Performance of an SIMO FM-DCSK Communication System

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***Abstract*—A single-input multiple-output (SIMO) architecture of the frequency-modulated (FM) differential code-shift keying (DCSK) modulation technique is proposed. The new scheme employs orthogonal Walsh functions at the transmitter, with parallel substreams transmitted with a single antenna to help achieve a significant increase of the data rate. Multiple antennas are used at the receiver end to form an SIMO structure so as to obtain a diversity gain. Simulation results demonstrate that at a higher signal-to-noise ratio, the proposed SIMO FM-DCSK architecture has an outstanding bit error rate performance, in contrast to the direct-sequence (DS) vertical Bell Labs layered space-time (VBLAST) scheme that uses a complicated Rake receiver and minimum mean-square error detection, at the same data rate over multipath fading channels. In particular, the new scheme does not require any prior knowledge of the channel states, exact synchronization, and the complex Rake receiver, making the proposed algorithm simpler and yet more efficient than the DS-VBLAST scheme.**

***Index Terms*—Direct-sequence vertical Bell Labs layered space-time (DS-VBLAST), error performance, frequency-modulated differential code-shift keying (FM-DCSK), single-input multiple-output (SIMO) communication system, Walsh function.**

I. Introduction

DIFFERING from the conventional modulation algorithms, chaotic modulation schemes use nonperiodic chaotic signals as the carrier [1], [2]. Different chaotic modulation schemes have been proposed to date [3]–[5], among which frequency-modulated (FM) differential code-shift keying (DCSK) is proven not only having the best noise performance but also possessing a superior capability of anti-interference over multipath fading channels without compensatory measures such as channel estimation, equalization, or Rake reception [6].

In this paper, the single-input multiple-output (SIMO) architecture is introduced into the FM-DCSK modulation scheme, to increase data rate and also obtain a diversity gain. Unlike the currently used multiple-input multiple-output (MIMO) systems, which are limited by the degrees of freedom in the antennas, multiple substreams are transmitted with only one single antenna at the transmitter end. The excellent cross-correlation characteristic of Walsh functions ensures multiple substream division, and the inherent auto-correlation characteristic of chaotic signals can effectively mitigate multipath effects. Multiple receiver antennas at the receiver end provide several independent copies of signals from the transmitter, which significantly decreases the error probability.

The proposed SIMO FM-DCSK scheme has many distinctive features from the currently promoted systems. Take the direct-sequence (DS) vertical Bell Labs layered space-time (VBLAST) scheme as an example for comparison. The new scheme requires no channel estimation, no Rake receiver, and no crucial requirement of exact synchronization. Through design and simulation it has been confirmed that the new scheme performs much better than its counterpart over multipath fading channels with the same global spread-spectrum factor, as reported below.

The rest of this paper is organized as follows. Section II reviews the principle of the FM-DCSK, while Section III describes the SIMO FM-DCSK scheme. Section IV shows the simulation results with a detailed comparison of performances between the new system and the DS-VBLAST at the same data rate. Finally, conclusions are drawn in Section V.

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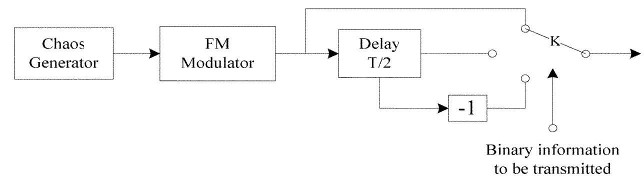


Fig. 1. Binary FM-DCSK modulator.

II. Principle of FM-DCSK Scheme

A. Modulation of the FM-DCSK

FM-DCSK uses a FM chaotic signal as the carrier, with a DCSK modulator, for transmission. A chaotic signal is generated by a chaotic mapping method [1], while the simple cubic chaotic map is chosen here for implementation. Together with a binary FM-DCSK modulator, the setting is illustrated in Fig. 1.

The binary FM-DCSK modulation unit transmits a reference segment of the FM chaotic signal, or its repeated or reverse segment, according to the digital information "1" or "0," respectively. The modulated signal is represented by two orthogonal basic functions, $g_1(t)$ and $g_2(t)$, as follows:

$$\begin{aligned} s_m(t) &= s_{m1}g_1(t) + s_{m2}g_2(t) \\ (s_{11} \quad s_{12}) &= (\sqrt{E_b} \quad 0) \\ (s_{21} \quad s_{22}) &= (0 \quad \sqrt{E_b}) \end{aligned} \tag{2-1}$$

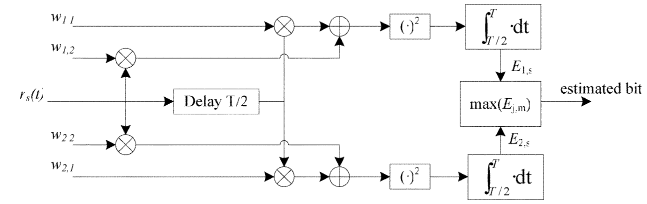


Fig. 2. FM-DCSK demodulator using GML detection.

where $s_m(t)$ is the modulated signal for transmission and E_b is the bit energy. The two basic orthogonal functions are

$$g_1(t) = \begin{cases} +c(t), & 0 \le t < \frac{T}{2} \\ +c\left(t-\frac{T}{2}\right), & \frac{T}{2} \le t < T \end{cases}$$
$$g_2(t) = \begin{cases} +c(t), & 0 \le t < \frac{T}{2} \\ -c\left(t-\frac{T}{2}\right), & \frac{T}{2} \le t < T \end{cases} \qquad (2\text{-}2)$$

where T is the bit duration and $c(t)$ is the FM chaotic carrier, whose bit energy has been normalized to one. The special forms of orthogonal functions (2-2) are called "chips" below.

Here, the differential modulating process follows the second-order Walsh functions

$$W_2 = \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}. \qquad (2\text{-}3)$$

The two row vectors w_1 and w_2 are multiplied with the carrier segment as the weights when the digital information is "1" or "0," respectively.

B. Demodulation of the FM-DCSK

Due to its differential modulating characteristic, it is not necessary for the FM-DCSK to recover the carrier at the receiver end, and it does not require precise synchronization. During the demodulation process, the GML detection rule [7] will be applied, as a universal method, for second-order Walsh functions used here and the higher-order Walsh functions which the transmitter employs. The FM-DCSK demodulator using GML detection is illustrated in Fig. 2.

As shown in the block diagram, the weighted energy received is

$$E_{j,s} = \frac{1}{2}\int_{T/2}^{T}\left[r_s(t)\cdot w_{j,2} + r_s\left(t-\frac{T}{2}\right)\cdot w_{j,1}\right]^2 dt, \quad j = 1, 2 \qquad (2\text{-}4)$$

where T is the bit duration, $r_s(t)$ is the received signal, and $w_{j,i}$ $(i, j = 1, 2)$ are the corresponding elements in the second-order Walsh functions, which are multiplied as the weights during the modulation. The demodulator needs to find the index j that maximizes $E_{j,s}$ (j = 1, 2), and then make a decision on the bit, either "1" or "0".

III. Configuration of Proposed SIMO FM-DCSK Scheme

A. Transmitter

The above-described Walsh function-based FM-DCSK modulation scheme is now extended to multiple substreams transmitted with a single antenna to achieve a higher data rate.

Consider a system with M substreams and N receiver antennas, denoted by (M, N). The M parallel substreams are modulated with the FM-DCSK method and then transmitted through a single antenna simultaneously, thus to achieve M-time higher data rate as compared to the original FM-DCSK with the same spreading factor.

Let β denote the chip length of each carrier segment, and f denote the global spread-spectrum factor. In order to serve M substreams, $2M$-order Walsh functions should be used for implementation. During the modulation, force $\beta = f/2M$ to make sure that the global spread-spectrum factor f is kept constant.

The mth transmitted substream of the M substreams can be expressed by the $2M$ orthogonal basis functions, as follows:

$$x_m(t) = \sum_{j=1}^{2M} x_{m,sj}\, g_j(t), \qquad 0 \le t \le T \qquad (3\text{-}1)$$

where T is the bit duration and $s = 0,1$ according to the information bit "0" and "1," respectively.

Take, for example, $M = 2$. In this case, the four order Walsh functions are

$$W_4 = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}. \qquad (3\text{-}2)$$

Each substream selects a couple of vectors to form the transmit signal. For example, the first substream takes w_1 and w_2 for bit "1" and "0," respectively, and the second substream takes the rest two vectors. Thus, the four basis functions are

$$g_1(t) = \begin{cases} +c(t), & 0 \le t < \frac{T}{4} \\ +c\left(t-\frac{T}{4}\right), & \frac{T}{4} \le t < \frac{T}{2} \\ +c\left(t-\frac{T}{2}\right), & \frac{T}{2} \le t < \frac{3T}{4} \\ +c\left(t-\frac{3T}{4}\right), & \frac{3T}{4} \le t < T \end{cases}$$
$$g_2(t) = \begin{cases} +c(t), & 0 \le t < \frac{T}{4} \\ -c\left(t-\frac{T}{4}\right), & \frac{T}{4} \le t < \frac{T}{2} \\ +c\left(t-\frac{T}{2}\right), & \frac{T}{2} \le t < \frac{3T}{4} \\ -c\left(t-\frac{3T}{4}\right), & \frac{3T}{4} \le t < T \end{cases}$$
$$g_3(t) = \begin{cases} +c(t), & 0 \le t < \frac{T}{4} \\ +c\left(t-\frac{T}{4}\right), & \frac{T}{4} \le t < \frac{T}{2} \\ -c\left(t-\frac{T}{2}\right), & \frac{T}{2} \le t < \frac{3T}{4} \\ -c\left(t-\frac{3T}{4}\right), & \frac{3T}{4} \le t < T \end{cases}$$
$$g_4(t) = \begin{cases} +c(t), & 0 \le t < \frac{T}{4} \\ -c\left(t-\frac{T}{4}\right), & \frac{T}{4} \le t < \frac{T}{2} \\ -c\left(t-\frac{T}{2}\right), & \frac{T}{2} \le t < \frac{3T}{4} \\ +c\left(t-\frac{3T}{4}\right), & \frac{3T}{4} \le t < T \end{cases} \qquad (3\text{-}3)$$

with vector coefficients

$$x_{1,0} = (x_{1,01} \;\; x_{1,02} \;\; x_{1,03} \;\; x_{1,04}) = \left(\sqrt{\frac{E_b}{2}} \;\; 0 \;\; 0 \;\; 0\right)$$
$$x_{1,1} = (x_{1,11} \;\; x_{1,12} \;\; x_{1,13} \;\; x_{1,14}) = \left(0 \;\; \sqrt{\frac{E_b}{2}} \;\; 0 \;\; 0\right)$$
$$x_{2,0} = (x_{2,01} \;\; x_{2,02} \;\; x_{2,03} \;\; x_{2,04}) = \left(0 \;\; 0 \;\; \sqrt{\frac{E_b}{2}} \;\; 0\right)$$
$$x_{2,1} = (x_{2,11} \;\; x_{2,12} \;\; x_{2,13} \;\; x_{2,14}) = \left(0 \;\; 0 \;\; 0 \;\; \sqrt{\frac{E_b}{2}}\right). \qquad (3\text{-}4)$$

Here, T is the bit duration and $E_b/2$ is the bit energy of each substream. Due to uniformity, the bit energy of each substream will be decreased to E_b/M, when M substreams are transmitted.

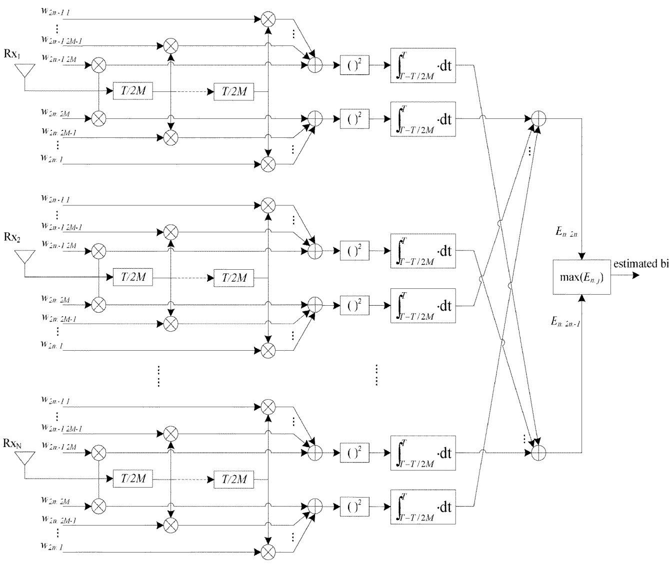


Fig. 3. Block diagram for detecting the mth substream.

B. Receiver

Over an L-tap multipath fading channel, the received signal in receiver antenna n at time t is

$$r_n(t) = \sum_{m=1}^{M} \sum_{l=1}^{L} h_n(l) x_m(t-l) + n_n(t) \qquad (3\text{-}5)$$

where $h_n(l)$ is the lth channel tap gain from the single transmit-antenna to receiver antenna n, and $n_n(t)$ is the additive white Gaussian noise at time t received in antenna n with zero mean and variance σ_n^2. The tap gains, $h_n(l)$, are modeled as i.i.d. Rayleigh-distributed random variables, with zero mean and variance 1 for each channel (after normalization).

The detection process is carried out through each receiver antenna independently, with the corresponding Walsh functions used in the respective substream. Then, the weighted energy calculated from each receiver antenna is combined for final decision making.

Consider, for example, the detection of the mth substream from the received signal. The weighted energy combined with N antennas can be expressed as

$$E_{m,j} = \frac{1}{2M} \sum_{n=1}^{N} \int_{T-T/2M}^{T} \left[\sum_{i=0}^{2M-1} r_n\left(t - i\frac{T}{2M}\right) \cdot w_{j,2M-i} \right]^2 dt, \quad j = 2m-1, 2m. \qquad (3\text{-}6)$$

Here, T is the bit duration, $r_n(t - iT/2M)$ is the received signal in receiver antenna n which has delay $iT/2M$, and $w_{j,2M-i}$ is the corresponding elements in the Walsh functions employed by substream m. If the mth substream selects vector w_{2m-1} for bit "1" and vector w_{2m} for bit "0," then the decision will be "1" if $E_{m,2m-1} > E_{m,2m}$ or "0" if $E_{m,2m-1} \leq E_{m,2m}$. The combined total energy in multiple receiver antennas provides several independent copies, thus achieving a diversity gain. The block diagram of detecting the mth substream is illustrated in Fig. 3.

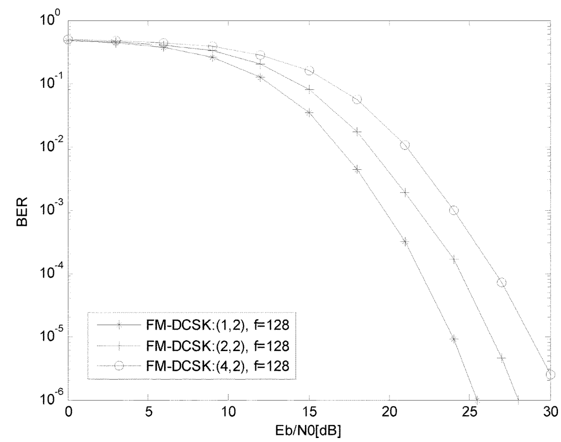


Fig. 4. Performance of SIMO FM-DCSK scheme with M substreams and two receiver antennas over a multipath fading channel, with $M = 1, 2, 4$.

It should be emphasized that the receiver processing here does not require any channel estimation and Rake receiver techniques, thereby significantly simplifying the design and reducing the cost of the receiver.

IV. Simulation and Analysis

A. Error Performance of SIMO FM-DCSK Scheme

The error performance of the proposed SIMO FM-DCSK scheme has been simulated over 3-tap multipath channels. The channels are assumed to be independently Rayleigh-faded and quasi-static, with power distribution of {0.4, 0.4, 0.2} and delays of $\{0, T/f, 2T/f\}$. The global spread-spectrum factor f is kept constant, $f = 128$, through out all simulations.

Fig. 4 shows the performance of the new scheme, when there are M variable substreams and two fixed receiver antennas. In spite of the orthogonal characteristic of Walsh functions, increasing M becomes somewhat worse in performance. In Fig. 5, $(2, N)$ systems are simulated with the results plotted. One can see that the increase of N improves performance significantly, which signifies a diversity gain of the proposed new system.

B. Performance Comparison Between SIMO FM-DCSK and DS-VBLAST Schemes

The VBLAST scheme was proposed as a wireless communicating architecture [8] and introduced into CDMA systems [9]. The proposed CDMA-VBLAST system is simplified here to a single-user scenario, called as DS-VBLAST (direct spreading VBLAST) for convenience below, so that the comparison between the new SIMO FM-DCSK and the DS-VBLAST schemes can be easily carried out and clearly shown. The DS-VBLAST system with M transmit-antennas and N receiver antennas is also denoted by (M, N), same as the SIMO FM-DCSK scheme. The PN code used for spreading is chosen to be an m-sequence, which possesses an outstanding auto-correlation characteristic. Notice that the length of an m-sequence will always be odd, whereas the global spread-spectrum factor of the SIMO FM-DCSK scheme will always be even. Therefore, similarly to the standard of IMT-2000 [12], an extra "0" is added at the end of each m-sequence to make the spreading factor be matched, thereby ensuring the same bandwidth efficiency of the two systems.

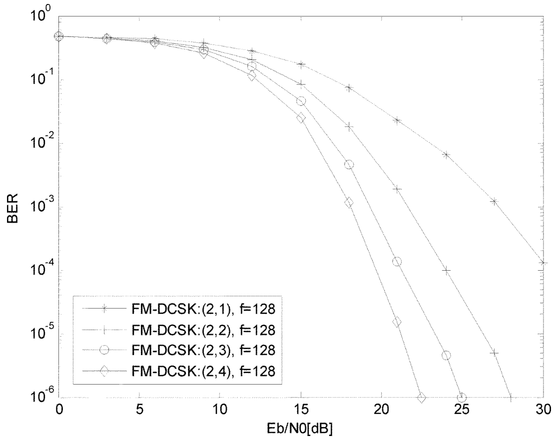


Fig. 5. Performance of the SIMO FM-DCSK scheme with two substreams and N receiver antennas over a multipath fading channel, with $N = 1, 2, 3, 4$.

Over a multiple-input multiple-output (MIMO) multipath channel, the system model can be written in a matrix form, as follows [10]:

$$R = [r_1, \quad r_2, \quad r_3, \quad \cdots \quad r_N]^T = HX + N_0$$
$$X = [x_1, \quad x_2, \quad x_3, \quad \cdots \quad x_M]^T$$
$$x_m = \begin{bmatrix} x_{m,1} & x_{m,2} & x_{m,3} & \cdots & x_{m,k} \\ 0 & x_{m,1} & x_{m,2} & \cdots & x_{m,k-1} \\ 0 & 0 & x_{m,1} & \cdots & x_{m,k-2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & x_{m,k-L+1} & x_{m,k-L} \end{bmatrix}$$
$$H = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,M} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,M} \\ \vdots & \vdots & \vdots & \vdots \\ h_{N,1} & h_{N,2} & \cdots & h_{N,M} \end{bmatrix}$$
$$h_{n,m} = [h_{n,m}(1) \quad h_{n,m}(2) \quad \cdots \quad h_{n,m}(L)] \qquad (4\text{-}1)$$

where r_n is the substream in receiver antenna n, and the superscript T denotes matrix transposition; the channel matrix is H, where $h_{n,m}$ is the channel vector between the mth transmit-antenna and the nth receiver antenna; matrix X denotes the spreading transmitted signal with BPSK modulation, and N_0 is the noise matrix.

Each receiver antenna uses a Rake receiver to separate the signals from L different paths, and then send the signals to the MMSE detector. Based on the calculation results from the channel estimator, the MMSE detector will perform the detection by employing a channel matrix of lth path of the form

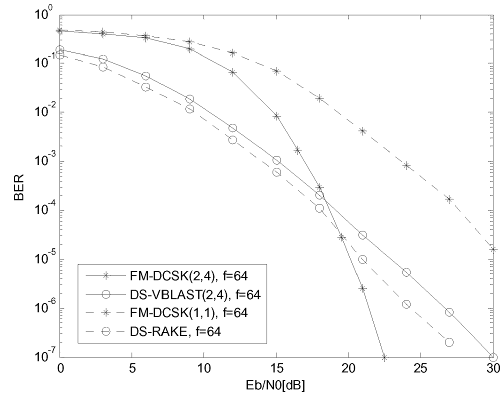
$$H_l = \begin{bmatrix} h_{1,1}(l) & h_{1,2}(l) & \cdots & h_{1,M}(l) \\ h_{2,1}(l) & h_{2,2}(l) & \cdots & h_{2,M}(l) \\ \vdots & \vdots & \vdots & \vdots \\ h_{N,1}(l) & h_{N,2}(l) & \cdots & h_{N,M}(l) \end{bmatrix} \qquad (4\text{-}2)$$

then generates a matrix w_l from H_l, where

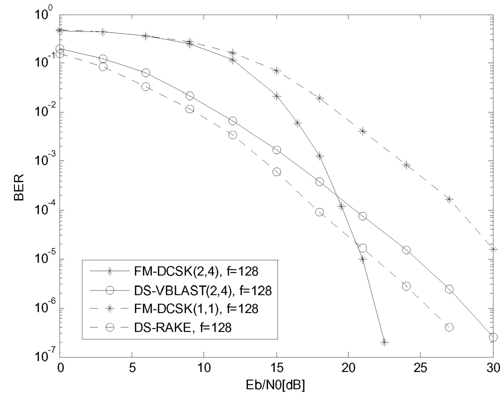
$$w_l = [H_l^H H_l + \sigma^2 I_M]^{-1} H_l^H \qquad (4\text{-}3)$$

in which the superscript H denotes complex conjugate transpose, σ^2 is the noise variance and I_M is the $M \times M$ identity matrix. The decision statistic of the lth path is formed as

$$\hat{y}_l = w_l R_l \qquad (4\text{-}4)$$



(a)



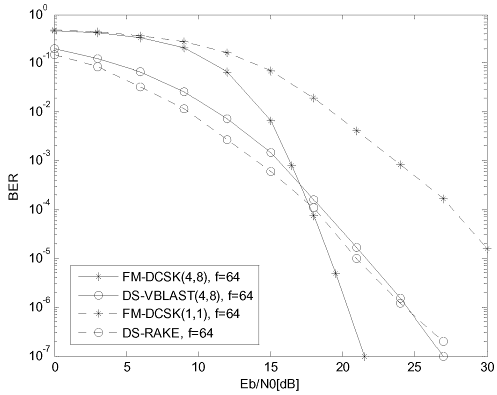
(b)

Fig. 6. Performance comparison between SIMO FM-DCSK and DS-VBLAST schemes over a multipath fading channel, with $M = 2$, $N = 4$: (a) $f = 64$ and (b) $f = 128$.

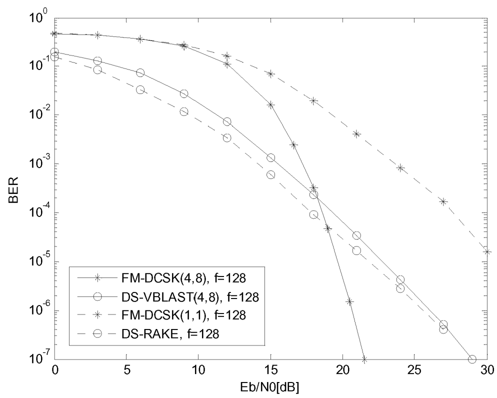
where R_l is the output matrix of the lth branch of Rake receiver. Decision can be made by threshold zero, giving

$$\hat{X} = q\left(\sum_{l=1}^{L} \hat{y}_l\right). \qquad (4\text{-}5)$$

Finally, the performances of the (2, 4) system and the (4, 8) system are simulated and compared, between the SIMO FM-DCSK and the DS-VBLAST schemes at the same data rate and the same channel parameters as given in Section IV-A, with results as shown by solid curves in Figs. 6 and 7. By all means, for both (2, 4) and (4, 8) systems, with spreading factors of 64 and 128 respectively, the SIMO FM-DCSK scheme outperforms the DS-VBLAST scheme at bit error rate (BER) of 10^{-6}. One can see that there is no potential error floor at BER of 10^{-6} in all curves, while the BER curves of SIMO FM-DCSK become steeper and steeper than that of DS-VBLAST. This results in the occurrence of crossover points at the E_b/N_0 interval of 17–20 dB and the BER interval of 10^{-3}-10^{-4}. Consequently, it ensures the advantageous BER performance of the proposed system at the BER of 10^{-6} to meet the data communication demands. The difference of the slopes mentioned above indicates that the performance of SIMO FM-DCSK with steeper slope is more sensitive to noise than DS-VBLAST at a higher signal-to-noise ratio (SNR); while the latter seems more sensitive to the difference between receiver and transmission antennas than the former, namely, the slope of the latter becomes steeper when the difference is changed from 2 to 4. The dotted curves in Figs. 6 and 7 denote



(a)



(b)

Fig. 7. Performance comparison between SIMO FM-DCSK and DS-VBLAST schemes over a multipath fading channel, with $M = 4, N = 8$: (a) $f = 64$ and (b) $f = 128$.

the performances of the conventional FM-DCSK scheme with a single transmitted substream and a single receiver antenna in comparison with the conventional DS scheme with the Rake receiver and the MRC combination. It can be seen that the proposed SIMO FM-DCSK scheme outperforms its conventional counterpart in both performance and data rate through its increasing numbers of substreams and receiver antennas. However, the DS-VBLAST scheme in the (2, 4) system performs somewhat worse than the conventional SISO DS scheme, and the former in the (4, 8) system performs almost the same as the latter at a higher power level.

Although a spreading spectrum expands the bandwidth of the transmitting signals, the proposed SIMO FM-DCSK system can be extended to a multiuser scenario. By keeping a fixed global spread-spectrum factor with higher-order Walsh functions employed at the transmitter end, the proposed SIMO FM-DCSK system can easily multiple the data rate, so as to increase the bandwidth efficiency. Take $M = 2$ and $f = 64$ for example, only one user can be served when employing the fourth-order Walsh functions with segment length of $f/4 = 16$, while two users can be served when employing the eighth-order Walsh functions with segment length of $f/8 = 8$. In other words, the higher the order, the more the number of users can be served by the proposed system.

V. Conclusion

A new SIMO architecture has been proposed and evaluated, which greatly enhances the performance of the FM-DCSK communication scheme with respect to both data rate and bit error rate. Through simulations over multipath fading channels, it has been found that there is some interfering among transmitted substreams with the increase of the number of substreams, but the SIMO FM-DCSK system can still significantly improve its performance if the number of receiver antennas is increased thanks to its improved diversity gain. A performance comparison between the SIMO FM-DCSK and the DS-VBLAST schemes subject to the same bandwidth efficiency has been carried out, which shows that the former outperforms the latter over multipath fading channels at the BER of 10^{-6} to meet the demand of data communications, although the latter has some advantages at BER of 10^{-3} to meet the demand of voice communications. Furthermore, the former does not require any knowledge about the channel state information, exact synchronization, and any Rake receiver. This implies that the proposed system has a simpler algorithmic design with lower transceiver cost than the latter. Therefore, it is expected that in the near future the proposed scheme can further reduce the demand of E_b/N_0 to a realistic level, at BER of 10^{-6}, and be applied to data communication services in some wireless communication systems equipped with some other advantageous subroutines and components such as channel coding. Last but not least, channel coding will a future research topic, which may provide a significant contribution to the BER performance of FM-DCSK [11].

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