Short PN Sequences for

Direct Sequence Spread Spectrum Radios

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Abstract

Traditional military spread spectrum systems use Direct Sequence Spread Spectrum (DSSS) for its jam resistance and low probability of intercept. Additionally, the transmission security afforded by long PN sequences in the waveform is important as is the ability to do code division multiple access (CDMA). DSSS systems as proposed for the unlicensed ISM band use a form of DS that has few of these attributes. The sequences used are so short that special attention must be placed on what are the best sequences to use. The Barker sequences are often chosen, but do they have the right characteristics? A Barker word has good autocorrelation sidelobes when preceded and succeeded by all zeros. Does it have good correlation sidelobes when preceded and succeeded by more Barker words with QPSK modulation? That is, the adjoining sequences can have any of four phases relative to it and this may cause some sequences that initially look good to not be. This paper examines 11, 13, 15, and 16 bit sequences for these properties and makes sequence recommendations.

1. Introduction

The Prism™ baseband processor (HFA3824) is a direct sequence spread spectrum modem that is set up to handle spreading ratios of 11, 13, 15, and 16 chips per bit. These give processing gains of 10.4 to 12 dB theoretically. This paper discusses the properties of suitable chipping sequences.

The IEEE 802.11 committee developing the standards for wireless LANs in the 2.4 GHz band has chosen the 11 bit Barker sequence for their DS spreading function. This sequence is well known in the industry as having 'optimal' autocorrelation properties. It produces a single peak and uniformly low sidelobes when correlated against time shifted versions of itself. These can be created by multipath echoes. Thus, it has very good rejection of multipath. The committee could have chosen the 13 bit Barker word for a little more processing gain, but didn't want to use any more bandwidth than necessary. Other users with non 802.11 schemes in mind will want to explore the options.

The autocorrelation properties of Barker words are often measured with all zero data to either side of the sequence being correlated for. The DS spreading of 802.11 places identical words to either side with 0, 90 or 180 degree relative phase rotations. Thus the correlation properties being sought are those of good autocorrelation with adjoining words of the same sequence at phase rotations of $k*90^o$ (k=0 to 3). The multipath performance of the receiver is also optimized by having a single sharp peak in the correlation with low sidelobes.

The Barker words are only defined to 13 bits, but maximal length sequences exist for all lengths of 2^n-1. This paper defines at least one 15 bit sequence which should have good properties. When checked in the real application, the maximal length sequence was found lacking and another sequence showed better performance.

2. Correlation Properties

The photographs that follow show some trial sequences and their correlation properties in the Prism™ evaluation circuits. The HFA3824 has a test port to monitor the correlator magnitude output in real time. This allows observation of the sidelobe structure of the code being used to analyze its suitability. The first code described below is the IEEE 802.11 defined code, an 11 bit Barker word. It can be defined by the HEX codeword 05B8 to the registers of the HFA3824. The 5 leading digits of this 16 bit word are ignored when the chip is programmed for 11 chips per bit operation. This makes the actual sequence:

101 1011 1000

Fig. 1 shows the correlator output of the chip with asynchronous transmit and receive chip clocks and random QPSK data. This clock offset causes the chip tracking to jitter by 0.25 chip as the optimum tracking point slides by. It is evidenced by the fuzzy nature of the correlation peak as the tracking loop continually readjusts the asynchronous sampling clock to sample close to the peak.

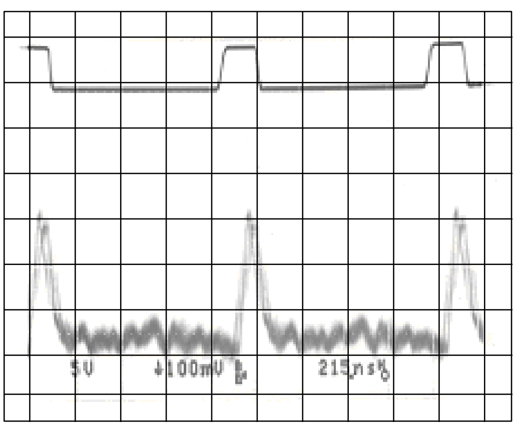

Fig. 1 11 Chip Barker Spreading Sequence

In Fig. 1, the upper trace is the receive bit clock for reference. The oscilloscope is triggered on the bit clock. The correlation is referenced to a graticle line just above the notations. The Barker words have uniformly low autocorrelation sidelobes as shown by the uniform and low values of the correlations except at the peak. The maximum sidelobe is theoretically 1/11th of the value of the peak. This photo shows that this is true even with adjacent symbols QPSK modulated. Any cyclic shift of the Barker word is a also good sequence as is a reversed Barker word.

The 13 bit Barker sequence for 13 chip per bit spreading is considered next. The 13 bit Barker sequence is coded into the HFA3824 registers as 1F 35 in hex notation. Again, the leading digits are ignored to truncate the 16 bit number to 13 bits. The resulting bit sequence is:

1 1111 0011 0101

The 13 bit Barker word has low correlation sidelobes and is a good sequence for spreading even though it has a large unbalance of 1s and 0s (9 to 4).

Fig. 2 shows the correlation of the 13 bit sequence. It has good sidelobe properties even with the adjacent symbols QPSK modulated. The bit clock to which the oscilloscope is triggered is at the top. The baseline reference for the correlation is the graticle line just above the notations.

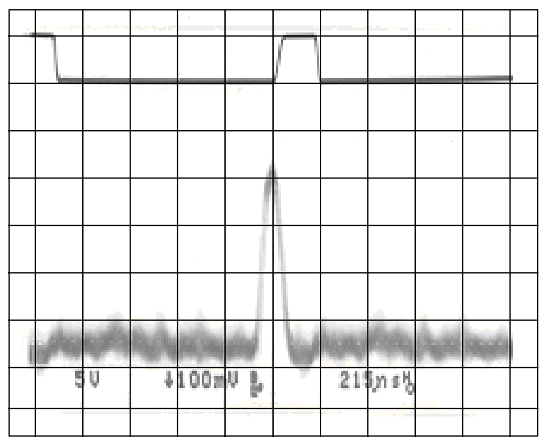

Fig. 2, 13 chip Barker spreading sequence

The maximal length sequence for 15 bits created with the generator polynomial: $x^4 + x + 1$ was considered. In hex notation it is 789A or in bits:

111 1000 1001 1010

This sequence did not have properties as good as the 13 bit Barker word as expected. It had some large sidelobes, as shown in Fig. 3. These sidelobes can cause a reduction in the performance of the radio. The performance of the demodulator is related to the ability to distinguish the peak from the rest in the presence of noise. If a large sidelobe exists, there is more likelihood that noise can raise its value higher than the real peak which will make a symbol error occur.

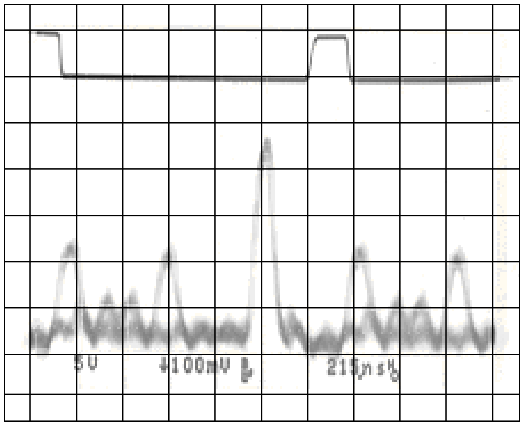

Fig 3, 15 bit maximal length sequence

To make a good 15 bit sequence, the 13 bit Barker word with two leading 0s was tried and gave better results. Using the sequence 1F35 again, the sequence is now better balanced in 1s and 0s and also has better sidelobe properties than the maximal length sequence in this application. The sequence is:

001 1111 0011 0101

Remember that PN sequence sidelobes are not usually measured with adjacent symbols QPSK modulated like was done here. Fig. 4 shows sidelobes are low and uniform, which is the desired result

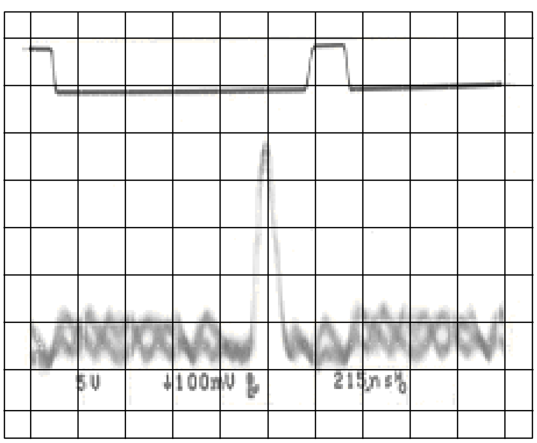

Fig 4, Extended Barker word for 15 bit

The next set is one of several 16 bit sequences examined. The unique word used in the 802.11 specification as a start frame delimiter was tried with the results shown in Fig. 5. This 16 bit sequence is coded into the HFA3824 registers as F134 in hex notation. It has poorer correlation properties than the extended 13 bit Barker word that follows.

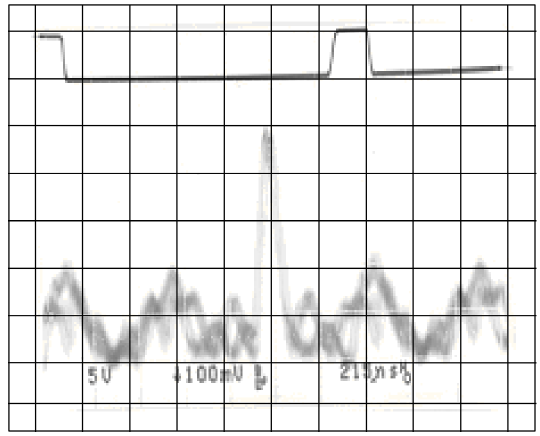

Fig 5, 16 bit synchronization sequence

The 16 bit code made from the 13 bit Barker word (1F35) with 3 leading 0s is shown in Fig. 6.. It has a nearly balanced number of 1s and 0s and shows good correlation sidelobes. This code has uniform sidelobes with a well defined peak. The sequence is:

0001 1111 0011 0101

The properties of this code are better for 16 chip applications than any other that was tried.

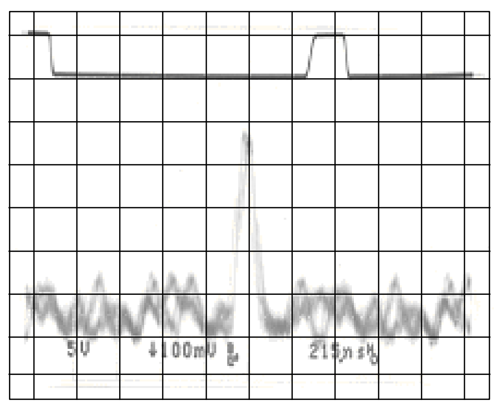

Fig. 6, 16 bit sequence made from Barker word

Shorter sequences can be programmed into the HFA3824 than 11 chips per bit using a subterfuge. Using a spreading sequence of half 1s and half 0s (00FF) makes a minimal (2 chips per symbol) spreading ratio to operate nearly unspread. This is equivalent to biphase-level data modulation in BPSK modes. The mid bit phase change provides essential tracking information to the bit timing loop. The design of the Prism™ baseband processor does not support wholly unspread (spread sequence = FFFF or 1 chip per symbol) operation. While it will acquire and track in an unspread mode, it makes errors at high SNR (due to low tracking loop gain) which is unacceptable. Using specialized sequences such as these, at a nominal spread ratio of 16 chips per symbol, a system designer can get effective spread ratios of 8, 4, and 2 chips per symbol.

3. Processing Gain

The FCC rules for the 2.4 GHz ISM band call for a DS spread spectrum waveform with at least 10 dB processing gain. The suggested test for processing gain is for interference rejection and this allows a slightly different definition of processing gain than is sometimes used.

Many textbooks call processing gain the ratio of spread rate to bit rate. The FCC rules use spread bandwidth to modulation bandwidth which can be different. This FCC rule is based on reducing the power spectral density and providing interference immunity. For example, a modulation with BPSK spreading and QPSK data modulation is the 802.11 DS standard which calls for 11 MCps spreading and 1 MSps QPSK data modulation. An incoming signal is filtered to 22 MHz, despread, and then filtered to 2 MHz bandwidth. Thus, an 11 to 1 bandwidth reduction is effected and this provides 10.4 dB of interference rejection. Interfering CW signals are spread to 22 MHz null to null and 91% of their energy is thus outside the final bandwidth. This meets the processing gain test even though the spread rate to data rate ratio is only 5.5. Indeed, 2048 QUAM could be used for the data modulation and 91% of the jammer energy would still be rejected even with a spread rate to bit rate ratio of unity. Of course, the J/S ratio would be worse by the increase in Eb/N0 required.

The spread spectrum defined by the 802.11 standard (11 chips per symbol) will not allow much, if any, CDMA capability. The reason is that processing gain is on the order of the required Eb/N0 that the modem needs to get good bit error rates. Thus, the signal to noise ratio in the spread bandwidth is near unity in BPSK mode and positive 3 dB in QPSK. This does not allow any CDMA in QPSK and only one other equal range channel in BPSK. However, it allows DS networks to be operated at least 10 dB closer together than unspread networks all other things being equal.

4. Summary

In summary, the best spreading codes to use for the Prism™ wireless chip set have been found and are 05B8 for 11 chips per bit and 1F35 for 13, 15, and 16 chips per bit. These are the 11 and 13 bit Barker words with added zeros for the longer sequences. Cyclic shifts of these sequences and reversed sequences are also good. Cross correlations between these have not been tested thoroughly, but the radios will not lock up on reversed sequences or different lengths. Cross correlations between cyclic shifted versions will be high.