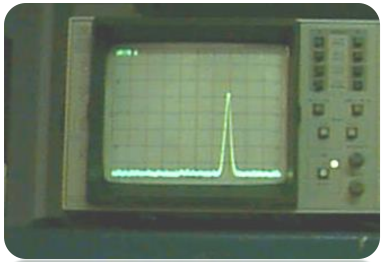
Dr. Ali Muqaibel

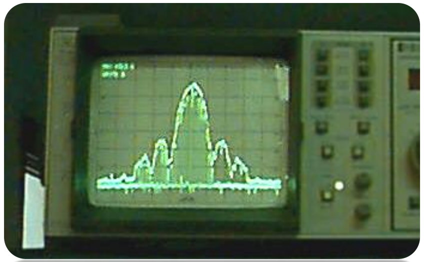
SPREAD SPECTRUM (SS) SIGNALS FOR DIGITAL COMMUNICATIONS

VERSION 1.1

Introduction



Narrow band signal
(data)



Wideband signal
(transmitted SS signal)

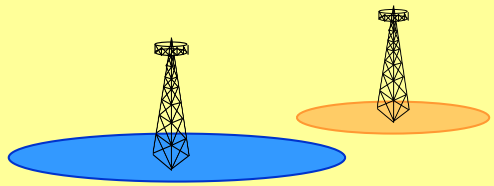
- In Spread Spectrum, the bandwidth W is much greater than the info rate R (bit/sec).
- Bandwidth Expansion Factor $B_e = \frac{W}{R} \gg 1$
- **Redundancy** is introduced to overcome interference (Radio & Satellite)
- **Coding** is an effective method for introducing redundancy.
- **Pseudo randomness** signals: appear like noise and are difficult to receive by the non-intended receivers.

Major Applications of SS

1. Combating/Suppressing Jamming/interference due to other users/self-interference (Multipath).
2. Covert (hidden)/Secure Communication/Privacy
   - Communication Security vs. information security
   - Spreading sequence can be very long -> enables low transmitted PSD-> low probability of interception (LPI) (especially in military communications)
3. CDMA: Coded division Multiple Access.. QUALCOMM lie!
   - CDMA allow multiple users to simultaneously use a common channel for transmission of information
   - Key=code
4. In Radar SS is used for time delay, velocity, and ranging.

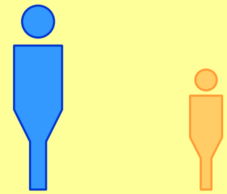
How Tele-operators Market CDMA

Coverage



For Coverage, CDMA saves wireless carriers from deploying the 400% more cell site that are required by GSM

Capacity

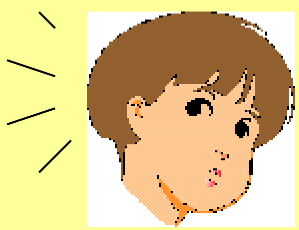


CDMA's capacity supports at least 400% more revenue-producing subscribers in the same spectrum when compared to GSM

Cost

A carrier who deploys CDMA instead of GSM will have a lower capital cost

Clarity



CDMA with PureVoice provides wireline clarity

Choice

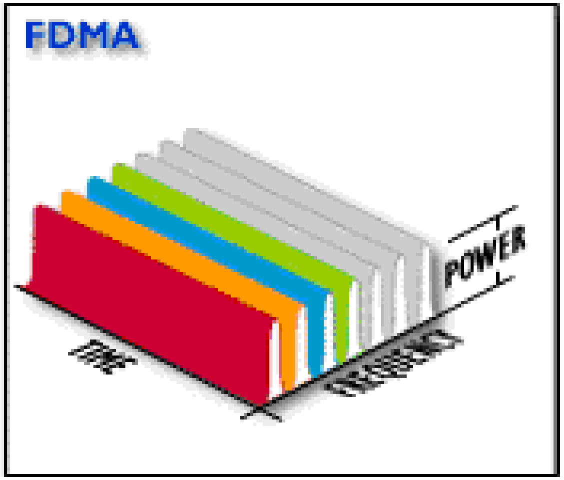
CDMA offers the choice of simultaneous voice, async and packet data, FAX, and SMS.

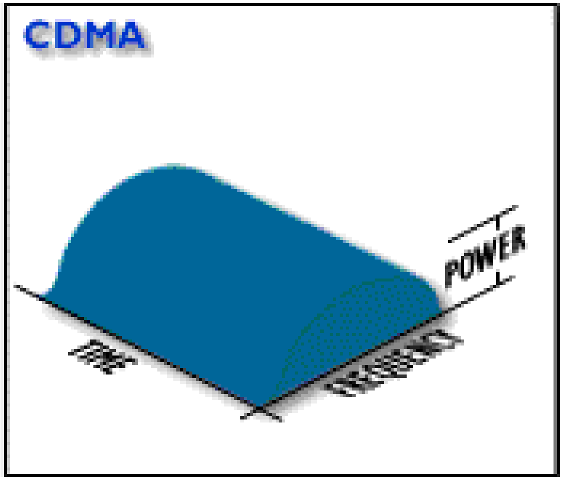
Customer satisfaction

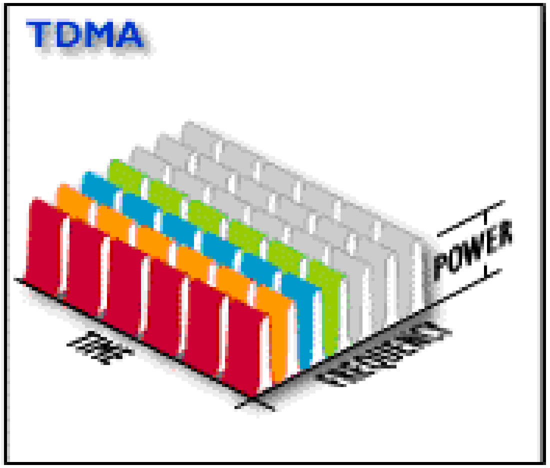
The Most solid foundation for attracting and retaining subscriber is based on CDMA

**From Samsung's narrowband CDMA (CDMAOne®) marketing (2001)*

Multiple access: FDMA, TDMA and CDMA







- FDMA, TDMA and CDMA yield conceptually the same capacity
- However, in wireless communications CDMA has improved capacity due to
  - statistical multiplexing
  - graceful degradation
- Performance can still be improved by adaptive antennas, multiuser detection, FEC, and multi-rate encoding

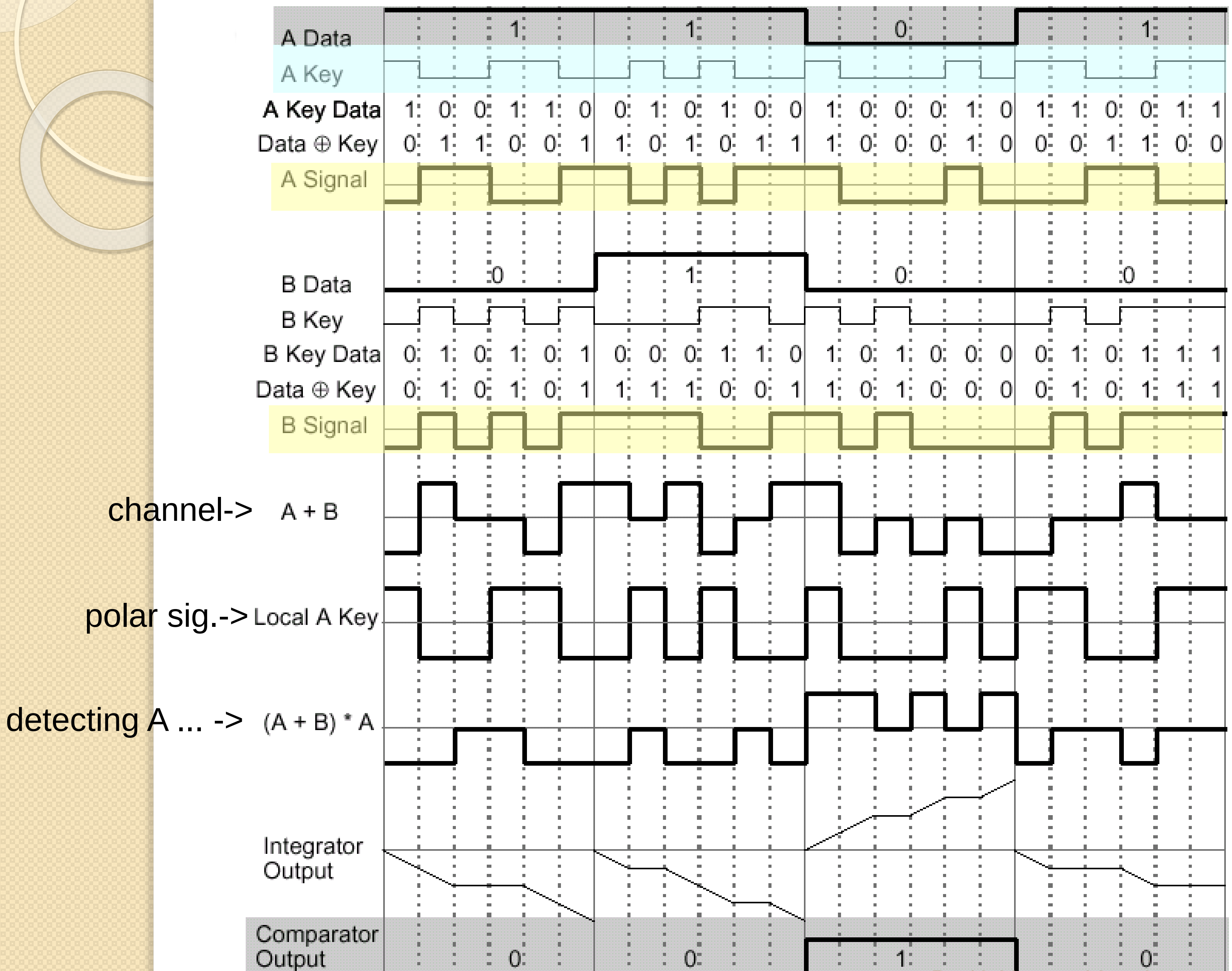
FDMA, TDMA and CDMA compared

- TDMA and FDMA principle:
  - TDMA allocates a time instant for a user
  - FDMA allocates a frequency band for a user
  - CDMA allocates a code for user
- CDMA-system can be *synchronous* or *asynchronous*:
  - Synchronous CDMA difficult to apply in multipath channels that destroy code orthogonality
  - Therefore, in wireless CDMA-systems as in IS-95,cdma2000, WCDMA and IEEE 802.11 users are asynchronous
- Code classification:
  - Orthogonal, as Walsh-codes for orthogonal or near-orthogonal systems
  - Near-orthogonal and non-orthogonal codes:
    - Gold-codes, for asynchronous systems
    - Maximal length codes for asynchronous systems

Coverage Objective

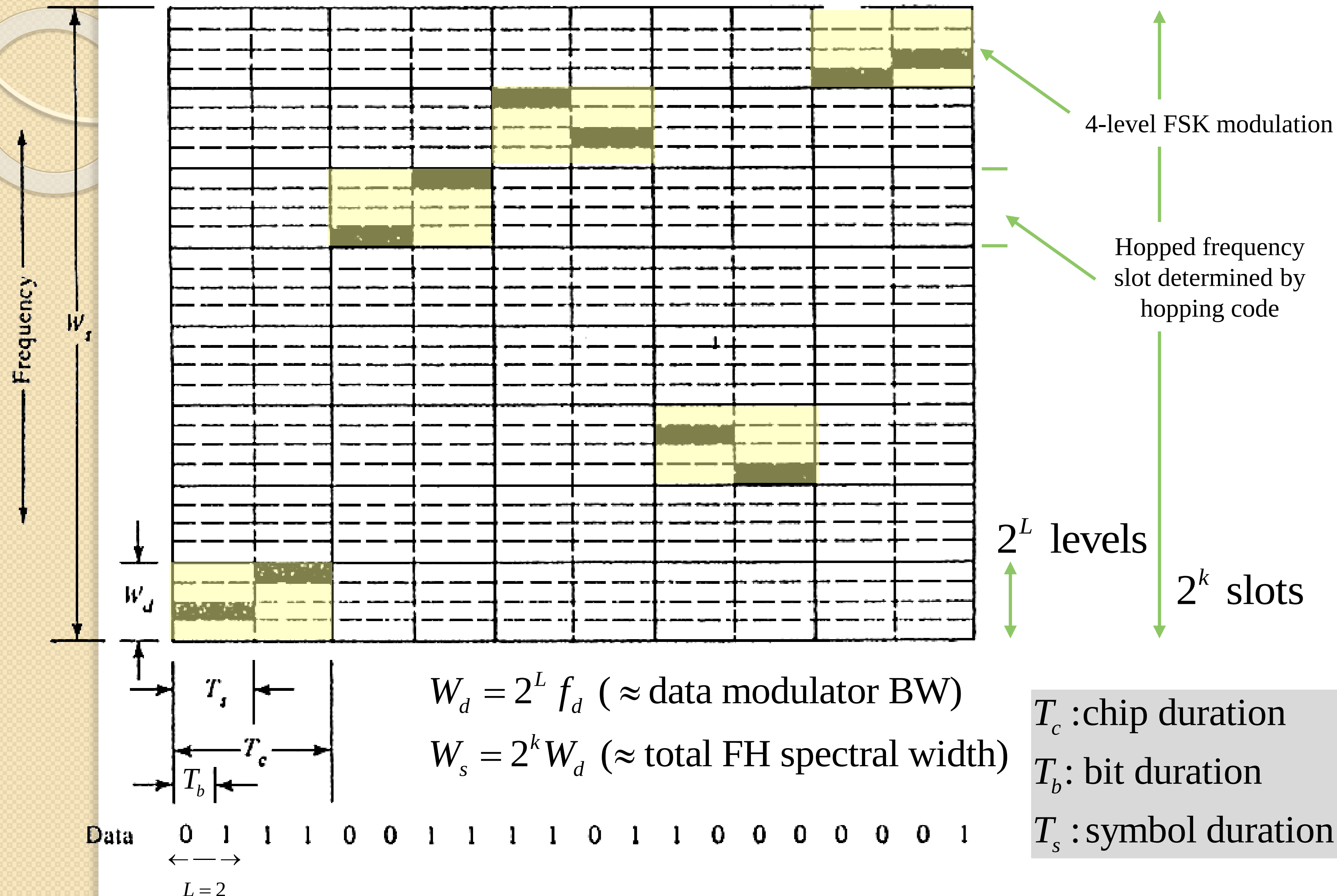
- Types of SS
  1. Direct Sequence SS (DSSS)
     - PSK/QPSK+ pseudo-noise (PN) sequence
  2. Frequency Hopping SS (FHSS)
     - M-ary FSK+PN
     - The pseudorandom sequence selects the frequency of the transmitted sequence randomly
- Anti-jamming (AJ) performance

Example of DS multiple access



Frequency Hopping Spread Spectrum (FH-SS)

(example: transmission of two symbols/chip)



$W_d = 2^L f_d$ (≈ data modulator BW)

$W_s = 2^k W_d$ (≈ total FH spectral width)

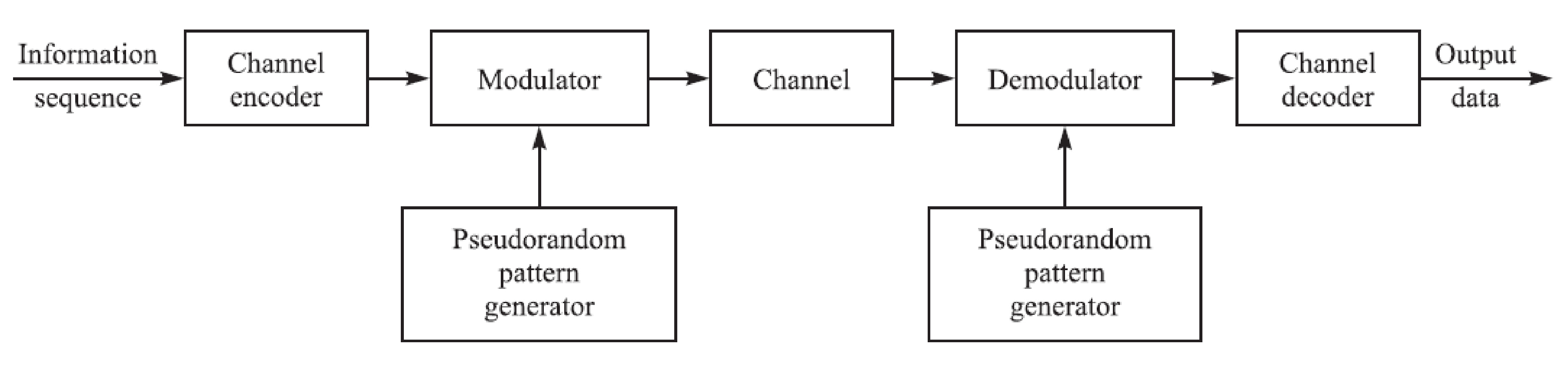
T_c :chip duration

T_b: bit duration

T_s :symbol duration

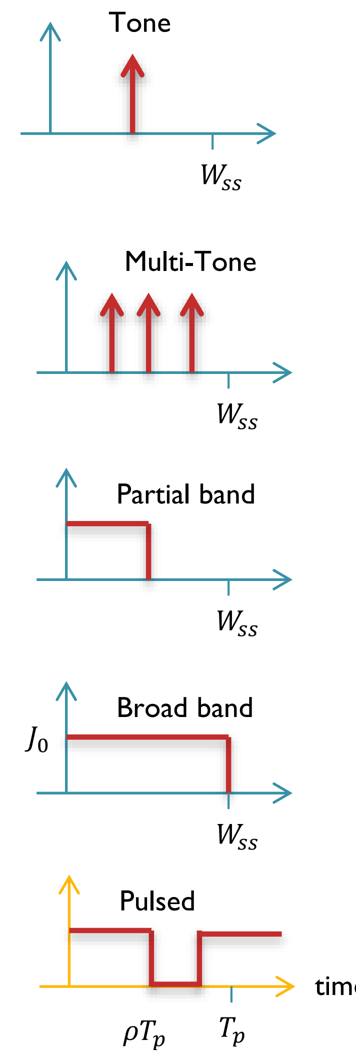
Model of SS Digital Comm. Sys.

- **The channel encoder:** coding is usually employed to enhance the gain.
- **Synchronization** (of the PN sequence)
  - Initially, training!, transmit a fixed PM bit pattern that the receiver will recognize in the presence of interference with high probability.



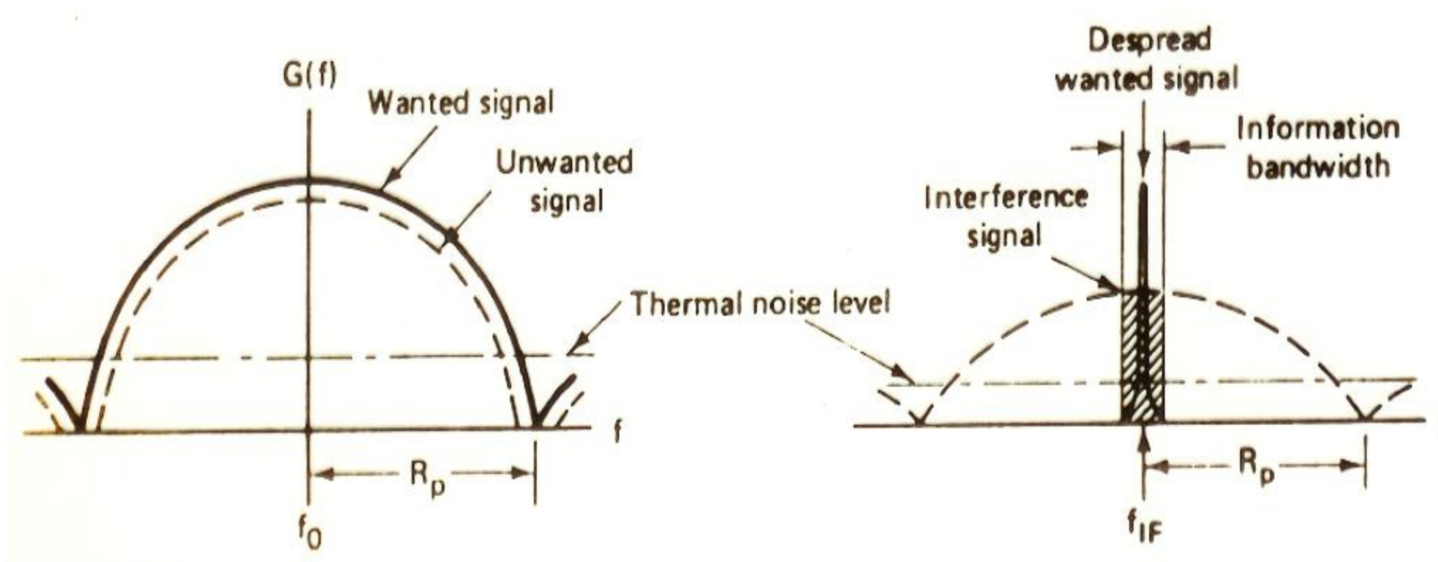
Interference & jamming

- It ch/s depends on its origin (military)
  1. Tone
  2. Multi-tone
  3. Partial band (Narrowband)
  4. Broadband
  5. Continuous/Pulsed (discontinuous)
  6. Fixed/ time variant
- 1 to 4 have similar effects on DSSS
- If the interference is broadband , it may be characterized as an equivalent AWGN
- In CDMA we can have multi user interference.



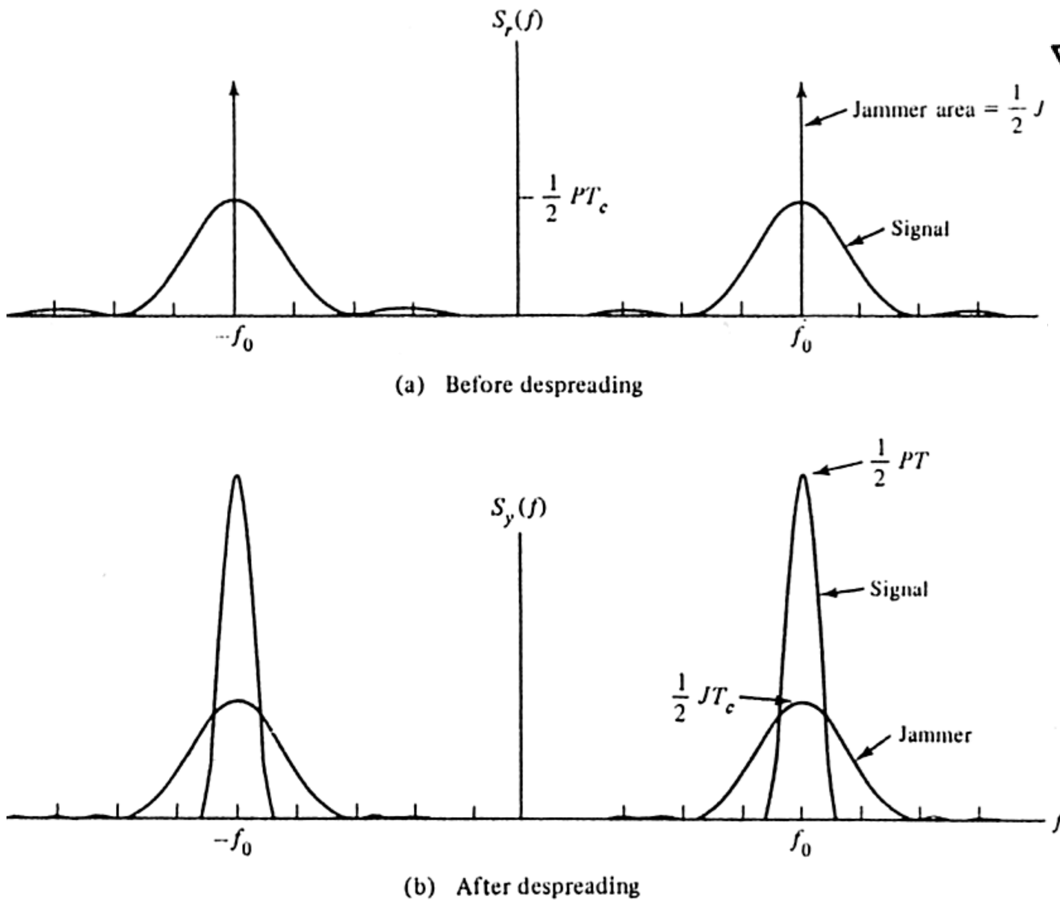
Objective (more details)

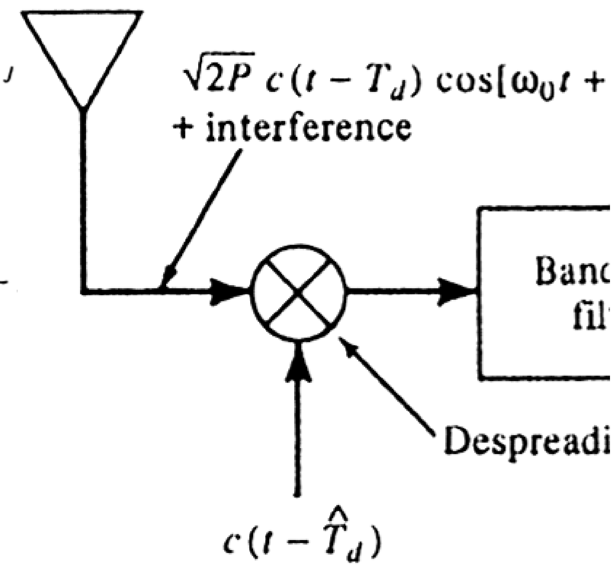
- Performance evaluation of SS in the presence of NB/broadband interference.
- Two types of modulation are considered:
  - PSK if phase coherence is possible for time longer than $\frac{1}{W}$.
  - FSK if phase coherence is not possible for time longer than $\frac{1}{W}$. Like the time varying channels (aircrafts)


G(f)
Wanted signal
Unwanted
signal
Thermal noise level
f
R_p
f_0
Despread
wanted signal
Information
bandwidth
Interference
signal
f
R_p
f_{IF}

Tone Jamming (cont.)

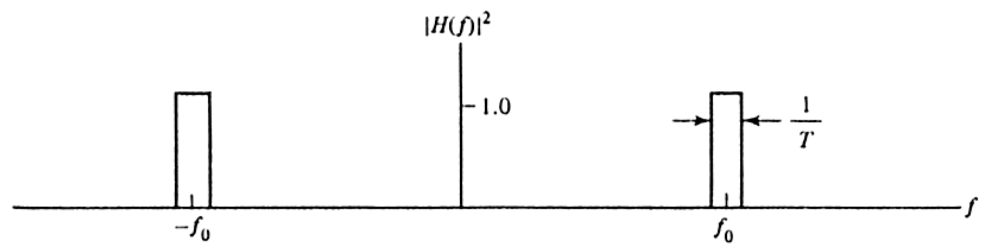
- Despreading spreads the jammer power and despreads the signal power:



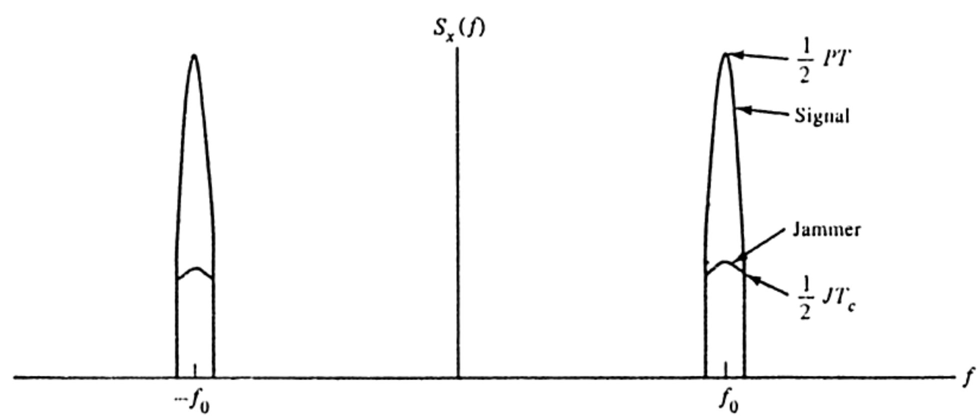


Tone Jamming (cont.)

- Filtering (at the BW of the phase modulator) after despreading suppresses the jammer power:

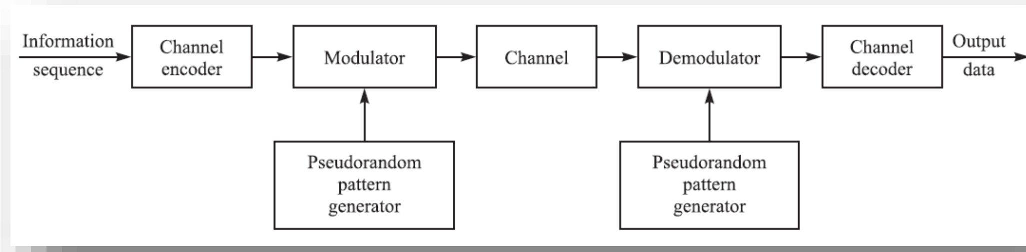


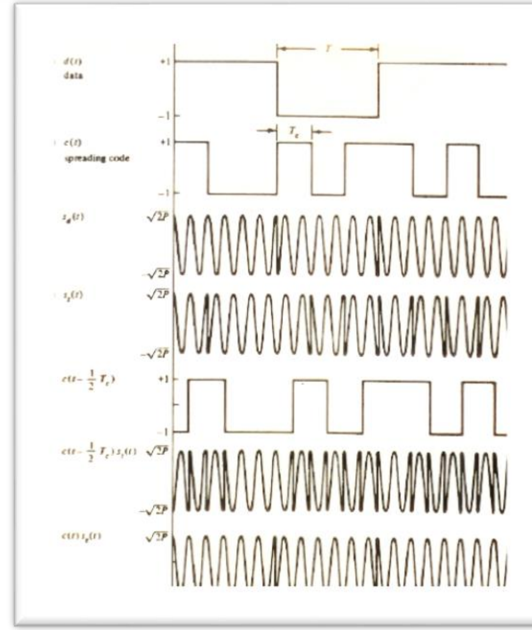
(c) IF filter power transfer function



(d) Output of IF filter

DSSS





- Revisit the model, and assume BPSK

$$Information\ Rate\ = R \quad bits/\sec.$$

$$Avialable\ Bandwidth = W\ Hz.$$

- The phase of the carrier is shifted pseudo-randomly according to the pattern from PN generator at a rate $W\ times/\sec.$

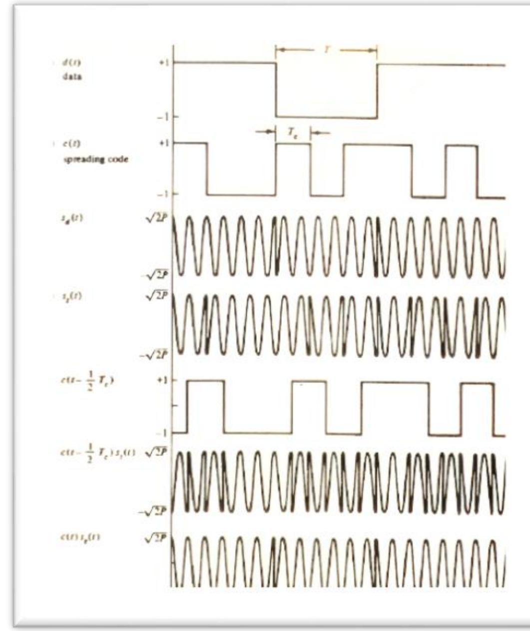
$$W = 1/T_c$$

- T_c : duration of the phase chip interval (Basic element in DSSS)

$$T_b = 1/R$$

- T_b : duration of a rectangular pulse (time of transmission for a bit)

Bandwidth Expansion Factor



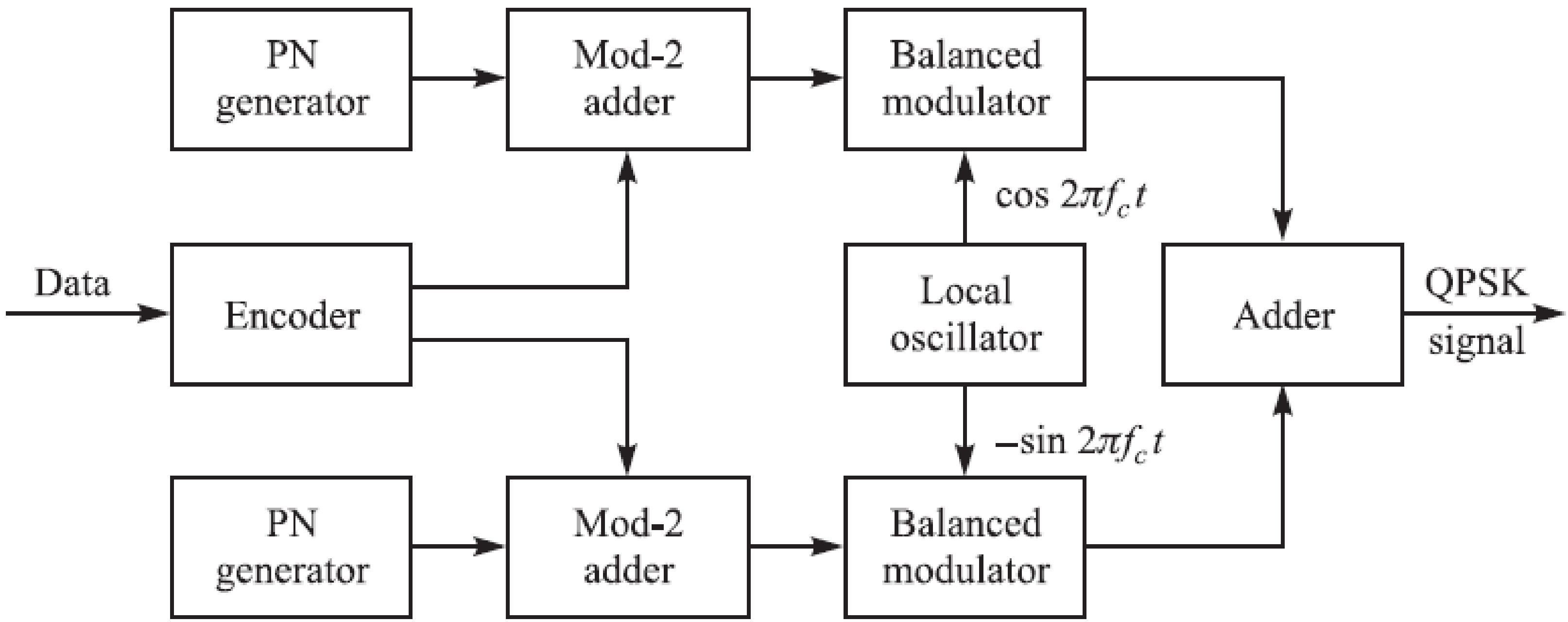
- Bandwidth Expansion Factor:

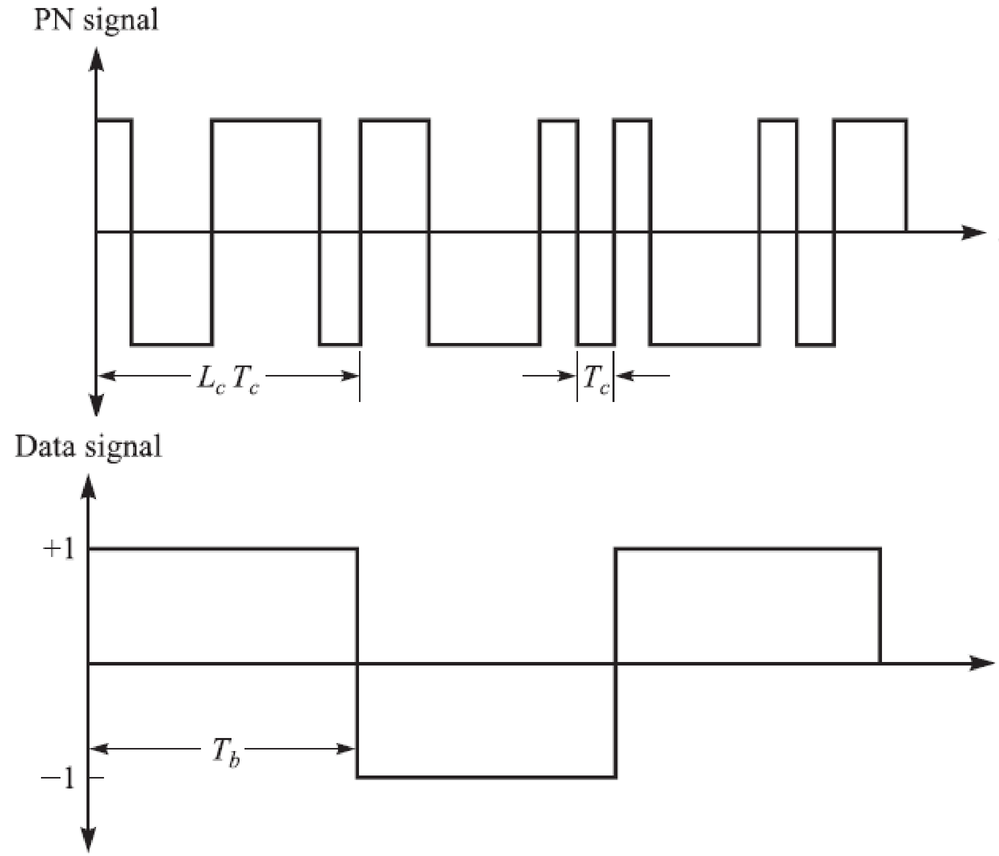
$$B_e = W/R = T_b/T_c$$

- In practice T_b/T_c is integer.
- $L_c = \# \, of \, chips \, per \, info. bit.$ =
- # of phase shifts during one bit transmission.
- Using $(n, k) = (kL_c, k)$ code.
- To transmit n chips, the time available in $k\,T_b$
- The code rate (block, convolutional):

$$R_c = \frac{k}{n} = \frac{1}{L_c}$$

DS-QPSK Modulator





- Bandwidth of $p(t) = \frac{1}{T_c}$
- Bandwidth of $g(t) = \frac{1}{T}$
- Bandwidth of $p(t)g(t) = \frac{1}{T} + \frac{1}{T_c} \approx \frac{1}{T_C}$

Forming the DS (Modulator)

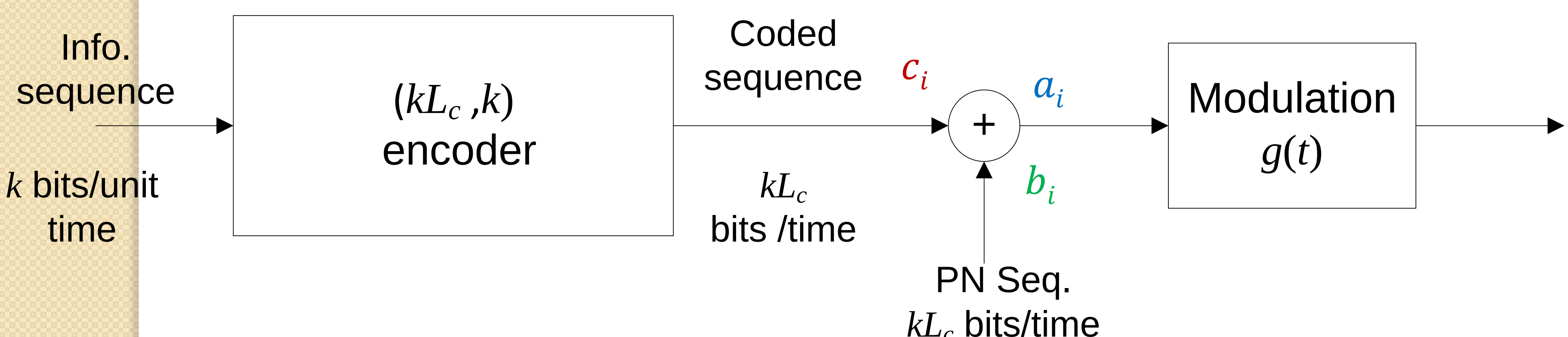
- Let $b_i \;=\; i^{th}$ bit of PN sequence. $(0,1)$

  $c_i \;=\; i^{th}$ bit from the encoder.

$a_i \;=\; b_i \;+\; c_i$ (same → $a_i \;=\; 0$, otherwise $a_i \;=\; 1$)

- then use a BPSK modulator.

$$g_i(t) = \begin{cases} g(t - iT_c) & (a_i = 0) \\ -g(t - iT_c) & (a_i = 1) \end{cases}$$



Alternative Modulator

- Modulation of c_i's first

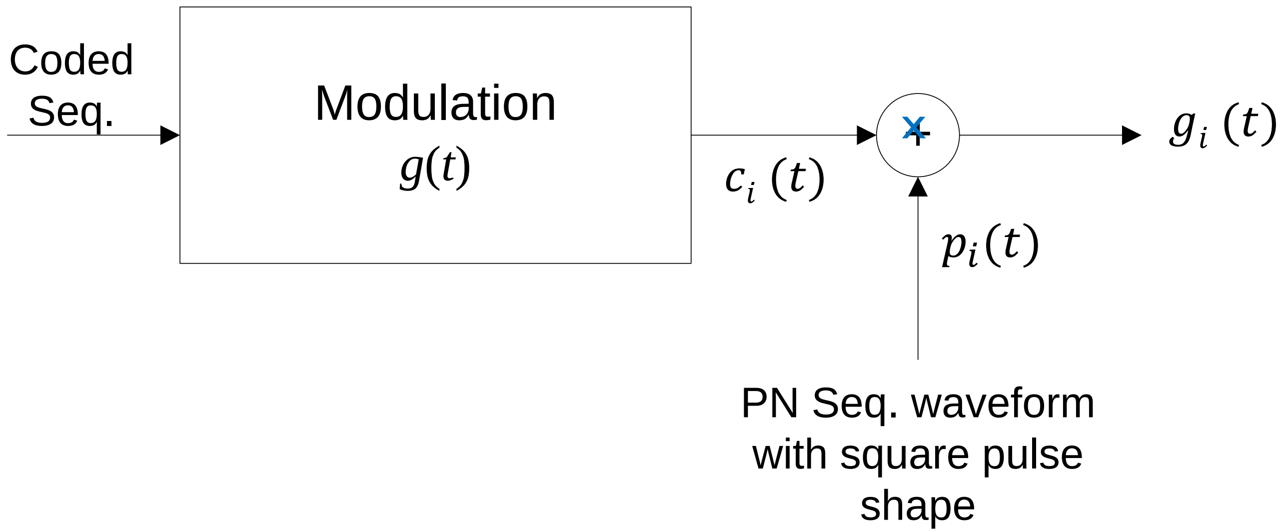
$$c_i\,(t) \;=\; (2\,c_i\; - 1)\,g(t - iT_c)$$

- output of PN sequence

$$p_i\,(t) \;=\; (2\,b_i\; - 1)\,p(t - iT_c)$$

- Multiplying Both

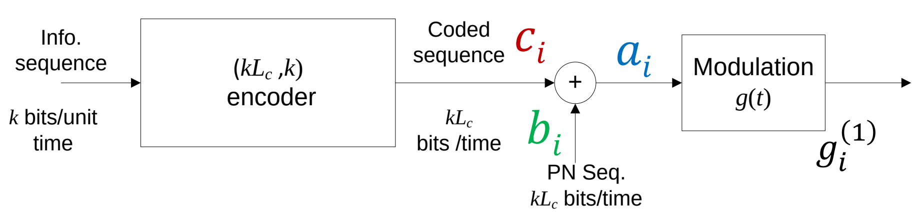
$$g_i\,(t) \;=\; (2\,b_i - 1)\,(2\,c_i\; - 1)\,g(t - iT_c)$$

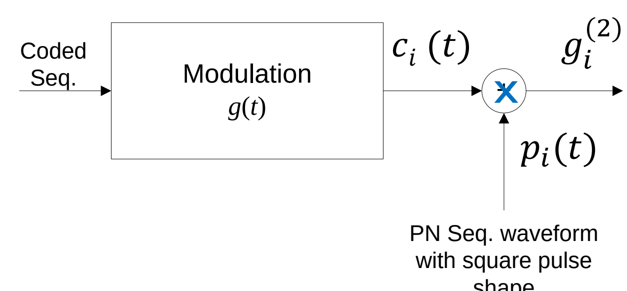


Equivalence of the two modulators

- The two modulators are equivalent and can be used for coded or uncoded systems
- The first is easier to implement.
- The second is easier to relate to demodulation

b_i	c_i	$a_i = b_i \oplus c_i$	$g_i^{(1)}$	$(2\,b_i - 1)\,(2\,c_i - 1)$	$\boldsymbol{g_i^{(2)}}$
0	0	0	$g(t)$	1	$g(t)$
0	1	1	$-\,g(t)$	-1	$-\,g(t)$
1	0	1	$-\,g(t)$	-1	$-\,g(t)$
1	1	0	$g(t)$	1	$g(t)$





Demodulator

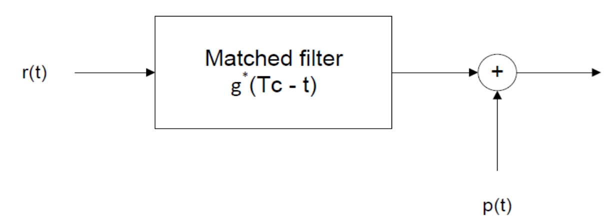
- The received signal for the j^{th} code element

" no de-spreading yet "

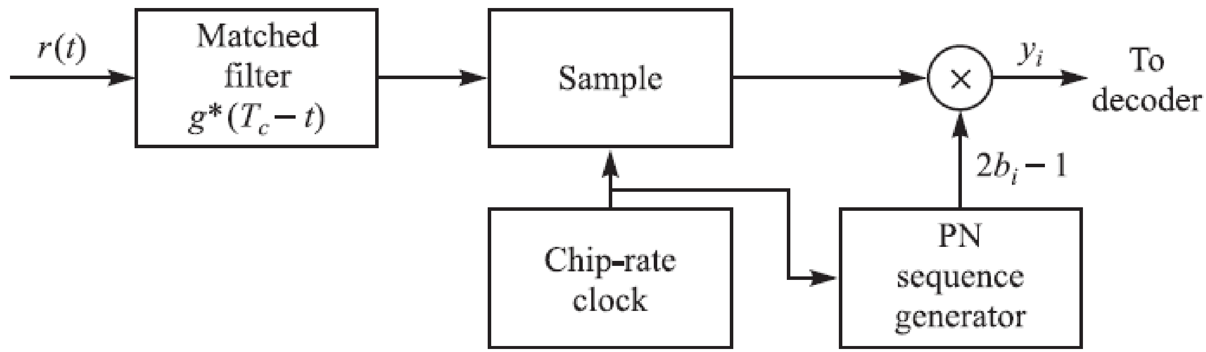
$$r_j(t) = P_j(t)\, c_j(t) + z(t)$$

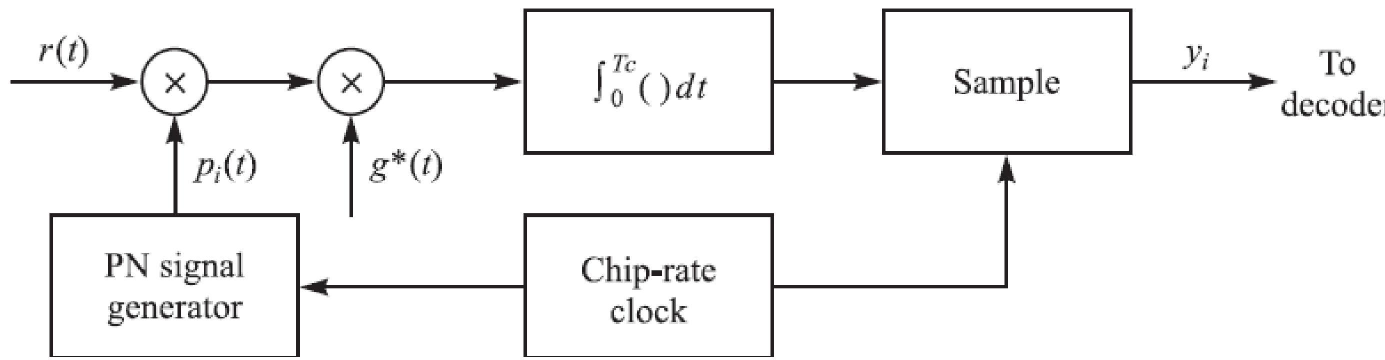
$$= (2\, b_j - 1)\,(2\, c_j - 1)\, g\,(t - j\, T_c) + z(t)$$

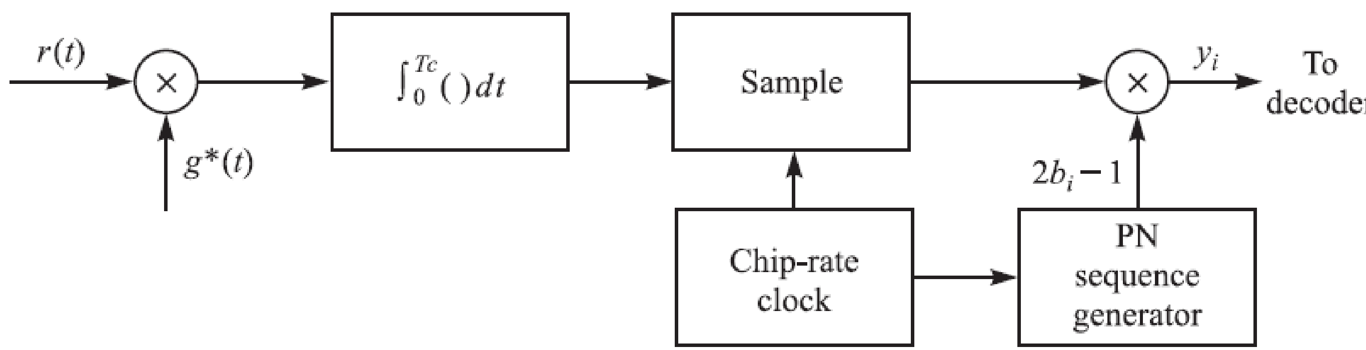
- $z(t)$ assumed to be stationary random process with zero mean)



Possible Demodulator structures for PN spread spectrum signals.







Demodulation

- Multiply by $(2b_i - 1)$ takes out the effect of the PN sequence.
- In modulator (b) we are multiply before filtering.
- In modulator (c) we are using a correlator instead of a matched filter.
- Optimality of matched filter assume "Gaussianity"
  - If $z(t)$ is not Gaussian>>> no optimality
  - If noise distribution is not known, we still can use it.

Error Rate Performance of Detector of the Decoder

The processing gain & the Jamming margin.

$$E_b = P_{av} Tb = \frac{P_{av}}{R}$$

E_b : Energy per bit in term of average power (P_{av}).

T_b : bit interval.

$\frac{P_{av}}{J_{av}}$: signal to jamming power ratio.

J_0 : the power spectral density (PSD) for the jamming signal. ($+N_0$)

$$J_0 = \frac{J_{av}}{W}.$$

$$\frac{E_b}{J_0} = \left(\frac{P_{av}}{R}\right) / \left(\frac{J_{av}}{W}\right) = \left(\frac{W}{R}\right) / (J_{av}/P_{av})$$

$$W/R = T_b/T_c = B_c = L_c = G_p$$

$Processing\ Gain\ (G_p)$

Processing Gain, SJR, and Jamming Margin

- **Processing gain** (G_p) : the advantage gained over the jammer that is obtained by expanding the BW of the transmitted signal.
- Let $\frac{E_b}{J_0}$ be interpreted as SNR (SJR) required for a specific error rate performance and
- $\frac{W}{R}$ available bandwidth expansion factor.
- $\frac{J_{av}}{P_{av}}$ **Jamming margin** of DSSS system i.e the largest value that $\frac{J_{av}}{P_{av}}$ can take and still satisfy the probability of error, P_e.
- The total average interference power is $J_{av} = 2J_0W$, where J_0 is the value of the power spectral density of an equivalent wideband interference.

$$\frac{E_b}{J_0} = 2\left(\frac{W}{R}\right) / \left(\frac{J_{av}}{P_{av}}\right)$$

Example (To be checked)

- Suppose we wish to maintain $P_e \leq 10^{-6}$, the system has $W/R = 500$. What is the Jamming margin ?
- For $P_e = 10^{-6}$ we require $E_b / J_0 = 10.5\ dB$.
- $Gp = 30\ dB$
- So , Jamming margin $= 33 - 10.5 = 22.5\ dB$.

That is the received signal can be detected reliably (at 10^{-6}) even when the interference is up to 100 times the received signal.

- One can design the system for a given Jamming margin.

In Class Exercise

- A user is communicating with a satellite using a signal of power $= 20dBW$. A jammer is transmitting $60dBW$ (continuous, full-band). The needed transmission rate is $100\ b/s$. The required $\frac{E_b}{J_0}$ is $10\ dB$.
- Find the required bandwidth?