Efficient Pseudonoise Code Design for Spread Spectrum Wireless Communication Systems

Mau-Lin Wu, Kuei-Ann Wen, and Chao-Wang Huang

***Abstract*—Power and bandwidth efficient communication schemes are of major concerns in wireless communication systems. One kind of efficient pseudonoise code is proposed in this paper that provides combined power-bandwidth efficiency. A novel algorithm for verifying the power and bandwidth efficient properties of a pseudonoise code is proposed with systematic analysis on code parameters. Applications of the derived codes had been implemented on 802.11 DS/SS system, which performs 36% bandwidth reduction and 14% power consumption reduction. Several new pseudonoise codes with different code lengths are also proposed.**

***Index Terms*—Bandwidth reduction, CMOS implementations, low power design, pseudonoise code, spread-spectrum communication, wireless LAN.**

I. INTRODUCTION

IN RECENT years, low-power design has become a very important issue in the modern very large scale integration (VLSI) design. A lot of design methodologies of minimizing power consumption in CMOS VLSI circuits were proposed in [1]–[4], where approaches of technology, circuit style and topology, architecture, and algorithm are included.

As is known, the power dissipation in CMOS VLSI systems contributed mostly from the dynamic power dissipation of the system. Therefore, there was much research that focused on reducing the dynamic power dissipation of CMOS circuits. The dynamic power dissipation of CMOS circuits relates to the transition activity t, capacitance load C_L, power-supply voltage V_{DD}, and switching frequency f_p, as seen in [5].

$$P_d = tC_L V_{DD}^2 f_p. \tag{1}$$

The dynamic power dissipation of CMOS circuits could be reduced by reducing switching frequency [6]–[9], power-supply voltage [10], [11] and capacitance load [12]–[14]. According to the methodology newly proposed in this paper, the authors designed the low-power system by reducing the transition activity.

We proposed one kind of efficient pseudonoise (PN) code that possesses both power and bandwidth efficiency. At first, the properties and definition of the power-saving pseudonoise (PSPN) code are shown. The correlation between the PSPN code and the performance of the spread spectrum communication system is then explored. By exploring the correlation, we proposed an efficient algorithm for search of PSPN code. Several examples of PSPN codes are derived. The properties of these codes are analyzed. Application of the proposed code had been done on spread spectrum communication system.

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II. PSPN

A. Conventional Definition of PN Code

The spreading code is the code sequence which is used to be multiplied with the data sequence and thus to spread the bandwidth of the data sequence. In general conditions, the PN codes are usually the good candidates for spreading codes. However, it is not easy to define PN code. In the past, a lot of PN codes were proposed and the randomness properties of these codes were demonstrated. For example, maximal length sequence (m-sequence) is the well-known and widely applied PN code. The randomness characteristics of m-sequence were demonstrated in [15]. The definition of PN code in [16] is that the binary sequence $\{a_n\}$ has the following "randomness criteria:"

1) The out-of-phase periodic autocorrelation function (ACF) should be a small constant, that is

$$R_a(\tau) = \sum_{n=0}^{N-1} \hat{a}_n \hat{a}_{n+\tau} = \begin{cases} N, & \tau \equiv 0 \\ c, & \tau \neq 0 \end{cases} \tag{2}$$

where $\hat{a}_n = (-1)^{a_n} \in \{+1, -1\}$, which is in bipolar binary code format and $a_n \in \{1, 0\}$, which is in binary code format.

2) In every period, the number of 1s is nearly equal to the number of 0s.
3) In every period, half the runs have length one; one-quarter have length two; one-eighth have length three, etc., as long as the number of runs of a given length exceeds 1.

However, there are a lot of PN codes, which are useful for spread spectrum communication but don't meet the above three randomness criteria. In the following, we will extend the definition of PN code to find the codes, which are applicable to wireless, spread spectrum communication system. We define the PN code according to the system performance of the spread spectrum communication system, to which the code is applied.

B. System Performance versus PN Code

For the system performance of the spread spectrum communication, the processing gain of the spreading code is one of major concern. The processing gain depends on the code length of the spreading code. On the other hand, one of the most important system performances of the spread spectrum communication system is the average acquisition time of the code acquisition structure in the receiver. The average acquisition time depends on the probability of detection P_D and the probability of false alarm P_F [17]. After further manipulations, we can correlate P_D and P_F to processing gain and periodic ACF of the spreading code [18]. The larger the processing gain is, the better the system performance is. The smaller the c value of (2) is, the better the system performance is. Therefore, the spreading code with good system performance can be derived by checking its out-of-phase value of the ACF of the spreading code. We derived an index of the spreading code to indicate the system performance.

Definition 1: The "**corrpower**" of a spreading code is the sum of squares of the periodic autocorrelation coefficients of the spreading code. We denote the corrpower of a spreading code $\{a_n\}$ by

$$CP\{a_n\} = \sum_{\tau=0}^{N-1} \{R_a(\tau)\}^2 \tag{3}$$

where $R_a(\tau)$ is the periodic autocorrelation function of the spreading code $\{a_n\}$.

Definition 2: The orthogonal degree of a spreading code $\{a_n\}$ is defined as

$$OD\{a_n\} = \frac{\{R_a(0)\}^2}{CP\{a_n\}}. \tag{4}$$

From the definition above, if the out-of-phase values of $R_a(\tau)$ were small, the system performance is better, $OD\{a_n\}$ would be close to 1. Therefore, the spreading code with larger orthogonal degree is the code with better system performance. One of the advantages of this definition of the spreading code is to skip the "randomness criteria," which are very difficult to meet. Another advantage of this definition is to directly consider the system performance of the spread spectrum system with the spreading code.

C. Power and Bandwidth versus PN Code

Definition 3: The toggle rate of the spreading code $\{a_n\}$ is defined as

$$TR\{a_n\} = \frac{\sum_{n=0}^{N-1} \text{sign}\{|a_n - a_{n+1}|\}}{N} \tag{5}$$

where $|x|$ means the absolute value of x, and

$$\text{sign}\{x\} = \begin{cases} 1, & x > 0 \\ 0, & x \leq 0. \end{cases}$$

For example, consider the code $\{a_n\} = [01\,001\,000\,111]$. The time diagram of the code $\{a_n\}$ is plotted in Fig. 1. It is very easy to verify that there are six toggles in one period of the code. Therefore, the toggle rate is $6/11 \approx 0.545$.

In the spread spectrum system, the data pattern of the output spreading data is decided by the data pattern of the spreading code. As we know, the CMOS VLSI system only consumes

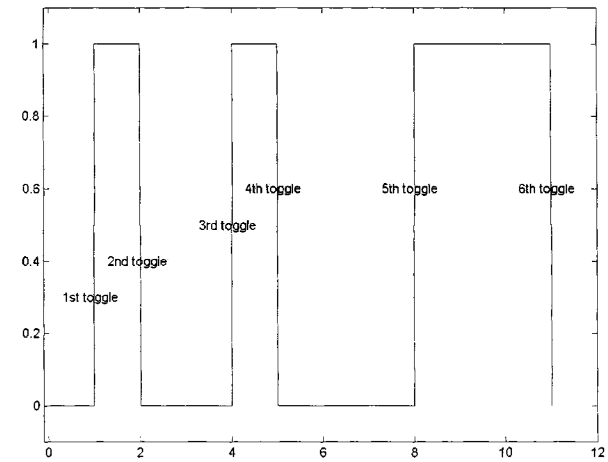

Fig. 1. Time diagram of code $\{a_n\}$, which is used to demonstrate the toggle rate of the code.

power during the period when the output signal is toggled. The relationship had been shown in (1). In the spreading output of the spread spectrum system, the transition activity depends on the transition activity of the spreading code. The larger toggle rate means much more transition activity of a spreading code. Therefore, the larger the toggle rate is, the more transition activity and the power consumption the spread spectrum VLSI system has. For low-power CMOS spread spectrum communication system design, a spreading code with low toggle rate is highly expected. Moreover, the time pattern of the output-spreading signal is decided by the spreading code. If the toggle rate is low, the changing of the output-spreading signal is slow. The slow changing in the time domain means the low frequency in the frequency domain. Therefore, it means narrow bandwidth occupation as well. The toggle rate of the spreading code could be used as a merit of figure for power consumption and bandwidth occupation of the spread spectrum system.

D. PSPN Code

From the previous discussions, we know that a PN code should have a great orthogonal degree, and a low-power spreading code requires low toggle rate. Therefore, a PSPN should be a spreading code with great orthogonal degree and low toggle rate. In the following, we proposed the definition of the PSPN code.

Definition 4: A PSPN code of length N with factor (α, β), $\text{PSPN}_N(\alpha, \beta)$, is the spreading code with the orthogonal degree α and the toggle rate β.

The main idea of this approach is to search a spreading code with good power, bandwidth, and system performance properties by calculating parameters of the code, instead of simulating the whole system. The computational complexity of the latter is much more than the previous one.

III. Derivation of PSPN Codes

In considerations of high performance, low-power, and bandwidth efficiency, a spreading code with large orthogonal degree and low toggle rate is the best choice. However, there is a tradeoff between the orthogonal degree and the toggle rate of

TABLE I
THE ORTHOGONAL DEGREES AND TOGGLE RATES OF SOME USEFUL PSPN CODES

Code length	Spreading code	Orthogonal degree	Toggle rate	Code name
11	00000100111	0.823	0.364	$PSPN_{11}$
15	000000101100111	0.882	0.400	$PSPN_{15}$
19	0000010011110100011	0.914	0.421	$PSPN_{19}$
20	00000001001110001101	0.862	0.400	$PSPN_{20}$
23	00000000101011011000111	0.883	0.435	$PSPN_{23}$
24	000000001100101011001111	0.857	0.417	$PSPN_{24}$
25	0000000010100011001001111	0.877	0.400	$PSPN_{25}$
26	00000000001100111010010111	0.805	0.385	$PSPN_{26}$

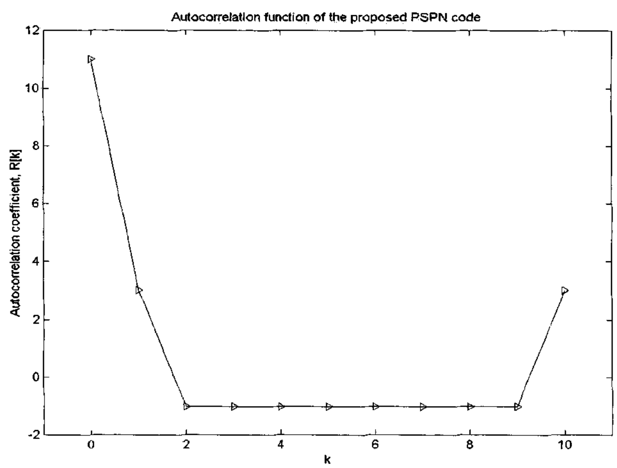

Fig. 2. Autocorrelation function of PSPN_{11} code.

the spreading code. In general, a spreading code with great orthogonal degree usually has high toggle rate, and a spreading code with low toggle rate usually has low orthogonal degree. In regard to orthogonal degree and toggle rate, lower and upper bound should be carefully specified. By system performance and power consumption simulation, we found that the PSPN codes with $\alpha \geq 0.8$ and $\beta \leq 0.45$ would be efficient for the spread spectrum communication application. Therefore, by an efficient searching algorithm, all the $\text{PSPN}_N(\alpha, \beta)$ codes with $\alpha \geq 0.8$ and $\beta \leq 0.45$ had been explored for $N = 1 \sim 26$. The efficient searching algorithm is described in details in the Appendix.

In Table I, part of $\text{PSPN}_N(\alpha, \beta)$ codes had been listed for illustration of the properties of the PSPN codes. The code length is used to subscript the code name for distinguishing, which is shown in the last column of Table I. The orthogonal degrees of these PSPN codes are larger than 0.80 and the toggle rates are all less than 0.45. PSPN_{11} is taken as an example to illustrate the computational complexity of orthogonal degree and the toggle rate of the PSPN code. If we express the PSPN_{11} code in the bipolar binary code format, then $\text{PSPN}_{11} = [1, 1, 1, 1, 1, -1, 1, 1, -1, -1, -1]$. By simple calculation, we find that the periodic autocorrelation function of PSPN_{11} code $R_a(\tau) = [11, 3, -1, -1, -1, -1, -1, -1, -1, 3, 11]$, which is plotted in Fig. 2. The out-of-phase values of the ACF are small except the two values of 3 at indexes of 1 and 10. The corrpower and orthogonal degree of PSPN_{11} code could be calculated from the autocorrelation function $R_a(\tau)$ by (3) and (4). Therefore,

$$CP\{\text{PSPN}_{11}\} = \sum_{\tau=0}^{N-1} \{R_a(\tau)\}^2 = 11^2 + 3^2 + (-1)^2 + \ldots + (-1)^2 + 3^2 = 147 \tag{6}$$

$$OD\{\text{PSPN}_{11}\} = \frac{\{R_a(0)\}^2}{CP\{\text{PSPN}_{11}\}} = \frac{11^2}{147} = \frac{121}{147} \cong 0.823. \tag{7}$$

It is easy to check that the toggle number of PSPN_{11} code is 4. The toggle rate of this code can be easily calculated by $4/11 = 0.364$. From the procedures of the calculations of the orthogonal degree and toggle rate of PSPN_{11} code, the reader may realize that it is a very simple and efficient method for searching the low-power and bandwidth efficient PSPN codes by calculating the orthogonal degree and toggle rate. The complemented and the shifted version of these PSPN codes are also PSPN codes and they have the same values of orthogonal degree and toggle rate. The shifted version of these PSPN codes could form a PSPN code set for multiuser application such as CDMA wireless communication system.

IV. Analysis and Simulation

Comparison between the proposed PSPN codes and conventional PN codes in bandwidth occupation, system performance, and power consumption can be observed with Tables I and II. Each PN code is subscripted with its code length. The PN_{11} code is exactly the Barker code, which is the specified PN code applied in the wireless local area network (WLAN) standard, IEEE 802.11 [19]. The PN_{15} code is the so-called maximal length sequence with degree 4 [15]. It is also called m-sequence. Other codes are codes with large orthogonal degree and the proposed efficient searching algorithm obtains them. The orthogonal degrees of the conventional PN codes are usually larger than those of PSPN codes, while they have larger toggle rates.

In the following, the bandwidth, system performance, and the power consumption of the proposed PSPN codes are analyzed.

TABLE II
THE CONVENTIONAL PN CODES AND THEIR ORTHOGONAL DEGREES AND TOGGLE RATES

Code length	Pseudo noise code	Orthogonal degree	Toggle rate	Code name
11	00010010111	0.924	0.545	PN_{11}
15	000010100110111	0.941	0.533	PN_{15}
19	0000010011010100111	0.914	0.526	PN_{19}
23	00000101001100110101111	0.960	0.522	PN_{23}
24	000000010101100110100111	0.947	0.500	PN_{24}

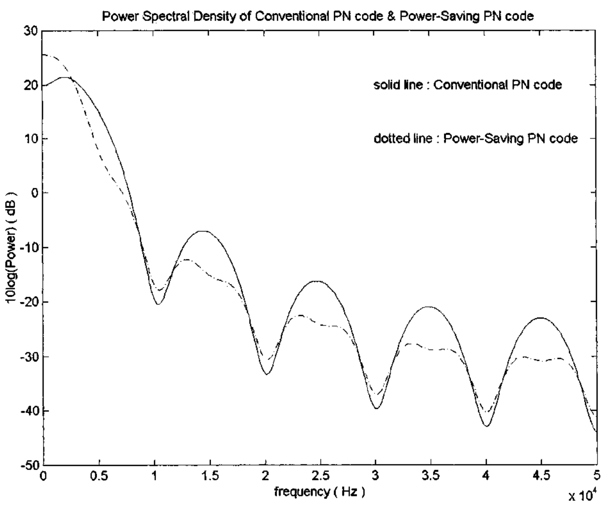

Fig. 3. Power spectral density of $PSPN_{11}$ code and PN_{11} code.

A. Bandwidth Analysis

For bandwidth analysis, we plotted the power spectral density of the proposed PSPN codes and the conventional PN codes. In Fig. 3, the power spectral density functions of $PSPN_{11}$ and PN_{11} are plotted for comparison. The power of the $PSPN_{11}$ code is observed to be more concentrated at low frequency. Define the 90% bandwidth and 95% bandwidth, BW_{90} and BW_{95}, as

$$\int_{-\mathrm{BW}_{90}}^{\mathrm{BW}_{90}} X(f)\,df = 90\% \times \int_{-\infty}^{\infty} X(f)\,df \tag{8}$$

$$\int_{-\mathrm{BW}_{95}}^{\mathrm{BW}_{95}} X(f)\,df = 95\% \times \int_{-\infty}^{\infty} X(f)\,df \tag{9}$$

where $X(f)$ is the power spectral density of the code and the unit of the BW_{90} and BW_{95} is Hertz.

By (8) and (9), we calculate these values of $PSPN_{11}$ code and PN_{11} code. BW_{90} of $PSPN_{11}$ code and PN_{11} code are $0.7147f_c$ and $1.121f_c$, respectively, where f_c is the chip rate of the spread spectrum system. f_c is equal to the data rate multiplied by the code length. It is shown that the bandwidth of $PSPN_{11}$ code is only about 74% of that of PN_{11} code. That is to say, the percentage of reduction of bandwidth of $PSPN_{11}$ code is about 36% compared to PN_{11} code. There is the similar result for BW_{95}. For other codes with different code lengths, the proposed PSPN codes perform 10% to 36% reduction of bandwidth. These results are included in Table III. We plot the bandwidth versus toggle rate plot in Fig. 4 and it prevails that the spreading code with a lower toggle rate has a narrower bandwidth. The positive correlation between bandwidth and toggle rate could be confirmed from this plot.

B. Performance Analysis

In the system performance analysis, we take $PSPN_{11}$ and PN_{11} codes as the examples to do the simulation. In the following, the probability of detection of the spread spectrum systems are simulated in different SNR values, which is in the range from -10 dB to 10 dB. The proposed algorithm in [18] is applied in this simulation to design the spread spectrum systems with constant probability of false alarm and maximal probability of detection. In the simulation, the constant probability of false alarm is set to 0.01. Because the bandwidth of $PSPN_{11}$ code is only 74% of that of PN_{11} code, the effective SNR value of $PSPN_{11}$ code should be compensated by 1.94 dB $(=-10\log 0.74)$. Based on these assumptions, the simulation results of the probabilities of detection are shown in Fig. 5. Because the probabilities of false alarm of these two systems are both equal to 0.01, the system with larger probability of detection performs better in this simulation. Therefore, it is shown that the system with $PSPN_{11}$ code performs better probability of detection than the system with PN_{11} code. The difference of the system performance is about 1 dB.

For the spread spectrum communication system, the bandwidth of the transmitted signal is usually several times of the bandwidth of the source data. If some interference signal appears within the bandwidth of the transmitted signal, it will be rejected by the despreading procedure in the receiver of the spread spectrum system. This is the interference-rejection characteristics of the spread spectrum system. Therefore, the bandwidth-efficient spread spectrum system we proposed in this paper will perform better in the viewpoint of interference. The probability that an interference signal occurs within the bandwidth of the transmitted signal is lower due to the narrower bandwidth of the transmitted signal. At the same time, the effective SNR of the derived system is higher than that of the conventional one. All the above effects conclude better system performance of the proposed spread spectrum system.

C. Power Consumption Simulation and Analysis

For the simulation of the power consumption, we implemented a spread spectrum system of CMOS VLSI circuits. This VLSI circuits are implemented by a 0.25–μm CMOS logic process. The function blocks of this spreading system are shown in Fig. 6. The VLSI circuit is designed by using the standard library of TSMC 0.25–μm CMOS logic process. Spreader is used to multiply the source data with the PN code.

TABLE III
BANDWIDTH COMPARISON RESULTS BETWEEN PSPN CODES AND PN CODES

Code length	BW_{90}			BW_{95}		
	PN code	PSPN code	% of reduction	PN code	PSPN code	% of reduction
11	1.121*fc*	0.7147*fc*	36%	1.822*fc*	1.419*fc*	22%
15	1.038*fc*	0.7493*fc*	28%	1.781*fc*	1.519*fc*	15%
19	0.9840*fc*	0.7667*fc*	22%	1.761*fc*	1.560*fc*	11%
23	0.9569*fc*	0.7618*fc*	20%	1.750*fc*	1.580*fc*	10%
24	0.8541*fc*	0.6746*fc*	21%	1.682*fc*	1.433*fc*	15%

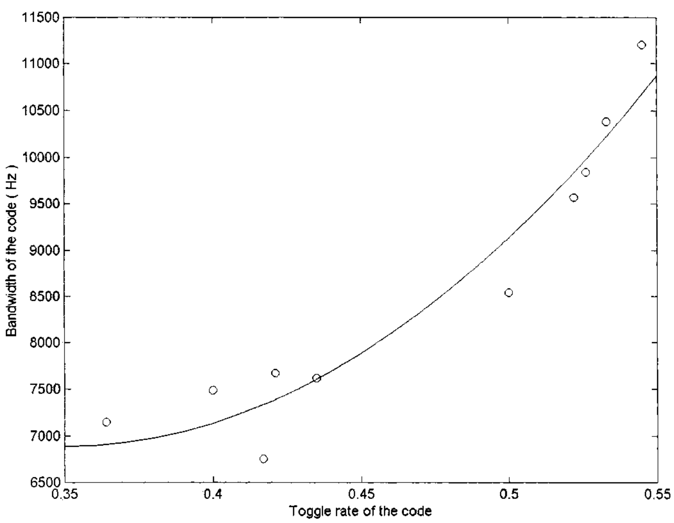

Fig. 4. Plot of bandwidth versus toggle rate of the spreading codes.

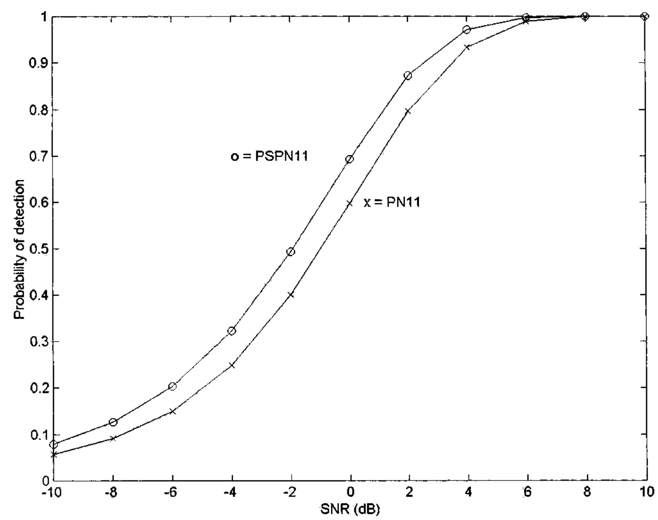

Fig. 5. System performance comparison between $PSPN_{11}$ code and PN_{11} code.

The block of "frequency divider" generates the clock with data rate. PN code generator generates the PN code. Despreader is used for despreading procedure and the decision circuit detects the signal. The transistor netlist of the blocks in Fig. 6 is implemented. The circuit level simulator Hspice simulates the power consumption of the transistor netlist. All the blocks shown in Fig. 6 are included in this power consumption simulation. The circuit schematics described in Fig. 6 could be operated by different spreading codes with different code lengths. That is to say, this is a soft-coded spread spectrum system. The simulation results of the power consumption are listed in Table IV. From Table IV, we find the percentages of reduction for power consumption range from 8% to 14% with PSPN codes compared to PN codes. The concept of low toggle rate means low-power consumption has been verified by the simulation results.

D. Power-Bandwidth-Product Performance Index

Because power consumption and bandwidth are both important system performances for a spread spectrum communication system, we define a power-bandwidth combined performance index to evaluate the power-bandwidth efficiency of the proposed PSPN codes. Because the effect of bandwidth to the system performance is more important than that of the power consumption, the weight of bandwidth is twice of that of power

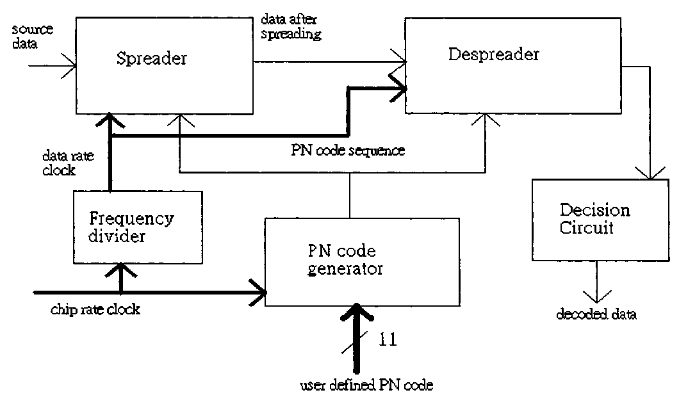

Fig. 6. Function blocks of the spreading system are plotted.

consumption. For the same reason, the weight of BW_{90} is two times of that of BW_{95}. The ***PBPI*** (***power-bandwidth performance index***) of the spread spectrum system is given by

$$\mathrm{PBPI} = \left[\frac{1}{Power \times (BW_{90}^2 \times BW_{95})^{2/3}}\right]^{1/3}. \qquad (10)$$

The PBPIs of the PN codes and PSPN codes in the case of 1–MHz chip rate are listed in Table V. The percentage of performance improvement for the proposed PSPN codes is listed in the last column of Table V. The percentages are between 16%

TABLE IV
COMPARISON OF POWER CONSUMPTION BETWEEN PSPN CODES AND PN CODES

Code length	Power consumption		% of reduction
	PN code	PSPN code	
11	1.409mW	1.208mW	14%
15	1.411mW	1.256mW	11%
19	1.420mW	1.292mW	9%
23	1.415mW	1.303mW	8%
24	1.390mW	1.281mW	8%

TABLE V
COMPARISON OF POWER-BANDWIDTH PERFORMANCE INDEX BETWEEN PSPN CODES AND PN CODES

Code length	Power-bandwidth performance index		% of performance improvement
	PN code	PSPN code	
11	0.742E-03	1.009E-03	36%
15	0.771E-03	0.960E-03	24%
19	0.790E-03	0.936E-03	18%
23	0.802E-03	0.933E-03	16%
24	0.856E-03	1.013E-03	18%

and 36% for different PSPN codes. This result is consistent with the results in Tables III and IV.

V. CONCLUSION

The low-power, bandwidth-efficient, and randomness properties of the spreading code could be verified by the toggle rate and the orthogonal degree of the spreading code. Because the calculation of the toggle rate and the orthogonal degree is very simple, we proposed an efficient algorithm to search a low-power and bandwidth-efficient PN code. The bandwidth efficient property of the proposed code is confirmed by calculating the power spectral density function of the code and the 90% and 95% power bandwidths of the code. The system performance of the proposed code is also simulated to verify that the proposed code is suitable for the spread spectrum applications. The power consumption property is confirmed by the circuit simulation. Several PSPN codes are proposed and analyzed in this paper, which are found by the proposed efficient algorithm. These proposed PSPN codes have better bandwidth and power consumption performance than the conventional system. These proposed PSPN codes are the good choice for the power-efficient and bandwidth-efficient spread spectrum communication systems.

APPENDIX
THE EFFICIENT SEARCHING ALGORITHM

The efficient searching algorithm of proposed PSPN code is described in this appendix. Let us assume that the code length is N and the minimal orthogonal degree and the maximal toggle rate of the PSPN code are α and β, respectively. The purpose of this proposed algorithm is to search all the PSPN code $\{a_n\}$ with $OD\{a_n\} \geq \alpha$ and $TR\{a_n\} \leq \beta$. The following are the procedures of the proposed algorithm:

Step 1: Set $I = -1$ and $FLAG[0 : 2^{N-1}] = 0$. $FLAG[I]$ is the flag for the status of the ith code $\{a_n\}$. $FLAG[I] = 0$ means the code is not checked yet. $FLAG[I] = 1$ means the code is checked and it is a PSPN code. $FLAG[I] = -1$ means the code is checked and it is not a PSPN code.

Step 2: $I = I + 1$. The code $\{a_n\} = [a_0 a_1 \cdots a_{N-1}]$ is denoted by

$$I = \sum_{n=0}^{N-1} a_n \times 2^n. \tag{A.1}$$

If $FLAG[I] \neq 0$, then go to Step 6.

Step 3: Calculate $TR\{a_n\}$. If $TR\{a_n\} > \beta$, then set $FOUND = -1$ and go to Step 5.

Step 4: Checking $OD\{a_n\} \geq \alpha$ by

$$\sum_{n=1}^{N-1} r_n^2 \leq (1-\alpha)N^2 \tag{A.2}$$

where r_n is the coefficients of $R_a(\tau) = [r_0 r_1 \cdots r_{N-1}]$. IF (A.2) holds, then set $FOUND = 1$, otherwise $FOUND = -1$.

Step 5: Set the shifted and complemented version codes of $\{a_n\}$ the same status as $\{a_n\}$.

- 5.1) Set $J = I$, $L = 2^{N-1}$, and $K = 0$.
- 5.2) $K = K + 1$.
- 5.3) If $J \geq L$, then $J = J - L + 1$.
- 5.4) Set $FLAG[J] = FOUND$ and $FLAG[L - 1 - J] = FOUND$.
- 5.5) $J = J \times 2$.
- 5.6) If $K < N$, then go to 5.2).

Step 6: If $I < 2^{N-1}$, then go to Step 2.

Step 7: The PSPN codes are those with $FLAG = 1$.

The above algorithm is a simplified exhaustive search method. Because the orthogonal degrees and toggle rates of the complemented and shifted version codes of $\{a_n\}$ are the same as those of $\{a_n\}$, only one of the codes is required to be calculated for verifying that they are PSPN codes or not. This is done by Step 5. Therefore, the total candidate codes for searching in this algorithm is $2^{N-1}/(2N)$, instead of 2^{N-1} for the exhaustive search. Because the computational complexity of toggle rate is much simpler than that of orthogonal degree, toggle rate is calculated first and the codes with $TR\{a_n\} > \beta$ are impossible to be a PSPN code and the computational of the orthogonal degrees of these codes are omitted. This is done by Step 2. This reduces the computational complexity of this algorithm. For the calculation of orthogonal degree, a modified approach is also proposed to reduce computational complexity. The condition of $OD\{a_n\} \geq \alpha$ can be reformed to

$$OD\{a_n\} = \frac{r_0^2}{r_0^2 + \sum_{n=1}^{N-1} r_n^2} = \frac{N^2}{N^2 + \sum_{n=1}^{N-1} r_n^2} \geq \alpha \qquad \text{(A.3)}$$

where the ACF of $\{a_n\}$ is $R_a(\tau) = [r_0 r_1 \cdots r_{N-1}]$.

After some manipulation, (A.3) is reformed to (A.2). In the right-hand side (RHS) of (A.2), $(1-\alpha)N^2$ is a constant and can be calculated in advance. In the left-hand side (LHS) of (A.2), we can find that (A.2) doesn't hold by only calculating several terms of r_n for some cases. For example, if there exists a number $k < N - 1$, such that

$$\sum_{n=1}^{k} r_n^2 > (1-\alpha)N^2 \qquad \text{(A.4)}$$

then we can be sure that (A.2) doesn't hold and $\{a_n\}$ is not a PSPN code. This is because $r_n^2 \geq 0$ and

$$\sum_{n=1}^{N-1} r_n^2 = \sum_{n=1}^{k} r_n^2 + \sum_{n=k+1}^{N-1} r_n^2 \geq \sum_{n=1}^{k} r_n^2 > (1-\alpha)N^2. \qquad \text{(A.5)}$$

The detailed calculation procedures of (A.2) are described in the following:

Step 1: Set $K = (1-\alpha)N^2$, $SUM = 0$, and $n = 0$.

Step 2: $n = n + 1$, calculate r_n.

Step 3: $SUM = SUM + r_n^2$. If $SUM > K$, then go to Step 5.

Step 4: If $n = N - 1$, then $OD\{a_n\} \geq \alpha$ holds and go to Step 6. Otherwise, go to Step 2.

Step 5: $OD\{a_n\} < \alpha$. $\{a_n\}$ is not a PSPN code. The procedure is finished.

Step 6: $\{a_n\}$ is a PSPN code.

Not all the coefficients of $R_a(\tau)$ are required to be calculated in the above approach, the computational complexity of $R_a(\tau)$ is $(N-1)N$ multiplication and $(N-1)^2$ addition. However, the computational complexity of the above approach is reduced to kN multiplication and $k(N-1)$ addition, where k depends on $\{a_n\}$. For general conditions, k is below $N/2$ for the non-PSPN codes. From the above descriptions, the computational complexity of this searching algorithm is nearly less than $1/(4N)$ times of that for an exhaustive search.

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