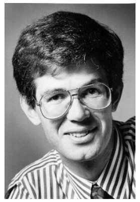
The Basics of Code Division Multiple Access



Jean-Paul M.G. Linnartz

Philips Research and TU/e

Outline

Multiple access methods

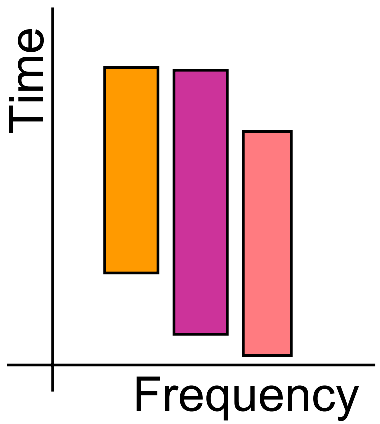
- FDMA, TDMA, CDMA

Spread spectrum methods

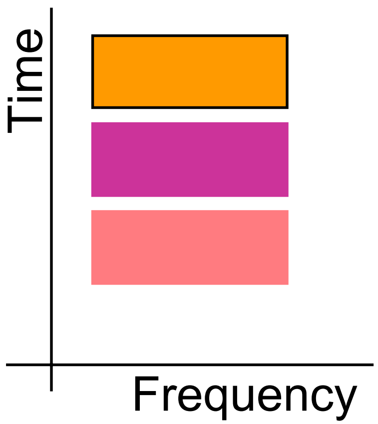
- Frequency Hopping
- Direct Sequence
  - More on code sequences
  - IS-95 cellular CDMA
  - Rake receiver
- Multi-Carrier CDMA
- UltraWideBand pulse radio

Multiple Access

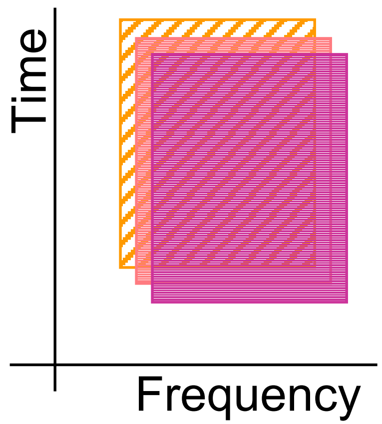
Frequency Division Multiple Access
FDMA



Time Division Multiple Access
TDMA



Code Division Multiple Access
CDMA



Code Division Multiple access

Advantages of spread-spectrum transmission

- Low spectral power density (undetectability)
- Random access
- Resistance to interference
- Resistance to multipath fading
  - Time-domain interpretation: separate all time-shifted paths
  - Freq-domain interpretation: signal is too wide to vanish in a fade

Spreading methods

Frequency Hopping

- Applied in GSM, Military, ISM bands, Blue tooth

Direct sequence

- Applied in IS-95 IS-136 Cellular CDMA, GPS, UMTS, W-CDMA, Military

Multi-Carrier CDMA

- In research

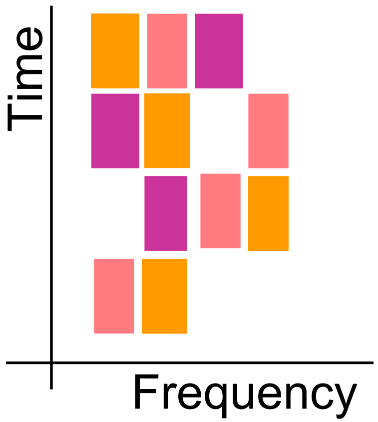
Ultra Wide Band

- Speculations only (in 1999)

Frequency Hopping

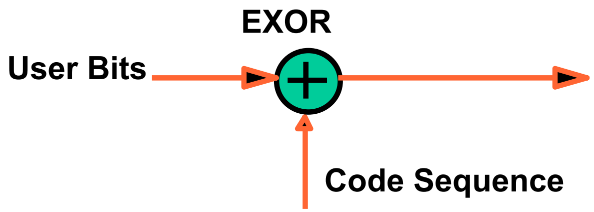
Slow hopping: The carrier frequency chances at every burst transmission (GSM can do slow-FH)

Fast hopping: Carrier changes its frequency several times during a single bit transmission



Direct Sequence

User data stream is multiplied by a fast code sequence



Example:

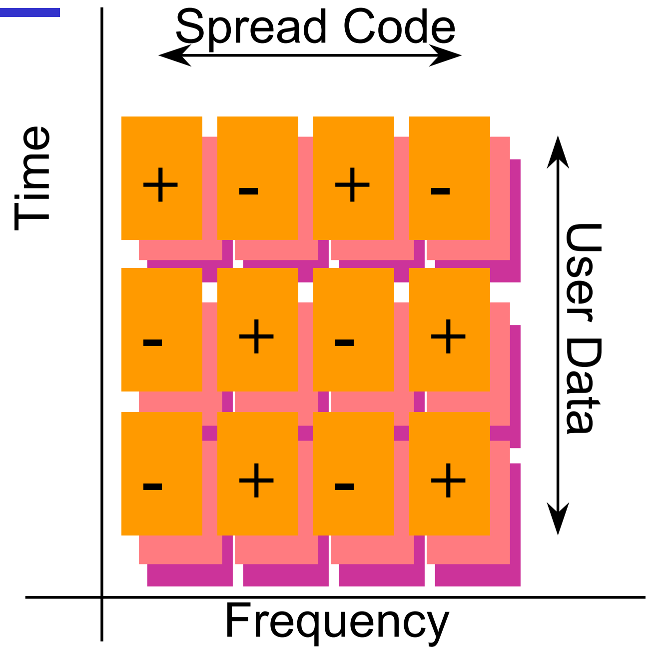
- User bits 101 (+ - +)
- Code 1110100 (+ + + - + - -); spead factor = 7

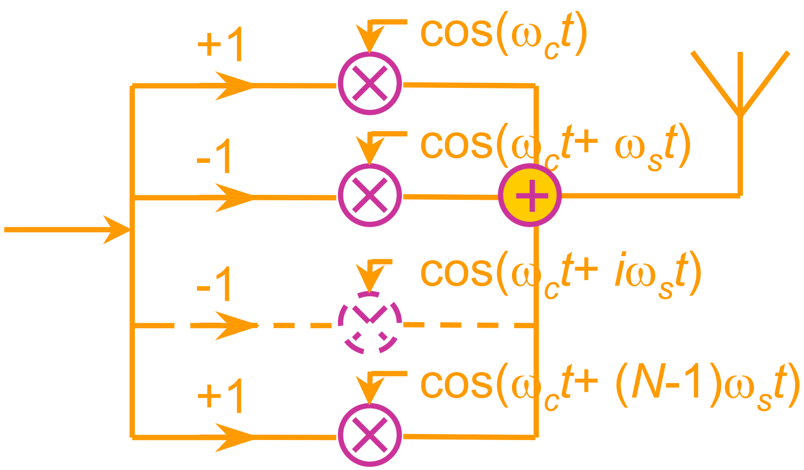
User bit$_{-1}$ = 1							User bit$_0$ = -1							User bit$_{+1}$ = 1						
1	1	1	-1	1	-1	-1	-1	-1	-1	1	-1	1	1	1	1	1	-1	1	-1	-1

Multi-Carrier

Direct Sequence + OFDM

Direct sequence where
spreading sequence is FFT
of normal code sequence





Code sequence: (hor) + - + -
Bit sequence: (vert) + - -

Ultra Wide Band

Transmission of very short pulses (fraction of a nanosecond), with bandwidth of many Gigahertz.

Receiver "correlates" to find pulses

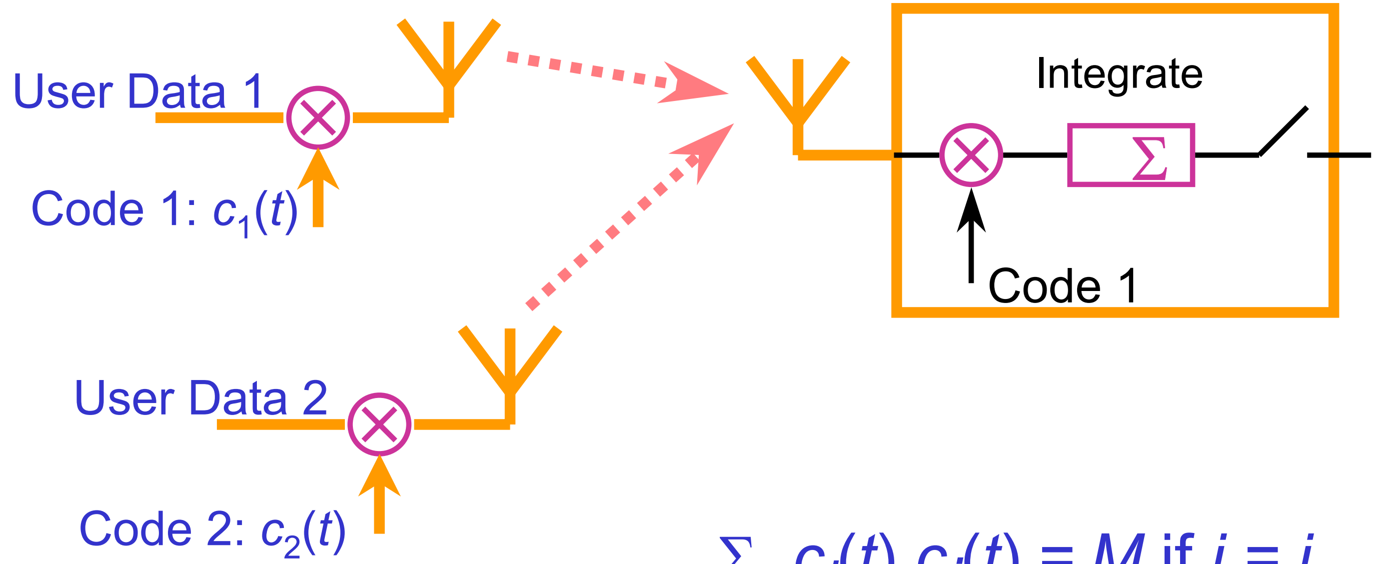
Practical problems:

- Synchronisation
- The signal will experience dispersion, and many individual reflections are received. It is extremely difficult to gather the energy from many paths
- While TX is power-efficient, the RX typically consumes a lot of power.

Direct Sequence CDMA

User separation in Direct Sequence

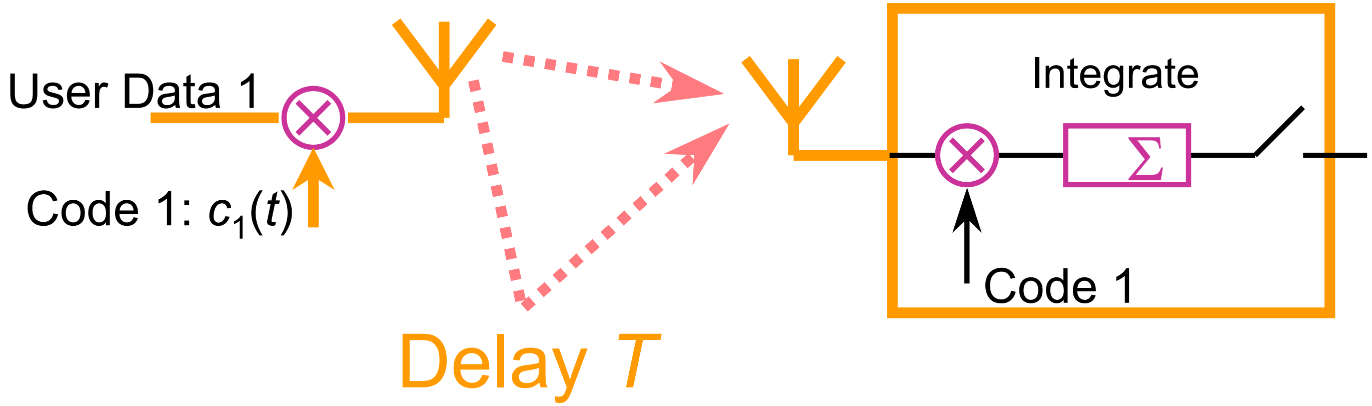
Different users have different (orthogonal ?) codes.



$$\Sigma_t \; c_i(t)\, c_j(t) = M \text{ if } i = j$$
$$= \text{"0" if } i \neq j$$

Multipath Separation in DS

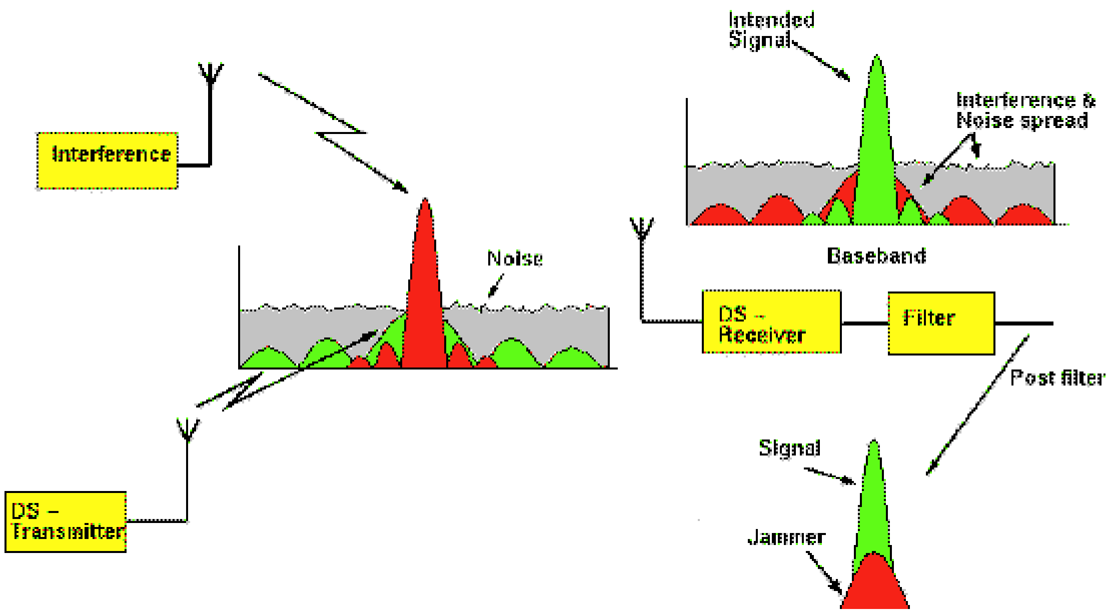
Different delayed signals are orthogonal



$$\Sigma_t\ c_i(t)\ c_i(t) \qquad = M$$

$$\Sigma_t\ c_i(t)\ c_i(t+T) \qquad = \text{“0” if } T \neq 0$$

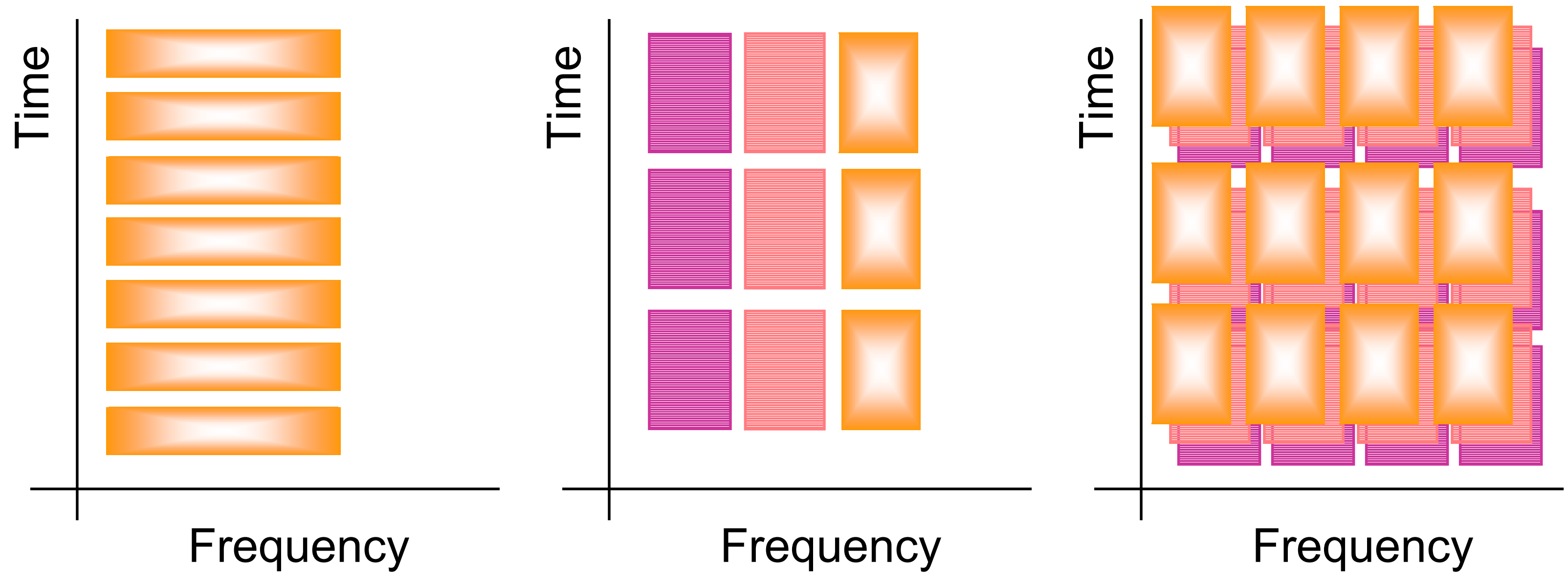
Power Spectral Density of Direct Sequence Spread Spectrum



Green: Wanted DS signal
Red: Narrowband jammer
Gray: Noise

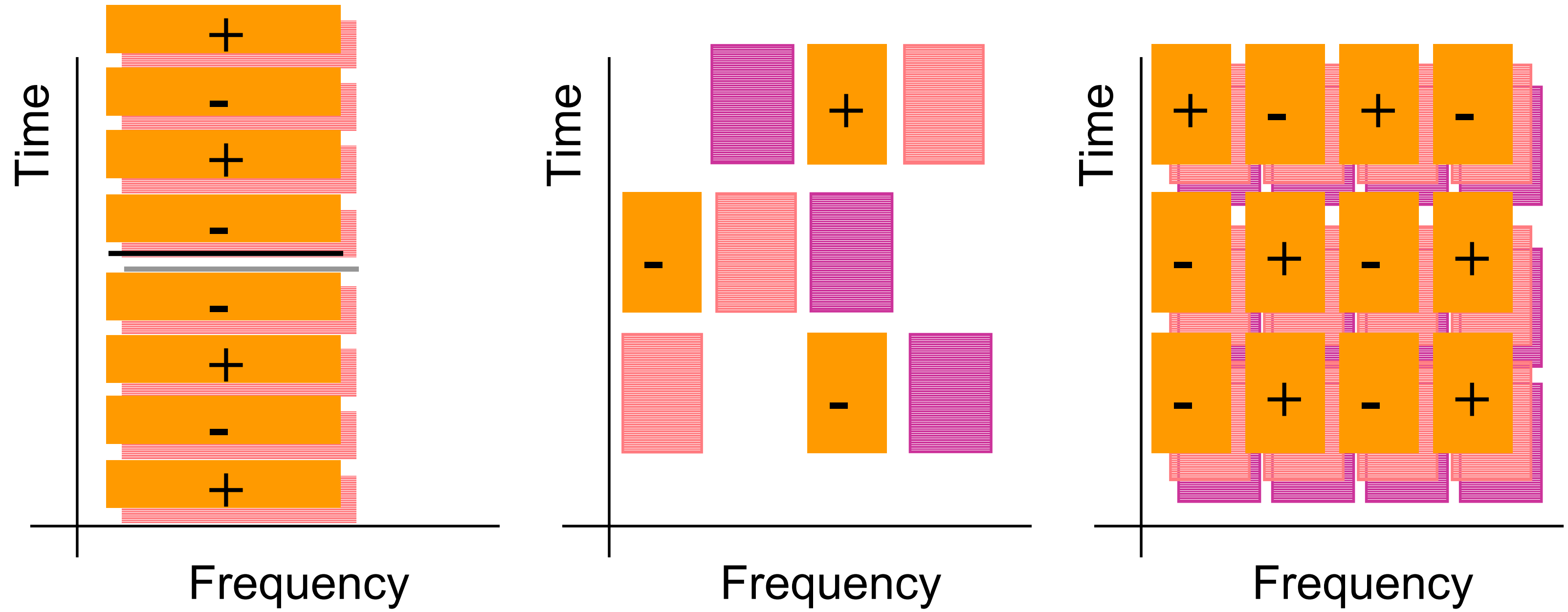
Effects of Multipath (I)

Wideband   Narrowband   OFDM



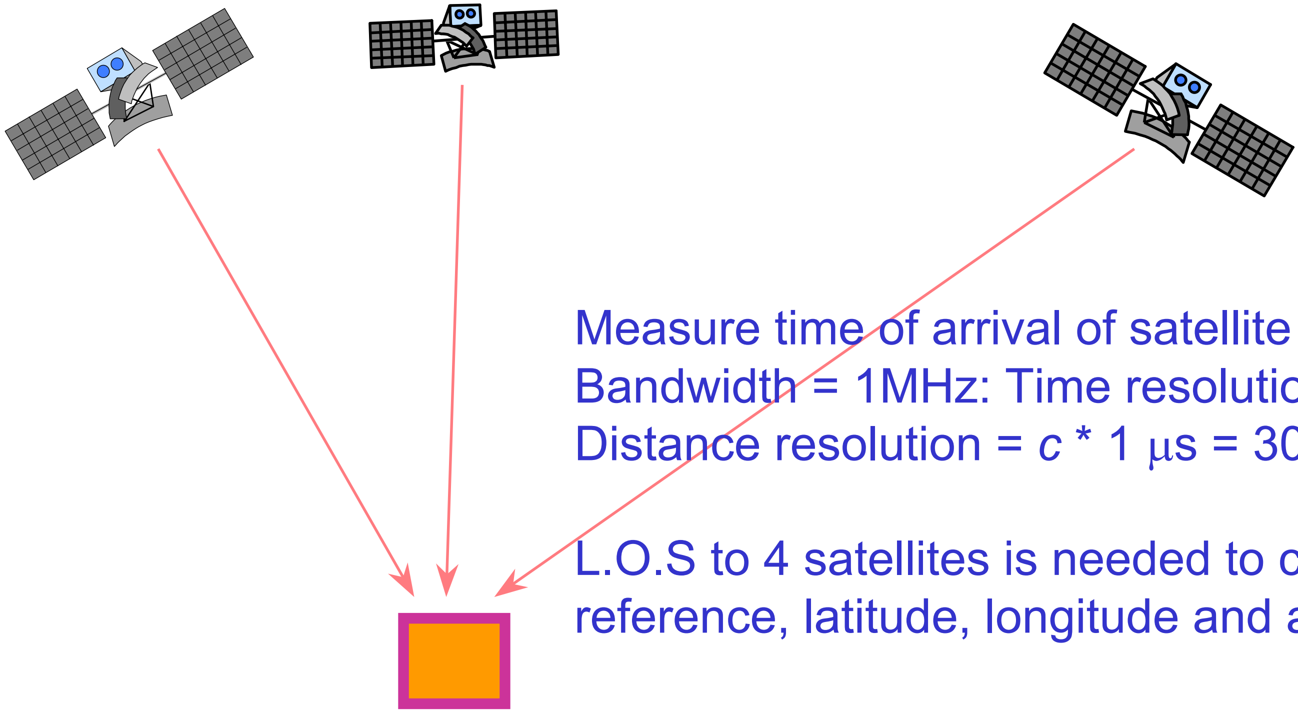
Effects of Multipath (II)

DS-CDMA | Frequency Hopping | MC-CDMA



DS in positioning systems

GPS: Global Positioning System



Measure time of arrival of satellite signals
Bandwidth = 1MHz: Time resolution = 1 μs
Distance resolution = c * 1 μs = 300 meter

L.O.S to 4 satellites is needed to calculate time reference, latitude, longitude and altitude.

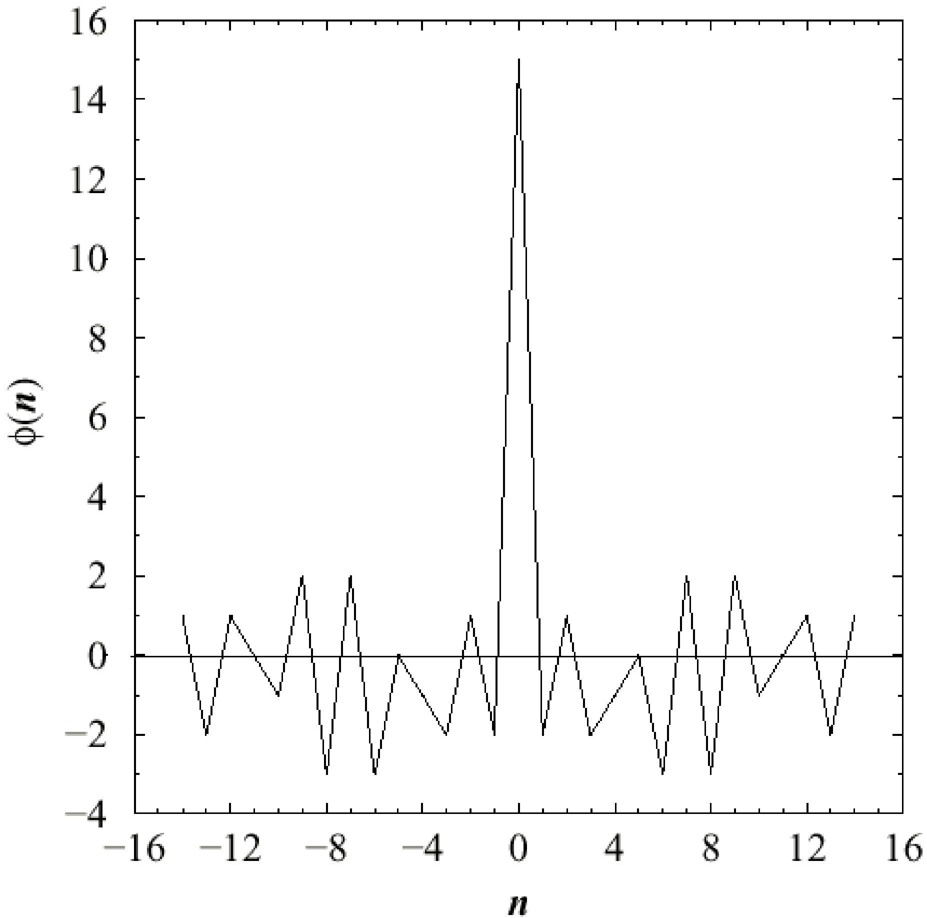
Spreading Sequence Characteristics

Desirable code properties include

•Low auto-correlation sidelobes

•Low cross-correlation

•Flat power spectrum



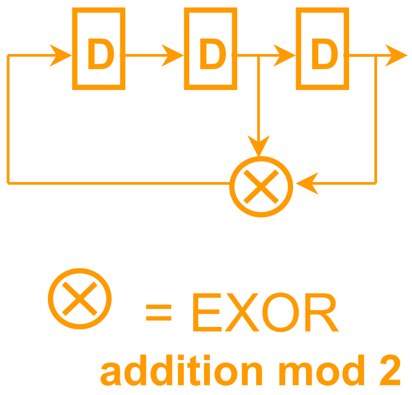
(A)periodic auto-correlation

Popular Codes: *m*-sequences

Linear Feedback Shift Register Codes:

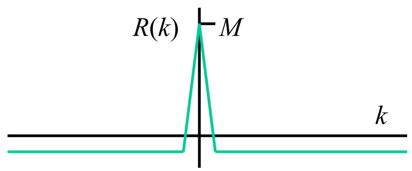
- Maximal length: $M = 2^L - 1$. Why?
- Every bit combination occurs once (except 0^L)
- Autocorrelation is $2^L - 1$ or -1

- Maximum length occurs for specific polynomia only



correlation:

$$R(k) = \sum_{m=0}^{M-1} c(m)c(m-k)$$

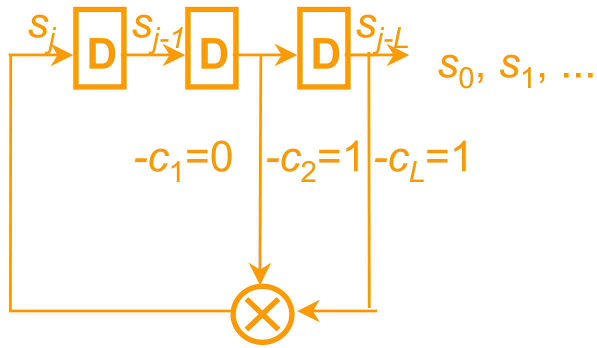


LFSR *m*-codes

Recursion

$$s_j = -c_1 s_{j-1} - c_2 s_{j-2} - .. - c_L s_{j-L}$$

$$1 s_j + c_1 s_{j-1} + c_2 s_{j-2} + .. + c_L s_{j-L} = 1$$



Output z-Polynomial:

$$S(z) = s_0 + s_1 z + s_2 z^2 + ...$$

Connection Polynomial:

$$C(z) = 1 + c_1 z + c_2 z^2 + c_3 z^3$$

⊗ = EXOR

c_i, s_i in {0,1}

addition mod 2

$$C(z)\ S(z) = P(z) = \text{intial state polynimial}$$

- Maximum length occurs for irreducable polynomia only

checlk

Popular Codes: *Walsh-Hadamard*

Basic Code (1,1) and (1,-1)

- Recursive method to get a code twice as long
- Length of code is 2^l
- Perfectly orthogonal
- Poor auto correlation properties
- Poor spectral spreading.
  - all "1" code (col. 0) is a DC sequence
  - alternating code (col. 1) is a spectral line
- Compare the WH with an FFT
  - butterfly structure
  - occurrence of "frequencies"

$$R_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$R_{2i} = \begin{bmatrix} R_i & R_i \\ R_i & -R_i \end{bmatrix}$$

$$R_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

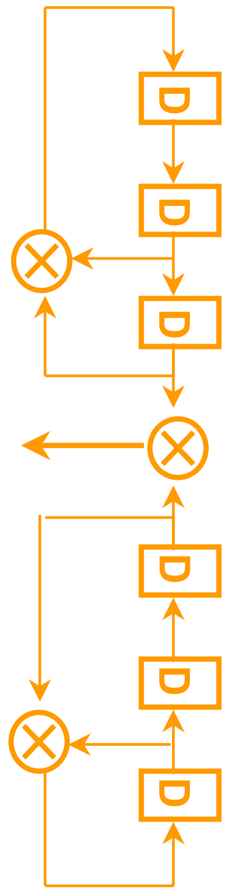
One column is the code for one user

Popular Codes: *Gold* Sequences

Created by Exor-ing two *m*-sequences

Gold sequence of length $m = 2^{l-1}$:

- use two LFSRs, each of length 2^{l-1}.



Better cross-correlation properties than maximum length LSFR sequences.

Prefered *m*-sequences: crosscorrelation only takes on three possible values: -1, -*t* or *t*-2.

Random Codes

Random codes cannot exploit orthogonality

Useful in distributed networks without coordination and without synchronisation

Maximum normalized cross correlation R_{max} (at zero time offset) between user codes

$$R_{max} = \frac{(Nu/N) - 1}{Nu - 1}$$

with N the spread factor and Nu the number of users

- Walsh-Hadamard codes $N = Nu$, so $R_{max}=0$
- Gold codes $N = Nu - 1$, so $R_{max} = 1/N$.

Cellular CDMA

IS-95: proposed by Qualcomm

W-CDMA: future UMTS standard

Advantages of CDMA

- Soft handoff
- Soft capacity
- Multipath tolerance: lower fade margins needed
- No need for frequency planning

Cellular CDMA

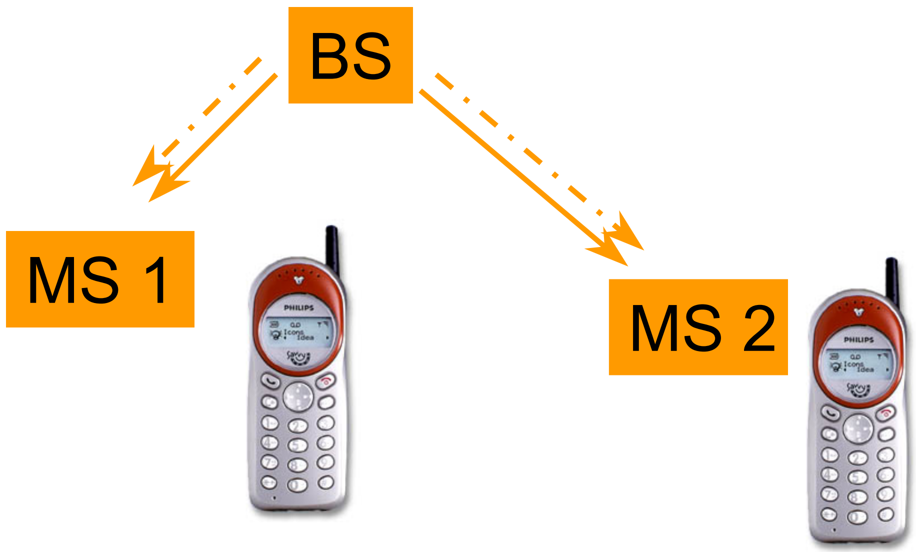
Problems

- Self Interference
  - Dispersion causes shifted versions of the codes signal to interfere
- Near-far effect and power control
  - CDMA performance is optimized if all signals are received with the same power
  - Frequent update needed
  - Performance is sensitive to imperfections of only a dB
  - Convergence problems may occur

Synchronous DS: Downlink

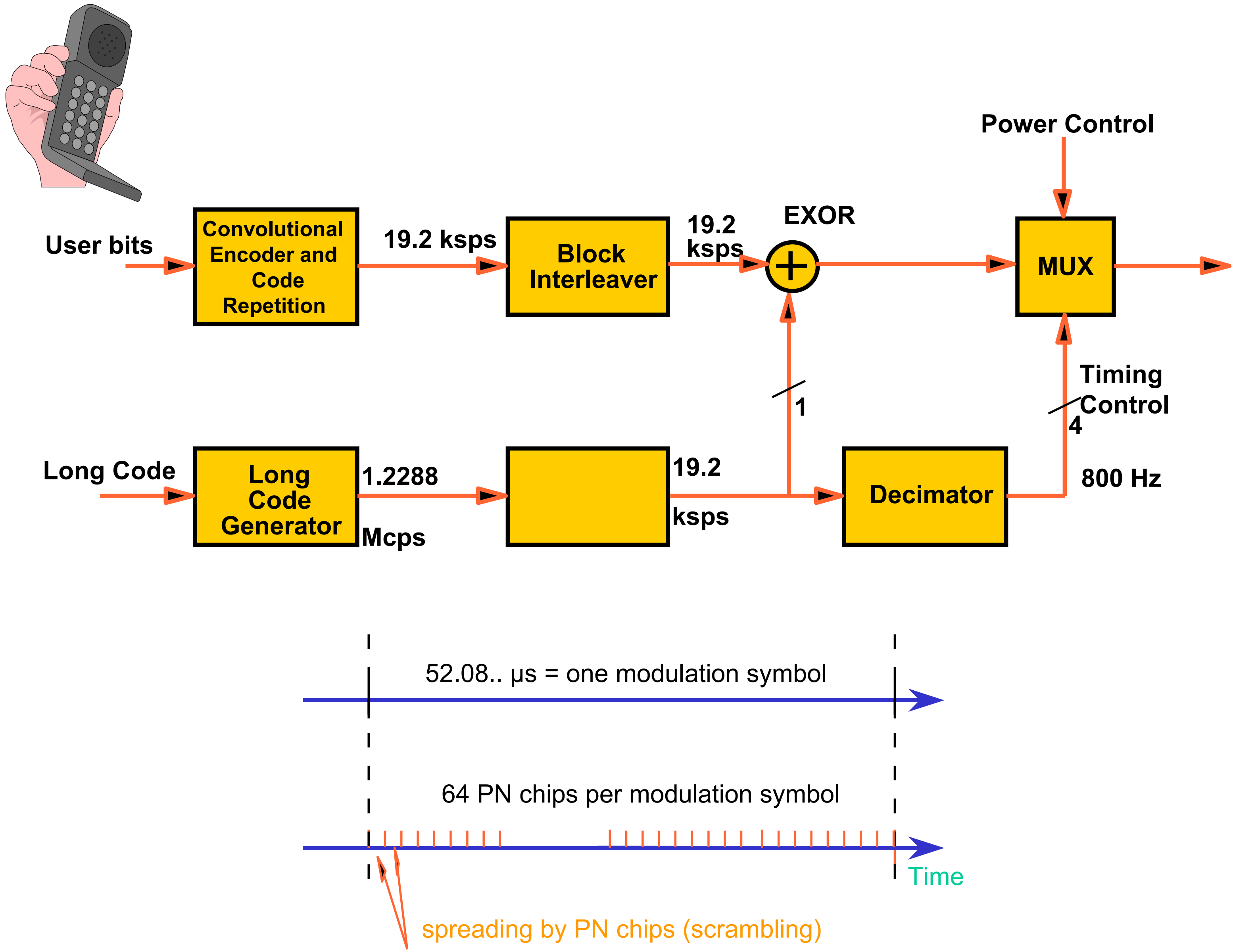
In the 'forward' or downlink (base-to-mobile): all signals originate at the base station and travel over the same path.

One can easily exploit orthogonality of user signals. It is fairly simple to reduce mutual interference from users within the same cell, by assigning orthogonal Walsh-Hadamard codes.



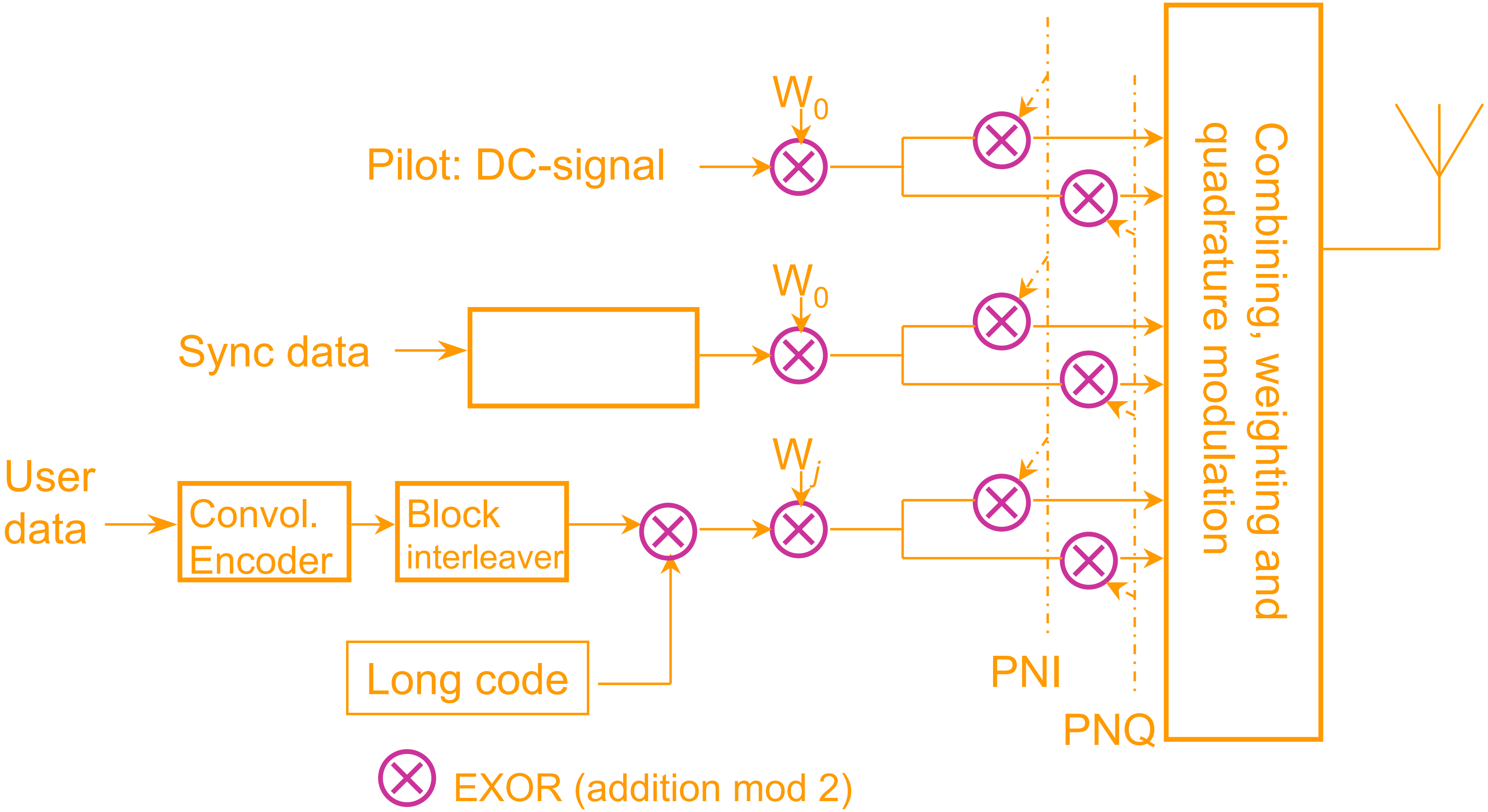
IS-95 Forward link ('Down')

- Logical channels for pilot, paging, sync and traffic.
- Chip rate 1.2288 Mchip/s = 128 times 9600 bit/sec
- Codes:
  - Length 64 Walsh-Hadamard (for orthogonality users)
  - maximum length code sequence (for effective spreading and multipath resistance
- Transmit bandwidth 1.25 MHz
- Convolutional coding with rate 1/2



$\oplus$ Modulo-2 addition

IS-95 BS Transmitter



Rationale for use of codes

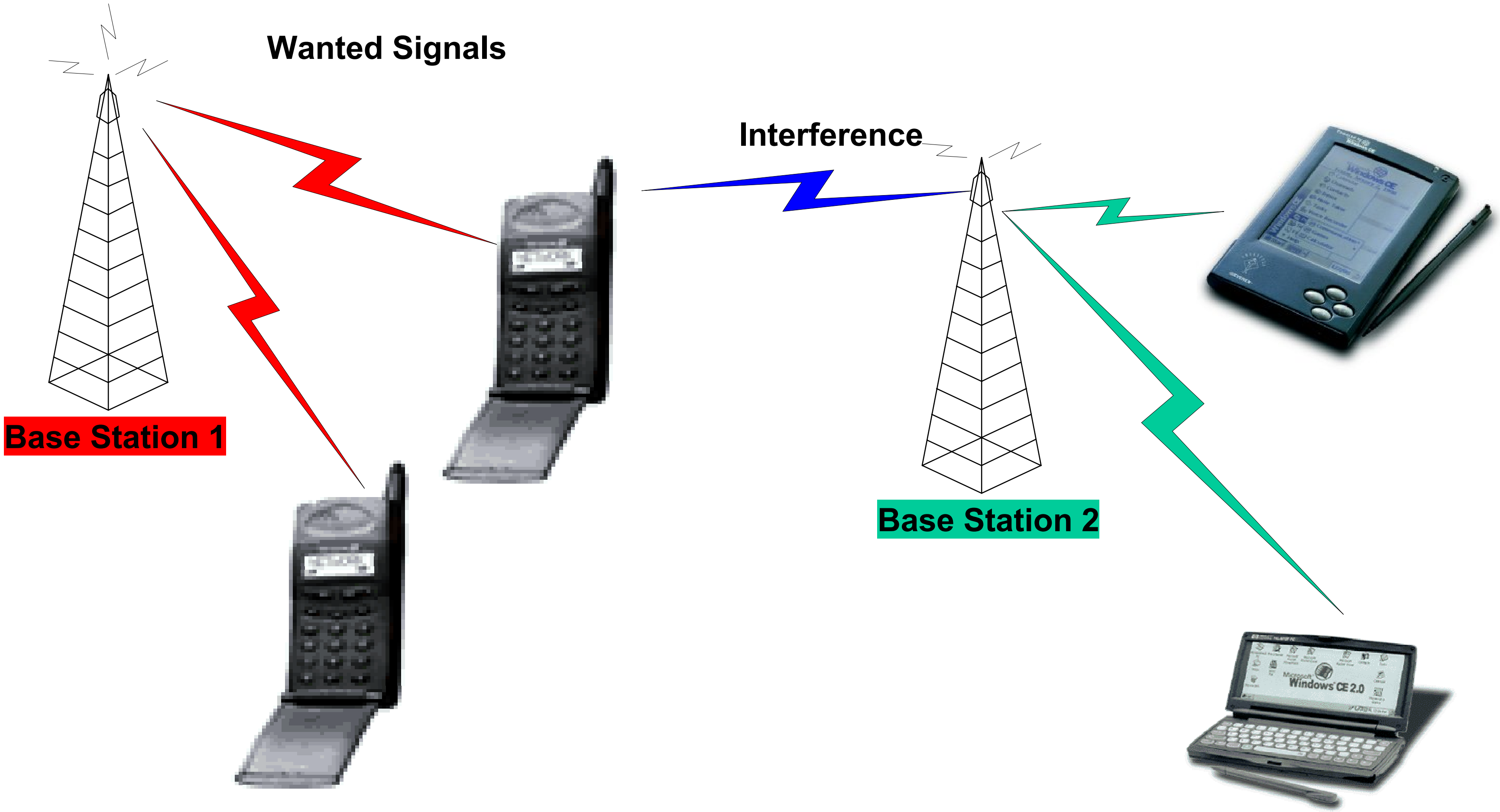
Long code: scrambling to avoid that two users in neighboring cells use the same code

short code: user separation inone cell

PN exor WH:

- maintains excellent crosscorrelation
- improves autocorrelation (multipath)

Power Control in CDMA Systems



Power Control

Aim of power control - optimise received power by varying transmitted power

Two methods - open loop and closed loop

Open loop - estimate path loss from channel measurements

Closed loop - use feedback from other end of link

What step size

- In UMTS steps power steps are about 1 db

What update rate

- In UMTS update rate is about 1500Hz

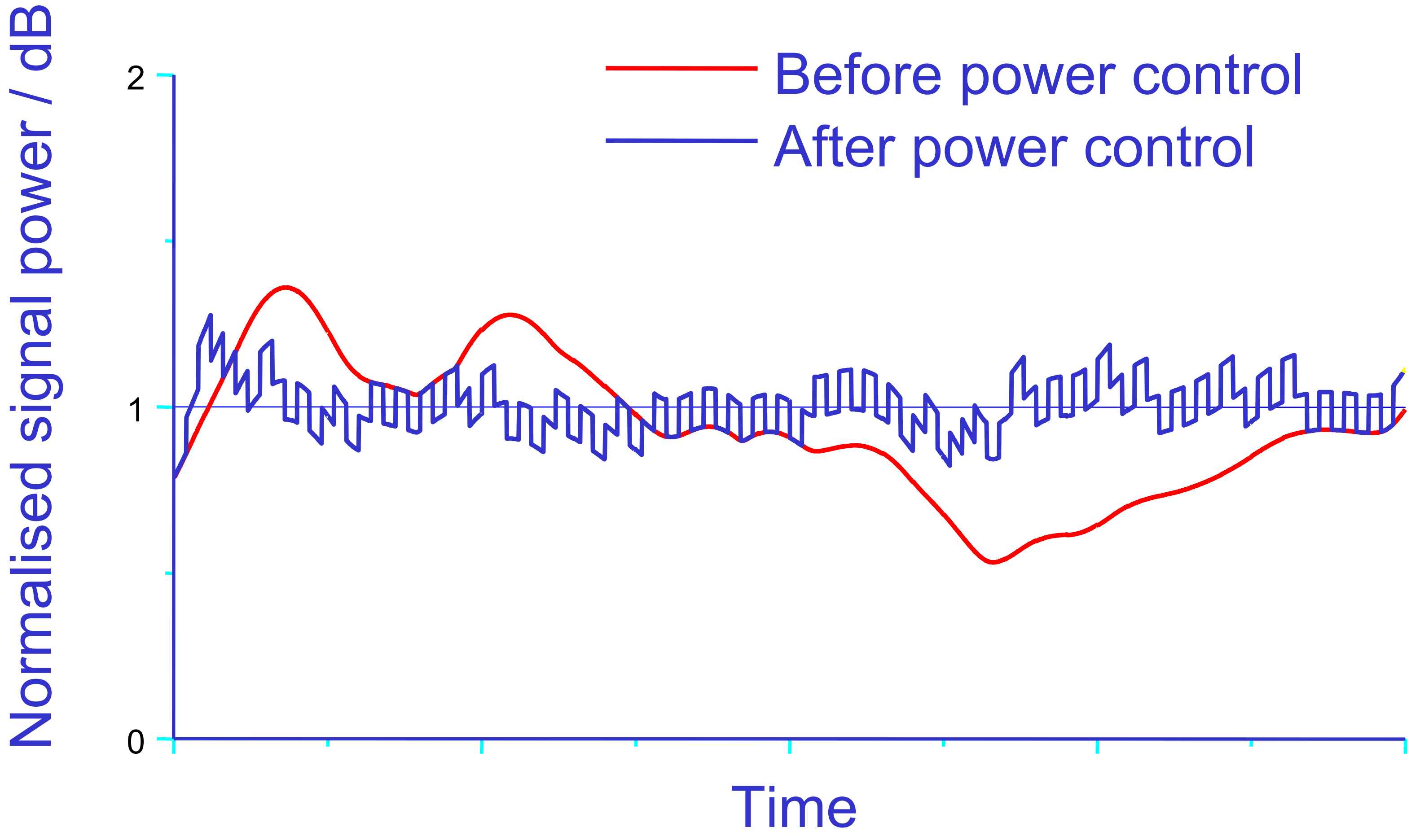
Power Control in IS-95

CDMA performance is optimized if all signals are received with the same power

Update needed every 1 msec. (cf. rate of fading)

Performance is sensitive to imperfections of only a dB

Example of Power Control Action from UMTS

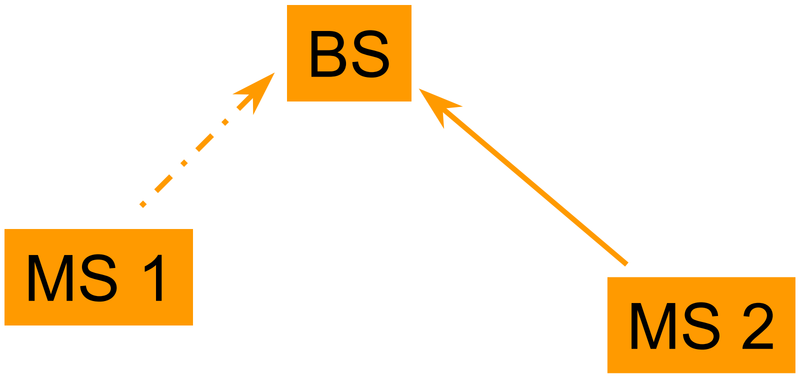


Asynchronous DS: uplink

In the ‘reverse’ or uplink (mobile-to-base), it is technically difficult to ensure that all signals arrive with perfect time alignment at the base station.

Different channels for different signals

power control needed



IS-95 Reverse link ('Up')

- Every user uses the same set of short sequences for modulation as in the forward link.

  Length = 2^{15} (modified 15 bit LFSR).

- Each access channel and each traffic channel gets a different long PN sequence.

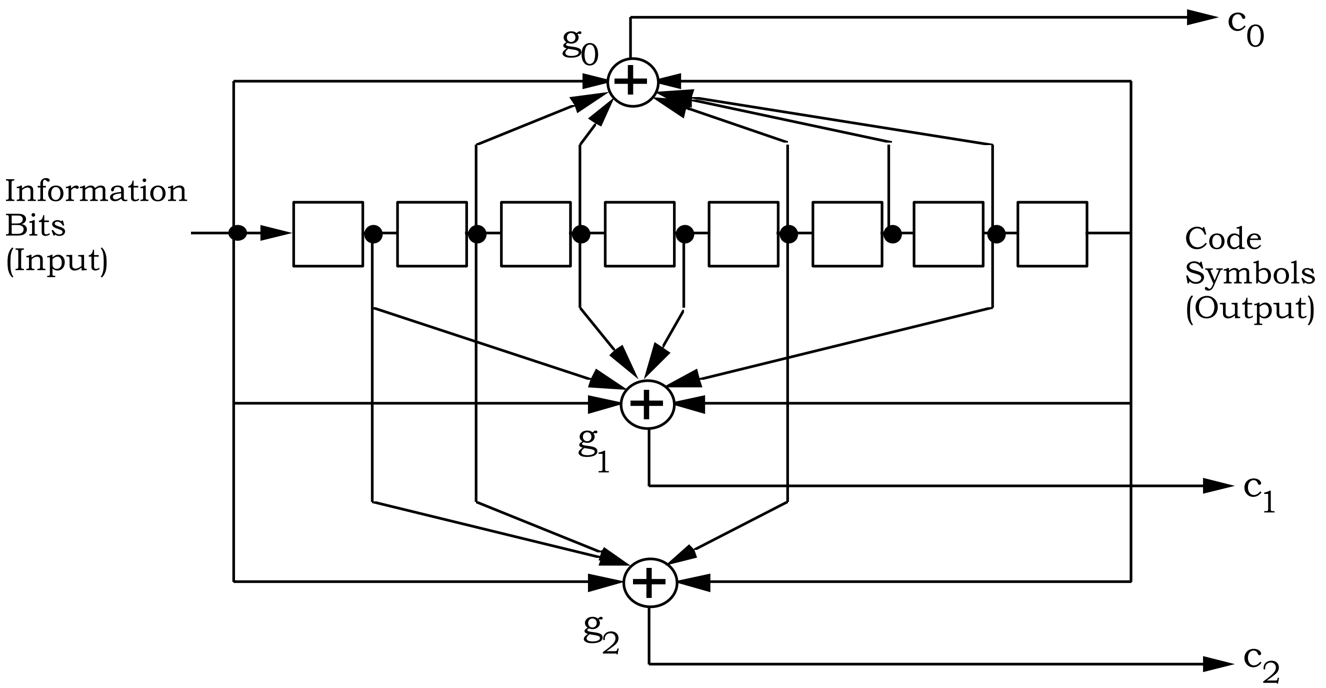
  Used to separate the signals from different users.

- Walsh codes are used solely to provide *m*-ary orthogonal modulation waveform.
- Rate 1/3 convolutional coding.

IS-95 Uplink

Rate 1/3 convolutional encoder:

every user bit gives three channel bits



Power Control in IS-95

CDMA performance is optimized if all signals are received with the same power

Update needed every 1 msec. (cf. rate of fading)

Performance is sensitive to imperfections of only a dB

Wideband-CDMA (IS-665)

Bandwidth (1.25), 5, 10 or 15 MHz

Chip rate (1.024), 4.096, 8.192 and 12.288 Mc/s

Spread factors 4 - 256

Spreading sequences:

- Down: variable length orhogonal sequences for channel separation, Gold sequences 2^{18} for cell separation
- Up: Gols sequences 2^{41} for user separation

Sequence length 2^{32} - 1

User data rate 16, 31 and 64 kbit/s

Power control: open and fast closed loop (2 kHz)

PS. SUBJECT TO CHANGES, TO BE CHECKED !!

Rake receiver

A rake receiver for Direct Sequence SS optimally combines energy from signals over various delayed propagation paths.

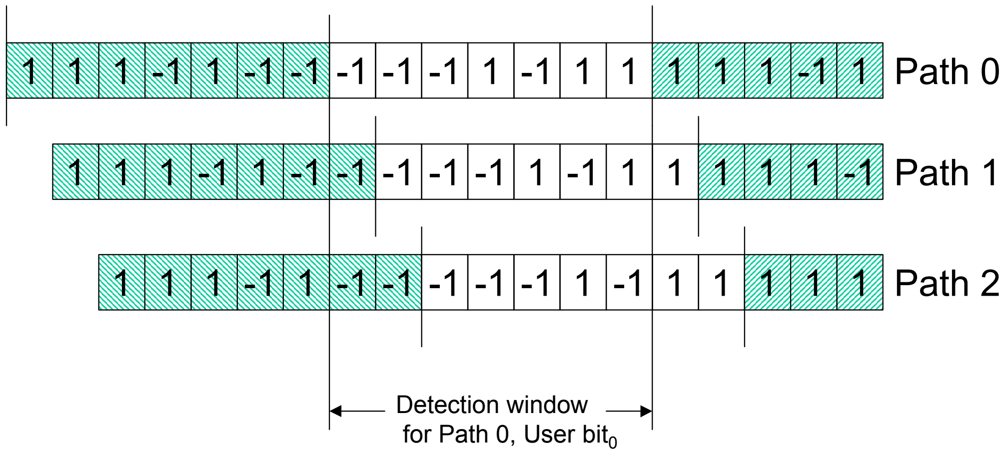
Effects of dispersion in DS

Channel Model

$$h(t) = \sum_{l=0}^{L-1} h_l \delta(t - lT_c)$$

h_l is the (complex Gaussian?) amplitude of the l-th path.

The Rake receiver correlates with each delayed path

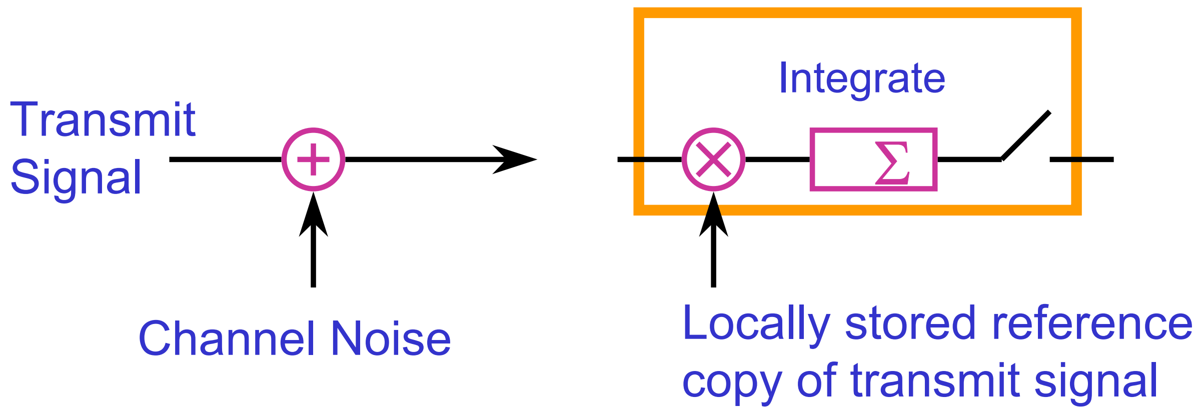


DS reception: Matched Filter Concept

The optimum receiver for any signal

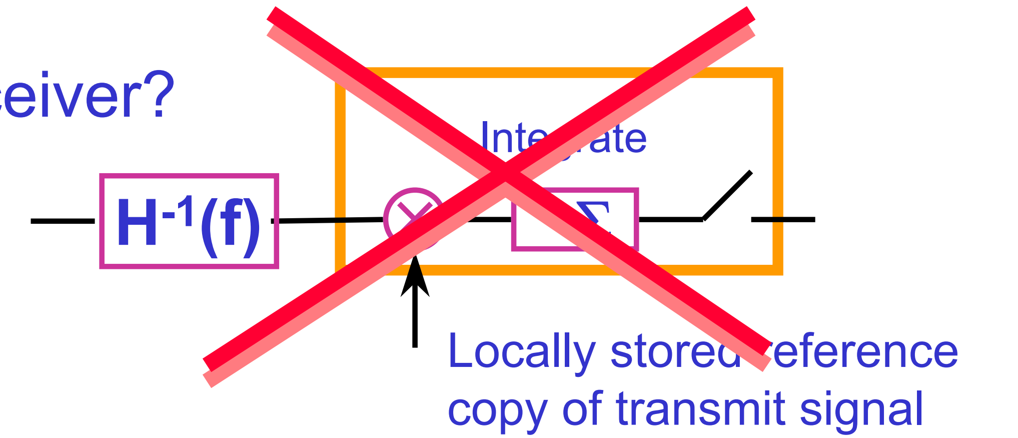
- in Additive white Gaussian Noise
- over a Linear Time-Invariant Channel

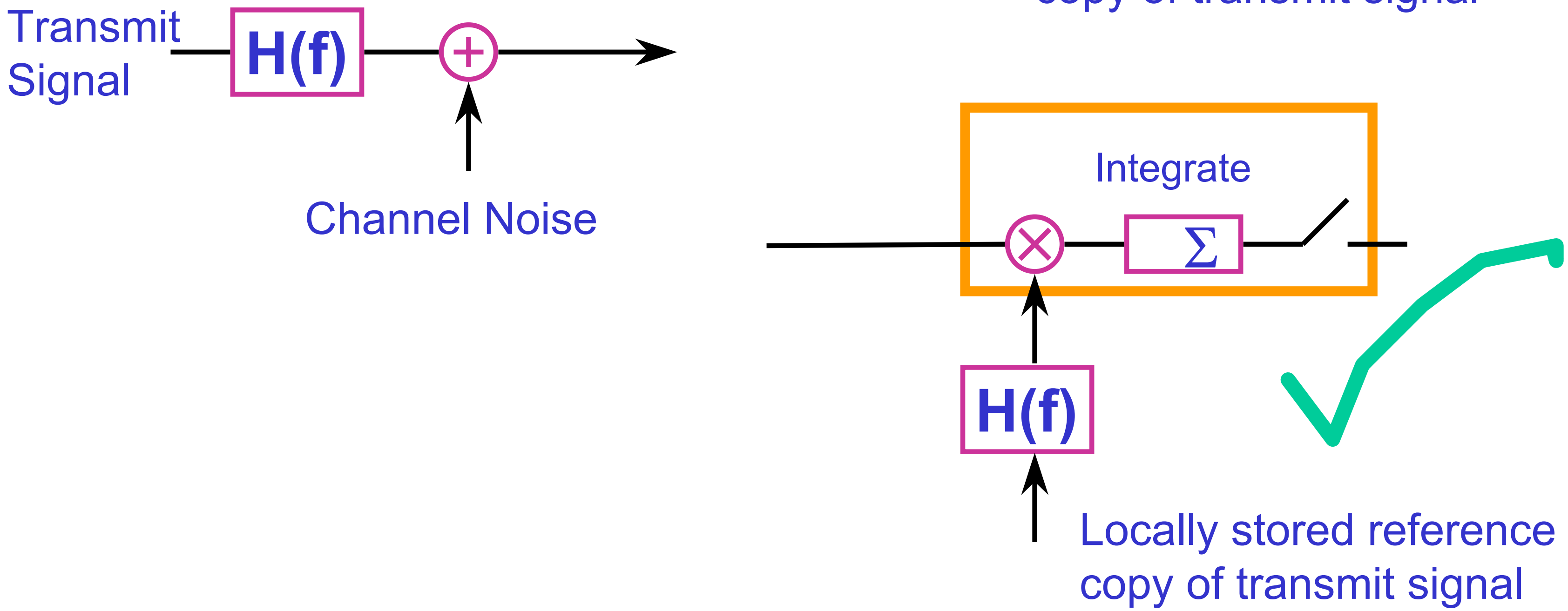
is ‘a matched filter’:



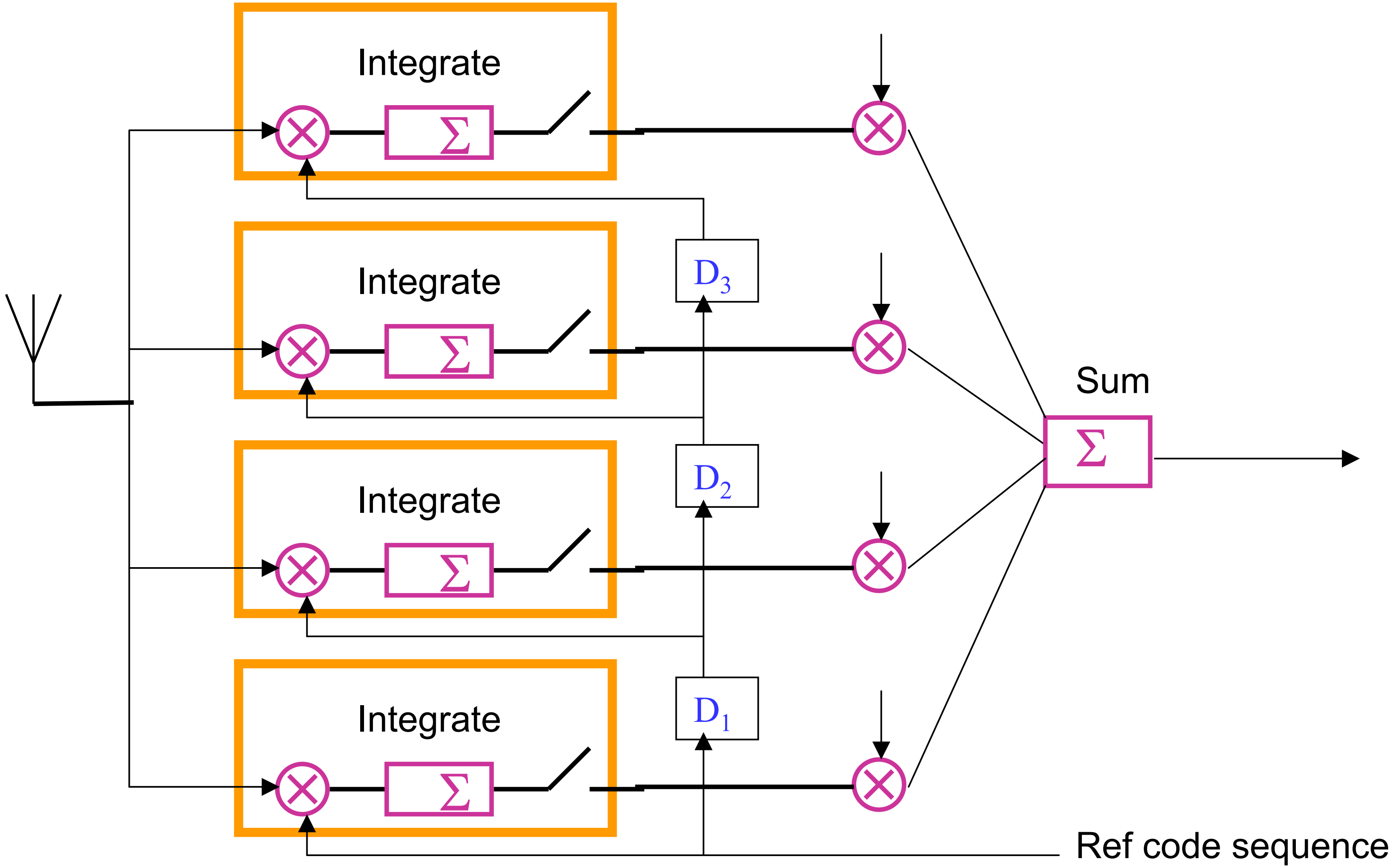
Matched Filter with Dispersive Channel

What is an optimum receiver?





Rake Receiver: Practical Implementation

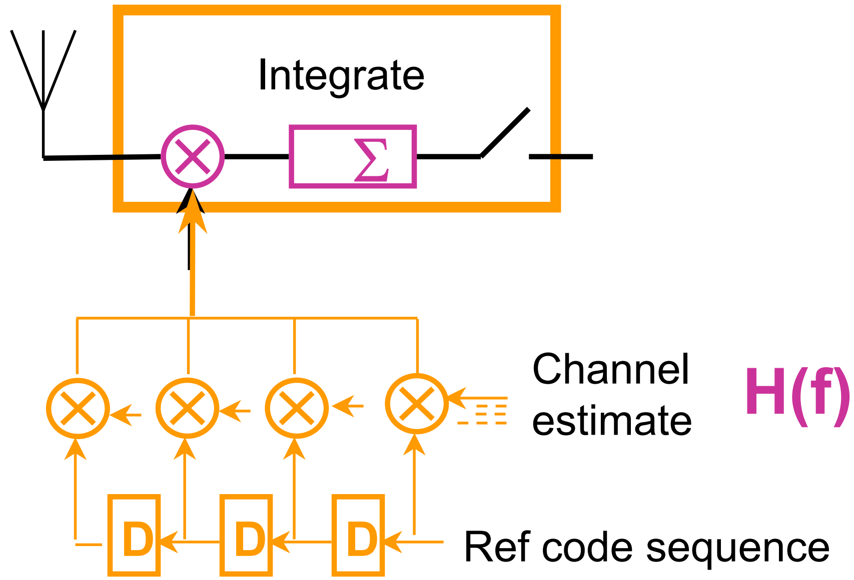


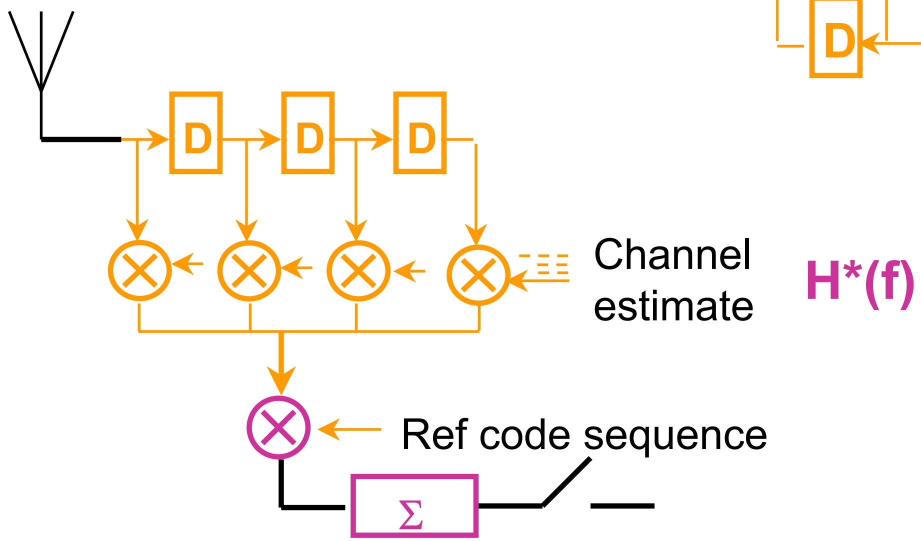
Rake Receiver

1956: Price & Green

Two implementations of the rake receiver:

- Delayed reference
- Delayed signal





BER of Rake Receivers

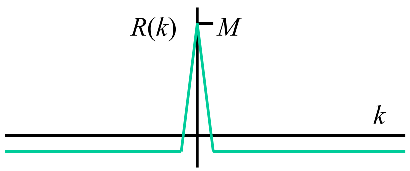
In the *i*-th finger, many signal components appear:

$$v_i = d_0 \sum_{l=0}^{L_p-1} h_l R^{>}(l-i) + d_{-1} \sum_{l=i+1}^{L_p-1} h_l R^{<}(|l-i|) + d_1 \sum_{l=0}^{i-1} h_l R^{<}(|i-l|) + noise$$

WANTED SIGNAL | INTERSYMBOL - | INTERFERENCE | NOISE

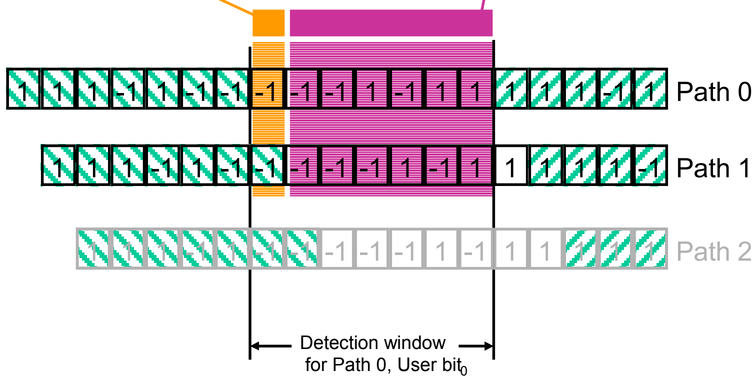
Full and partial correlation:

$$R(k) = \sum_{m=0}^{M-1} c(m)c(m-k)$$



$$R^{<}(k) = \sum_{m=0}^{k-1} c(m)c(m-k)$$

$$R^{>}(k) = \sum_{m=k}^{M-1} c(m)c(m-k)$$



BER of Rake

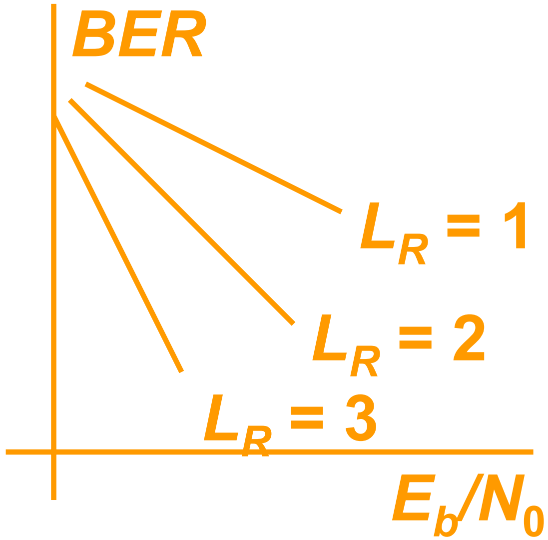
Ignoring ISI, the local-mean BER is

$$BER = \frac{1}{2}\sum_{j=0}^{L_R} \pi_j \left[1 - \sqrt{\frac{\gamma_j}{\gamma_j + 1}}\right]$$

where

$$\pi_j = \prod_{\substack{i=1 \\ i \neq j}}^{L_R} \frac{\gamma_j}{\gamma_j - \gamma_i}$$

with γ_i the local-mean SNR in branch *i*.

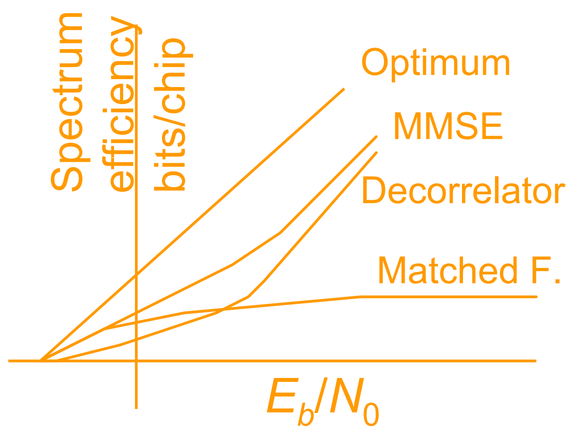


J. Proakis, "Digital Communications", McGraw-Hill, Chapter 7.

Advanced user separation in DS

More advanced signal separation and multi-user detection receivers exist.

- Matched filters
- Successive subtraction
- Decorrelating receiver
- Minimum Mean-Square Error (MMSE)



Source: Sergio Verdu

Concluding Remarks

DS-CDMA is a mature technology for cellular telephone systems. It has advantages, particularly in the downlink.

The rake receiver ‘resolves’ multipath delays

DS-CDMA has been proposed also for bursty multimedia traffic, but its advantages are less evident