COMPLETELY DC-FREE DIRECT SEQUENCE SPECTRUM SPREADING SCHEME FOR LOW POWER, LOW COST, DIRECT CONVERSION TRANSCEIVER

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ABSTRACT

We introduce a novel scheme for spread spectrum systems, which we call the offset code spreading scheme. By employing the scheme, we can implement a direct-conversion receiver for a differential-binary phase shift keying system with a DC-cut high pass filter. This will allow us to eliminate the DC-offset by carrier leakage and mitigate the 1/f noise of the mixer. System simulations show that a 10-bit offset code spreading system requires 3dB less signal-to-noise ratio than a pseudo-random noise sequence based system for the same bit error rate performance.

1. INTRODUCTION

To implement a low cost wireless transceiver, we should optimize system level design concurrently with circuit-level design. The direct conversion receiver architecture combined with D-BPSK (differential-binary phase shift keying) is promising for low cost implementations because of its simplicity. However, there are some design problems. In a direct conversion receiver, DC offset due to carrier leakage and 1/f mixer noise degrade performance[1]. A straightforward solution is to introduce a high pass filter (HPF) following a mixer. There are some drawbacks in using this HPF; (1) signal energy close to DC is lost, and (2) a large sized capacitor and resistor are required to implement an on-chip HPF with low cut-off frequency. This paper presents spreading sequences optimized for D-BPSK, which, after differential encoding, generate DC-free encoded data, irrespective of the original data sequence. The spectrum of the encoded data meets the FCC CFR47.15.247 bandwidth requirement[2].

2. DC-FREE SPECTRUM

Although PN (pseudo-random noise) sequences are employed in many DSSS (direct sequence spread spectrum) systems, the generated spectrum does not suit direct-conversion receivers with a DC-cut HPF since it has its peak at DC. In order to minimize the energy lost due to the filter, it is desirable to have a spectrum that has no energy at DC. To meet this criterion independent of the data, the sequence must be even-bit. If we use BPSK, not D-BPSK, the solution is simple since we just employ a sequence that has equal number of ones and zeros. That is not the case in D-BPSK, since such a sequence will have an unequal number of ones and zeros after differential encoding.

On the other hand, spectra generated by some non DC-free even-bit spreading sequences are completely DC-free after differential encoding. While these encoded sequences are completely DC-free, they have periodicity even with random data, and so their spectra have sharp peaks corresponding to the data rate. Consequently, they may not meet the FCC requirement. This occurs if the spreading symbol that represents ‘0’ is complementary to the symbol that represents ‘1’. For example, let {0010} represent the spreading symbol for ‘1’ and {1101} represent ‘0’. Differentially encoded sequences of {0010} and {1101} are {1100} and {0110}, respectively, when the preceding bit is assumed to be one. While the encoded sequences are DC-free, the 4th bit of each is zero. When the preceding bit is zero, differentially encoded sequences of {0010} and {1101} are {0011} and {1001}, respectively. Therefore the encoded data has the structure $\{\cdots \text{xxx1xxx0xxx1xxx0} \cdots\}$. The generated spectrum has sharp peaks as shown in Fig. 1(a), and it does not meet the FCC requirement.

A mathematical demonstration shows this is the case for any even-bit sequence. Let $S_{2n,1}$ represent the spreading symbol for ‘1’ and $S_{2n,0}$ represent ‘0’.

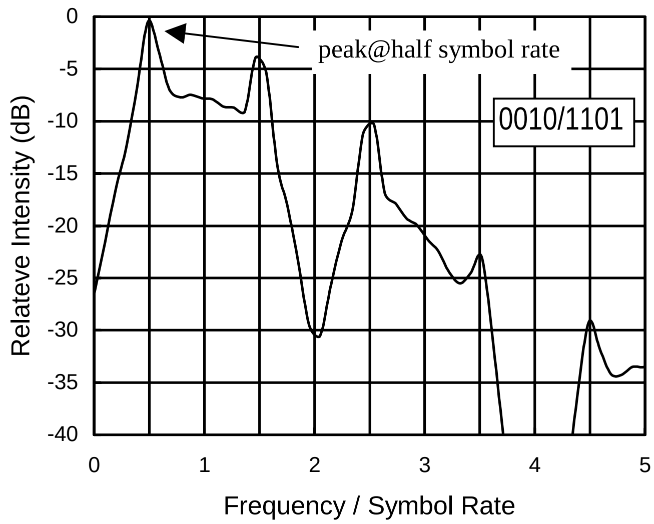
$$S_{2n,1} = \{a_1, a_2, \cdots, a_{2n-1}, a_{2n}\} \quad (1)$$

$$S_{2n,0} = \{\overline{a_1}, \overline{a_2}, \cdots, \overline{a_{2n-1}}, \overline{a_{2n}}\}. \quad (2)$$

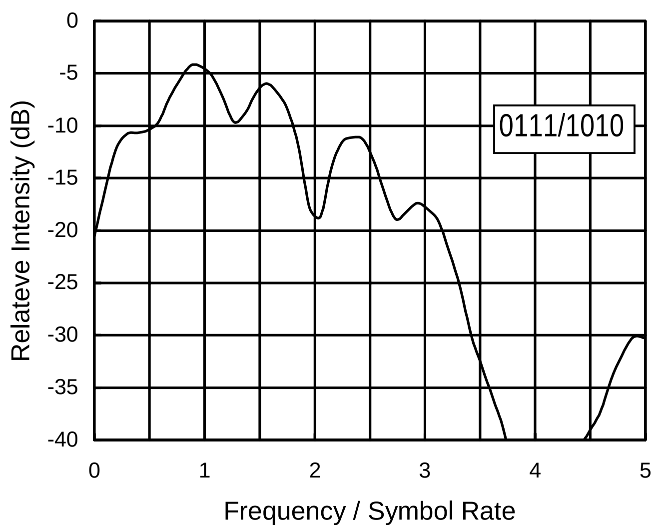
$E_{2n,1}$ and $E_{2n,0}$, differentially encoded sequence of $S_{2n,1}$ and $S_{2n,0}$, are expressed as follows,

$$E_{2n,1} = \{p \oplus a_1, p \oplus a_1 \oplus a_2, \cdots, p \oplus a_1 \cdots \oplus a_{2n}\} \quad (3)$$

$$E_{2n,0} = \{p \oplus \overline{a_1}, p \oplus \overline{a_1} \oplus \overline{a_2}, \cdots, p \oplus \overline{a_1} \cdots \oplus \overline{a_{2n}}\} \quad (4)$$



(a)



(b)

Fig.1. 4-bit spreading spectra
(a) conventional differential. (b) offset differential.

where p is the preceding bit of the encoded data. The final bit of $E_{2n,1}$ and $E_{2n,0}$, represented by $b_{2n,1}$ and $b_{2n,0}$, respectively, are,

$$b_{2n,1} = p \oplus a_1 \oplus a_2 \cdots \oplus a_{2n-1} \oplus a_{2n} \quad (5)$$

$$b_{2n,0} = p \oplus \overline{a_1} \oplus \overline{a_2} \cdots \oplus \overline{a_{2n-1}} \oplus \overline{a_{2n}} \quad . \quad (6)$$

Exclusive OR of $b_{2n,1}$ and $b_{2n,0}$ can be developed,

$$\begin{aligned} b_{2n,1} \oplus b_{2n,0} &= (p \oplus a_1 \cdots \oplus a_{2n})(p \oplus \overline{a_1} \cdots \oplus \overline{a_{2n}}) \\ &= (p \oplus p) \oplus (a_1 \oplus \overline{a_1}) \cdots \oplus (a_{2n} \oplus \overline{a_{2n}}) \\ &= 0 \oplus \underbrace{1 \oplus 1 \cdots \oplus 1}_{2n} \\ &= 0 \end{aligned} \quad . \quad (7)$$

Therefore, $b_{2n,1}$ and $b_{2n,0}$ is necessarily the same value. This brings periodicity in the encoded sequence which does not easily allow the generated spectrum to meet the FCC bandwidth requirement.

3. OFFSET CODE SPREADING

Our solution is to introduce an offset in the spreading sequence. For example, when {0111} is the symbol for '1', {1000} is its complement. Differentially encoded sequences of {0111} and {1000} are {1010} and {0000}, respectively, when the preceding bit is one. The 4th bit of both sequences is '0', which produces the same periodicity as described above. In addition, {0000} is clearly not DC-free. Now we introduce an offset in the third bit. The symbol for '0' becomes {1010}. Differentially encoded sequences then become {1010} and {0011}, again assuming that the preceding bit is one. Both of the sequences have two zeros and two ones. When the preceding bit is zero, the encoded sequences are {0101} and {1100}. Therefore the encoded sequence is completely DC-free, irrespective of data sequence. Note that the 4th bits of the two sequences are different, so no periodicity exists. The resulting spectrum has no sharp peaks as shown in Fig. 1(b).

An offset introduced in a pair of even-bit sequences always makes the final bit of an encoded sequence that represents '1' different from one that represents '0'. This is shown next.

Let $T_{2n,1}$ represent the spreading symbol for '1'.

$$T_{2n,1} = \{c_1, c_2, \cdots, c_m, \cdots, c_{2n}\}. \quad (8)$$

At this point, an offset is introduced in the symbol for '0' on the m-th bit. Then, the spreading symbol for '0' $T_{2n,0}$ becomes,

$$T_{2n,0} = \{\overline{c_1}, \overline{c_2}, \cdots, c_m, \cdots, \overline{c_{2n}}\}. \quad (9)$$

As in the equations (3)-(6), $d_{2n,1}$ and $d_{2n,0}$, the final bits of differentially encoded sequences of $T_{2n,1}$ and $T_{2n,0}$, respectively, are,

$$d_{2n,1} = q \oplus c_1 \oplus c_2 \cdots \oplus c_m \cdots \oplus c_{2n-1} \oplus c_{2n} \quad (10)$$

$$d_{2n,0} = q \oplus \overline{c_1} \oplus \overline{c_2} \cdots \oplus c_m \cdots \oplus \overline{c_{2n-1}} \oplus \overline{c_{2n}} \quad (11)$$

where q is the preceding bit. Exclusive OR of $d_{2n,1}$ and $d_{2n,0}$ is calculated as follows.

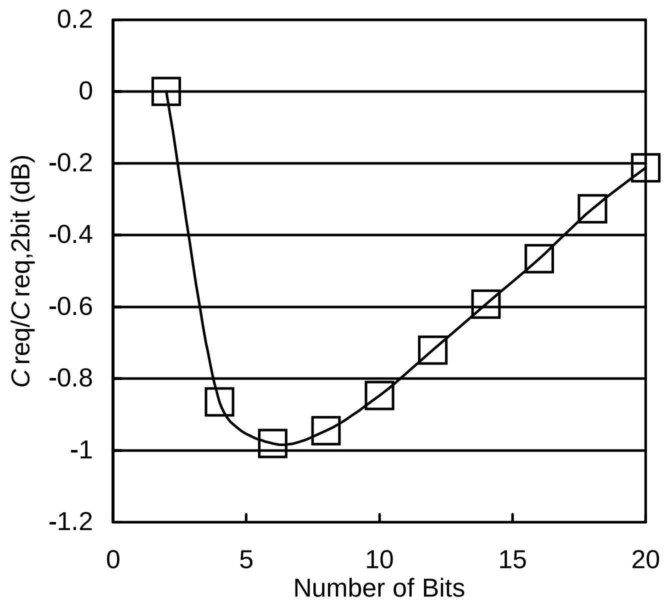


Fig. 2. Normalized required carrier power to achieve BER=1% vs. number of bits.

$$
\begin{aligned}
& d_{2n,1} \oplus d_{2n,0} \\
&= \left(q \oplus c_1 \cdots \oplus c_m \cdots \oplus c_{2n}\right)\left(q \oplus \overline{c_1} \cdots \oplus c_m \cdots \oplus \overline{c_{2n}}\right) \\
&= (q \oplus q) \oplus \left(c_1 \oplus \overline{c_1}\right) \cdots \oplus (c_m \oplus c_m) \cdots \oplus \left(c_{2n} \oplus \overline{c_{2n}}\right) \\
&= 0 \oplus \underbrace{1 \oplus 1 \cdots \oplus 0 \cdots \oplus 1}_{2n} \\
&= 0 \oplus 0 \oplus \underbrace{1 \oplus 1 \cdots \oplus 1}_{2n-1} \\
&= 1
\end{aligned} \quad . \quad (12)
$$

This shows $d_{2n,1}$ is necessarily different from $d_{2n,0}$. Note that the sequence before differential encoding has the periodicity in m-th bit irrespective of data. This removes the periodicity after differential encoding.

Since the offset bit has no information, one may think that the offset code scheme throws away one chip per symbol. However, in the even-bit spreading case, which is essential for completely DC-free spectra, that is not the case. There are n-1 correctable errors in a 2n-chip symbol. After one chip is used for the offset, we have remaining (2n-1) useful chips. In this case, the number of correctable errors is again n-1.

4. TRANSCEIVER SYSTEM SIMULATIONS

4.1. Sequence Design

Our target is to operate a 1Mbps D-BPSK system in the 2.4GHz ISM-band. To allow for multiple access, the maximum occupied bandwidth per channel is chosen to be 10MHz. Therefore, the maximum number of bits per sequence, or the processing gain, is limited to 10. Another reason to restrict it to 10 is that the sensitivity performance depends weakly on the number of bits in a sequence.

Table 1. Numbers of DC-free&FCC compliant spectra.

# of bit	Total	DC-free	DC-free & FCC compliant
2	2 x 4	2	2
4	4 x 16	8	2
6	6 x 64	36	20
8	8 x 256	144	46
10	10 x 1024	600	238

When the required BER is BER_{req}, the required chip error rate CER_{req} can be calculated as follows,

$$
\begin{aligned}
BER_{\mathrm{req}} &= 1 - \sum_{i=0}^{n-1} \left(1 - CER_{\mathrm{req}}\right)^{2n-1-i} \cdot CER_{\mathrm{req}}{}^{i} \cdot \binom{2n-1}{i} \\
&= f\,(CER_{\mathrm{req}})
\end{aligned} \qquad (13)
$$

therefore,

$$CER_{\mathrm{req}} = f^{-1}(BER_{\mathrm{req}})\,. \quad (14)$$

We have a analytical equation of CER as a function of carrier to noise ratio (CNR) in D-BPSK[3],

$$CER_{\mathrm{req}} = \frac{1}{2}\exp\left(-CNR_{\mathrm{req}}\right). \quad (15)$$

CNR is the ratio of the signal power to the noise power which is the noise level N_0 multiplied by the bandwidth of the channel selection filter B. N_0 depends on the source noise, the gain of the receiver and its noise factor. It does not depend on the number of bits in the spreading sequence. As a result, the required carrier power C_{req} is calculated as follows,

$$
\begin{aligned}
C_{\mathrm{req}} &= CNR_{\mathrm{req}} \cdot N_0 \cdot B \\
&= -\ln(2 \cdot CER_{\mathrm{req}}) \cdot N_0 \cdot (n+1) \cdot B_0 \qquad (16) \\
&= -\ln(2 \cdot f^{-1}(BER_{\mathrm{req}})) \cdot N_0 \cdot (n+1) \cdot B_0
\end{aligned}
$$

where B_0 is the same as the symbol rate which is 1MHz in our system. The cutoff frequency of the channel selection filter is (n+1) B_0 Hz in our system to allow for all kinds of variations. Note that the effect of the DC-cut HPF is neglected in this calculation.

In Fig. 2, the required carrier power C_{req} to achieve a BER of 1% is plotted against the length of the spreading sequence, 2n. The curve has been normalized so that 0dB refers to the power level required to achieve a BER of 1% when a 2-bit sequence is employed. The curve has a broad minimum. It reveals that the performance depends weakly on the number of bits in a sequence. As a consequence, 2/4/6/8/10-bit sequences are exhaustively explored in this paper.

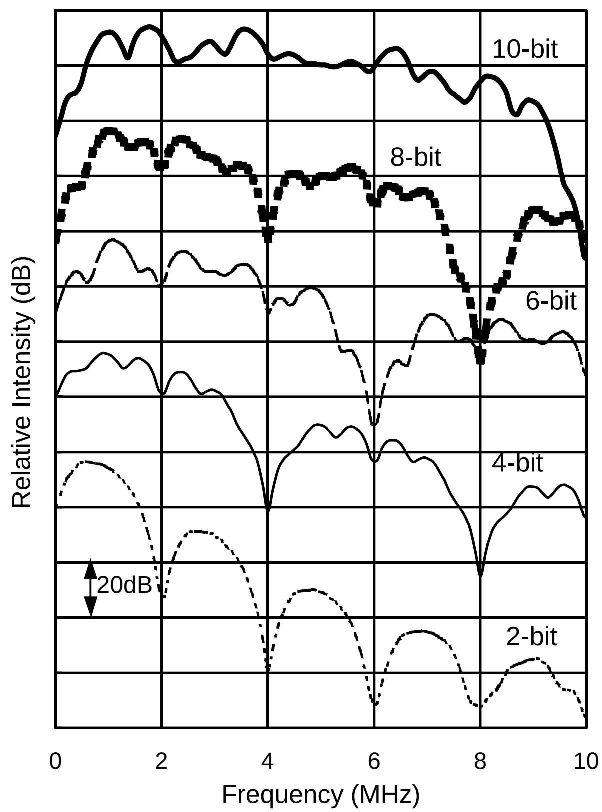


Fig. 3. Offset code spreading spectra.

Each 2*n*-bit sequence has 2*n* offset code pair candidates since each bit can be an offset. Therefore, there are $2n \cdot 2^{2n}$ combinations. The spectra generated by all the possible pair combinations are analyzed, and the number of completely DC-free and FCC compliant sequences among them are summarized up to the 10-bit case in Table 1. The symbol rate is 1M symbol/sec as described above and fixed hereafter.

While there are many sequence pairs that generate completely DC-free spectra which meet the FCC CFR47.15.247 bandwidth requirement, which is the best pair in terms of the system performance? Considering that the energy close to DC is lost through the DC-cut HPF, the spectrum generated by the best code should have the least energy close to DC. Taking the filter area penalty into account the cutoff frequency is fixed to be 500kHz, and a pair of sequences that have the least energy up to 500kHz are selected from each even-bit case. Fig. 3 shows the baseband spectra of these sequences with random data after differential encoding and Table 2 summarizes the best pairs for each even-bit case. It compares the energy below 500kHz of the spectra which use the offset code spreading scheme versus those which use the PN spreading scheme. It is remarkable that in 10-bit case the energy to be lost through the DC-cut HPF using the offset code spreading scheme is only 0.12% of

Table 2. The best sequences.

# of bit	Sequences	Energy below 500kHz	Ref. PN
2	01 / 11	29.1%	62.3%
4	0111 / 1010	9.5%	34.9%
6	010010 / 111101	2.7%	24.7%
8	00100010 11010101	0.33%	17.4%
10	0101110111 1010001001	0.12%	13.7%

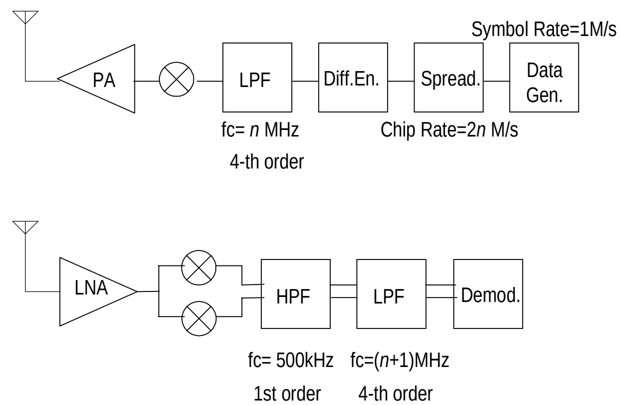


Fig. 4. Block diagram of transmitter and receiver.

total energy, while it is 13.7% using the PN spreading scheme. With these sequences, system simulations are carried out.

4.2. Transceiver System Design

Fig. 4 depicts the block diagram of the transmitter and the receiver. The transmitter consists of a data generator, a spreader, a differential encoder, a pulse shaper, an upconversion mixer and a power amplifier. The data generator has a symbol rate of 1 Mbps. The spreader spreads the data from the data generator with a chip rate of 2*n* Mchips/sec, where n=1,2,3,4,5. The pulse shaper is a 4-th order Bessel LPF (low pass filter) whose cutoff frequency is *n* MHz. The receiver consists of a LNA (low noise amplifier), I/Q (in-phase/quad-phase) mixers, DC-cut HPFs, and channel selection filters, and a demodulator. The DC-cut filters are first order HPFs whose cutoff frequency is 500kHz as described above. The channel selection filters are 4-th order Butterworth LPF whose cutoff frequency is *n*+1 MHz. For example, a 4-bit spreading system has a 3 MHz cutoff in the channel selection filters. The demodulator consists of an analog differential detector and a digital matched filter. The matched filter can correct chip errors up to *n*-1 errors.

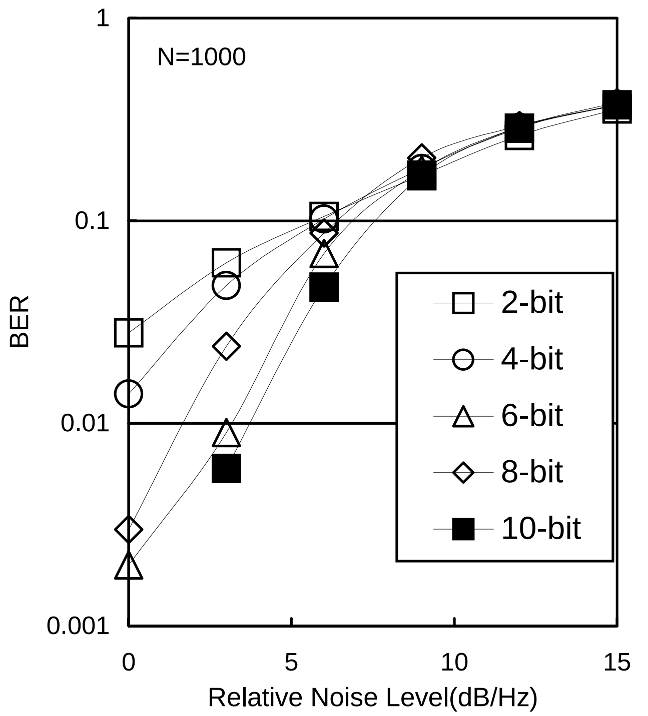


Fig. 5. BER performance of various 2*n* -bit sequence pairs.

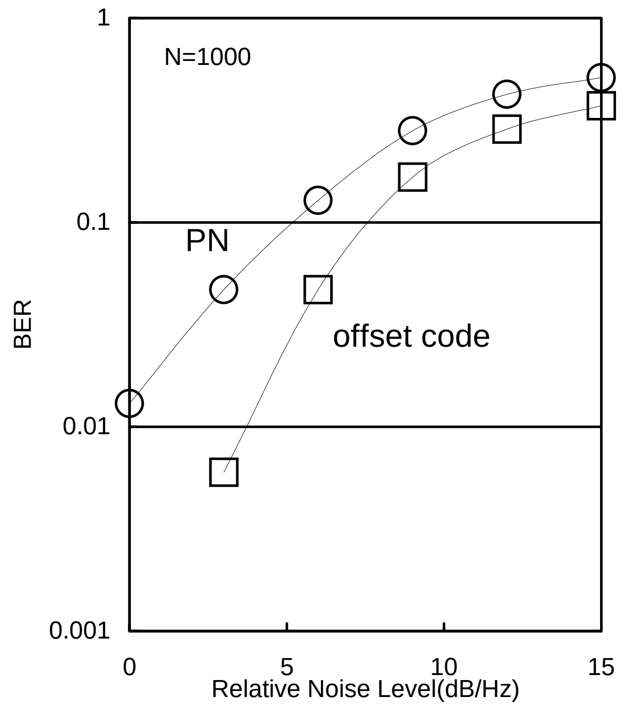


Fig. 6. BER comparison of offset code vs. PN.

4.2. Simulation Results

Simulations are performed with various noise levels and bit-error-rate (BER) is calculated. Fig. 5 shows the results of the simulations. The 10-bit sequence has the best performance with the same level of noise. This means that it can operate at a lowest signal power to achieve a certain BER. This result is different from what Eqn. (16) predicts, since Eqn. (16) does not account for the energy lost in the HPF.

Next, the 10-bit offset code spreading system is compared to a PN spreading system using a 500kHz HPF for the receiver. The PN sequence employed has a period of 15. At a chip rate of 10 M/sec, BER is simulated with various noise levels. As depicted in Fig. 6, it is shown that the 10-bit offset code spreading system requires 3dB less CNR than a PN-sequence system to achieve a BER of 1%. The difference is mainly due to the fact that the spectra energy below 500kHz for the PN sequence case is 100 times greater than the offset code case.

5. CONCLUSIONS

The offset code spreading scheme is introduced to make the spread spectrum in D-BPSK system completely DC-free and meet the FCC bandwidth requirement. The system can utilize a DC-cut HPF following the downconversion mixer without significant signal energy loss. System simulations show a 10-bit sequence can achieve the best sensitivity performance among 2/4/6/8/10-bit sequences. Compared to the conventional PN sequence spreading system, the offset code spreading scheme has 3dB better sensitivity performance to achieve a BER of 1%.

6. REFERENCES

[1] Thomas H. Lee, *The Design of CMOS Radio-Frequency Integrated Circuits*, Cambridge University Press, 1998.

[2] http://www.fcc.gov/

[3] M. Schwartz, W. R. Bennett, and S. Stein, *Communication systems and techniques*, pp. 304-310, pp. 585-587, McGraw-Hill, Inc., 1966.