SPREAD SPECTRUM - DSSS

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ACHIEVEMENTS: *demonstration of some of the principles of a direct sequence spread spectrum (DSSS) system.*

PREREQUISITES: *it would be advantageous to have completed some of the analog experiments in Volume A1, involving linear modulation and demodulation.*

ADVANCED MODULES: *DIGITAL UTILITIES, NOISE GENERATOR*

***EXTRA MODULES**: a total of three SEQUENCE GENERATOR modules is required.*

RECOMMENDED INSTRUMENTATION: *some means of displaying the spectra of the signals to be examined would be an advantage; eg, the PICO Virtual Instrument, together with a PC.*

PREPARATION

the need

In some situations it is required that a communication signal be difficult to detect, and difficult to demodulate even when detected. Here the word ‘detect’ is used in the sense of ‘to discover the presence of’. The signal is required to have a low probability of intercept - LPI.

In other situations a signal is required that is difficult to interfere with, or ‘jam’.

The ‘spread spectrum’ signal has properties which help to achieve these ends.

Spread spectrum signals may be divided into two main groups - direct sequence spread spectrum (DSSS), and frequency hopping spread spectrum (FHSS). This experiment is concerned with demonstrating some of the principles of the first.

principle of DSSS

Consider the frequency translation of a baseband message (of bandwidth B Hz) to a higher part of the spectrum, using DSBSC modulation. The resulting signal occupies a bandwidth of 2B Hz, and would typically override the noise occupying the same part of the spectrum. This makes it easy to find with a spectrum analyser (for example), and so the probability of intercept is high. A local carrier, synchronized with that at the transmitter, is required at the receiver for synchronous demodulation. The recovered signal-to-noise ratio is 3 dB better than that measured at its original location in the spectrum. This 3 dB improvement comes from the fact that the contributions from each sideband add coherently, whereas the noise does not. This can be called a 3 dB ‘processing gain’, and is related to the fact that the transmission bandwidth and message bandwidth are in the ratio of 2:1.

In a spread spectrum system literally thousands of different carriers are used, to generate thousands of DSBSC signals each derived from the same message. These carriers are spread over a wide bandwidth (much wider than 2B Hz), and so the resulting DSBSC signals will be spread over the same bandwidth.

If the total transmitted power is similar to that of the single DSBSC case, then the power of an individual DSBSC in the spread spectrum case is thousands of times less. In fact, over the bandwidth occupied by one of these DSBSC signals, it would be literally ‘buried in the noise’, and difficult to find with a spectrum analyser (for example).

Instead of the total transmitted power being concentrated in a band of width 2B Hz, the multiple carriers have spread it thinly over a very wide bandwidth.

The signal-to-noise ratio for each DSBSC is very low (well below 0 dB).

To recover the message from the transmitted spread spectrum signal all that a receiver requires is thousands of local carriers, at the same frequency and of the same relative phase, as all those at the transmitter !

question: where do all these carriers come from ?

answer: from a pseudo random binary sequence (PRBS) generator.

Given a stable clock, and a long sequence, it may be shown that the spectrum of a pseudo random binary sequence generator is a good source of these carriers [1]. A second PRBS generator, of the same type, clocked at the same rate, and appropriately *aligned*, is sufficient to regenerate all the required local carriers at the receiver demodulator.

In the spread spectrum context the PRBS signal is generally called a PN - pseudo noise - signal, since its spectrum approaches that of random noise.

Having the correct sequence at the receiver means that the message contributions from each of the thousands of minute DSBSC signals combine in phase - coherently - and add up to a finite message output. Otherwise they add with random phases, resulting in a (very) small, noise-like output.

The key to a successful message recovery is the knowledge of the PN sequence used at the transmitter.

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[1] the PRBS is a periodic signal

processing gain

To achieve most of the claims made for the spread spectrum it is necessary that the bandwidth over which the message is spread be very much greater than the bandwidth of the message itself. Each DSBSC of the DSSS signal is at a level below the noise, but each is processed by the synchronous demodulator to give a 3 dB SNR improvement. The total improvement is proportional to the number of individual DSBSC components. In fact the *processing gain* of the system is equal to the ratio of DSSS bandwidth to message bandwidth.

a DSSS generator

To generate a spread spectrum signal one requires:

1. a modulated signal somewhere in the RF spectrum
2. a PN sequence to spread it

These two are combined as shown in Figure 1.

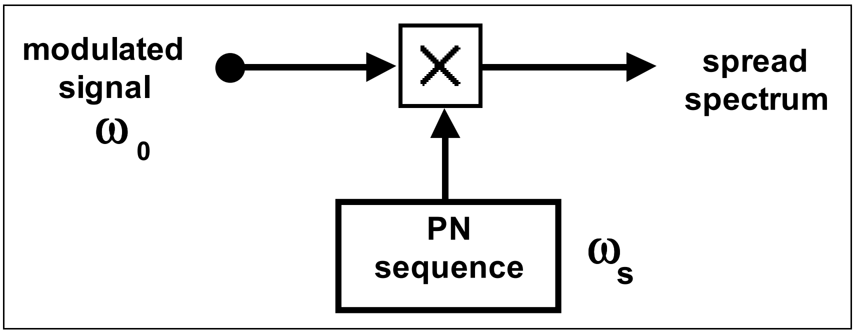

Figure 1: basis of spread spectrum

There are two bandwidths involved here: that of the modulated signal, and the spreading sequence. The first will be very much less than the second. The output spread spectrum signal will be spread either side of the original RF carrier (ω_0) by an amount equal to the bandwidth of the PN sequence.

Most of the energy of the sequence will lie in the range DC to ω_s, where ω_s is the sequence clock. The longer the sequence the more spectral components will lie in this range. It is necessary and usual that $\omega_0 >> \omega_s$, although in the experiment to follow the difference will not be large.

The modulated signal can be of any type, but typically digitally-derived, such as binary phase shift keyed - BPSK. In this case the arrangement of Figure 1 can be expanded to that of Figure 2.

A digital message is preferred in an operational spread spectrum system, since it makes the task of the eavesdropper even more difficult [2].

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[2] it also offers some simplifications at the transmitter

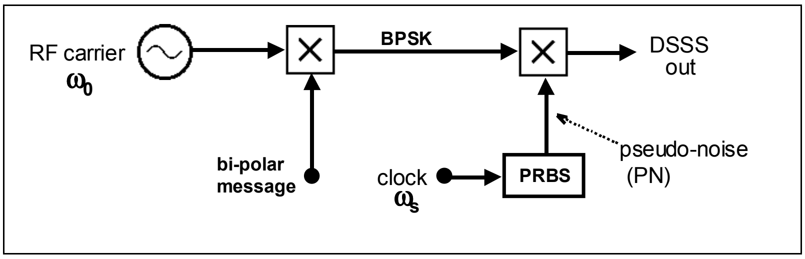

Figure 2: a spread BPSK signal

The arrangement of Figure 2 can be simplified by noting that, if the clock of the bi-polar message is a sub-multiple of the clock of the PN sequence, then the modulo-two sum of the message and the PN sequence can be used to multiply the RF carrier, generating a DSSS signal with a single multiplier. Such a simplification will not be implemented in this experiment.

a DSSS demodulator

A demodulator for the DSSS of Figure 1 is shown in block form in Figure 3.

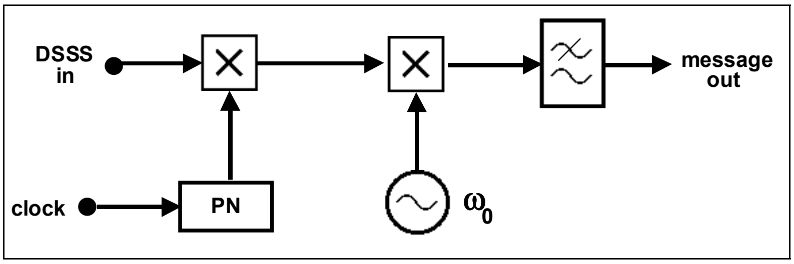

Figure 3: DSSS demodulator

The input multiplier performs the de-spreading of the received signal, and the second multiplier translates the modulated signal down to baseband. The filter output would probably require further processing - not shown - to 'clean up' the waveform to binary format.

The PN sequence at the receiver acts as a 'key' to the transmission. It must not only have the same clock and bit pattern; it must be *aligned* properly with the sequence at the transmitter.

sequence alignment

Sequence alignment is examined in the experiment entitled *PRBS Generation* (in Volume D1). Alignment of the two generators of Figures 2 and 3 is a simple matter if there is no delay introduced by the transmission path (not likely in practice, but simple in the laboratory). When delay is included, as in a practical system, alignment is a non-trivial exercise. It will not be examined in this experiment.

Also not shown are means of acquiring the carrier ω_0. A stolen carrier will be used in the experiment.

code division multiple access CDMA

When there is no DSSS signal present at the input to the demodulator there is none-the-less a noise output.

Should there be, in addition, a DSSS signal present, but derived from a PN sequence other than that being used by the demodulator, this will also produce a noise output, since such a signal (it can be shown) looks like random noise. However, if it was derived from the same sequence as that being used at the demodulator, and this sequence was correctly aligned, then instead of a noise output the message would appear.

Since the transmission medium - free space in practice - is linear (meaning that superposition applies) more than one DSSS can occupy the same spectrum space. The required message can be selected by choosing the appropriate sequence at the demodulator. All the others appear as noise.

Such an arrangement is an example of a code division multiple access (CDMA) spread spectrum system.

Currently under development is a pair of TIMS modules which will enable a demonstration of CDMA with fewer modules than would be required if the transmitter of this experiment was duplicated. Enquiries to tim@tims.com.au

the PN spectrum

The PN signal, being periodic, has a line spectrum. This spectrum is determined by the PN clock period T_c and the sequence length N (the number of bits, or clock periods, before the pattern repeats).

- the spectral lines are separated by $(1/NT_c)$ Hz.
- there is a DC component of amplitude (1/N).
- the amplitude of an individual line in the spectrum is weighted, where:

$$\text{weight} = \sqrt{\frac{2(N+1)}{N^2}} \left(\frac{\sin(\pi n / N)}{\pi n / N} \right), \quad n \neq 0 \qquad \text{........ 1}$$

It is clear that a plot of these weights will show them lying within an envelope having a sync function shape. Most of the energy of the PN sequence lies below the first minimum (when n = N); that is, below the clock frequency.

For approximate analysis it is often assumed that the shape of the power spectral density is rectangular, extending from DC to $(1/T_c)$ Hz.

spectral analysis

Some important measurements to be made with a spread spectrum system are of the various spectra. A simple wave analyser, as described in the experiment entitled *Spectrum analysis - the WAVE ANALYSER*, in Volume A2, is not suitable for the purpose.

A *PICO Virtual Instrument* SPECTRUM ANALYSER is recommended.

EXPERIMENT

a DSSS model

This experiment will be concerned with modelling the systems of Figures 2 and 3.

the message

The message comes from a SEQUENCE GENERATOR.

To obtain a reasonable processing gain the message clock needs to be much slower than the PN clock. Being a sub-multiple of the PN clock is also an advantage (see Tutorial Question Q8). The2 kHz MESSAGE from the MASTER SIGNALS module has been used - 1/48 of the 100 kHz master clock.. You may prefer a larger division ratio. This can be achieved with further division using the DIGITAL UTILITIES module.

Select a short message sequence for stable oscilloscope displays (both toggles of the on-board switch UP).

the transmission medium

The transmitter is connected to the receiver via an ADDER, acting as a non-bandlimiting (and so no delay) transmission path. The second input to the ADDER will be used for inserting noise. The inclusion of a finite delay would introduce problems with aligning the receiver PN sequence.

clocks

Since the PN clock is a sub-multiple of the carrier, only one of these needs to be recovered by the receiver. In the experiment they are stolen from the transmitter.

generation

T1 *model the block diagram of Figure 2. This is shown in Figure 4. The ADDER is included for inserting noise from a NOISE GENERATOR (module not shown).*

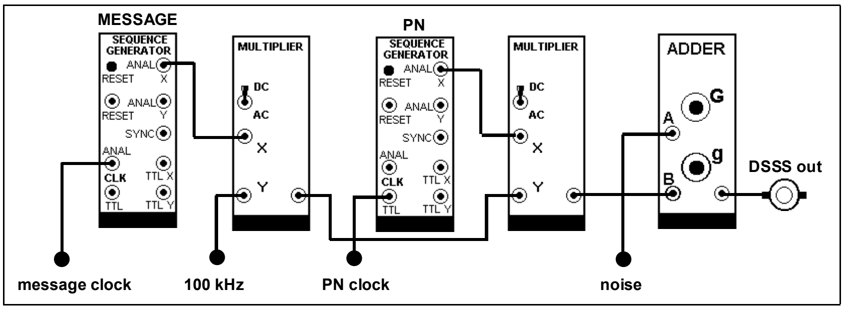

Figure 4: the transmitter model

T2 *before inserting the SEQUENCE GENERATOR modules, select a short sequence for the message (both toggles of the on-board switch SW2 UP), and the same long sequence for the PN generators (both toggles of the on-board switch SW2 DOWN).*

T3 *initially use the 100 kHz TTL available from MASTER SIGNALS, divided by 12, using a DIGITAL UTILITIES module (not shown), for the PN generator clock.*

T4 *initially reduce the noise output from the ADDER to zero.*

The next three Tasks could be omitted, but they confirm that both MULTIPLIER modules are operating as expected.

T5 *instead of connecting the bi-polar message sequence to the X input of the first MULTIPLIER, connect instead the 2 kHz MESSAGE (sinusoidal) signal. This makes the output from the first MULTIPLIER a DSBSC signal, easily recognisable on the oscilloscope. Check this.*

T6 *instead of connecting the PN sequence to the X input of the second MULTIPLIER, connect instead the VARIABLE DC module set to near +2 volt. This makes the second MULTIPLIER a voltage controlled amplifier with a gain of about unity. Thus the 'DSSS output' will be a well-recognisable DSBSC based on a 2 kHz message. Check your levels with this recognisable signal.*

T7 *using the PICO SPECTRUM ANALYSER, examine the output spectrum. Confirm it is a DSBSC.*

When satisfied that the MULTIPLIER modules are behaving as expected, return their inputs to the signals previously connected.

T8 *synchronize the oscilloscope to the SYNCH signal (START-OF-SEQUENCE) of the message generator. Examine signals throughout the system. Some will be familiar, others not. There are no adjustments to be made, except for the output amplitude from the ADDER.*

T9 *using the PICO SPECTRUM ANALYSER, examine the output spectrum. With an 8.333 kHz PN clock, confirm that the output spectrum - the DSSS signal - has its energy concentrated over about 8 kHz either side of the 100 kHz carrier.*

T10 *now add noise. Adjust the noise level so that, while observing the spectrum of the ADDER output, the DSSS signal can be seen above the noise level.*

T11 *while still observing the spectrum, increase the spread of the DSSS signal. This is done by increasing the PN sequence clock rate by choosing a lower division of the 100 kHz TTL - choose divide-by-2, for a 50 kHz clock.*

The increase of PN clock rate has widened the spectrum of the PN sequence to about 50 kHz (from 8 kHz). Since the DSSS signal contains the same energy as before, it has been spread more thinly over the spectrum, and it will have sunk deeper into, and got 'lost' in, the noise.

This is one of the main purposes of spread spectrum.

demodulation

T12 *model the receiver of Figure 3 as suggested in Figure 5 below. Both the 100 kHz carrier, and the PN sequence, are stolen from the transmitter. Not shown is a PHASE SHIFTER for the 100 kHz carrier. This is used to maximize the output amplitude (it will also change its polarity).*

T13 *the bandwidth of the output filter is chosen to suit the message. Use a TUNEABLE LPF (shown in Figure 5), or the 3 kHz LPF in the HEADPHONE AMPLIFIER. For restoration of the output to a TTL format a DECISION MAKER would be included, but this is not necessary for this experiment. Visual comparison of the sent and received sequences is adequate.*

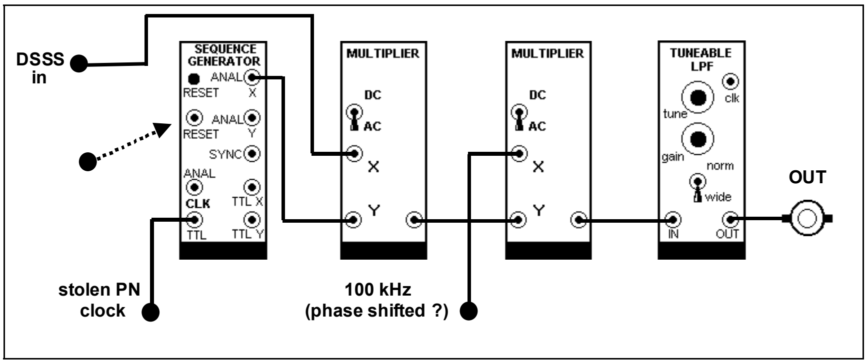

Figure 5: the receiver model

Although there are two stolen clocks shown, in practice it is often only necessary to acquire, by what ever means, a single clock. This is because one can be a known sub-multiple of the other.

T14 *observe the output, when the transmitter is connected to the input. Probably there will be 'nothing' - or nothing resembling the expected output sequence. Varying the phase of the 100 kHz carrier should not change things.*

The problem is that the receiver PN sequence, although synchronized with that at the transmitter, is not correctly aligned in time. With *no transmission delay* it is a simple matter to achieve this.

T15 *bring the two sequences into alignment by momentarily connecting the start-of-sequence SYNC output of the transmitter SEQUENCE GENERATOR to the RESET input of the receiver SEQUENCE GENERATOR.*

T16 *re-examine the output from the demodulator. The message should have been recovered (being a short sequence, this is easy to confirm visually). Adjust the bandwidth of the demodulator output filter for minimum bandwidth consistent with reasonable waveshape. Remember, a DECISION MAKER could be used to regenerate a perfect copy of the original, but this is not necessary for our present purpose.*

interference

T17 *with the system set up and showing the demodulated sequence at the receiver output, replace the noise with a 100 kHz sinusoid from a VCO. This represents an interfering signal (a very elementary form of jamming). Monitor the VCO with the FREQUENCY COUNTER.*

T18 *while watching the demodulator output, sweep the VCO frequency through its full frequency range.*

the wanted sequence will still be present at the demodulator output, but there will be negligible sign of the effects of the interfering signal. You have demonstrated another important property of spread spectrum.

CDMA

It was seen earlier that, when the 'incorrect' PN sequence was used at the receiver, there was negligible output from the receiver even when a DSSS signal was present at the input. In fact, it was the correct sequence, but it was mis-aligned. The same result would have been observed if the sequence had been changed.

In fact, many DSSS signals can be present at the same time, on the same carrier or otherwise, and will appear to the receiver as noise. Only when using the correct PN sequence (correctly aligned) will a message appear at the output.

The required message is recovered by using the correct code - so this is code division multiplex, or code division multiple access - CDMA.

CDMA can be demonstrated with TIMS by modelling two or more transmitters, with different PN codes for each, and adding their outputs. This becomes a big system, but it is possible.

As stated earlier, two new modules are being developed for TIMS which will simplify such a demonstration. Enquiries to tim@tims.com.au

TUTORIAL QUESTIONS

Q1 *sketch the amplitude spectrum of a PN sequence clocked at 50 kHz, and with a length of 2047 bits. Annotate with as much numerical information as you can.*

Q2 *consider a DSBSC signal derived from a single tone. How many lines would there be in the spectrum of the spread signal ? You will have to supply some data regarding the spreading sequence.*

Q3 *explain the principle difference between the channel selection process in phase division multiplex (PDM), and code division multiple access (CDMA). Thus explain why PDM can only support two channels, whereas this restriction is not present in CDMA.*

Q4 *unlike the two channel*[3] *DSBSC multiplexing system examined in the experiment entitled* **Phase division multiplex** *(in Volume A2), CDMA is capable of supporting more than two independent channels. What do you see as a limit to the number of channels which could be accommodated in a code division multiple access (CDMA) spread spectrum system ?*

Q5 *consider a DSBSC signal derived from a single tone. How many lines would there be in the de-spread spectrum ? You will have to supply some data regarding the spreading sequence.*

Q6 *the message bandwidth is typically much less than that of the spreading PN sequence. However there is an advantage in making it at least as wide as the spacing of the spectral lines of the latter. Why might this be ?*

Q7 *what have you read about the effects of multi-path fading on a DSSS signal ?*

Q8 *what advantage is there in making the message bit rate a sub-multiple of the PN bit rate ?*

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[3] ie, two *message* channels

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