \( w_2 \) for bit “1” and vector \( w_2 \) for bit “0”, then the decision will be “1” if \( E_{GML} > 0 \) or “0” if \( E_{GML} \leq 0 \).

![Fig. 1. Block diagram of the transmitter in the proposed SIMO FM-DCSK UWB system](image)

![Fig. 2. Block diagram of differential correlation (DC) detection](image)

![Fig. 3. Block diagram of generally maximum likelihood (GML) detection](image)
$$E_{gML} = \sum_{n=1}^{N} \sum_{i=0}^{M-1} \left[ \sum_{i=0}^{M-1} r_i(t-i\frac{T}{M}) w_{n,m,i} \right] dt$$

(5)

Considering the delay modules in the block diagrams of the two receiver schemes, the amounts of the delay blocks in the DC scheme are much less than the GML detection. Since the delays of each block (unit delay) are equal to $T/M$, the DC scheme is relatively simpler and easier to implement. Meanwhile, it is noted that the unit delay depends on the Walsh function order $M$ when the bit duration $T$ is constant or the data rate $R$ is fixed. Therefore, the requirements of unit delay are lowered with the increase of $M$. However, in this case, the amounts of the delay blocks are increased in the GML detection scheme. It means that the complexity of the GML detection scheme is increased with $M$ increasing. Furthermore, both the performances of the two receivers and the complexity of the transmitter are affected by the order $M$. Thus, $M$ is a considerably important system parameter, which will be further investigated through the simulations shown in the next section.

### III. Simulation and Results

In this section, simulation results of the proposed SIMO FM-DCSK UWB system are presented using different detection methods (i.e., DC and GML) and different system parameters (i.e., Walsh function orders $M$ and receive antennas $N$). All the simulations are performed under the representative indoor channels, i.e., IEEE 802.15.4a CM1 channels [13], which is based on line-of-sight (LOS) indoor residential. The parameters are set as follows: bit duration $T = 1\mu s$, chaotic pulse width $T_p = 2.5\text{ns}$, sampling frequency for simulation $f_s = 8\text{GHz}$. Cubic chaotic map is chosen for chaos generator. It is assumed that the channel impulse response is invariant in the frame duration with 50 bits.

#### A. Comparison between the DC and GML detections of the proposed SIMO FM-DCSK UWB system

In this sub-section, the comparisons of BER performance and implement complexity between the DC and the GML detections are performed in the proposed system.

First, the performances of the two detections are evaluated through simulations in CM1, and the existing FM-DCSK UWB scheme is given for comparing. Fig. 4 shows the proposed SIMO FM-DCSK UWB system outperforms the existing system significantly, no matter what kind of detection scheme is performed. Among the three schemes, the SIMO FM-DCSK UWB based on GML detection has the best BER performance, and it is better than the existing schemes about 3dB and better than the corresponding DC detection about 0.5dB.

<table>
<thead>
<tr>
<th>TABLE I. DELAY REQUIREMENTS OF THE TWO DETECTIONS</th>
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<tbody>
<tr>
<td><strong>DC detection</strong></td>
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<tr>
<td>Unit delay</td>
</tr>
<tr>
<td>Block amount</td>
</tr>
<tr>
<td>Total delay</td>
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As mentioned above, the GML detection possesses the best BER performance but the highest complexity among the three detection schemes. Considering the delay modules in the Fig. 2 and Fig. 3, although the unit delays of each block are the same, more delay blocks appear in the GML scheme. The delay requirements of the two schemes are shown clearly in the Tab.1. It can be observed that the GML detection has much higher demands of delay lines than the DC detection especially when $M$ is larger. In other words, the proposed scheme based on the GML detection is more complex and harder to implement. Accordingly, by trading off the performance and the complexity, the DC detection becomes the right choice of the proposed system for the low data rate and low power applications in WPAN.

#### B. BER performance of the proposed SIMO FM-DCSK UWB (DC) scheme with different system parameters

Next, the focus will be on the proposed SIMO FM-DCSK UWB system with the DC detection. And it will be further considered with different parameters in this sub-section.

First, the influence of the Walsh function order $M$ is considered. In the DC detection based on $M$ order Walsh function, the collected effective signal energy in each receiver antenna is equal to $(1-1/M)E_s$, which is increased with the increase of $M$. On the other hand, some adverse effects are also caused by the increase of $M$, such as more noise energy and more inter-pulse interference (IPI). Besides the energy of each pulse is lowered with $M$ increasing, which may be too low to combat the noise effect when $M$ is large enough. Consequently, an optimal $M$ may exist in the proposed scheme corresponding to the best BER performance.

Fig. 5 shows that the performance of the proposed scheme is improved with the increase of $M$ at the beginning. But the performance gain is reduced when $M$ is added to a certain value, such as $M = 8$ shown in the Fig. 5. It can be observed that the performances of the proposed system are close when $M = 8, 16, 32$ and 64. These results verify the qualitative analysis in the above paragraph. Considering that the implement complexity is increased as the order $M$ increases, $M = 8$ is an optimal value for the proposed system in the IEEE 802.15.4a application, by trading off the performance and the complexity.
Fig. 5. BER performance of the proposed SIMO FM-DCSK UWB (DC detection) with different Walsh function order $M$

Fig. 6. BER performance comparison between the proposed SIMO FM-DCSK UWB (DC detection) systems with different receiver antenna number $N$ and the existing FM-DCSK UWB system

Next, consider the other important parameter (i.e., receiver antenna number $N$) of the proposed system with the optimized Walsh function order. In Fig. 6, the performances of the SIMO FM-DCSK UWB based on DC detection with the same Walsh function order ($M=8$) and different antenna number ($N=1, 2, 4$) are shown, as well as the existing FM-DCSK UWB system (i.e., $M=2$ and $N=1$) is given for comparison. It is clear that the performance is improved about 2dB for each additional antenna. And comparing the existing system, the new scheme with $M=8$ and $N=4$ has about 4.5dB performance gain. Indeed, the complexity of the proposed system is heightened as increasing the antenna number $N$. Consequently, the appropriate $N$ value can be determined according to the specific requirements of the practical application.

IV. CONCLUSIONS

Combining the existing FM-DCSK UWB with SIMO FM-DCSK scheme, a novel SIMO FM-DCSK UWB system has been proposed. Single sub-stream signal based on high order Walsh function has been transmitted to accord with the low rate applications as well as simplify the complexity of multiple sub-streams transmission in the existing SIMO FM-DCSK scheme. Two feasible detection schemes of the proposed system have been indicated and evaluated through simulations in the IEEE 802.15.4a channel. Simulations have shown that the proposed system, with either DC or GML detection, has significant performance gain compared with the existing system, and the GML detection outperforms the DC detection about 0.5dB. By trading off the performance and the complexity, the DC detection has been considered to be the appropriate receiver scheme of the proposed system for the low power and low cost applications. And the performance of the proposed system with DC detection has been further investigated with different system parameters $M$ and $N$. It has been found that an optimal Walsh function order value $M=8$ and about 2dB performance gains for each additional receiver antenna. With the advantages of superior performance and relatively low complexity, the proposed SIMO FM-DCSK UWB system based on differential correlation detection is believed to be a potential scheme for the IEEE 802.15.4a low-rate and low-power application.

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