Spread Spectrum Communications and CDMA

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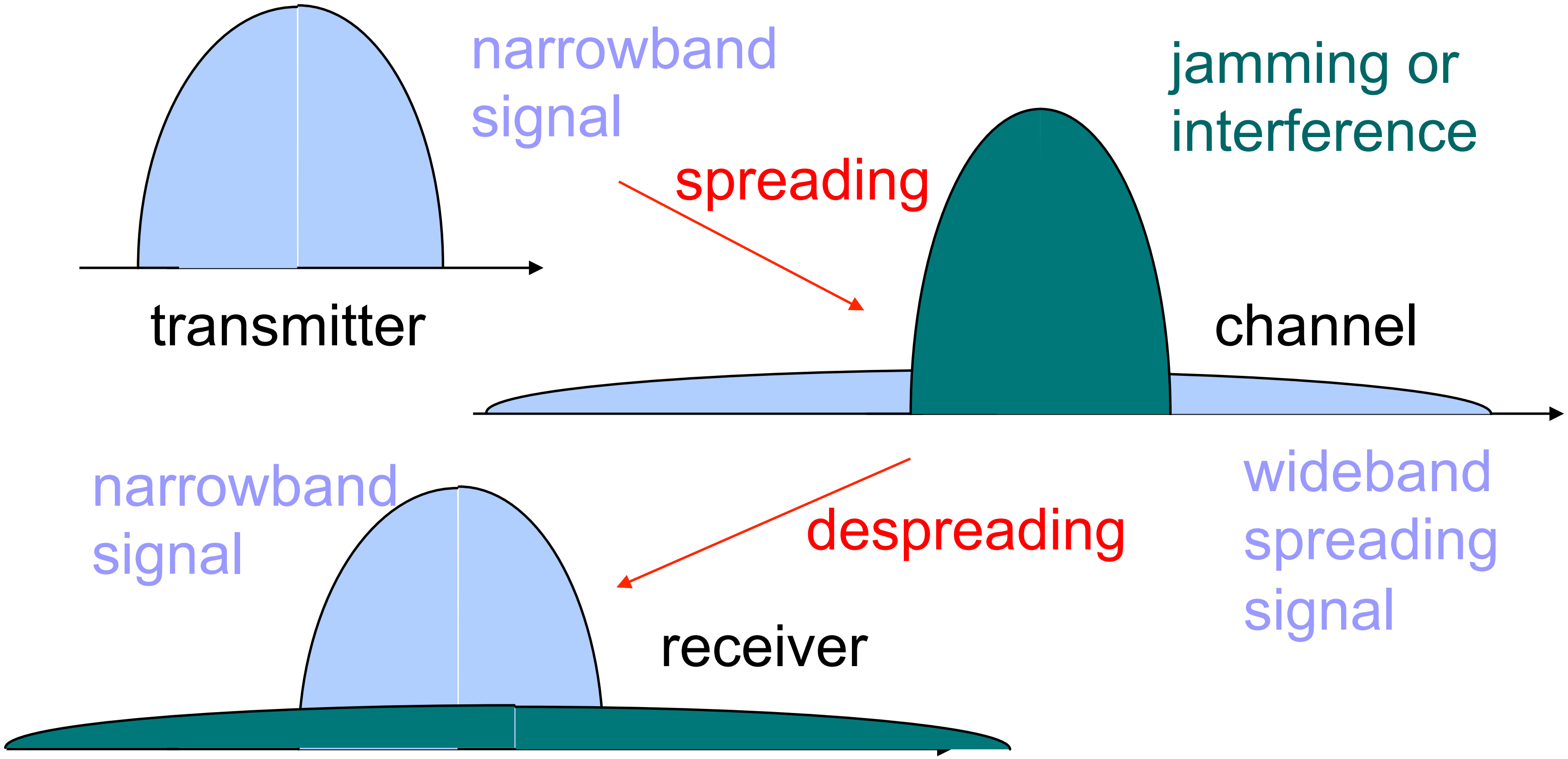
Why Spread Spectrum?

- anti-jamming
- low probability of interception
- low interference
- system capacity and flexibility
- anti-interference
- anti-multipath fading
- ranging

Anti-Jamming/Interference



jamming/interference as a wideband noise

First Spread Spectrum Communication Patent

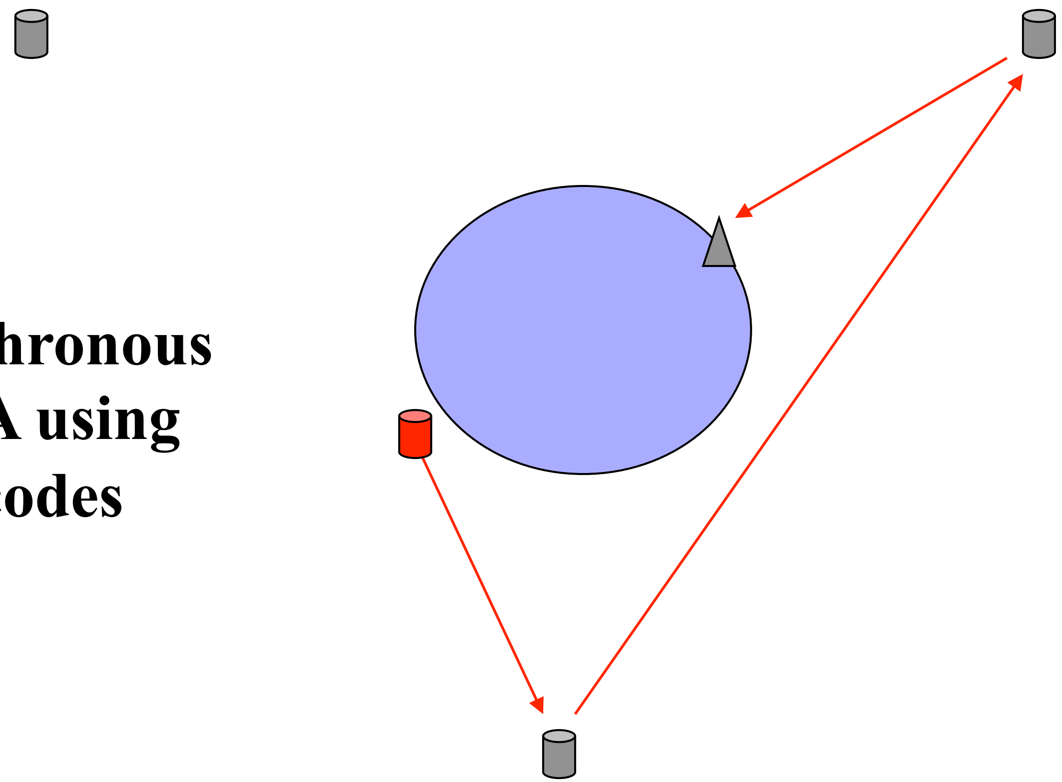
From Wikipedia

- **Hedy Lamarr** (November 9, 1914 – January 19, 2000) was an Austrian-born American actress and engineer. Though known primarily for her film career as a major contract star of MGM's "Golden Age", she also co-invented an early form of spread spectrum communications technology, a key to modern wireless communication.
- Avant garde composer George Antheil, a son of German immigrants and neighbor of Lamarr, had experimented with automated control of musical instruments, including his music for *Ballet Mecanique*, originally written for Fernand Léger's 1924 abstract film. This score involved multiple player pianos playing simultaneously.
- Together, Antheil and Lamarr submitted the idea of a *secret communication system* in June 1941. On August 11, 1942, U.S. Patent 2,292,387 was granted to Antheil and "Hedy Kiesler Markey". This early version of frequency hopping used a piano roll to change between 88 frequencies and was intended to make radio-guided torpedoes harder for enemies to detect or jam.

GPS: Spread Spectrum Ranging

- 24 satellites in orbits
- up to 6 satellites observable everywhere on earth
- signals from 4 satellites for locating (3-dim and time)
- using Gold codes
- C/A code: 1.023 MHz
- P code: 10.23 MHz

Tracking and Data Relay Satellite System

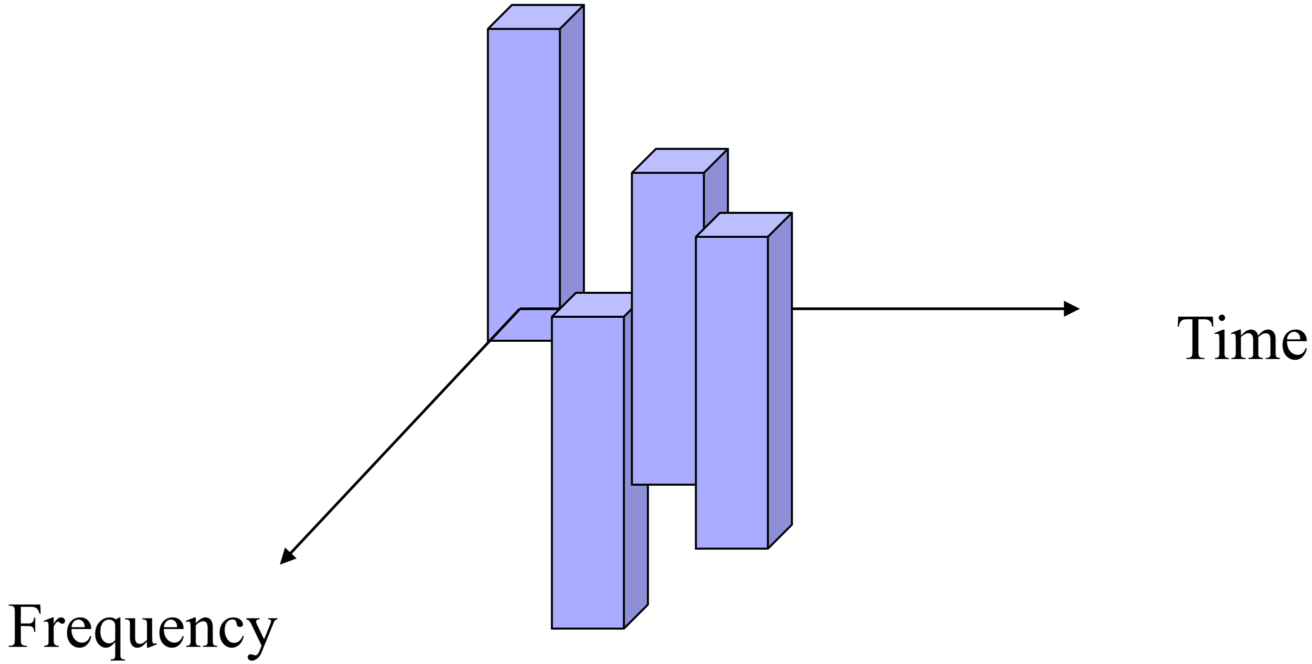


Asynchronous CDMA using Gold codes

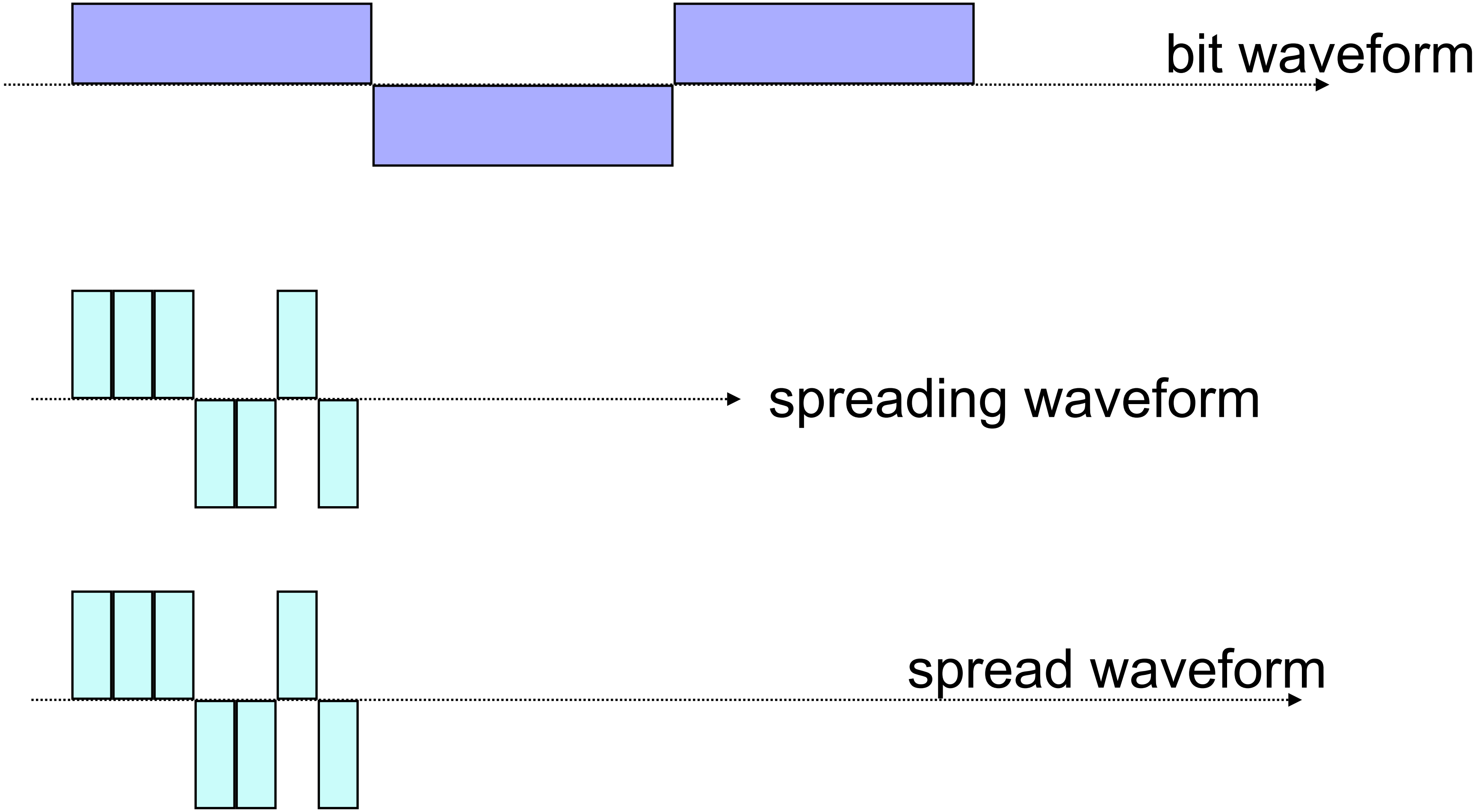
Forms of Spread Spectrum

- Direct Sequence (DS)
- Frequency Hopped (or Hopping) (FH)
- hybrid DS+FH

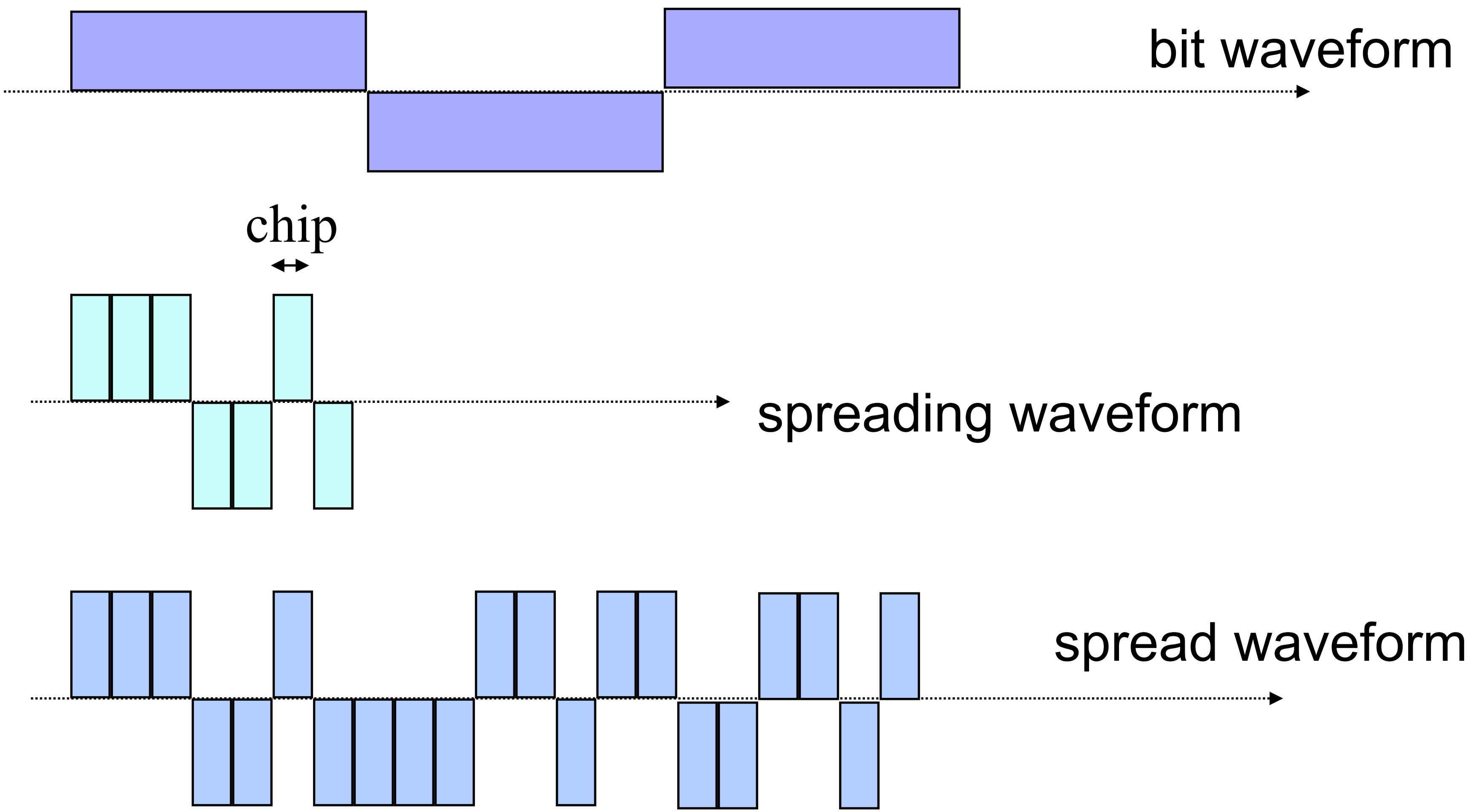
FH-SS System



DS-SS



DS-SS



Desired Spreading Waveform

- average close to zero
- auto-correlation function close to a delta function, i.e., close to a white noise
- cross-correlation close to a delta function so that simultaneous transmission over the same frequency spectrum possible, to reduce MAI.
- spectrum expansion factor known as processing gain (processing gain should be large)

Processing Gain

- FCC defines processing gain based on signal bandwidth measurement after spreading and original narrowband signal bandwidth measurement.

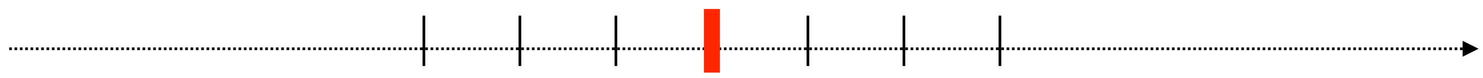
Maximal Length Codes

- A cyclic code with length $L = 2^n - 1$
- (L+1)/2 1s and (L-1)/2 0s
- Auto-correlation

$$\varphi(\tau) = \begin{cases} L, \tau = 0 \\ -1, \tau \neq 0 \end{cases}$$

m-Sequence

L=7 m-sequence: 1110010 (+ + + - - + -)



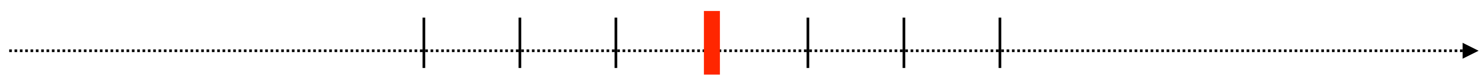
m-Sequence

L=7 m-sequence: 1110010 (+ + + - - + -)

\+ + + - - + -

\+ + + - - + -

\+ + + + + + +

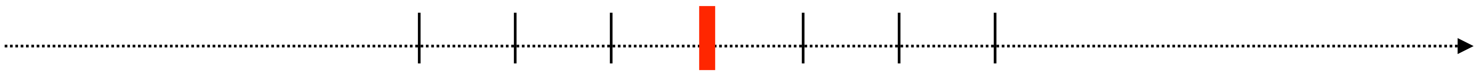


m-Sequence

L=7 m-sequence: 1110010 (+ + + - - + -)

\+ + + - - + -
\- + + + - - +

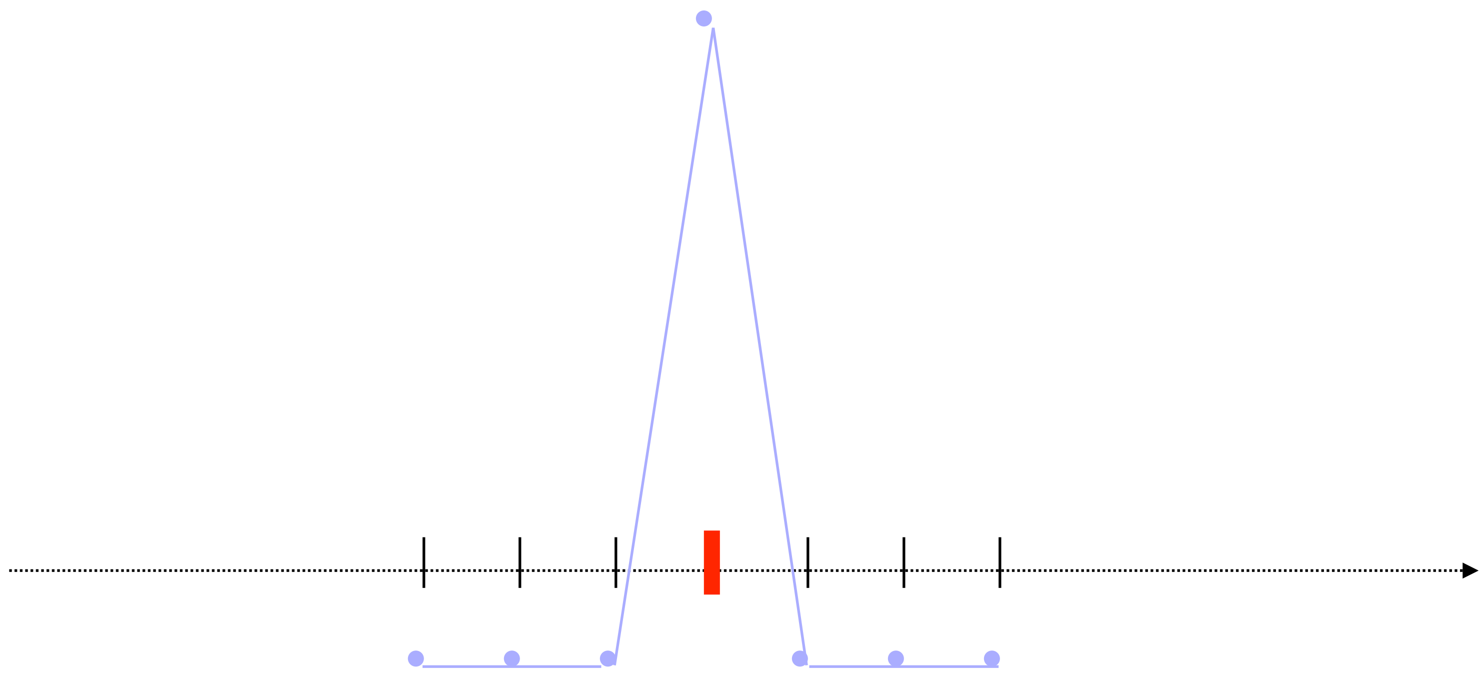
\- + + - + - -



m-Sequence

L=7 m-sequence: 1110010 (+ + + - - + -)

processing gain = chip rate / symbol rate



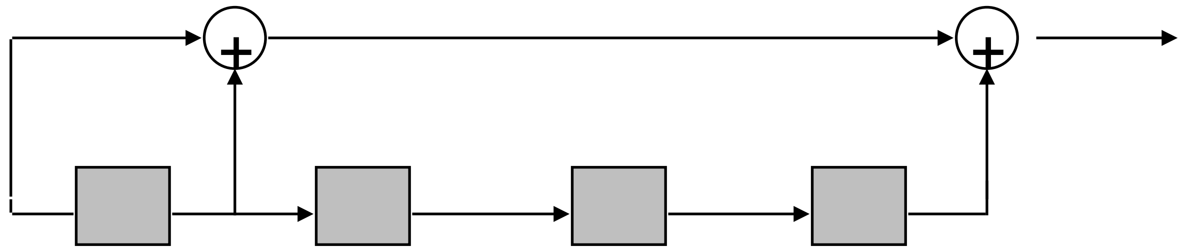
Runs of 127-chip m-sequence

Run Length	# of 1 runs	# of 0 runs	# of chips
1	16	16	32
2	8	8	32
3	4	4	24
4	2	2	16
5	1	1	10
6	0	1	6
7	1	0	7
			total 127

Maximal Length Codes

- Any circular shift of an m-sequence is another *m*-sequence.
- Any modulo-2 addition of two *m*-sequences is another *m*-sequence.
- *m*-sequence is thus appropriate only for synchronous CDMA.
- Spreading codes for asynchronous CDMA is thus needed.

Generation of m-Sequence

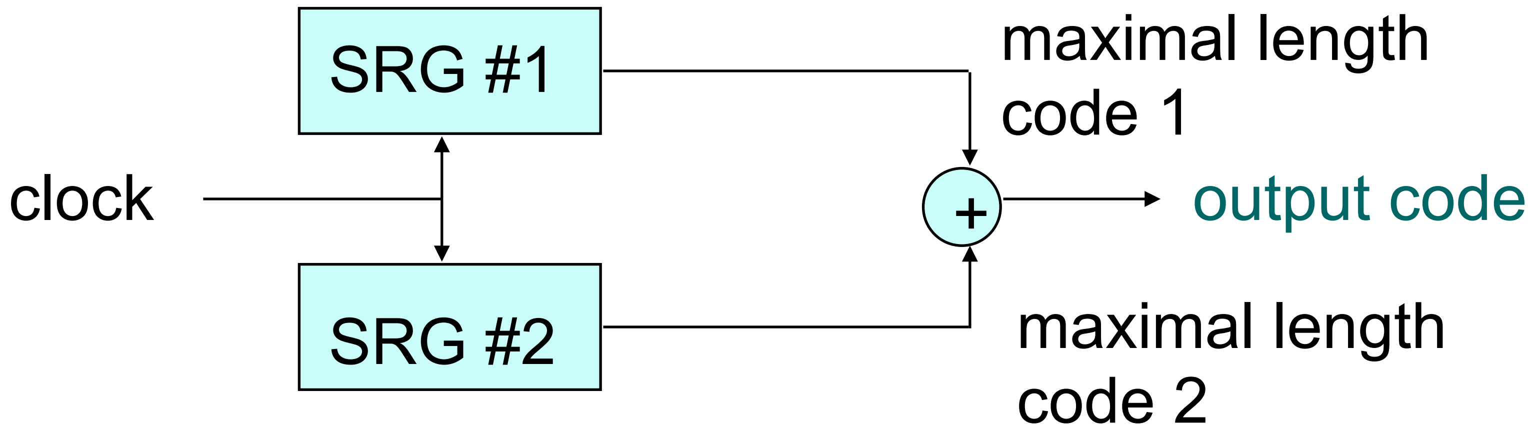


generating polynomial = $1 + x + x^4$

m-sequence can be easily generated by shift-register.

It is the longest code sequence that can be generated by a given number of stages of delays. This is why called maximal length codes.

Gold Codes

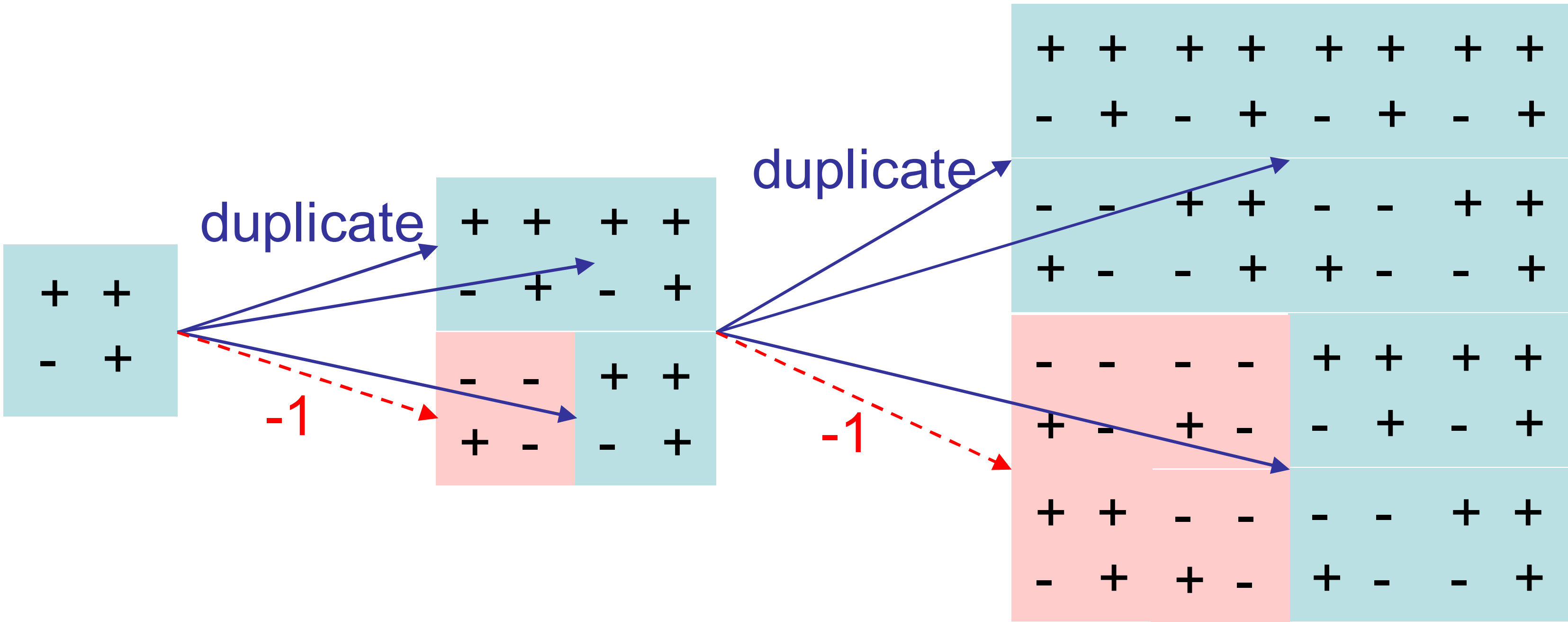


auto-correaltion and cross-correlation side lobes bounded by

$2^{(n+1)/2}+1$ n odd

$2^{(n+2)/2}-1$ n even

Walsh-Hadamard Codes



Summary of Part 15

- ISM: industrial, scientific, medical
- 902-928 MHz; 2.4-2.4835 GHz; 5.725-5.85 GHz, 24G Hz, 60G Hz
- RF output power less than 1 W to antenna
- antenna gain less than 6 dBi; if higher, must be reduced by the same amount
- effective EIRP less than 36 dBm

Part 15 DS-SS

- Minimum 6 dB bandwidth is 500 KHz at 900-MHz and 1 MHz at 2.4-GHz.
- Power density in any 3-KHz must be less than 8 dBm in average over 1 sec.
- Processing gain must be at least 10 dB.
- For hybrid systems, the processing gain must be at least 17 dB.

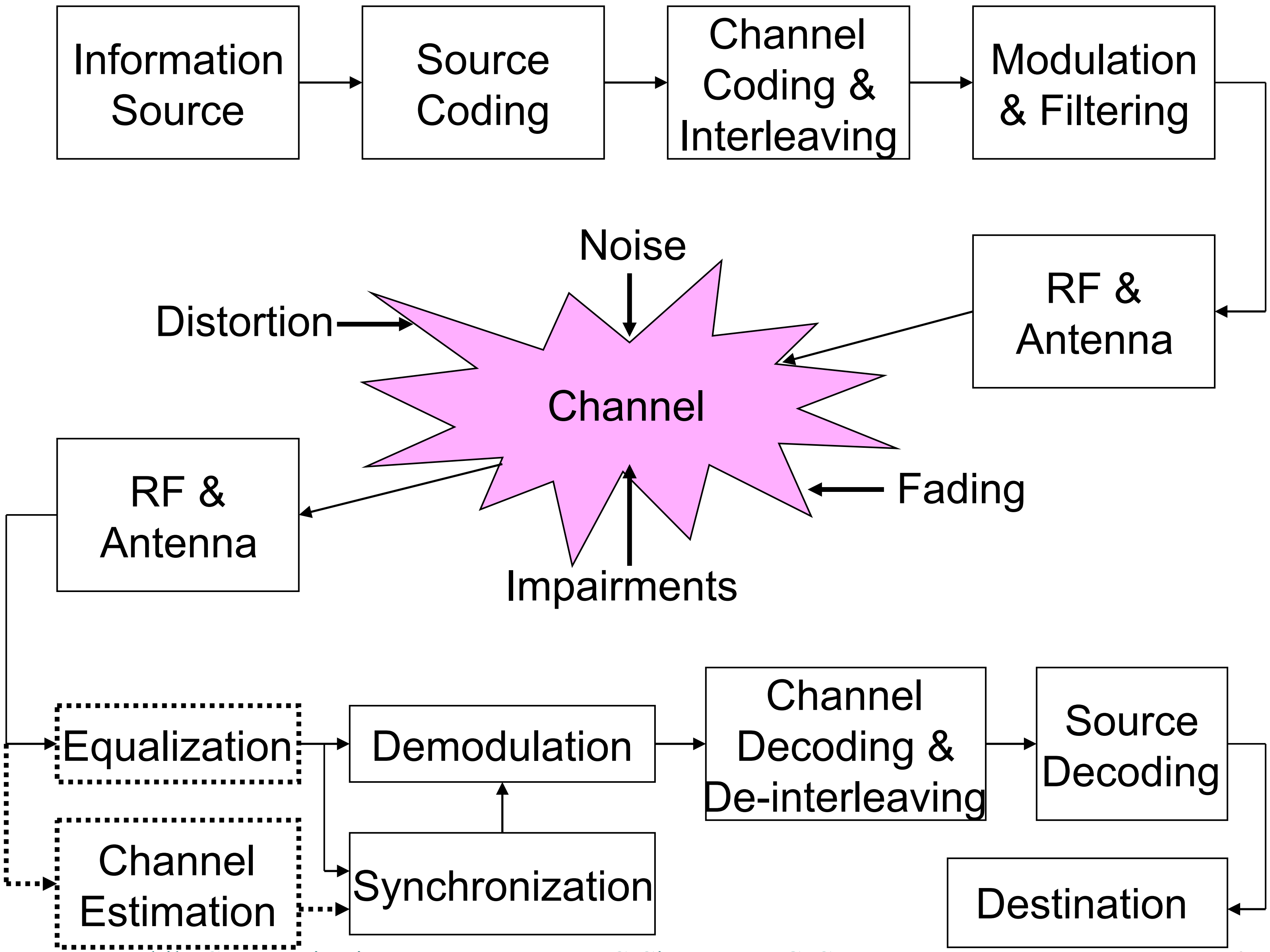
Part 15 FH-SS

- Minimum channel separation is 25 KHz.
- Maximum 20 dB bandwidth is 500 KHz at 900-MHz and 1 MHz at 2.4-GHz.
  - ✓ That is, more than 99% power within 1M Hz at 2.4G Hz ISM band.
- Number of frequency channels is at least 50 at 900-MHz and 75 at 2.4-GHz.
- Average occupied time is less than 0.4 sec in 20 sec at 900-MHz and 0.4 sec in 30 sec at 2.4-GHz, at least 2.5 hops/sec.

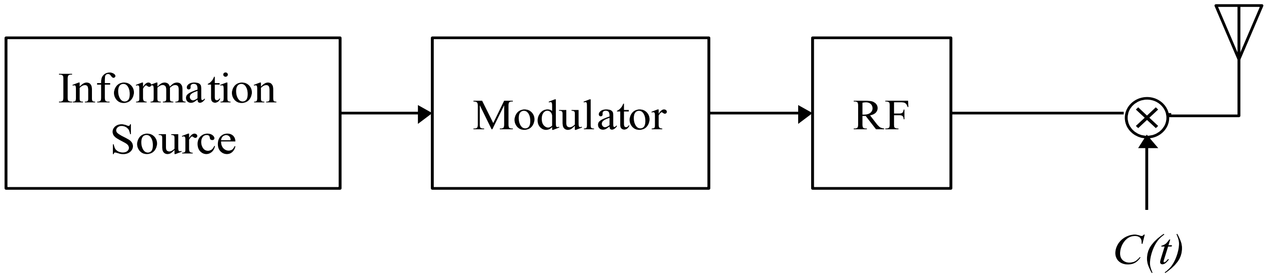
DS *vs.* FH

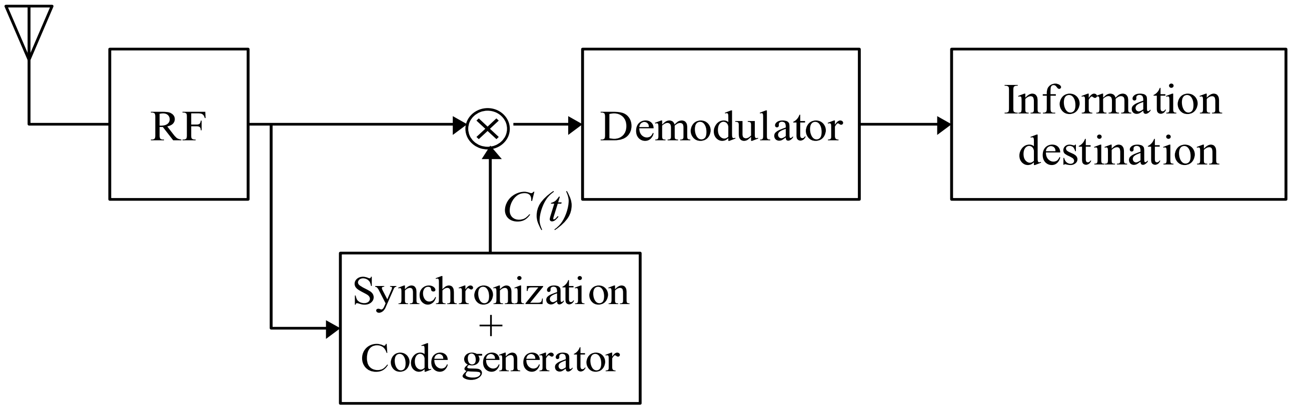
Direct Sequence	Frequency Hopped
more noise-like	instaneous narrowband
operable below ambient noise	must have positive SNR
	usually FEC required
near-far problem	
	more robust in nonlinear environments
	easy to synchronize and implement
less co-channel interference	

Narrow-Band Digital Communication System



Spread Spectrum Systems (Wideband Communications)

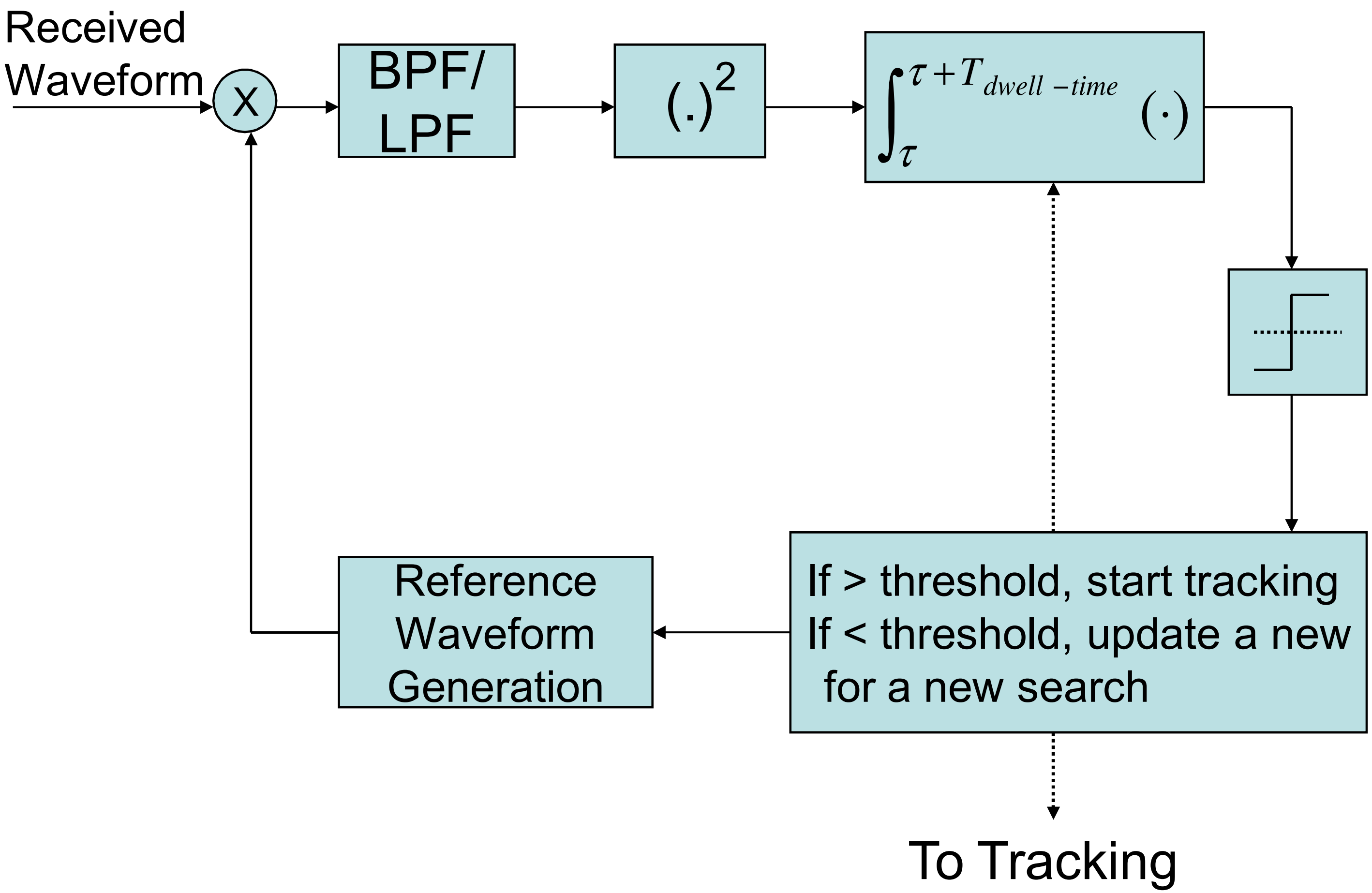




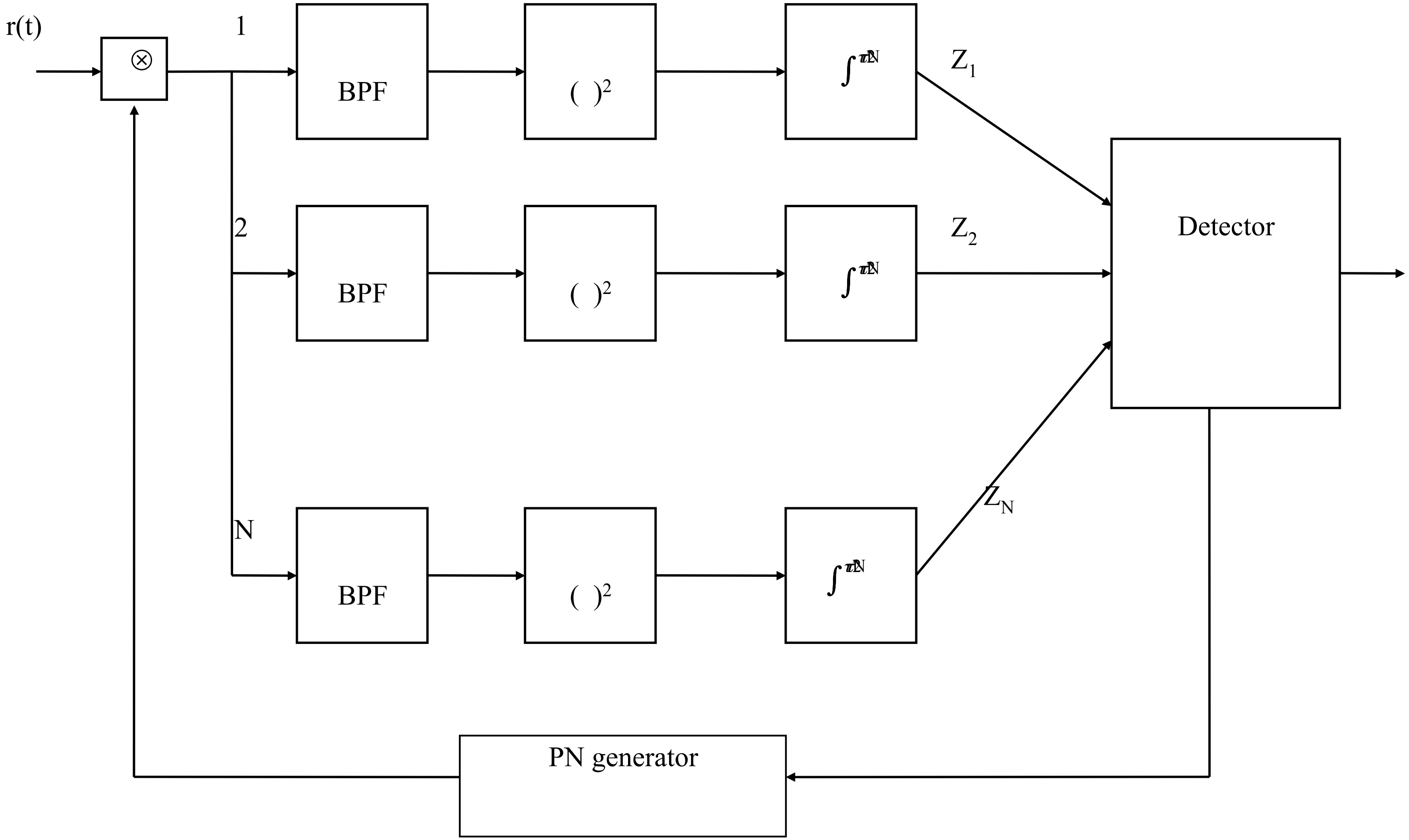
Spread Spectrum Synchronization

- Acquisition (coarse synchronization)
  - ✓Single dwell
  - ✓Multi-dwell
  - ✓Serial search
  - ✓Parallel search
  - ✓Sequential search
- Tracking (fine synchronization)
  - ✓Delay-Locked Loop (DLL)
  - ✓Tau-Dither Loop (TDL)

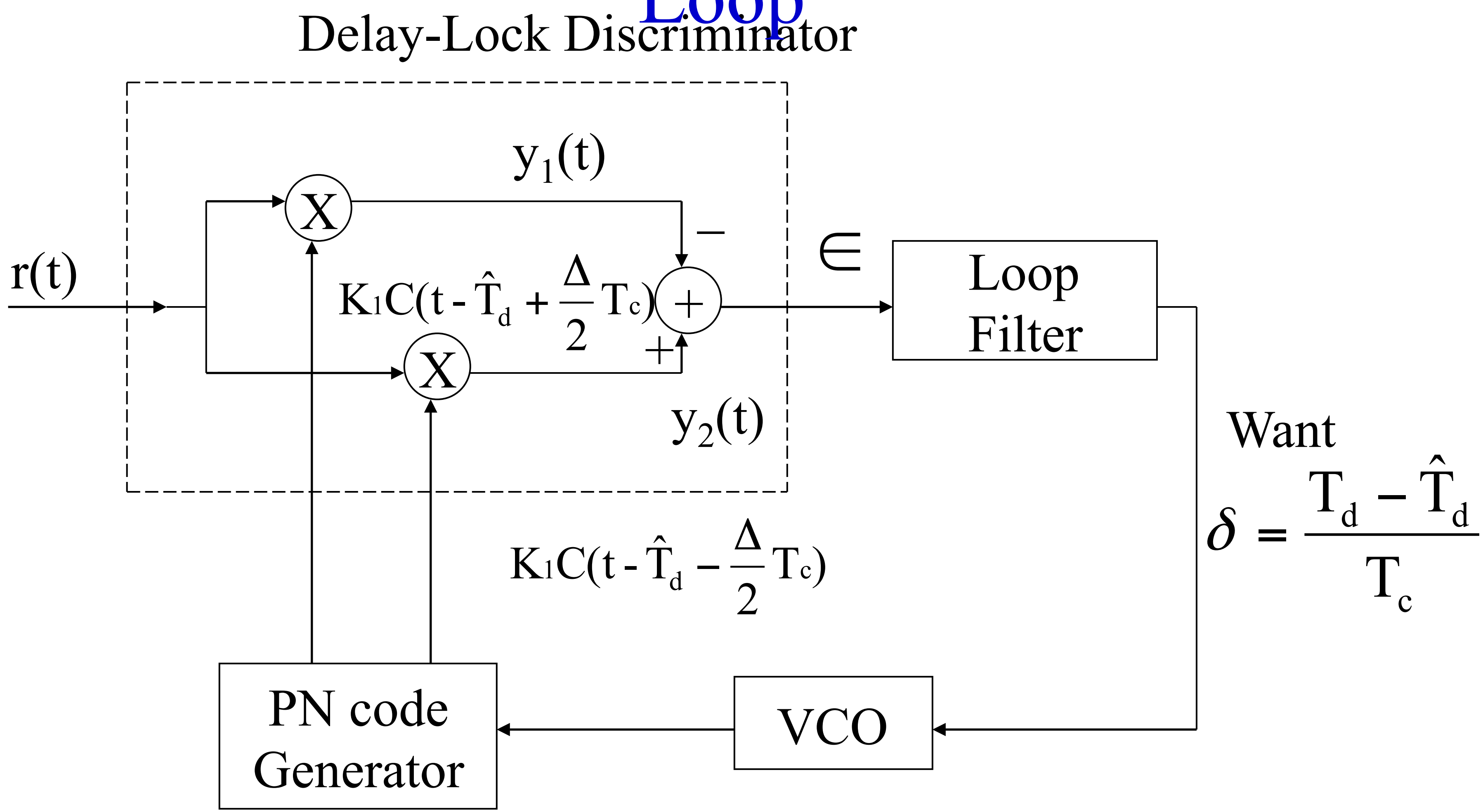
Single-Dwell Code Acquisition



Multi-dwell Acquisition



Baseband Full Time Early-Late Tracking Loop

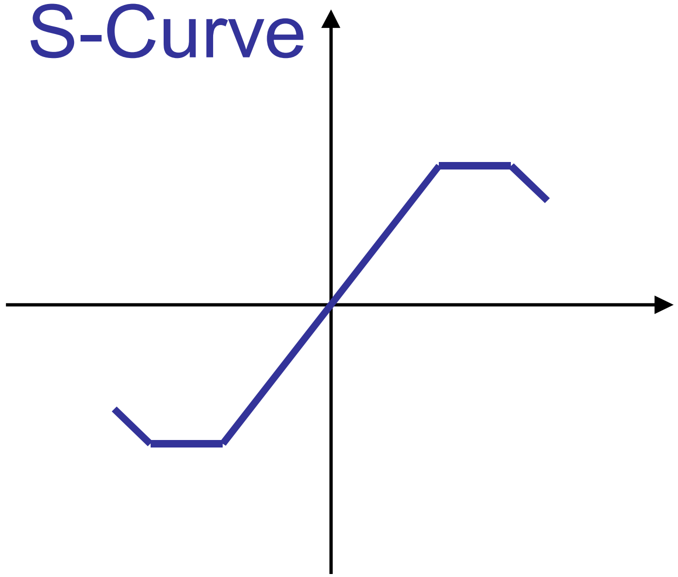


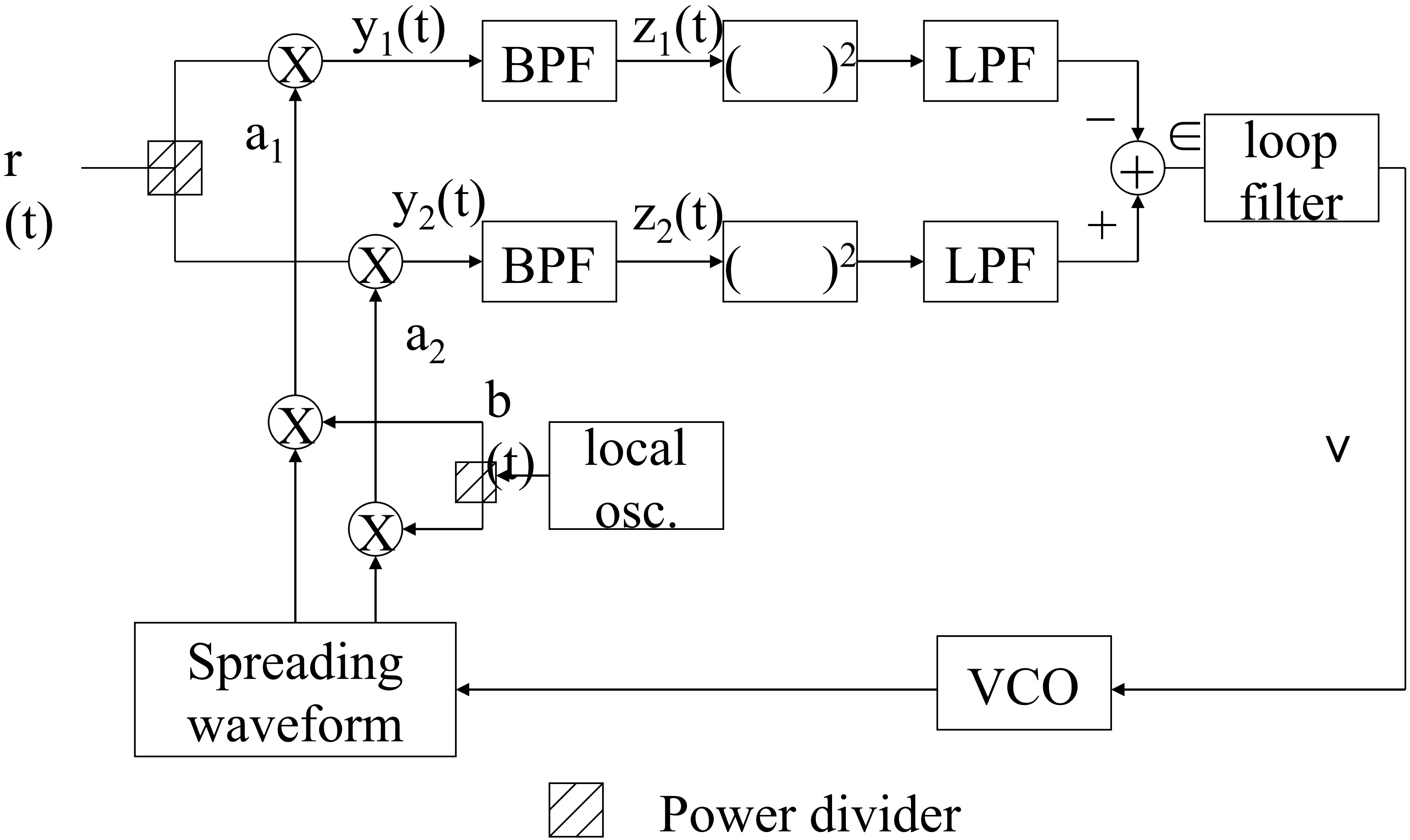
Noncoherent Full Time Early-Late Tracking Loop

Two difficulties to use coherent loops:

(1) recovering carrier before code tracking

(2) coherence reference at low SNRs




r
(t)
a_1
$y_1(t)$
BPF
$z_1(t)$
$(\quad)^2$
LPF
−
∈
loop
filter
$y_2(t)$
BPF
$z_2(t)$
$(\quad)^2$
LPF
+
a_2
b
(t)
local
osc.
v
Spreading
waveform
VCO
Power divider

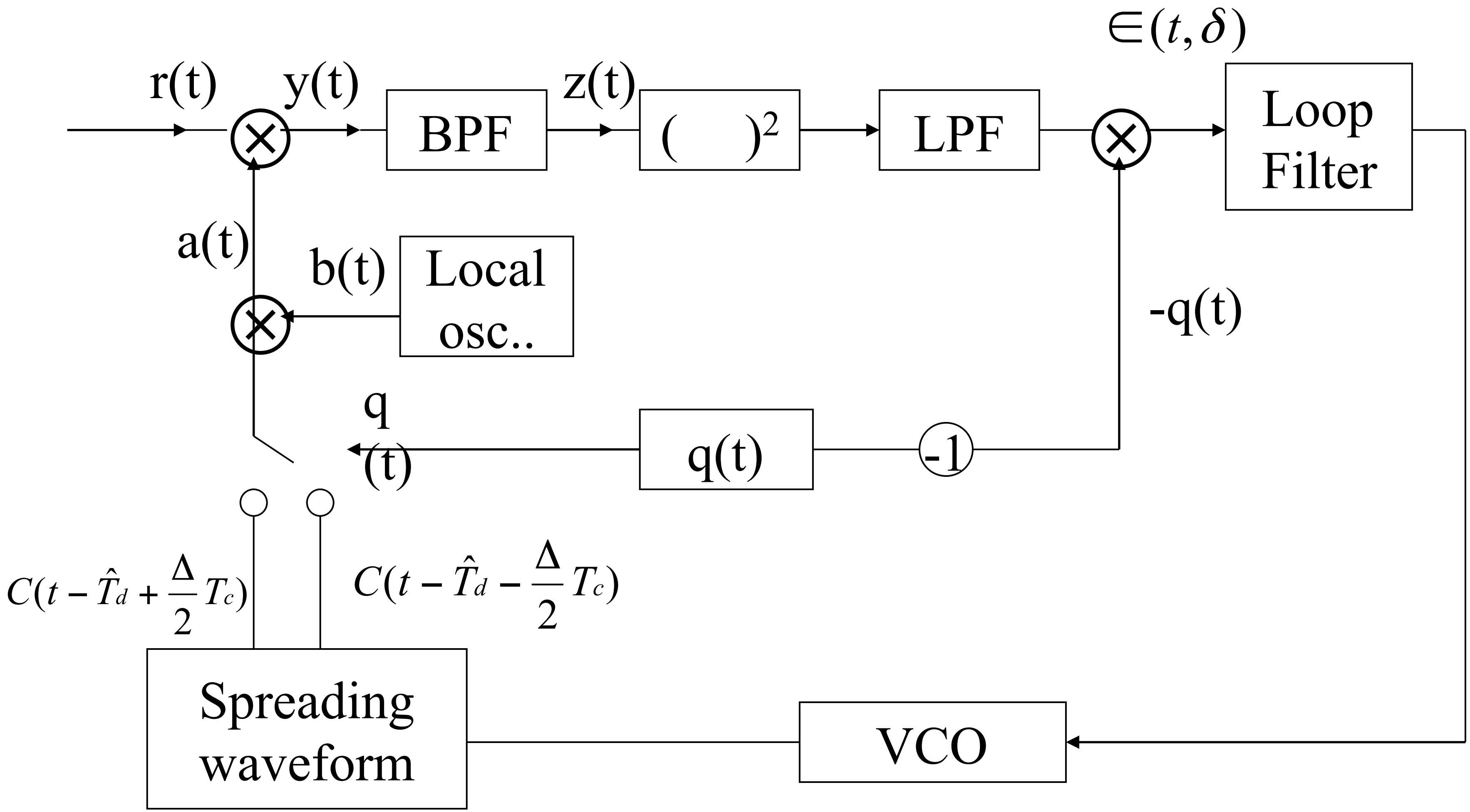
Tau-Dither Noncoherent Loop

Big problems for DLLs:

(1) Early and late IF channels must be precisely amplitude balanced.

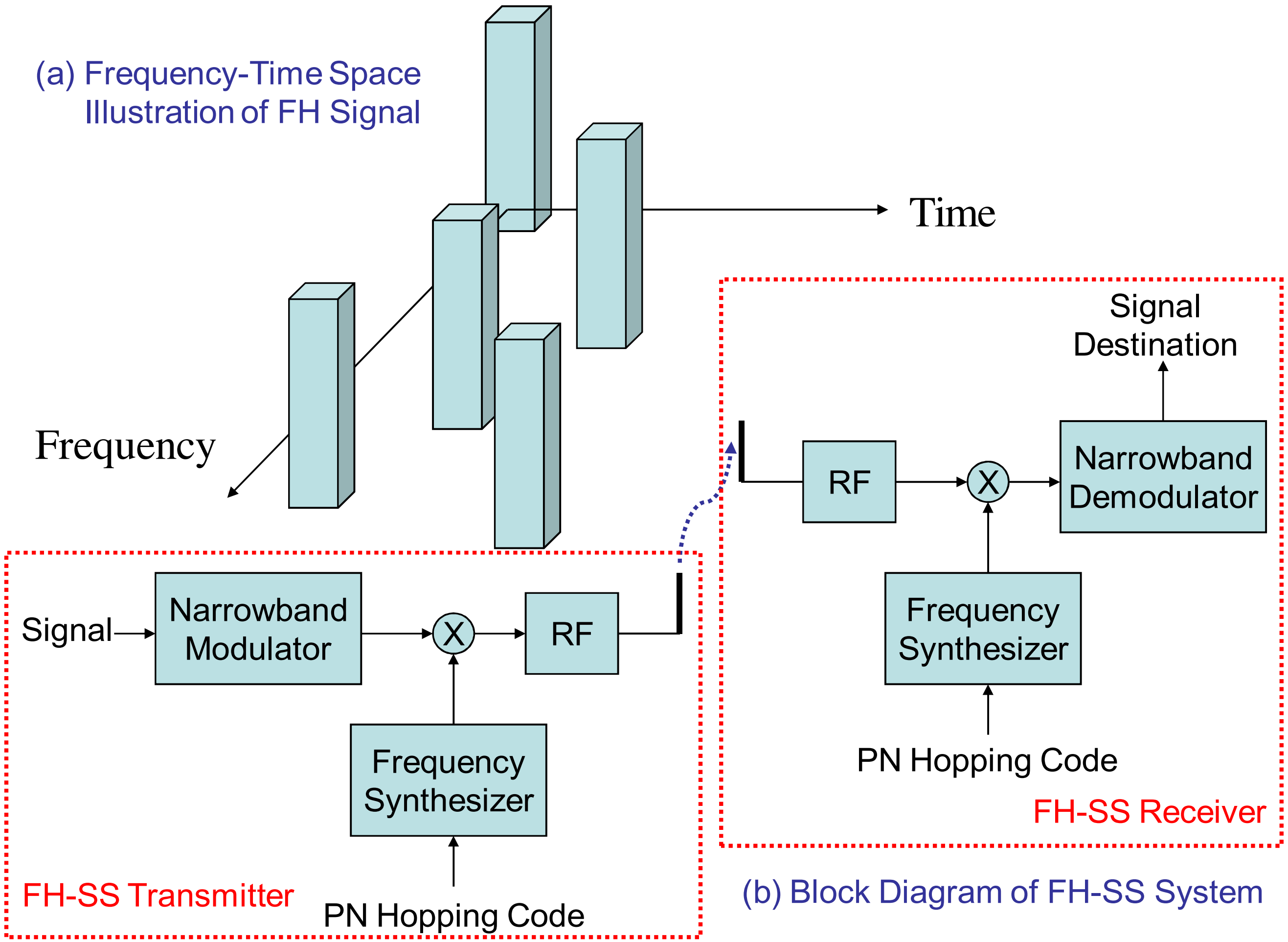
Otherwise, the discriminator characteristic is offset and does not reach zero output when tracking perfectly.

(2) Cost for two arms.



$$r(t) = \sqrt{2P}C(t - T_d)\cos\left[W_o t + \theta_d(t - T_d) + \varphi\right] + n(t)$$

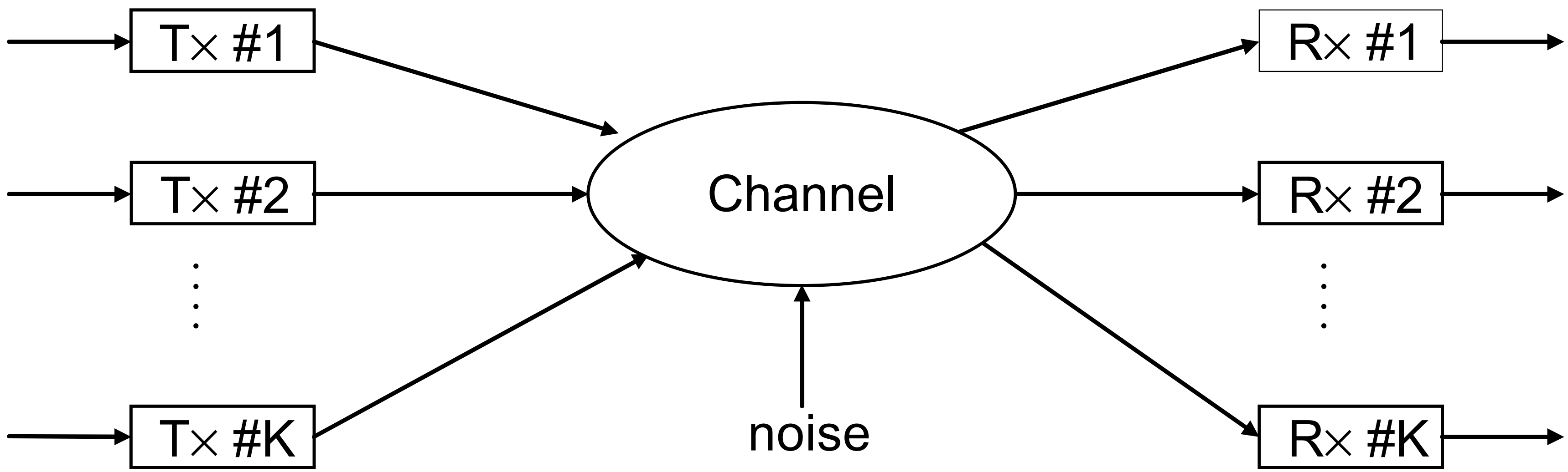
Frequency Hopping Spread Spectrum Communication Systems



Hopping Codes for FHSS

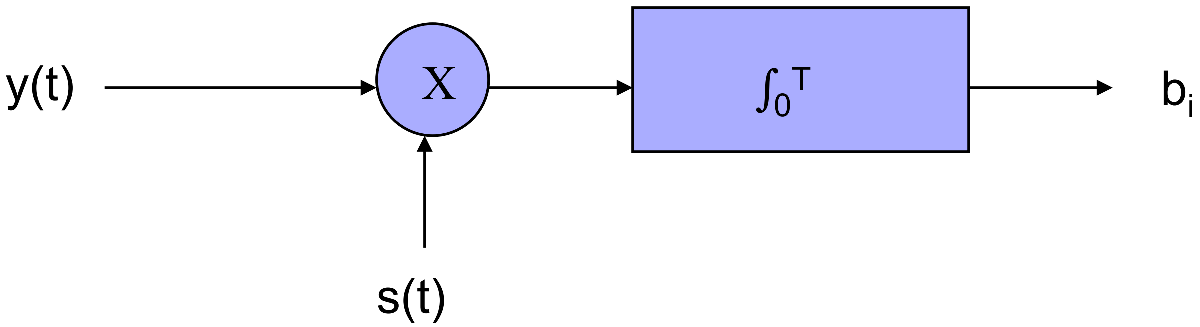
- Multiple access for FH-SS is possible
  - ✓ Each user-pair adopts a hopping sequence
    - Typically orthogonal
    - Non-coherent way
  - ✓ Performance measure is probability of hit.
- Hopping code design
  - ✓ Minimizing probability of direct hits (i.e. hopping into the same frequency band at the same time)
  - ✓ Minimizing adjacent channel interference

Code Division Multiple Access (CDMA)



CDMA allows multiple transmissions
using different signature sequences simultaneously
over the same frequency band at the same time,
but suffers from multiple-access interference (MAI)
and near-far problem.

Origin of Multiuser Detection
[Verdu and Poor]



Conventional optimal receiver (correlation/matched filter) considers one tx-rx pair detection and is MAI (multiple access interference) limited in performance.

However, CDMA tx-rx pairs simultaneously transmit over the same spectrum. Optimal detection shall consider all users' signal, **b**=(b_1 ….. b_K). Unfortunately, such an optimal receiver generally has NP hard complexity.

Multiuser Detection Techniques

- De-correlating Receiver, $\mathbf{R}^{-1}\mathbf{y} = \mathbf{A}\mathbf{b}$
  - **R**: cross-correlation matrix
  - can be polynomial complexity in many cases
  - worst case NP hard
- MMSE receiver
- LMMSE receiver
- IC (interference cancellation)
  - based on conventional structure
  - detecting the strongest user first, then 2nd, ...