

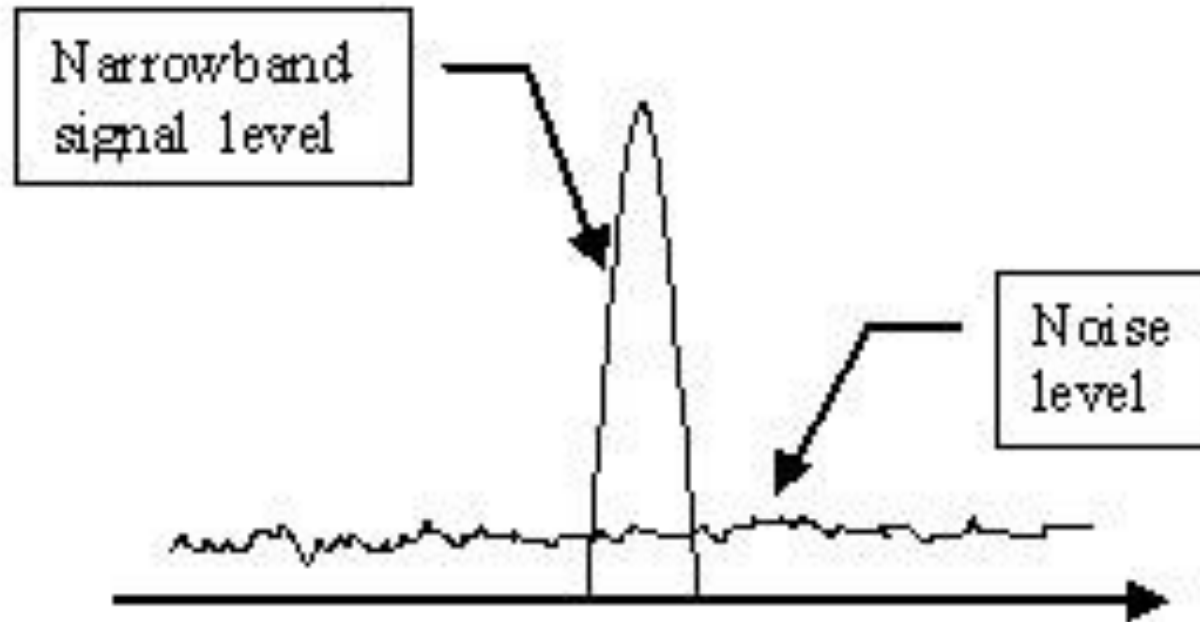
Communication Systems based on Software Defined Radio (SDR)

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Introduction to Spread Spectrum

Spread Spectrum refers to a system originally developed for military applications, to provide secure communications by spreading the signal over a large frequency band.

Figure 1 represents a narrow band signal in the frequency domain. These narrowband signals are easily jammed by any other signal in the same band. Likewise, the signal can also be intercepted since the frequency band is fixed and narrow.



The idea behind spread spectrum is to use more bandwidth than the original message while maintaining the same signal power. A spread spectrum signal does not have a clearly distinguishable peak in the spectrum. This makes the signal more difficult to distinguish from noise and therefore more difficult to jam or intercept. This concept is illustrated in Figure 3.

We present now the block diagram of a typical communication system with the difference that the modulator/demodulator has as input the spreading generator. This piece will be explored in following sections.

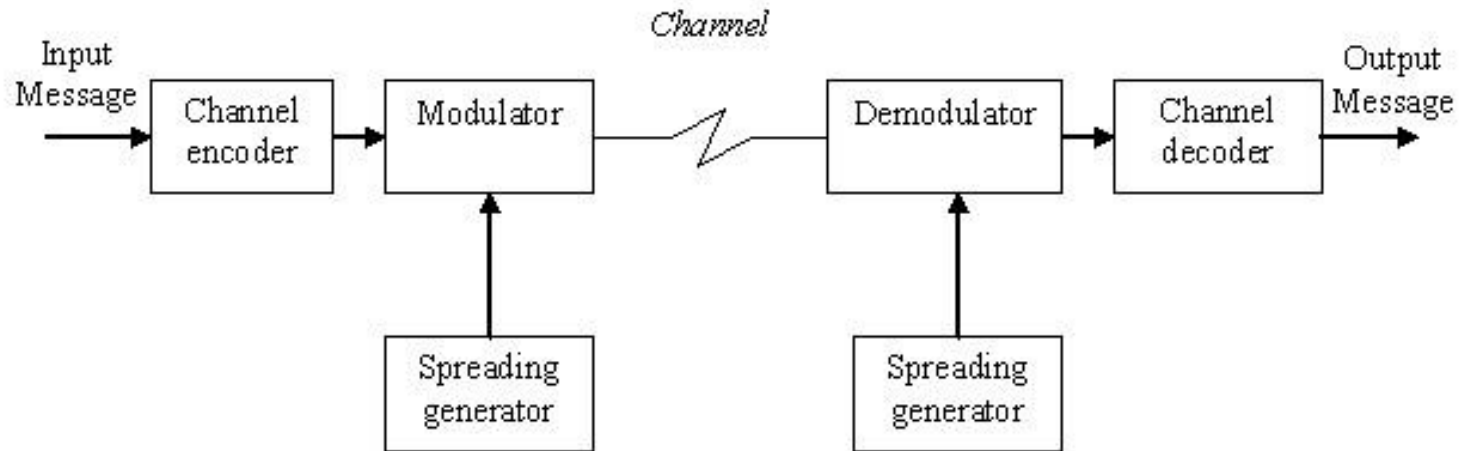


Figure 2: Block diagram of the spread spectrum communication system

There are two predominant techniques to spread the spectrum:

- 1) Frequency hopping (FH), which makes the narrow band signal jump in random narrow bands within a larger bandwidth.

- 2) Direct sequence (DS) which introduces rapid phase transition to the data to make it larger in bandwidth.

We will focus on Direct Sequence Spread Spectrum technique since it is the mostly used in the industry (CDMA, UMTS, 802.11, GPS).

Direct sequence spread spectrum (DSSS) introduces rapid phase transition to the data making it larger in bandwidth. As the period T of a signal gets shorter in time (or rate R increases), the bandwidth B of the signal increases: $R = 1/T = 2B$ (Nyquist Rate)

The following figures explain it:

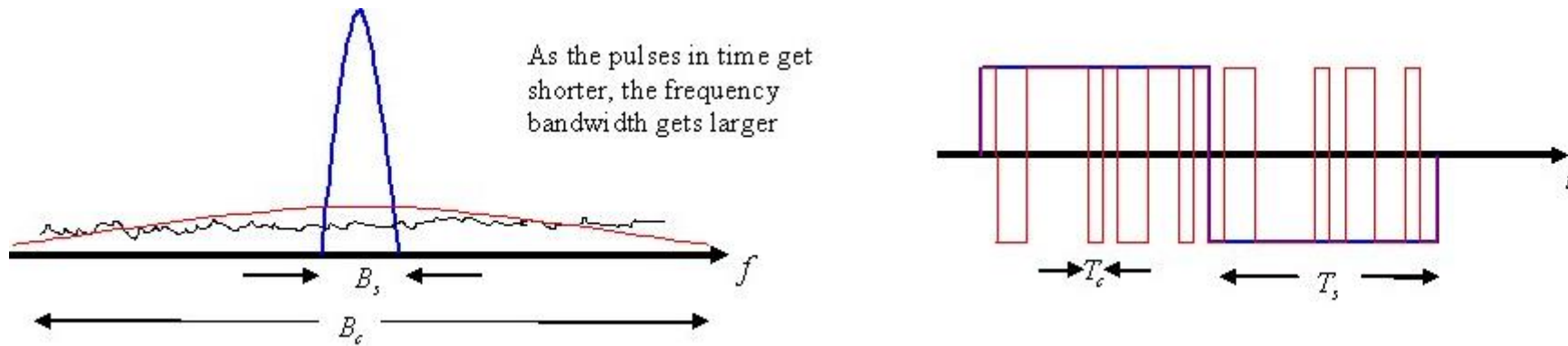


Figure 3: Rate and period are related to bandwidth by $R_s = 1/T_s = 2B$ when pulse shaping is used. $B_c \gg B_s$.

The rapid phase transition (chip rate) signal has a larger bandwidth given that the rate is greater (without changing the power of the original signal) and behaves similar to noise in such a way that their spectrums are similar for bandwidth in scope. In fact, the power density amplitude of the spread spectrum output signal is similar to the noise floor. The signal is “hidden” under the noise.

To get the signal back, the exact same high bandwidth signal is needed. This is like a key, only the demodulator that “knows” such a key will be able to demodulate and get the message back. This “key” is in fact a pseudo random sequence (rapid phase transition) also known as pseudo noise (PN). These sequences are generated by m-sequences.

m-Sequences

These codes (DSSS codes) will all be treated as pseudonoise (PN) sequences because resembles random sequences of bits with a flat noiselike spectrum.

This sequence appears to have random pattern but in fact can be recreated by using the shift register structure in Figure 4 with $M=4$, polynomial x^4+x^3+1 and initial state '1 1 0 0'.

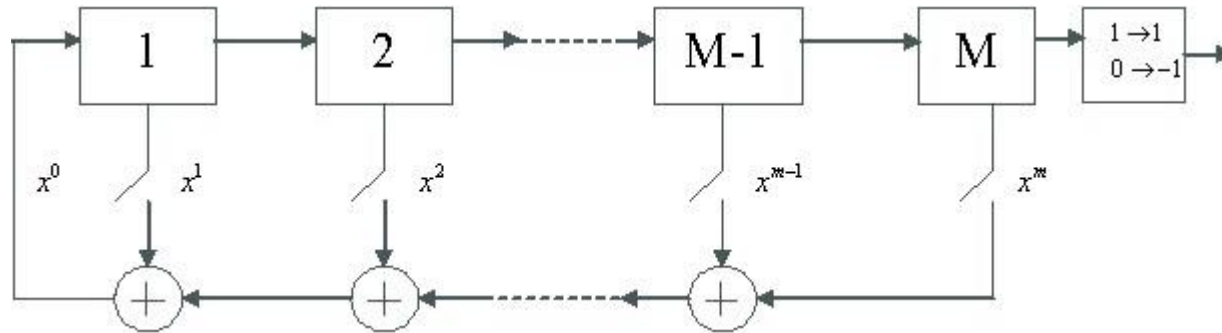
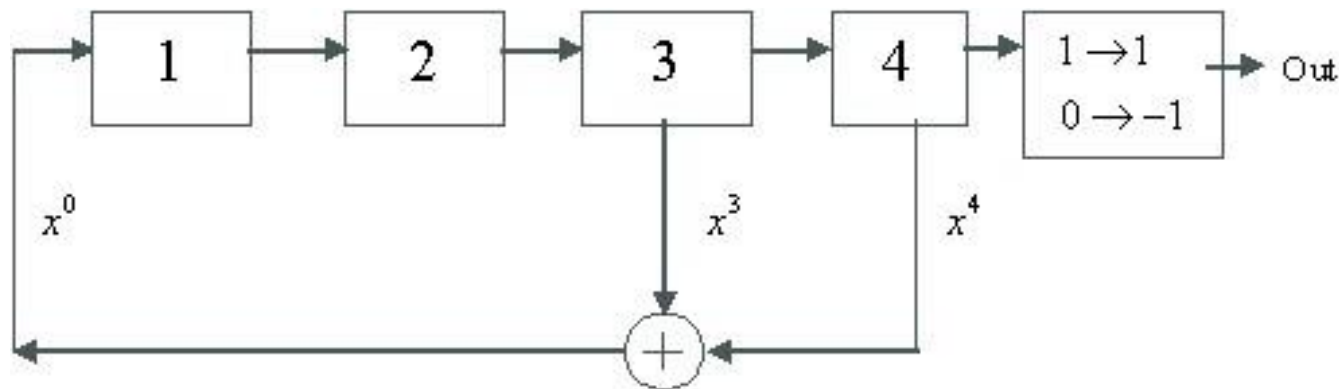


Figure 4: Shift register structure for m-sequence

Where '⊕' represent modulo 2 addition.

Using this scheme, the initial state is only needed to generate exactly the same sequence of length $2m-1$ (the only forbidden state is all zeros since the register will lock in this state).



And initial seed:

Register #	1	2	3	4	Output
Initial value	0	0	1	1	

The values after shifts will be:

First Shift	0	0	0	1	1→1
Second Shift	1	0	0	0	1→1
Third Shift	0	1	0	0	0→-1
Fourth Shift	0	0	1	0	0→-1
Fifth Shift	1	0	0	1	0→-1
Sixth Shift	1	1	0	0	1→1

Take for example: PN1 = 1 1 -1 -1 -1 1 -1 -1 1 1 -1 1 -1 1 1

After the fifteenth shift, the values on the registers will be again the starting seed.

Properties of m-Sequences

Period: $2^m - 1$

After this number of '1' and '-1' the sequence will start to repeat since the starting symbols will be the same.

Autocorrelation:

The formal definition of discrete autocorrelation is:

$$\langle x[n+m]x^*[n] \rangle = \langle \phi[m] \rangle = \frac{1}{L} \sum_{n=0}^{L-1} x[n+m]x^*[n] = \begin{cases} 1 & , m = 0 \\ -1/L & , m \neq 0 \end{cases}$$

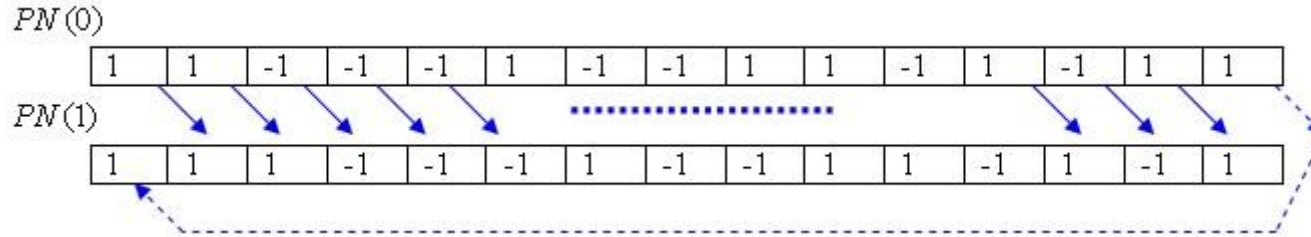
Consider the previous sequence

$PN(0) = \{a_1, a_2, \dots, a_{15}\} = 1 \ 1 \ -1 \ -1 \ -1 \ 1 \ -1 \ -1 \ 1 \ 1 \ -1 \ 1 \ -1 \ 1 \ 1$

If we perform the following operation:

$$\sum_i a_i a_i = 15 \text{ which is multiply each value by itself and add them all (} \langle \phi[0] \rangle \text{).}$$

Now take $PN(1)$,



$$\sum_i a_i a_{i+1} \quad \langle \phi[1] \rangle$$

Performing the same operation:

This is the autocorrelation for each shift point. If we take them all and plot them so that there are 15 points before 0 and 15 after:

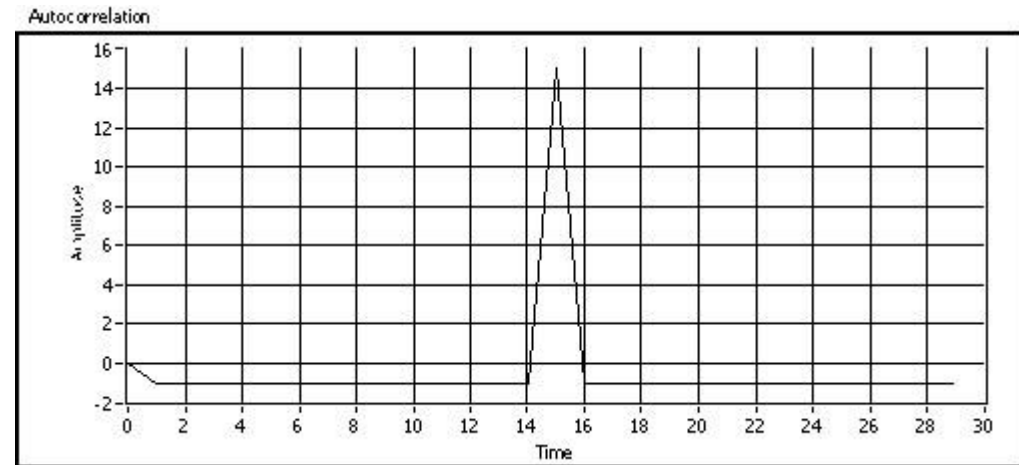
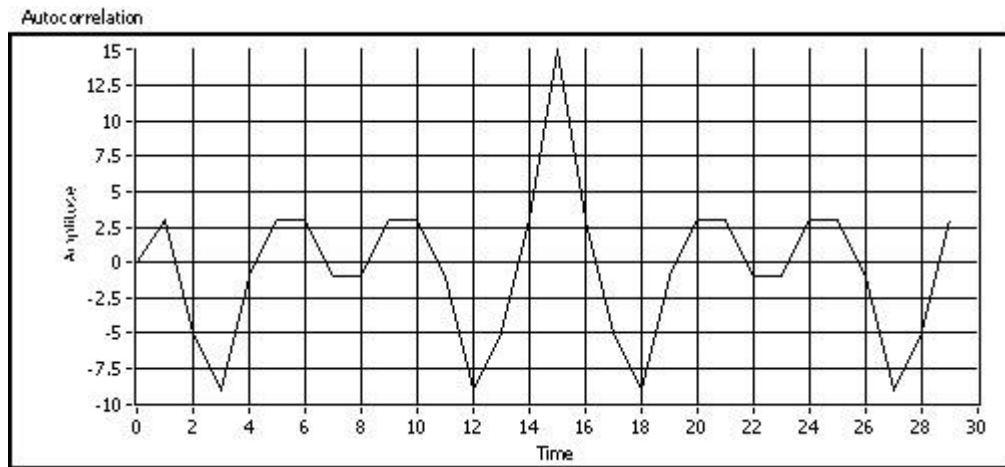


Figure 5: Correlation of a) example sequence and b) other sequence with polynomial x^4+1

As seen, only if the end user having the exact sequence is able to demodulate the message when the sequence is synchronized (peak at correlation = 1). Other users will have very little amplitude of the original signal. This is the principle of Code Division Multiple Access (CDMA) cellular systems, in other words, share the same frequency and time with multiple users with different codes.

The block diagram of the DSSS communication system for QPSK is presented in Figure 6. Notice that the PN sequence is introduced here to both in-phase (I) and quadrature (Q) components.

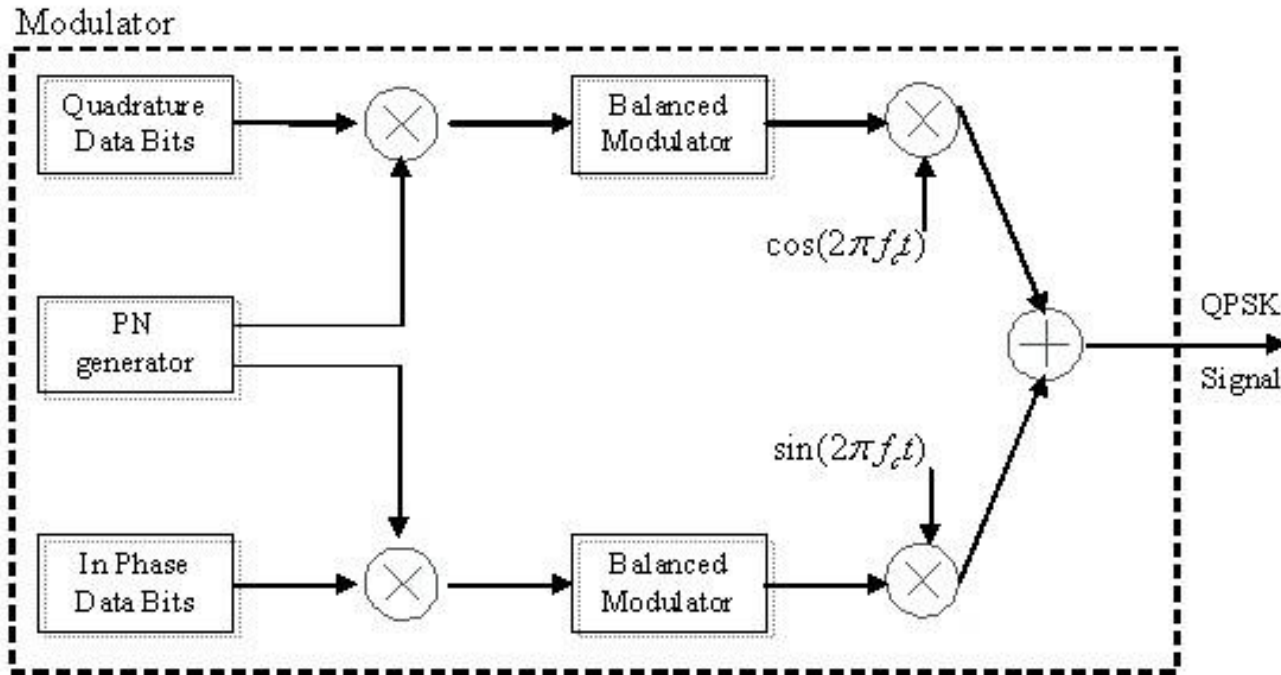


Figure 6: Block diagram of the spread spectrum QPSK modulator

The sequence should be long enough (with respect to the message signal) to have the noise-like spectrum. This is the relation between spreading sequence rate T_c and message rate T_b : $N T_c = T_b$

In practical systems, N is an integer number and it is the number of phase shift of the PN sequence for each message bit. For example, for GPS systems $N = 1024$.

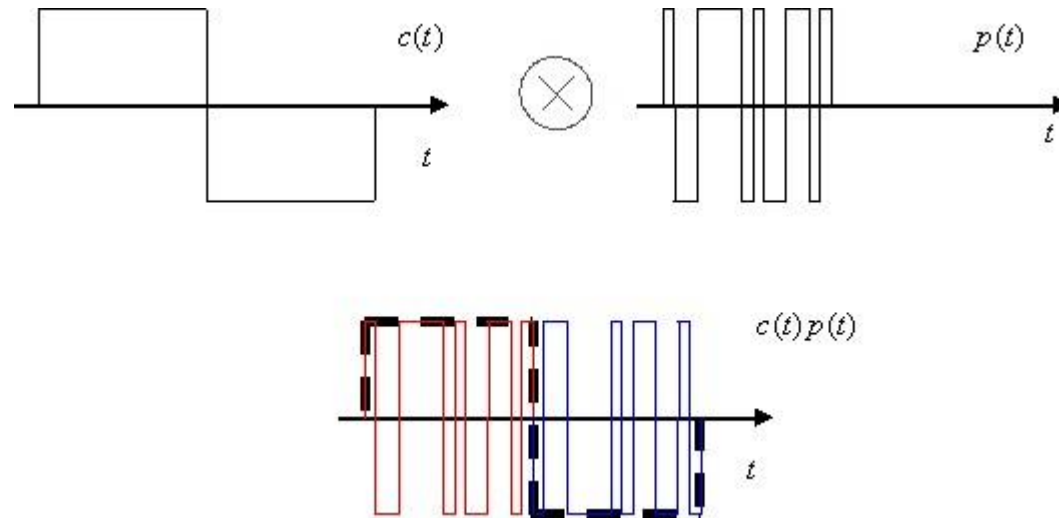


Figure 7: Spreading the message, each bit of the message will contain the entire PN sequence

The new message has now $R=R_c$ and therefore $B=B_c$

The output combined baseband sequence is: $s(t) = p(t)c(t)$

Where $s(t)$ is the sent baseband waveform, $p(t)$ is the PN waveform and $c(t)$ is the bit sequence.

Despreading

Received baseband waveform is the combination of the transmitted waveform and noise in the channel.

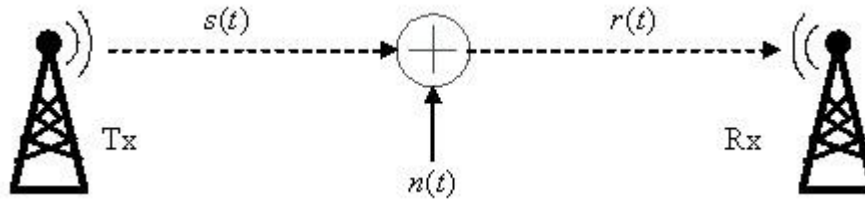


Figure 8: Simple additive white Gaussian noise (AWGN) channel model.

The received signal will be combined again with the spreading sequence. Notice that the noise $n(t)$ is also going to be processed on the same procedure but correlation properties will not increase the noise power.

The received signal will be the combination of the transmitted signal plus noise: $r(t) = s(t) + n(t)$

We can substitute the sent waveform by the combination of the PN sequence and the bit sequence.

$$r(t) = p(t)c(t) + n(t)$$

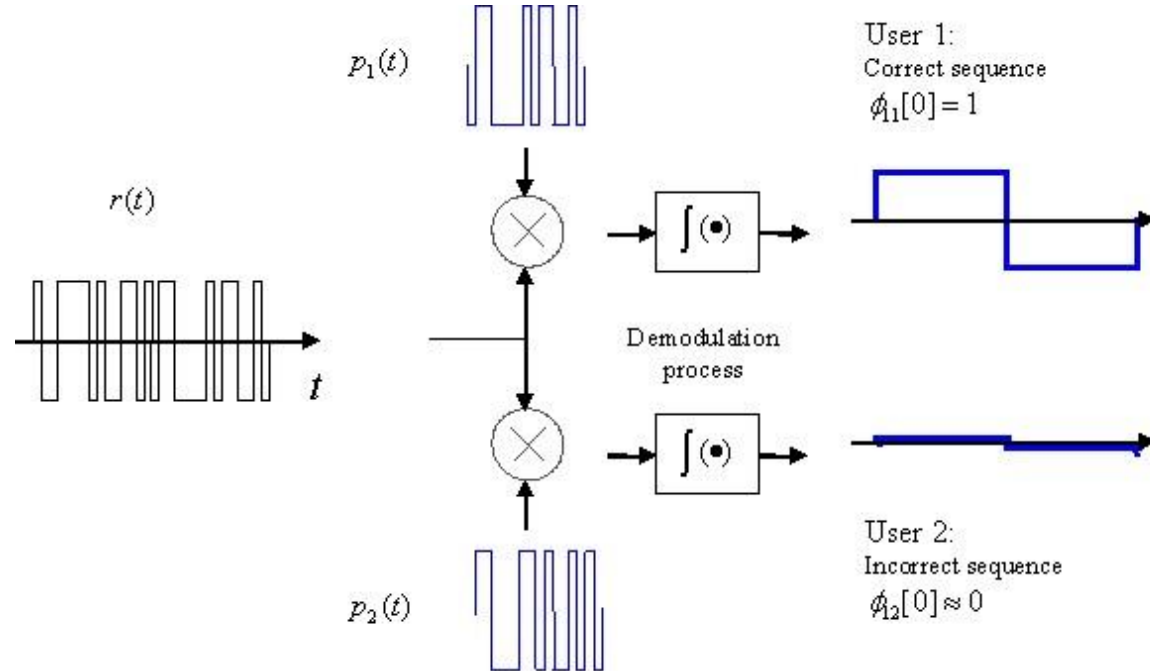
The modulator will multiply it by the PN sequence $p(t)$:

$$p(t)r(t) = p(t)p(t)c(t) + p(t)n(t)$$

If $p(t)$ is synchronized, $p(t)p(t)=1$ and $p(t)n(t)$ is like multiplying noise times noise which gives other kind of noise $\tilde{n}(t)$ (similar in amplitude).

$$p(t)r(t) = c(t) + \tilde{n}(t)$$

Example: Recuperate original signal for two different users. User 1 has the correct sequence. User 2 has different sequence and therefore the output message will have many errors (no information)



M-sequences are the basics of PN sequences and they are used in real systems (GPS) but these are not the only PN sequences. Since Spread Spectrum is the basis of CDMA, we will highlight the basis of two of the most used sequences involved in the system: Gold sequences (WCDMA) and Walsh-Hadamard sequences (IS-95).

Gold Sequences

Gold sequences help generate more sequences out of a pair of m-sequences giving now many more different sequences to have multiple users. Gold sequences are based on *preferred pairs* m-sequences. For example, take the polynomials $1+x^2+x^5$ and $1+x+x^2+x^4+x^5$:

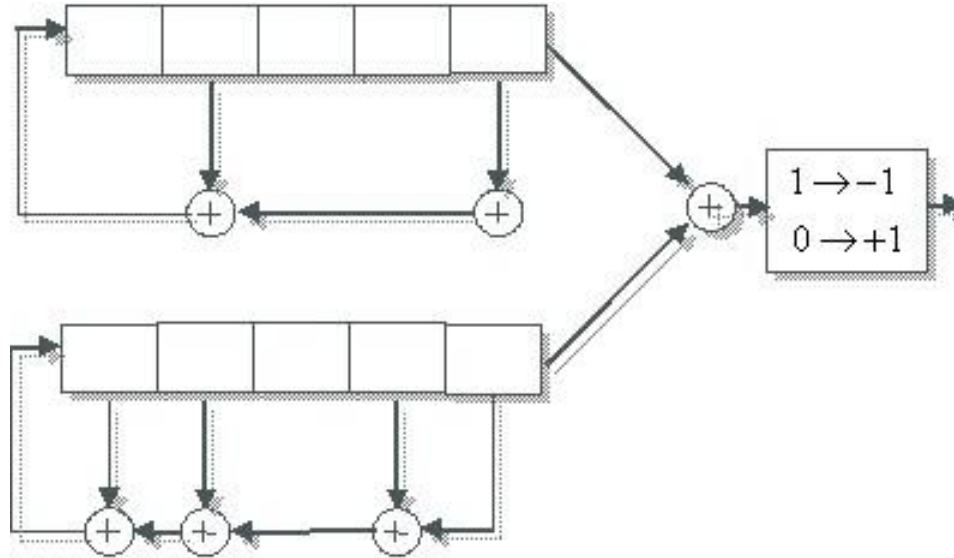


Figure 10: Example of gold sequence generator using one preferred pair of m-sequences: $1+x^2+x^5$ and $1+x+x^2+x^4+x^5$

Remember m-sequences gave only one sequence of length $2^m - 1$. By combining two of these sequences, we can obtain up to $2^m - 1$ plus the two m-sequences themselves, generate $2^m + 1$ sequences (each one length $2^m - 1$) that can be used to spread different input messages (different users CDMA).

The m-sequence pair plus the $2^m - 1$ Gold sequences form the $2^m + 1$ available sequences to use in DSSS. The wanted property about Gold codes is that they are balanced (i.e. same number of 1 and -1s).

Walsh-Hadamard Sequences

Other common sequences are Walsh-Hadamard sequences currently used in CDMA systems. These sequences are orthogonal (i.e. $\sum b_i b_j = 0$ where i is a row of the matrix), convenient properties for multiple users. The sequences are the rows of the Hadamard matrix H_M defined for $M=2$ as:

$$H_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix}$$

For larger matrices use the recursion:

$$H_{2M} = \begin{bmatrix} H_M & H_M \\ H_M & -H_M \end{bmatrix}$$

Example for

$$H_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

Orthogonal codes have perfect properties of cross correlation (if no shift is implemented).

Conclusions

We have now explored different sequences that can spread the signal like noise would behave. Spread spectrum systems expand beyond this point to many different paths: modulation schemes, performance under fading, under interference, capacity in CDMA systems, etc.

To finalize, we would like to point out the advantages and disadvantages of using spread spectrum:

Advantages:

- **Privacy. Secure communications because signal is “hidden” like noise.**
- **Non interference with other signals in the same band.**
- **Possible to share frequency and time at same time (CDMA).**
- **Protection against jamming.**

Disadvantages:

- **Increase bandwidth (wideband circuitry, channel model for wideband systems behaves different over frequency)**
- **Increase complexity**

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