CCSDS

The Consultative Committee for Space Data Systems

Report Concerning Space Data System Standards

DATA TRANSMISSION AND PN RANGING FOR 2 GHZ CDMA LINK VIA DATA RELAY SATELLITE

INFORMATIONAL REPORT

CCSDS 415.0-G-1

GREEN BOOK

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CONTENTS

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1 INTRODUCTION

1.1 SCOPE

This document describes the concepts and the use of spread-spectrum modulation in existing Radio Frequency (RF) satellite communications systems. It is a supplement to the CCSDS Code Division Multiple Access (CDMA) Recommended Standard (reference [1]), that contains a detailed specification of the particular Pseudo-random Noise (PN) spread-spectrum modulation formats implemented in the low-rate data transmission and PN range tracking services currently used by several space agencies. The formats are those in use by the NASA Tracking and Data Relay Satellite System (TDRSS), the ESA Advanced Relay and TEchnology MISsion (ARTEMIS), and the JAXA Data Relay & Tracking Satellite (DRTS). The functions and required capabilities of each element of these PN spread links are also provided, including the typical signal flow and equipment characteristics and constraints involved.

1.2 PURPOSE

The CDMA Recommended Standard (reference [1]) is intended to provide a comprehensive description of the PN spread-spectrum modulation formats used in relay satellite CDMA links and to give associated technical requirements from the system level to the component level. This Green Book is written to support the CDMA Recommended Standard in providing a summary of performance and implementation issues, ranging from providing basic system description, capabilities listing, and theoretical background for readers seeking a general understanding of existing systems to documenting the detailed technical requirements necessary for implementing hardware that is compatible with the CDMA Recommended Standard (reference [1]).

1.3 APPLICABILITY

This Report is applicable to programs/projects planning to use and/or implement compatible spread-spectrum systems for near-Earth missions. Near-Earth spectral regulations require that missions do not violate certain power spectral density limits. Using PN patterns to spread the spectrum reduces the power spectral density, allowing the signal to meet these requirements.

In addition to CDMA, spread spectrum also provides a level of security, and once spread-spectrum modulation is used, the small additional step of coherently turning around the signal at the user spacecraft allows other features. For example, if the network element measures the time between the transmitted and received PN epoch of the digital spreading pattern the information can be used for spacecraft range tracking. Once the tracking is in place, using the PN pattern for time transfer (accurately correlating the spacecraft clock against UTC) again requires only a small additional effort.

This Report deals with near-Earth missions only, supported by a Data Relay System. The use of digital sequences for deep space missions, as described in CDMA Recommended Standard (reference [1]) is for ranging purposes, not for spectrum spreading, and is not the subject of this book.

Deep space missions operate where the Signal-to-Noise Ratio (SNR) is very low and use a ranging pattern with a somewhat random digital pattern that has a high ‘101010 …’ periodic component, which results in high spectral density. The use of the term PN in that book does not refer to the pseudo-random codes used for deep-space ranging.

There are several kinds of spread spectrum. For the purpose of this document, only Direct Sequence Spread Spectrum (DSSS) is considered. Although, there are some similarities, this book does not cover CDMA systems used in Global Positioning System (GPS) and cell-phone applications.

1.4 STRUCTURE OF THIS DOCUMENT

Section 1, this section, is an introduction.

Section 2 discusses receiver PN code, carrier acquisition, and Doppler compensation.

Section 3 covers PN code basics which include auto- and cross-correlation, generation of PN codes, polynomial representation of PN generators, and specifics of maximal and Gold codes.

Section 4 discusses the algorithm used to select the codes that make up the CCSDS family of codes and tabulates the number of codes available for coherent operations.

Section 5 gives details of applying the codes selected for CCSDS and explains how to use the parameters in the PN code library to generate the codes.

Annex A is a summary of the codes applied to forward, return, coherent and non-coherent links.

Annex B is a tutorial that covers properties and characteristics of spread-spectrum links used for CDMA. It covers basic architecture, transmitter, receiver and features that spread spectrum makes available to the network. Some of these features are spacecraft ranging using the PN code, time transfer using the PN code, and immunity to interfering signals.

Annex C contains acronyms and definitions relevant to CDMA and PN spread-spectrum modulation.

Annex D provides a list of works consulted in addition to those listed in 1.5.

1.5 REFERENCES

The following documents are referenced in this Report. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Report are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

[1] *Data Transmission and PN Ranging for 2 GHz CDMA Link via Data Relay Satellite*. Recommendation for Space Data System Standards, CCSDS 415.1-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, September 2011.

[2] Lloyd R. Welch. "Lower Bounds on the Maximum Cross Correlation of Signals." *IEEE Transactions on Information Theory* 20, no. 3 (May 1974): 397–399.

[3] T. Kasami. *Weight Distribution Formula for Some Class of Cyclic Codes*. Technical Report No. R-285. Urbana, Illinois: University of Illinois, 1966.

[4] "Maximal Recursive Sequences with 3-Valued Recursive Cross-Correlation Functions." *IEEE Transactions on Information Theory* 14, no. 1 (January 1968): 154–156.

[5] John Proakis and Masoud Salehi. *Digital Communications*. 5th ed. McGraw-Hill Science/Engineering Series in Electrical and Computer Engineering. Boston: McGraw-Hill, 2008.

[6] *Space Network Users' Guide (SNUG)*. Revision 9. 450-SNUG. Greenbelt, Maryland: NASA Goddard Space Flight Center, August 2007.

[7] *User Spacecraft Clock Correlation System (USCCS) Users' Guide*. Volume 1. Revision 3. 531-TR-001. Greenbelt, Maryland: NASA Goddard Space Flight Center, April 1, 1999.

2 RECEIVER ACQUISITION

2.1 GENERAL

In order to keep the acquisition time to a minimum, during the receiver acquisition period, no data (commands or idle pattern) should be sent via the forward link. If data is sent, the additional phase transitions increase the bandwidth over that of the pure de-spread carrier. Depending on the bandwidth used by the de-spreader to determine lock, if there is data modulation, the de-spreader may not lock or a false PN lock may occur. For example, a narrow de-spreader bandwidth will allow operation at low SNR but may not pass sufficient energy to the lock detector if modulation is ON. In the event of a false lock, the receiver will not be able to correlate the PN code and de-spread and demodulate the commands. If in addition, the link is coherent, the return PN code will not yield the correct range measurement. (See B4.2 for more on PN lock.)

When acquiring the forward signal, the receiver first searches for the PN short code (I channel). With digital equipment it is common to use multiple parallel correlators to speed up acquisition.

For a non-coherent service, when the receiver is locked to the forward-link command I channel PN code, the carrier is then tracked by the receiver, forward-link data is demodulated, and data is output from the receiver. The long (range) code may be ignored, and since its power is 1/10th of that on the I (command) channel, the receiver may be a PN spread Binary Phase-Shift Keying (BPSK) receiver.

For coherent services, when the receiver is locked to the forward-link command I channel PN code:

a) The carrier is tracked by the receiver, and forward-link data is demodulated.

   The recovered carrier is used to coherently generate the return carrier for the return link at a transmit frequency of 240/221 times the received frequency (network transmit frequency plus effects caused by Doppler). For systems where the PN code rate is coherent with the carrier, only a single tracking loop is required in the spacecraft receiver.

b) The receiver locally generated PN long code is synchronized with the network PN long code (Q-range channel).

   For the purpose of ranging or time transfer, the user-transmitted PN long code is synchronized with the received PN long code from the network. Although the codes are different, they are of the same length, and the epochs are aligned. The return PN code and carrier are used to spread and modulate the return I and Q channel data as required by the mode of service.

2.2 PN CODE ACQUISITION

Differing from near-Earth or Deep Space Network (DSN) ground stations, sweeping the forward-link carrier frequency is not the method of choice for acquisition when using spread-spectrum modulation. Signal acquisition with a spread-spectrum modulation requires frequency and phase locking as with any coherent modulation such as Phase Shift Keying (PSK), but with spread-spectrum modulation, the receiver's internally generated copy of the PN spreading code must also be correlated with the frequency and phase of the code in the received signal. Since the user receiver has no knowledge of the phase of the received PN code, the receivers are designed to search the entire code for the proper correlation phase. A short PN I channel code is used to lessen the burden, and multiple correlators are sometimes used. Once it is found, the user receiver tracks the received short PN code and the carrier frequency and phase. For the case of the network receiver and a coherent turnaround service, the network receiver may contain an estimate of the user orbit, and hence an estimate of the round-trip delay, and thus not have to search the entire code.

For a non-coherent return service, the network receiver will have no a-priori information on the phase of the return code and will have to search the entire code. For the two cases where a complete code search is required, forward command and non-coherent return, a short code is used. For the forward channel, a length of 1023 chips is used, and for the return channel a length of 2047 chips is used. For the coherent case, once the short code is acquired, the system is designed so that the forward long code (range code) requires at most an additional 255 phase points to be searched.

2.3 DOPPLER COMPENSATION

In order to further reduce the command receiver acquisition burden, the carrier frequency (and PN chip rate) may be Doppler compensated on a continuous basis. In some designs, the command receiver expects the signal to be close enough to the assigned Best Lock Frequency (BLF) that frequency lock can be quickly obtained and hence the receiver need only search the PN code phase. For quick acquisition, the oscillator for a spread-spectrum receiver needs to be stable and the BLF known. Temperature Compensated Crystal Oscillators (TCXOs) are often used. Non-spread-spectrum receivers can use less expensive oscillators since the ground simply sweeps across a wide enough range to be sure the unknown BLF is crossed. If the signal were not Doppler compensated, then, when the receiver-generated PN code is on frequency and in phase with the received PN code, the frequency of the de-spread carrier might be far enough from the BLF that the signal would not pass the lock detection filter with sufficient power to alert the receiver that the PN code is correlated.

PN spread links are capable of functioning even when there are higher spectral density interferers in the band (also see B4.3). The immunity to the interferer is enhanced by requiring Doppler compensation so that the spread-spectrum signal reaches the receiver at the receiver's center frequency and a narrow filter can be used for lock detection. The receiver then acquires the forward-link PN codes (command I channel PN short code and Q channel range PN long code). Once acquired, Doppler compensation can be inhibited at the network element and the user receiver will track the carrier and PN code. Inhibiting Doppler compensation after acquisition has been required for collecting tracking data in the past.

Return-signal Doppler compensation may be performed at the ground station to allow implementation of receivers with narrow acquisition and tracking bandwidths. The compensation done at the ground station is used to determine the round-trip (two-way) Doppler and hence the radial velocity component, which leads to an orbit solution based on the Doppler effect.

3 PN CODE BASICS

3.1 CORRELATION PROPERTIES

This section presents an overview of correlation properties in general and of pseudo-random noise codes. Then correlation properties of specific PN codes (maximal, preferred maximal, and Gold) are considered. In spread-spectrum systems, the spreading signal is formed by continually repeating a finite-length PN code. To be usable for direct-sequence spreading, this PN code (composed of binary units called chips to distinguish them from data bits or code symbols) should exhibit the following characteristics:

– Codes must have a sharp (1-chip wide) autocorrelation peak to enable code-synchronization. (See discussion of autocorrelation below.)

– The codes must have a low cross-correlation value. The lower this cross-correlation, the more users can be allowed in the system. This holds for both full-code correlation and partial-code correlation. (See discussion of cross-correlation below.)

– The codes should be ‘balanced’, meaning that the difference between the number of ‘ones’ and ‘zeros’ in the code may be no greater than 1. This requirement is necessary (but not sufficient) for good spectral-density properties (spreading the energy equally over the whole frequency band).

3.2 AUTOCORRELATION

The autocorrelation of a signal is a measure of how easy it is to differentiate between the signal and every time-shifted variant of itself (over successive time intervals). Autocorrelation for a finite, discrete signal is defined in equation 1 where T is an element time delay (i.e., chip duration) and the number of elements in the sequence is its length, L. Sequence values are taken to be +1 and −1 (not 1 and 0).

$$r_{gg}(T) = \sum_{i=1}^{L} g(i)g(i-T) \qquad \text{Un-normalized} \qquad (1)$$

A signal with an autocorrelation value of L for T=0 and a value of 0 for $T \neq 0$ is said to be orthogonal to a time-shifted version of itself. PN sequences used for DSSS systems should have a sharp autocorrelation property, meaning that the value of the autocorrelation, which has a maximum of L at T=0, should diminish sharply as the magnitude of T increases. This property simplifies the PN acquisition process. For any value of $T \neq 0$, if half of the bits agree and half do not agree, the value of $r_{gg}(T)$ will be 0. For the signals used in this document, L is odd (see equation 7) so the smallest magnitude of $r_{gg}(T)$ will be 1, not 0.

3.3 CROSS-CORRELATION

Cross-correlation is similar to an autocorrelation except that it is computed between two different signals, for example, between two particular PN codes that are members of a PN code family. As with the autocorrelation, it is computed as the sum of the products between the two signals at different lags. Cross-correlation for finite-length discrete signals is defined in equation 2.

$$r_{gh}(T) = \sum_{i=1}^{L} g(i)h(i-T) \quad \text{Un-normalized} \tag{2}$$

Cross-correlation is generally used when measuring the difference between two different time series.

The Un-normalized ($r_{gh}(T)$) cross-correlation peak is:

– L if the second sequence matches the first sequence;

– if there is no relation at all between the sequences (half chips agree, half do not);

– $-L$ if the second sequence is an inverted form of the first sequence.

The signals are said to be orthogonal when all pair-wise cross-correlations of two signals are 0. In concept this is attractive, but the known orthogonal codes have disadvantages, making them inappropriate for CDMA. PN sequences used for DSSS systems should have low cross-correlation values, meaning that the value of $r_{gh}(T)$ should remain below some level for all values of T. This property helps to keep signals isolated and avoid a false PN correlation.

3.4 GENERATION OF PN CODES

At the design stage, PN codes are typically generated using Linear Feedback Shift Registers (LFSR) but in digital circuits are commonly implemented as look-up tables. The LFSR can be described by a generator polynomial, which uniquely describes the shift register circuit. For a given LFSR and associated generator polynomial, there are two conventions for representing a LFSR, Fibonacci and Galois. The discussion here uses the structure known as the Fibonacci feedback generator. This approach is used in maximal-length sequences and Gold code generators. Figure 3-1 is an example of a PN code generator, based on the Fibonacci feedback approach, and gives the associated polynomial.

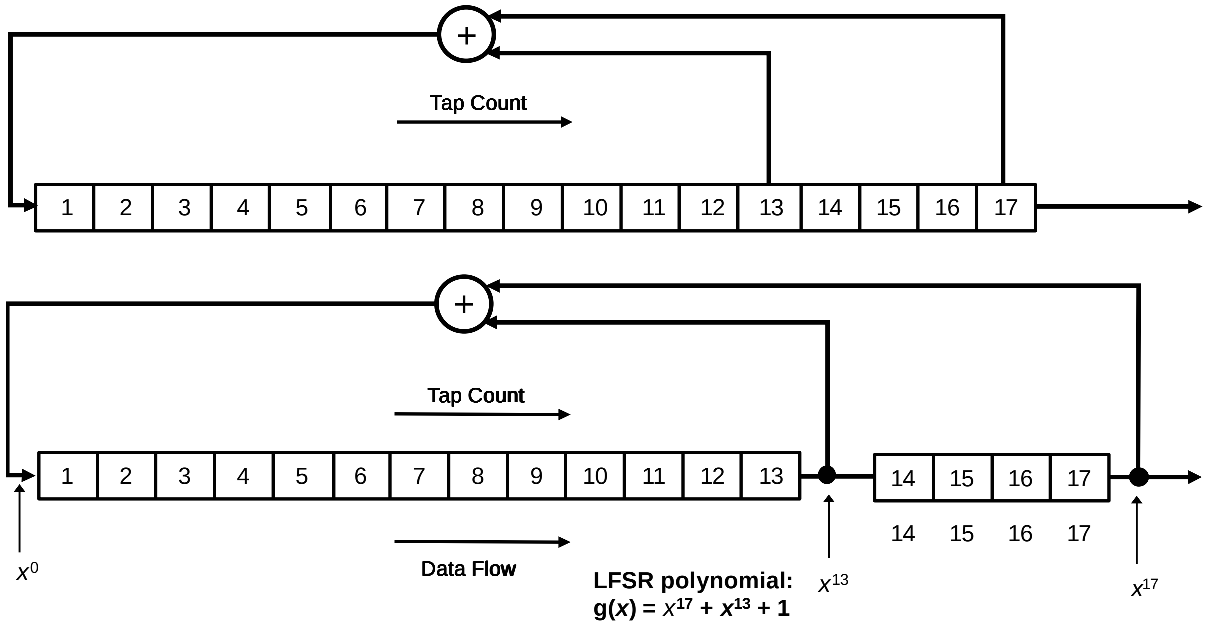

Figure 3-1: Two Drawings of the Same Fibonacci Implementation of LFSR

3.5 RELATION OF POLYNOMIAL TO SHIFT REGISTER TAP LOCATIONS

The combination of taps and their location is specified by the generator or characteristic polynomial. An example polynomial for the register in figure 3-1 with 17 cells (17 is arbitrarily chosen) is given as:

$$g(x) = x^{17} + x^{13} + 1 \quad (3)$$

Various conventions are used to map the polynomial terms to register stages in the shift register implementation. The convention used in the CDMA documents has the output at the highest number cell. If the cell numbering were reversed, the shift register and the output pattern would be the same, but the polynomial representation would be different; the x^{13} would become x^4. If the numbering convention is misinterpreted, a reverse pattern will be generated (see 3.7.3).

In the polynomial $g(x) = x^{17} + x^{13} + 1$, the trailing '1' represents x^0, which is the input to the first stage of the register and the output of the XOR. x^{13} is the output of register stage 13 and x^{17} the output of the last stage of the shift register.

Some key points to note about LFSRs and the polynomial used to describe them are:

– The last tap of the shift register is the highest cell number and always used in the shift register feedback path (if it is not used, the shift register structure is not the length of the last cell).

– The length of the shift register can be deduced from the exponent of the highest order term in the polynomial and thus the highest order term in the polynomial defines the length.

– The lowest order term, x^0, of the polynomial is the signal connecting the 'XOR' output and is the input to the shift register. It does not feed back into the parity calculation along with the other taps identified in the polynomial.

3.6 PN CODE TYPES

Among the various types of PN codes used for DSSS applications, there are some which exhibit perfect (orthogonal) cross-correlations between component codes and others which exhibit very low cross-correlations. An example of a code family with orthogonal codes is the set known as Walsh codes (reference [2]). These are used in systems where the PN sequence is synchronous with the data sequence as with cell phones. Examples of PN codes with low cross-correlation are maximal-length codes (m-sequences) and Gold codes. These are explained in detail below. Other codes in this category include Kasami-codes (reference [3]).

Code-selection has a large impact on the performance of a CDMA system. Code selection and cross-correlation properties are key performance factors. However, in systems where the data and PN sequences are asynchronous (as in SNIP and CCSDS PN spread links), PN codes with low (but nonzero) cross-correlation properties are sometimes preferable because of the difficulty in calculating cross-correlation properties in general and because of the known properties of certain types of PN sequences.

The codes included in the CDMA Recommended Standard (reference [1]) belong to the maximal-length and Gold (reference [4]) codes families.

3.7 MAXIMAL-LENGTH CODES

3.7.1 GENERAL

Shift register generated codes are not orthogonal but they can have a narrow autocorrelation peak. When the length of such a shift register (number of cells) used to generate a PN code is given by N, the period L (length) of the shift-register code can be as long as:

$$L = 2^N - 1 \tag{4}$$

Not all LFSRs and hence not all characteristic polynomials produce a maximal PN pattern. It is the property of primitiveness of the characteristic polynomial that assures maximal length of the generated code. The maximum length is one less than 2^N since 'all zeros' in the shift register does not produce a pattern other than zero.

A maximal-length sequence for a shift register of length N is referred to as an m-sequence. Such sequences can be created by applying a single shift register with a number of specially selected feedback-taps. An 18-stage shift register is shown in figure 3-2 with *n* selectable taps.

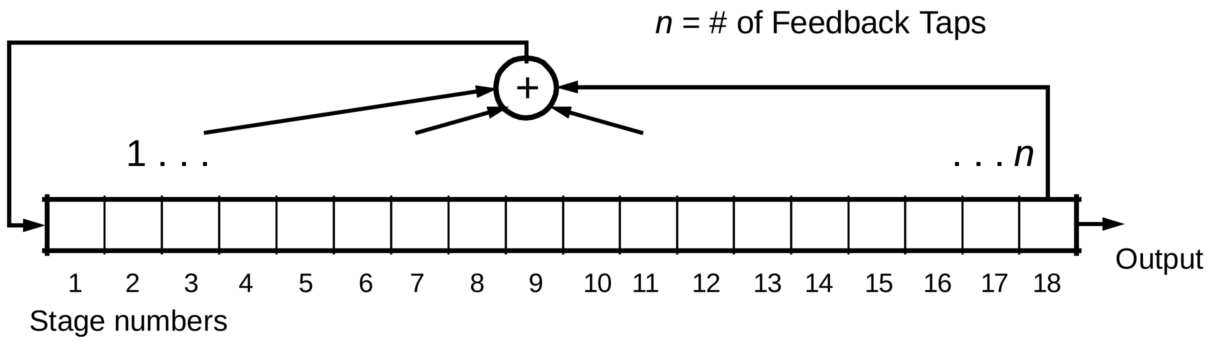

Figure 3-2: Maximal-Length Code Generator

The number of possible codes is dependent on the number of possible sets of feedback-taps that produce an m-sequence. Maximal sequences have a number of special properties. Some of those properties which will be used in the code selection process are:

– m-sequences are balanced: the number of ‘ones’ exceeds the number of ‘zeros’ by only 1.

– The spectrum of an m-sequence has a sinc^2 envelope. (the lack of spectral spikes is important for CDMA)

– The shift-and-add property can be formulated as follows:

$$T^k u = T^i u \oplus T^j u \tag{5}$$

where u is an m-sequence, $\oplus$ is a bit by bit exclusive OR, T is the shift of the sequence, and by combining two shifts of this sequence (relative shifts i and j) the same m-sequence is obtained, yet with another relative shift, k.

– The un-normalized autocorrelation function is two-valued:

$$r_{uu}(T) = \begin{cases} L = 2^N - 1 & T = kL = k(2^N - 1) \\ -1 & T \neq kL = k(2^N - 1) \end{cases} \qquad k = 0, 1, 2, \ldots \tag{6}$$

where k is an integer value, and T is the relative shift (r_{uu} not normalized).

There is no general formula for the cross-correlation of two different m-sequences, so exhaustive computer analysis is required for choosing those sequences with the lowest cross-correlation. Only some rules can be formulated.

Gold and Kasami showed that for certain well-chosen m-sequences, the cross-correlation takes on only three possible values, namely -1, $-t$ or $t-2$, where

$$t(N) = \begin{cases} 2^{(N+1)/2} + 1 & for\, N odd \\ 2^{(N+2)/2} + 1 & for\, N even\ but\ N \neq (0 \bmod 4) \end{cases} \quad (7)$$

This is referred to as Gold's theorem. Two such sequences are called *preferred sequences*. Here t depends solely on the length, N, of the LFSR used. Preferred pairs for shift-registers with a length equal to $4k$, where k is an integer, do not exist.

A zero third moment (discussed further in 3.9) is another characteristic that is desirable for m-sequence codes used in DSSS. The third moment of a code is a measure of its symmetry or its skew.

3.7.2 MAXIMAL-LENGTH CODES HAVE AN EVEN NUMBER OF TAPS

Since a register with N cells can contain 2^N different bit patterns, but the 'all-zeros' condition is the only one that must not be used, the length of a maximal-length pattern (if it exists) is $L = 2^N - 1$.

If the number of taps is odd and the register contains all 'ones', the output of the exclusive OR and thus the register input will be '1'. In this case the pattern generated would be 'all one' forever, which has a repeat length of 1, not $2^N - 1$.

So for an odd number of taps, a register content of 'all zero' and 'all one' would have to be eliminated, resulting in a pattern length less than $2^N - 2$ and thus not maximal. This implies that the characteristic polynomial will have an odd number of terms.

3.7.3 GENERATING A REVERSE CODE

A code and its reverse (same code but running in the opposite direction, also called mirror code) are both valid codes and have the same properties (the same third-moment values for example). To generate the reverse code, the taps are flipped left to right; for example, if one code tap set is '10011011', the complement is '11011001'. In terms of the polynomial representation,

$$g(x) = x^7 + x^6 + x^4 + x^3 + 1 \quad (8)$$

becomes

$$g(x) = x^7 + x^4 + x^3 + x^1 + 1 \quad (9)$$

3.8 GOLD CODES

Gold sequences form a large class of sequences that have good periodic cross-correlation properties. Gold codes are not orthogonal, but have low cross-correlation at arbitrary delay, T.

Hence Gold codes perform well for systems with asynchronous data and spreading code. Gold Codes contain fixed feedback-tap locations and user-specific initial conditions.

Gold codes are constructed by EXOR-ing two preferred m-sequences of the same length with each other as shown in figure 3-3 and section 5. Thus for a Gold sequence of length $L = 2^N - 1$, two LFSRs are used, each with N cells. If the LFSRs are chosen appropriately, Gold sequences have better cross-correlation properties than maximum-length LFSR sequences.

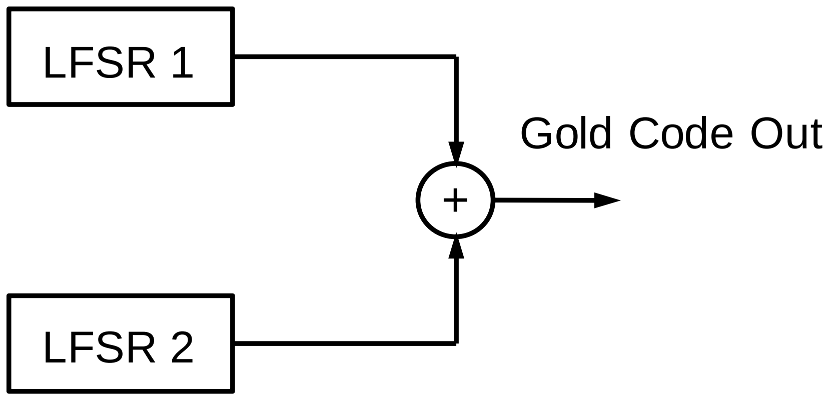

Figure 3-3: Gold Code Generator

Gold showed that the cross-correlation of any pair of codes from a given register pair take on only three values, −1, $-t$, and $t-2$, where t is defined in equation 7. Cross-correlations between codes from different register pairs do not have good correlation properties, requiring a computer search to find desirable register pairs. Autocorrelation values are not two-valued as for m-sequences, but instead, in addition to the peak value of L, they take on the same three values of the cross-correlation function. Hence autocorrelation is bounded by t. Proakis (reference [5]) has a table 12.2-1 showing that for $N \geq 10$, cross-correlation peaks for m-sequences can be as high as 0.37 of the autocorrelation peak, while for Gold codes, the ratio is only 0.06. Even though Kasami codes have better cross-correlation properties than Gold codes, an unexpected result is that the signal-to-noise performance of asynchronous DSSS depends more on code period and set size than on cross-correlation parameters.

The number of codes available for a given set of shift registers is two more than for a single maximal pattern shift register; the number of codes is 2^N+1. For a fixed initial value in one of the registers, there are 2^N values that can be the initial value in the other register. In this case one register can have an initial value of ‘all zeros’ since the output of the XOR will be nonzero. It will be the pattern generated by the other shift register. And finally, the other register can be set to ‘all zeros’, resulting in the pattern from the register that is initialized with a nonzero value. For the codes chosen in the CDMA Recommended Standard, one register is always initialized with a nonzero value, limiting the number of codes to 2^N. Selected codes are further limited based on other properties.

3.9 CHOOSING CODES, MAXIMAL AND GOLD

The forward command link uses a short (N=10) Gold code in order to keep the time to acquire the code short. Short maximal codes have poor cross-correlation.

For Ranging, long codes are needed for position ambiguity resolution. The time to acquire the forward long code is kept short by its synchronization with the short forward Gold code. For long m-sequences, cross-correlation peaks are relatively small.

Time to acquire the return long-range code is aided by an approximate knowledge of the user range, which can be used to limit the correlation search and keep acquisition time short.

Short (N=11) Gold codes for are selected for a non-coherent return link for which no a-priory knowledge is available.

It is unusual for the correlation process to use the full length of the long ranging codes; generally a partial autocorrelation of some length M is done, where $M < L$. It is therefore important that the chosen m-sequences have good partial autocorrelation properties. The third moment is a measure of the distribution or skew of the 1s and −1s in the code. A third moment close to zero is preferred and is defined as:

$$S^3 = \frac{1}{L}\sum_{n=0}^{L-1}\left(\sum_{i=0}^{M-1} g_{n+i}\right)^3 \qquad (10)$$

where $\{g_i\}$ are the sequence values, +1 and −1, M is the subsequence length, and L is the total length of the code. Ideally the inner sum would be zero, but at a practical level they should have a similar value for all n. In the code library, the maximal codes have been ordered by their third-moment values, where the lower the third-moment value, the lower they are in the assignment list. The study of the third moment showed that values of third moment closest to zero are desired because these codes produce a more random subsequence and are therefore less susceptible to false lock at an erroneous time (phase) offset.

Spurious codes are caused by the filtering and hard-limiting of a Staggered Quadrature Pseudo-random Noise (SQPN) signal. These can cause a problem: if a spurious code matches an assigned code, then false lock can occur. The code assignments were generated where the I and Q spur codes do not duplicate any of the generated I or Q channel codes based on the initial conditions.

All of the codes in a particular family are generated from a single circuit or a related set of circuits. Circuits to generate maximal-length codes differ only in the feedback taps of the circuit.

3.10 SUMMARY

PN maximal codes are a possible choice for DSSS because of their good autocorrelation and (sinc) spectrum but they can have poor cross-correlation properties. Preferred pairs of maximal codes have better and predictable cross-correlation properties. Gold code families formed from preferred pairs have the useful property of the preferred pairs.

4 ALGORITHM FOR SELECTING PRIMITIVE POLYNOMIALS

Not all LFSRs and hence not all characteristic polynomials produce a maximal PN pattern. It is the property of primitiveness of the characteristic polynomial that assures maximal length of the generated code. A primitive polynomial is irreducible; like a prime number, it is divisible by only one and itself. Although much work has been done on maximal-length codes, of the published tables available at the time this work was done, a complete listing of primitive polynomials of order 18 was not found.

Therefore software was written to test all possible codes meeting system requirements for primitiveness following the procedure described herein. The results stated in tables 4-1 and 4-2 were determined using the techniques describe below.

Table 4-1: Number of Maximal-Length Codes That Meet Return Coherent Requirements

Number of Feedback Taps	Possible Maximal-Length Codes	Maximal-Length Codes that meet Return Coherent Chip Offset Criteria	Left over Maximal-Length Codes for Forward Ranging
10	2910	2045	866
12	1470	1083	387
Sum	4380	3128	1252

Table 4-2: Number of Maximal-Length Codes Available for Forward Ranging Codes

Number of Feedback Taps	Total Possible Ranging Codes	Codes Allocated to Another Library	Ranging Codes Available for CCSDS
8	2296	1650[1]	646
10	2910	2045[2]	865[3]
12	1470	1083[2]	387[3]
Sum	6676	4778	1898[4]

[1]Codes are already allocated to the SNIP return coherent link maximal-length codes.
[2]Codes are already allocated to the CCSDS return coherent maximal-length codes.
[3]Codes that do not fit the criteria for return coherent maximal-length codes because of spurious QPSK effects, but can be used on forward UQPSK link.
[4]Sum is greater than the 1252 left over since codes with eight taps are also included.

Two basic facts about shift registers' producing maximal-length codes can be employed to eliminate codes and decrease the set to be studied:

a) there must be a tap in the register corresponding to the highest order (output) coefficient of the characteristic polynomial (definition of shift-register length); and

b) there must be an even number of taps (3.7.2), which implies an odd number of terms in the polynomial.

Using these criteria alone, combinational analysis will show that it is possible to construct 19448 codes using eight taps (${}_{17}C_7$ = $\binom{17}{7}$ = 19448), 24310 codes using 10 taps (${}_{17}C_9$ = 24310), and 12376 codes using 12 taps (${}_{17}C_{11}$ = 12376). When all three cases are allowed, a total of 56134 codes are available. When only 10 or 12 taps are allowed, a total of 36686 codes are available. However, these will not necessarily guarantee m-sequences or exhibit other desirable properties.

For a shift register to produce a code of maximal length, the corresponding characteristic polynomial must be primitive, which implies that it also must be irreducible. Software was written to test each possible polynomial for irreducibility. It was found that 2296 polynomials of 9 terms (corresponding to a shift register of 8 taps) were irreducible, and that 4380 polynomials of 11 or 13 terms (corresponding to a shift register of 10 or 12 taps) were irreducible.

5 CONVERTING PN CODE LIBRARY PARAMETERS TO PN CODES

5.1 CRITERIA AND SELECTION REQUIREMENTS

CCSDS services use Gold codes and maximal-length codes for various services. This section provides details on specific PN code properties, generation criteria, code selection for each of the services that use PN spread modulation, and examples for interpreting the PN code library. Throughout this document, and in this section in particular, code generation that applies to the PN code library is shown in terms of shift registers. This is not intended to imply a particular design, since current and future implementation, often in Field-Programmable Gate Arrays (FPGAs), may use other methods.

5.2 GOLD CODES FOR CCSDS SYSTEMS

5.2.1 GENERAL

Gold Codes are used by CCSDS in the forward I channel (command link) and return non-coherent links. The forward and return channels use different Gold code generator structures with a 10-stage shift-register set used for the forward channel and an 11-stage shift-register set used for the return channel. Short codes allow for quicker PN acquisition than a long code. Within each forward and return set, the codes differ only in the initial conditions of one shift register. The following subsections explain Gold codes used in these links in detail.

5.2.2 COMMAND LINK GOLD CODES

5.2.2.1 General

Figure 5-1 provides the Gold code generator configuration used in the forward command link. Command link shift registers use two common-clock registers of length 10. The feedback taps are the same for all users, and the codes differ only in the initial conditions of register A. For CCSDS command link, the initial conditions are given in the PN Code Library, Table C1 (published separately).

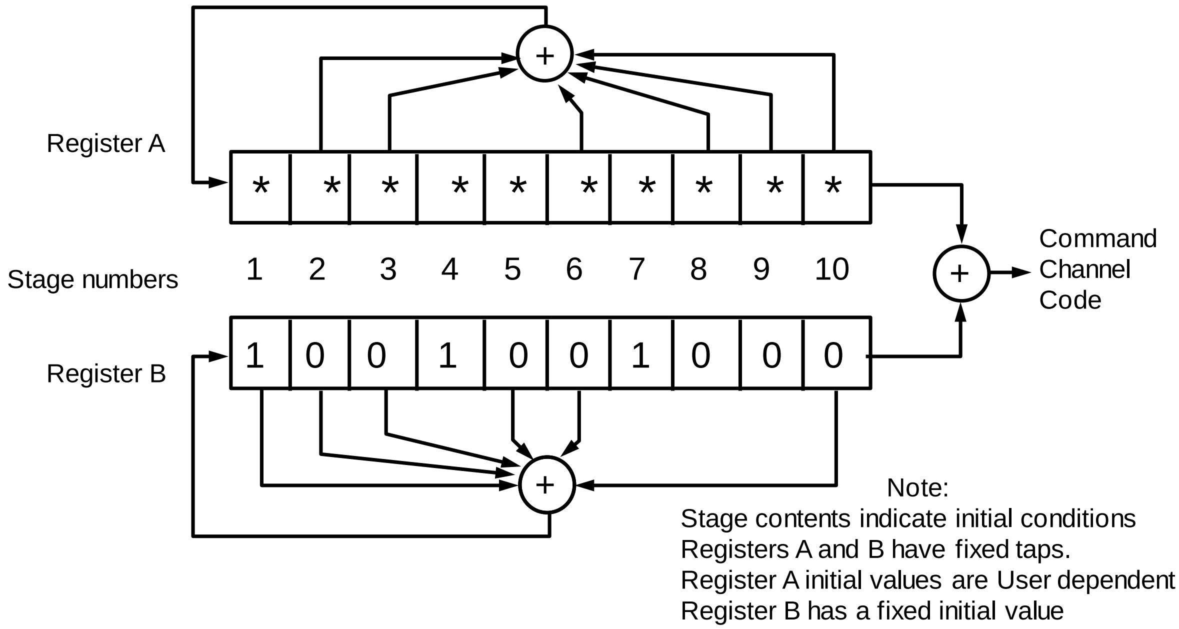

Figure 5-1: CCSDS Command Link Gold Code Generator

5.2.2.2 Command Link—Available Codes

The set of Gold codes corresponding to this shift-register set hold the following properties:

a) A total of 2^{10} = 1024 sequences (codes) can be generated by altering the initial conditions of only one of the shift registers. With Gold codes, register A can be set to 'all zeros'. This setting would not be allowed for a single register used for a maximal code.

b) Each code is $2^{10}-1$ = 1023 symbols long.

c) Of the 1024 possible codes, 767 are balanced codes (see 5.2.2.3); i.e., each code has 512 'ones' and 511 'zeros'. (All 1024 codes were generated, and the 'ones' and 'zeros' were counted. 512 'ones' and 511 'zeros' were true for only 767 of the 1024 possible codes.)

5.2.2.3 Command Link—Code Criteria

Balance and low cross-correlation values are considered as the selection criteria for the forward command link PN code libraries. A balanced code is one in which the number of 'ones' is one more than the number of 'zeros'. This type of code is preferable because of its smooth sinc^2 transmitted spectrum. It is also desirable to use codes that are 'unique', which is accomplished by choosing codes with low cross-correlation values. Because command codes are Gold codes, they have minimum cross-correlation values. Not only are the correlation side lobes small compared to the maximum autocorrelation value (2^N-1), but the frequency of occurrence of correlation lobes is also relatively small.

5.2.2.4 Command Link—Code Example

The command link code libraries were modeled after the shift-register set shown in figure 5-1. Figure 5-2 depicts an example of a forward command channel code generator configuration with initial conditions for a specific code library selection.

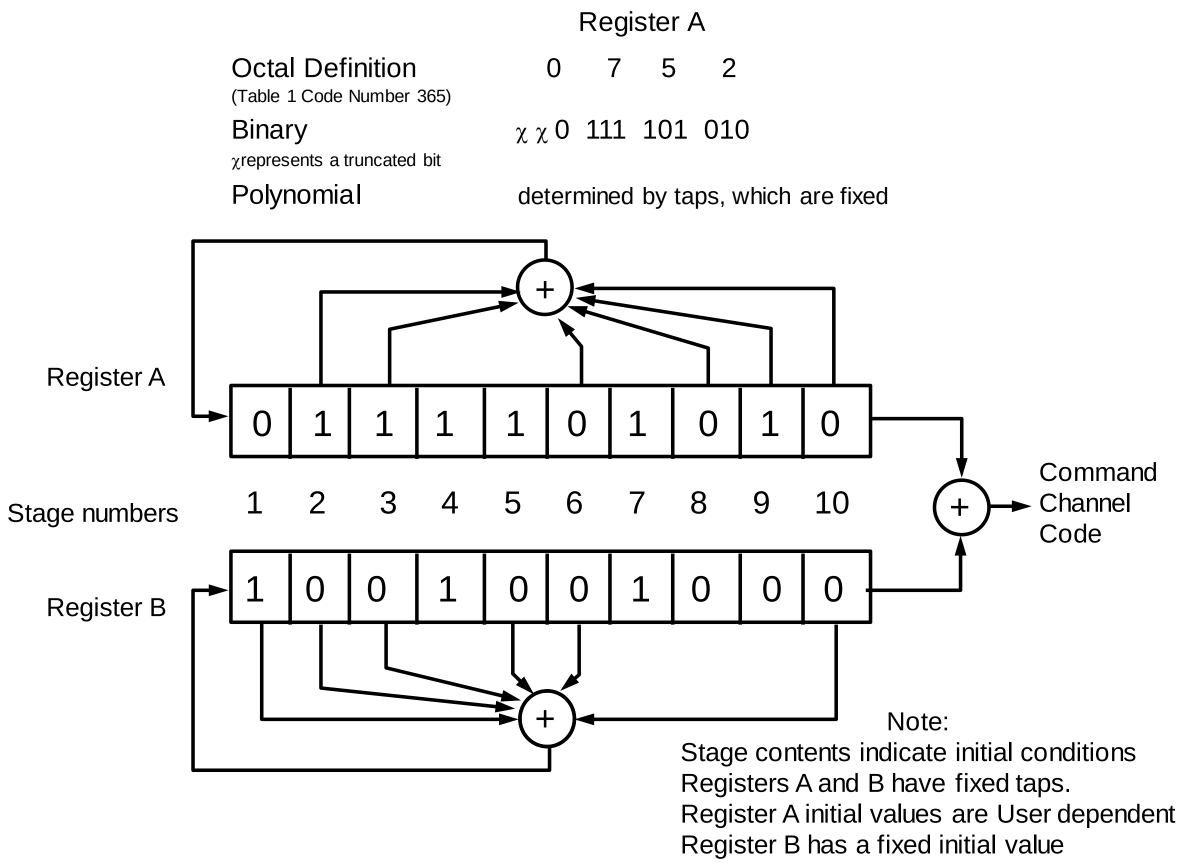

Figure 5-2: Example Command Link Gold Code Generator Initial Conditions

5.2.3 RETURN NON-COHERENT LINK GOLD CODES

5.2.3.1 General

The return non-coherent link uses Gold codes that are shorter than the maximal-length ranging code for their good cross-correlation properties and in order to allow for quick acquisition. Figure 5-3 provides the Gold code generator shift register used in the return link. The return link shift register uses three common-clock registers of length 11. The feedback taps are the same for each user. The codes differ only in the initial conditions of registers A and C for each user.

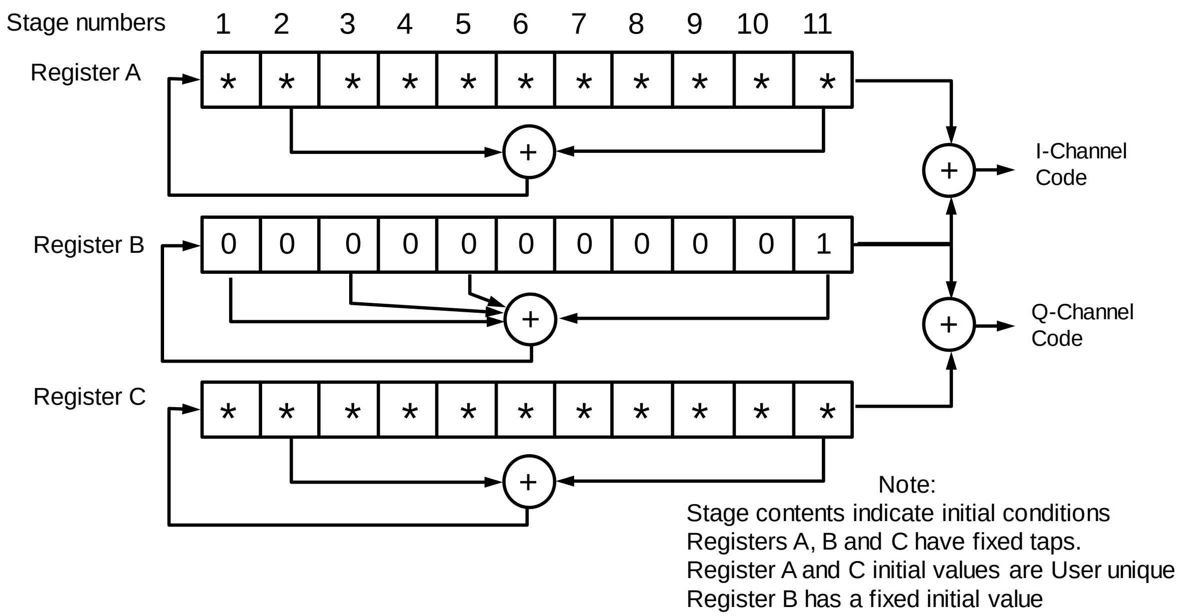

Figure 5-3: Return Link Non-Coherent PN Gold Code Generator

5.2.3.2 Return Non-Coherent Link—Available Codes

The set of Gold codes associated with this shift-register set has the following properties:

a) There are 2^{11} = 2048 codes generated (for each of the I and Q channel) by altering the stage contents of one of the two shift registers (register A for the I channel codes and register C for the Q channel codes). With this register structure, A and C can be set to 'all zeros', and a PN code is still generated. The 'all zeros' selection, however, is not used.

b) Each code is $2^{11}-1$ = 2047 symbols long.

c) Of the 2048 codes, there are 2^{10} = 1024 balanced codes in the set. Since registers A and C have the same feedback taps and the I and Q output receives the same pattern from register B, the available I and Q codes are members of the same Gold code set. The library selections are such that registers A and C have different user initial values, so the codes in each pair are not the same. Since the 'all zeros' selection is not used, the result is 511 code pairs.

5.2.3.3 Return Non-Coherent Link—Code Criteria

The following four criteria are considered in the selection of the non-coherent return link PN code libraries: balance, low cross-correlation values, no duplicate code assignments, and minimized spurious code effects. A balanced code is preferable because it will have a smooth transmitted spectrum. It is also desirable to use codes that are 'unique', which is accomplished by choosing codes with low cross-correlation values. Because these codes are

Gold codes, they have minimum cross-correlation values. Not only are the side lobes small compared to the maximum autocorrelation value (2^N-1), but the frequency of occurrence is also relatively small. To avoid interference, I or Q code assignments should not be duplicated. Spurious codes are caused by the filtering and hard-limiting of a SQPN signal. If a spurious code matches an assigned code, false lock may occur and thus cause interference. To avoid this type of interference, codes are selected to ensure that such spurious code matches are not generated (see 3.9).

It has been shown that if the Q channel sequence is delayed 1/2 chip (SQPN), then the spurious sequences generated on the I and Q channels because of filtering and hard-limiting are:

– I channel spur = $i \oplus q \oplus q_1$;

– Q channel spur = $q \oplus i_{-1} \oplus i$;

where i and q are the binary sequences on the I and Q channel respectively, q_1 is the q sequence delayed by one chip and i_{-1} is the i sequence advanced by one chip.

In figure 5-3, registers A and C are identical, so I and Q are members of the same Gold code set.

Term-by-term modulo-2 additions of two members of a set of PN codes results in another member of the same PN code set. From the equations above, it is obvious that the spurious codes which occur on the I and Q channels are also members of the same set of Gold codes and therefore are capable of causing false lock. To avoid the possibility of false lock, the choice of I and Q channel code pairs must be made so that the spurious codes on the I and Q channels do not duplicate any of the 510 gold codes in the non-coherent return-link libraries. A detailed analysis of spurious codes can be found in the literature.

5.2.3.4 Return Non-Coherent Link—Code Example

The non-coherent return link code libraries were modeled after the shift-register set shown in figure 5-3. There are no restrictions on the initial conditions of registers A and C. The initial conditions are expressed as four-digit octal numbers. Each octal digit is converted to its 3-bit binary representation, giving a 12-digit binary number. Since the shift-register design uses only 11 cells each, the most significant digit is truncated. Figure 5-4 shows example initial conditions of registers A and C for the generator shown in figure 5-3.

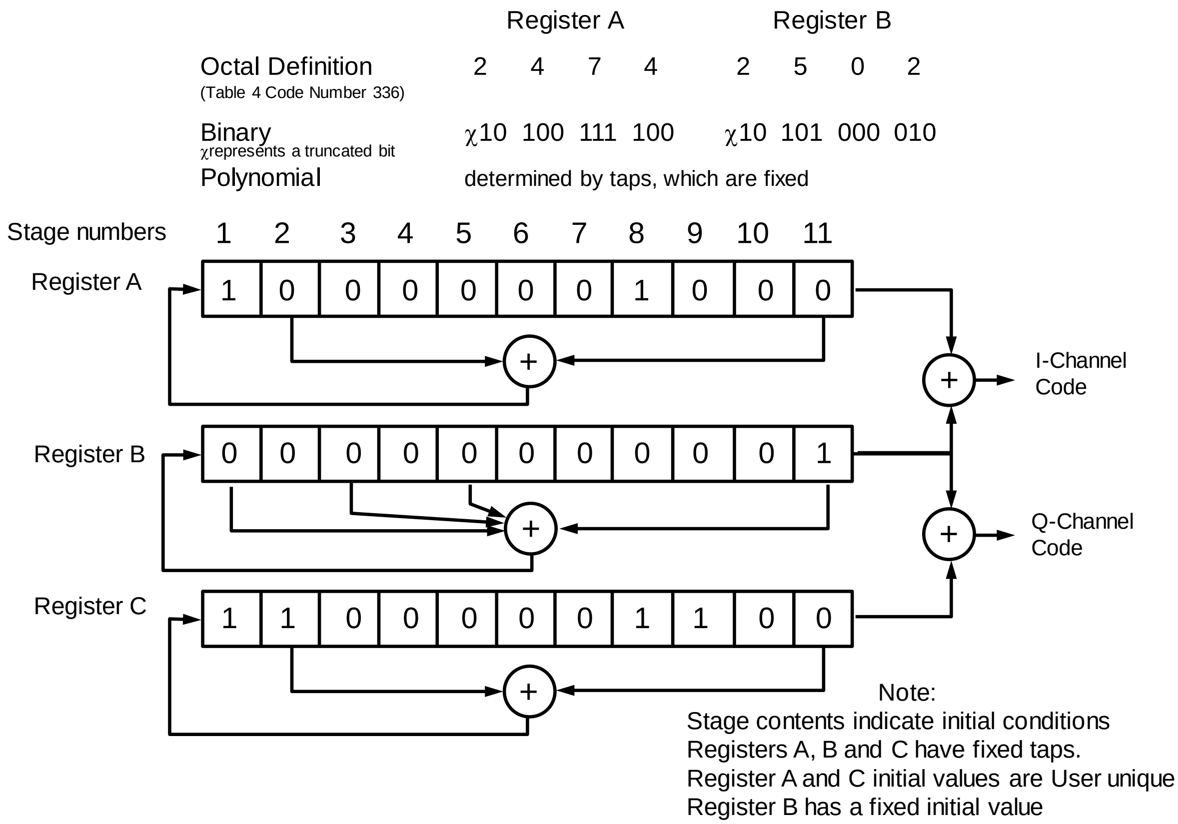

Figure 5-4: Example Return Link Non-Coherent Gold Code Generator

5.3 MAXIMAL-LENGTH CODES

5.3.1 GENERAL

Maximal-length codes are used on both the forward range channel and coherent return, (I channel only when Q not spread) for ranging and time transfer.

Sets of maximal-length codes (m-sequences) are produced by varying the feedback tap locations, given the constraints on the total number of taps. The set from which the ranging code libraries are selected is restricted to the possible tap combinations with 8, 10, or 12 taps. The set from which the return coherent link code libraries are selected is restricted to code possibilities with 10 or 12 taps. As discussed in 3.7.2, only an even number of taps are used for maximal codes.

5.3.2 FORWARD RANGE CHANNEL CODES

5.3.2.1 General

The network element transmitter is always used for commanding via a PN spread short code. When it is also used for ranging, the range channel is PN spread with the long range code and the modulation is QPSK (where the I and Q channels have a 10:1 power ratio, UQPSK, but are not staggered—see figure B-5a). The shift register used to generate the range channel codes is an 18-stage register with as many as 12 tap connections, as shown in figure 5-5.

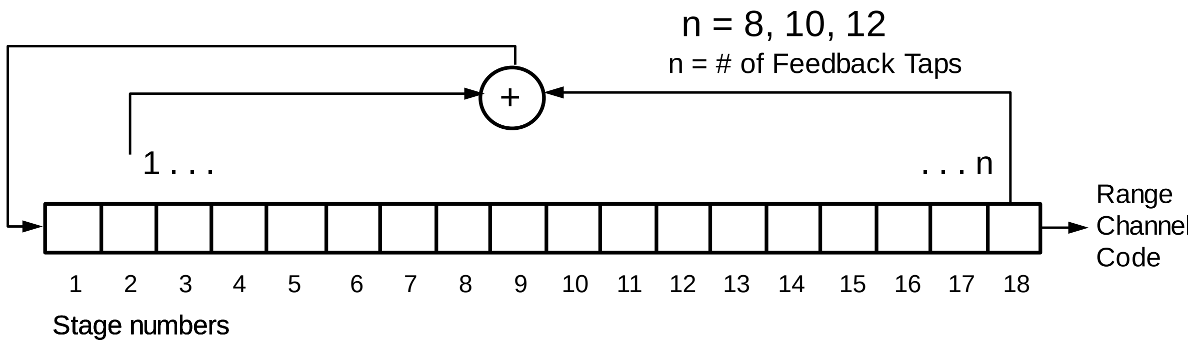

Figure 5-5: Range Channel Code Generator

5.3.2.2 Forward Range Channel—Available Codes

The initial conditions for the ranging code shift register depicted above are the same for each code. The codes differ in their unique feedback tap assignments. Libraries of codes were selected from the set having the following properties:

a) Codes are of length $2^{18}-1 = 262143$.

b) Codes are truncated to an integer multiple (256) of the 1023 command code length, 1023*256 = 261888. Thus the last 262143−261888=255 bits of the code are not generated before the shift register is reset to its initial 'all ones' condition. This truncation process permits rapid acquisition of the longer code since only 256 of its phases need to be searched for correlation. The 'all ones' initial condition of the register is synchronized to the '1001001000' state of the B register of the command channel code generator as shown in figure 5-1.

c) 1898 maximal-length codes meet the required criteria using 8, 10, or 12 taps.

5.3.2.3 Forward Range Channel Code Criteria

The following criteria were considered in the selection of the forward ranging channel PN code libraries: maximal length and balance. Maximal-length codes are required to ensure that the full transmitted sequence of 261888 bits (truncated from 262143) is not a repeated periodic subsequence, thus avoiding false lock. Maximal-length codes are produced by corresponding primitive polynomials, shown in the shift-register version in figure 5-5. (See 3.7 for a detailed description of the criteria for producing maximal-length codes.)

Additionally, maximal-length codes exhibit the favorable property of balance, which ensures a smooth transmitted spectrum. Balance is defined as having one more ‘one’ than ‘zero’. For the Ranging Codes, however, the full code is not transmitted; thus the truncated balance is of interest. The balance of the truncated code produced for the forward ranging channel is at most off by a factor of 255/262143, approximately 0.1%. Thus it is assumed that all codes are ‘essentially’ balanced.

5.3.2.4 Forward Range Channel—Code Example

The range channel code libraries were modeled after the shift register in figure 5-6, which produces a maximal-length pattern. This figure also shows the relationship between the octal definition of the code, as listed in the libraries, and the corresponding shift register feedback tap locations.

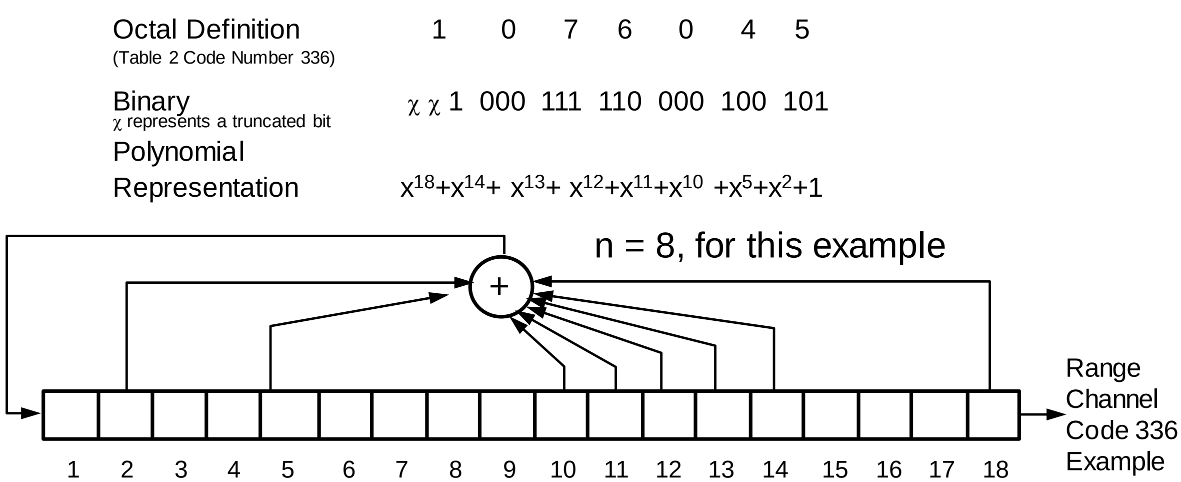

Figure 5-6: Example Range Channel Code Feedback Taps

5.3.3 RETURN COHERENT LINK CODES

5.3.3.1 General

Figure 5-7 shows the shift register used to generate the maximal-length codes for the return coherent links.

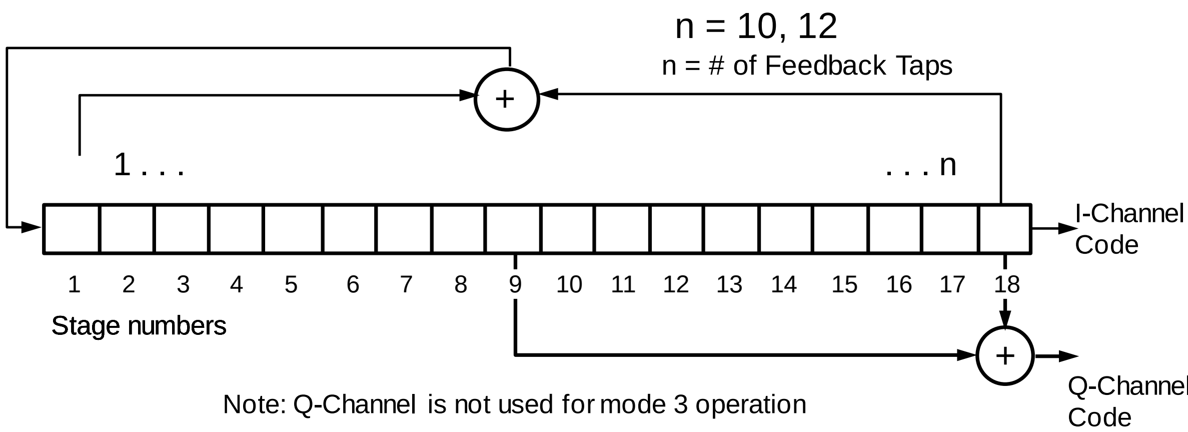

Figure 5-7: Return Coherent Link Code Generator

5.3.3.2 Return Coherent Link—Available Codes

The above shift register is an 18-stage linear shift register utilized for the return coherent link codes. The Q channel code is generated by modulo-2 summing the 9th and 18th stages, as shown in the figure above. The assigned codes differ in their unique feedback tap assignments. The maximum number of feedback taps for an assigned code is 12. The initial conditions are the same for each code, an ‘all ones’ condition. Libraries of codes were selected from the set having the following properties:

a) Codes are of length $2^{18}-1 = 262143$.

b) Codes are truncated to 261888 to synchronize the shift register with the forward range channel. Thus the last 262143−261888 = 255 bits of the code are not generated before the shift register is reset to its initial ‘all ones’ condition.

c) 3128 maximal-length codes are available when using 10 or 12 taps.

5.3.3.3 Return Coherent Link—Code Criteria

The following criteria were considered in the selection of the return coherent link PN code libraries: maximal length, balance, a channel offset in excess of 20000 chips, and minimized spurious code effects. Maximal-length codes are produced by shift registers with corresponding primitive polynomials as depicted in the return coherent link feedback tap example of figure 5-8. Maximal-length codes assure certain favorable properties.

A balanced code is desired because of its smooth transmitted spectrum. In the case of maximal-length codes, the balance is assured when there is one more ‘one’ than ‘zero’. The full code is not transmitted; rather, it is the truncated balance that is of interest. The balance of the truncated code produced for the return coherent link channel is at most off by a factor of 255/262143, approximately 0.1%. Thus it is assumed that all codes are ‘essentially’ balanced. Since dual channels are used for one of the coherent mode operations, assigned codes must have an I-to-Q (or Q-to-I) channel difference greater than 20,000 chips to avoid channel ambiguity. As depicted in figure 5-7, the I and Q channel codes are simultaneously generated by the same shift register. The Q channel code is the modulo-2 addition of two phase shifted versions of the I channel code. Employing a basic property of binary maximal-length sequences, the Q channel is simply a shifted version of the I channel.

In order to minimize the spurious code effects created by filtering and hard limiting, a minimum offset of 5000 chips is imposed between the codes and the spurious codes generated. This is necessary to avoid interference, because the spurious codes are simply a shifted version of the channel codes. This relationship is obvious by the shift and add property given in the equations below:

- I channel spur = $i \oplus q \oplus q_1$;
- Q channel spur = $q \oplus i_{-1} \oplus i$,

  where i and q are the binary sequences on the I and Q channels respectively, q_1 is the q sequence delayed by one chip and i_{-1} is the i sequence advanced by one chip.

5.3.3.4 Return Coherent Link—Code Example

The return coherent link code libraries were modeled after the shift register in figure 5-7. The relationship between the octal definition of the library codes and the corresponding shift register feedback tap locations is seen in figure 5-8. All remaining code assignments adhere to the specified criteria.

The return coherent link code assignments are listed in the CCSDS PN code library.

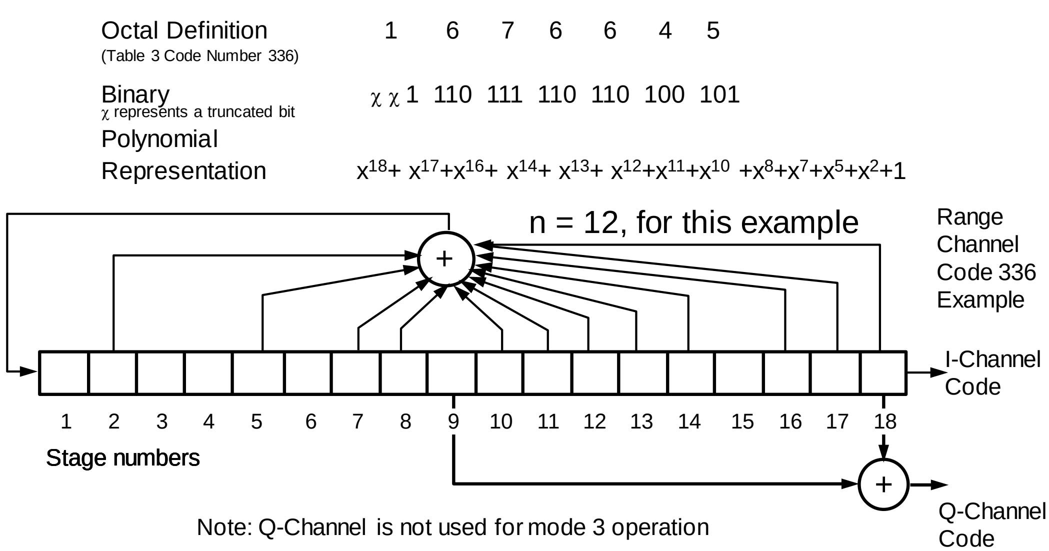

Figure 5-8: Example Return Coherent Link Feedback Tap

ANNEX A

SUMMARY OF PN CODE IMPLEMENTATION
FOR 2-GHZ BAND LINKS

	Forward	Channel	Return
Coherent (Transponder only)	Command Channel 1023 length Gold code (short code)	I	261888 length PN (truncated maximal $2^{18}-1$, different from Fwd)
	Range Channel 218−1=262143 maximal truncated to 261888 = 256 × 1023 coherent with short code	Q	261888 length PN (same as I channel but offset by > 20,000 chips)
Non-Coherent (Transponder or Transceiver)	Same as Coherent	I	2047 length Gold code
	Since range channel not needed when Non-Coherent, PN spread BPSK with Command channel only can be selected	Q	2047 length Gold code Different from I channel
Hybrid (Transponder only)	Same as Coherent	I	(same as coherent except Q channel not spread) 261888 length PN (truncated maximal $2^{18}-1$, different from Fwd)
		Q	Not Spread (data rate > 300 ks/s)

ANNEX B

SPREAD SPECTRUM AND CODE DIVISION MULTIPLE ACCESS

B1 INTRODUCTION

With conventional satellite commanding, a signal is sent from the ground to the satellite in space (uplink signal is away from the Earth) and telemetry is sent from the spacecraft to the ground (downlink toward the Earth). Command data rates are generally of the order of 1 kb/s and are transmitted at high power, while telemetry rates are higher and are limited in power because of limited spacecraft resources. This results in a high Power Spectral Density (PSD) for the uplink, or 'forward link' (Fwd) signal, which is emitted away from the Earth, and a lower PSD for the downlink, or 'return link' (Rtn) signal, which is emitted toward the Earth. When using a relay satellite at Geosynchronous Earth Orbit (GEO) altitude and a user satellite in Low Earth Orbit (LEO), the Fwd signal is emitted from the relay toward the Earth and would violate PSD regulatory levels. Even though the Rtn link PSD is generally lower than the Fwd link, LEO satellites are very close to the Earth and a Rtn signal that is strong enough to reach the relay satellites at GEO would often also violate PSD limits. Spreading the spectrum solves PSD problems for both directions but consumes a wide bandwidth. Fortunately, signals can be distinguished by using different spreading codes, allowing for CDMA. The spreading codes allow many satellites to use the same frequency with overlapping signals, simultaneously. Once it is decided to use spread spectrum, range measurements using the PN spreading code are a natural benefit, as is the use of the code for time transfer, and provide some level of security. If the system is coherent, then Doppler tracking can be performed.

The Space Network Interoperable Panel (SNIP) was an agreement among three space agencies: NASA, ESA, and JAXA (formally NASDA). The Panel established a CDMA protocol for near-Earth Relay Satellite links, and it is used in the NASA TDRSS Space Network (reference [6]). The technical aspects of the SNIP agreement are the basis for the CDMA Recommended Standard (reference [1]). However, a new family of PN spreading codes has been developed specifically for CCSDS agencies. These codes have been developed to be compatible with the SNIP codes.

This annex provides the background information associated with implementing PN spread modulation modes. Subsection B2 provides a basic introduction to spread-spectrum modulation concepts, emphasizing the Direct Sequence Spread Spectrum (DSSS) approach addressed in the Recommended Standard. Subsection B2 discusses implementation of DSSS modulation at the system level, including also a discussion of PN code selection. Subsection B3 provides relevant information concerning the PN spread modulation modes used in NASA's Space Network. These subsections form the basis for the PN spread modulation system and subsystem-level requirements given in B4.

B2 INTRODUCTION TO SPREAD SPECTRUM MODULATION CONCEPTS

B2.1 BASIC PRINCIPLES OF SPREAD SPECTRUM

Spread spectrum is a family of communications techniques in which the RF bandwidth used to transmit a given data signal is much wider than what would normally be used with non-spread-spectrum modulation techniques. Figure B-1 is a general block diagram of a spread-spectrum communication system.

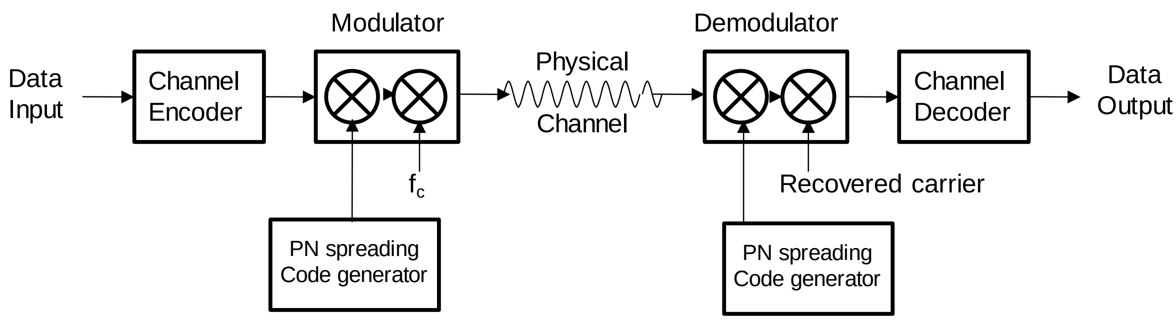

Figure B-1: Spread Spectrum Digital Communication Model

As specified in the CDMA Recommended Standard (reference [1]), the PN code data rate (chip rate) is a function of the Fwd or Rtn carrier frequency. At the user spacecraft, the PN rate is seen as:

$$R_{PN} = (31/(221 \times 96))\, f_{Fwd} = (31/(240 \times 96))\, f_{Rtn} \quad (11)$$

Because of the Doppler effect, the PN rate seen on the Rtn at the ground station will not equal the rate transmitted by the ground station. Neglecting the Doppler effect, for user frequencies across the 2200 to 2300 MHz band, the PN rate will vary from R_{PN} = 2.960 to 3.095 Mc/s. For a Rtn carrier frequency in the center of the band, at 2250 MHz, this results in a rate of R_{PN} = 3.027 Mc/s.

B2.2 SPREAD SPECTRUM TRANSMITTER

Figure B-2 is a linear voltage spectrum of a modulated but un-spread signal and a spectrum of a spread and modulated signal. The signal at the transmitter is clearly identifiable since there is no noise, but at the receiver the spectrum of the spread signal is generally below the noise background and hence often cannot be seen on a spectrum analyzer at the receiver. In addition, when signals are spread by different spreading codes (different PN patterns) a receiver set for a particular code will be able to select that code, since the other signals will be indistinguishable from the noise background. This condition allows for CDMA, where several signals all use the same carrier frequency.

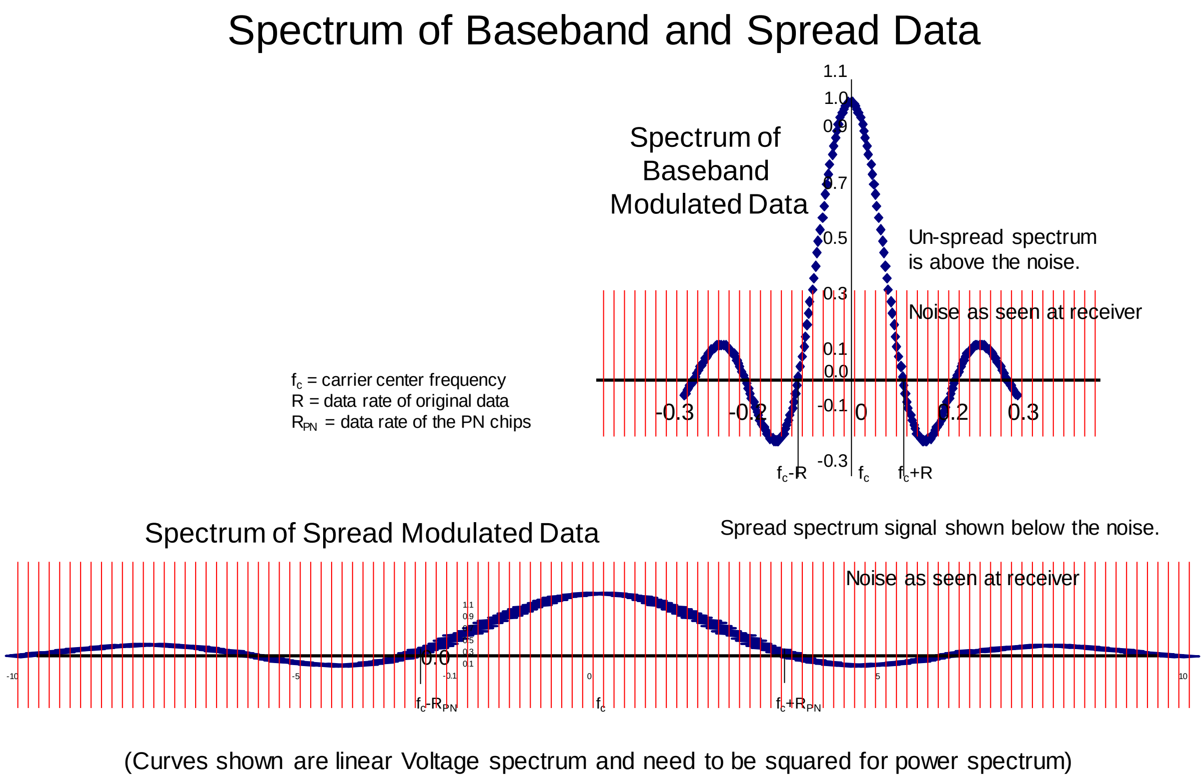

Figure B-2: Spectrum of Baseband and Spread Data

To accomplish the spectrum spreading, a pseudo-random data pattern is used to convert data at its initial data rate to a much higher data rate. For a given transmit power, the area under the power spectrum curve is the same for the spread and un-spread transmission. Since the null-to-null spacing is a function of the modulation symbol rate, for spread data, the spectrum is much wider, at least 10 times as wide for the CCSDS specification. Hence the peak spectral density of the power spectrum is less than 1/10 the level of the un-spread spectrum. In figure B-3, a factor of approximately 5 is used to keep the figure simple, but an actual system would use a factor of 10 or greater; and for the CCSDS specification, the spreading factor is not an integer product of the data rate.[1] The PN spreading pattern is deterministic, periodic, and known by both the transmitter and receiver. It is independent of the data signal and is chosen to appear as random as possible.

[1] For some systems such as GPS and cell phones, the spreading factor is an integer product of the data rate.

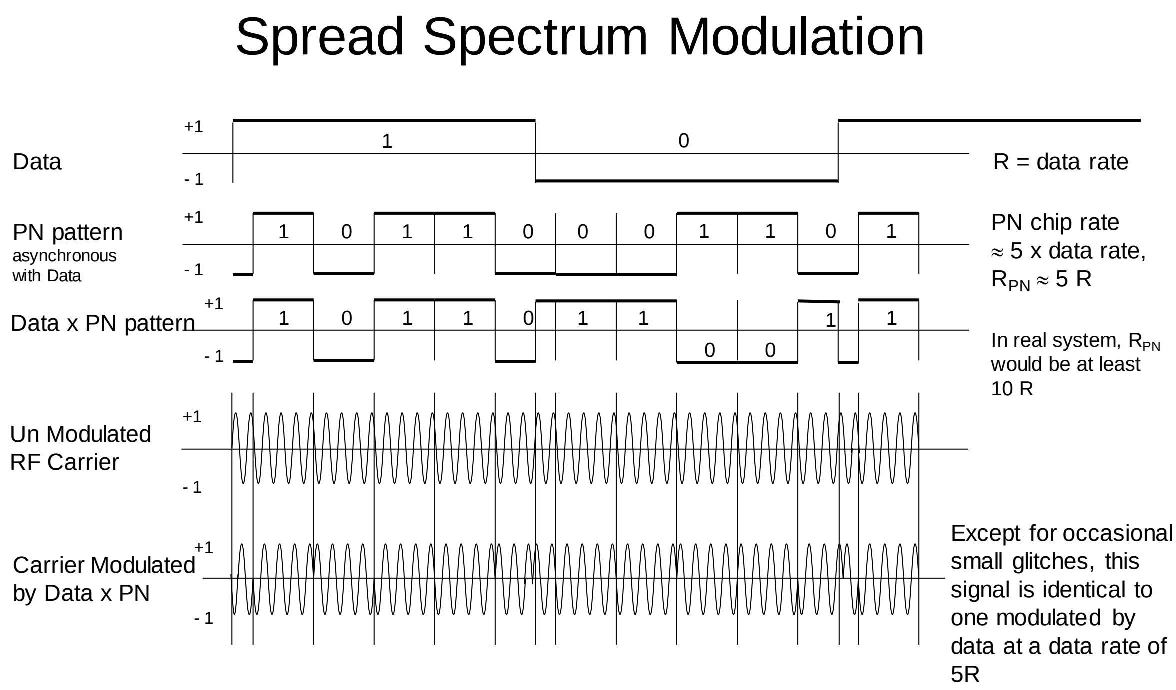

Figure B-3: Spread and Modulated Signals

The steps in generating a spread-spectrum modulation shown in figure B-3 are:

a) Mix (multiply) the data with the PN spreading pattern,

b) Mix the spread data pattern with an IF or RF carrier. This is also shown in figure B-5a. The result will be a spread spectrum as shown in figure B-2.

B2.3 SPREAD SPECTRUM RECEIVER

At the receiver, a similar algorithm is used, where the known PN pattern is synchronized to the PN pattern of the received signal and mixed with it. This removes the PN pattern transitions (phase inversions) and ultimately reduces the signal to its original narrow bandwidth. The signal is thus de-spread and then demodulated. These processes are illustrated generically in figure B-4. It should be noted that the receiver is not implemented with the functions in the reverse order of the transmitter.

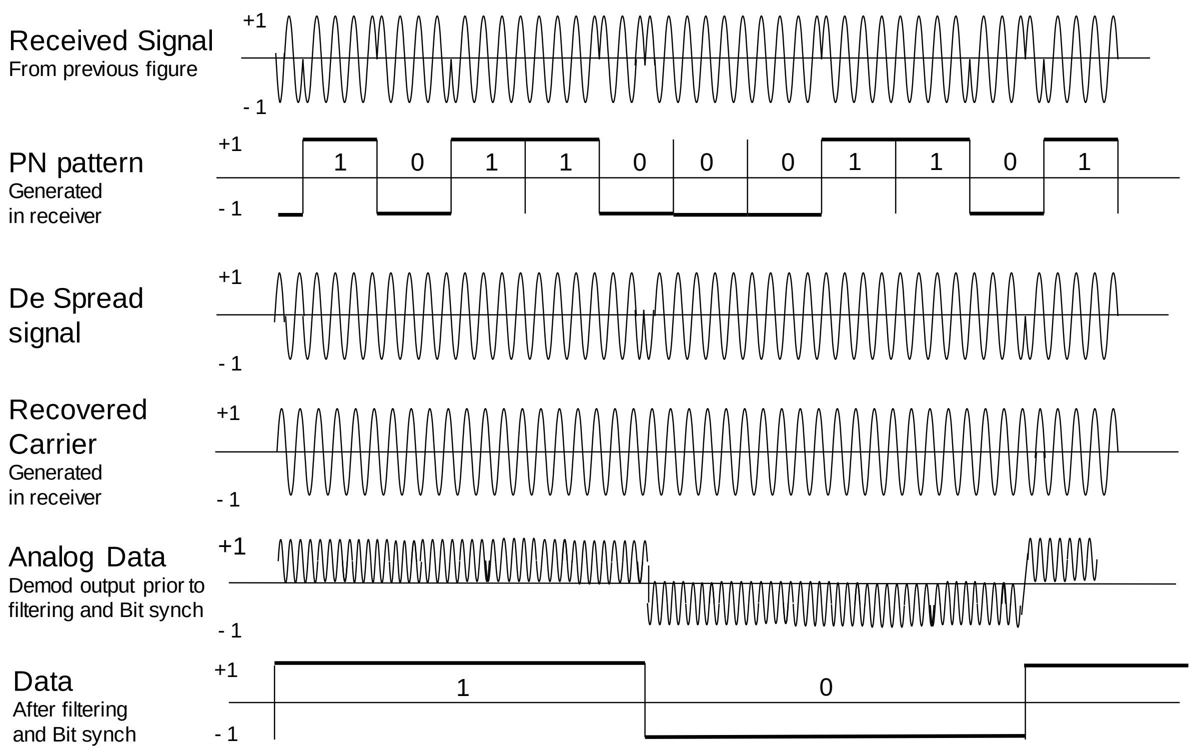

Figure B-4: Spread Spectrum Receiver

In principle the demodulation and the de-spreading can be reversed. However, in a real system with noise, the link is designed for the required data rate and the PN chips are typically at a ten-to-several-thousand-times higher data (chip) rate. The chip SNR (or E_c/N_0) will be 10 dB to more than 30 dB below the data E_b/N_0, and the chip error rate will be extremely high, close to 50 percent. An example is given following figure B-6b for the Fwd signal.

A correlation process is used in the de-spreader for determining when the PN pattern generated in the receiver is properly synchronized with the pattern in the received signal. This process is susceptible to falsely determining the pattern correlation, especially when the signal strength is high. A strategy must be used to check that the circuit does not falsely think it is properly correlated.

A parameter used in describing spread-spectrum systems is the spreading factor given in equation 12. The spreading factor, *SF*, is in effect a loss factor. At the receiver, the loss is regained and the term ‘processing gain’, G_p, is sometimes used. There is no real gain: the receiver just recovers what was ‘lost’ in the spreading process. Processing gain can be expressed as the ratio of transmission bandwidth (*BWt*, the bandwidth of the spread signal), and the information bandwidth (*BWi*, the bandwidth of the baseband or coded data signal):

$$SF = G_p = \frac{BWt}{BWi} \cong R_{PN}/R_{Data} \qquad (12)$$

This spreading factor impacts each of the spread-spectrum advantages discussed below. For spread-spectrum systems it is, in general, advantageous to have the largest spreading factor possible, subject to bandwidth constraints. The larger the spreading factor, the better the CDMA performance.

B3 CDMA SERVICES

B3.1 GENERAL

Figures B-5a,B-5b, B-6a, and B-6b are block diagrams of the network and user elements in a DSSS RF communications system. The network element transmits Fwd service data to the user element and the user element transmits Rtn service data back to the network. In these figures, a QPSK-type modulation format is used to transmit the PN spread signals. This modulation format is typically referred to as Quadrature PN (QPN) modulation, or SQPN modulation if the QPSK symbols are staggered. However, a BPSK modulation format could also be used to transmit the PN spread data.

In both the network and the user transmitters, data bits (or coded data symbols) are split into I and Q channels, which are spread separately by modulo-2 adding the data to PN sequences. The spreading operation is depicted conceptually in figures B-5a and B-6b. In these figures, distinct and different PN sequences (with a common clock and a synchronized epoch) are used on the I and Q channels for the Fwd signal. This approach is not a requirement for DSSS, as one could use the same spreading sequences on both channels; for the Rtn coherent case this is done.

Spread data sequences are input to BPSK modulators on each channel, and the outputs of these are combined to produce the QPN/SQPN signal. At the receiver side (figures B-5b and B-6a), carrier acquisition, PN acquisition, de-spreading, and symbol timing recovery are depicted as separate operations although the carrier and PN de-spreading are interconnected.

In the CDMA Recommended Standard (reference [1]) the Fwd I and Q channel (command and ranging channel) PN chips are aligned and at the same chip rate, but the channel power is unbalanced with 10/11 the power on the command channel and 1/11 the power on the range channel. This is referred to as Unbalanced QPSK (UQPSK). This modulation is also referred to as PN spread QPSK (QPN).

The Rtn channel is also a form of QPSK, where the I and Q channel chips are staggered, and the modulation is referred to as staggered PN spread QPSK. For the Fwd UQPSK the short PN code on the higher-power I channel is used to correlate to the long PN code on the Q that is used for ranging. This does not require staggering, and preferably the I and Q are time correlated. The Fwd range PN code needs to be time correlated with only one channel of the Rtn range code (the I) and the Rtn higher data rate makes SQPSK preferred over aligned QPSK.

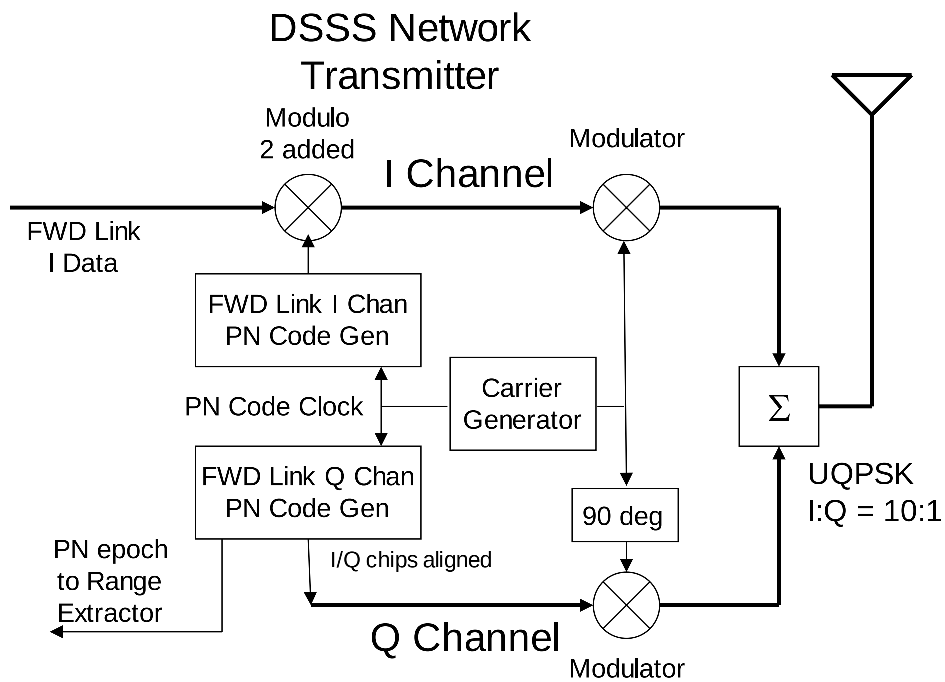

Figure B-5a: Example DSSS System Network Element Transmitter

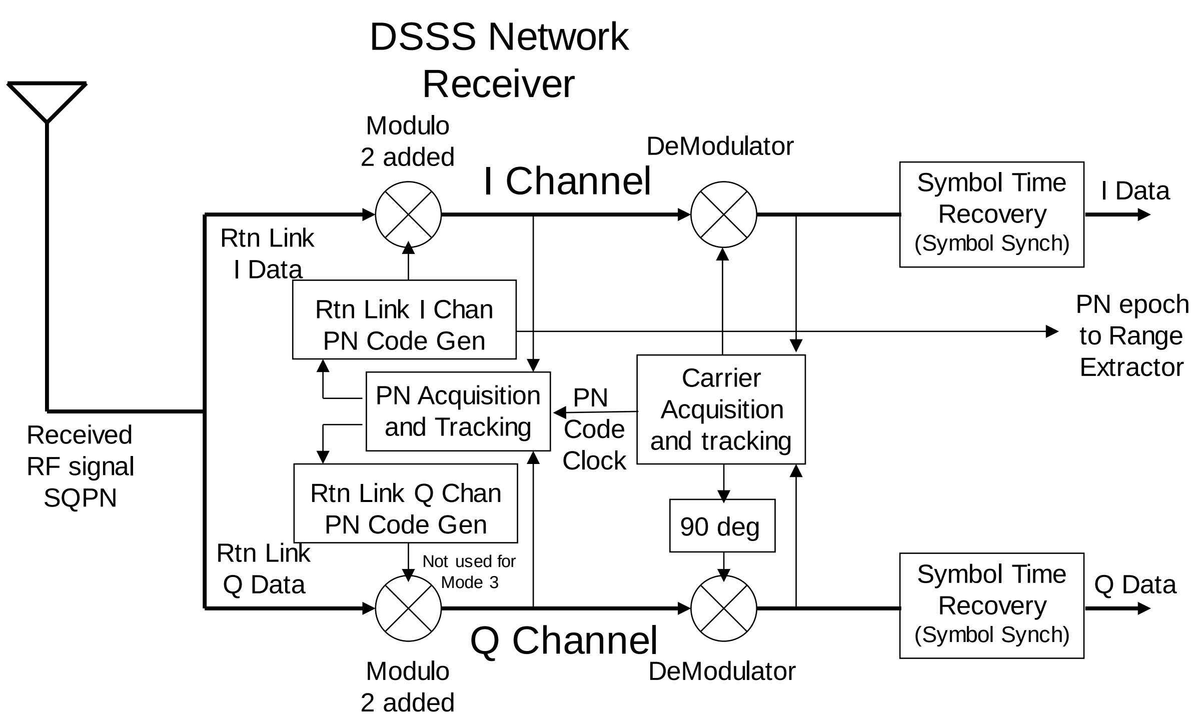

Figure B-5b: Example DSSS System Network Element Receiver

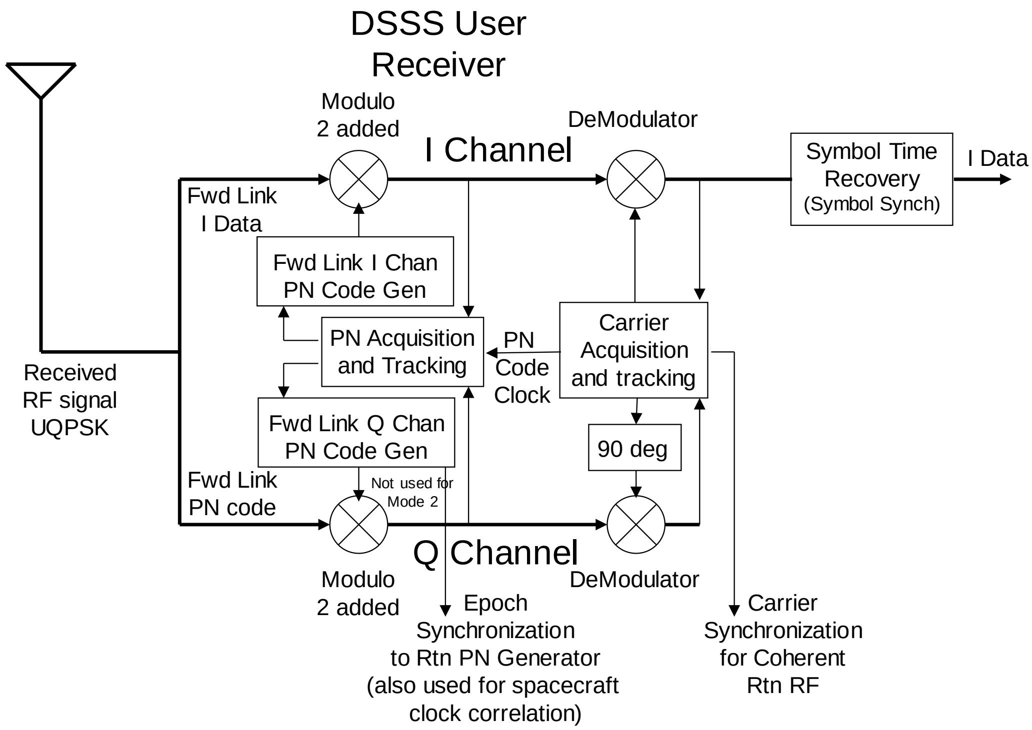

Figure B-6a: Example DSSS System User Element Receiver

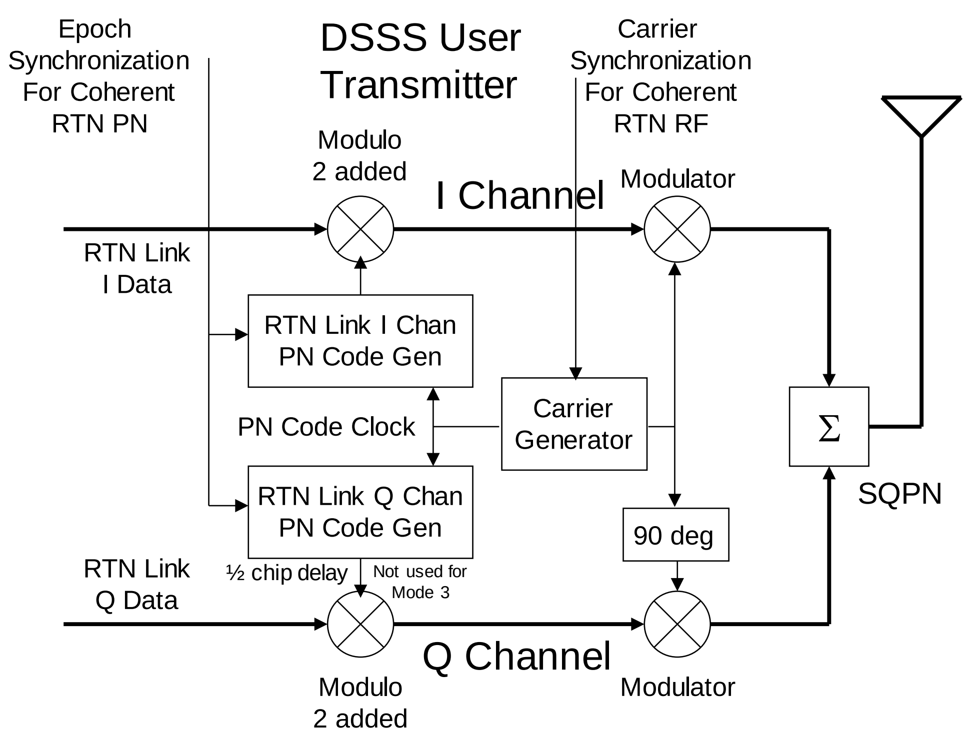

Figure B-6b: Example DSSS System User Element Transmitter

PN acquisition is accomplished using a correlator to synchronize the PN sequence generated internally with the received sequence. Once this synchronization is accomplished, the internally generated PN sequence de-spreads the data signal.

As an example of why a correlator is used rather than a direct chip comparison between the received chip values and the internally generated PN pattern chip values, a 1 kb/s Fwd data rate can be considered, where the channel is operating near threshold. The SNR (the E_c/N_0) for the Range channel will be much lower than the SNR on the 1 kb/s command data. It will be 10 dB less because of the lower power and it will be another (3 Mc/s/1 Kb/s) = 3000 = 34.8 dB less because of the higher chip rate. Individual chips values (0 or 1) cannot be identified at such a low SNR, requiring that a correlation process be used.

The user element in figure B-6b is configured to synchronize the epoch of the Rtn signal spreading sequences with the detected Fwd signal epoch. This facilitates the ranging measurement indicated in figures B-5a and B-5b by the signals that go from the transmitter and receiver to the range extractor.

B3.2 FORWARD SERVICES PN SPREAD SIGNAL FORMATS

Forward services with data rates equal to and below 300 kb/s are recommended to incorporate spread-spectrum modulation techniques to satisfy ITU power flux density restrictions. The achievable data rate limit for PN spread links is 300 kb/s with a PN chip rate of 3 Mc/s, based on the general PN spreading requirement of a 10:1 ratio of PN chip rate to symbol rate. This modulation scheme employs a non-staggered QPSK format with PN spread data on the I channel, also known as the command channel, and a ranging PN sequence with no data on the Q channel, also known as the range channel. Spread Spectrum BPSK (SS-BPSK) is also possible for forward services and results in an increase of power on the command channel by 0.41 dB. Since the power ratio for the QPSK case is 10:1, with the higher power on the command link, the command link contains 10/11 the total power. Suppression of the range channel will allow 1/11 more power on the command channel, or 11/10 the previous amount = 0.41 dB additional.

The command channel makes use of a shorter (and thus rapidly acquirable) PN code. The range channel contains a longer PN code, which satisfies the range ambiguity resolution requirements. The length of the command channel PN code is $2^{10}-1$, where the length of the range channel PN code is exactly 256 times the command channel PN code length. Also, the codes are synchronized (the first chip in the command channel code occurs at the same point in time as the first chip in the range channel code). Once the receiver acquires the command channel epoch, acquisition of the range channel PN code timing is greatly simplified and thus the overall acquisition time is reduced.

The PN code chip rate is coherently related to the transmit frequency in several agency relay satellites. This feature permits the receiver to use the receiver PN code clock to predict the received carrier frequency, thereby minimizing receiver complexity and further reducing acquisition time.

For data rates $\leq$ 300 kb/s, the forward service data is directly modulo-2 added to the command channel PN code sequence. The forward service data will be asynchronous with the carrier and the PN code. When the command channel does not contain any actual forward service data, the forward service command channel signal is the command channel PN code sequence. A 10:1 power ratio (command channel to range channel power) is normally used.

B3.3 RETURN LINKS USING SPREAD SPECTRUM

When initially implemented, it was recommended that return services that use PN spread modes have the PN code clock coherently related to the transmitted carrier frequency. This feature permits the transmitter to use a common source for generating the carrier and the PN code clock frequencies. This was important when the system was originally conceived and circuits were all analog. Today, when processing is done in an FPGA, with chip rate, data rate, and RF not being an integer multiple of the FPGA clock rate, and separate tracking loops are used in the digital circuits, this coherence is less important. For a coherent PN spread return service, the carrier frequency is coherently derived from the received forward frequency, and the epoch of the return service PN code (the longer ranging code) is synchronized with the received forward service range channel PN epoch. Three modes of service are summarized below:

a) A PN spread coherent service supports up to 300 kb/s uncoded on the I and Q channels (600 kb/s or ks/s total if coding is used) using SQPN modulation with a PN spreading code (ranging code length $256 * (2^{10}-1) = 261888$) whose epoch is synchronized to that of the received forward service range channel code to support ranging. SS-BPSK can also be used in this mode of operation.

b) A PN spread non-coherent service supports the same data rates as above but does not provide ranging. There is no CDMA requirement for coherent turnaround or synchronization of the PN code. These links use the short PN code (length $2^{10}-1$) on both I and Q channels. SS-BPSK can also be used in this mode of operation.

c) PN spreading only on the I channel is a coherent hybrid service. Up to 300 kb/s (uncoded) can be placed on the I channel, which is PN spread in a manner identical to that used in the first case. This allows PN ranging. On systems where available, coherent turnaround of the carrier frequency also facilitates support for two-way Doppler. The Q channel in this mode is unspread, and available for high rate data.

B3.4 TRACKING SERVICES USING SPREAD SPECTRUM

B3.4.1 General

The tracking services that use PN spreading are range measurements and time transfer. Tracking services are not standalone services; rather, they are integrated into the forward and return services. Doppler tracking requires a coherent RF turnaround at the user spacecraft but does not require the PN spreading used for CDMA and is not discussed here.

Range measurement can be achieved when using a coherent PN spread signal by measuring the time elapsed between the transmission of a PN code epoch on the forward and the reception of the turned-around PN code epoch on the return link. This provides two-way range measurements but requires accurate knowledge of the relay satellite orbit. When channel delays are subtracted, the result can provide a system accuracy of a few tens of nanoseconds.

Figure B-7 shows the geometry of the range measurement. The full range that the signal travels, from the ground network element to the relay satellite at GEO to the user satellite and then back to the ground network elements, is of the order of 140,000 km. The range channel PN code is 1023 × 256 = 261,888 chips long and is transmitted at approximately 3.08 Mc/s, making the period of the code 261888/3.08 Mc/s = 0.085 sec. At the speed of light, this will cover a distance of d = c t = 2.9979×10^{5} km/s × 0.085 s = 25491 km. It initially appears that the range cannot unambiguously be measured with these range PN patterns. But, since the maximum range variation of a LEO satellite as seen by a GEO relay satellite is only a little more than half the Earth's radius, the required range variation measurement to be 8000 km is considered, and the two-way variation is thus 16000 km. The 25000 km unambiguous range of the PN code is sufficient for this measurement. The PN code is long enough to unambiguously locate a LEO satellite. More detail is covered in the subsection on Time Transfer, B3.5.

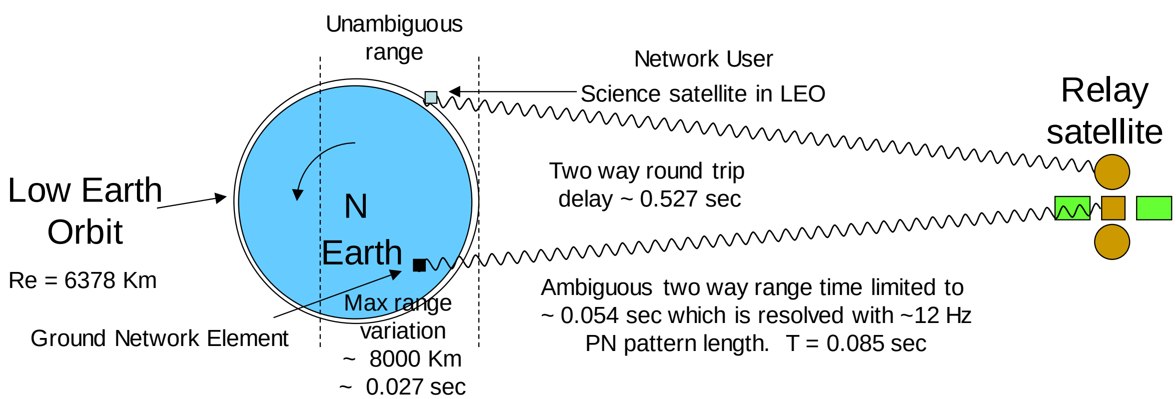

Figure B-7: Ambiguous and Unambiguous Range

B3.4.2 Range Code Turn Around Delay

The user element delay typically was 325 ±100 ns with analog transponders, which is nominally the period of one PN chip. With digital transponders the delay can be up to several microseconds. A valid and accurate orbit solution can be obtained even if this value is of the order of a few milliseconds. The delay itself is not the critical factor as long as it is known; the stability of the delay is the critical factor and is often required to be of the order of ±30 ns.

In recent transponders, using digital circuits, the range turnaround delay tends to be longer than in older analog equipment. As long as the range measurement can be made to an accuracy of around 30 ns, the error in the two-way measurement will be 9 m (4.5 m position measurement error). As long as the absolute delay is known and stable, the only reason it can cause a problem is if the spacecraft moves from one position to another between the time that the signal enters the spacecraft and the time it leaves. Since a LEO spacecraft is moving at a much lower speed than the RF ranging wave, the turnaround time delay is far less critical than the stability of the delay. A LEO spacecraft has a speed of about 7.5 km/sec, while the speed of the radio wave is 3×10^5 km/sec, a factor of 40000. So for a 30 ns accuracy, the absolute delay can be 1.2 ms before it contributes an error of the same magnitude as that caused by the knowledge of only 30 ns.

The user must also account for the delay from the antenna to the transponder and back to the antenna and the ground station delays when doing the orbit solution.

B3.4.3 Using Range PN Codes for Spacecraft Clock Correlation

User spacecraft time transfer can be performed when using a coherent spread-spectrum link and is very similar in concept to a ranging measurement. The time transfer ability provides an accurate method, on the order of microseconds, to acquire the data necessary to calibrate a spacecraft clock. The Mission Operations Center (MOC) can use the ground station UTC time of transmission and the time of receipt of the range code epochs to accurately determine the time difference between the satellite clock and UTC. To facilitate the time transfer measurement, the ground station must record the station UTC clock reading at the time of transmission and arrival of the epoch portion of the PN range code. Correlating the spacecraft clock with the range times is discussed in detail in the next subsection.

B3.5 TIME TRANSFER

B3.5.1 General

The network element may make available a time transfer service that allows the user to correlate the user’s on-board clock to within approximately 1 µs of UTC. The NASA Space Network (SN) refers to this service as the User Spacecraft Clock Correlation System (USCCS) (reference [7]). In order to make use of this service, the user transponder must incorporate certain features described here and in the CDMA Recommended Standard (reference [1]).

B3.5.2 Geometry of Signal Flow

Figure B-7 is an overview of the signal path via a relay satellite. For all two-way, coherent services, a PN spread signal travels from the network element to the relay satellite, to the user, back to the relay satellite, and to the network element. The time delay between the network transmission of the signal and its reception of the return signal is a measure of the two-way range time to the user via the relay satellite. Combined with orbit knowledge of the relay satellite and other information related to delays along the path, this time measurement is used to determine 'range' and eventually the user spacecraft orbit. For orbit determination, the transit time, and the absolute time (UTC) that the transit time was measured is needed. Equally valid would be a measure of the UTC time that an identifiable point in the PN pattern (the 'all ones' epoch for example) leaves the network element and the UTC time of the arrival of that point in the PN pattern when it gets back to the network element. For ranging, the delta time is used, since it can be measured more accurately than the UTC absolute time. The time that a signal epoch leaves the network element (ground station) is referred to as t_1, the time it arrives at the user spacecraft as t_2, and the time it returns to the network element as t_3, as shown in figure B-8.

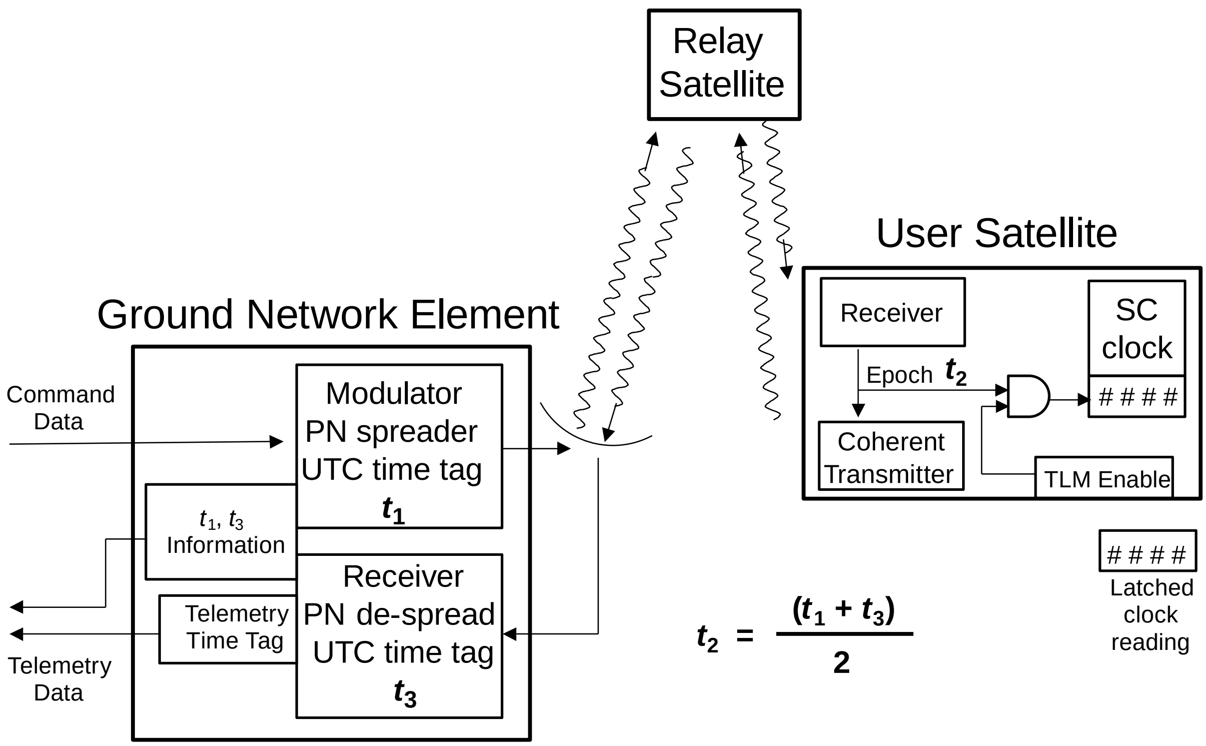

Figure B-8: Time Transfer Signal Flow

B3.5.3 Clock Correlation

For the purpose of ranging, the forward range (long code) epoch UTC transmit times, t_1, and the received range epoch UTC times, t_3, are recorded at the network element, and can be made available to the user processing center (figure B-8). Using these times, one can determine the time that the epoch was at the spacecraft,

$$t_2 = (t_1 + t_3)/2. \tag{13}$$

This equation is correct independent of the motion of the user spacecraft but is limited to about 1 μs accuracy because of the motion of the relay satellite and ground-based network element.

Using the received forward epoch at the user element to stimulate a reading of the spacecraft mission elapsed time or UTC clock, and sending that reading to the operation center via spacecraft telemetry, spacecraft clock error may be determined. Clock correlation accuracy is also limited to the accuracy of the network-element recorded epoch time, which is generally maintained to better than 1 μs of UTC. When microsecond or sub-microsecond time correlation is desired, there are additional orbit geometry considerations and relativistic effects that the user must consider.

B4 PROPERTIES OF CDMA

B4.1 GENERAL

This subsection lists some of the features and shortcoming of a CDMA system:

a) All users are on the same center frequency and use the same turnaround ratio. For the 2 GHz band it is 221/240 = (forward frequency)/(return frequency).

b) There are no service-to-service reconfigurable parameters for the CDMA.

c) CDMA does not require channel management, only code management. There are no modulation indexes to adjust. No chip shaping is required.

d) CDMA is easily filtered to meet SFCG and other spectral masks; CDMA meets ITU PSD limits.

e) CDMA capacity is duty-cycle limited, not fixed as with Frequency-Division Multiple Access (FDMA).

f) Service initialization can be on-demand (quick user access to the network).

g) It provides resistance to jamming, interference (B4.3), eavesdropping, multipath, and fading.

h) It is susceptible to false lock on strong signal.

B4.2 PN LOCK AND PN FALSE LOCK

Several circuits in a receiver require a lock detection to inform the following stage that the data or frequency in the earlier stage is valid. For example, the circuit that tracks the incoming carrier frequency and phase is informed by a previous circuit that a signal has been detected so that a filter value may be changed to optimize the signal tracking, which has different requirements from the acquisition or search state. In this subsection the PN lock is discussed.

In order to obtain PN lock, the PN code generated in the receiver must be at exactly the same rate (frequency) as the PN code that spreads the received signal and must be in phase with the received code. This is similar to carrier tracking. Figure B-9 is a conceptual display of how such a circuit may work. As the receiver applies different phases of the internally generated code to the received signal, at some point it will have the right phase and bits will be generated. The first part of figure B-9 show the properly de-spread signal where the bit level remains at +1 volt (or −1 volt) for the bit duration. The bottom part of the figure shows an RC filter and a comparator. When the bit voltage stays at +1 volt for the full bit duration, the capacitor charges to a value above the threshold set in the comparator, and comparator output shows a high level. The middle portion of the figure shows a case where the de-spreader is not in phase and not locked, and the 'bit level' changes often from +1 to −1, never allowing the capacitor to charge to the threshold level. Once lock is detected, the PN search circuit stops applying the PN code at different phases and instead makes small adjustments to keep the code in phase with the code that spread the received signal.

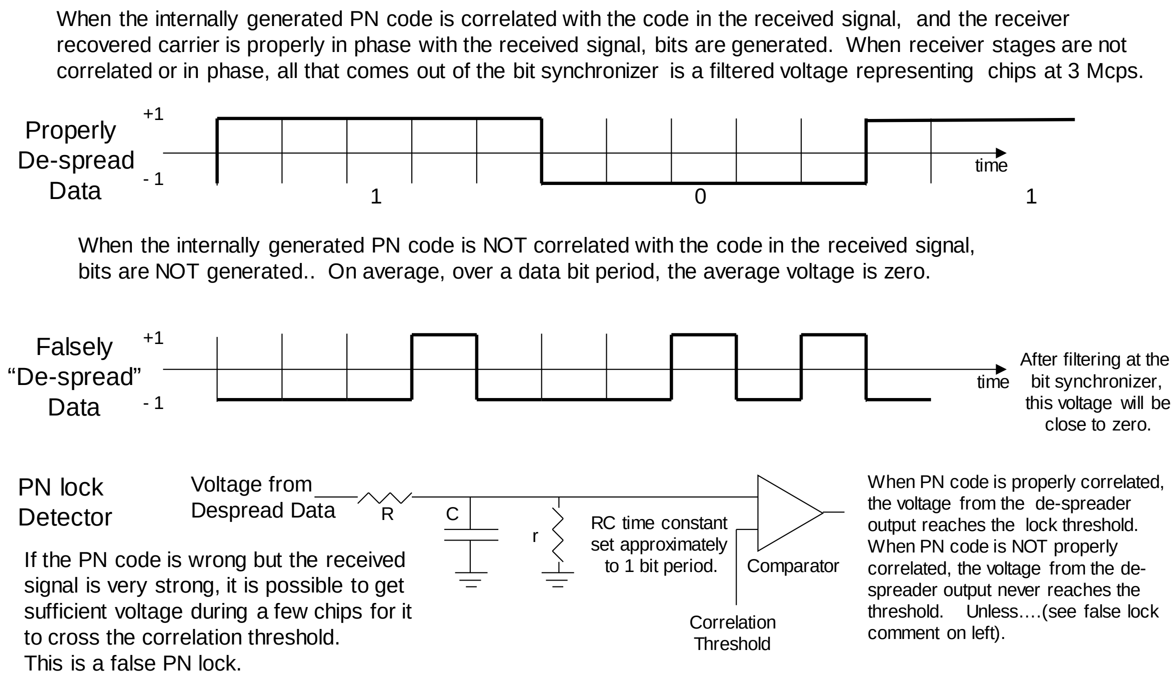

Figure B-9: PN Lock and False Lock

Using an analog concept, PN lock is determined by a voltage's being larger than a predetermined threshold. In a digital circuit, it is determined by a count's being higher than a preset number. In order to avoid false lock, an additional circuit or logic is needed. It is often necessary to search all code phases even though a particular phase meets the lock threshold.

Receivers of PN spread signals are susceptible to false locking to strong signals with a PN code different from the intended one. This is referred to as the 'Near-Far' problem. From figure B-9 it can be seen that if the signal during a chip period or several chip periods is sufficiently strong, the voltage generated can cross the threshold and trigger a PN lock state even with the wrong code or with the wrong phase of the right code. It is important that all users have a power level (Effective Isotropic Radiated Power [EIRP]) such that the receiving node accepts all of the signals with a power level over a limited range. It may seem that a receiver Automatic Gain Control (AGC) should set the signal level so that the following circuit that has the PN lock detect does not false lock, but one needs to remember that the PN spread signals are generally below the noise floor as shown in figures B-2 and B-10.

B4.3 IMMUNITY TO INTERFERING SIGNALS

The receiver de-spreading process is the same as the original spreading process in that the PN pattern is mixed with the signal. When the spread signal is mixed with the in-phase PN pattern, the result is the original lower data rate (narrow bandwidth) signal. However, when the received signal also includes a narrow band interferer, the mixing of the PN pattern will spread the interferer just as the transmitter spreads the original signal.

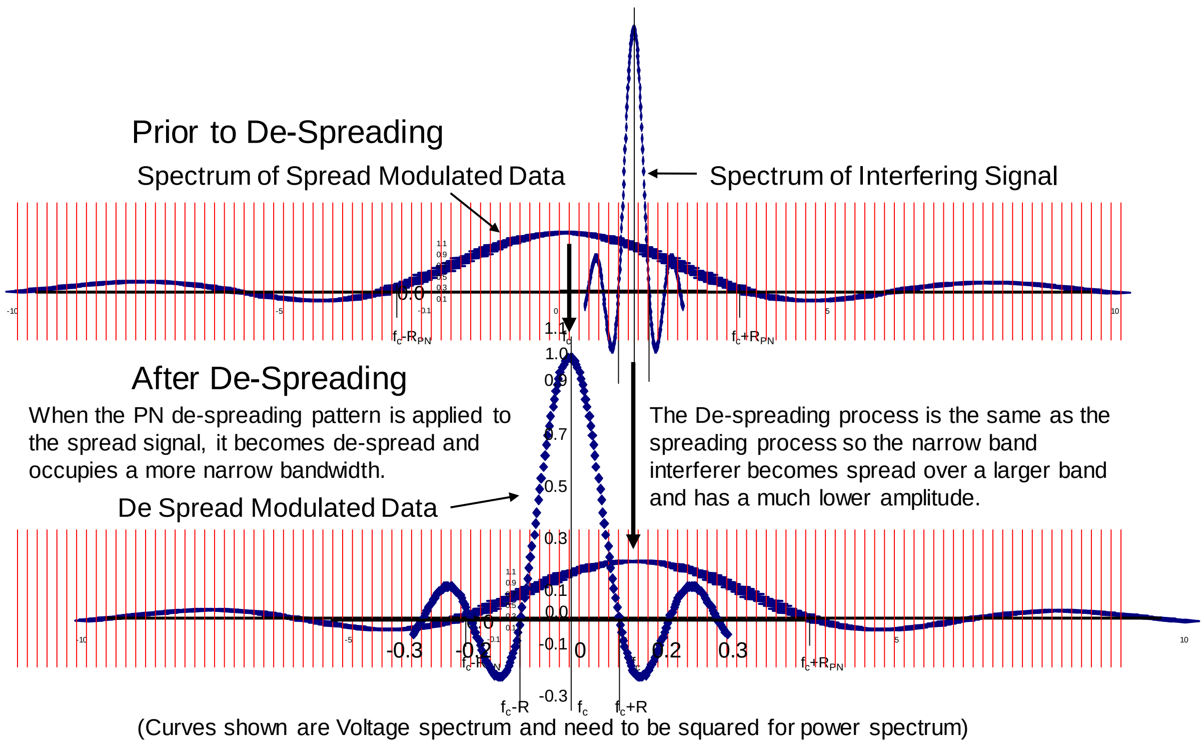

Figure B-10: De-Spreading of Desired Signal and Narrow Band Interferer

ANNEX C

ACRONYMS AND DEFINITIONS

C1 ACRONYMS AND ABBREVIATIONS

AGC	automatic gain control
BPSK	binary phase-shift keying
CDMA	code division multiple access
DSN	Deep Space Network
DSSS	direct sequence spread spectrum
EIRP	effective isotropic radiated power
ESA	European Space Agency
FDMA	frequency-division multiple access
FPGA	field-programmable gate array
Fwd	forward link (from network element to satellite)
GEO	geosynchronous earth orbit
GN	Ground Network
JAXA	Japan Aerospace Exploration Agency
ks	kilo-symbol
LEO	low earth orbit
LFSR	linear feedback shift register
MA	Multiple Access
Mc	mega-chip
MOC	mission operations center
RC	resistor-capacitor
PN	pseudo-random noise
PFD	power flux density
PSD	power spectral density
PSK	phase shift keying
RF	radio frequency

Rtn	return link (from satellite to network element)
SQPN	staggered quadrature pseudo-random noise (PN spread SQPSK)
SN	Space Network (NASA's TDRSS)
SNIP	Space Network Interoperable Panel
SNR	signal to noise ratio
TCXO	temperature compensated crystal oscillator
TDRSS	Tracking and Data Relay Satellite System
VCO	voltage controlled oscillator

C2 DEFINITIONS

acquisition: In RF communications systems, the process by which the receiver tracking loops lock to estimates of the received signal frequency and phase as a necessary precursor to data detection.

acquisition time: The time interval required for a receiver in an RF communications system to complete the acquisition process necessary to output meaningful data.

bandwidth; BW: A limited span of frequencies of a continuous frequency band, or the range of contiguous frequencies within which the performance of a device, with respect to some characteristic, falls within specified limits.

baseband: The original band of frequencies that contain the information in a data signal prior to modulation.

baseband signaling: Transmission of a digital or analog signal at its original frequencies; i.e., a signal in its original form, not changed by modulation.

baud: A unit of modulation rate, or rate of modulation symbols. (Also see **baud rate**.)

baud rate: Rate at which a characteristic (i.e., phase, frequency, amplitude) of a carrier wave is changed by the modulating signal. An exception is staggered (or offset) QPSK, which is treated as if it is not staggered. For BPSK, the baud rate is the same as the data or code symbol rate.

bit: The basic unit of information in a binary communications system (often represented by a value of '0' or '1'); a binary digit.

bit error rate; BER (also called bit error ratio): In a communications system, the ratio of data bits which are erroneously detected by the receiver to the total number of data bits received (also called probability of error). At the physical channel level of a coded link where the binary digits are called code symbols, this is called the Symbol Error Rate (SER).

bit synchronization: Synchronization in which a decision instant is brought into alignment with the received bit or code symbol; more specifically, alignment of the received bit sequence with another where the second sequence, referred to as a clock and represented as a '101010…' pattern, is set so that the '10' or '01' element of the clock is aligned with each received bit. When operating on coded data, this function is called (code) symbol synchronization and is more complicated when soft decision code symbols are used.

carrier frequency: The frequency of the signal onto which the baseband signal is modulated.

channel: Any medium that a communication link uses to transport the electromagnetic waves that include data.

characteristic polynomial: In this document, a polynomial that is an algebraic representation of a particular linear feedback shift register. The coefficients of the powers of x in the polynomial are nonzero, where the cells in the shift register have taps, and zero otherwise; the coefficient of x^0 is a '1'.

chip: A PN sequence bit or that portion of PN spread data of duration equal to that of the PN pattern chip and time aligned with the pattern chip. PN chips are pieces of the data bit.

chip rate: The rate of the subparts (chips) into which the information signal bits are broken. The chip rate is usually at least 10 times the data or coded-data symbol rate.

coherent: In an RF communications system, signal A is considered to be coherent with signal B if their carrier frequencies are related by a known, fixed ratio. With regard to a PN sequence, sequence A is coherent with sequence B if chip rates are related by a known fixed ratio. For ranging, the epochs of the PN sequences are aligned and the pattern lengths are the same, but the sequences may be of different chip patterns. The PN chip rate may be coherent with the RF carrier rate.

correlator: The spread-spectrum receiver component that demodulates an spread-spectrum signal.

de-spreading: The process used by a correlator to recover narrowband information from a spread-spectrum signal. Appling the same process as PN spreading, with the same code as the spreading code, when synchronized with the code in the spread signal, will de-spread the signal and return the original narrowband information. It is worth noting that since the de-spreading process is the same as the spreading process, any unwanted signal will be spread by the process that de-spreads the desired signal.

detection: In a communications system, the process by which the receiving equipment produces an estimate of the transmitted sequence based on the noisy received signal.

direct sequence spread spectrum; DSSS: Application of a spreading pattern to a baseband signal.

epoch: (See **PN epoch.**)

forward link; Fwd: An RF communication link starting from the network element and ending at the user of that network, generally a satellite in this application. A forward link can have multiple hopping points along the path.

irreducible polynomial: A polynomial that is divisible only by one and itself (similar to a prime number).

mode: As used in SNIP and TDRSS terminology, forward-to-return-channel PN code coherency. Mode 1 is coherent, mode 2 is not coherent, and mode 3 is coherent but only with return link I channel, since the Q is not spread.

modulation: The process, or result of the process, of varying a characteristic of a carrier in accordance with an information-bearing signal.

network: The element of a two-way RF link responsible for initiating and managing the contact and performing functions such as information transfer, range calculation, or time transfer. A network may include one or more elements and may be space based.

PN chip jitter: The unwanted phase variations of the PN code chip or chip clock, measured in degrees RMS of the chip period or percent (RMS) of the nominal chip width.

PN chip rate: (See **chip rate**.)

PN chip skew: For a QPSK (OQPSK, SQPSK) modulation, the deviation of the chip transitions between the I and the Q channels from the intended offset.

PN code: (See **pseudo-random noise sequence**.)

PN epoch: A repeating reference pattern within the code, used as a reference for phase measurement into the code. Usually the longest consecutive string of 'ones' in the PN code.

PN sequence: (See **pseudo-random noise sequence**.)

PN de-spreading: The process of taking a signal in its wide PN spread bandwidth and reconstituting it in its original much-narrower bandwidth.

PN spreading: A process used to distribute or spread the power of a signal over a bandwidth which is much greater than the bandwidth of the original signal itself. By breaking the data bits into smaller pieces, chips, the effective data rate is increased, resulting in the wider spectrum. (Also see **de-spreading**.)

power flux density; PFD: The rate of flow of (electromagnetic) energy per unit area perpendicular to the direction of flow. Used to measure radiation density at a given point. Units would be watts per square meter (Energy/time/area = W/m^2). It may include power at a wide band of frequencies.

power spectral density; PSD: The time average power in the signal per unit bandwidth. Units would be Watts/Hz.

primitive polynomial: A polynomial of degree n that divides x^m-1 for m no less than x^n-1 (i.e., does not divide x^m-1 unless $m \geq 2^n-1$). Primitive polynomials are irreducible and for coefficients that are modulo 2 must have an odd number of terms. Such polynomial with even numbers of terms will be divisible by (x+1). The characteristic polynomial's being primitive is a necessary and sufficient condition for its associated LFSR to generate a maximal PN pattern.

pseudo-random noise sequence: A sequence of binary numbers, +1 and −1 (or '1' and '0'), which appears to be random, but is in fact perfectly deterministic. Certain classes of PN sequences have very specific and useful properties.

quadrature phase shift keying; QPSK: A form of phase shift keying in which two bits are modulated at once, selecting one of four possible carrier phase shifts (45, 135, 225, or 315 degrees). QPSK allows the signal to carry twice as much information as ordinary binary PSK using the same bandwidth. In QPSK modulation, an electromagnetic carrier wave is varied in phase while ideally keeping a constant amplitude and frequency in the period between the phase jumps.

return link; Rtn: An RF communication link from the user of the network, a satellite, to the network node (usually a ground station). A return link may have multiple hopping points along the path.

shift register: A storage device consisting of a data input port, a clock input port, an output port, and a single bit memory storage; the shift register retains the value currently stored in memory at its output port until such time as an input clock pulse is received. At this time, the register sets the value in memory to the value on its input port. PN pattern generators in this document are made conceptually of concatenated shift registers. An FPGA implementation is functionally the same.

Space Network: The NASA system of several geosynchronous relay satellites combined with the ground stations and the ground data transportation of data.

spread spectrum: A wideband modulation that imparts noise-like characteristics to an RF signal and spreads the information energy over a wider bandwidth than would occur from conventional PSK or PM modulation. (See **PN spreading**.)

staggered quadrature PN modulation; SQPN modulation: SQPSK modulation where the PN spreading chips are staggered on the carrier with the chips on one channel delayed by one half of a modulation symbol (chip) period with respect to the other channel.

user: The element in an RF communications link which exchanges data with the network element, i.e., a science satellite. The user is responsible for any required transponder/transceiver operations (i.e., when the service is coherent: dispreading the forward link, generation of the PN spreading on the return link, generation of coherent return link carrier, and synchronizing the return PN sequence with the forward sequence).

ANNEX D

WORKS CONSULTED

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