16.543 Communication Theory I
Lecture Notes 10

Introduction to Spread Spectrum, CDMA and IS-95

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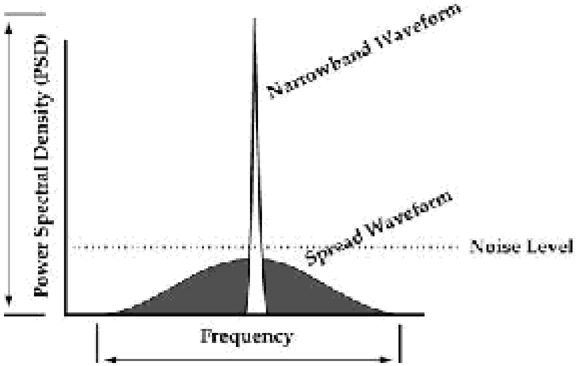
What is Spread Spectrum?

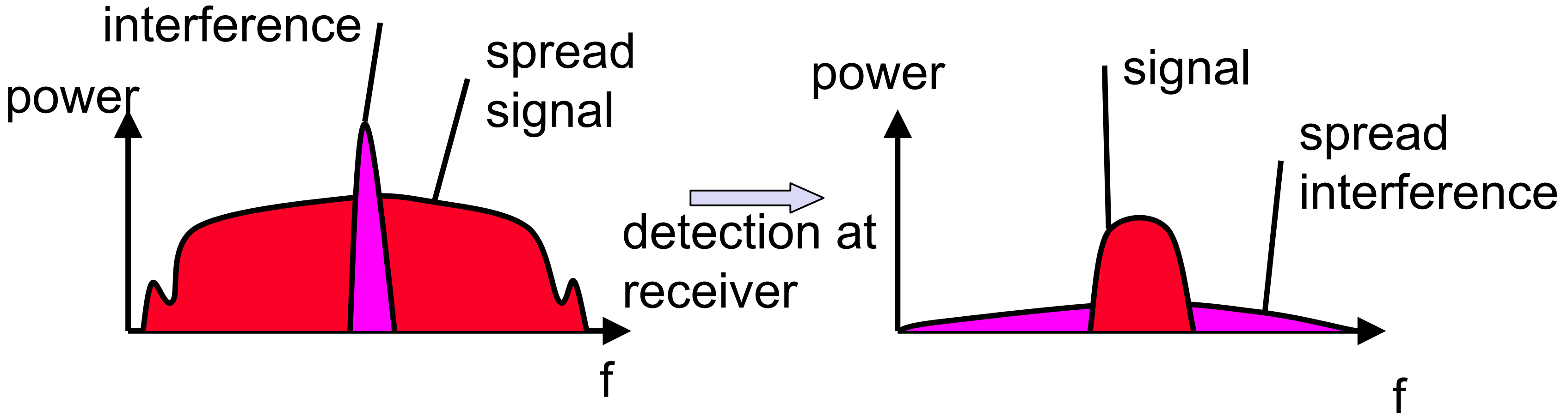
- "Spread Spectrum (SS)" is a type of modulation in which the data is scattered (spread) across the available frequency band in a pseudo-random pattern
- It is basically a system in which the transmitted signal is spread over a frequency band much wider than the minimum bandwidth required to transmit the signal
- The idea behind SS is to transform a signal with bandwidth B_s into a noise-like signal of much larger bandwidth B_{ss}
  - Increasing the signal bandwidth increases the probability of correct reception
  - Spreading the data across the spectrum makes the signal resistant to noise, interference, and snooping



- The signal when spread is embedded in noise
- It is assumed that the total power transmitted by the spread signal is the same as that in the original signal

Spread Spectrum Technology

- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code

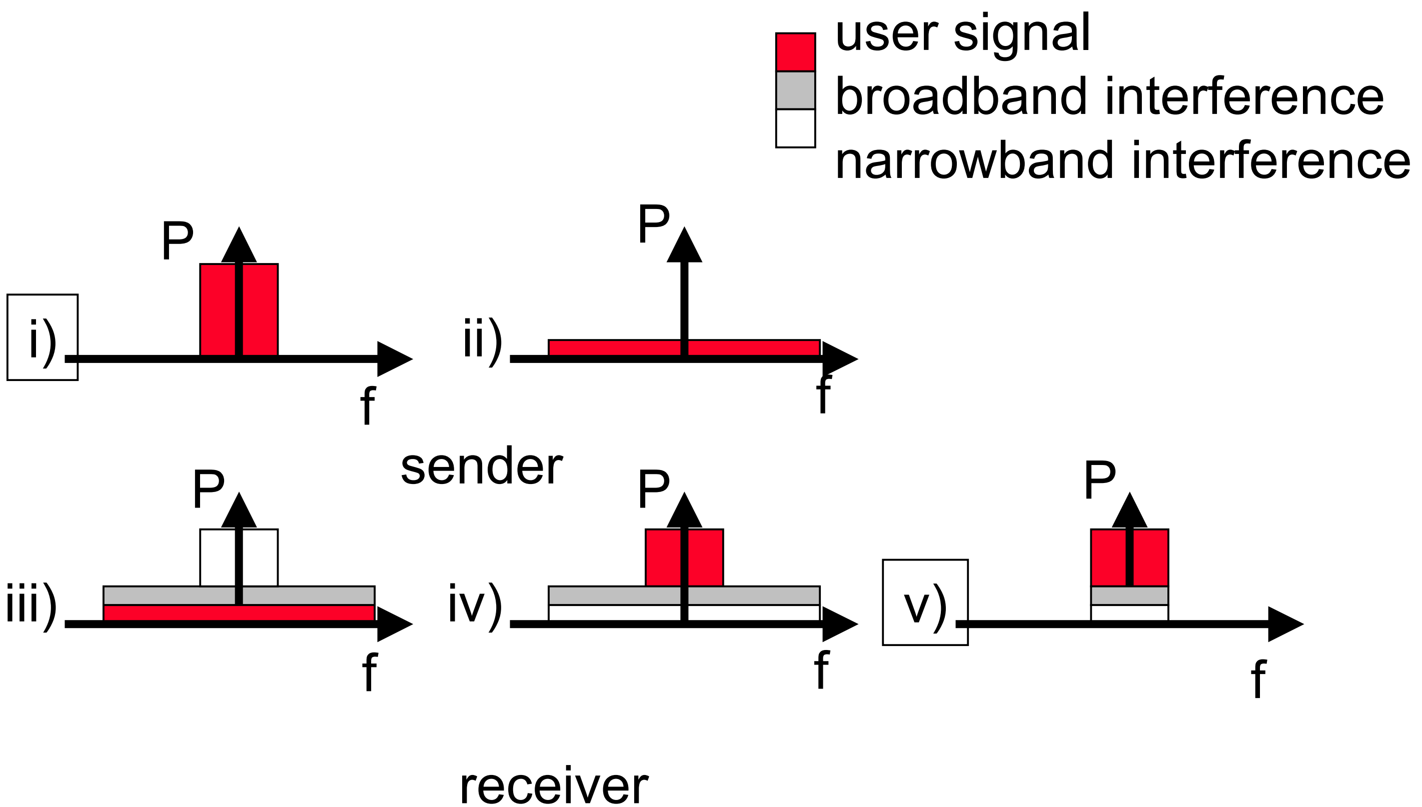


Spread Spectrum Technology

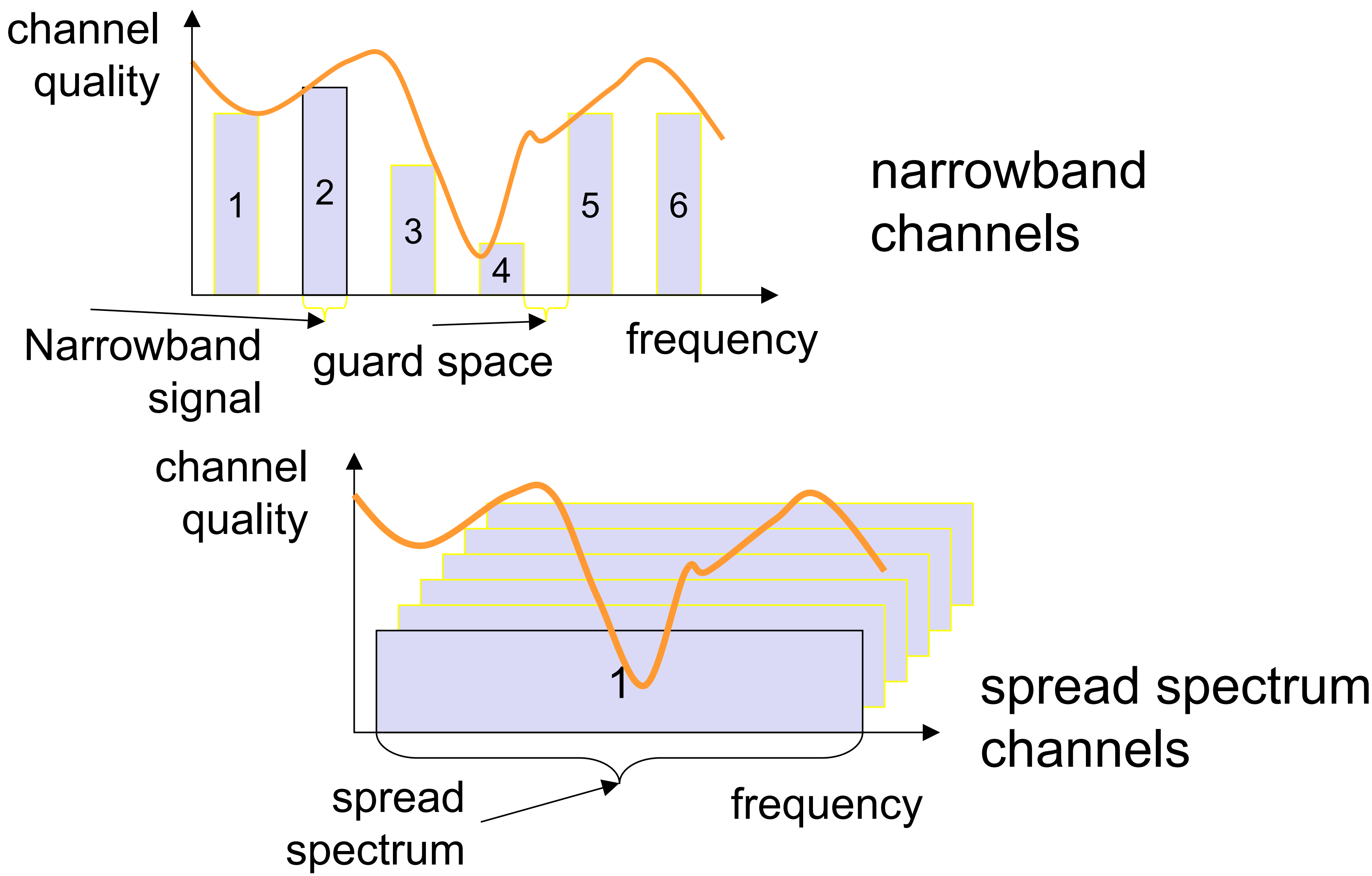
- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof
- Alternatives: Direct Sequence (DS/SS), Frequency Hopping (FH/SS)
- Spread spectrum increases BW of message signal by a factor *N*, Processing Gain

$$\text{Processing Gain } N = \frac{B_{ss}}{B} = 10\log_{10}\left(\frac{B_{ss}}{B}\right)$$

Effects of spreading and interference

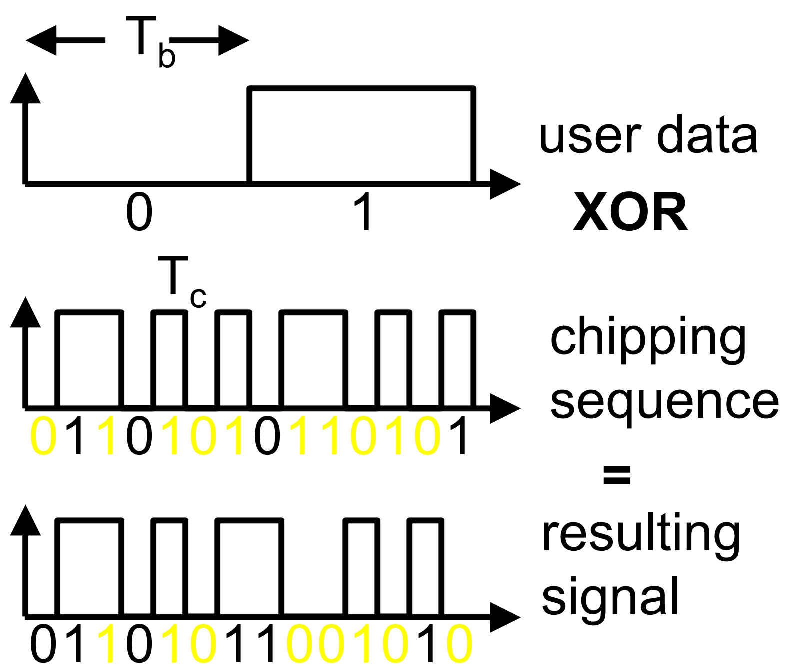


Spreading and frequency selective fading

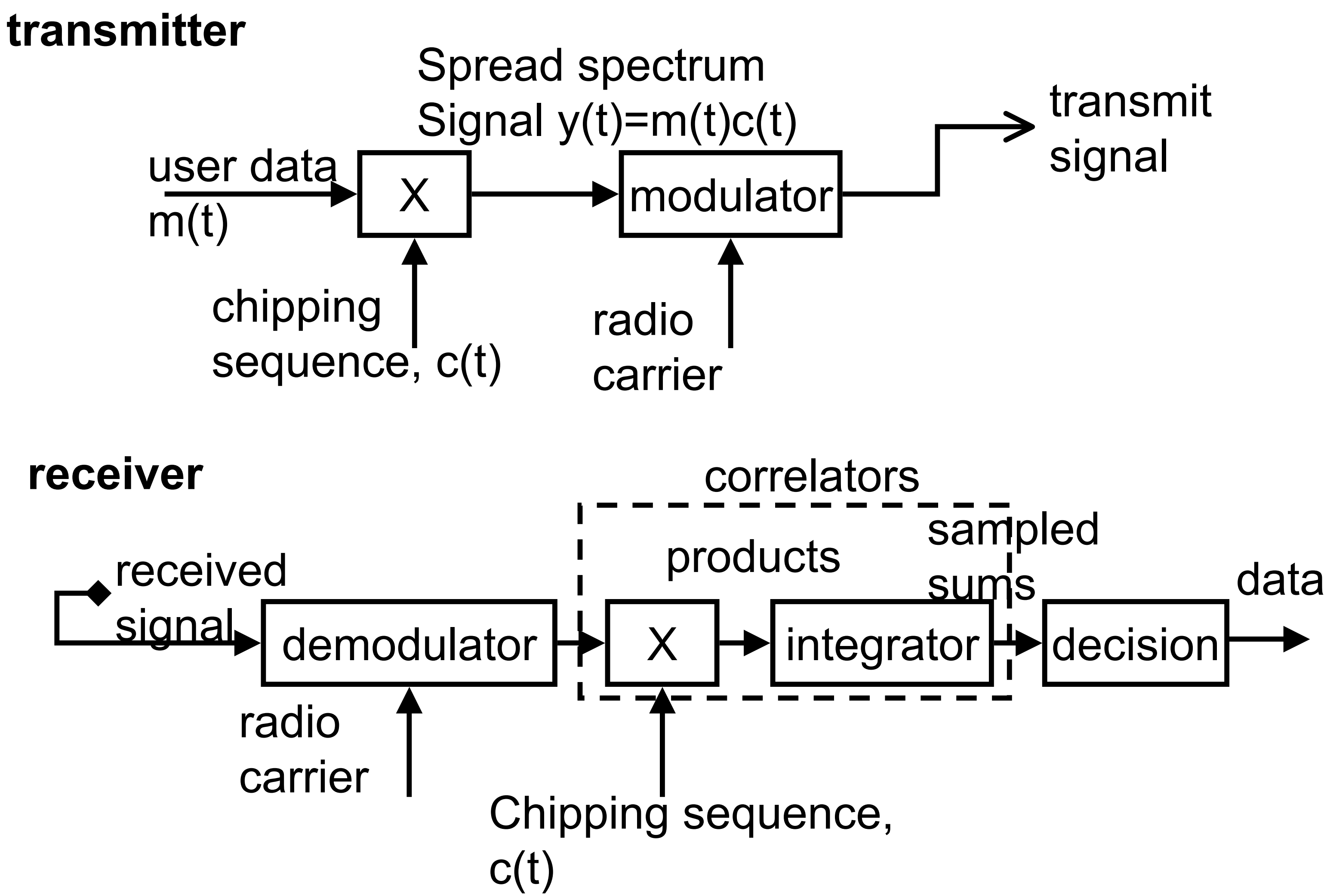


DSSS (Direct Sequence Spread Spectrum) I

- XOR the signal with pseudonoise (PN) sequence (chipping sequence)
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
- But, needs precise power control



DSSS (Direct Sequence Spread Spectrum) II



DS/SS Comments III

- Pseudonoise(PN) sequence chosen so that its autocorrelation is very narrow => PSD is very wide
  - Concentrated around $\tau \leq T_c$
  - Cross-correlation between two user's codes is very small

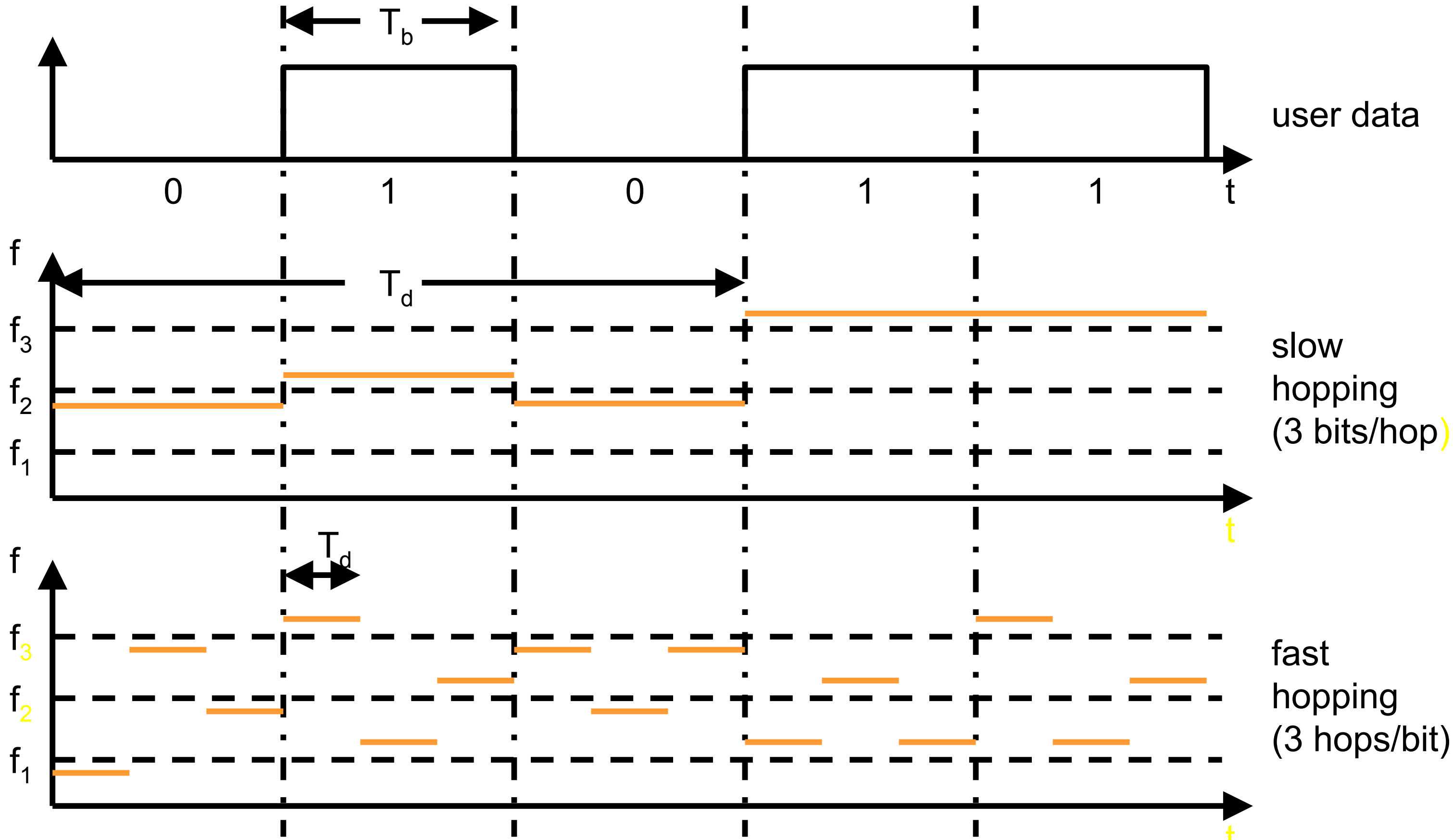
DS/SS Comments IV

- Secure and Jamming Resistant
  - Both receiver and transmitter must know c(t)
  - Since PSD is low, hard to tell if signal present
  - Since wide response, tough to jam everything
- Multiple access
  - If $c_i(t)$ is orthogonal to $c_j(t)$, then users do not interfere
- Near/Far problem
  - Users must be received with the same power

FH/SS (Frequency Hopping Spread Spectrum) I

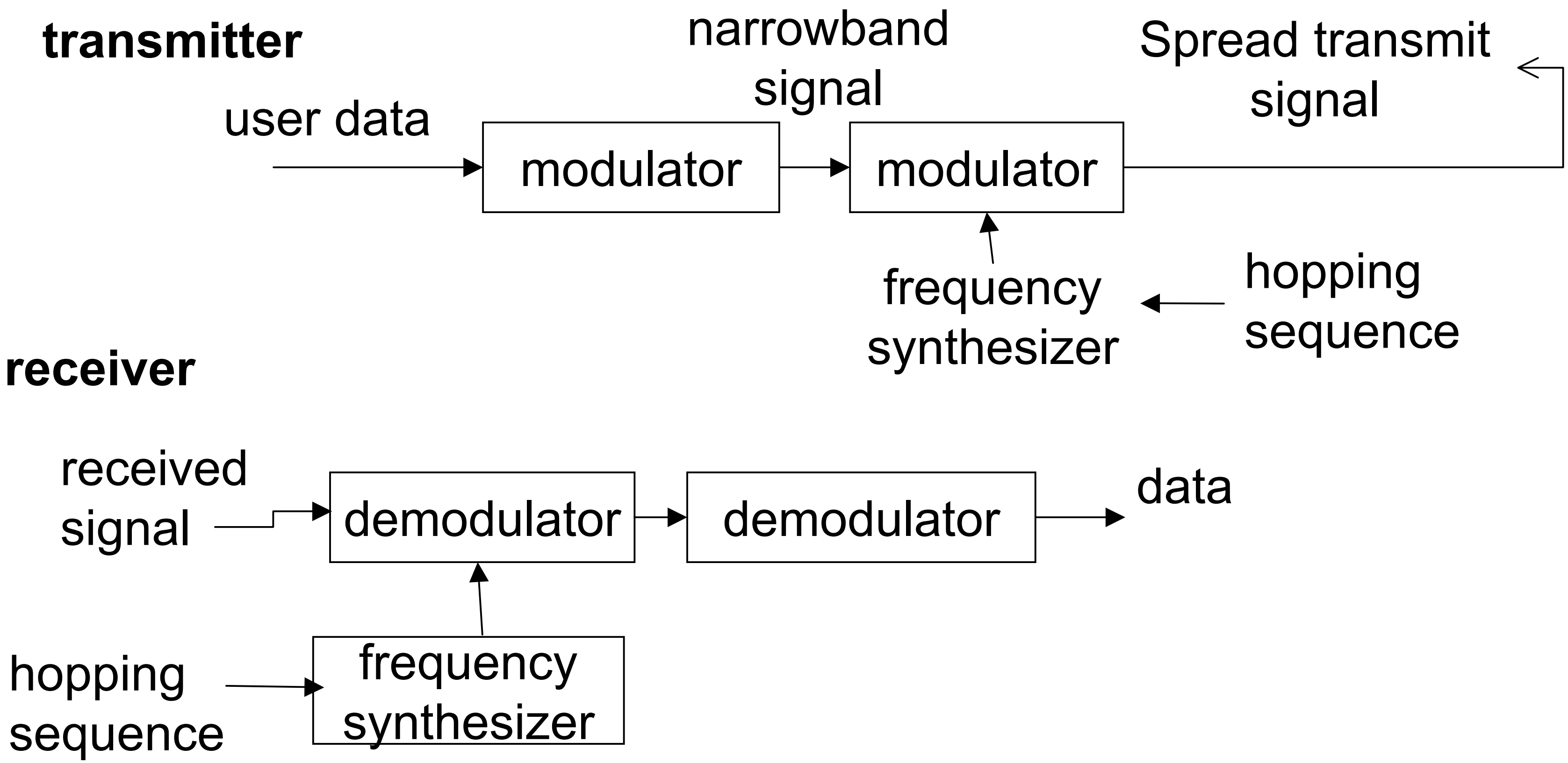
- Discrete changes of carrier frequency
  - sequence of frequency changes determined via PN sequence
- Two versions
  - **Fast Hopping**: several frequencies per user bit (FFH)
  - **Slow Hopping**: several user bits per frequency (SFH)
- Advantages
  - frequency selective fading and interference limited to short period
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DS/SS
  - simpler to detect

FHSS (Frequency Hopping Spread Spectrum) II



T_b: bit period T_d: dwell time

FHSS (Frequency Hopping Spread Spectrum) III



- If total signal power is interpreted as the area under the spectral density curve, then signals with equivalent total power may have either a large signal power concentrated in a small area or a small signal power spread over a large area
- Typically, the power of the SS signal is spread between 10-30 dB
  - Power of the radiated signal is spread over 10-1000 times the original power
- At the Tx, the baseband signal is usually ***spread*** by a code sequence
  - Spreading is achieved by encoding (modulating) the original signal with a pseudo-random code sequence or pseudo-noise (PN) code sequence, which is independent of the information bits
- Then, at the Rx, the signal is ***despread*** by the same amount through a cross-correlation using a locally generated version of the PN sequence
  - Cross-correlation with the correct sequence recovers the modulated information massage in the same narrowband as the original data
- The significance of SS is evident from Claude Shannon's capacity equation

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

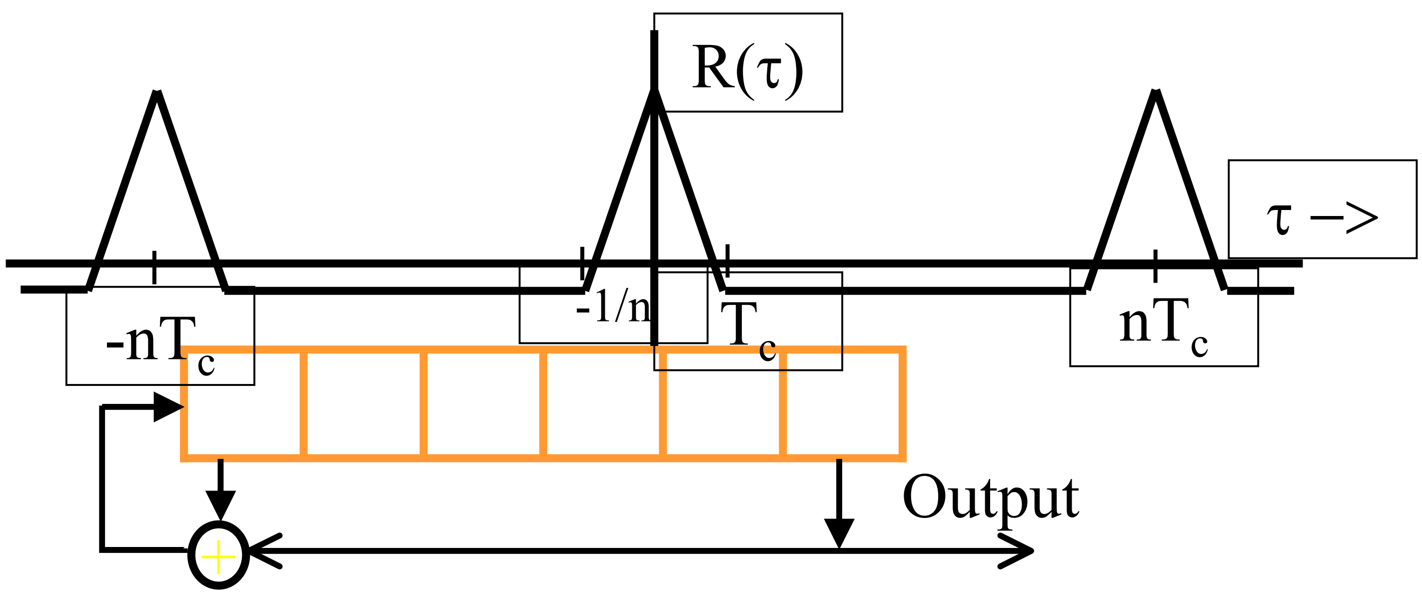
where, C = channel capacity in bits, B = bandwidth in hertz, S = signal power, and N = noise power
- From this equation, the effect of increasing the bandwidth becomes apparent

Performance of DS/SS Systems

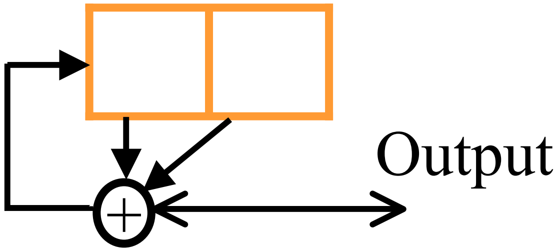
- Pseudonoise (PN) codes
  - Spread signal at the transmitter
  - Despread signal at the receiver
- Ideal PN sequences should be
  - Orthogonal (no interference)
  - Random (security)
  - Autocorrelation similar to white noise (high at τ=0 and low for τ not equal 0)

PN Sequence Generation

- Codes are periodic and generated by a shift register and XOR
- Maximum-length (ML) shift register sequences, *m*-stage shift register, length: $n = 2^m - 1$ bits



Generating PN Sequences



- Take m=2 =>L=3
- c_n=[1,1,0,1,1,0, . . .], usually written as bipolar c_n=[1,1,-1,1,1,-1, . . .]

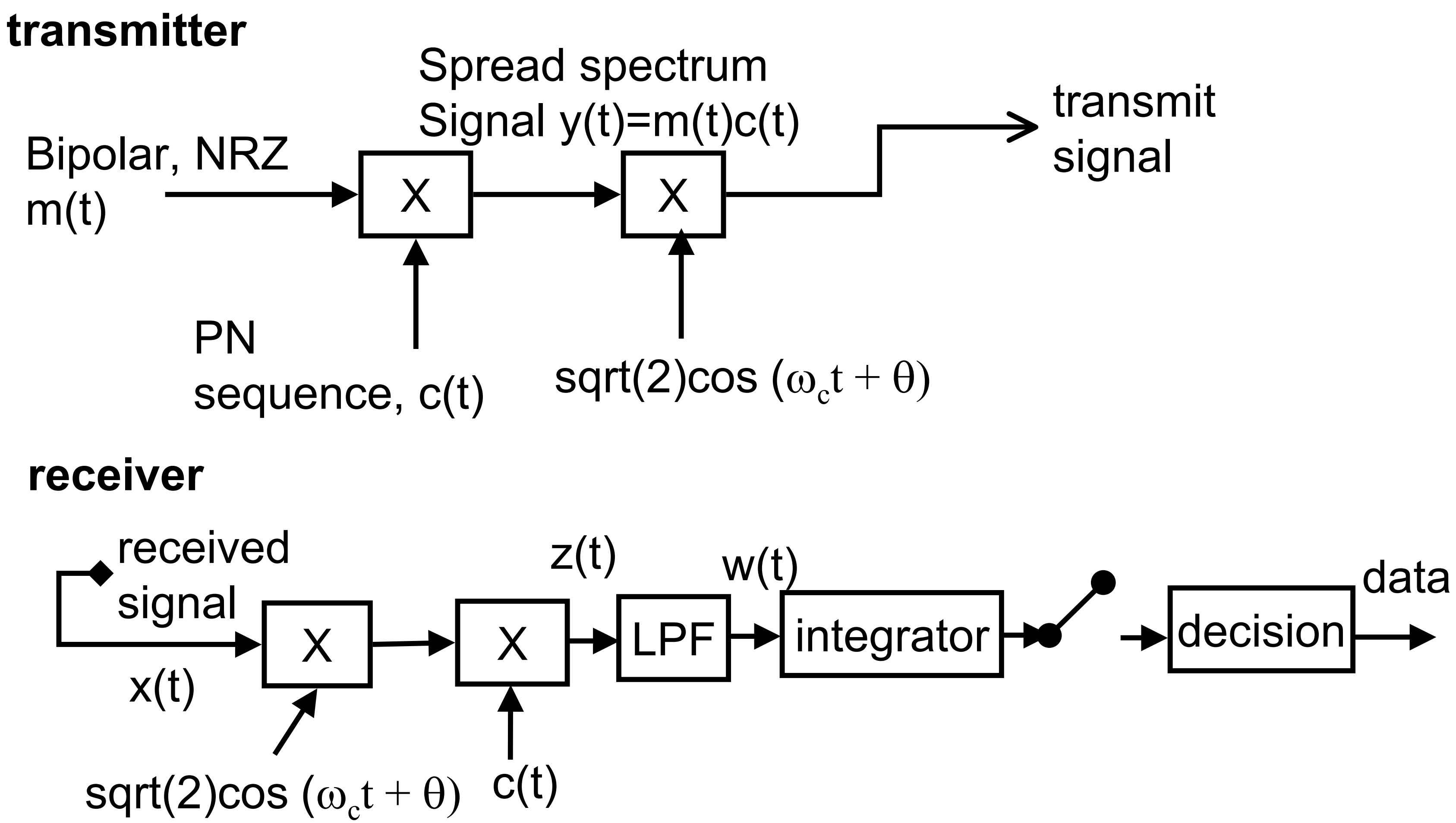
$$R_c(m) = \frac{1}{L}\sum_{n=1}^{L} c_n c_{n+m} = \begin{cases} 1 & m = 0 \\ -1/L & 1 \le m \le L-1 \end{cases}$$

m	Stages connected to modulo-2 adder
2	1,2
3	1,3
4	1,4
5	1,4
6	1,6
8	1,5,6,7

Problems with *m*-sequences

- Cross-correlations with other *m*-sequences generated by different input sequences can be quite high
- Easy to guess connection setup in 2*m* samples so not too secure
- In practice, Gold codes or Kasami sequences which combine the output of m-sequences are used.

Detecting DS/SS PSK Signals



Optimum Detection of DS/SS PSK

- Recall, bipolar signaling (PSK) and white noise give the optimum error probability

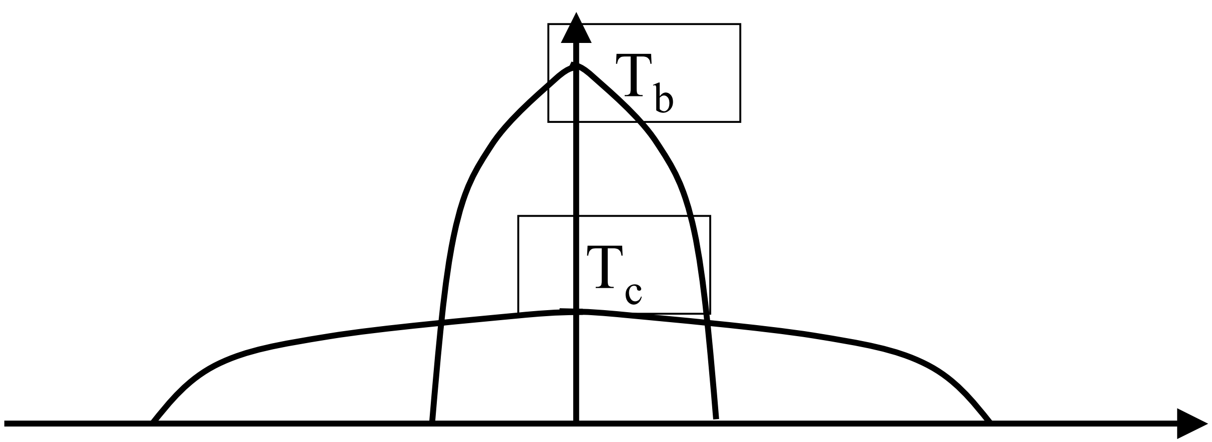
- Not effected by spread
  - Wideband noise no … g
  - Narrowband noise

$$P_b = Q\left(\sqrt{\frac{2E_b}{\aleph}}\right)$$

Signal Spectra

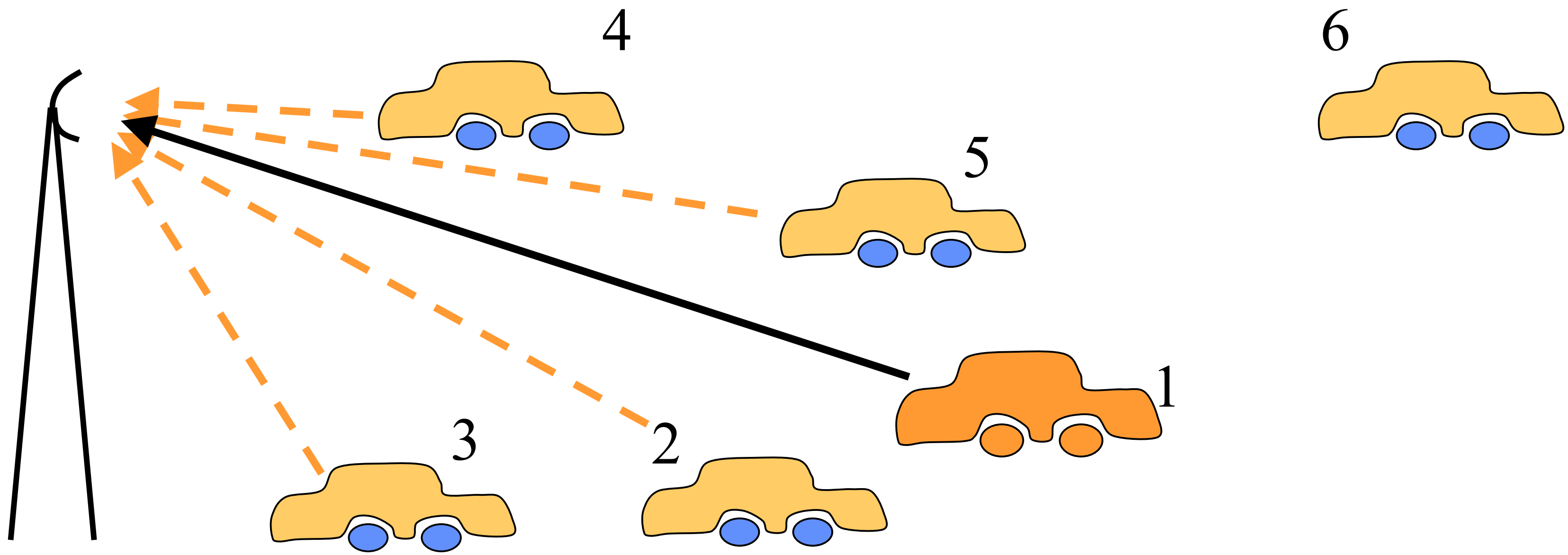
$$\text{Processing Gain } N = \frac{B_{ss}}{B} = 10\log_{10}\left(\frac{B_{ss}}{B}\right) = \frac{T_b}{T_c}$$

- Effective noise power is channel noise power plus jamming (NB) signal power divided by *N*



Multiple Access Performance

- Assume *K* users in the same frequency band,
- Interested in user 1, other users interfere



Signal Model

- Interested in signal 1, but we also get signals from other *K-1* users:

- At receiver,

$$\begin{aligned} x_k(t) &= \sqrt{2}\, m_k(t-\tau_k)\, c_k(t-\tau_k)\cos\left(\omega_c(t-\tau_k)+\theta_k\right) \\ &= \sqrt{2}\, m_k(t-\tau_k)\, c_k(t-\tau_k)\cos\left(\omega_c t+\phi_k\right) \qquad \phi_k = \theta_k - \omega_c\tau_k \end{aligned}$$

$$x(t) = x_1(t) + \sum_{k=2}^{K} x_k(t)$$

Interfering Signal

- After mixing and despreading (assume τ_1=0)

$$z_k(t) = 2\, m_k(t-\tau_k)\, c_k(t-\tau_k) c_1(t) \cos(\omega_c t + \phi_k) \cos(\omega_c t + \theta_1)$$

- After the integrator sampler

$$w_k(t) = m_k(t-\tau_k)\, c_k(t-\tau_k) c_1(t) \cos(\phi_k - \theta_1)$$

$$I_k = \cos(\phi_k - \theta_1) \int_0^{T_b} m_k(t-\tau_k)\, c_k(t-\tau_k) c_1(t)\, dt$$

At Receiver

- $m(t) = +/-1$ (PSK), bit duration T_b
- Interfering signal may change amplitude at τ_k

$$I_k = \cos\left(\phi_k - \theta_1\right)\left[b_{-1}\int_0^{\tau_k} c_k\left(t-\tau_k\right)c_1\left(t\right)dt + b_0\int_{\tau_k}^{T_b} c_k\left(t-\tau_k\right)c_1\left(t\right)dt \right]$$

$$I_1 = \int_0^{T_b} m_1\left(t\right)\, c_1\left(t\right)c_1\left(t\right)dt$$

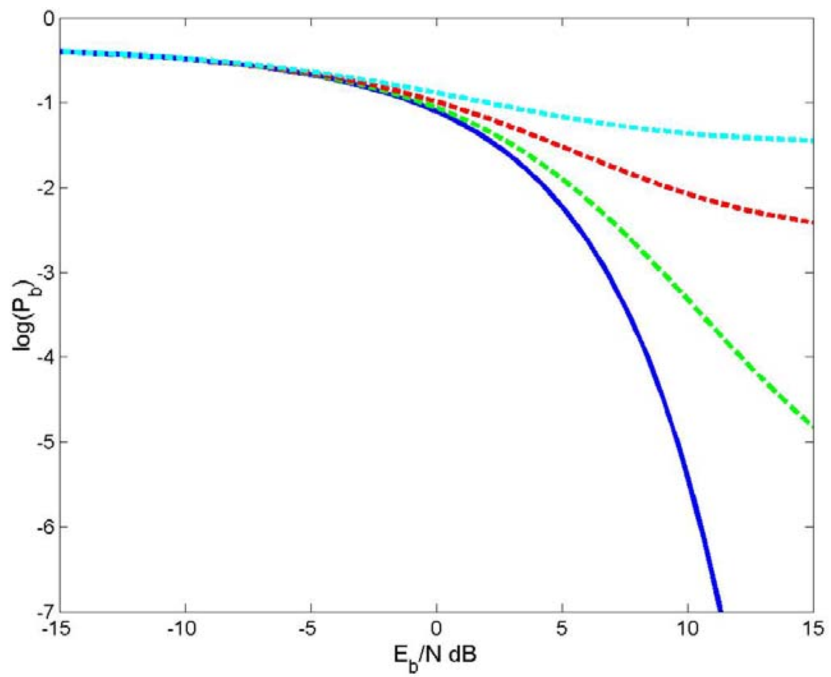
$$\int_0^{T_b} c_1\left(t\right)c_1\left(t\right)dt = A \quad \int_0^{T_b} c_k\left(t-\tau_k\right)c_1\left(t\right)dt = 0$$

Multiple Access Interference (MAI)

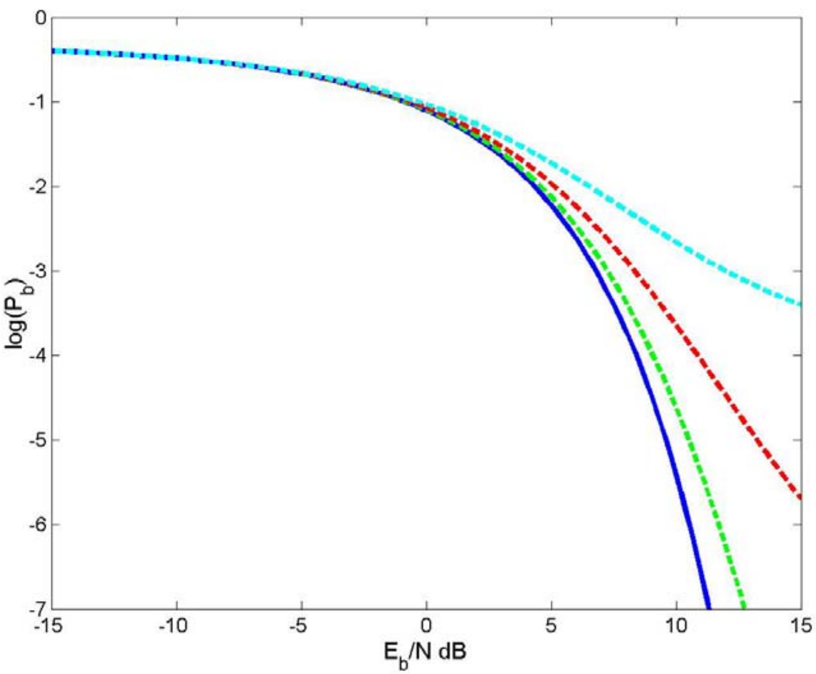
$$P_b = Q\left[\frac{1}{\sqrt{(K-1)/3N + \aleph/2E_b}}\right]$$

- If the users are assumed to be equal power interferers, can be analyzed using the central limit theorem (sum of IID RV's)

Example of Performance Degradation



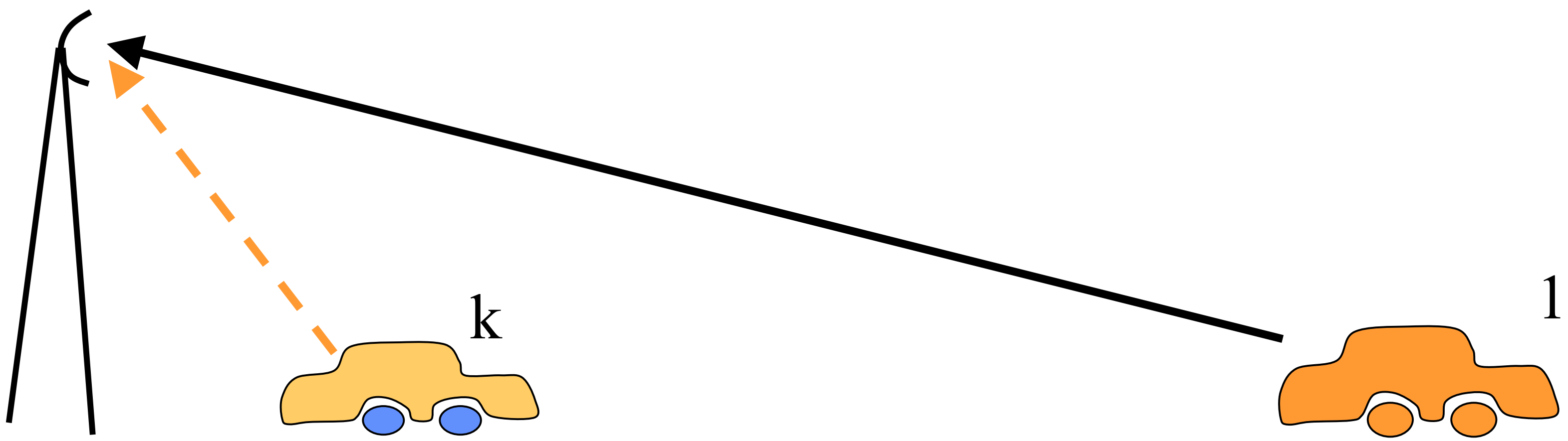
N=8



N=32

Near/Far Problem (I)

- Performance estimates derived using assumption that all users have same power level
- Reverse link (mobile to base) makes this unrealistic since mobiles are moving
- Adjust power levels constantly to keep equal

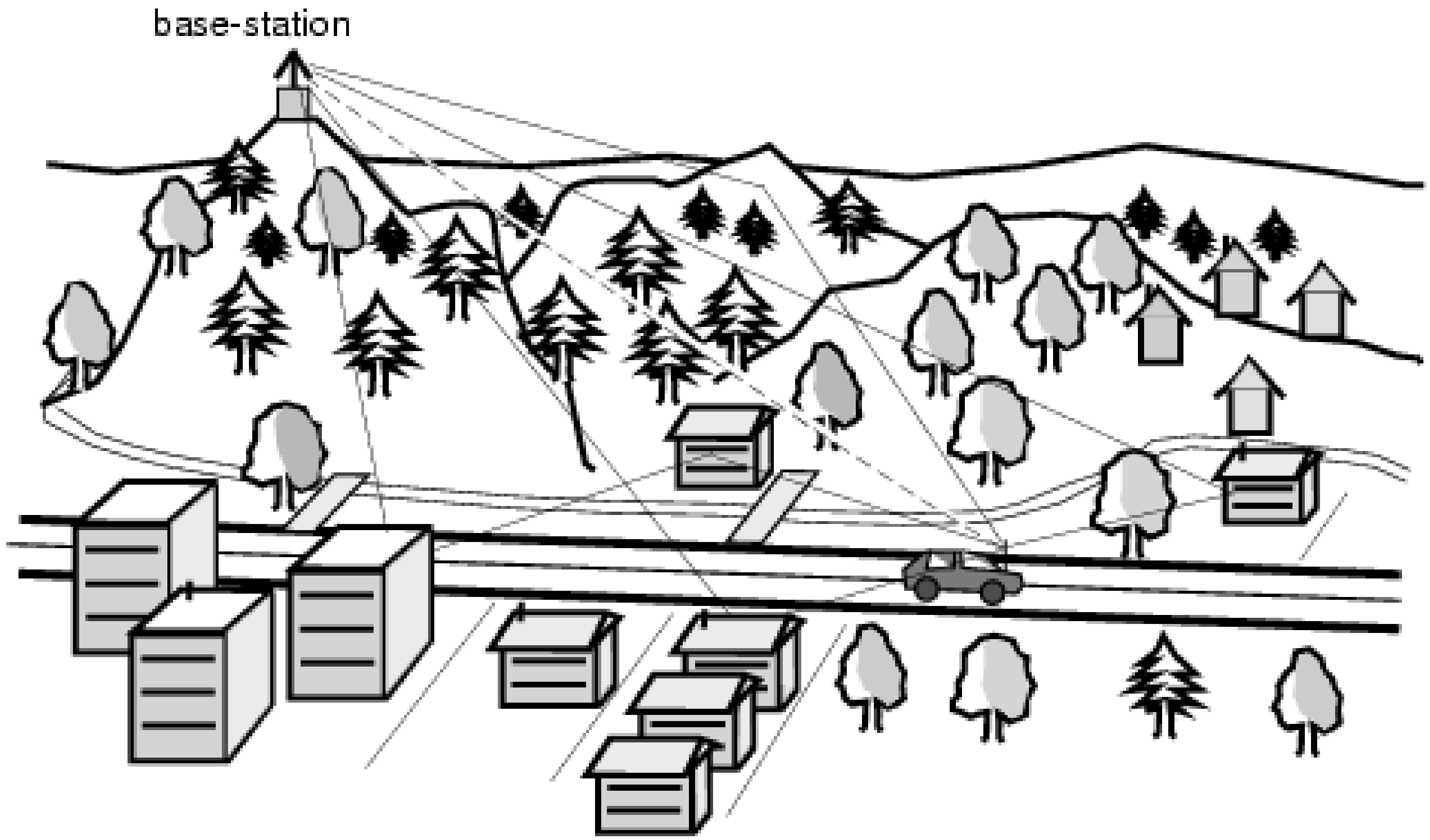


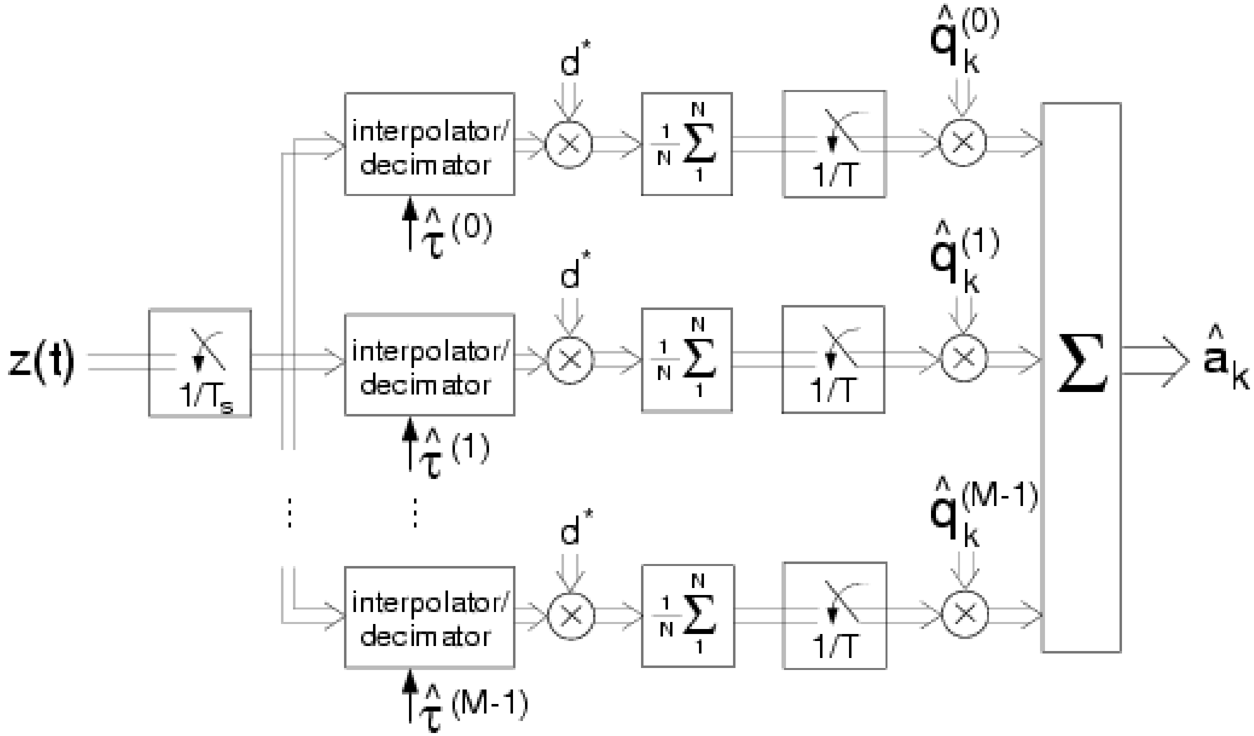
Near/Far Problem (II)

$$P_b^{(1)} = Q\left[\frac{1}{\sqrt{\sum_{k=2}^{K} E_b^{(k)} \Big/ 3E_b^{(1)} N + \aleph \Big/ 2E_b^{(1)}}}\right]$$

- K interferers, one strong interfering signal dominates performance
- Can result in capacity losses of 10-30%

Multipath Propagation





- Received signal sampled at the rate $1/T_s \geq 2/T_c$ for detection and synchronization
- Fed to all *M* RAKE fingers. Interpolation/decimation unit provides a data stream on chiprate $1/T_c$
- Correlation with the complex conjugate of the spreading sequence and weighted (maximum-ratio criterion)summation over one symbol

RAKE Receiver

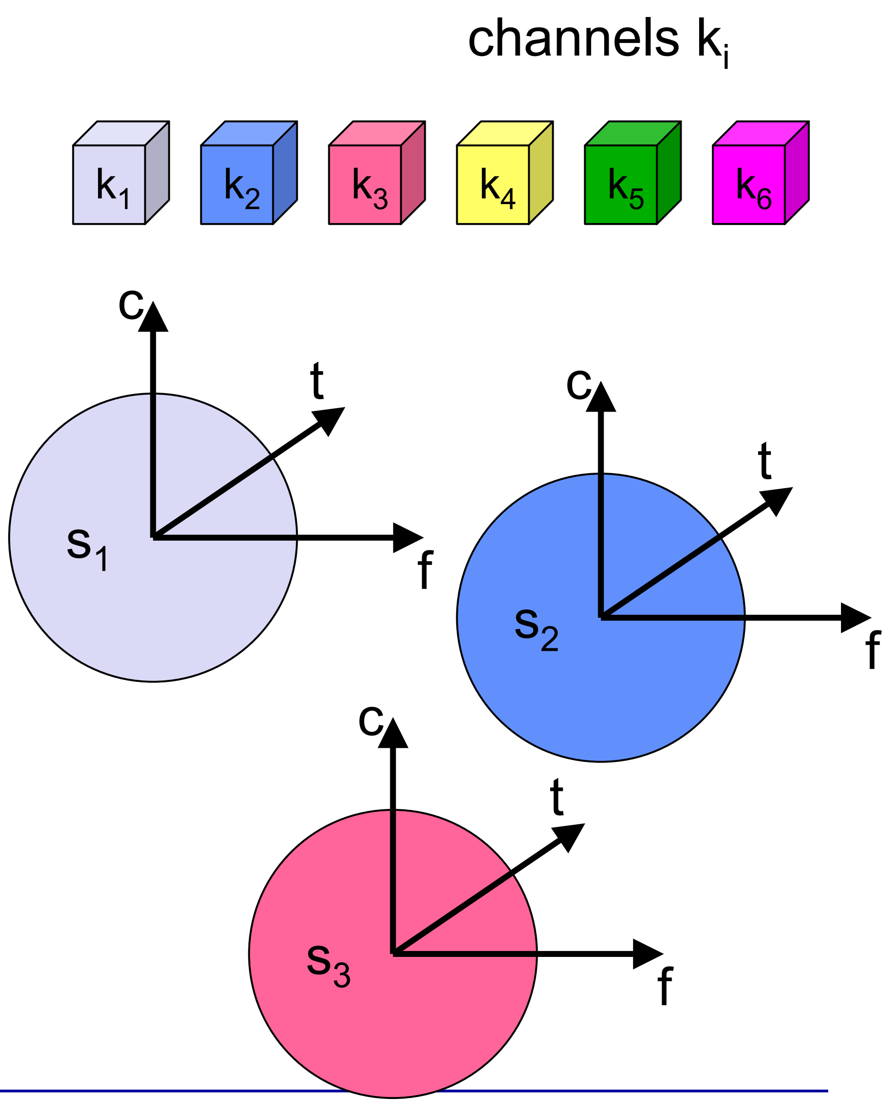
- RAKE Receiver has to estimate:
  - Multipath delays
  - Phase of multipath components
  - Amplitude of multipath components
  - Number of multipath components
- Main challenge is receiver synchronization in fading channels

Case Study: Spread Spectrum and CDMA in IS-95 Cellular Systems

Adapted from Slides from Scott Baxter and others.

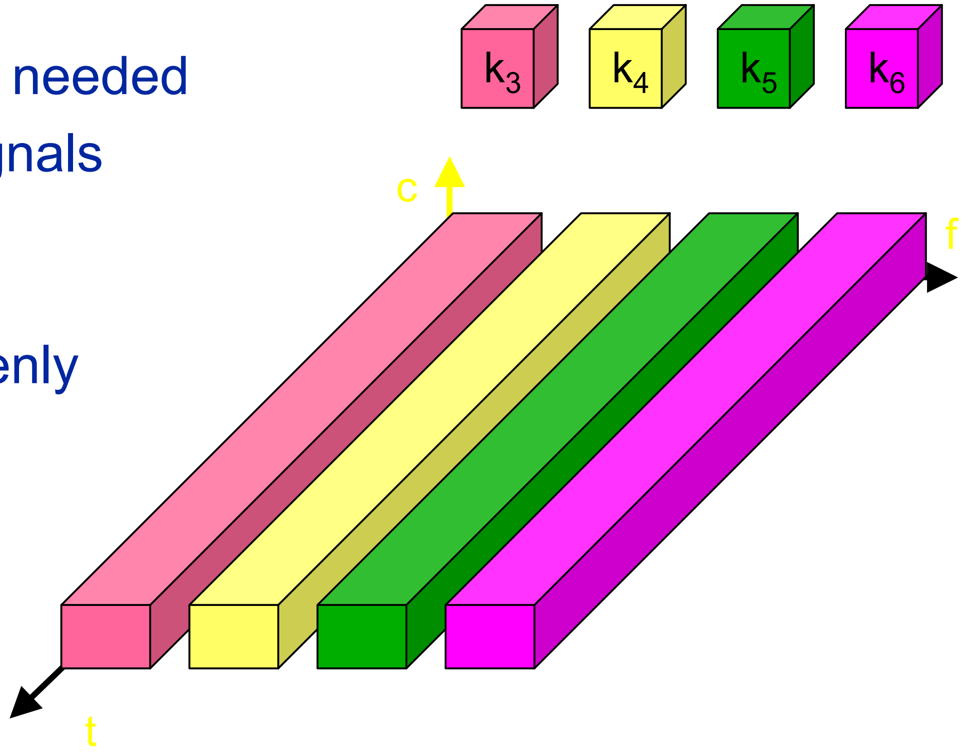
Multiplexing

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)
- Goal: multiple use
  of a shared medium
- Important: guard spaces needed!



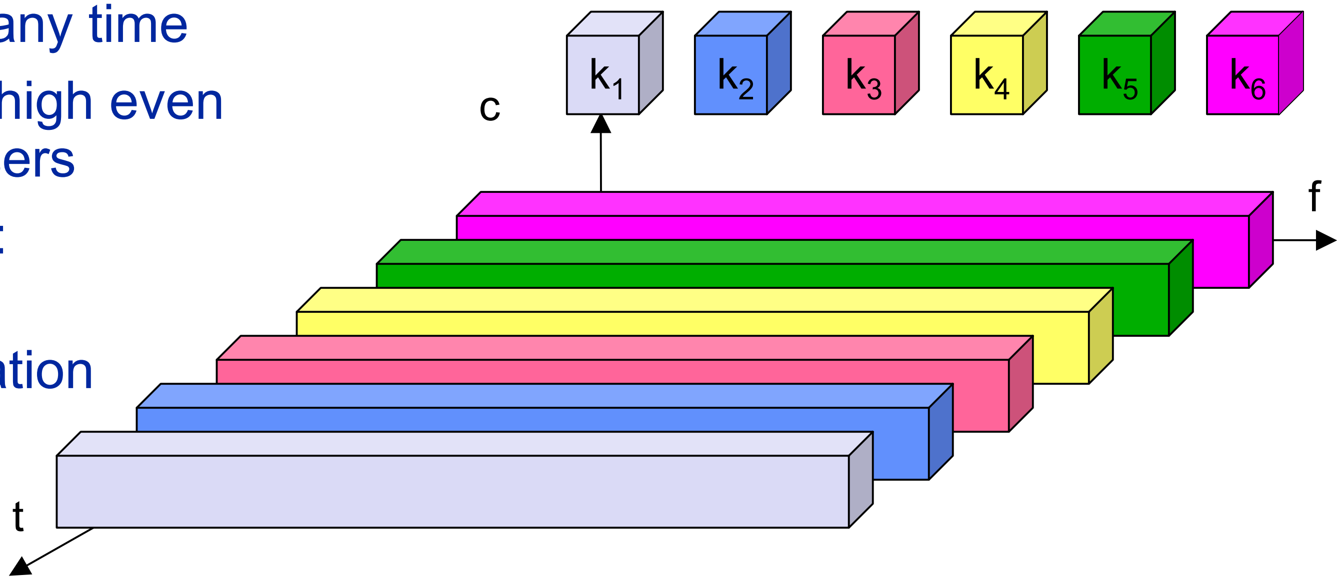
Frequency multiplex

- Separation of spectrum into smaller frequency bands
- Channel gets band of the spectrum for the whole time
- Advantages:
  - no dynamic coordination needed
  - works also for analog signals
- Disadvantages:
  - waste of bandwidth
    if traffic distributed unevenly
  - inflexible
  - guard spaces



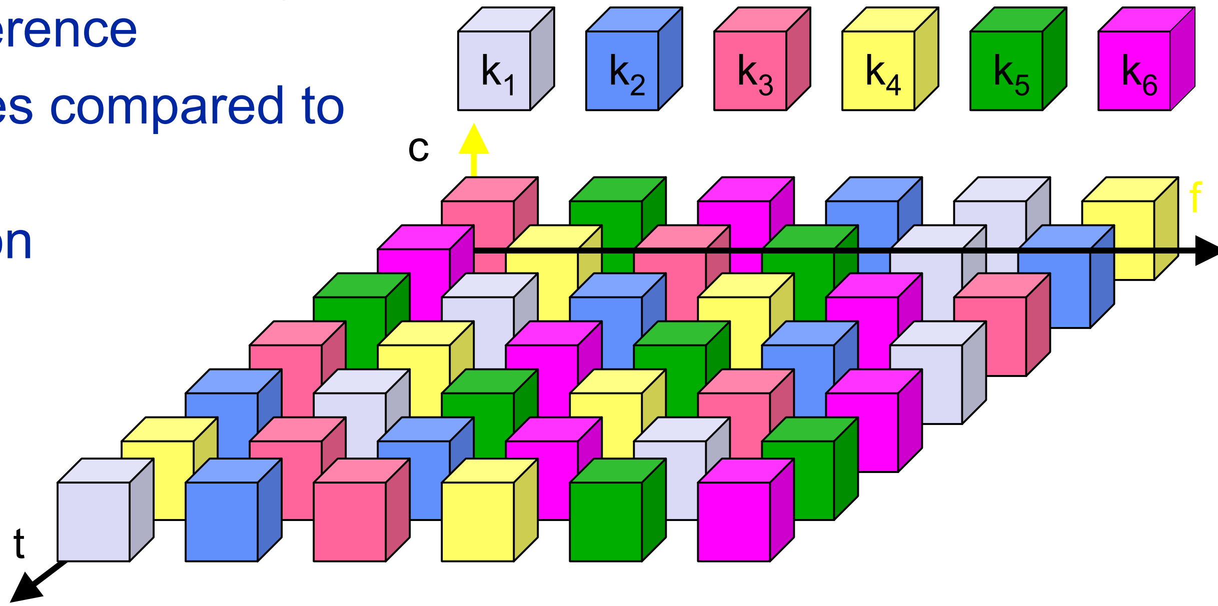
Time multiplex

- Channel gets the whole spectrum for a certain amount of time
- Advantages:
  - only one carrier in the medium at any time
  - throughput high even for many users
- Disadvantages:
  - precise synchronization necessary

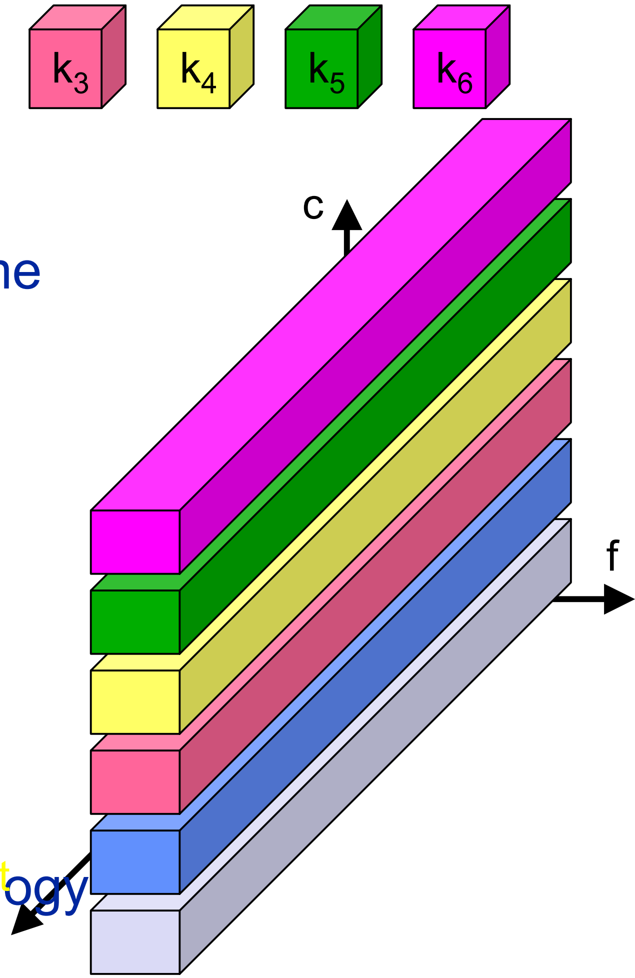


Time and frequency multiplex

- A channel gets a certain frequency band for a certain amount of time (e.g. GSM)
- Advantages:
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code multiplex
- Precise coordination required



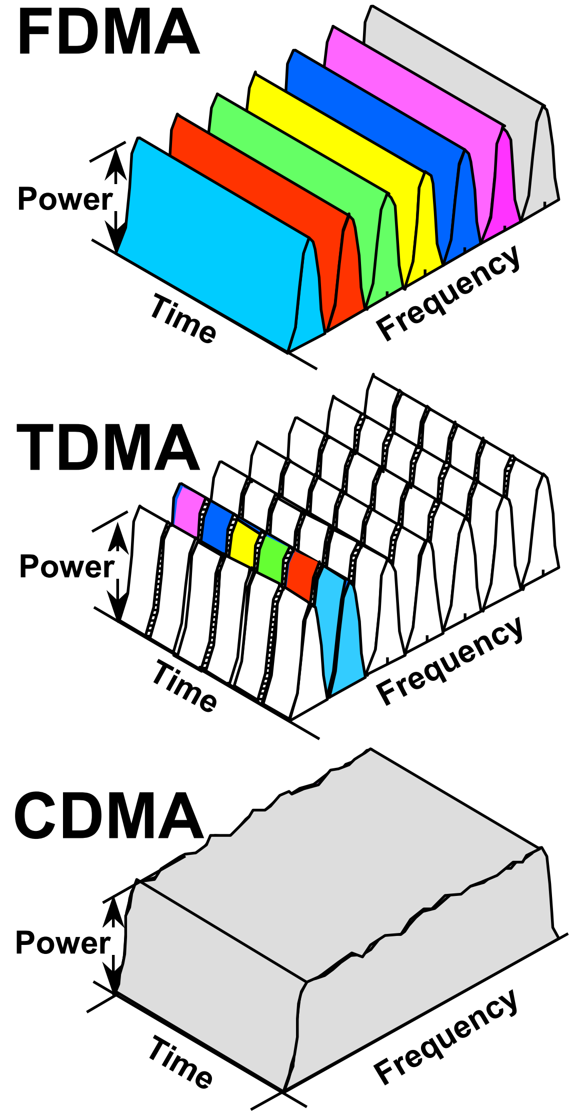
Code multiplex



- Each channel has unique code
- All channels use same spectrum at same time
- Advantages:
  - bandwidth efficient
  - no coordination and synchronization
  - good protection against interference
- Disadvantages:
  - lower user data rates
  - more complex signal regeneration
- Implemented using spread spectrum technology

Multiple Access Technologies/Summary

- FDMA (example: AMPS)
  - Frequency Division Multiple Access
  - each user has a private frequency
- TDMA (examples: IS-54/136, GSM)
  - Time Division Multiple Access
  - each user has a private time on a private frequency
- CDMA (IS-95, J-Std. 008)
  - Code Division Multiple Access
  - users co-mingle in time and frequency but each user has a private code



CDMA: Using A New Dimension

- All CDMA users occupy the same frequency at the same time! Frequency and time are not used as discriminators
- CDMA operates by using CODING to discriminate between users
- CDMA interference comes mainly from nearby users
- Each user is a small voice in a roaring crowd -- but with a uniquely recoverable code

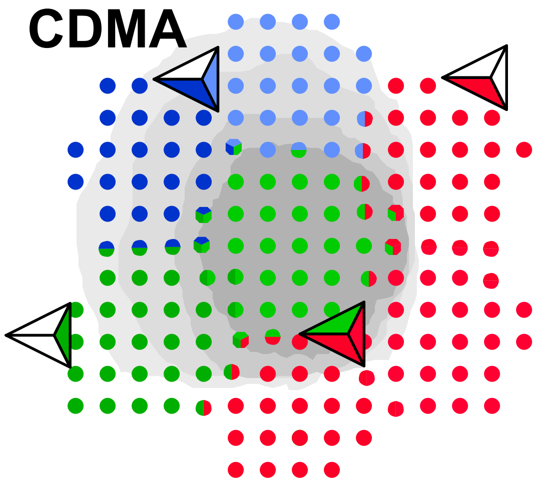


Figure of Merit: C/I
(carrier/interference ratio)
AMPS: +17 dB
TDMA: +14 to +17 dB
GSM: +7 to 9 dB.
CDMA: -10 to -17 dB.
CDMA: E_b/N_o ~+6 dB.

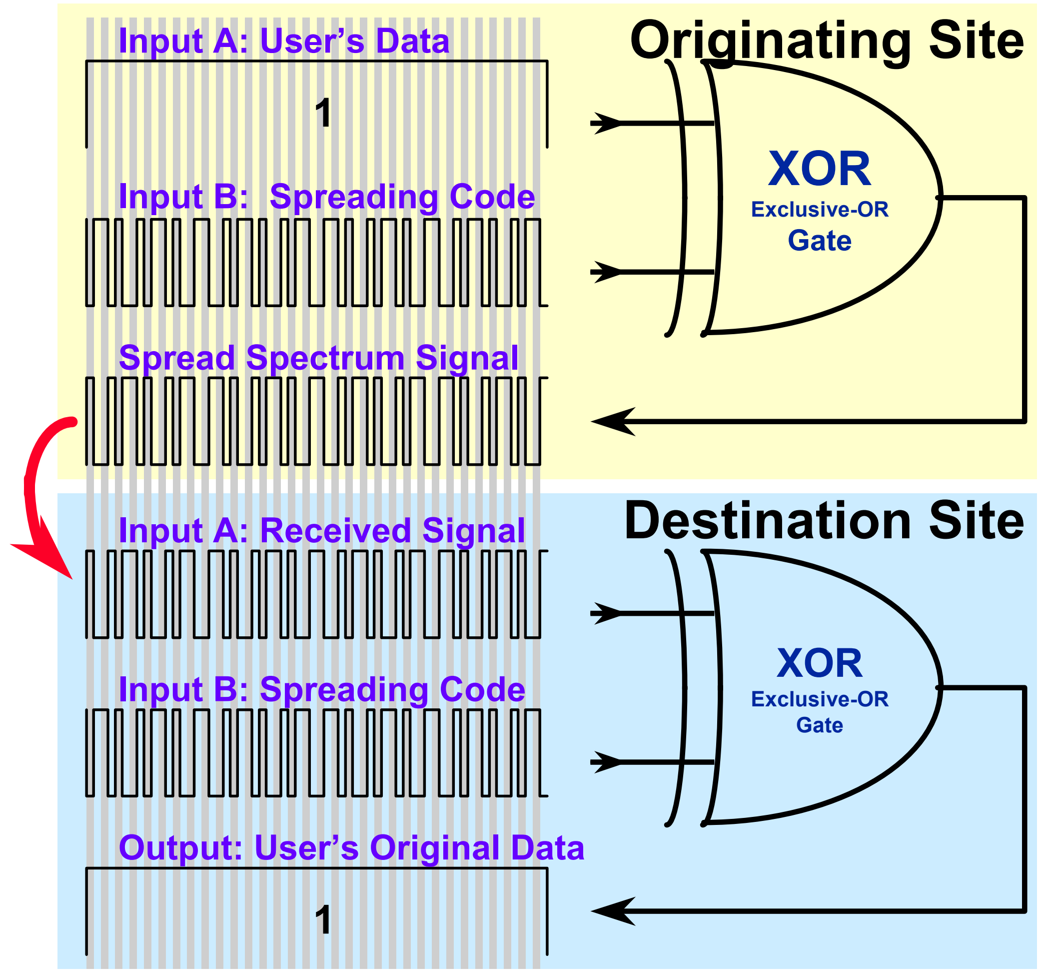
DSSS Spreading: Time-Domain View

At Originating Site:

- Input A: User's Data @ 19,200 bits/second
- Input B: Walsh Code #23 @ 1.2288 Mcps
- Output: Spread spectrum signal

via air interface

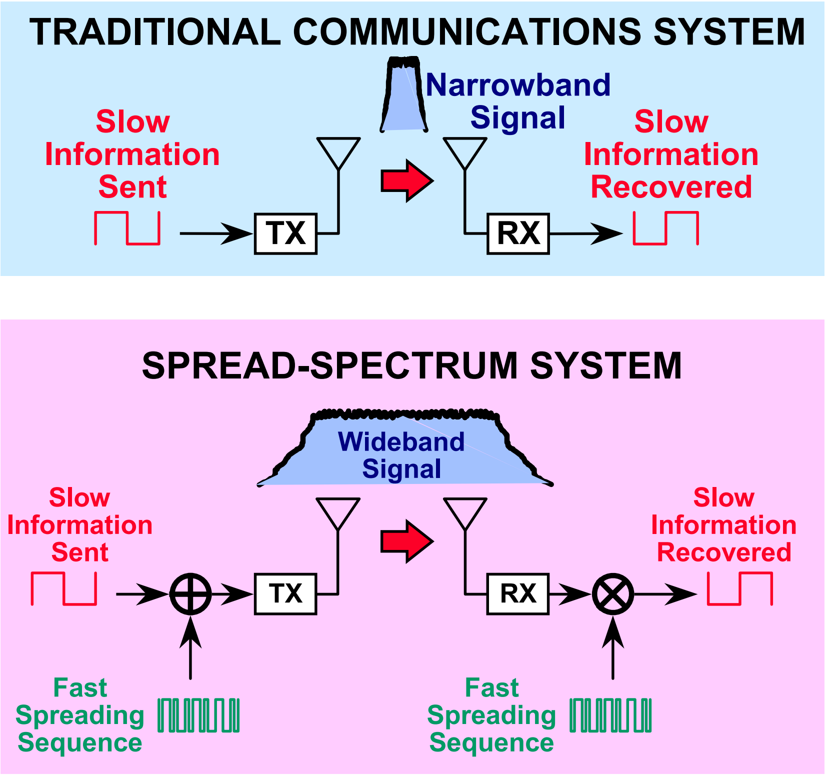
- **At Destination Site:**
- Input A: Received spread spectrum signal
- Input B: Walsh Code #23 @ 1.2288 Mcps
- Output: User's Data @ 19,200 bits/second just as originally sent



Drawn to actual scale and time alignment

Spreading from a Frequency-Domain View

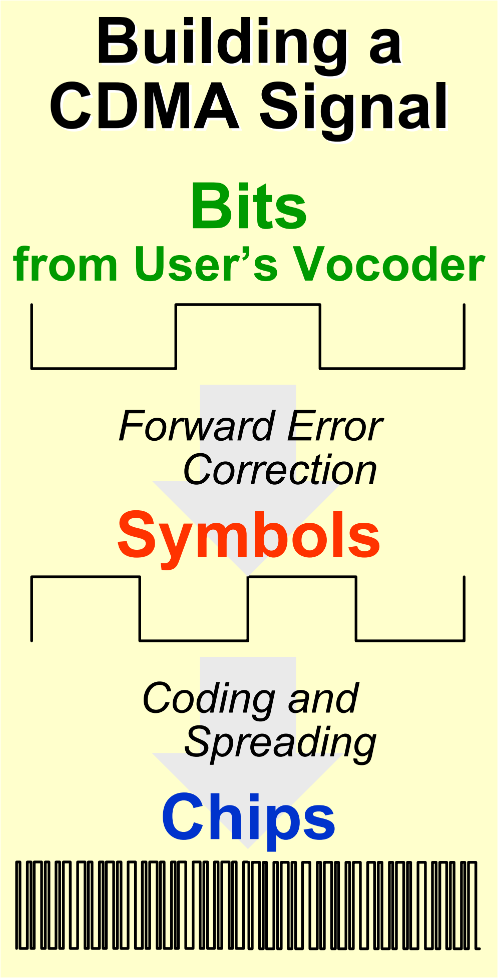
- Traditional technologies try to squeeze signal into minimum required bandwidth
- CDMA uses larger bandwidth but uses resulting processing gain to increase capacity



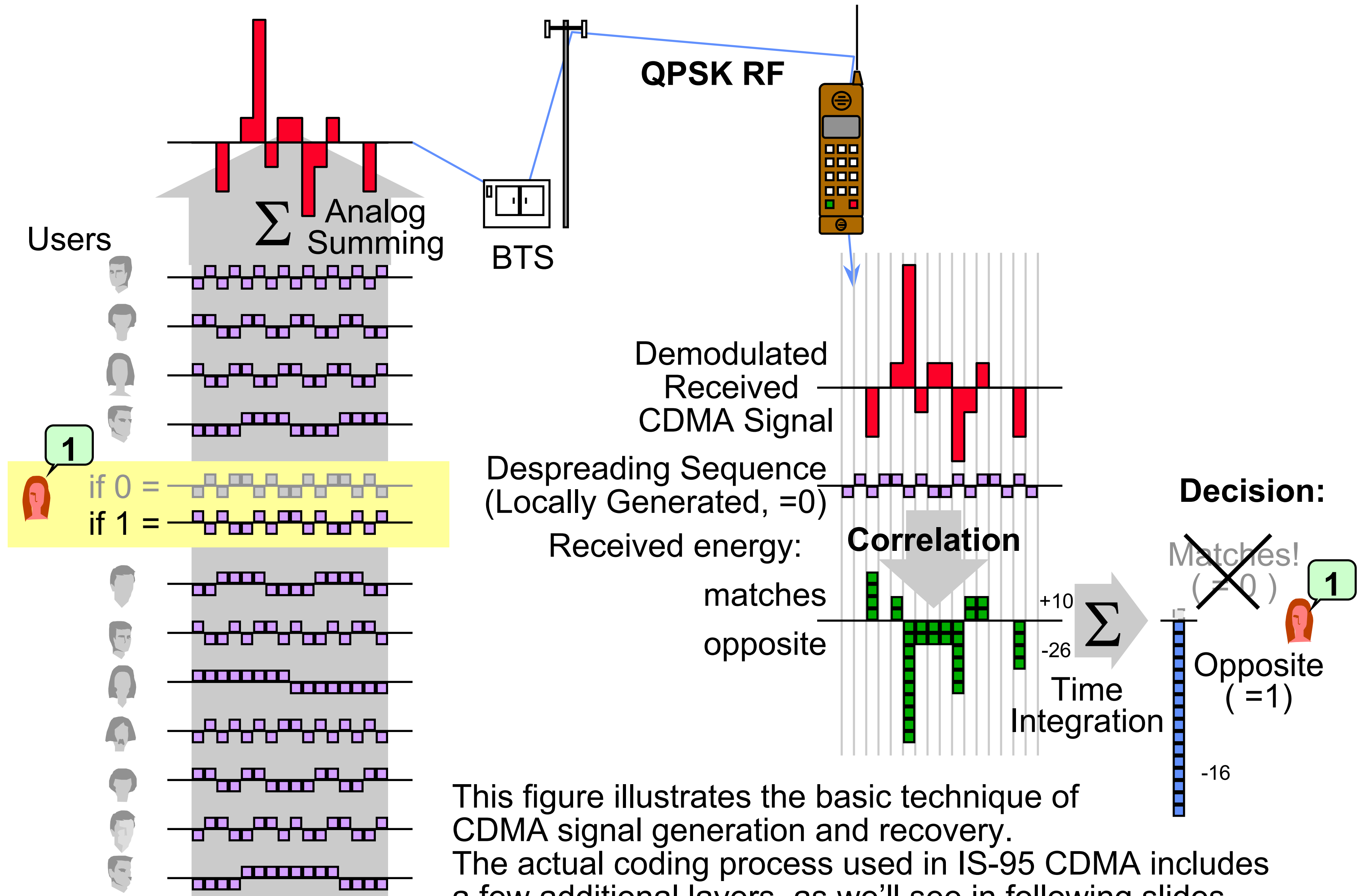
Spread Spectrum Payoff:
Processing Gain

CDMA Uses Code Channels

- A CDMA signal uses many chips to convey just one bit of information
- Each user has a unique chip pattern, in effect a code channel
- To recover a bit, integrate a large number of chips interpreted by the user's known code pattern
- Other users' code patterns appear random and integrate in a random self-canceling fashion, don't disturb the bit decoding decision being made with the proper code pattern

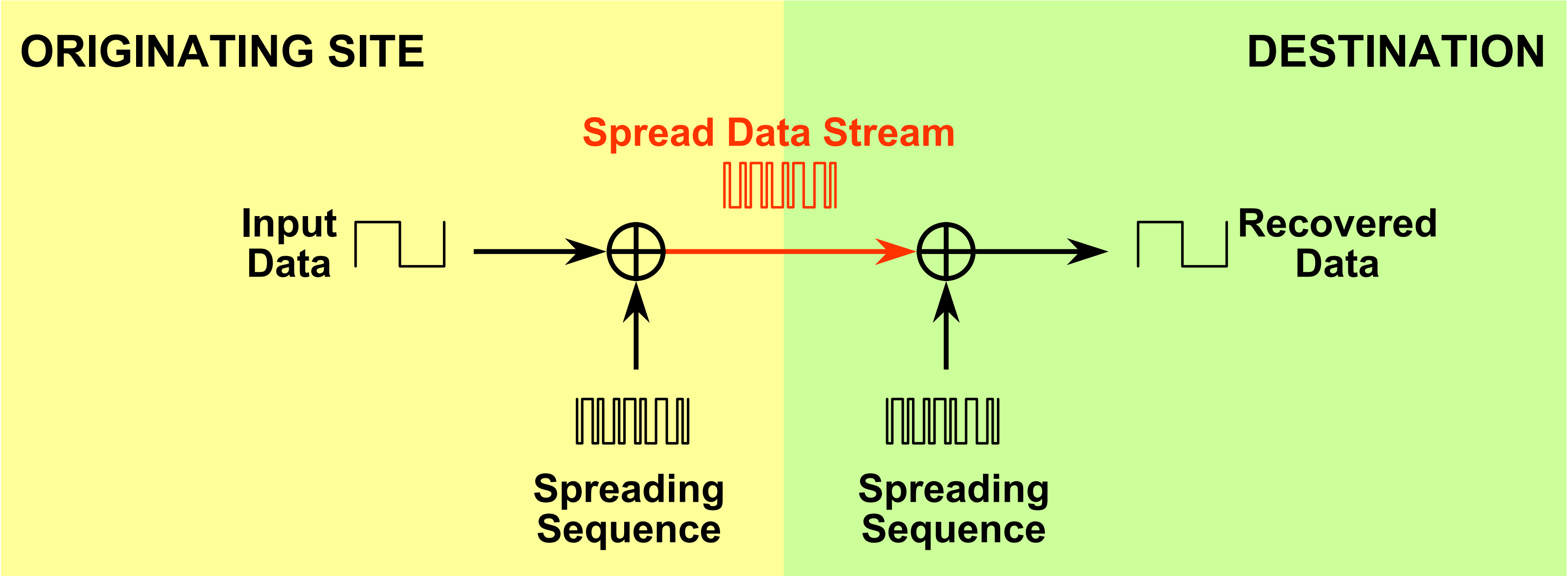


CDMA: The Code “Magic” “behind the Veil”



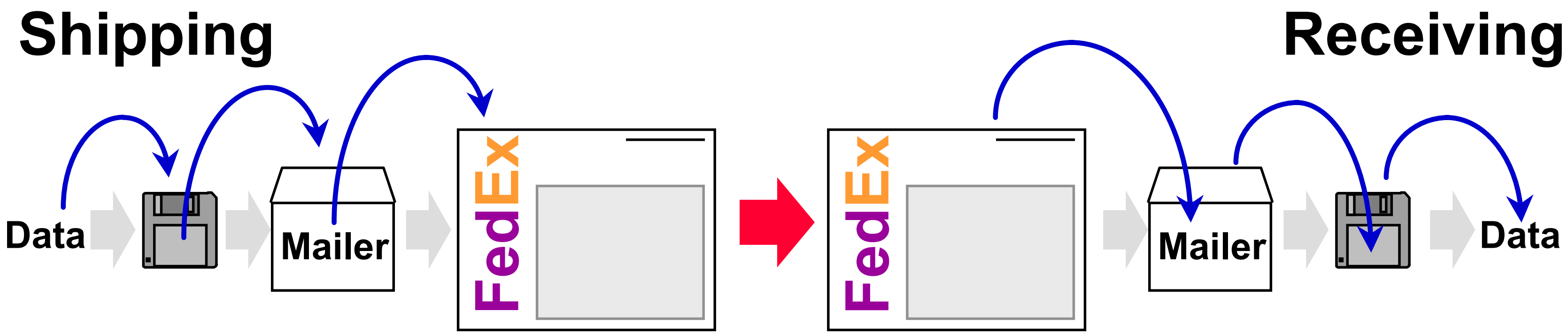
This figure illustrates the basic technique of CDMA signal generation and recovery.
The actual coding process used in IS-95 CDMA includes a few additional layers, as we’ll see in following slides.

Spreading: What we do, we can undo



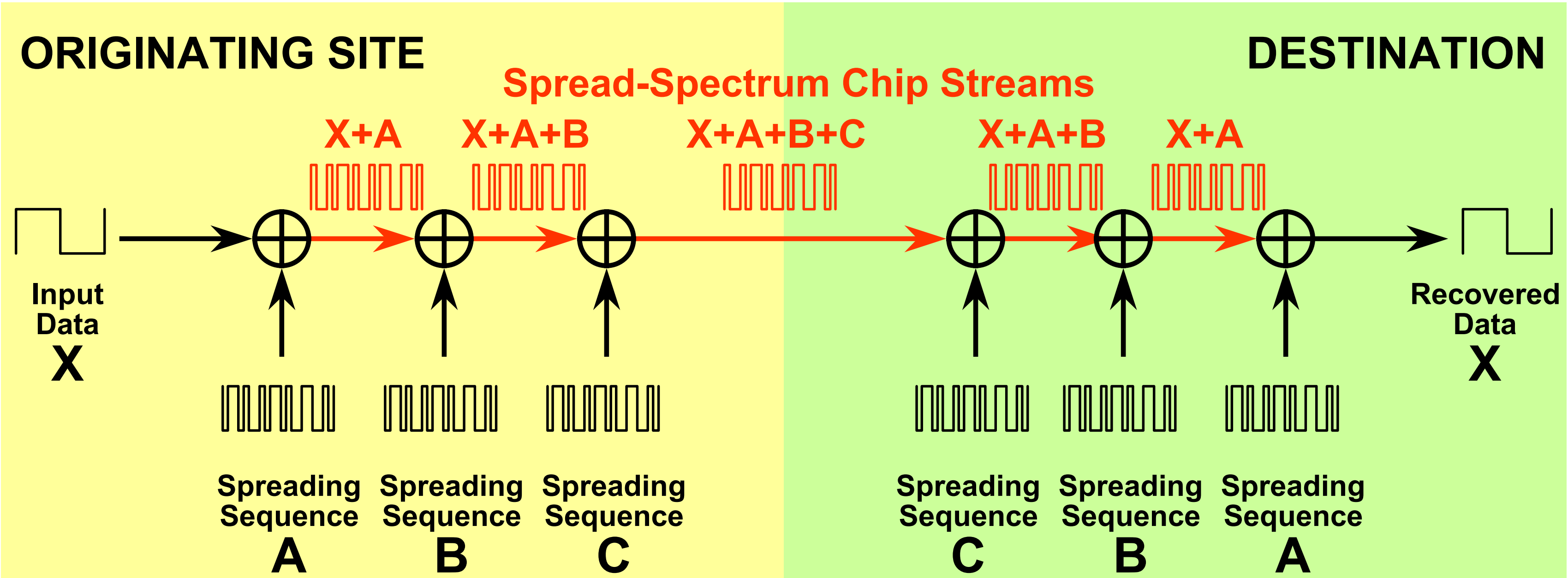
- Sender combines data with a fast spreading sequence, transmits spread data stream
- Receiver intercepts the stream, uses same spreading sequence to extract original data

"Shipping and Receiving" via CDMA



- Whether in shipping and receiving, or in CDMA, packaging is extremely important!
- Cargo is placed inside "nested" containers for protection and to allow addressing
- The shipper packs in a certain order, and the receiver unpacks in the reverse order
- CDMA "containers" are spreading codes

CDMA's Nested Spreading Sequences



- CDMA combines three different spreading sequences to create unique, robust channels
- The sequences are easy to generate on both sending and receiving ends of each link
- "What we do, we can undo"

One of the CDMA Spreading Sequences: Walsh Codes

- 64 “Magic” Sequences, each 64 chips long
- Each Walsh Code is precisely Orthogonal with respect to all other Walsh Codes
  - it’s simple to generate the codes, or
  - they’re small enough to use from ROM

Unique Properties:
Mutual Orthogonality

EXAMPLE:

Correlation of Walsh Code #23 with Walsh Code #59

```
#23  0110100101101001100101101001011001101001011010011001011010010110
#59  0110011010011001100110010110011010011001011001100110011010011001
Sum  0000111111110000000011111111000011110000000011111111000000001111
```

Correlation Results: 32 1’s, 32 0’s: Orthogonal!!

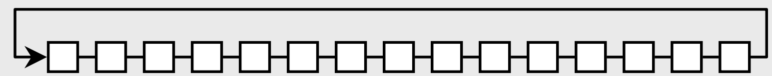
WALSH CODES

#	---------- 64-Chip Sequence ----------
0	0000000000000000000000000000000000000000000000000000000000000000
1	0101010101010101010101010101010101010101010101010101010101010101
2	0011001100110011001100110011001100110011001100110011001100110011
3	0110011001100110011001100110011001100110011001100110011001100110
4	0000111100001111000011110000111100001111000011110000111100001111
5	0101101001011010010110100101101001011010010110100101101001011010
6	0011110000111100001111000011110000111100001111000011110000111100
7	0110100101101001011010010110100101101001011010010110100101101001
8	0000000011111111000000001111111100000000111111110000000011111111
9	0101010110101010010101011010101001010101101010100101010110101010
10	0011001111001100001100111100110000110011110011000011001111001100
11	0110011010011001011001101001100101100110100110010110011010011001
12	0000111111110000000011111111000000001111111100000000111111110000
13	0101101010100101010110101010010101011010101001010101101010100101
14	0011110011000011001111001100001100111100110000110011110011000011
15	0110100110010110011010011001011001101001100101100110100110010110
16	0000000000000000111111111111111100000000000000001111111111111111
17	0101010101010101101010101010101001010101010101011010101010101010
18	0011001100110011110011001100110000110011001100111100110011001100
19	0110011001100110100110011001100101100110011001101001100110011001
20	0000111100001111111100001111000000001111000011111111000011110000
21	0101101001011010101001011010010101011010010110101010010110100101
22	0011110000111100110000111100001100111100001111001100001111000011
23	0110100101101001100101101001011001101001011010011001011010010110
24	0000000011111111111111110000000000000000111111111111111100000000
25	0101010110101010101010100101010101010101101010101010101001010101
26	0011001111001100110011000011001100110011110011001100110000110011
27	0110011010011001100110010110011001100110100110011001100101100110
28	0000111111110000111100000000111100001111111100001111000000001111
29	0101101010100101101001010101101001011010101001011010010101011010
30	0011110011000011110000110011110000111100110000111100001100111100
31	0110100110010110100101100110100101101001100101101001011001101001
32	0000000000000000000000000000000011111111111111111111111111111111
33	0101010101010101010101010101010110101010101010101010101010101010
34	0011001100110011001100110011001111001100110011001100110011001100
35	0110011001100110011001100110011010011001100110011001100110011001
36	0000111100001111000011110000111111110000111100001111000011110000
37	0101101001011010010110100101101010100101101001011010010110100101
38	0011110000111100001111000011110011000011110000111100001111000011
39	0110100101101001011010010110100110010110100101101001011010010110
40	0000000011111111000000001111111111111111000000001111111100000000
41	0101010110101010010101011010101010101010010101011010101001010101
42	0011001111001100001100111100110011001100001100111100110000110011
43	0110011010011001011001101001100110011001011001101001100101100110
44	0000111111110000000011111111000011110000000011111111000000001111
45	0101101010100101010110101010010110100101010110101010010101011010
46	0011110011000011001111001100001111000011001111001100001100111100
47	0110100110010110011010011001011010010110011010011001011001101001
48	0000000000000000111111111111111111111111111111110000000000000000
49	0101010101010101101010101010101010101010101010100101010101010101
50	0011001100110011110011001100110011001100110011000011001100110011
51	0110011001100110100110011001100110011001100110010110011001100110
52	0000111100001111111100001111000011110000111100000000111100001111
53	0101101001011010101001011010010110100101101001010101101001011010
54	0011110000111100110000111100001111000011110000110011110000111100
55	0110100101101001100101101001011010010110100101100110100101101001
56	0000000011111111111111110000000011111111000000000000000011111111
57	0101010110101010101010100101010110101010010101010101010110101010
58	0011001111001100110011000011001111001100001100110011001111001100
59	0110011010011001100110010110011010011001011001100110011010011001
60	0000111111110000111100000000111111110000000011110000111111110000
61	0101101010100101101001010101101010100101010110100101101010100101
62	0011110011000011110000110011110011000011001111000011110011000011
63	0110100110010110100101100110100110010110011010010110100110010110

Other Sequences: Generation & Properties

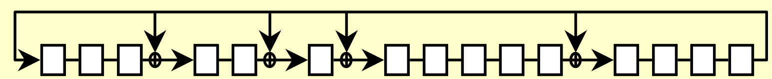
- Other CDMA sequences are generated in shift registers
- Plain shift register: no fun, sequence = length of register
- Tapped shift register generates a wild, self-mutating sequence 2^N-1 chips long (N=register length)
  - Such sequences match if compared in step (no-brainer, any sequence matches itself)
  - Such sequences appear approximately orthogonal if compared with themselves not exactly matched in time
  - false correlation typically <2%

An Ordinary Shift Register



Sequence repeats *every **N** chips,* where N is number of cells in register

A Tapped, Summing Shift Register

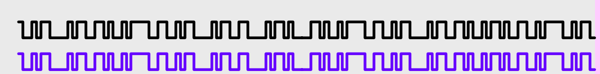


Sequence repeats *every **2^N-1** chips,* where N is number of cells in register

A Special Characteristic of Sequences Generated in Tapped Shift Registers

Compared In-Step: Matches Itself

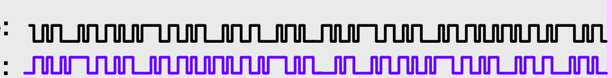
Sequence:
Self, in sync:



Sum: **Complete Correlation: All 0's**

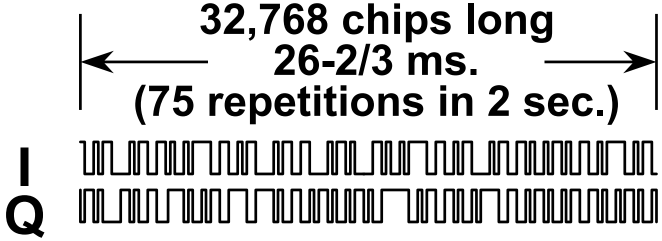
Compared Shifted: Little Correlation

Sequence:
Self, Shifted:



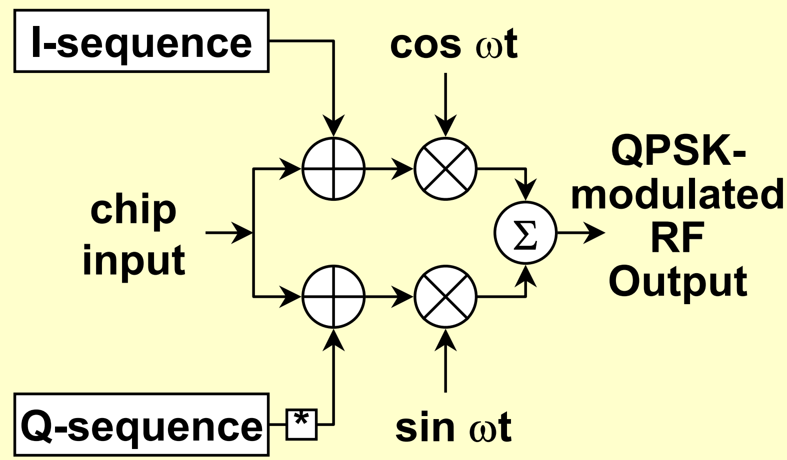
Sum: **Practically Orthogonal: Half 1's, Half 0's**

Another CDMA Spreading Sequence: The Short PN Code



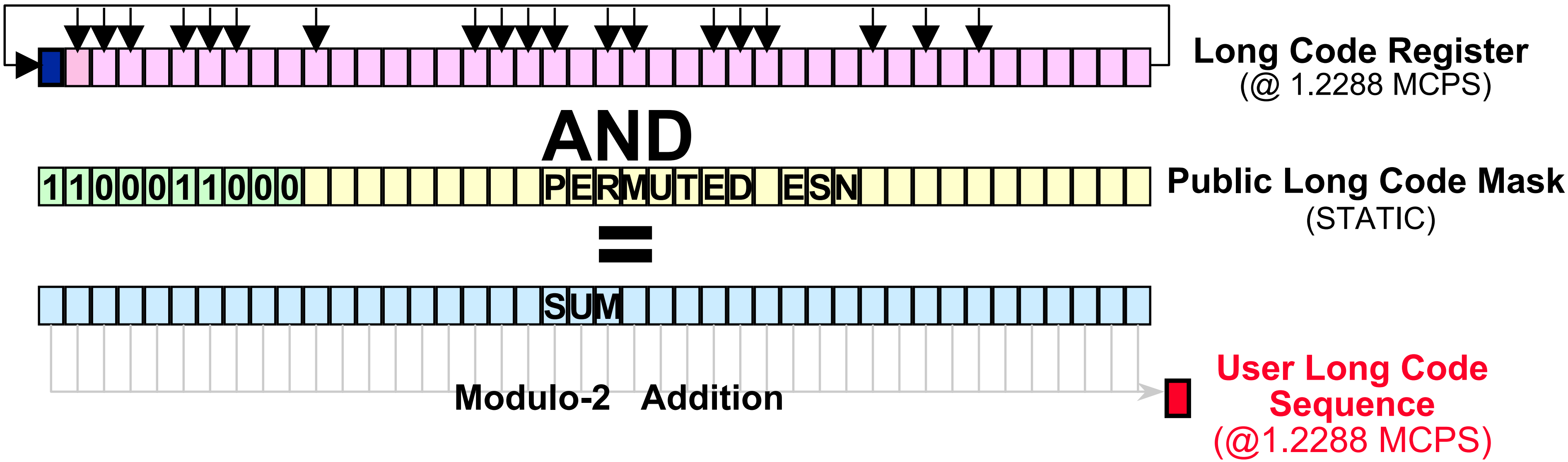
- The short PN code consists of two PN Sequences, I and Q, each 32,768 chips long
  - Generated in similar but differently-tapped 15-bit shift registers
  - They're always used together, modulating the two phase axes of a QPSK modulator

CDMA QPSK Phase Modulator Using I and Q PN Sequences



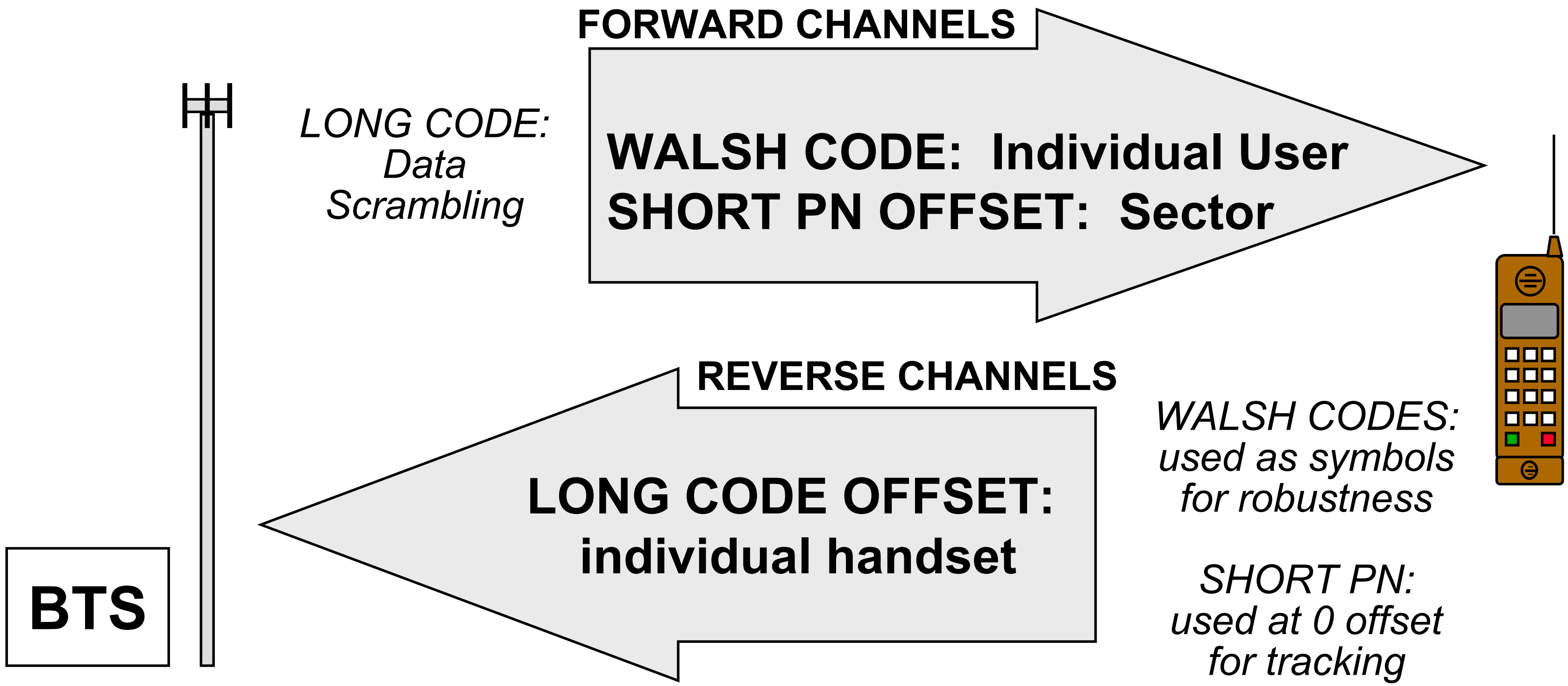
* In BTS, I and Q are used in-phase. In handset, Q is delayed 1/2 chip to avoid zero-amplitude crossings which would require a linear power amplifier

Third CDMA Spreading Sequence: Long Code
Generation & Masking to establish Offset



- Generated in a 42-bit register, the PN Long code is more than 40 days long (~4x10^{13} chips) -- too big to store in ROM in a handset, so it's generated chip-by-chip using the scheme shown above
- Each handset codes its signal with the PN Long Code, but at a unique offset computed using its ESN (32 bits) and 10 bits set by the system
  - this is called the "Public Long Code Mask"; produces unique shift
  - private long code masks are available for enhanced privacy
- Integrated over a period even as short as 64 chips, phones with different PN long code offsets will appear practically orthogonal

Putting it All Together: CDMA Channels



- The three spreading codes are used in different ways to create the forward and reverse links
- A forward channel exists by having a specific Walsh Code assigned to the user, and a specific PN offset for the sector
- A reverse channel exists because the mobile uses a specific offset of the Long PN sequence

Other Technologies: Recovering the Signal / Avoiding Interference

- In conventional radio technologies, the desired signal must be strong enough to override any interference
- AMPS, TDMA and GSM depend on physical distance separation to keep interference at low levels
- Co-channel users are kept at a safe distance by careful frequency planning
- Nearby users and cells must use different frequencies to avoid interference

AMPS-TDMA-GSM

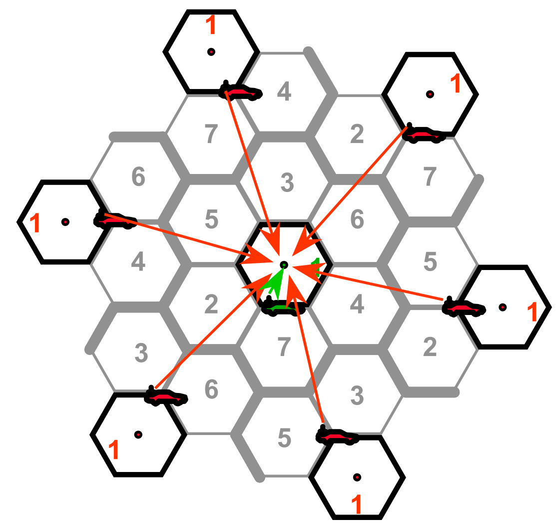
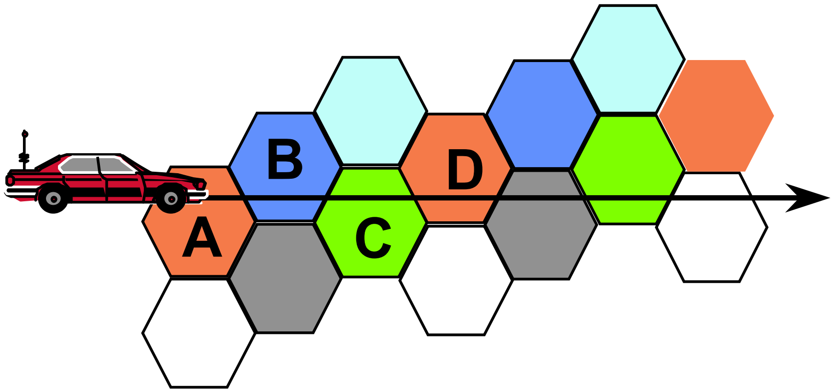


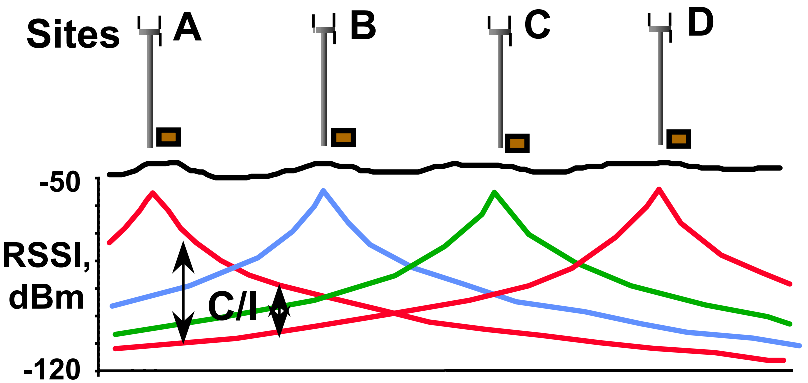
Figure of Merit: C/I
(carrier/interference ratio)
AMPS: +17 dB
TDMA: +14 to 17 dB
GSM: +7 to 9 dB.

C/I and Frequency Reuse

- The Carrier-to-Interference ratio, “C/I”, is a primary quality statistic in every wireless technology
- All wireless technologies depend on frequency reuse to multiply capacity
- If the radio signal is delicate, a high C/I is required and cells sharing the same frequency must be physically far apart
- If the radio signal is robust, or uses special techniques to distinguish users, then cells sharing the same frequencies can be closer without ill effects.



Tech-nology	Modulation Type	Channel Bandwidth	Quality Indicator
AMPS	Analog FM	30 kHz.	C/I ≅ 17 dB
NAMPS	Analog FM	10 kHz.	C/I ≅ 17 dB
DAMPS	DQPSK	30 kHz.	C/I ≅ 17 dB
GSM	GMSK	200 kHz.	C/I ≅ 6-9 dB
CDMA	QPSK, OQPSK	1,250 kHz.	$E_b/N_o \cong$ 6dB



Wireless Technologies: A Summary

MAJOR TECHNOLOGIES DEPLOYED IN NORTH AMERICA

Technology	Standards Documents	First Used	Modul-ation	Service Types	Band-width	Users/ Carrier
AMPS Advanced Mobile Phone Service	EIA/TIA 553 IS-19 mobile IS-20 base sta.	1983	Analog FM 17 dB C/I	Voice	30 kHz	1
NAMPS Narrowband AMPS	IS-88	1990	Analog FM 17 dB C/I	Voice SMS	10 kHz	1
D-AMPS Digital AMPS North American TDMA	IS-54B	1993	Digital DQPSK 14 dB C/I (fragile)	Voice Data	30 kHz	3 (6 in future?)
	IS-136	1995		+CAVE +DCCH +SMS		
GSM European 2nd-Generation TDMA	ETSI/TIA/ITU multiple documents	1992	Digital GMSK 6 dB C/I (robust)	Voice SMS Cell Bcst frq hop'g	200 kHz	8 (16 in future?)
CDMA Code Division Multiple Access	IS-95B, Joint Std. 008, + features stds	1995	Digital QPSK Spread Spectrum	Voice SMS Data +more	1250 kHz	22 8kb 17 13kb

Major Global Analog Wireless Technologies

	AMPS IS553	NAMPS IS-91	TACS	NMT450	NMT900	C-450
Frequency Band	800	800	900	450	900	450
Channel Spacing	30 kHz.	10 kHz.	25	25	12.5	20
Speech Modulation	FM	FM	FM	FM	FM	FM
Freq. Deviation	12 kHz.	5 kHz.	9.5	5.0	5.0	4.0
Signaling Modulation	Dir.FSK	Dir.FSK	Dir.FSK	Aud.FFSK	Aud.FFSK	Dir.FSK
Signalling Bit Rate	10 kb/s	10 kb/s	8 kb/s	1200 b/s	1200 b/s	5280 b/s
Overlay Signalling?	no	no	no	no	no	yes
Paging/Access	CCH (f)	CCH (f)	CCH (f)	CCH (f)	CCH (f)	CCH (f)
In-Call Supervision	SAT	DSAT	SAT	?	?	overlay
In-Call Control	ST	DSAT	ST	?	?	overlay
Call Control	ST	DSAT	ST	?	?	overlay
Handoff Logic	BTSLCR	BTSLCR	BTSLCR	BTSLCR	BTSLCR	BTSLCR

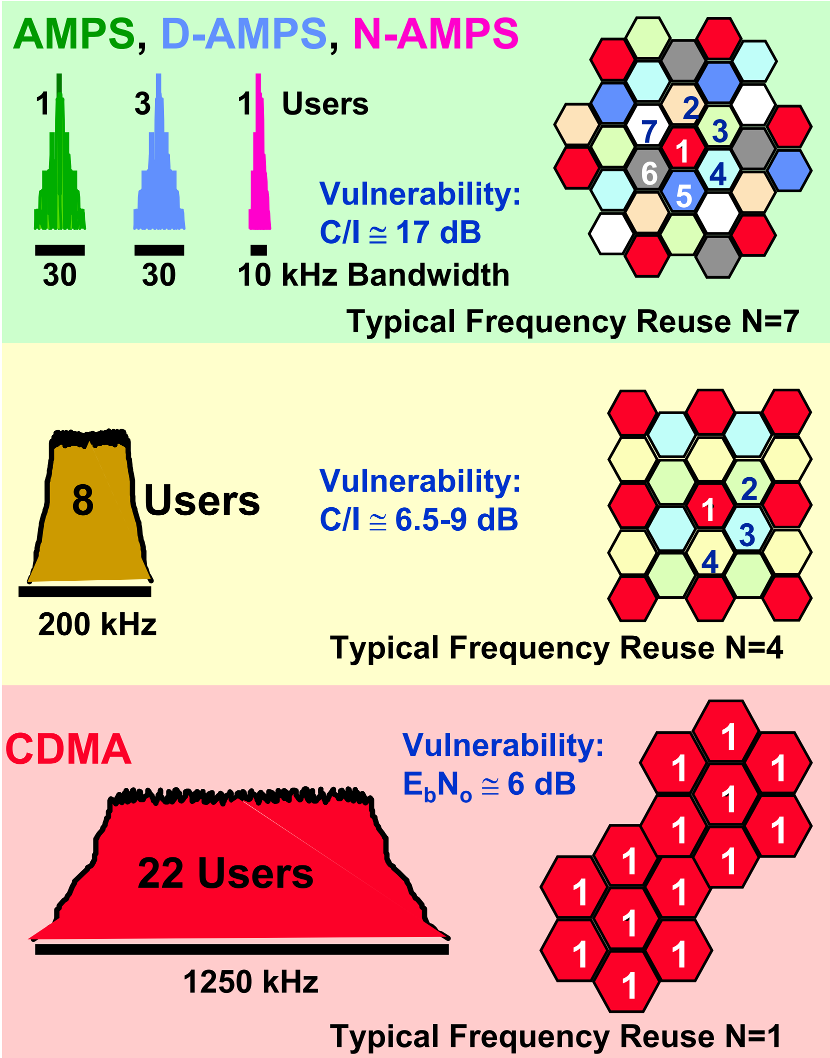
Major Global Digital Wireless Technologies

	GSM, DCS1800 PCS1900	D-AMPS *IS-54* *IS-136*	CDMA *IS-95* *JStd008*	Japan PDC	CT-2	DECT
Access Method	TDMA	TDMA	CDMA	TDMA	TDMA	TDMA
Frequency Band(s)	900 1800 1900	800 1900*	800 1900	8/900 1400	865	1880
Channel Spacing	200	30, 50*	x	50/25i	100	1728
Modulation type	GMSK	DQPSK	QPSK	DQPSK	GFSK	GFSK
Signal Bandwidth	200+	30	1250+	50	100	1800
Signalling Modulation	GMSK	DQPSK	QPSK	DQPSK	GFSK	GFSK
Transmission, kb/s	~240	~44	1229ss	42	72	1152
Paging/Access ch.	CCH (t)	CCH(f)	CCH(c)	CCH(f)	BCH	BCH
Signalling kb/s	~30	~44	9.6	x	32	32
Info kb/s	14.4	x	9.6,14.4	11.2	32	32
Info frames/s	~200	50	50	50	packets	100
In-Call signalling	TCH, SDCCH	TCH, SACCH	TCH	ACCH SACCH	hybrid	hybrid
Handoff Logic	MAHO	MAHO+	MDHO	?	?	MDHO

Spectrum Usage and System Capacity:
Signal Bandwidth, C/I and Frequency Reuse

Each wireless technology (AMPS, NAMPS, D-AMPS, GSM, CDMA) uses a specific modulation type with its own unique signal characteristics

- Signal Bandwidth determines how many RF signals will “fit” in the operator’s licensed spectrum
- **Robustness of RF signal determines tolerable level of interference and necessary physical separation of cochannel cells**
- Number of users per RF signal directly affects capacity



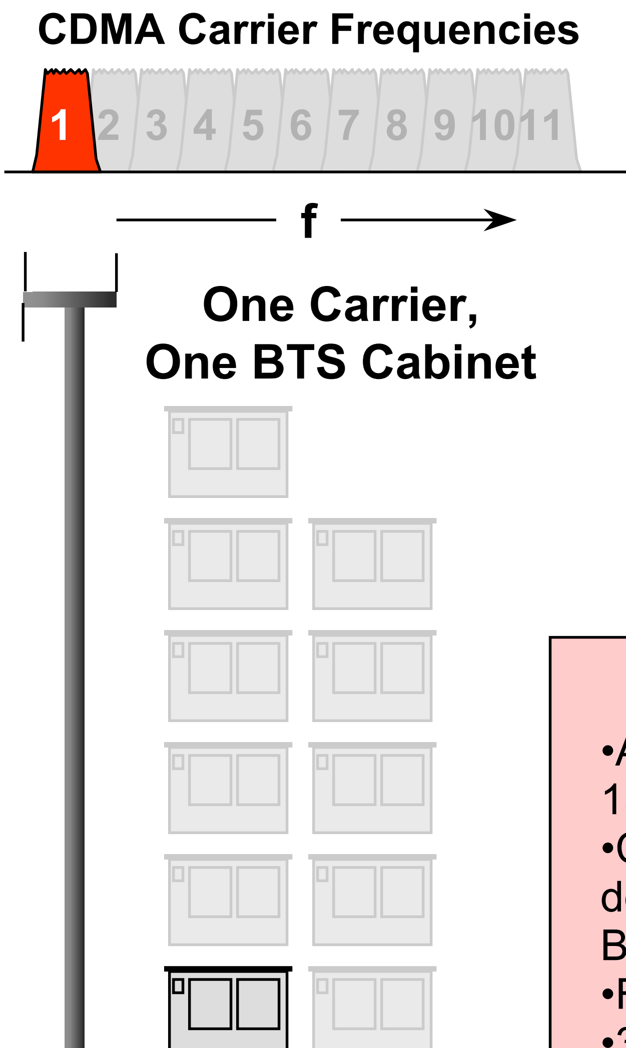
Capacity Comparison of Wireless Technologies: 800 MHz. Cellular Applications

Band	800 (A,B)		
Fwd or Rev Spectrum	12.5 MHz		
Technology	AMPS	TDMA	CDMA
Req'd C/I or Eb/No, dB	17	17	6
Freq Reuse Factor N	7	7	1
RF Signal BW, kHz	30	30	1250
Total # RF Signals	416	416	9
RF Sigs per Cell @ N	59	59	9
# Sectors per Cell	3	3	3
# CCH per Sector	1	1	0
RF Signals per Sector	18	18	8
Voicepaths/RF Signal	1	3	17
Voicepaths per Sector	18	54	136
P.02 Erlangs per Sector	11.5	44	123.1
Voicepaths per Site	54	162	408
P.02 Erlangs per Site	34.5	132	369.3
Capacity vs AMPS @800	1	3.8	10.7

Capacity Comparison of Wireless Technologies: 1900 MHz. PCS Applications

Band	800 (A,B)			1900 (A,B,C)			1900 (D,E,F)		
Fwd or Rev Spectrum	12.5 MHz			15 MHz			5 MHz		
Technology	AMPS	TDMA	CDMA	TDMA	GSM	CDMA	TDMA	GSM	CDMA
Req'd C/I or Eb/No, dB	17	17	6	17	6.5-9	6	17	6.5-9	6
Freq Reuse Factor N	7	7	1	7	4	1	7	4	1
RF Signal BW, kHz	30	30	1250	30	200	1250	30	200	1250
Total # RF Signals	416	416	9	500	75	11	166	25	3
RF Sigs per Cell @ N	59	59	9	71	18	11	23	8	3
# Sectors per Cell	3	3	3	3	3	3	3	3	3
# CCH per Sector	1	1	0	1	0	0	1	0	0
RF Signals per Sector	18	18	8	22	6	11	6	2	3
Voicepaths/RF Signal	1	3	17	3	7.5	17	3	7.5	17
Voicepaths per Sector	18	54	136	66	45	187	18	15	51
P.02 Erlangs per Sector	11.5	44	123.1	55.3	35.6	173.3	11.5	9.01	41.2
Voicepaths per Site	54	162	408	198	135	561	54	45	153
P.02 Erlangs per Site	34.5	132	369.3	165.9	106.8	519.9	34.5	27.0	123.6
Capacity vs AMPS @800	1	3.8	10.7	4.8	3.1	15.1	1.0	0.78	3.6

CDMA Capacity Today: Single Carrier

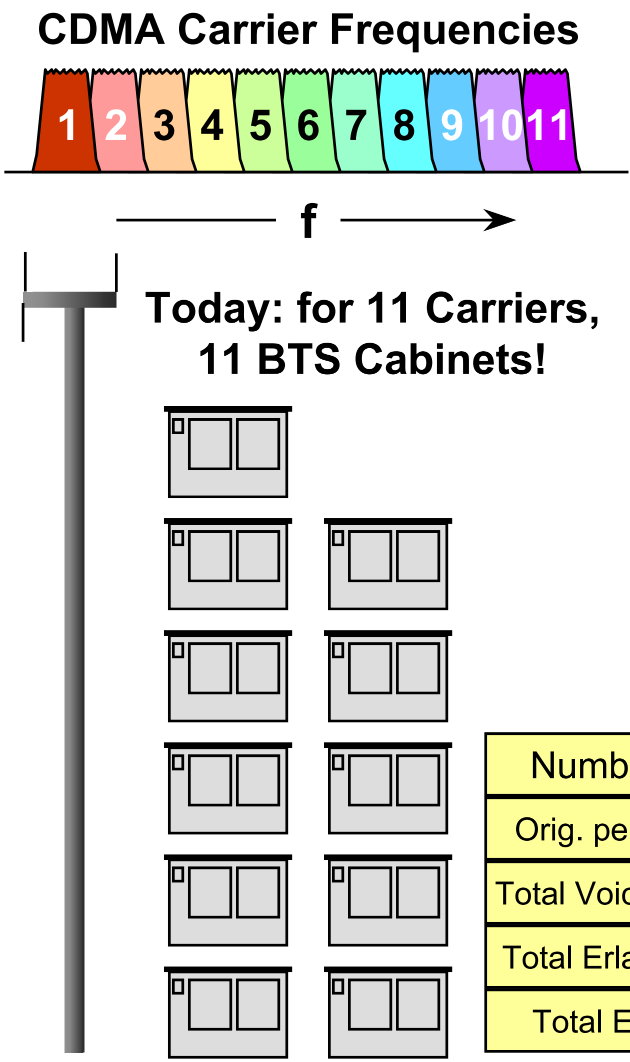


- One-carrier operation is used by most CDMA systems during initial deployment
  - operators' initial traffic needs are light
  - manufacturers are still working to develop practical multi-carrier BTS
- One-carrier operation is wasteful
  - poor trunking efficiency with just one carrier
  - not using all of available spectrum
    - Cellular: 5-6 carriers possible
    - PCS A,B,C: 11 carriers possible
    - PCS D,E,F: 3 carriers possible

One-Carrier Capacity Per Sector & BTS

•Assumptions: One sector/one carrier can support 13 originations, 9 users in soft handoff
•Capacity: very conservatively, 13 trunks (SH users don't count; their erlangs already counted on other BTS or sectors)
•From Erlang-B tables, 13 trunks, P.02, 7.4 erlangs
•3 sectors x 7.4 erlangs = 22.2 erlangs total BTS

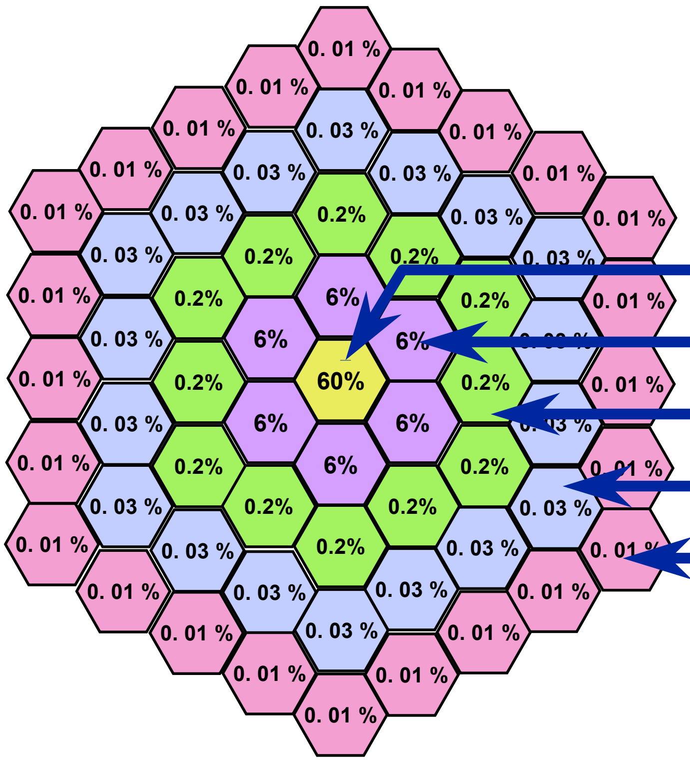
Future CDMA Capacity: Multiple Carriers



- Multi-carrier operation is necessary to realize the true capacity potential of CDMA
  - uses all of available spectrum
    - Cellular: 5-6 carriers possible
    - PCS A,B,C: 11; D,E,F: 3 carriers possible
- All carriers work together as a “pool” and new calls may be assigned by the system to any carrier
- Allows high-capacity applications
  - system expansion without cell splitting
  - costs competitive with wireline systems
  - wireless local loop applications
- Multi-carrier operation faces major issues
  - TX combiners or multicarrier linear amplifiers
  - Innovative use of beacons and other techniques to stimulate required hard handoffs

Number of Carriers	1	2	3	4	5	6	7	8	9	10	11
Orig. per Sector/Carrier	13	13	13	13	13	13	13	13	13	13	13
Total Voice Paths/Sector	13	26	39	52	65	78	91	104	117	130	143
Total Erlangs per Sector	7.4	18.4	30.1	42.1	54.4	66.8	79.3	91.9	105	117	130
Total Erlangs per BTS	22.2	55.2	90.3	126	163	200	238	276	313	352	390

CDMA Interference & Capacity Environments



1 X 60 = 60

6 X 6 = 36

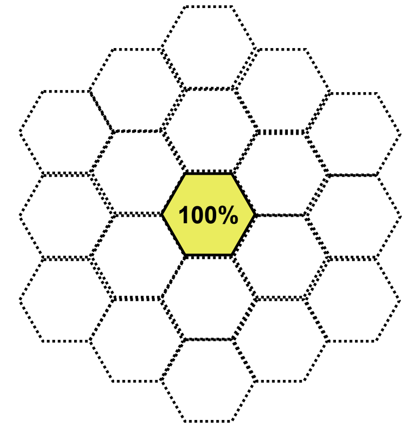
12 X 0.2 = 2.4

18 X 0.03 = 0.54

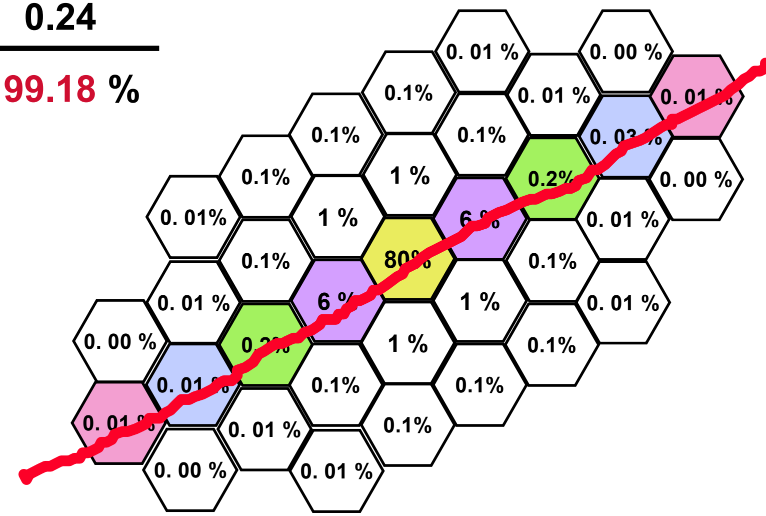
24 X 0.01 = 0.24

TOTAL = 99.18 %

HOMOGENEOUS URBAN AREA

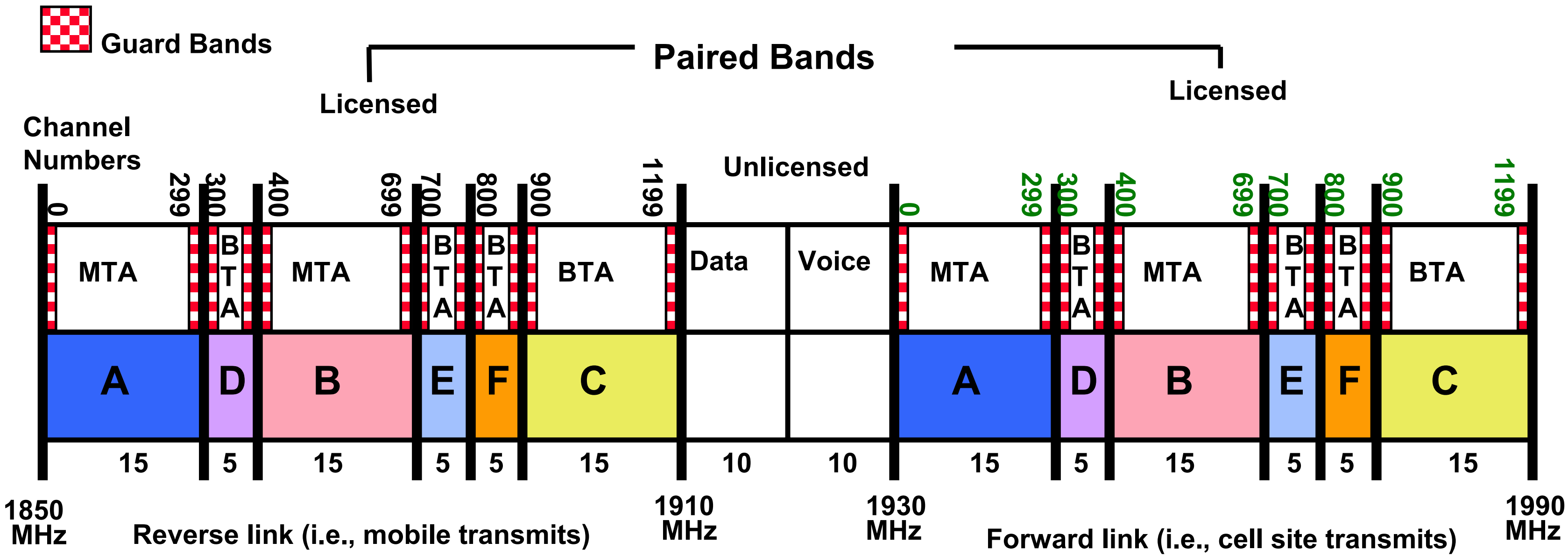


ISOLATED CELL IN RURAL AREA



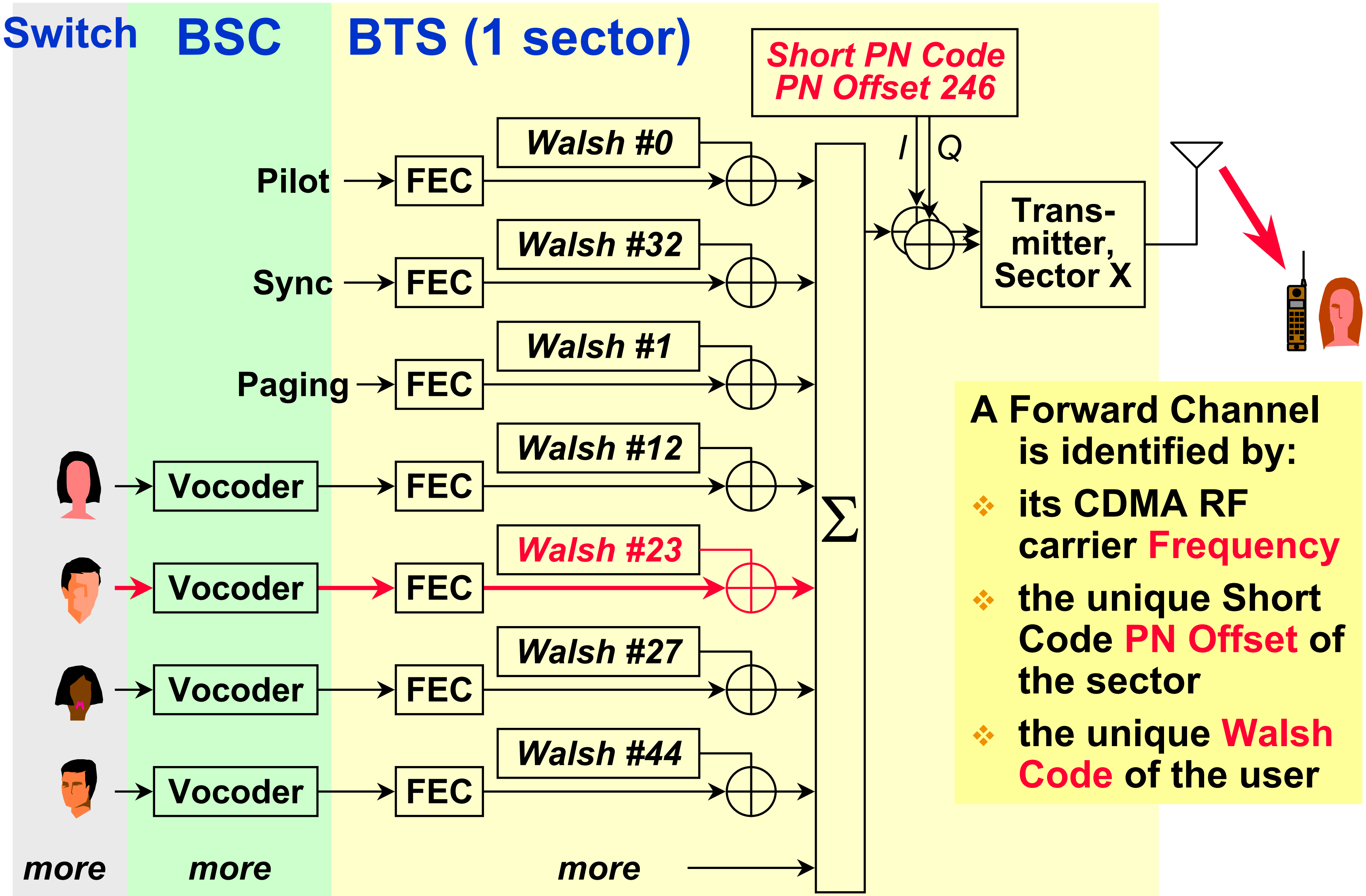
ALONG A HIGHWAY

CDMA PCS 1900 MHz Spectrum Usage



- A, B, and C licenses can accommodate 11 CDMA RF channels in their 30 MHz of spectrum
- D, E, and F licenses can accommodate 3 CDMA RF channels in their 10 MHz of spectrum
- 260 kHz guard bands are required on the edges of the PCS spectrum to ensure no interference occurs with other applications just outside the spectrum

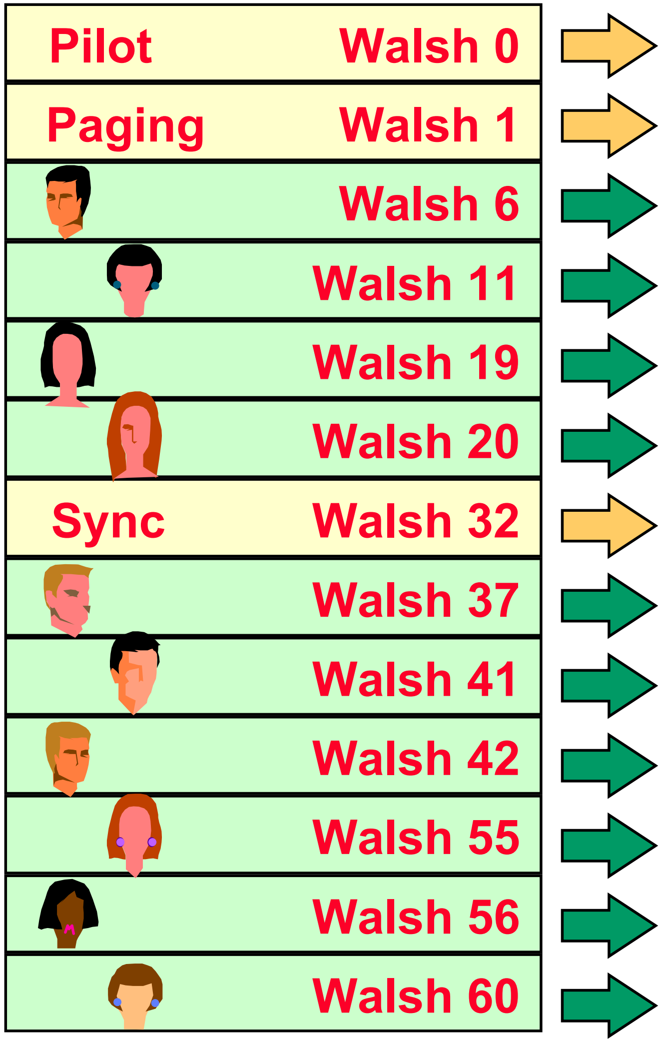
Code Channels in the Forward Direction



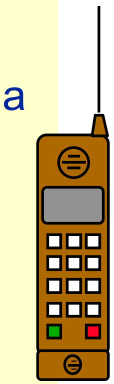
A Forward Channel is identified by:

- its CDMA RF carrier **Frequency**
- the unique Short Code **PN Offset** of the sector
- the unique **Walsh Code** of the user

Functions of the CDMA Forward Channels



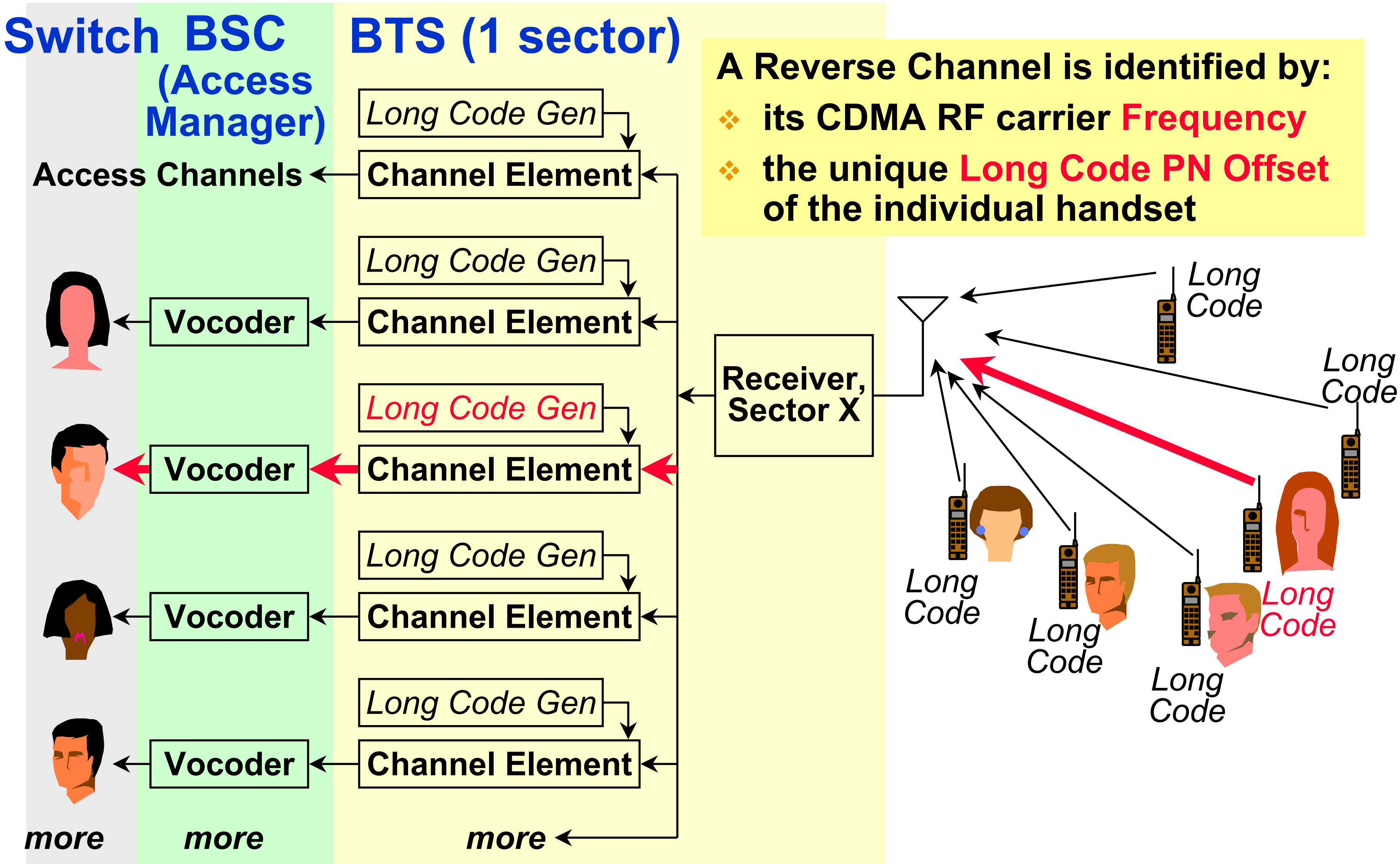
- **PILOT**: WALSH CODE **0**
  - The Pilot is a “structural beacon” which does not contain a character stream. It is a timing source used in system acquisition and as a measurement device during handoffs
- **SYNC**: WALSH CODE **32**
  - This carries a data stream of system identification and parameter information used by mobiles during system acquisition
- **PAGING**: WALSH CODES **1 up to 7**
  - There can be from one to seven paging channels as determined by capacity needs. They carry pages, system parameters information, and call setup orders
- **TRAFFIC**: any **remaining** WALSH codes
  - The traffic channels are assigned to individual users to carry call traffic. All remaining Walsh codes are available, subject to overall capacity limited by noise



Code Channels in the Reverse Direction

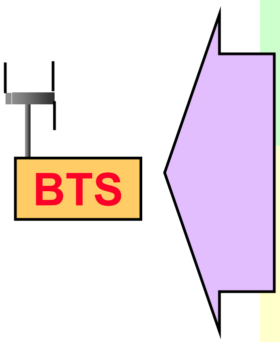
A Reverse Channel is identified by:

- **its CDMA RF carrier Frequency**
- **the unique Long Code PN Offset of the individual handset**

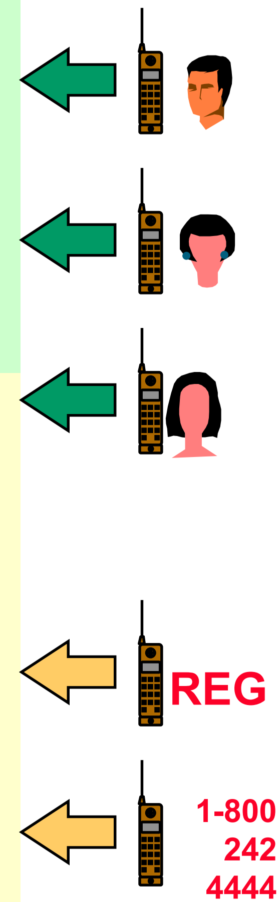


Functions of the CDMA Reverse Channels

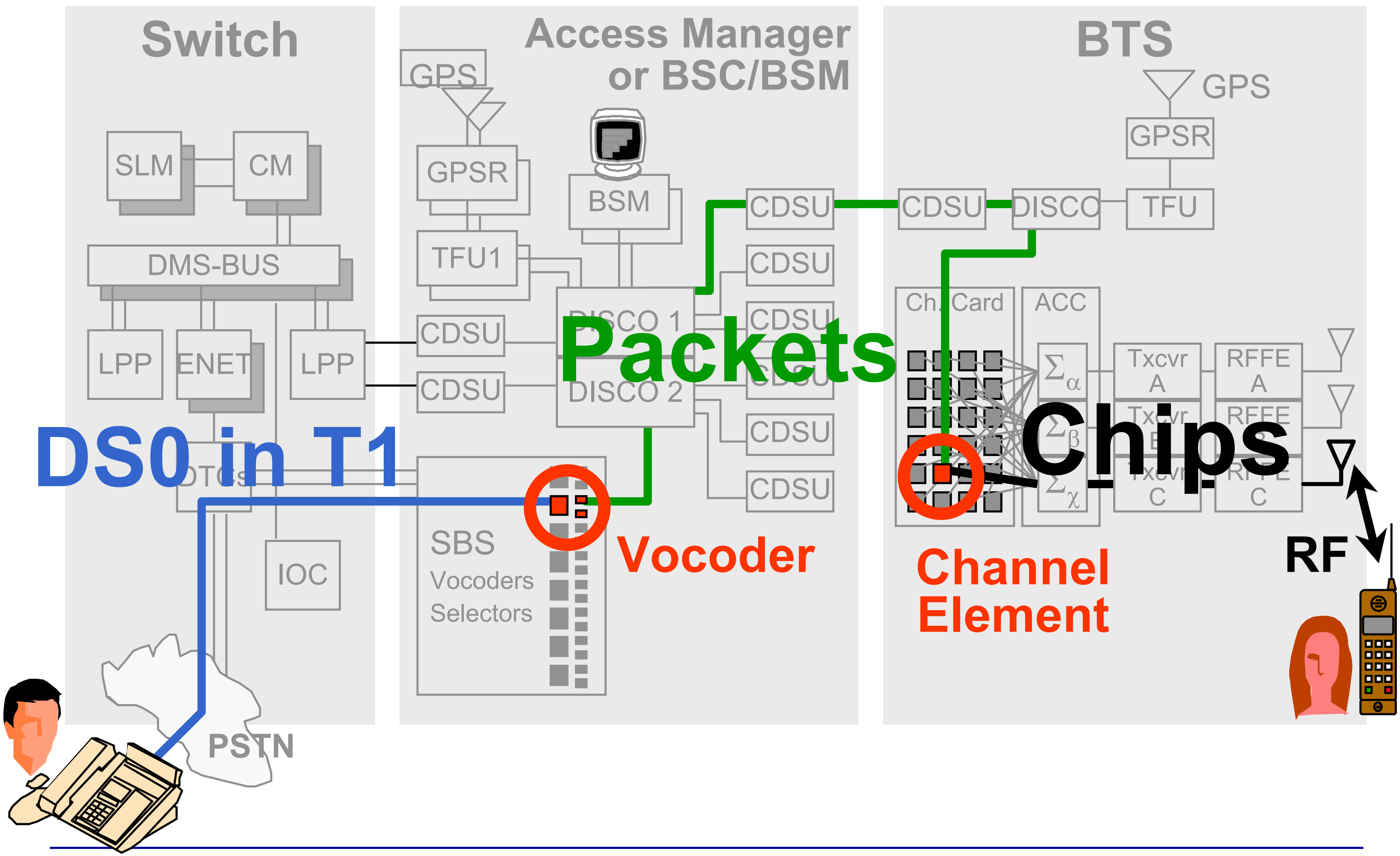
There are two types of CDMA Reverse Channels:



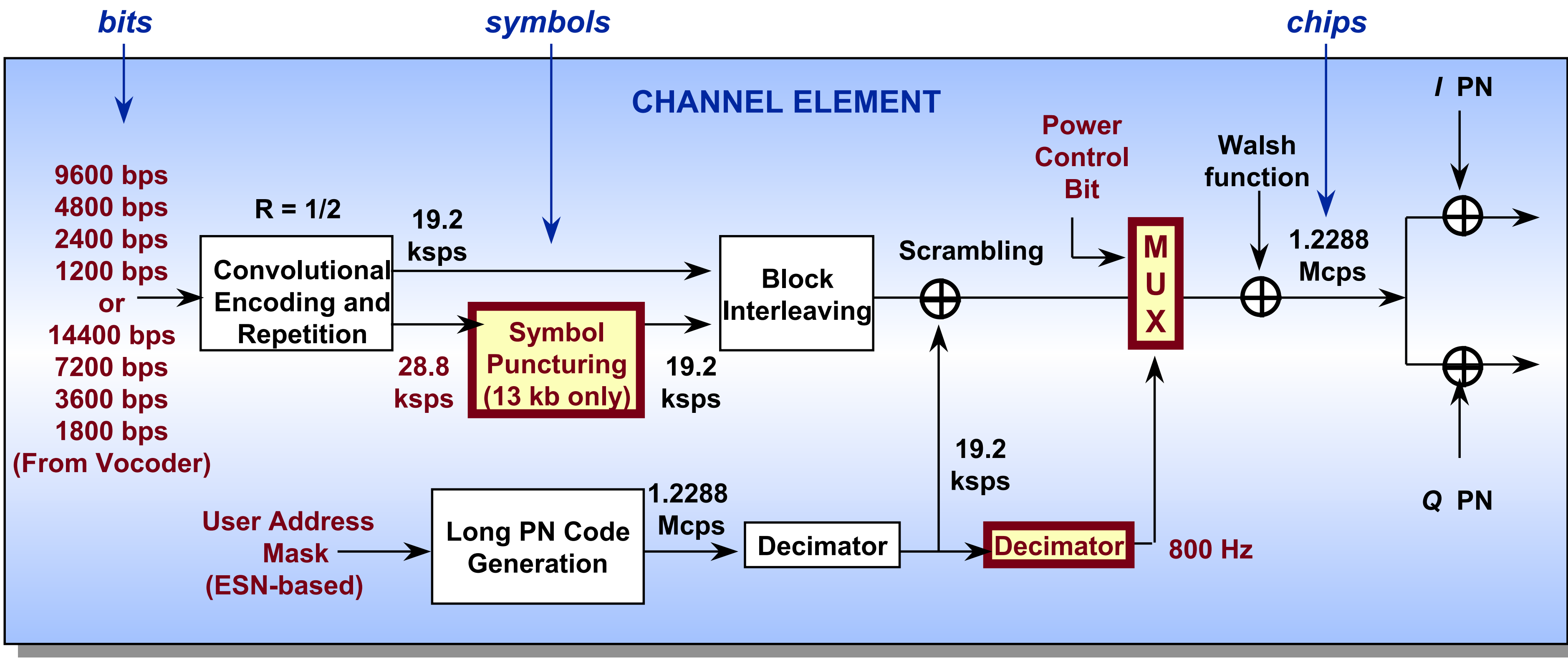
- **TRAFFIC CHANNELS** are used by individual users during their actual calls to transmit traffic to the BTS
  - a reverse traffic channel is defined by a user-specific public or private Long Code mask
  - there are as many reverse Traffic Channels as there are CDMA phones in the world
- **ACCESS CHANNELS** are used by mobiles not yet in a call to transmit registration requests, call setup requests, page responses, order responses, and other signaling information
  - an access channel is defined by a public long code mask specific to the BTS sector
  - Access channels are paired with Paging Channels. There can be up to 32 access channels per paging channel



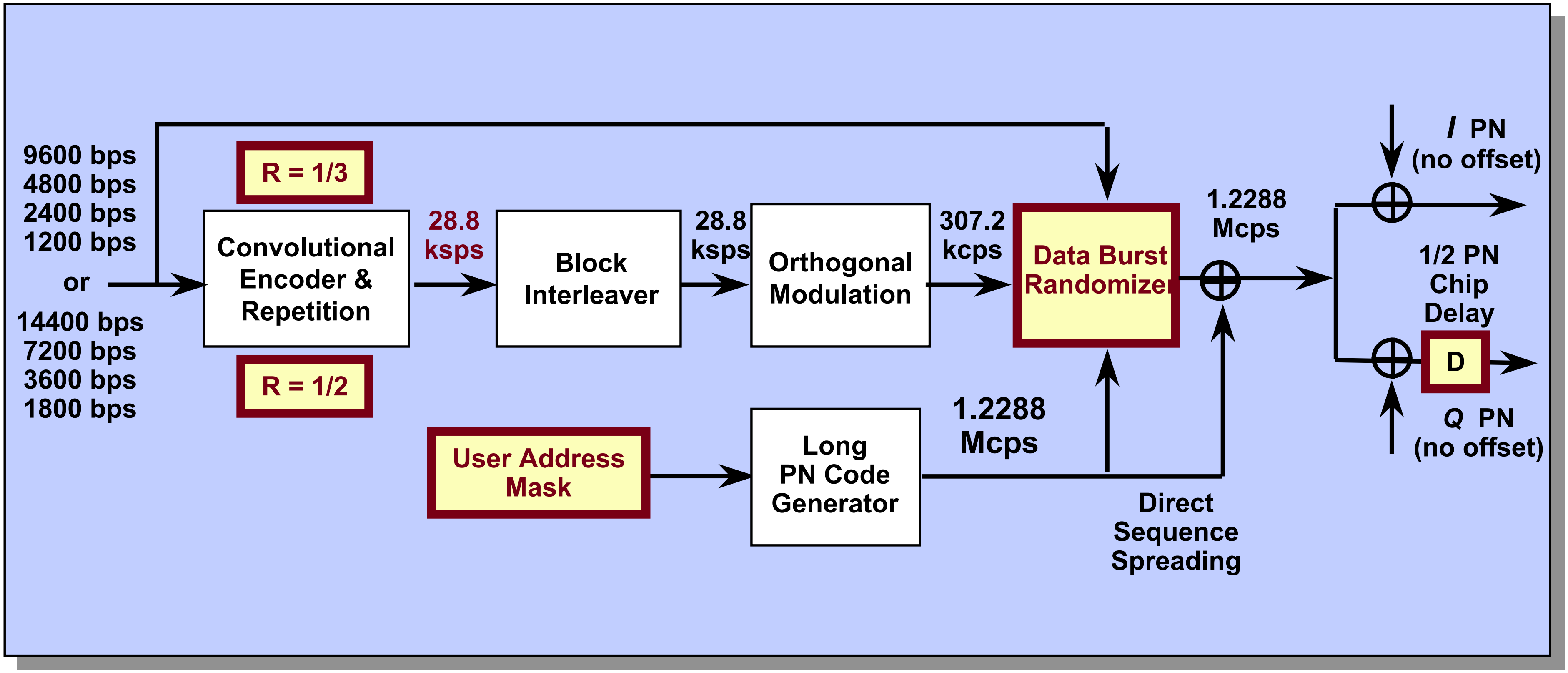
Basic CDMA Network Architecture



Forward Traffic Channel: Generation Details from IS-95



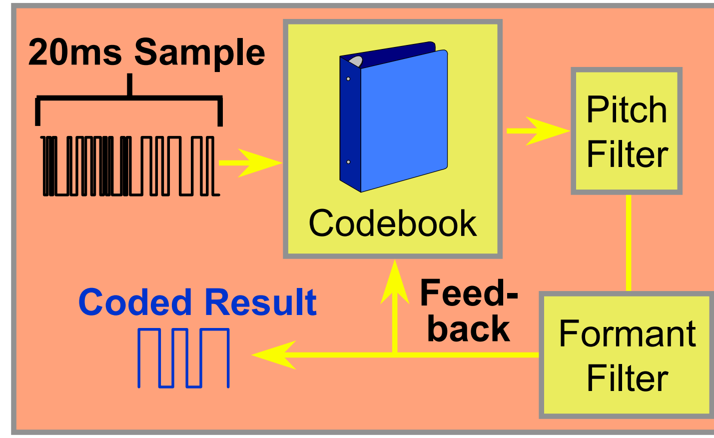
Reverse Traffic Channel: Generation Details from IS-95



Variable Rate Vocoding & Multiplexing

- Vocoders compress speech, reduce bit rate, greatly increasing capacity
- CDMA uses a superior Variable Rate Vocoder
  - full rate during speech
  - low rates in speech pauses
  - increased capacity
  - more natural sound
- Voice, signaling, and user secondary data may be mixed in CDMA frames

DSP QCELP VOCODER

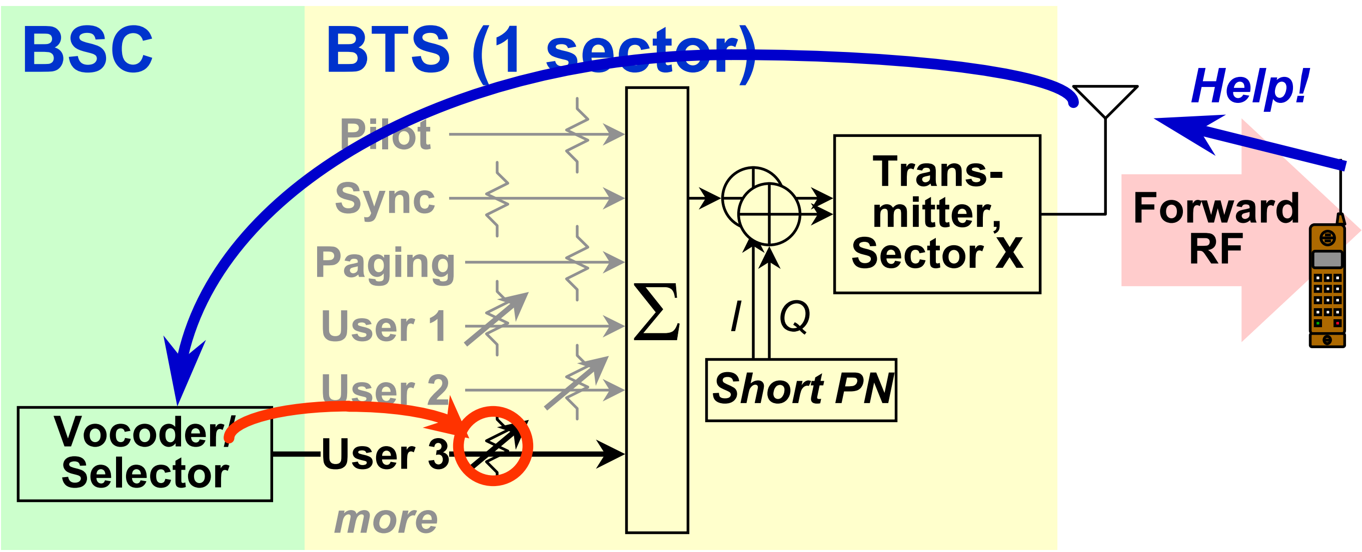


bits	Frame Sizes
288	Full Rate Frame
144	1/2 Rate Frame
72	1/4 Rt.
36	1/8

Frame Contents: can be a mixture of

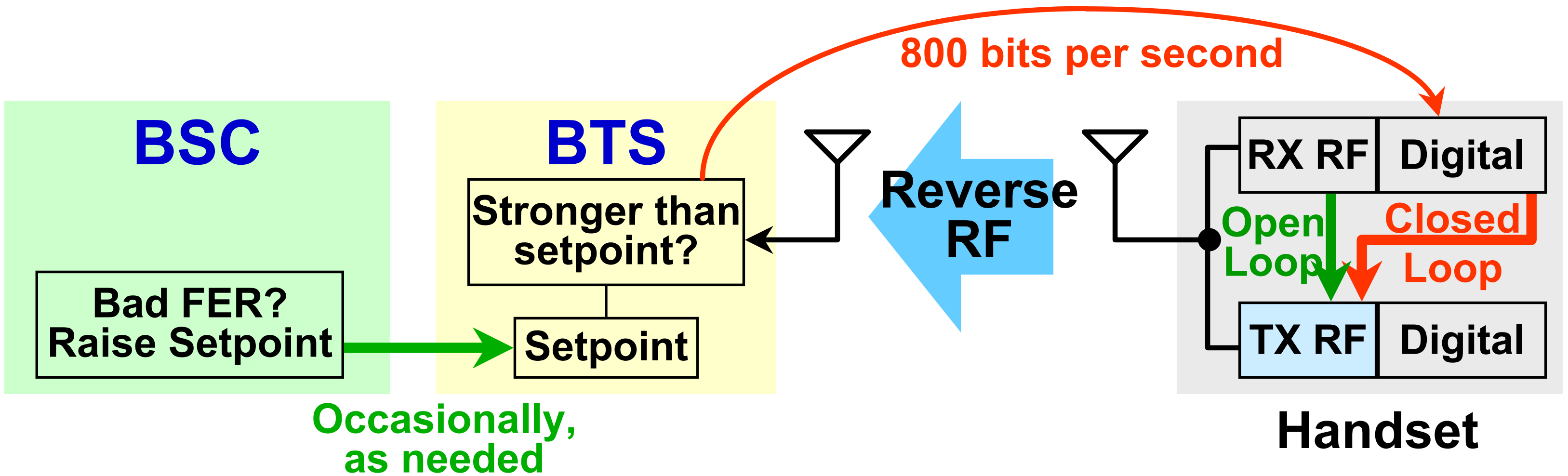
Voice **Signaling** **Secondary**

Forward Power Control



- The BTS continually reduces the strength of each user’s forward baseband chip stream
- When a particular handset sees errors on the forward link, it requests more energy
- The complainer’s chip stream gets a quick boost; afterward, continues to diminish

Reverse Power Control



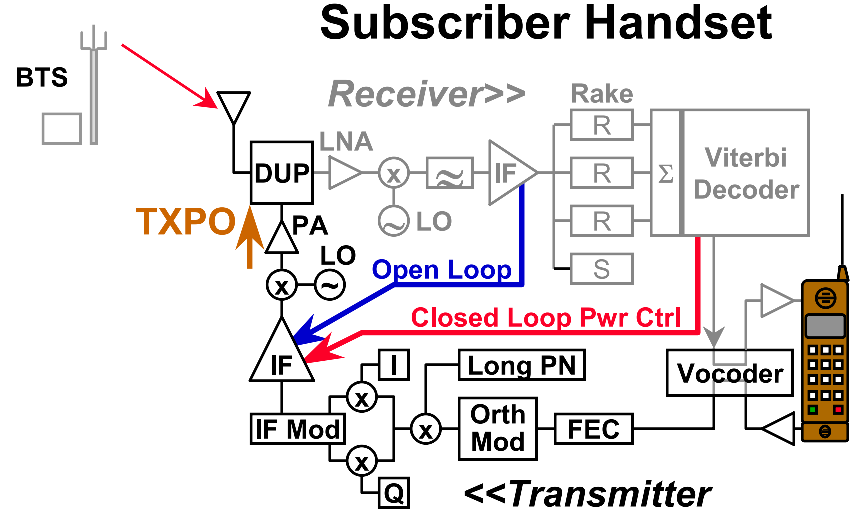
- Three methods work in tandem to equalize all handset signal levels at the BTS
  - Reverse *Open* Loop: handset adjusts power up or down based on received BTS signal (AGC)
  - Reverse *Closed* Loop: Is handset too strong? BTS tells up or down 1 dB 800 times/second
  - Reverse *Outer* Loop: BSC has FER trouble hearing handset? BSC adjusts BTS setpoint

Details of Reverse Link Power Control

- **TXPO Handset Transmit Power**
  - Actual RF power output of the handset transmitter, including combined effects of **open loop power control** from receiver AGC *and* **closed loop power control** by BTS
  - can't exceed handset's maximum (typ. +23 dBm)

TXPO = -(RX_{dbm}) -C + TXGA
C = +73 for 800 MHz. systems
= +76 for 1900 MHz. systems

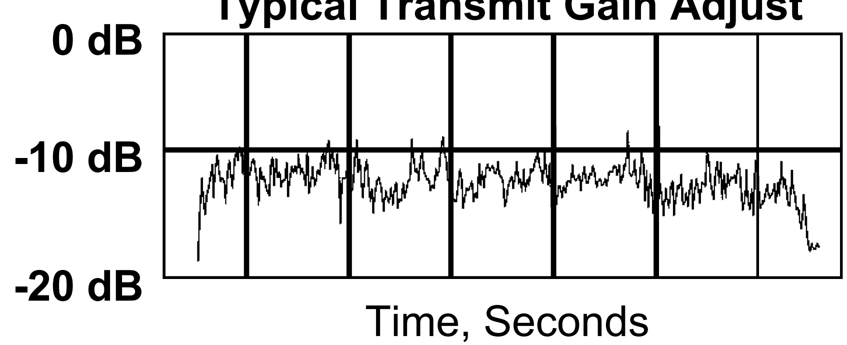
Subscriber Handset



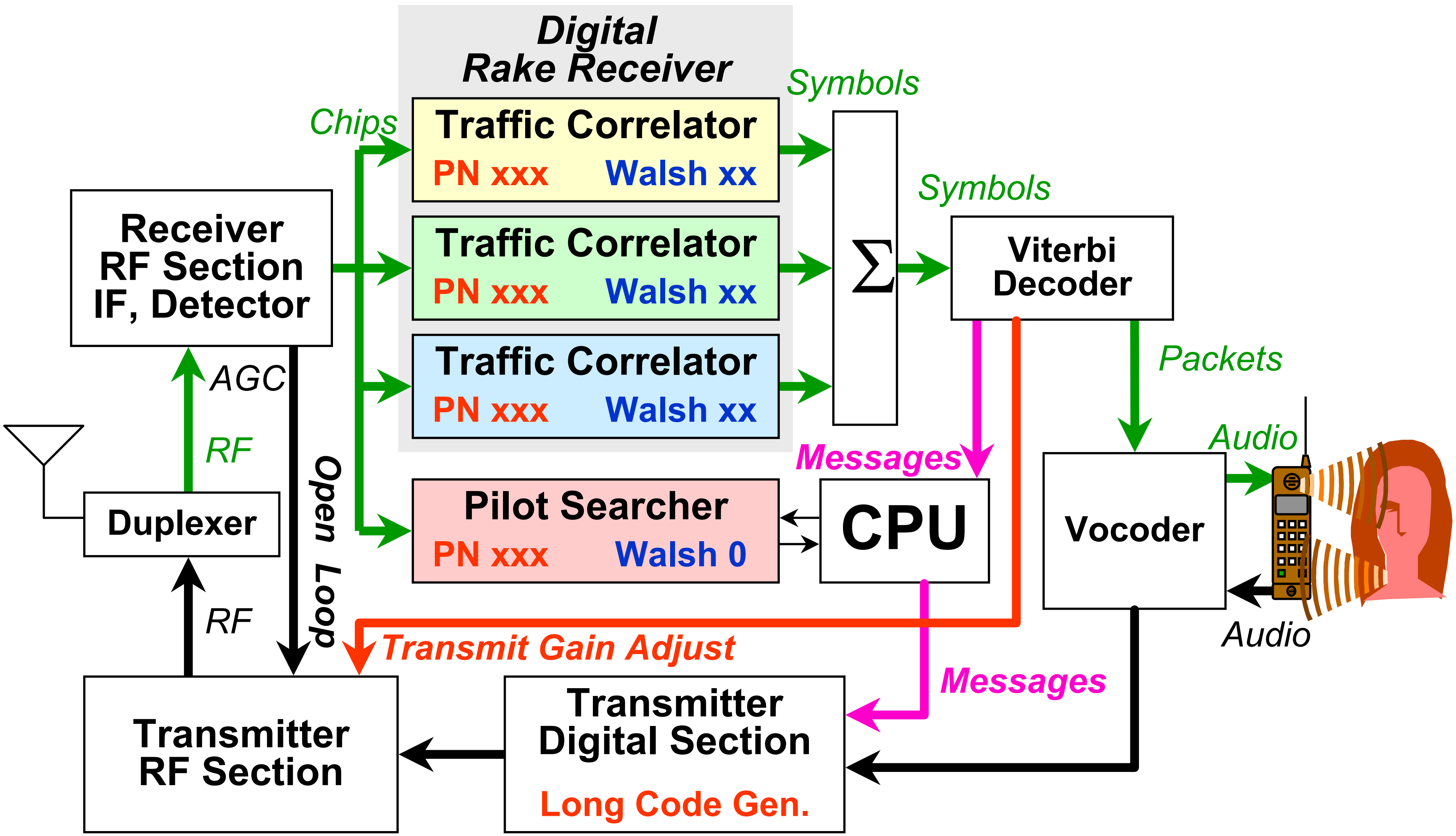
Typical TXPO:
+23 dBm in a coverage hole
0 dBm near middle of cell
-50 dBm up close to BTS

- **TXGA Transmit Gain Adjust**
  - Sum of all **closed-loop power control** commands from the BTS since the beginning of this call

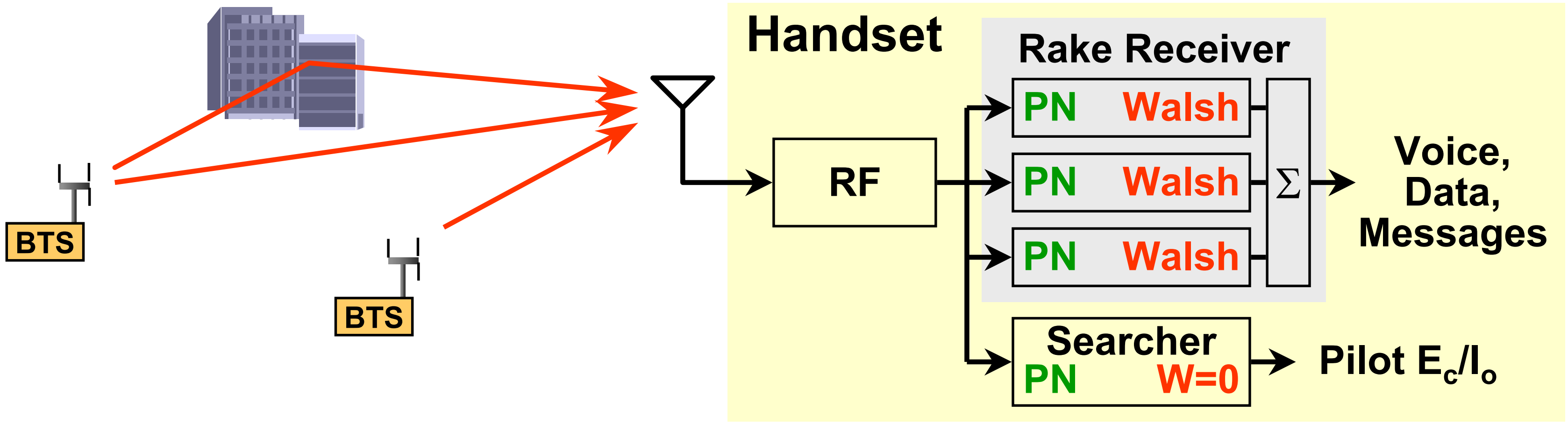
Typical Transmit Gain Adjust



What's In a Handset?

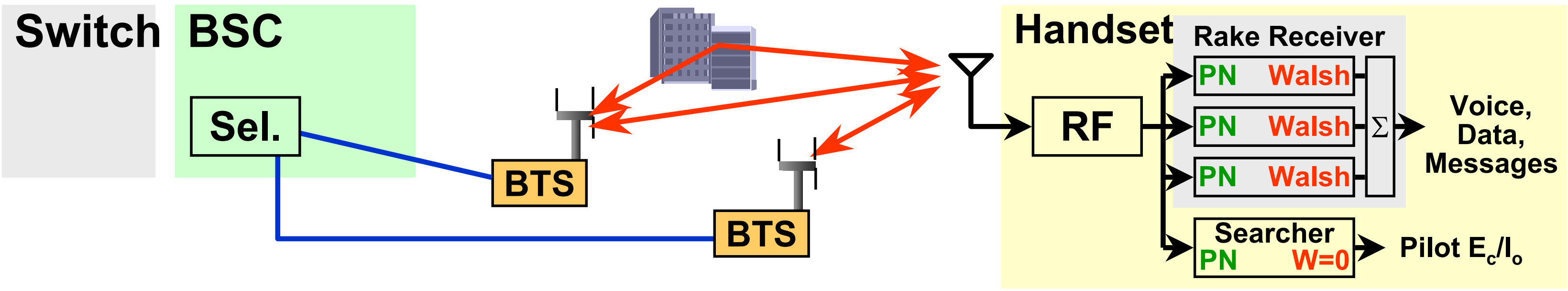


The Rake Receiver



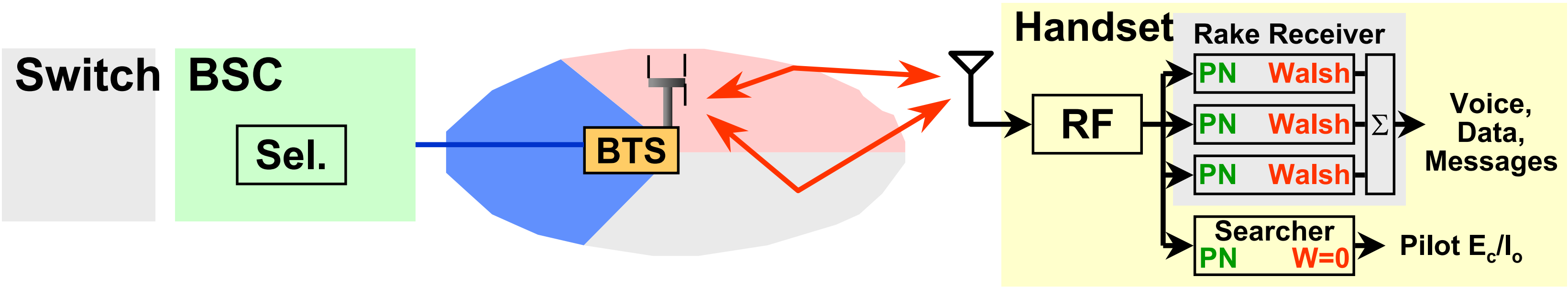
- Every frame, handset uses combined outputs of the three traffic correlators ("rake fingers")
- Each finger can independently recover a particular PN offset and Walsh code
- Fingers can be targeted on delayed multipath reflections, or even on different BTSs
- Searcher continuously checks pilots

CDMA Soft Handoff Mechanics



- CDMA soft handoff is driven by the handset
  - Handset continuously checks available pilots
  - Handset tells system pilots it currently sees
  - System assigns sectors (up to 6 max.), tells handset
  - Handset assigns its fingers accordingly
  - All messages sent by dim-and-burst, no muting!
- Each end of the link chooses what works best, on a frame-by-frame basis!
  - Users are totally unaware of handoff

Softer Handoff



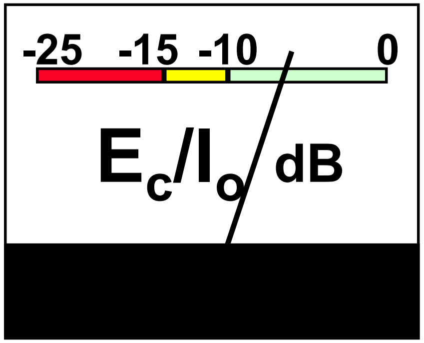
- Each BTS sector has unique PN offset & pilot
- Handset will ask for whatever pilots it wants
- If multiple sectors of one BTS simultaneously serve a handset, this is called Softer Handoff
- Handset is unaware, but softer handoff occurs in BTS in a single channel element
- Handset can even use combination soft-softer handoff on multiple BTS & sectors

Overall Handoff Perspective

- Soft & Softer Handoffs are preferred, but not always possible
  - a handset can receive BTS/sectors simultaneously only on *one* frequency
  - all involved BTS/sectors must connect to a *networked BSCs. Some manufacturers do not presently support this, and so are unable to do soft-handoff at boundaries between BSCs.*
  - *frame timing* must be same on all BTS/sectors
- If any of the above are not possible, handoff still can occur but can only be "hard" break-make protocol like AMPS/TDMA/GSM
  - intersystem handoff: hard
  - change-of-frequency handoff: hard
  - CDMA-to-AMPS handoff: hard, no handback
    - – auxiliary trigger mechanisms available (RTD)

What is Ec/Io?

- E_c/I_o
  - "cleanness" of the pilot
    - foretells the readability of the associated traffic channels
  - guides soft handoff decisions
  - digitally derived: ratio of good to bad energy seen by the search correlator at the desired PN offset
  - Never appears higher than Pilot's percentage of serving cell's transmitted energy
  - Can be degraded by strong RF from other cells, sectors
    - Imperfect orthogonality, other PNs are ~-20 dB.
  - Can be degraded by noise

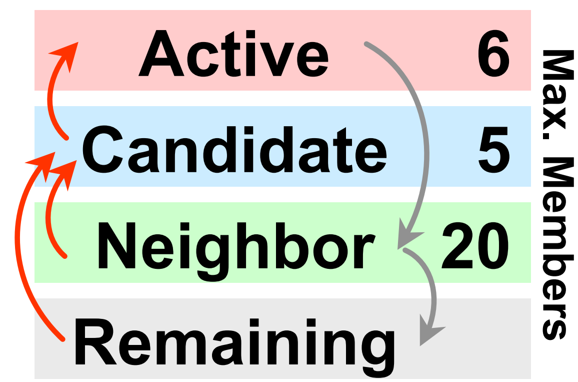


E_c	**Energy of desired pilot alone**
I_o	**Total energy received**

Pilot Sets and Soft Handoff Parameters

- Handset views pilots in *sets*
- Handset sends message to system whenever:
  - It notices a pilot in neighbor or remaining set exceeds T_ADD
  - An active set pilot drops below T_DROP for T_TDROP time
  - A candidate pilot exceeds an active by T_COMP
- Handoff setup processing time usually substantially faster than 1 second
- System may grant all requested handoffs, or may apply special manufacturer-specific screening criteria

PILOT SETS

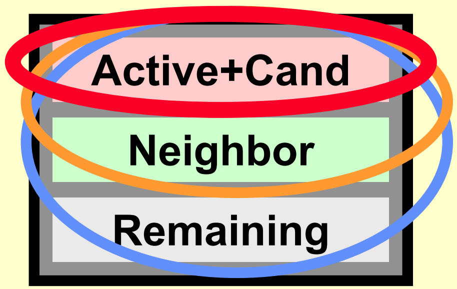


HANDOFF PARAMETERS

T_ADD	T_DROP
T_TDROP	T_COMP

Pilot Search Order, Speed, and Implications

SEARCHING FOR PILOTS:



The searcher checks pilots in nested loops.

Actives and candidates are the innermost loop.

Neighbors are next, advances one pilot each time Act+cand finish

Remaining is slowest, advances one pilot each time Neighbors finish

- Actives & candidates have the biggest influence.
  - Keep window size as small as possible
  - During soft handoff, this set dominates searcher
    - Minimize excessive Soft HO!
- Neighbor set is second-most-important
  - Keep window size as small as possible
  - Keep neighbor list as small as possible
  - But don't miss any important neighbors!
- Remaining Set: pay your dues, but get no reward
  - You must spend time checking them, but the system can't assign one to you

SEARCH TIME FOR ONE PILOT AS A FUNCTION OF WINDOW SIZE

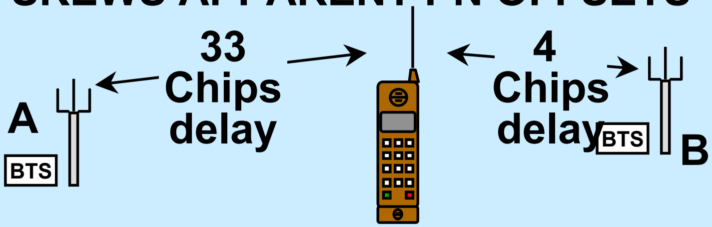
Window Size (Chips)	Datafill Value	Max Delay (μs)	Search Time (ms)
14 (±7)	4	5.7	19
20 (±10)	5	8.1	15
28 (±14)	**6**	**11.4**	**10**
40 (±20)	7	16.3	12
60 (±30)	8	24.4	18
80 (±40)	9	32.6	19
100 (±50)	10	40.7	25
130 (±65)	11	52.9	30
160 (±80)	12	65.1	40
226 (±113)	13	92	54
320 (±160)	14	130	76
452 (±226)	15	184	108

Notice that when the window size is set to 28 chips, the search time has a minimum.

Optional: Quick Primer on Pilot Search Windows

- The phone chooses one strong sector's signal and "locks" to it as "Primary PN"
  - accepts its offset as being exactly the PN announced by that BTS' messages
  - measures the offsets of all other signals by timing comparison with it
- In messages, system gives to handset a neighbor list of nearby sectors' PNs
- Propagation delay "skews" the apparent PN offsets of all other sectors, making them seem earlier or later than expected
- To overcome skew, when the phone searches for a particular pilot, it scans an extra wide "delta" of chips centered on the expected offset (called a "search window")
- Search window values can be datafilled individually for each Pilot set:
- There are pitfalls if the window sizes are improperly set
  - too large: search time increases, slows
  - too small: overlook pilots from far away
  - too large: might misinterpret identity of a distant BTS' signal

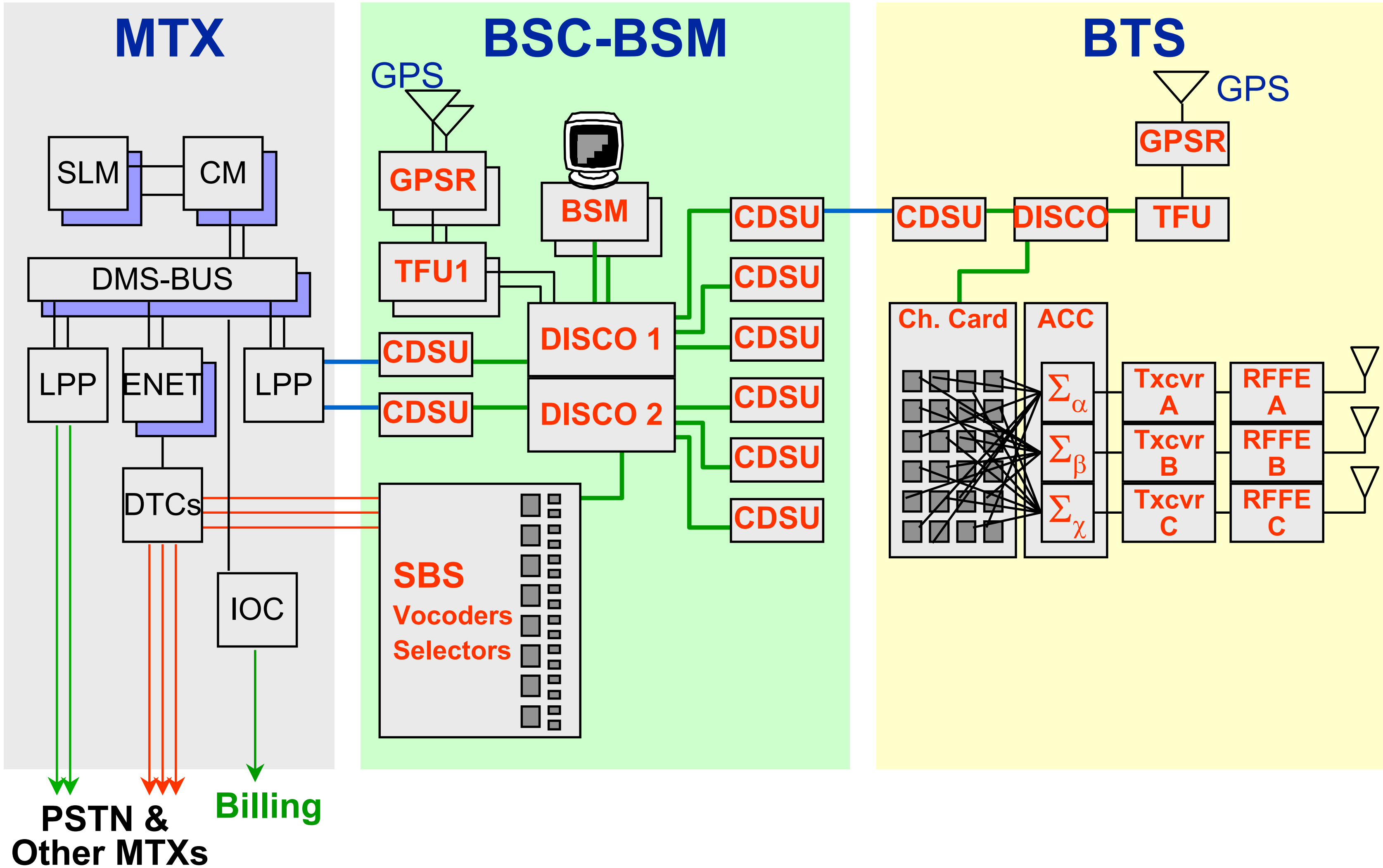
PROPAGATION DELAY SKEWS APPARENT PN OFFSETS



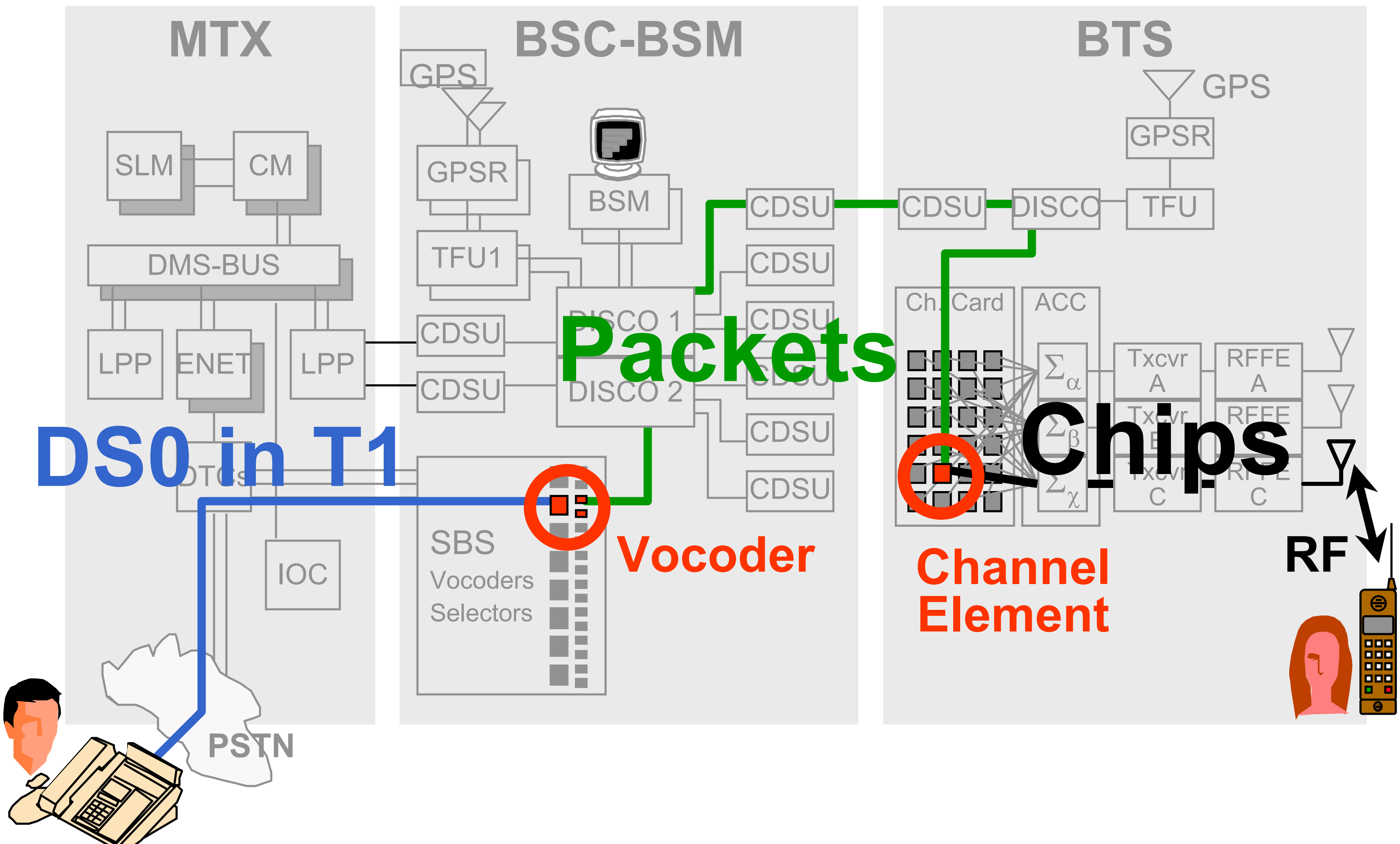
If the phone is locked to BTS A, the signal from BTS B will seem 29 chips earlier than expected.
If the phone is locked to BTS B, the signal from BTS A will seem 29 chips later than expected.

One chip is 801 feet or 244.14 m
1 mile=6.6 chips; 1 km.= 4.1 chips

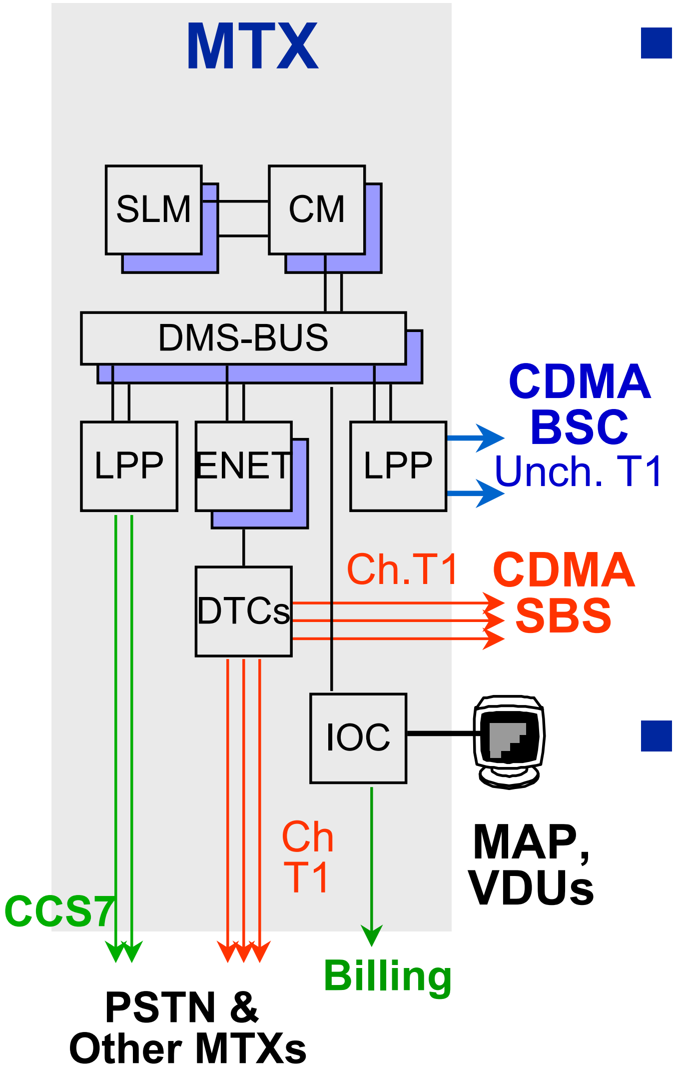
NORTEL CDMA System Architecture



Signal Flow: Two-Stage Metamorphosis

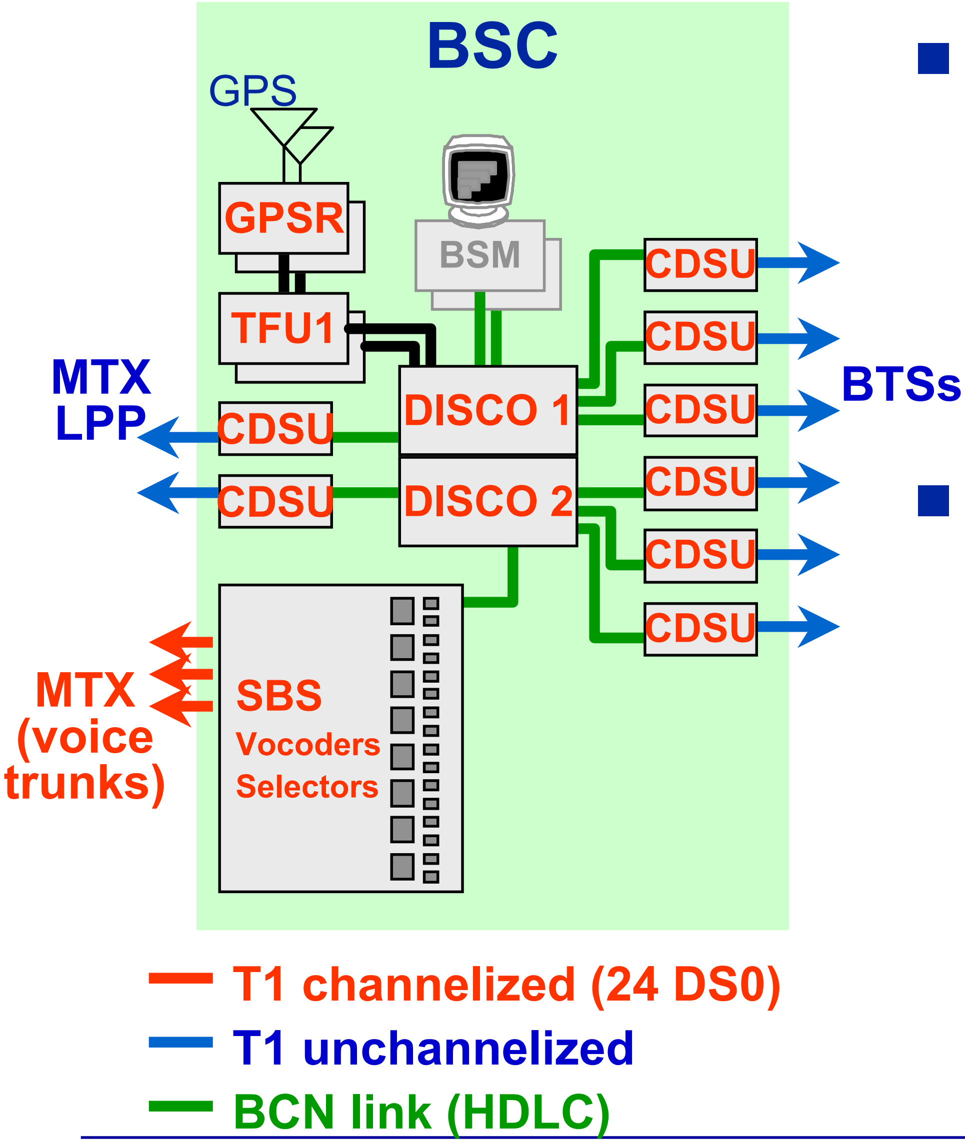


Architecture: The MTX



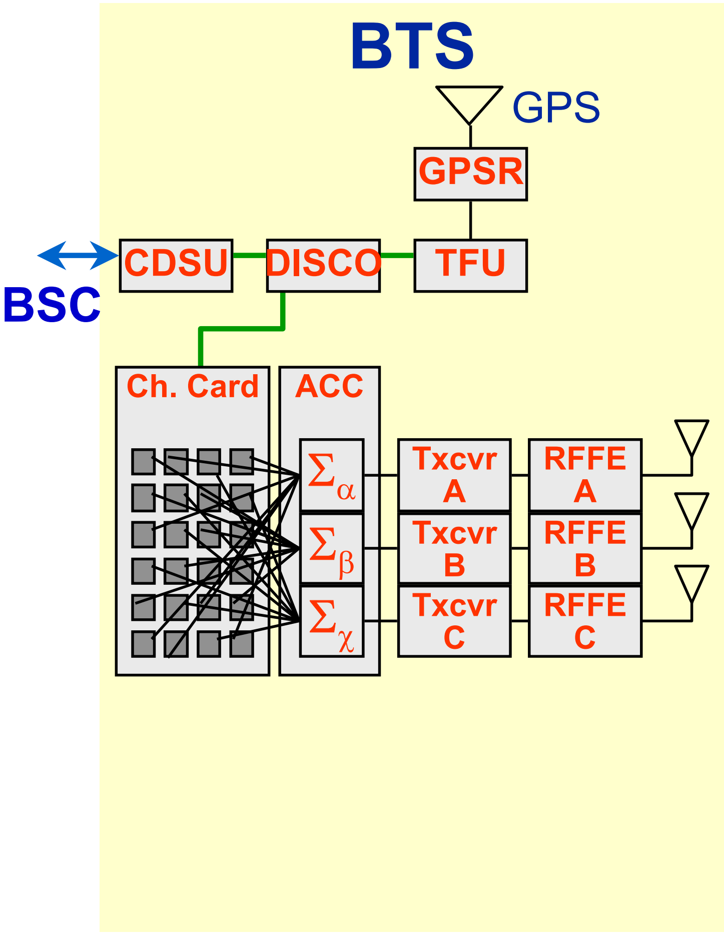
- Primary functions
  - Call Processing
  - Mobility Management
    - HLR-VLR access
    - Intersystem call delivery (IS-41C)
    - Inter-MTX handover (IS-41C)
  - Billing Data Capture
  - Calling Features & Services
  - Collecting System OMs, Pegs
- High reliability, redundancy

Architecture: The BSC



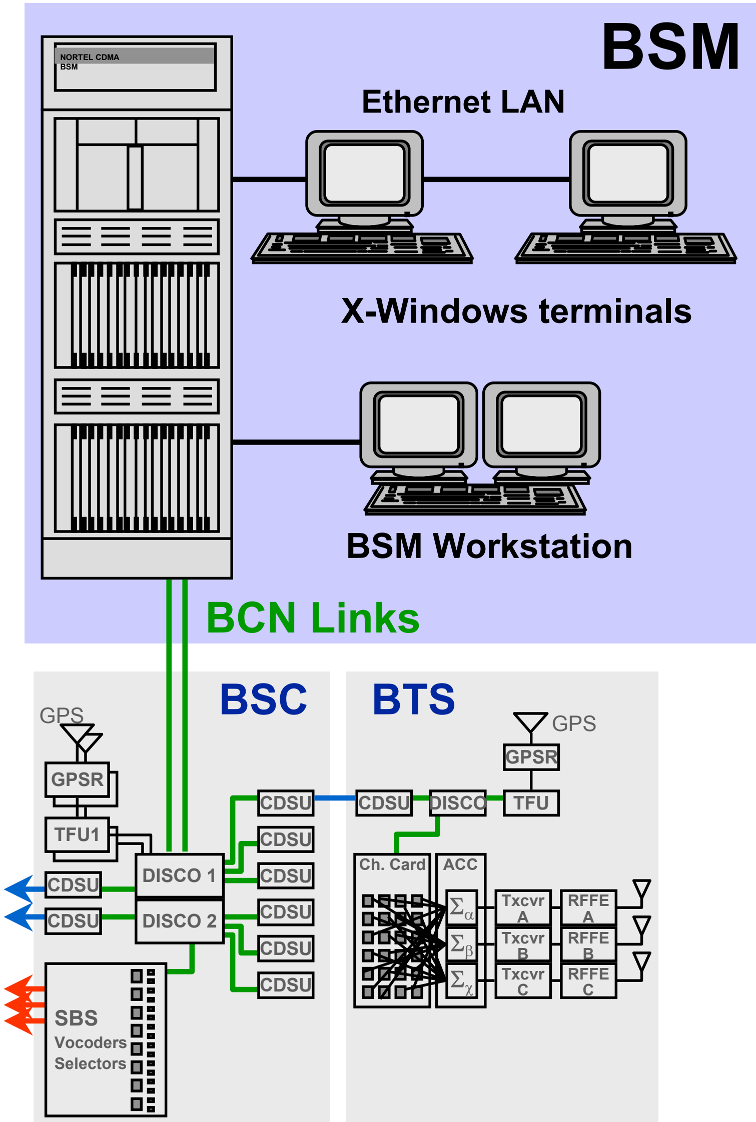
- Primary functions
  - vocoding
  - soft handoff management
  - FER-based power control
  - routing of all traffic and control packets
- Scaleable architecture
  - expand SBS to keep pace with traffic growth
  - expandable DISCO

Architecture: The BTS



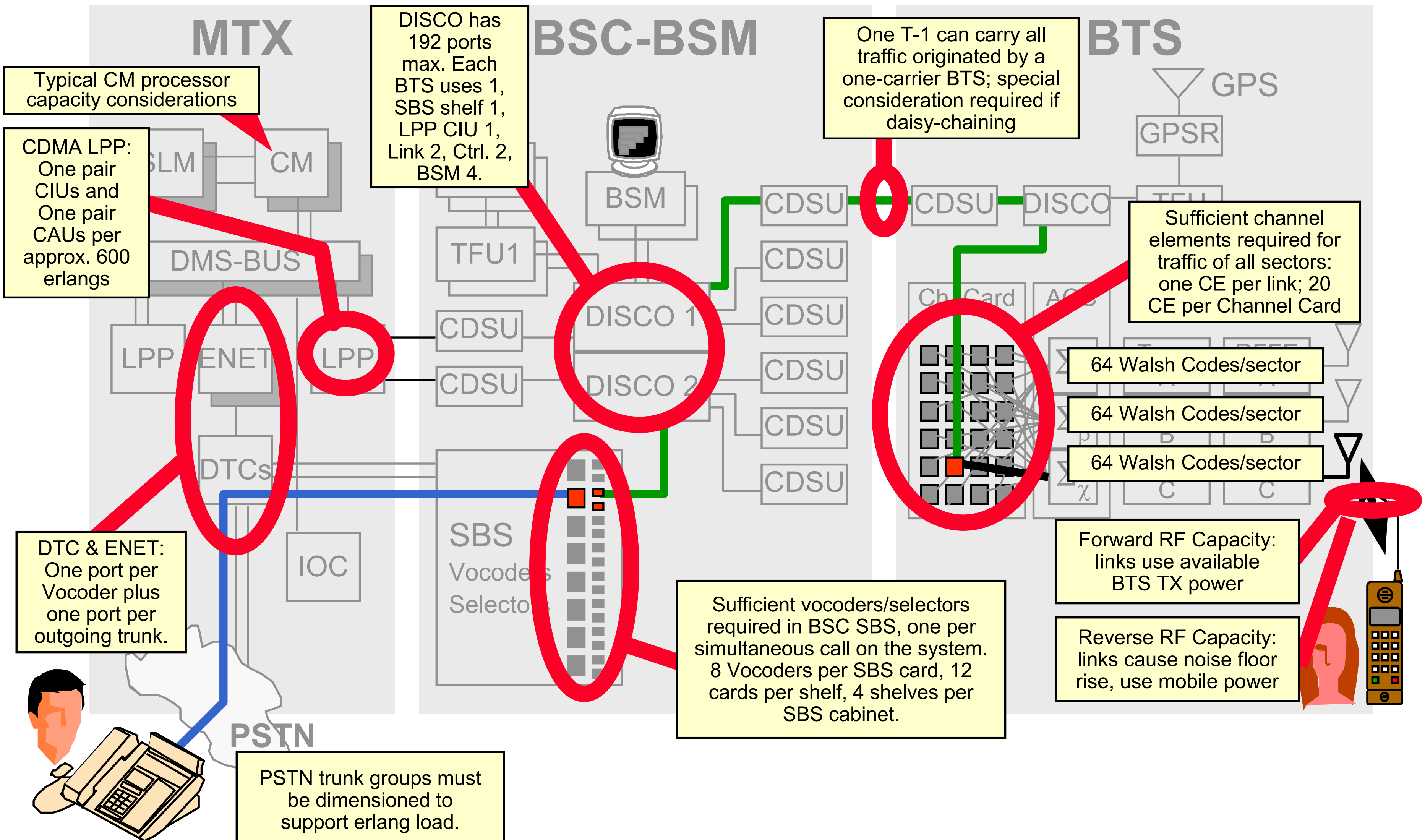
- Primary function: Air link
  - generate, radiate, receive CDMA RF signal IS-95/J.Std. 8
  - high-efficiency T1 backhaul
  - test capabilities
- Configurations
  - 1, 2, or 3 sectors
  - 800 MHz.: indoor
  - 1900 MHz.: self-contained outdoor, remotable RFFEs
  - future: 1900 MHz. indoor, 800 & 1900 multi-carrier options

Architecture: The BSM



- Primary functions: OA&M for CDMA components
  - Configuration management
    - BSC, BTS configuration and parameters
  - Fault management
    - Alarm Reporting
  - Performance management
    - interface for CDMA statistics and peg counts collection
  - Security management
  - Unix-based

Summary of CDMA Capacity Considerations



CDMA Message Structure & Protocols

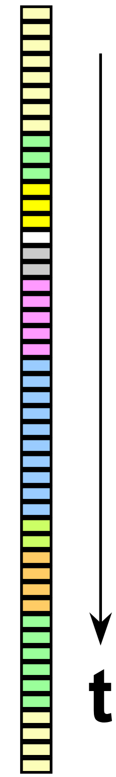
- CDMA messages on both forward and reverse links are normally sent via dim-and-burst
- Messages include many fields of binary data
- The first byte of each message identifies message type to allow the recipient to parse the contents
- To ensure no messages are missed, all CDMA messages bear serial numbers and important messages contain a bit set to request acknowledgment
- Messages not promptly acknowledged are retransmitted several times, after which the sender may release the call
- Collection tools parse all messages for review and analysis

EXAMPLE:
A POWER MEASUREMENT REPORT MESSAGE

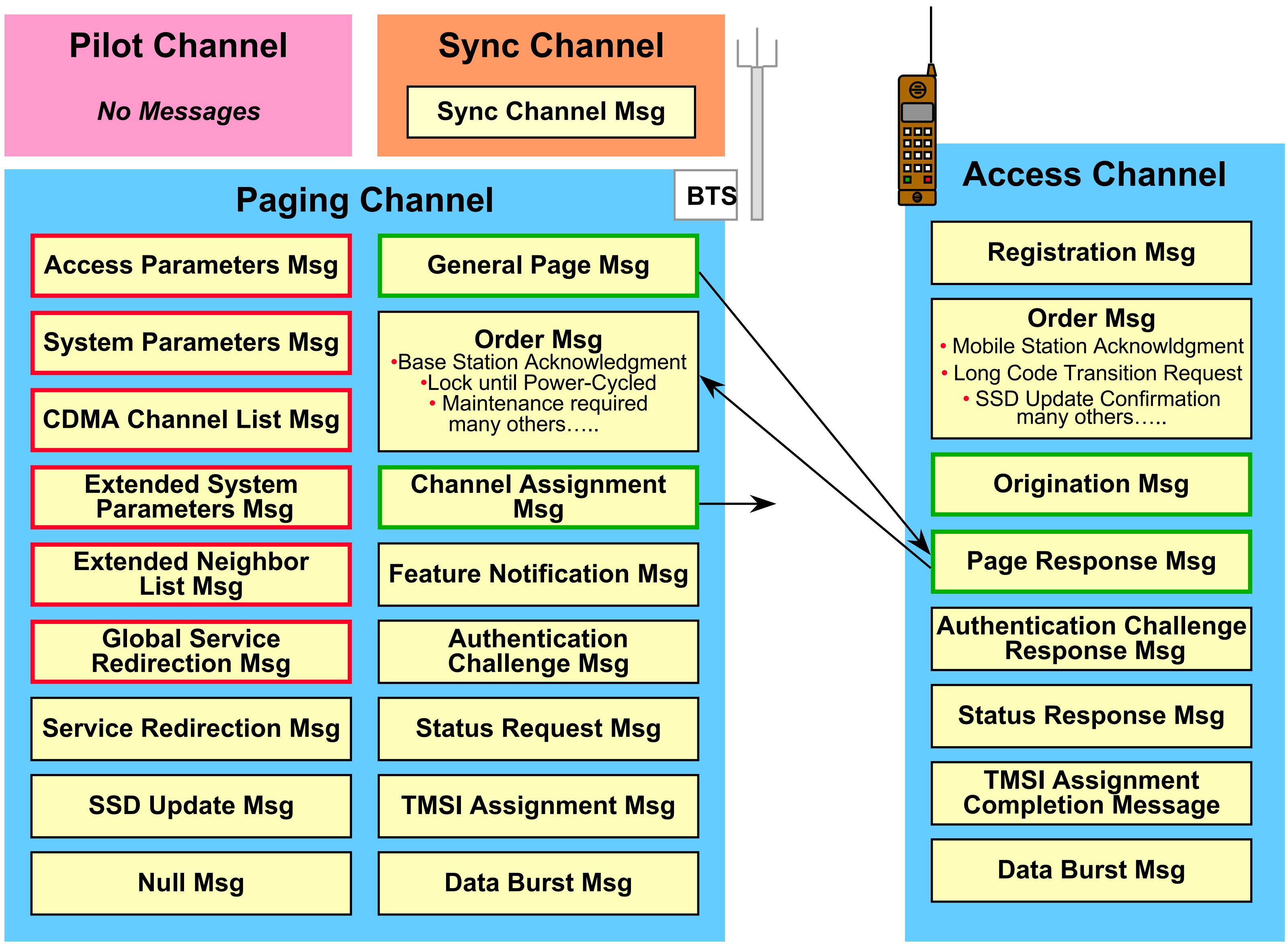
Field	Length (in bits)
MSG_TYPE (‘00000110’)	8
ACK_SEQ	3
MSG_SEQ	3
ACK_REQ	1
ENCRYPTION	2
ERRORS_DETECTED	5
POWER_MEAS_FRAMES	10
LAST_HDM_SEQ	2
NUM_PILOTS	4

NUM_PILOTS occurrences of this field:

Field	Length (in bits)
PILOT_STRENGTH	6
RESERVED (‘0’s)	0-7



Messages In Acquisition and Idle States



Messages During a Call: Conversation State

Forward Traffic Channel

- **Order Msg**
  - Base Station Acknowledgment
  - Base Station Challenge Confirmation
  - Message Encryption Mode
- **Authentication Challenge Msg**
- **TMSI Assignment Msg**
- **Send Burst DTMF Msg**
- **Set Parameters Msg**
- **Power Control Parameters Msg.**
- **Retrieve Parameters Msg**
- **Analog Handoff Direction Msg**
- **SSD Update Msg**
- **Mobile Station Registered Msg**
- **Alert With Information Msg**
- **Service Request Msg**
- **Service Response Msg**
- **Service Connect Msg**
- **Service Option Control Msg**
- **Status Request Msg**
- **Flash With Information Msg**
- **Data Burst Msg**
- **Extended Handoff Direction Msg**
- **Neighbor List Update Msg**
- **In-Traffic System Parameters Msg**

Reverse Traffic Channel

- **Service Request Msg**
- **Service Response Msg**
- **Service Connect Completion Message**
- **Service Option Control Message**
- **Status Response Msg**
- **Flash With Information Msg**
- **Data Burst Message**
- **Pilot Strength Measurement Msg**
- **Handoff Completion Msg**
- **Origination Continuation Msg**
- **Authentication Challenge Response Msg**
- **TMSI Assignment Completion Message**
- **Send Burst DTMF Msg**
- **Parameters Response Message**
- **Power Measurement Report Msg**
- **Order Message**
  - Mobile Sta. Acknowledgment
  - Long Code Transition Request
  - SSD Update Confirmation
  - Connect

How a Phone "Wakes Up": System Acquisition Process

- Power up: self diagnostics, battery check
- Find a frequency with CDMA RF
  - last frequency used? other recent history?
  - home market? preferred roaming list?
- Scan all PN offsets (Pilot W0), find best Ec/Io
- Lock Traffic Correlators on best PN offset, read the sync channel (W32)
  - learn true PN offset, SID/NID, time & leap seconds, Long Code state, paging channel
- Read the Paging Channel (W1): collect all the current configuration messages
  - System Parameters Message
  - Extended System Parameters Message
  - Access Parameters Message
  - CDMA Channel List Message
  - Extended Neighbor List Message
  - Global Service Redirection Message
- Register if required
- Now you're ready to operate!

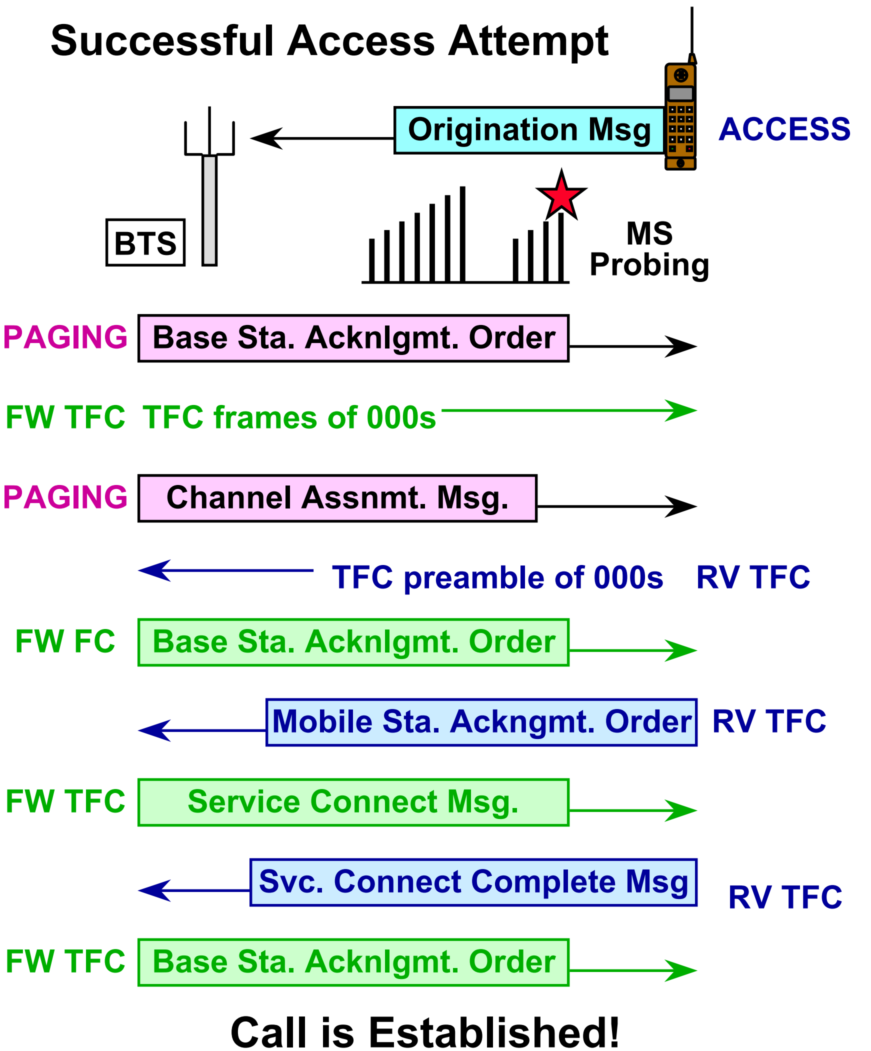
A phone goes through this system acquisition process when it first wakes up. Also, at the end of each call, it repeats the process beginning at step 3, just to ensure it is using the strongest signals available.

Phone Operation on the Access Channel

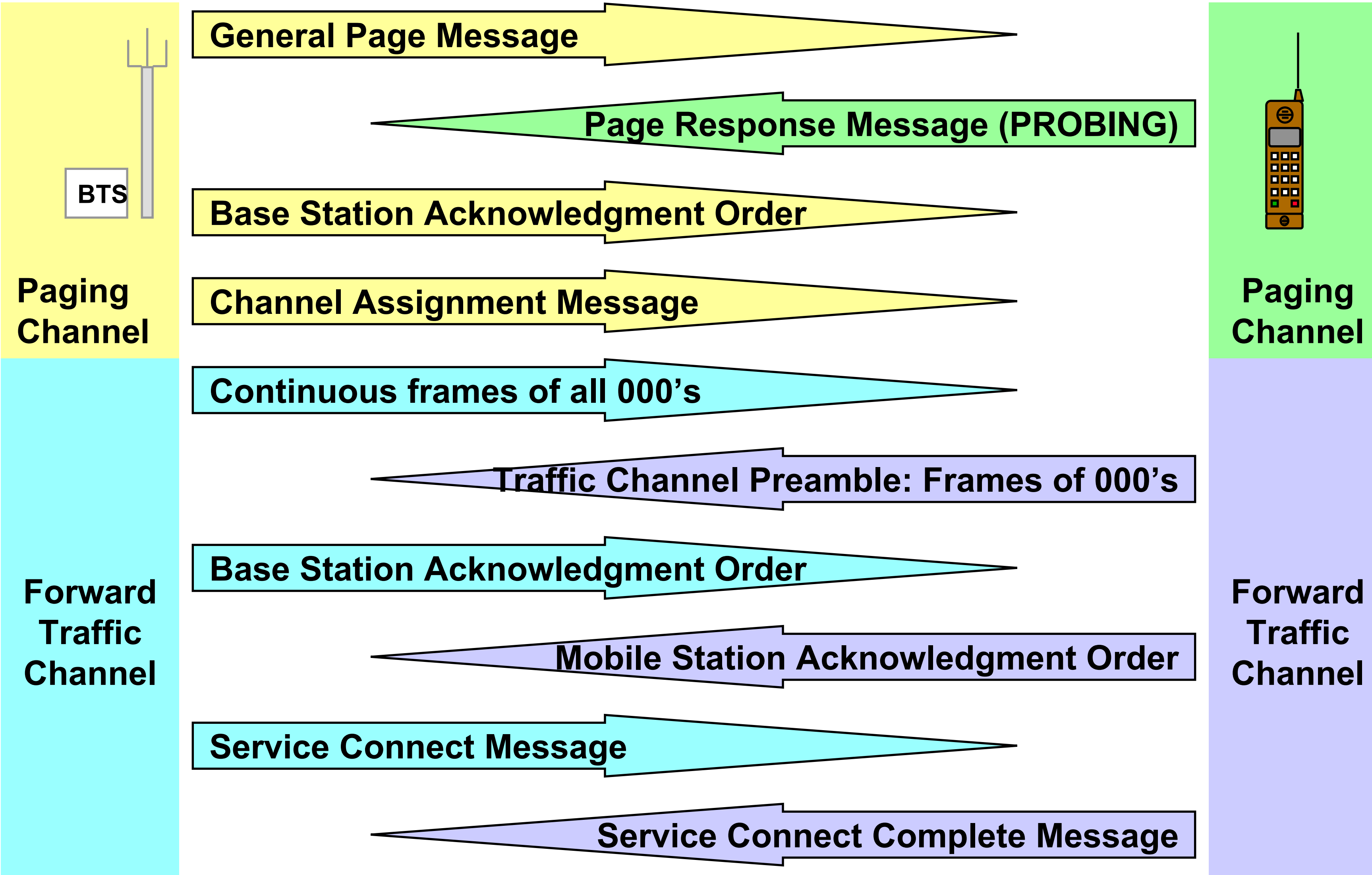
- The access channel is a long code offset defined by the paging channel. Each paging channel can have from 1 to 32 access channels, for handsets to use when attempting to first contact that sector while not yet in a call.
- Phone actions on the access channel:

Registration, Origination, Page Responses

- On the access channel, phones are not yet under BTS closed-loop power control
- Phones access the BTS by "probing" at power levels determined by receive power and an open loop formula
  - If a "probe" is not acknowledged by the BTS within about 400 mS., the phone will wait a random ~200 ms. time then probe again, stronger
  - There can be up to 15 probes in a sequence and up to 15 sequences in an access attempt
- Access Parameters message on paging channel sets values of all the parameters

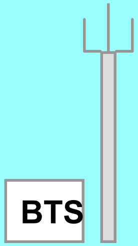


Incoming Call Delivery Scenario

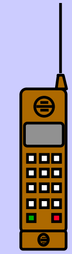


The Call is now officially Established!

The Handoff Process



Forward Traffic Channel



Forward Traffic Channel

The handset pilot searcher notices energy from another sector or BTS, meeting any of these criteria:

- •New Pilot Stronger Ec/Io than T_Add
- •Candidate Pilot just got T_Comp better than an ac tive
- •Old Pilot stayed below T_Drop for T_Tdrop time

← Pilot Strength Measurement Message

→ Base Station Acknowledgment Order

•Selector arranges channel elements/Walsh codes in requested sectors and begins using them, too.

→ Extended Handoff Direction Message

← Mobile Station Acknowledgment Order

•Handset verifies which assigned PNs it can now hear.

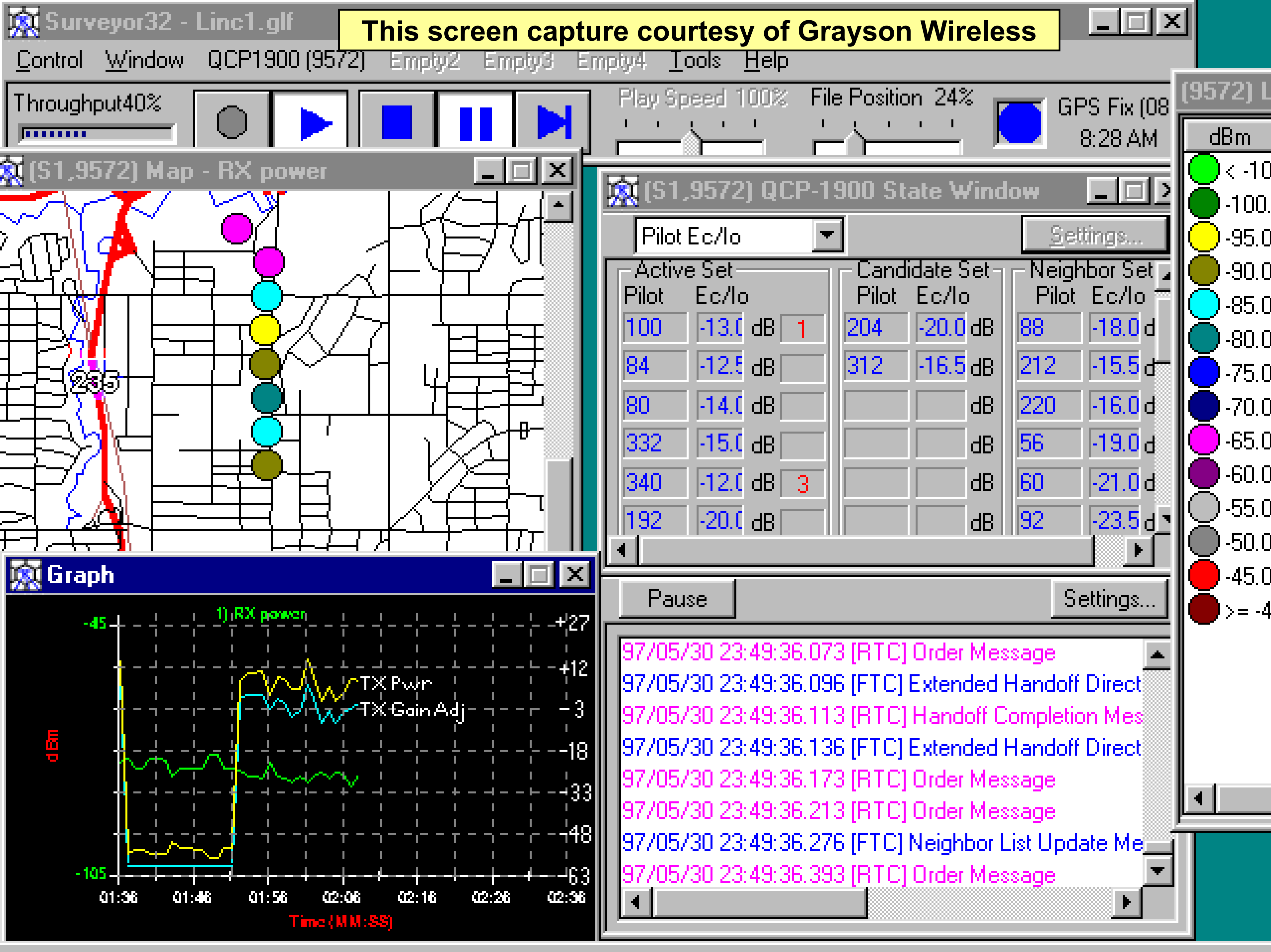
← Handoff Completion Message

→ Base Station Acknowledgment Order

→ Neighbor List Update Messasge

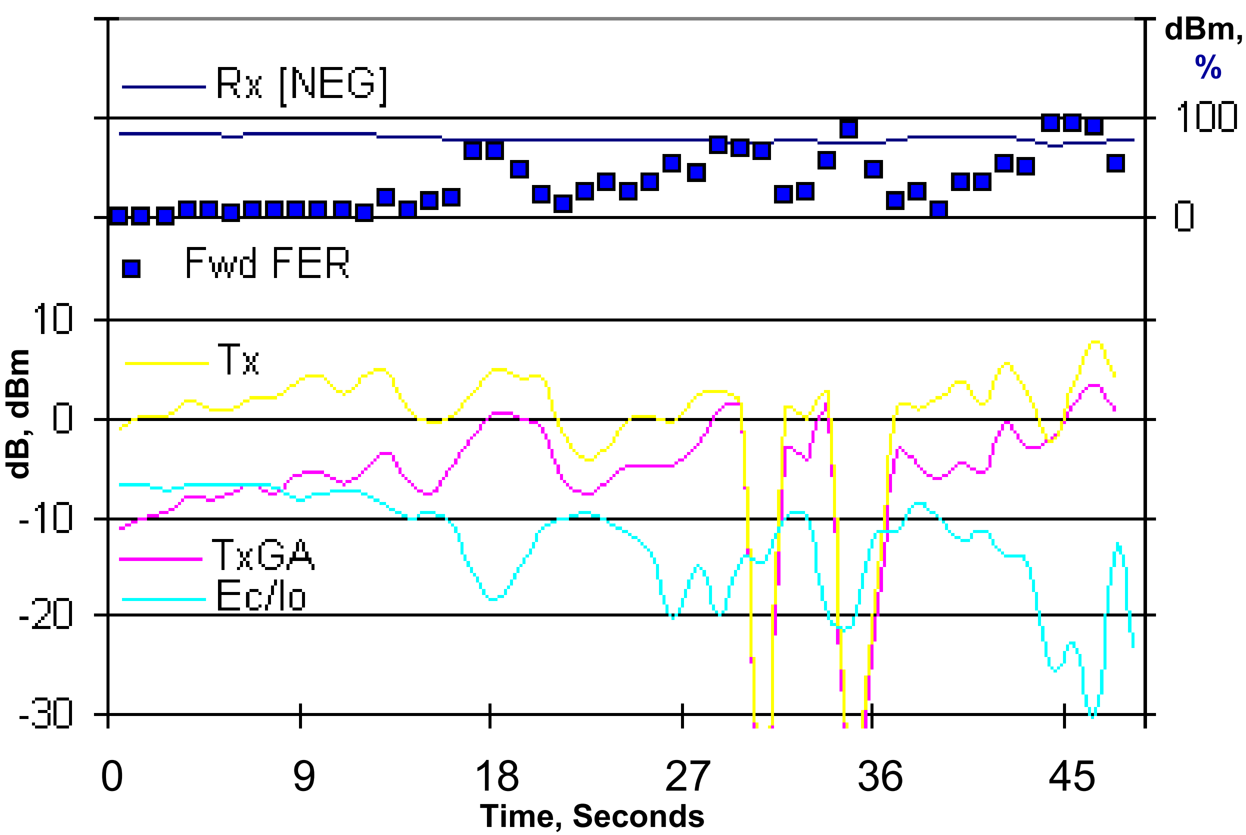
← Mobile Station Acknowledgment Order

The new Handoff condition is now officially Established!


This screen capture courtesy of Grayson Wireless
Surveyor32 - Linc1.glf
Control Window QCP1900 (9572) Empty2 Empty3 Empty4 Tools Help
Throughput40%
Play Speed 100%
File Position 24%
GPS Fix (08
8:28 AM
(S1,9572) Map - RX power
235
(S1,9572) QCP-1900 State Window
Pilot Ec/Io
Settings...
Active Set
Pilot Ec/Io
100 -13.0 dB 1
84 -12.5 dB
80 -14.0 dB
332 -15.0 dB
340 -12.0 dB 3
192 -20.0 dB
Candidate Set
Pilot Ec/Io
204 -20.0 dB
312 -16.5 dB
Neighbor Set
Pilot Ec/Io
88 -18.0
212 -15.5
220 -16.0
56 -19.0
60 -21.0
92 -23.5
Pause
Settings...
97/05/30 23:49:36.073 [RTC] Order Message
97/05/30 23:49:36.096 [FTC] Extended Handoff Direct
97/05/30 23:49:36.113 [RTC] Handoff Completion Mes
97/05/30 23:49:36.136 [FTC] Extended Handoff Direct
97/05/30 23:49:36.173 [RTC] Order Message
97/05/30 23:49:36.213 [RTC] Order Message
97/05/30 23:49:36.276 [FTC] Neighbor List Update Me
97/05/30 23:49:36.393 [RTC] Order Message
Graph
1) RX power
TX Pwr
TX Gain Adj
dBm
-45
-105
+27
+12
-3
-18
-33
-48
-63
01:36 01:46 01:56 02:06 02:16 02:26 02:36
Time (MM:SS)
(9572) L
dBm
< -10
-100.
-95.0
-90.0
-85.0
-80.0
-75.0
-70.0
-65.0
-60.0
-55.0
-50.0
-45.0
>= -4

Dropped Call Example

This dropped call is a dramatic example of big forward link problems. As the call begins, forward FER is low with good E_c/I_o, RX, TX, and TXGA. RX gets steadily better, TX and TXGA are climbing. At 18 seconds, suddenly E_c/I_o withers, FER explodes, and both TX and TXGA increase. After four scary seconds, we recover, but briefly.



E_c/I_o dives again and FER roars while RX, TX and TXGA rise. At 30 seconds, FER is so bad that the transmitter mutes. E_c/I_o recovers briefly but falters again and we mute at 34 seconds. RX, TX, and TXGA are all high. E_c/I_o briefly recovers, but then fades. The call slides to an ugly death.

Maximum Timing Budget for CDMA Cells

- The range of a CDMA cell is normally limited by the attenuation that occurs along ordinary propagation paths. Occasionally, a site is located atop a high mountain or other location from which it can see a very large distance, so large that timing considerations must be recognized. Search windows are the main concern.
- The BTS uses acquisition and demodulation search windows much like the pilot search windows used by the mobile. The maximum setting is 4095/8 chips (512 chips -1/8 chip). A mobile 38.8 miles from the site would be at the edge of this maximum window setting, and could not originate or be acquired during handoff beyond this distance.
- The mobile is not restricted on acquiring the system forward channels but its pilot search windows are limited to 452 chips. Neighbor pilots couldn't be recognized if coming from a cell more than 34.3 miles closer or farther than the cell to which the mobile is locked.
- The IS-95 and J-Std008 specify a maximum of 350 μsec maximum round trip delay, BTS-Handset. This is a distance of 32.6 miles.
- General Observation: If your cell radius exceeds 30 miles, be careful.

A Word About Soft Handoff for Former AMPS/TDMA Personnel

- Former AMPS/TDMA optimizers may feel an instinctive obligation to minimize handoff activity, with good reason. In AMPS/TDMA, handoffs involved muting and real risk of a drop. Since the mobile could be served by just one sector at a time, there was pressure to be sure it was the *best* available sector, but also pressure not to do many handoffs. *Ping-pong* is unpopular in AMPS/TDMA.
- In CDMA, there is no muting or audible effect during soft/softer handoff, and there is no pressure to use just the right sector -- if several are roughly as good, use them all, up to 6 at a time.
  - The noise level on the reverse link actually decreases during soft handoff - by roughly 4 db. - allowing the system to handle from 1.5 to 2 times as many subscribers as otherwise.
  - The forward link noise does rise, but not to troublesome levels
  - There *is* an additional cost for doing soft handoff: each involved BTS must dedicate a TCE channel element to the handoff. However, even if *every* user is *constantly* involved in soft handoff, this increases the cost of a BTS a small percentage.

How Much Soft Handoff is Normal?

- How much soft handoff is normal?
  - Expectations in early CDMA development were for roughly 35%
  - The level of soft handoff which *should* be used depends on how much diversity gain can be achieved, and terrain roughness
    - If the reverse link budget assumed 4 dB soft handoff gain, and propagation decays 35 dB/decade, 42% of the sector's area is within the last 4 dB. of coverage where soft handoff occurs.
    - In typical markets, terrain irregularities scatter RF beyond cleanly designed cell edges; soft handoff is typically 50-60%
    - In rough terrain, proper soft handoff may rise to 70% or more
- In a system not yet well-tuned, soft handoff may be clearly excessive
  - The main cause is usually excessive RF overlap between cells
  - RF coverage control is the most effective means of reducing and managing soft handoff (BTS attenuation, antenna downtilting)
  - Thresholds T_ADD and T_DROP can be adjusted to reduce soft handoff, but this penalizes mobiles that *need* soft handoff to escape interference from the excessively overlapping sites

Controlling soft handoff percentage with T_ADD and T_DROP is like limiting allowed hospital days for various illnesses. It works, but some patients may drop.

Hostile CDMA RF Environments

- The CDMA handset is designed with a digital "rake receiver" including three correlators ("fingers") which can demodulate signals from up to three sectors simultaneously, combining and using the energy from all three to improve reception. Implications:
  - If **One** dominant signal: this is a good situation; the three fingers will be looking for resolvable multipath components; good diversity
  - If **Two** usable signals: good situation; soft handoff & diversity
  - If **Three** usable signals: good situation; soft handoff & diversity
  - If **Four** roughly equal signals: workable but not ideal. Three best signals are demodulated; other remains an interferer. 3 vs. 1
  - If **Five** roughly equal signals: probably workable but not good. Three best are demodulated; remaining two are interferers. 3 vs. 2
  - If **Six** roughly equal signals: very frightening. Three best signals are demodulated; three remaining signals are interferers. 3 vs. 3
- The system can provide up to 6-way soft handoff, but anything above three-way is an indication that there is too much RF coverage overlap. More than three-way soft handoff should be the notable exception rather than the rule.