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Subcarrier Allocation in Multi-carrier DCSK System for Performance Enhancement

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Abstract– Recently, multicarrier differential chaos shift keying (MC-DCSK) modulation has been proposed to avoid the usage of delay lines as well as to obtain higher data rate in comparison to DCSK. Thanks to better energy efficiency, MC-DCSK outperforms DCSK in bit error rate (BER) performance, but it still performs much worse than conventional coherent BPSK. This paper shows how to get great improvement in BER performance of MC-DCSK by assigning multiple subcarriers to the reference signal. A novel subcarrier allocated MC-DCSK system is proposed, where every reference signal is transmitted for multiple times on different subcarriers and all received copies are averaged for noise cleaning. With the optimal subcarrier allocation strategy, the proposed system can achieve the lowest BER that is almost identical to that of the conventional coherent BPSK system.

1. Introduction

In recent years, considerable attention has been paid to designing chaos-based digital modulations [1]-[4]. In these systems, spectrum spreading and digital modulation are performed simultaneously by mapping data symbols to dissimilar wideband chaotic signals. Since chaotic signals serving as the carriers are non-periodic, difficult to predict and quite easy to generate, chaos-based digital modulation schemes not only enjoy all the merits of traditional spread spectrum (SS) systems (i.e., low probability of detection, anti-jamming, mitigation of multi-path fading and so on) but also show good communication security with low cost [5].

Up to now, many schemes have been proposed [6]-[9], in which differential chaos shift keying (DCSK) and its frequency modulated version have attracted more research interests for good performance and low cost. However, DCSK suffers from low bit rate and delay line problem in UWB communications, as the reference and data-bearing signals are transmitted in sequential time periods [10]. For high bit rate as well as delay line removal, multi-carrier DCSK (MC-DCSK) has been recently proposed in [11], where one reference signal together with multiple data-bearing signals are sent simultaneously on all subcarriers. Even though MC-DCSK could outperform DCSK in noise performance due to higher energy efficiency, the noise performance of MC-DCSK is still much worse than that of the conventional coherent BPSK.

To remarkably improve the noise performance of MC-DCSK, subcarrier allocation strategy is considered here and a novel MC-DCSK system using multiple subcarriers to send repeated reference signals is proposed in this paper. Our goal is to exploit this repetition of received reference signals for noise reduction, which can be achieved by averaging all corrupted copies of any reference signal. The bit error rate (BER) performance of the proposed system is evaluated over additive white Gaussian noise (AWGN) channel by simulation, and the optimal BER performance is obtained with the optimal subcarrier allocation strategy. In addition, to clean the noisy data-bearing signals, noise reduction algorithm given in [12] is also applied to the proposed system. Relevant performance comparisons are given, which confirms the significant advantages of the proposed subcarrier allocation strategy.

2. Subcarrier allocated MC-DCSK system

In the original MC-DCSK system in [11], a serial high rate bit stream is converted into multiple parallel low rate bit sub-streams. Data bits in all sub-streams use the same chaotic message bearer, which will be sent along with all bit-streams in a parallel way on different subcarriers.

Like the original MC-DCSK, subcarrier allocated MC-DCSK (SA-MC-DCSK) also convert a serial bit stream into multiple sub-streams, all of which use a chaotic signal $x(t)$ as the message bearer, denoted as

$$x(t)=\sum_{k=1}^{\beta} x_k h(t-kT_c) \tag{1}$$

where β is the spreading factor, x_k is the k-th sample of chaotic sequence, and $h_T(t)$ is the impulse response of a square-root-raised cosine filter with a roll-off factor α, normalized energy and duration T_c. To satisfy the Nyquist criterion, frequency spectrum of $h_T(t)$ is limited to $[-B_c/2, B_c/2]$ with $B_c=(1+\alpha)/T_c$.

Unlike the original MC-DCSK, several copies, rather than a single copy, of the message bearer in (1) (i.e., the reference signal) accompanied by all bit-streams are sent. This could be achieved by allocating more subcarriers to the reference signal.

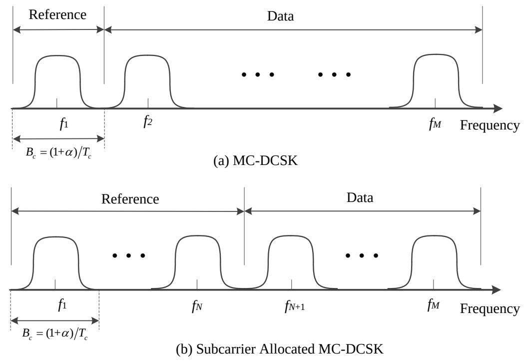

Fig.1 PSD of MC-DCSK and subcarrier allocated MC-DCSK systems

The power spectral densities (PSD) of the original MC-DCSK system and the proposed system are shown in Fig.1, where all subcarriers are disjoint and an ideal case without guard bands is considered. As shown in Fig.1 (a), the original MC-DCSK utilizes M subcarriers $f_1,..,f_M$, in which f_1 is assigned to the reference signal (i.e., the message bearer in (1)), while the others are allocated to M-1 bit-streams that share the same reference signal. In the proposed system displayed in Fig.1 (b), we consider assigning N (M>N>1) subcarriers $f_1,\ldots,f_N$ to the reference signal, so that N copies of each reference signal are sent together with M-N bit streams simultaneously. Thus, the transmitted signal of subcarrier allocated MC-DCSK is expressed as

$$s(t)= \sum_{j=1}^{N} x(t)\cos(2\pi f_j t+\theta_j)+\sum_{j=1}^{M-N} b_j x(t)\cos(2\pi f_{j+N} t+\theta_{j+N}) \quad (2)$$

In which, b_j is the data bit carried by the j-th subcarrier, and θ_j is phase angle introduced in the carrier modulation process.

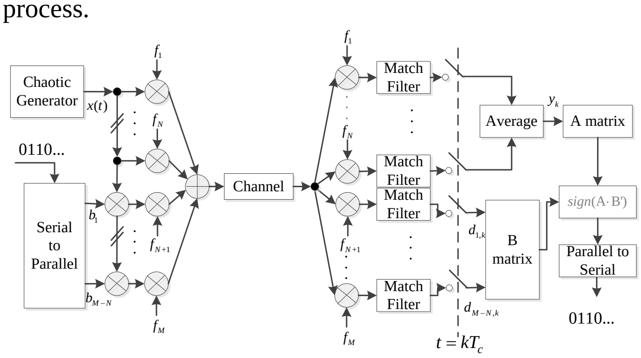

Fig.2 System configuration of subcarrier allocated MC-DCSK

Fig.2 gives a possible configuration of SA-MC-DCSK system. The system's architecture presented here is in its most simple form so as to keep low complexity. Many modifications could be performed to this system for further performance improvement. As shown in Fig.2, the overall configuration of the proposed system is almost identical to that of the original MC-DCSK, expect for two small differences in the transmitter and the receiver, respectively. Firstly, transmitter in Fig.2 sends N replica of each reference signal on the subcarriers $f_1,\ldots,f_N$, while only one copy is transmitted in the original MC-DCSK. Secondly, at the receiver side, all received copies of any reference signal are averaged, and the averaged signal will be used in correlation computing.

If perfect sinusoidal carrier and bit synchronizations have been achieved, the outputs of the j-th sampler in Fig.2 can be represented as

$$r_j(t=kT_c)=\begin{cases} x_k+n_{j,k}, & 1\le j\le N \\ b_{j-N}x_k+n_{j,k}, & N<j\le M \end{cases} \quad (3)$$

Here, we assume that the received signal is only corrupted by an AWGN noise with PSD of $N_0/2$. $n_{j,k}$ is the k-th sample of the noise that corrupts the signal transmitted on the j-th subcarrier.

The reference signal can be estimated by averaging the outputs of the upper N samplers, which can be denoted as

$$y_k=x_k+\frac{1}{N}\sum_{j=1}^{N} n_{j,k} \quad (4)$$

Since noises that pollute the signals sent on different subcarriers are independent and identical distributed, the variance of the noise content in (4) is N times smaller than that of $n_{j,k}$, contributing positively to the improvement in BER performance.

In Fig.2, data-bearing signal that carries the bit of the i-th data stream is recovered as the output of the i+N-th sampler

$$d_{i,k}=b_i x_k+n_{i+N,k},\quad i=1,\ldots M-N \quad (5)$$

By correlating the estimated reference signal in (4) with recovered data-bearing signal in (5), the decision variable for the bit of the i-th data stream is

$$Z_i=\sum_{k=1}^{\beta} y_k\cdot d_{i,k},\quad i=1,\ldots M-N \quad (6)$$

According to [11], energy efficiency of SA-MC-DCSK can be evaluated by the Data-energy-to-Bit-energy Ratio (DBR) represented as

$$\text{DBR}=\frac{M-N}{M} \quad (7)$$

The DBR of the original MC-DCSK system is equal to that of SA-MC-DCSK with N=1 as the proposed system turns into the original MC-DCSK system when N=1.

For comparison, the DBRs of subcarrier allocated MC-DCSK with various N are plotted in Fig.3 against the number of subcarriers M. Clearly, SA-MC-DCSK with N=1 (i.e., the original MC-DCSK) has the highest energy efficiency as merely one subcarrier is dedicated to sending the reference. With more subcarriers being allocated to the reference signal, energy efficiency declines accordingly. This DBR decrease will contribute negatively to the BER performance. However, for larger N, more received copies of any reference signal are averaged, which contributes positively to the BER performance as a result of weaker noises in decision variables. Therefore, we believe that the proposed system shows optimal BER performance when a balance between these two contributions is achieved. In the following section, we will discuss how to get the optimal BER performance.

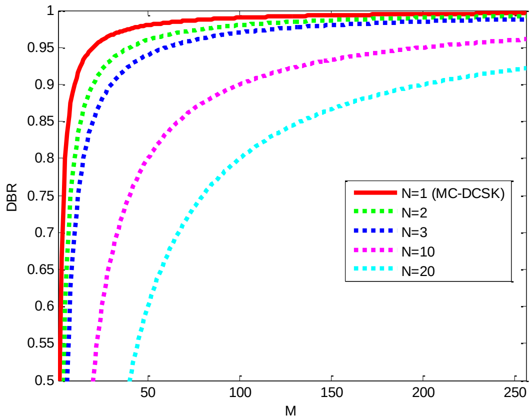

Fig.3 DBRs of subcarrier allocated MC-DCSK

4. Performance evaluation

In this section, the proposed system as well as the original MC-DCSK is simulated over AWGN channel. In these two systems, chaotic sequences are generated by the logistic map $x_{i+1} = 1-2x_i^2$ in [5]. The roll-off factor α is set to 0.25. The total bandwidth of all subcarriers is 4*M*Hz. For fixed bit duration T and subcarrier number M, the spreading factor can be computed by $\beta = TB/M(1+\alpha)$.

To study the optimal performance behavior of SA-MC-DCSK, simulated BERs of the proposed scheme are given in Fig.4 for various subcarrier numbers *M*. All curves are plotted against number *N* of subcarriers allocated to the reference signal under a certain signal-to-noise ratio (SNR) level.

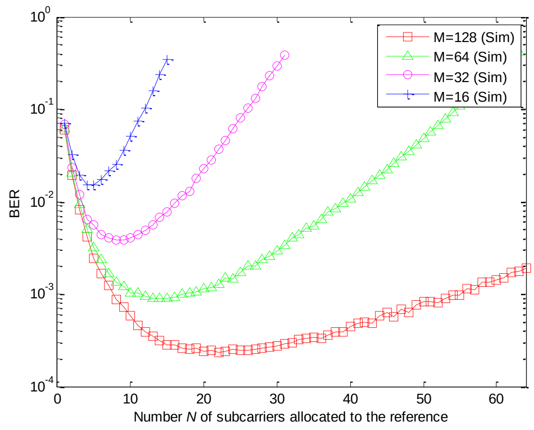

Fig.4 Relationship between *N* and the BERs of subcarrier allocated MC-DCSK with β=128 and $E_b/N_0 = 10dB$

When *N* increases, it is observed in Fig.4 that the BERs under a fixed SNR level first drop and then tend to rise. This interesting phenomenon is caused by the interaction between reduced noise in the estimated reference in (4) and decreased DBR in (7). On one hand, the estimated reference in (4) becomes cleaner if *N* grows, making BER performance improved. On the other hand, with more subcarriers being occupied by the reference signals, DBR in (7) becomes smaller, leading to degraded performance. As a result, the lowest BER can be obtained by SA-MC-DCSK if an optimal *N* is used. For example, it is observed in Fig.4 that with β=128 and $E_b/N_0 = 10dB$, the optimal values of *N* are 22, 14, 9 and 4 for *M*=128, 64, 32 and 16 respectively.

Besides, it is also noticed in Fig.4 that the distance between the lowest BER and the BER with *N*=1(i.e., BER of the original MC-DCSK) become larger if *M* increases. This means that the performance improvement brought by applying subcarrier allocation grows with the total number of subcarriers.

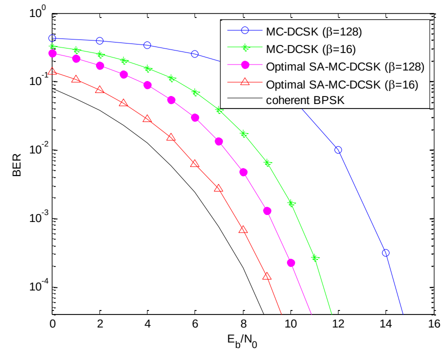

Fig.5 BER comparison between MC-DCSK and SA-MC-DCSK with the optimal *N*

To further investigate the performance improvement achieved by subcarrier allocation, simulated BER curves of SA-MC-DCSK with the optimal *N* (labeled as 'Optimal SA-MC-DCSK') are plotted in Fig.5. Here, BER curves of the original MC-DCSK and conventional coherent BPSK are also given for comparison. It is obvious that the proposed system with optimal *N* performs much better than the original MC-DCSK. This superiority in performance grows with spreading factor β . For instance, the obtained BER gain is 3-4dB when β is 16, while 4-5dB gain is achieved when β equals to 128. By assigning the optimal number of subcarriers to the reference signal in MC-DCSK, the distance between the performances of MC-DCSK and the conventional coherent BPSK has been shortened to less than 1dB.

The noise performance of the proposed system can be further improved if the noisy data-bearing signals are also cleaned. Considering the fact that each data-bearing signal, either in its identical or inverted version, is transmitted for multiple times in the proposed system, all received data-bearing signals could also be averaged for noise reduction if the modulations are removed. Fortunately, this problem is perfectly solved by a simple noise reduction algorithm proposed in [12]. For this reason, the algorithm in [12] is employed here to reduce the noise contents in all received data-bearing signals. This could be achieved by replacing the data-bearing signal $d_{i,k}$ in decision variable in (6) with $d_{i,k}^*$, denoted as

$$d_{i,k}^{*}=\frac{\sum_{\substack{j=1\\j\neq i}}^{M-N} sign\left[\sum_{k=1}^{\beta} d_{i,k}d_{j,k}\right]d_{j,k}}{\sum_{\substack{j=1\\j\neq i}}^{M-N}\left|\sum_{k=1}^{\beta} d_{i,k}d_{j,k}\right|} \tag{8}$$

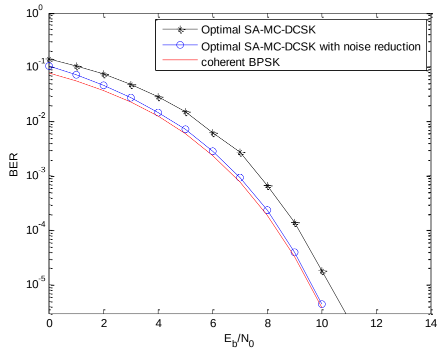

Fig.6 The optimal BER performance of SA-MC-DCSK with noise reduction algorithm in [12]

Fig.6 evaluates the effect of this simple algorithm on BER performance of SA-MC-DCSK. In this figure, the spreading factor is 16. It is interesting to find that, with the help of this noise reduction algorithm, the optimal BER performance obtained by subcarrier allocated MC-DCSK (labeled as 'Optimal SA-MC-DCSK with noise reduction') happens to be almost same to that of the conventional coherent BPSK.

4. Conclusion

In this paper, a novel MC-DCSK system is proposed based on subcarrier allocation. In this new system, more subcarriers are dedicated to sending repeated copies of the reference signal, which is shared by all data-bearing signals transmitted on the remaining subcarriers. Before performing correlation at the receiver side, all received copies of each reference signal are averaged for noise reduction.

With the optimal number of subcarriers allocated to the reference signal, the proposed system achieves the best BER performance which is 1dB worse than that of the conventional BPSK system.

Combined with the algorithm that reduces the noises in all received data-bearing signals, the proposed system can get the optimal BER performance almost same to that of the convention coherent BPSK system.

Acknowledgments

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