Abstract

This paper discusses the construction and evaluation of the performance of a direct-sequence spread spectrum (DSSS) system. The system, based upon a previously published design, uses a special type of injection-locked oscillator called a "synchronous oscillator" for code synchronization. The DSSS system was constructed in a manner that provides a test-bed for demonstrating spread spectrum principles and allows researchers to evaluate their own sub-system design concepts. The DSSS system, designed as a one-way link in the 420-450 MHz band, is constructed to operate in accordance with Federal Communications Commission rules and regulations pertaining to the Amateur Radio Service (Part 97). Unlike conventional DSSS systems which combine digital data with a pseudorandom (PN) code sequence, the system described here directly modulates an FM modulated carrier with the PN code sequence. The criteria used for evaluation are synchronization time, processing gain, and probability of bit-error rate. Because the DSSS receiver uses an inexpensive and practical direct conversion process before despreading, the receiver lacks good sensitivity. In spite of the limited range of the system, fundamental concepts of DSSS were evaluated and the measurements agreed favorably with theoretical values.

Introduction

There are several techniques by which spread spectrum can be implemented. One technique is called "direct-sequence." Direct-sequence spread spectrum is achieved in this paper by directly modulating a conventional narrowband frequency-modulated (FM) carrier with a high rate digital code. The direct modulation is binary phase-shift keying (BPSK). The high rate digital code is referred to as a PN (pseudo-noise) code because it exhibits random-like properties which are necessary for providing good spectral characteristics and security.

Regulatory Aspects

The operation of a radio transmitter, with a few exceptions, requires a license for the transmitter and usually the operator. In developing this spread spectrum system it was important that the final result be capable of actually radiating so that field tests could be performed as part of the system evaluation. Transmitter radiation in free space leads to the problem of insuring that the system is operating legally.
US government agencies, including the military, generally do not require the licensing of radio transmitters provided they are used for official activities. Government and military transmitters do, however, require some type of authorization from a regulating authority. This authorization is necessary to insure the systematic operation of radio transmitters in a manner which will not cause interference to other stations. To accomplish this, there are governmental committees or military departments that establish frequency allocation standards and other guidelines of operation. These organizations coordinate their activities with the State Department, or in the case of non-governmental operations, the Federal Communications Commission (FCC). The problem of acquiring military or governmental authorization to operate a spread spectrum transmitter was considered arduous for a research activity of this nature. Therefore, the decision was made to provide for transmitter operation in the Amateur Radio Service.

The Amateur Radio Service is ideally suited for experimental transmitter operation of this nature. Amateur Radio is a service regulated by the FCC for US citizens to operate radio transmitters for hobby purposes, without business interests, to further the art of radio communications. Radio experimentation, such as this research project provides, is fundamental to the nature of the Amateur Radio Service (1:556-558).

**Basic System Configuration**

Construction of the DSSS system is based upon an article appearing in **OST Magazine**, May 1989, by Andre' Kesteloot (2:14-21). The system as described by Kesteloot is intended for use in the Amateur Radio Service. For this study, several design modifications were required. The resulting DSSS system, shown in Figure 2, consists of a transmitter unit and a receiver unit. The transmitter consists of an FM exciter, a PN code generator, a double-balanced mixer (DBM), an RF amplifier, a bandpass filter, and an antenna. The receiver consists of an antenna, an RF preamplifier, a DBM, a PN code generator, a synchronous oscillator, and a narrowband FM receiver.

The DSSS system operates as a one-way link in the 420-450 MHz band with an output power of approximately 100 mw. It uses a process called the "stored reference" design approach, in which a replica of the PN code used for spreading the signal is contained within the receiver. The process of demodulation requires that the spreading PN code must be synchronized to the stored reference PN code. The process of synchronization is accomplished by a special circuit called a synchronous oscillator. The capability of the synchronous oscillator to perform spread spectrum synchronization is evaluated in this paper.

![Figure 2. Detailed Block Diagram](image-url)

The PN code generator provides the pseudorandom digital waveform that is used to spread the frequency modulated carrier to produce a DSSS signal. The PN code generator is designed to be programmable from the transmitter and the receiver front panel. The PN code generator can output linear recursive sequences (LRS) for any polynomial up to, and including, degree-12. This class of PN codes is generated by digital feedback shift-registers. A digital shift-register of degree-\(n\) is a device consisting of \(n\) consecutive binary storage elements. The PN code generator for this system is clocked at the rate of 2.7875 MHz as derived from the FM exciter.
The PN code sequence used in this analysis has the following parameters:

- \( t_c = \text{chip rate} = 2.7875 \text{ MHz} \)
- \( T_c = \text{chip time} = 362.5 \text{ ns} \)
- \( n = \text{code sequence polynomial degree} = 7 \)
- \( N = \text{sequence length} = 127 \text{ bits} \)
- \( T_N = \text{code period} = N \cdot T_c = 46.04 \mu s \)

**Synchronization**

The problem of synchronization in DSSS systems is that of aligning the receiver's locally generated PN code sequence with the spreading modulation superimposed on the incoming signal. This process is often accomplished in two steps. The first step, called "acquisition", consists of bringing the two spreading signals into coarse alignment. Once acquisition has occurred, the second step, called "tracking" takes over and continuously maintains fine alignment, usually by means of a feedback loop.

The synchronization technique used in the system described here uses a device called a "synchronous oscillator" (SO). Kesteloot (2) states that the SO provides the function of a phase-locked loop (PLL) while offering several advantages: simpler to implement and better noise immunity. Uzunoglu and White (3,4), co-developers of the patented SO, have provided theoretical and experimental results of its performance.

The synchronous oscillator is a synchronization network used for both acquisition and tracking. Fundamentally, the SO is a free-running oscillator in the absence of an externally applied signal. In the presence of a signal, the oscillator acquires and tracks the input waveform. An important feature of the SO is its ability to lock and track an input signal whose frequency is an integer multiple or a rational integer number such as 4, 1/4, and 3/2. The SO possesses a constant output signal amplitude in the tracking region and an adaptive tracking bandwidth proportional to the input signal level. A phase shift exists between the input and the output of the SO when it is synchronized that depends on the difference between the free-running frequency of the SO and the injected frequency.

At the transmitter, the PN code generator is clocked (chip rate) from a source coherently derived from the TA451 exciter. The exciter signal, at 9 times the crystal frequency, is divided by 40 to produce the 2.7875 MHz chip rate. This chip rate is precisely 1/160 of the carrier frequency. At the receiver, the output of the SO, which free-runs at approximately 111.5 MHz, is divided by 40 to re-create the transmitted chip rate. The transmitter and receiver chip rates will not be precisely the same because of variations such as oscillator instabilities, doppler, and multipath. Furthermore, the starting point of their respective sequences will not be identical (i.e. epoch misalignment).

The output of the receiver DBM, at 446 MHz, is input to the SO completing the feedback path and allowing synchronization. When this occurs, the SO feature of division by an integer is implemented. The input to the SO at 446 MHz is divided by 4 and tracked by the 111.5 MHz oscillator. The SO output is divided by 40, re-conditioned, and passed on to drive the receiver PN code generator. The output of PN code generator is applied to the LO port of the DBM to despread the signal.

The rate difference between the transmitted sequence and the receiver's locally generated sequence establishes a "sliding correlator" process. When correlation occurs, the signal power over a large bandwidth collapses into a narrowband signal having much greater power per unit bandwidth. The despread DBM output at 446 MHz is instantaneously injected into the synchronous oscillator where acquisition and tracking begin. Provided the rate difference of the two PN code sequences is not outside the tracking range of the SO, the oscillator will become "locked".

**Performance Testing and Results**

Tests of synchronization time, processing gain, and bit-error rate were conducted in the laboratory. Tests regarding the ease of synchronization and the communications range were field tested. The effects of interference were conducted in the laboratory. Synchronization time was measured with instrumentation configured as shown in Figure 3. A received signal level of 0 dbm was used to ensure a large SNR. The FSK demodulator was adjusted to keep the HP5326A Interval Timer enabled until it sensed an audio tone of approximately 2 kHz from the receiver. When the DSSS transmitter was keyed, the SYNC pulse was generated from the PN code generator at the code period rate of 1/T_N. The SYNC pulse will not be generated until the transmitter is keyed. At the first SYNC pulse, the HP5326A is enabled and disabled when the 2 kHz tone is received by the FSK demodulator. The time difference between the start and stop signals is the total synchronization time. The additional propagation times resulting from the FSK demodulator, the FM narrowband receiver, and the propagation path are small by comparison and are neglected. In fact, these delays are somewhat offset by the fact that the first SYNC start pulse is actually delayed by one code period equal to 46.04 \mu s. The mean acquisition time was measured to be 164.1 ms.
The theoretical value of the processing gain was compared to a measured value. By definition, processing gain $G_p$ is

$$G_p = \frac{B_{SS}}{B_D}$$  \hspace{1cm} (1)

where,

- $B_{SS}$ = bandwidth of the DSSS signal in Hz
- $B_D$ = minimum bandwidth necessary to send the information in Hz.

A null-to-null bandwidth is assumed for the spread spectrum signal and a bounded power spectral density bandwidth (4 kHz) is assumed for the analog voice channel. The measured $G_p$ was determined by the expression

$$G_p = \frac{\text{output SNR}}{\text{input SNR}}.$$ \hspace{1cm} (2)

The theoretical processing gain is 31.4 dB and the measured value was 27.0 dB, a difference of only 4.4 dB. This is reasonable allowing for conversion losses and bandwidth approximations.

The bit-error rate for audio FSK at 300 bps was measured with instrumentation configured as shown in Figure 4. The DSSS transmitter and receiver were connected directly through a stepped attenuator from 0 to 110 dB in 1 dB increments. The SYNC outputs were connected to the HP1746A oscilloscope to observe that the transmitter and receiver were synchronized. The

HP1746A was set to the dual trace (chop) mode to trigger on the transmitter SYNC pulse. The receiver synchronous oscillator TUNE control was adjusted, when needed, to maintain code rate and epoch alignment with the transmitter PN code. The FSK modulator was configured to output 300 bps FSK with 2025 Hz and 2225 Hz tones. The simulated data was generated by an HP8006A word generator.

Test data consisted of a PN sequence of length 65535 bits ($2^{16} - 1$) in order to assure randomness over the measurement interval. However, a time delay of greater than 1 ms was present between the waveform at input A (transmitted waveform) and the waveform at input B (received waveform). This caused excessive errors to be falsely recorded by the counter. To correct this problem, a digital time-delay device was inserted in the measurement system. The digital time-delay device delayed the transmitted waveform by an adjusted amount so that the waveforms were aligned before comparison. In Figure 5, measured data is compared to a theoretical plot of non-coherent FSK for the probability-of-error versus SNR ($E_b/N_0 = 2SNR$). The large difference between the measured BER and the theoretical curve is attributed to poor receiver sensitivity.

Before field tests were conducted, receiver sensitivity was measured in the laboratory to determine the maximum path loss that could be tolerated before the DSSS system lost synchronization. The maximum path loss was measured by connecting the DSSS transmitter, through a stepped attenuator, into the DSSS receiver. Problems with synchronization began at 40 dB of attenuation. Using the expression for free-space path loss, a predicted range of only 5 to 10 meters was expected.
implemented at 300 bps and, allowing for poor receiver sensitivity, produced reasonably expected bit-error rate versus SNR performance. The range of the DSSS system was extremely limited; however the range was predicted and verified prior to the field tests. The DSSS system was found to be unaffected by the presence of a CW carrier at the same input power and center frequency of the spread spectrum signal.

Although the limited range was disappointing, this does not detract from the research effort. A direct conversion receiver, such as used by the DSSS receiver, is simple, inexpensive, and easy to build. Commercial receivers requiring good sensitivity use a superheterodyne technique. Reference 5 provides additional details regarding this effort.

References

1. Federal Communications Commission. Part 97. Amateur Radio Service. Title 47 CFR Ch. I, Section 97.71. Washington: Government Printing Office, 1 Oct 1988.

2. Kesteloot, Andre'. "A Practical Direct-Sequence Spread-Spectrum UHF Link." QST Magazine, 5:14-21 (May 89).

3. Uzunoglu, Vasil and Marvin H. White. "The Synchronous Oscillator: A Synchronization and Tracking Network." IEEE Journal of Solid-State-Circuits, Vol. SC-20, No.6; 1214-1225 (December 1985).

4. Uzunoglu, Vasil and Marvin H. White. "Some Important Properties of Synchronous Oscillators." Proceedings of IEEE, Vol. 74.

5. Stephens, James P. "Direct-Sequence Spread Spectrum System." Masters Thesis, Air Force Institute of Technology, 1 June 90.