Module - 5

principles of Spread Spectrum

1) Spread spectrum communication systems:

In digital communication, the important design parameters are transmitter power and channel bandwidth.

Let R denote the information (bit) rate at the input to the transmitter.

Let W denote the channel bandwidth.

Then Bandwidth expansion factor Be is defined as

$$Be = \frac{\text{Channel Bandwidth}}{\text{Information bit rate}}$$

$$\boxed{Be = \frac{W}{R}} \longrightarrow (1)$$

The factor Be represents the amount of redundancy introduced through the channel coding.

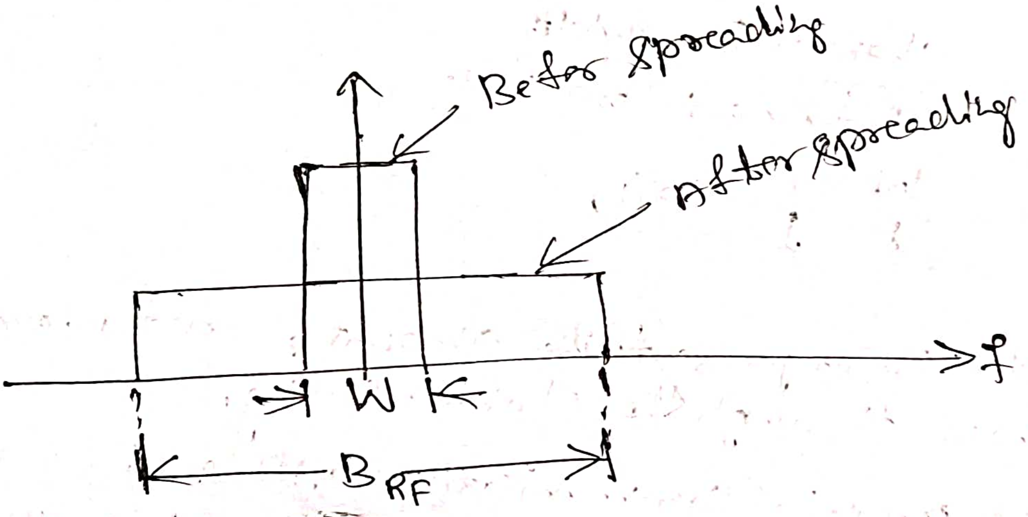
In most practical communication systems, Be is in the range of $2 \leq Be \leq 5$. This is the basic methodology for the design of digital communication systems for AWGN channels.

To overcome the degradation in performance caused by interference, we may further increase the bandwidth of the transmitted signal so that the $Be = \frac{W}{R}$ is much greater than unity. This is one characteristic of a spread spectrum signal.

The second important characteristic of spread spectrum signal is that the information signal at the modulator is spread in bandwidth by means of code called pseudorandom code that appears random to the receivers other than the intended receiver. The receiver uses the knowledge of the code to demodulate the signal. Channel coding is an important element in the design of an efficient spread spectrum communication system.

Spread spectrum is a technique in which a transmitted signal occupies a much larger bandwidth than the bandwidth required by the message signal (ie baseband information signal.)

The fig ① shows the basic concept of spread spectrum.



Fig①. Illustration of the Concept of Spread spectrum. The transmitted data sequence occupies a much more bandwidth than the minimum required bandwidth.

The performance of the communication system is measured by the ratio of spread Bandwidth to information bandwidth.

pseudo random (PN) codes are used to achieve the spreading of the spectrum.

Spread spectrum signals was originally used for military communication either (1) to provide resistance to jamming (antijam protection) or (2) to hide the signal by transmitting it at low power which made it difficult for unintended listener to detect its presence in noise.

Spread spectrum signal provide reliable communications in a variety of civilian applications including digital cellular communications, ~~cordless~~ cordless telephones, and interoffice wireless communications.

Model of a Spread Spectrum Digital Communication System :

The figure 2 shows the model of a spread-spectrum digital communication system.

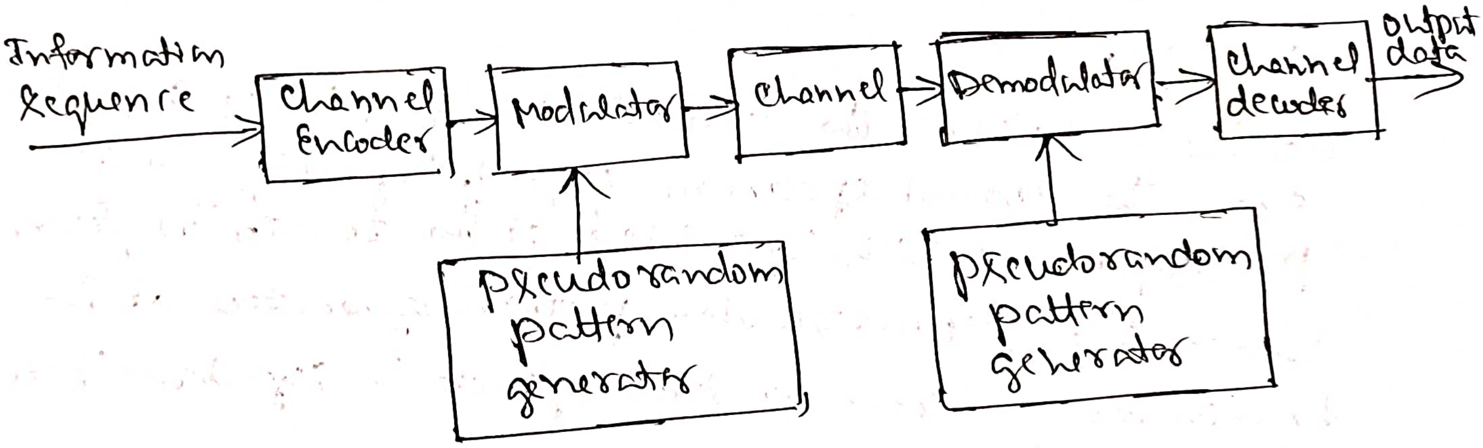


Figure 2: Model of a spread spectrum digital communication system.

The important elements of spread spectrum digital communication system are:

1) Channel Encoder and decoder
2) Modulator and Demodulator
3) Two pseudorandom pattern generators

The binary information sequence is applied to the input of the Channel Encoder. K.R.

The channel Encoder Encodes the input binary sequence according to some Error Control coding technique.
The Coded sequence is then given to the modulator.
The modulator ~~pseudo~~ gets pseudo random or pseudo noise (PN) sequence from the pseudo-random pattern generator. This pseudo noise (PN) sequence spreads the the signal randomly over the wide frequency band. The signal at the output of the modulator is the spreaded spectrum modulated signal.
The Interference is introduced in the channel during the transmission of the ~~sp~~ spread spectrum signal.
The interference may be broadband or narrowband and Either Continuous in time or discontinuous (pulsed) in time.

At the receiver, the demodulator gets coded signal back from the spread spectrum signal, by using the same PN sequence which was used at the transmitting End.
Hence the pseudo random pattern generators at the transmitter and receiver side operate in synchronization with Each other.
The channel decoder at the receiver gets the binary information sequence back.
Thus the receiver can detect the transmitted spread spectrum signals only if it knows the pseudo noise (PN) sequence. For any arbitrary receiver it is difficult to know the pseudo noise noise since it appears like noise.

Note that the PN sequence at modulator is used with Either PSK (or FSK) to shift the phase (or frequency) of PSK (or FSK) signal pseudo randomly.

Types of Modulation : 1) Direct Sequence Spread Spectrum (DSSS)
2) Frequency Hopped SS (FHSS).

Direct Sequence Spread Spectrum Systems (DSSS)

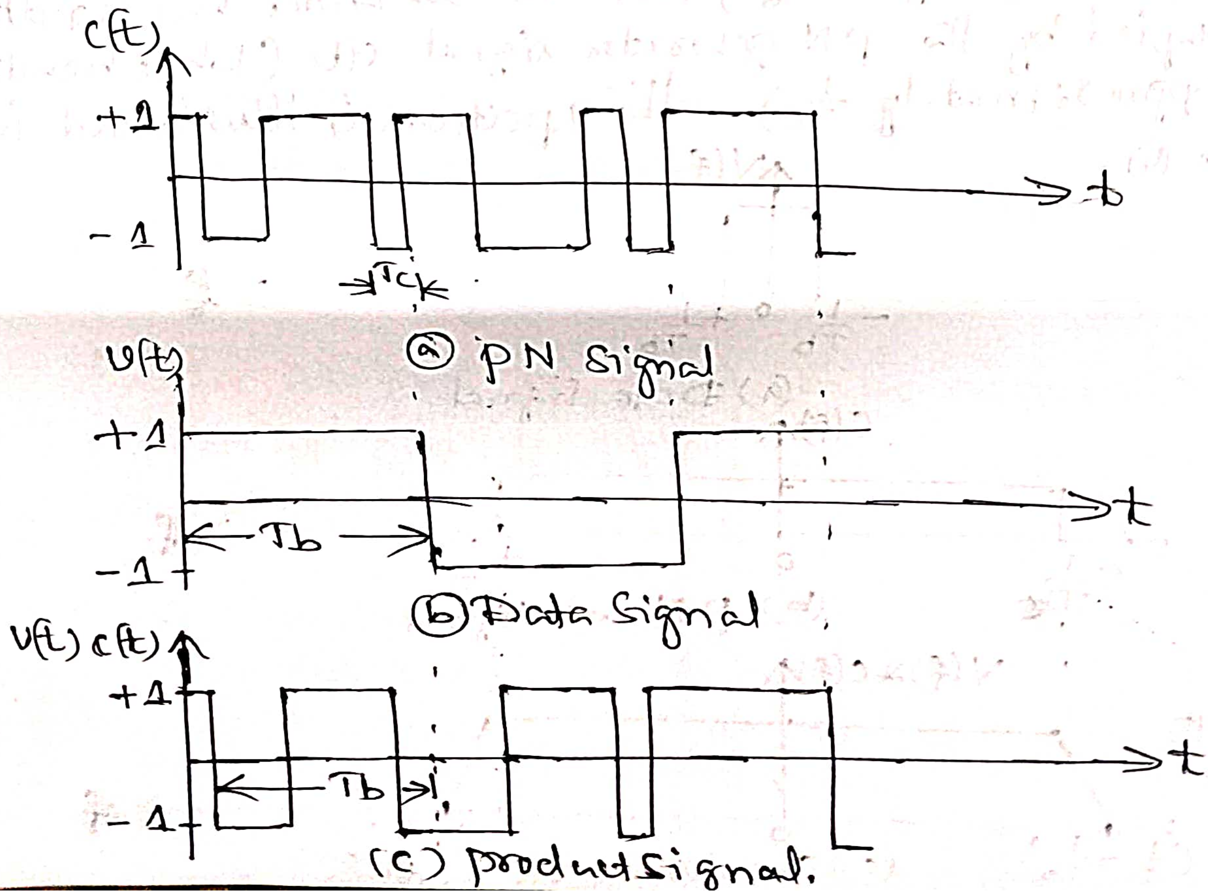
Consider the transmission of a binary information sequence by means of binary PSK.

The information rate is R bits per second and the bit interval is $T_b = \frac{1}{R}$ seconds.

The available channel Bandwidth is B_c Hz where $B_c \gg R$.

At the modulator, the bandwidth of information signal is expanded to $W = B_c$ Hz by shifting the phase of the carrier pseudorandomly at a rate of W times/second according to the pattern of PN generator.

The basic method for accomplishing spreading is shown in fig ③.



The information base band Data signal is denoted as $v(t)$ is given by

$$v(t) = \sum_{n=-\infty}^{\infty} a_n\, g_T(t - nT_b) \longrightarrow (1)$$

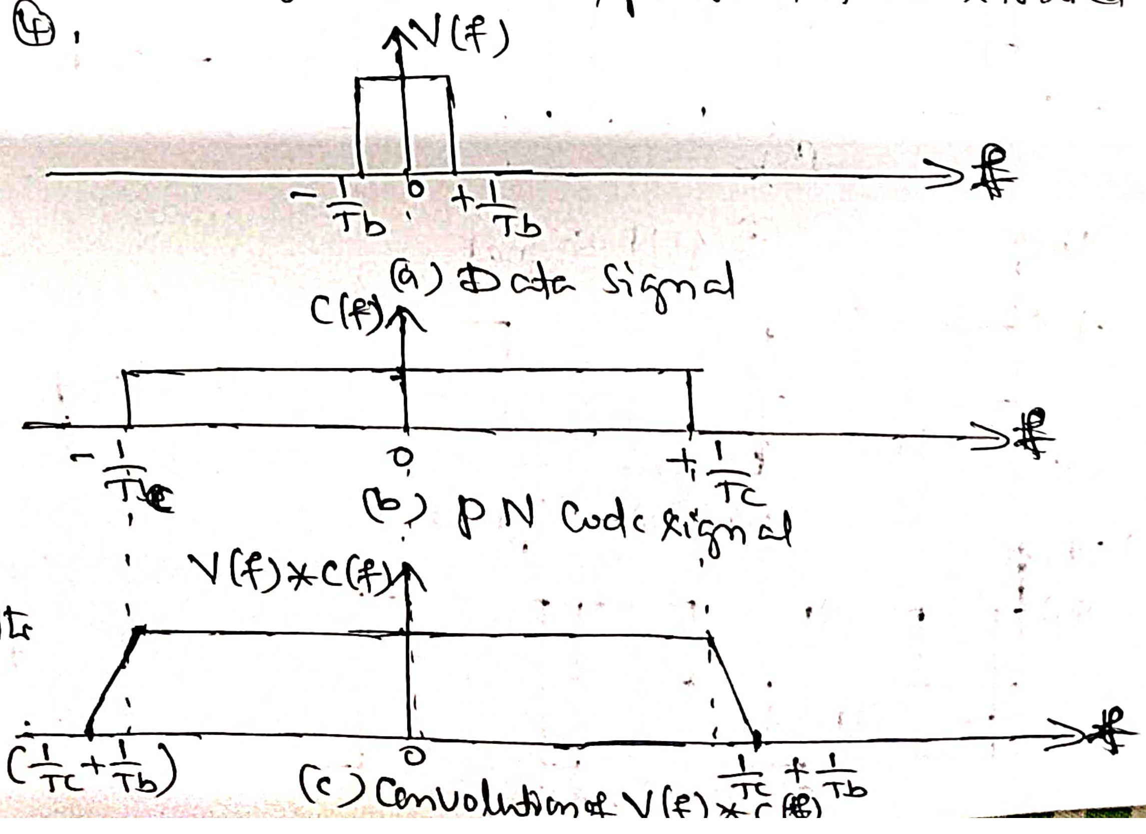
where $\{a_n = \pm 1, -\infty < n < \infty\}$ and $g_T(t)$ is a rectangular pulse of duration T_b.

The PN sequence generator signal $c(t)$ is expressed as

$$c(t) = \sum_{n=-\infty}^{\infty} c_n\, p(t - nT_c), \longrightarrow (2)$$

where $\{c_n\}$ represents the binary PN code sequence of ± 1 and $p(t)$ is a rectangular pulse of duration T_c, as shown in figure (3).

This multiplication operation serves to spread the bandwidth of information bearing signal (ie Data signal whose bandwidth is approximately R Hz) into the wider bandwidth occupied by the PN generator signal $c(t)$ (whose bandwidth is approximately $\frac{1}{T_c}$). The spectrum is illustrated in figure (4).



(a) Data Signal

(b) PN Code Signal

(c) Convolution of V(f) * C(f)

Fig (4): Convolution of the Spectra of the data signal with PN code signal.

The product signal $v(t)\,c(t)$ amplitude modulates the the carrier $A_c \cos 2\pi f_c t$ and generates the DSB-SC signal.

$$\therefore\ u(t) = v(t)\,c(t) \cdot A_c \cos 2\pi f_c t$$

$$\text{ie } u(t) = A_c\, v(t)\,c(t) \cos 2\pi f_c t \rightarrow (3)$$

But $v(t)\,c(t) = \pm 1$ for any t

$$\therefore\ u(t) = A_c \cos[2\pi f_c t + \theta(t)] \rightarrow (4).$$

Where $\theta(t) = 0$ when $v(t)\,c(t) = 1$ and $\theta(t) = \pi$ when $v(t)\,c(t) = -1$,

Therefore, the transmitted signal is a binary PSK signal.

The rectangular pulse $p(t)$ is usually called a chip and its time duration T_c is called the chip interval. The reciprocal $\frac{1}{T_c}$ is called the chip rate

The number of chips of the PN code sequence per information bit is given by

$$L_c = \frac{T_b}{T_c} \rightarrow (5)$$

Another interpretation is that L_c represents the number of possible 180° phase transitions in the transmitted signal during the bit interval T_b.

Demodulation:

The demodulation of the signal is shown in fig (5).

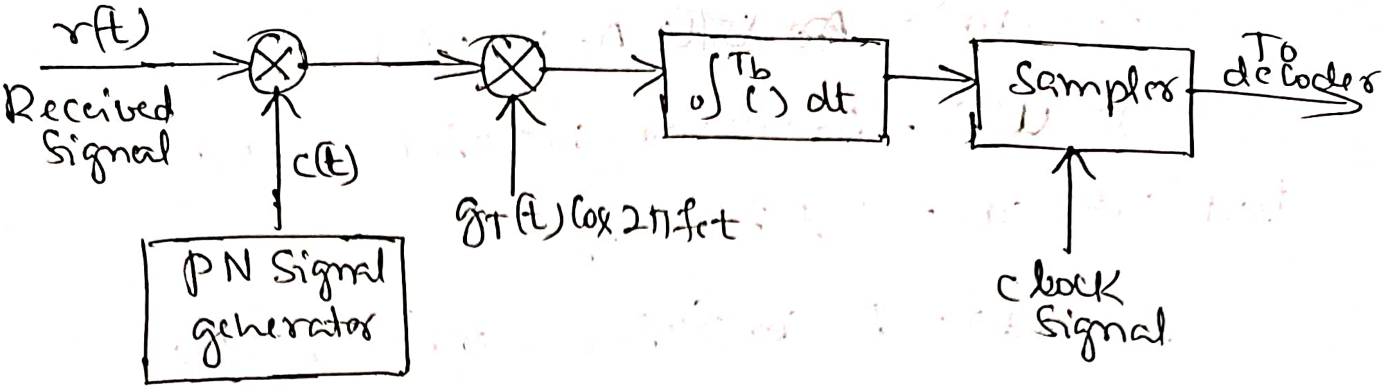


Figure 5: Demodulation of DS spread spectrum Signal.

The received signal is first multiplied by a replica of the waveform c(t) generated by the PN code sequence generator at the receiver, which is synchronized to the PN code in the received signal. This operation is called despreading.

$$\therefore \quad A_c v(t)\, c(t) \cos 2\pi f_c t \cdot c(t) = A_c v(t)\, c^2(t) \cos 2\pi f_c t$$

But $c^2(t) = 1$, then

$$A_c v(t)\, c(t) \cos 2\pi f_c t \cdot c(t) = A_c v(t) \cos 2\pi f_c t \rightarrow (6)$$

The resulting signal $A_c v(t) \cos 2\pi f_c t$ occupies a bandwidth of R Hz approximately which is the bandwidth of the information Data signal. The demodulator the despread signal is correlator (or matched filter).

Since the demodulator has a bandwidth that is identical to the bandwidth of the despread signal, the only additive noise that corrupts the signal at the demodulator is the noise that falls within the information bandwidth of the received signal.

Effect of Despreading on a Narrowband Interference

Suppose that the received signal is

$$r(t) = A_c\, v(t)\, c(t) \cos 2\pi f_c t + i(t) \rightarrow (1)$$

Where $i(t)$ denotes the interference. The despreading operation at the receiver yields

$$r(t)\, c(t) = [A_c\, v(t)\, c(t) \cos 2\pi f_c t + i(t)]\, c(t)$$

$$= A_c\, v(t)\, c^2(t) \cos 2\pi f_c t + i(t)\, c(t)$$

i.e $r(t)\, c(t) = A_c\, v(t) \cos 2\pi f_c t + i(t)\, c(t) \quad \because c^2(t) = 1$

$\rightarrow (2)$

The effect of multiplying the interference $i(t)$ with $c(t)$ is to spread the bandwidth of $i(t)$ to W Hz.

As an example, consider the sinusoidal interfering signal, $i(t) = A_I \cos 2\pi f_I t \rightarrow (3)$

where f_I is the frequency within the bandwidth of the transmitted signal. Its multiplication with $c(t)$ results in a wideband interference with spectral density $I_0 = \frac{P_I}{W}$

where $P_I = \frac{A_I^2}{2}$ is the average power of the interference.

The desired signal is demodulated by a matched filter (or correlator) that has bandwidth R, then the total power in the interference at the output of the demodulator is

$$I_0 R_b = \frac{P_I R_b}{W} = \frac{P_I}{\frac{W}{R_b}} = \frac{P_I}{\left(\frac{T_b}{T_c}\right)} = \frac{P_I}{L_c} \rightarrow (4)$$

Therefore, the power in the interfering signal is reduced by an amount equal to the bandwidth expansion factor $\frac{W}{R}$. The factor $\frac{W}{R} = \frac{T_b}{T_c} = L_c$ is called "processing gain" of the spread spectrum system.

The reduction in interference power is the basic reason for using spread spectrum signals to transmit digital information over channels with interference.

In summary, the desired signal at the receiver is spread back to a narrow bandwidth, while any interference signals are spread over a wide bandwidth. The net effect is a reduction in the interference power by the factor $\frac{W}{R}$ which is the processing gain of the spread spectrum system.

The use of PN code sequence provides a degree of privacy (or security) that is not possible with conventional modulation.

Probability of Error:

The transmitted PSK modulated signal is represented as

$$s(t) = a_0 g_T(t) \cos 2\pi f_c t, \quad 0 \le t \le T_b \rightarrow (1)$$

where $a_0 = \pm 1$ and pulse $g_T(t)$ is defined as

$$g_T(t) = \begin{cases} \sqrt{\frac{2E_b}{T_b}}, & 0 \le t \le T_b \\ 0, & \text{otherwise} \end{cases} \rightarrow (2)$$

PN sequence generator output $c(t)$ is expressed as

$$c(t) = \sum_{n=0}^{L_c-1} c_n p(t - nT_c) \rightarrow (3)$$

where L_c is the number of chips per bit

T_c is the chip interval

The code chip sequence $\{c_n\}$ is uncorrelated (white)

ie $E(c_n c_m) = E(c_n) E(c_m)$, for $n \ne m \rightarrow (4)$

The received signal is given by

$$r(t) = a_0\, g_T(t-t_d)\, c(t-t_d) \cos(2\pi f_c t + \phi) + i(t) \rightarrow (5)$$

and $i(t) = i_c(t) \cos 2\pi f_c t - i_s(t) \sin 2\pi f_c t \rightarrow (6)$

where $i_c(t)$ and $i_s(t)$ are two quadrature components

$$y(T_b) = g_b + y_i(T_b) \rightarrow (7)$$

$$(SNR)_o = \frac{2E_b}{I_o} \rightarrow (8)$$

$$\therefore \; P_2 = Q\left(\sqrt{\frac{2E_b}{I_o}}\right) \rightarrow (9)$$

where I_o is the power spectral density of an equivalent broadband interference.

Problem:

1. The SNR required at the detector to achieve reliable communication in a DS spread spectrum communication system is 13 dB. If the interference-to-signal power at the receiver is 20 dB, determine the processing gain required to achieve reliable communication.

Soln: Given $\left(\frac{P_t}{P_s}\right)_{dB} = 20\, dB$

ie $\frac{P_t}{P_s} = 100$

Also, given $(SNR)_D = 13\, dB$

(or) $(SNR)_D = 20$.

$\therefore$ processing gain L_c is given by

$$L_c = \frac{1}{2}\left(\frac{P_t}{P_s}\right)(SNR)_D = \frac{1}{2} \times 100 \times 20 = 1000$$

In dB, $\boxed{L_c = 30\, dB}$

The Interference Margin

The ratio $\frac{\mathcal{E}_b}{I_0}$ given in Eqn $P_2 = Q\left(\sqrt{\frac{2\mathcal{E}_b}{I_0}}\right)$ may be expressed as

$$\frac{\mathcal{E}_b}{I_0} = \frac{P_S T_b}{P_I/W} = \frac{P_S/R}{P_I/W} = \frac{W/R}{P_I/P_S} \rightarrow (10)$$

or

$$10 \log \frac{P_t}{P_S} = 10 \log \frac{W}{R} - 10 \log \left(\frac{\mathcal{E}_b}{I_0}\right) \rightarrow (11)$$

The interference margin is given by

$$\left(\frac{P_t}{P_S}\right)_{dB} = \left(\frac{W}{R}\right)_{dB} - \left(\frac{\mathcal{E}_b}{I_0}\right)_{dB} \rightarrow (12)$$

Problem (1):

Suppose we require an $\left(\frac{\mathcal{E}_b}{I_0}\right)_{dB} = 10$ dB to achieve reliable communication. What is the processing gain that is necessary to provide an interference margin of 20 dB?

Soln: WKT if $\frac{W}{R} = 1000$, then $\left(\frac{W}{R}\right)_{dB} = 30$ dB.

Given interference margin $\left(\frac{P_t}{P_S}\right)_{dB} = 20$ dB.

This means that the average interference power at the receiver may be 100 times the power P_S of the desired signal and we ~~still~~ can still maintain reliable communication.

Performance of Coded Spread Spectrum Signals

$$\text{Coding gain} = R_c d^H_{min} \rightarrow (13)$$

where R_c is the code rate and d^H_{min} is the minimum Hamming distance of the code.

$$\therefore \left(\frac{Pt}{PS}\right)_{dB} = \left(\frac{W}{R}\right)_{dB} + (CG)_{dB} - \left(\frac{\varepsilon b}{I_0}\right)_{dB} \rightarrow (14)$$

where $(CG)_{dB}$ denotes the coding gain in dB.

Some Applications of DS Spread Spectrum Signals

1) Low-Detectability Signal transmission
2) Code division multiple access (CDMA)
3) Communication over channels with Multipath
4) Wireless LANS.

1.) Low Detectability Signal transmission:

In this application, the information bearing signal is transmitted at a ~~low~~ very low power level relative to the background channel noise and thermal noise that is generated in front end of a receiver.

If the DS spread spectrum signal occupies a bandwidth W and the power spectral density of the additive noise is No W/Hz, then the noise power in the bandwidth 'W' is given as

$$\boxed{PN = WNo}$$

The average received ~~power~~ signal power at the intended receiver is PR. If $\frac{PR}{PN} \ll 1$; then we can hide the presence of the signal from the receivers that are in the vicinity of intended receiver. But the intended receiver can get ~~the~~ back (or) recover the information bearing signal from the background noise with the help of the processing gain and the coding gain.

~~However~~ However, any other receiver that has no knowledge of the PN code sequence is unable to take advantage of the processing gain and coding gain. So, the presence of information bearing signal is difficult to detect. Hence, the transmitted signal has a low probability of being intercepted (LPI) and it is called LPI signal.

Problem ①:

A DS spread-spectrum signal is designed so that the power ratio $\frac{P_R}{P_S}$ at the intended receiver is 10^{-2}. If the desired $\frac{E_b}{N_o} = 10$ for acceptable performance, determine the minimum value of the processing gain.

Soln: Given $\frac{E_b}{N_o} = 10$, & $\frac{P_R}{P_N} = 10^{-2}$.

$$\therefore \frac{E_b}{N_o} = \frac{P_R T_b}{N_o} = \frac{P_R L_c T_c}{N_o} = \left(\frac{P_R}{W N_o}\right) L_c = \left(\frac{P_R}{P_N}\right) L_c.$$

ie $$\frac{E_b}{N_o} = \left(\frac{P_R}{P_N}\right) L_c$$

ie $$10 = (10^{-2}) L_c$$

$$10 = \frac{1}{10^2} \cdot L_c$$

$$10 = \frac{1}{100} L_c$$

$$\therefore L_c = 10 \times 100 = \underline{\underline{1000}}$$

2) Code Division Multiple Access (CDMA)

It is a technique or a type of digital communication in which each transmitter - receiver user pair has its own distinct signature code for transmitting over a common channel bandwidth.

A major advantage of CDMA is that a large number of users can be accommodated if each user transmits messages for a short period of time. In such a multiple access system, it is relatively easy to add new users or to decrease the number of users without reconfiguring the system. CDMA is used in digital cellular telephone service to mobile users.

If there are Nu simultaneous users, the desired signal to noise interference power ratio at the given receiver is

$$\frac{P_S}{P_N} = \frac{P_S}{(N_u-1)P_S} = \frac{1}{N_u-1} \rightarrow (1)$$

From this relation, we can determine the number of users that can be accommodated simultaneously.

problem (1):

Suppose that the desired level of performance for a user in a CDMA system is an error probability of 10^{-6}, which is achieved when $\frac{E_b}{I_0} = 20$ (13 dB). Determine the maximum number of simultaneous users that can be accommodated in a CDMA system if the bandwidth-to-bit rate ratio is 1000, and the coding gain is $R_c d_{min}^H = 4$ (6 dB)

Soln: Given $\frac{E_b}{I_0} = 20$ (13 dB), $R_c d_{min}^H = 4$ (6 dB)

WKT,

$$\frac{E_b}{I_0} = \frac{W/R}{N_u - 1} R_c d_{min}^{H}$$

ie
$$20 = \frac{W/R}{N_u-1}(4)$$

$$\frac{20}{4} = \frac{W/R}{N_u-1}$$

$$5 = \frac{W/R}{N_u-1}$$

$$5(N_u-1) = W/R$$

$$5N_u - 5 = W/R$$

$$\therefore 5N_u = \frac{W}{R} + 5$$

$$N_u = \frac{(W/R+5)}{5}$$

Now for $\frac{W}{R} = 1000$, we get

$$N_u = \frac{(1000+5)}{5} = \frac{1005}{5} = 201$$

ie $\boxed{N_u = 201}$

3) Communication over channels with Multipath:

DS spread spectrum is a particularly effective way to generate a wide band signal for resolving multipath signal components. By separating the multipath components, effects of fading can be reduced. For example, in LOS communication systems where there is a direct path and a secondary propagation path resulting from signals reflecting from building and surrounding terrain, the demodulator at the receiver may synchronize to the direct signal component and ignore the existence of the multipath component. In such a case, the multipath component becomes a form of interference (ISI) on the demodulation of subsequent transmitted signals.

ISI can be avoided if we reduce the symbol rate $\frac{1}{T}$ such that $T \gg T_m$. In this case, we use DSSS signal with a bandwidth W to resolve the multipath.
Thus, the channel is frequency selective and the appropriate channel model is the tapped-delay line model with time varying coefficients. The optimum demodulator for this channel is a filter matched to the tapped delay channel model called RAKE demodulator.

4) <u>Wireless LANs</u> : The spread spectrum signals have been used in the IEEE Wireless LAN standards 802.11 and 802.11b which operate in the 2.4GHz ISM (Industrial scientific medical) unlicensed frequency band. The available bandwidth is subdivided into 14 overlapping 22 MHz channels.

In 802.11 standard, an 11 chip Barker sequence is modulated and transmitted at a chip rate of 11 MHz i.e at the chip duration of 0.909 μsec. The 11-chip Barker sequence is {1, −1, 1, 1, −1, 1, 1, 1, −1, −1, −1}.
The Barker sequence is modulated Either with BPSK or QPSK. When BPSK is used with 11 chips per bit, a data rate of 1 Mbps is achieved. When QPSK modulation is used with 11 chips per symbol (2 bits), a data rate of 2 Mbps is achieved.

DSSS is also used in higher speed (second generation) IEEE 802.11b wireless standard which operates in the same 2.4 GHz ISM band.
In 802.11 b, the 11-MHz chip rate is maintained, but the Barker sequence is replaced by a set of 8 chip waveform sequence called Complementary Code Shift Keying (CCK) which can be viewed as direct sequence spread spectrum modulation with

multiple spreading sequences. The use of CCK modulation results in a data rate of 11 Mbps.