

Signal Processing in Communications II: CDMA

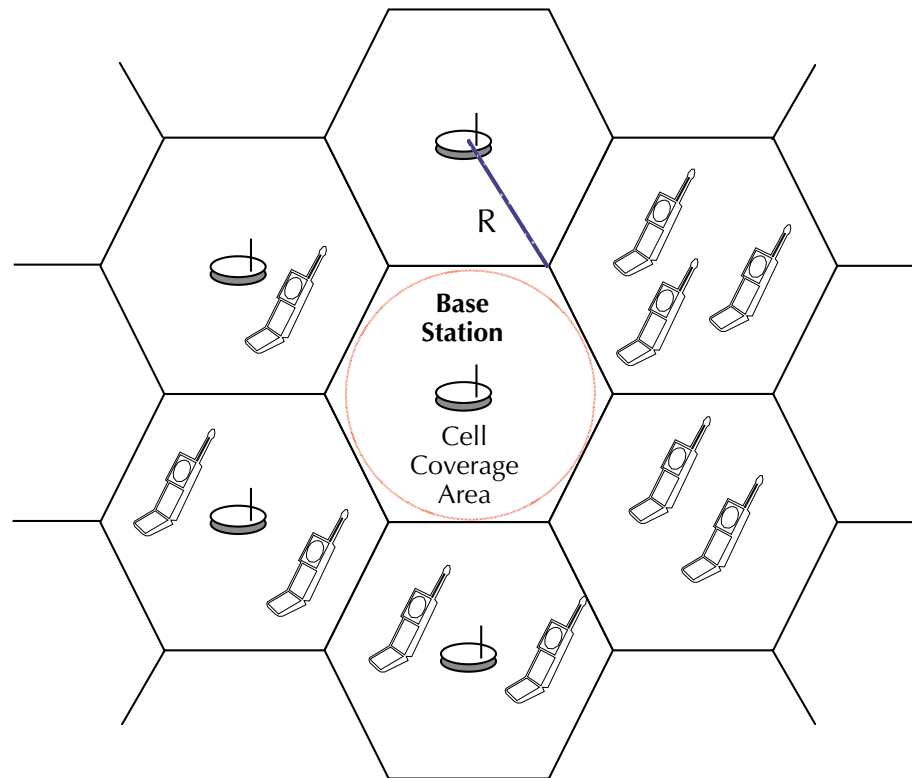
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Outline

- The Cellular Transmission Environment
- Direct-Sequence Code Division Multiple Access
- Signal Processing for CDMA
- The IS-95 CDMA Digital Cellular System
- The Next Generation: A Look at 3G Systems

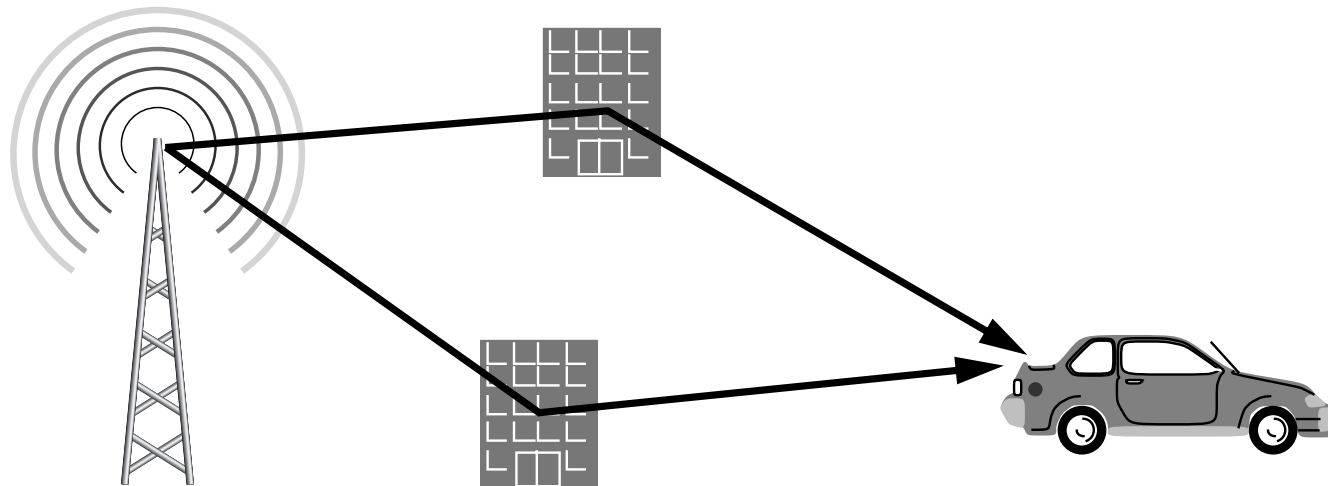
The Cellular Transmission Environment



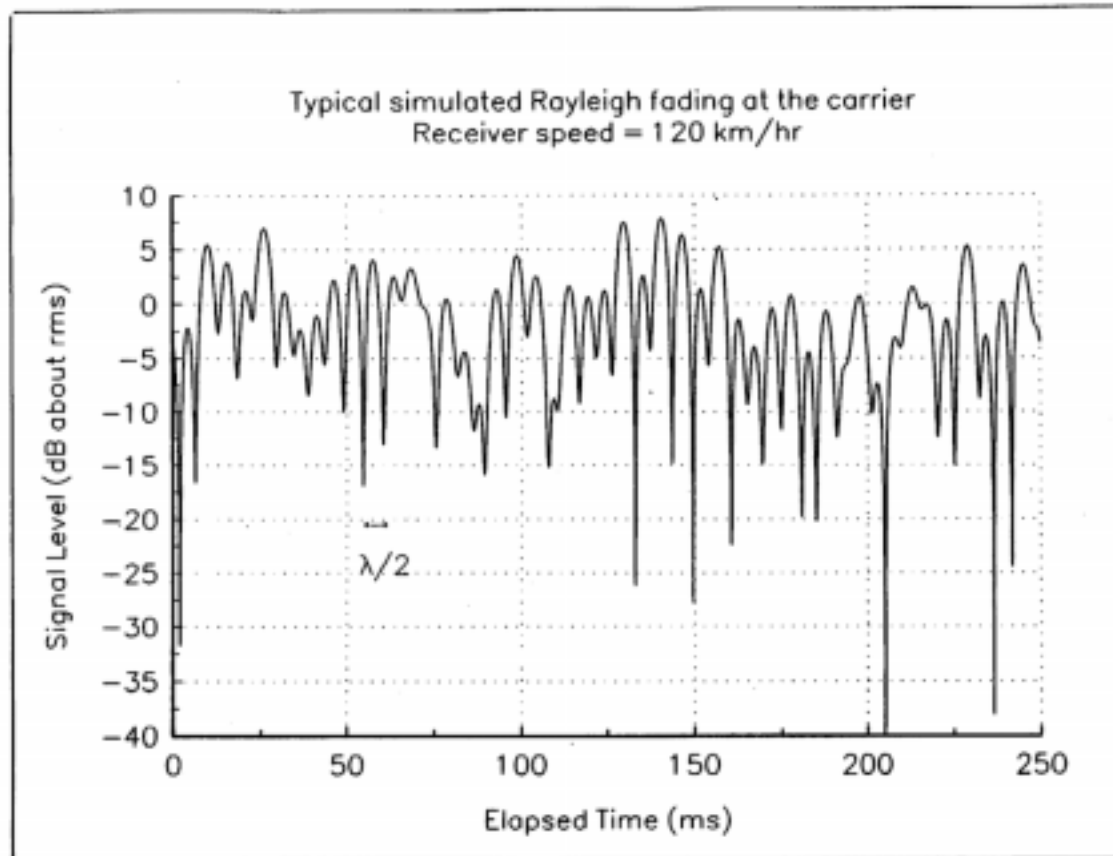
- Each cell is given a fraction of the available spectrum resources
- High dynamic range environment:
Interference floor often well above the thermal limit!
 - Intercell (cochannel/adjacent-channel) interference
 - Intracell ("self") interference

Multipath Propagation and Shadowing

- Radio waves are blocked by objects: buildings, hills, etc.
 - Dependent on local terrain, etc.
 - Slowly time-varying amplitude shifts (long-term fading)
- Radio waves reflect off of objects: buildings, people, etc.
 - Rapid time-varying amplitude shifts
 - Intersymbol interference



Fading Under Multipath Conditions: Cellular



(from [Fun93])

- Plot of received power fading over time; 900 MHz carrier
- Dynamic range due to fading alone > 40 dB
- Variability occurs on a *millisecond* basis!

Multipath Modeling

- Model the RF multipath channel as an FIR filter:

$$\text{Impulse Response } h(t) = \sum_{k=0}^{n_p} a_k \delta(t-t_k) e^{jq_k}$$

- Each $\delta(t-t_k)$ represents one received multipath arrival
- Stochastic parameters:
 - number of paths (n_p)
 - delay spread ($t_n - t_0$)
 - local mean (slow fading component of a_k)
 - phase, amplitude variation (q_k, a_k)

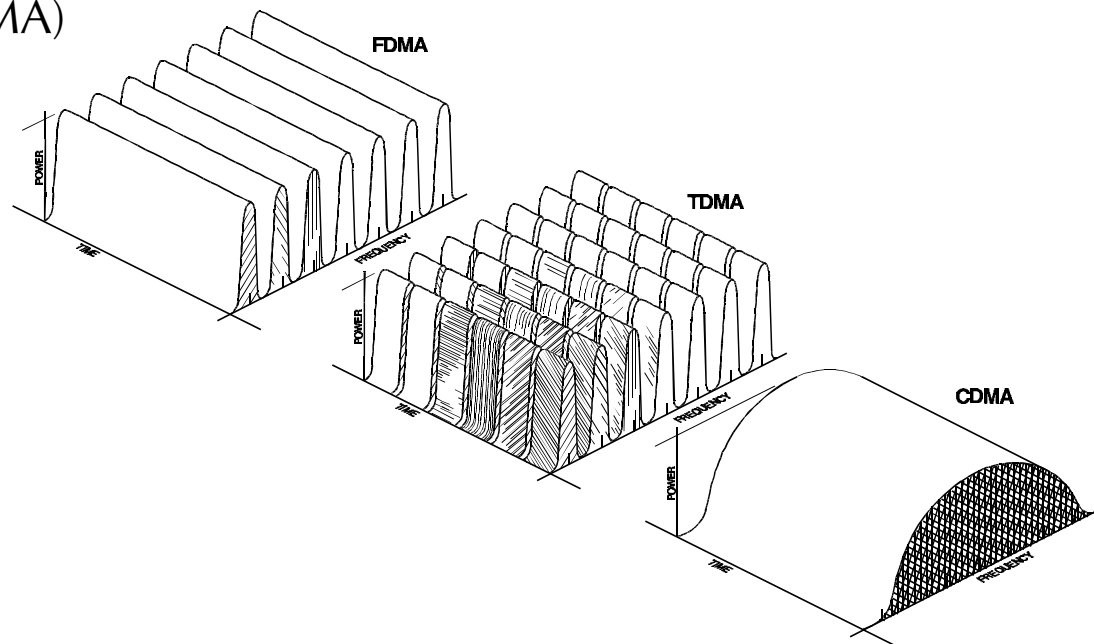
What Do We Mean by Multiple Access?

- Multiple access is the means by which limited spectral resources are allocated to users, all of whom are competing for said resources.
- Three basic multiple access strategies:

Frequency (FDMA)

Time (TDMA)

Code (CDMA)



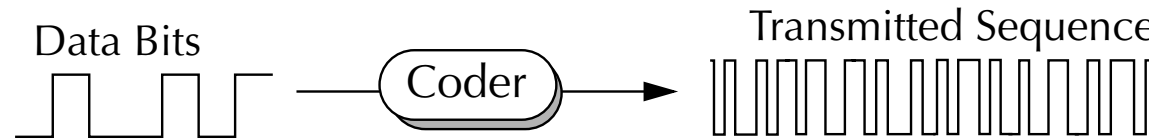
(Figure from [Qual92])

- From a theoretical standpoint, in Gaussian white noise, TDMA, CDMA, FDMA are *equivalent* in achievable capacity!!! They are different from an *implementation* standpoint only.

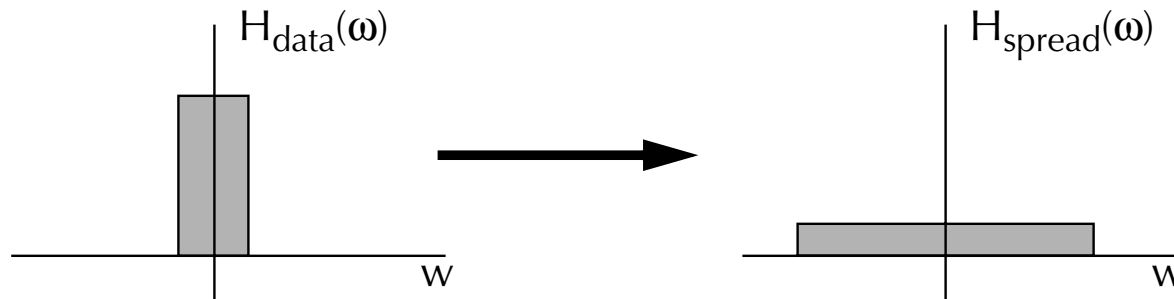
What is Direct-Sequence Spread-Spectrum?

- Idea: Each data bit is encoded into a higher-frequency, *user-specific* sequence for transmission.

- Time Domain:
Spread rate = $N \cdot \text{Bit Rate}$



- Frequency Domain:
Transmit bandwidth = $N \cdot \text{Data bandwidth}$



Concepts in Orthogonality: A Little Story....

Suppose...

User 1 wants to transmit data symbol "a"

User 2 wants to transmit data symbol "b"

We allow both users transmit *at the same time* -
but at 4X the data rate!

User 1: $a \cdot (-1 \ 1 \ -1 \ 1)$. $(-1 \ 1 \ -1 \ 1)$ is user 1's *signature sequence*

User 2: $b \cdot (1 \ 1 \ 1 \ 1)$. $(1 \ 1 \ 1 \ 1)$ is user 2's *signature sequence*

$\xrightarrow{\text{time}}$

So the receiver gets a sequence:

... (b-a), (b+a), (b-a), (b+a) ...

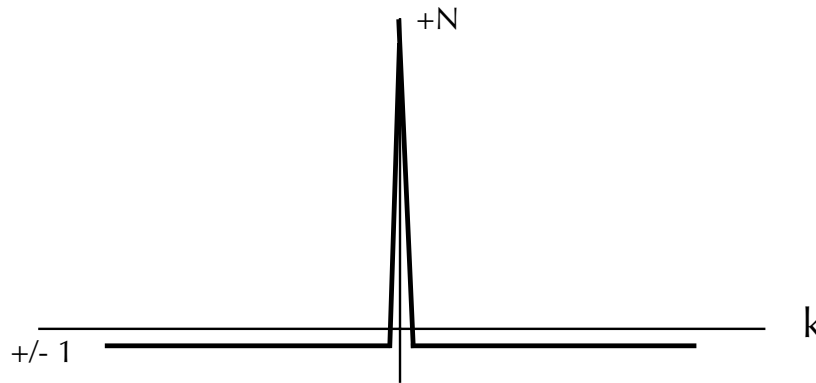
If we take an inner product of this with $(-1, 1, -1, 1)$, we get $(4 \cdot a)$!

*Because the two signature sequences are orthogonal,
we can achieve perfect recovery in the receiver!!!*

Properties of Spreading Codes

- Autocorrelation: spreading sequence $s(n)$ should “look” like white noise. If $s(n)$ is encoded as a sequence of ± 1 's:

$$\sum_{i=0}^{N-1} s(i)s((i-k)\text{modulo}N) = N\delta(k)$$

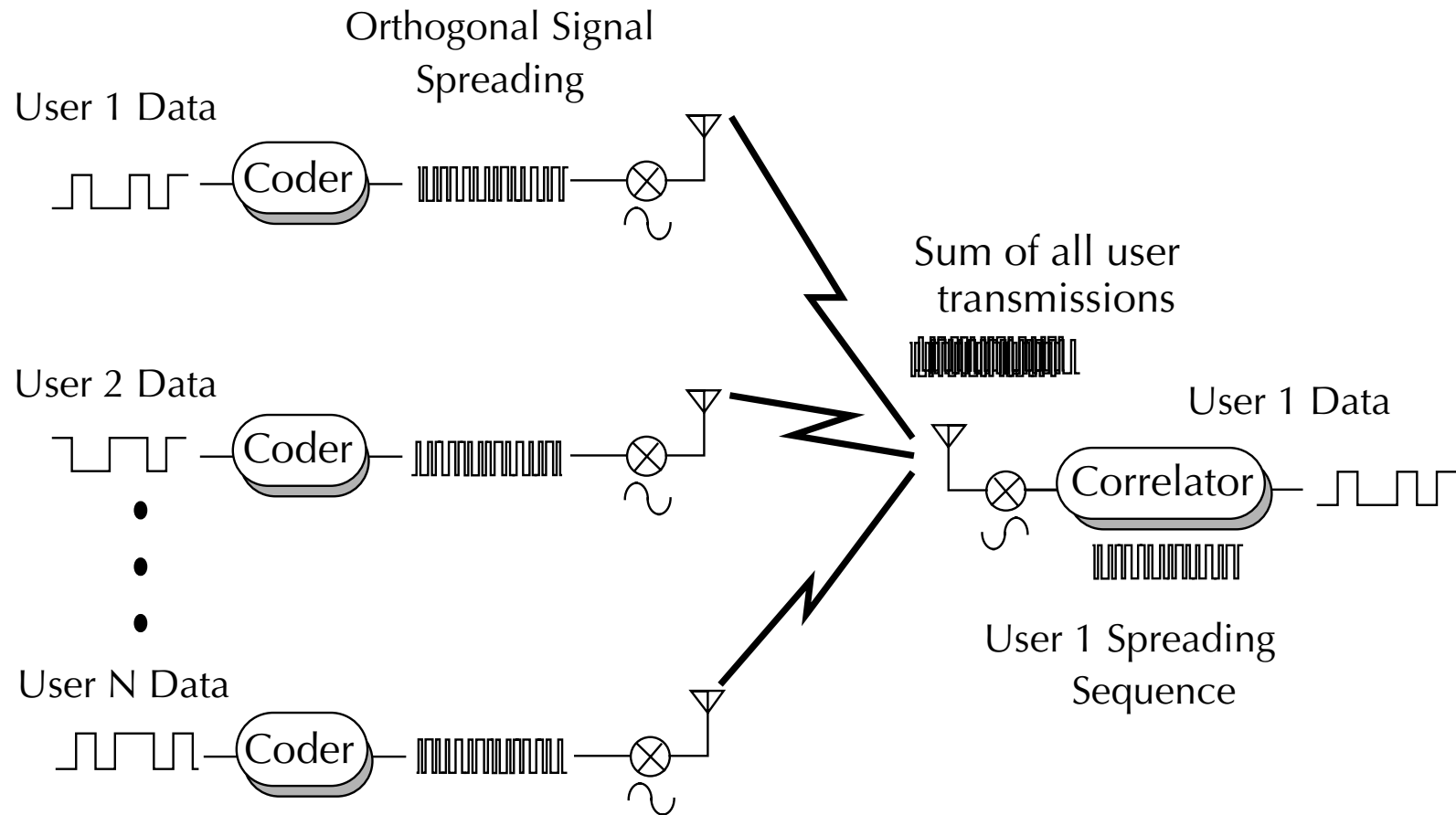


- Crosscorrelation: if $s_a(n)$ and $s_b(n)$ are both spreading sequences:

$$\sum_{i=0}^{N-1} s_a(i)s_b((i-k)\text{modulo}N) = \begin{cases} 0, & a \text{ not equal to } b \\ N\delta(k), & a \text{ equal to } b \end{cases}$$

In practice, it is extremely difficult to meet both constraints simultaneously, for a reasonably large set of codes!

Direct-Sequence CDMA

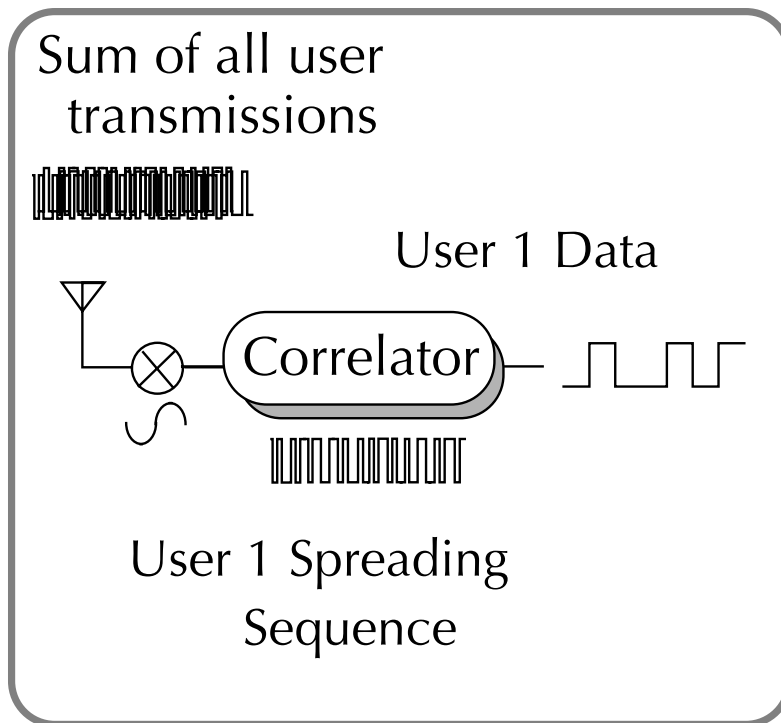


Users transmit at the same time, in the same frequency!

Key Receiver Block: The Correlator

- Matches received signal to the specific user sequence
- Effectively, it behaves as a code modulator + integrator

Basic CDMA receiver structure



$$\text{Output} = \sum_{i=1}^N W[i]X[i]$$

$W[i]$ = spreading sequence

$X[i]$ = received data

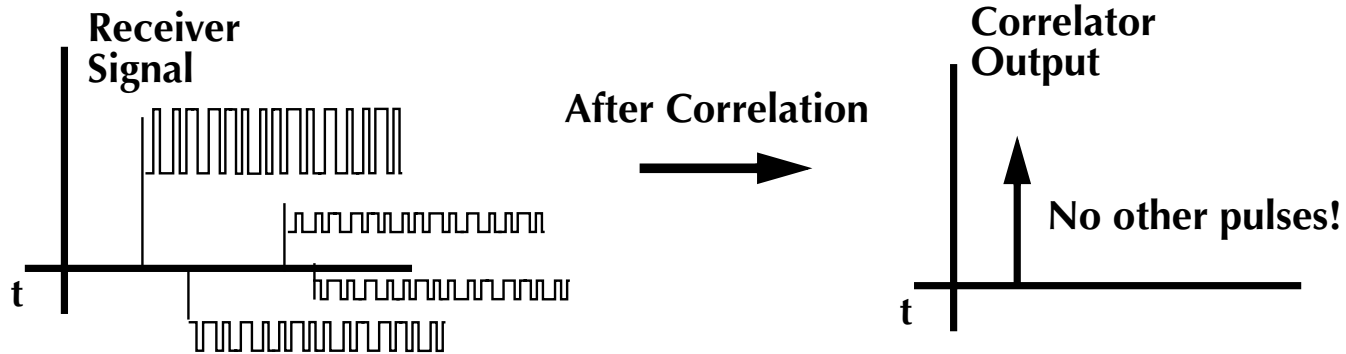
(See [Sheng96])

Issues in Spread-Spectrum System Design

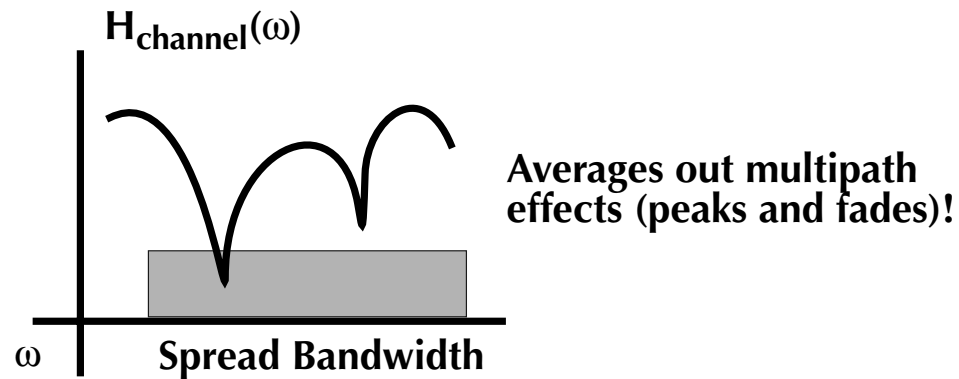
- The Near-Far Problem
 - Most codes have finite crosscorrelation performance (codes can “leak” into each other)
 - If one user close to antenna, one user far, the near user’s crosscorrelation leakage can swamp out the far user
 - Extremely accurate power control is required
- Available code space
 - Sufficient codes must exist to support the desired number of users / difficult for large number of users
- Receiver Timing Recovery
 - Since we desire perfect autocorrelation (e.g, for multipath rejection), receiver timing is critical!
 - Very accurate receiver timing recovery needed

Multipath "Immunity"

- Time Domain

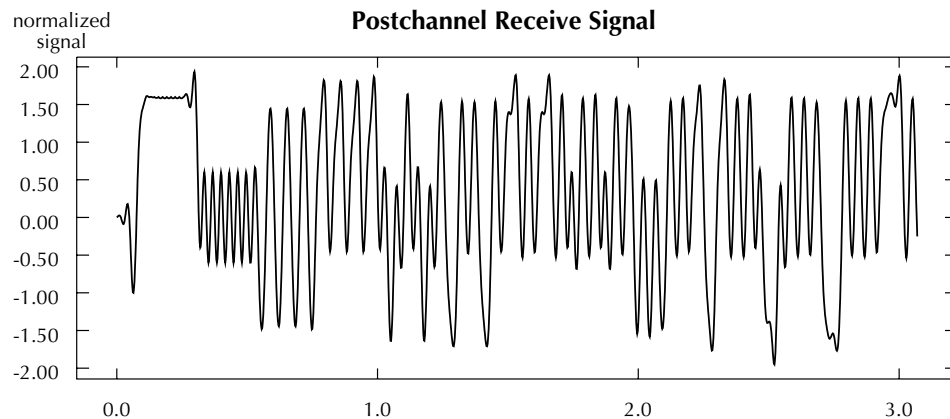
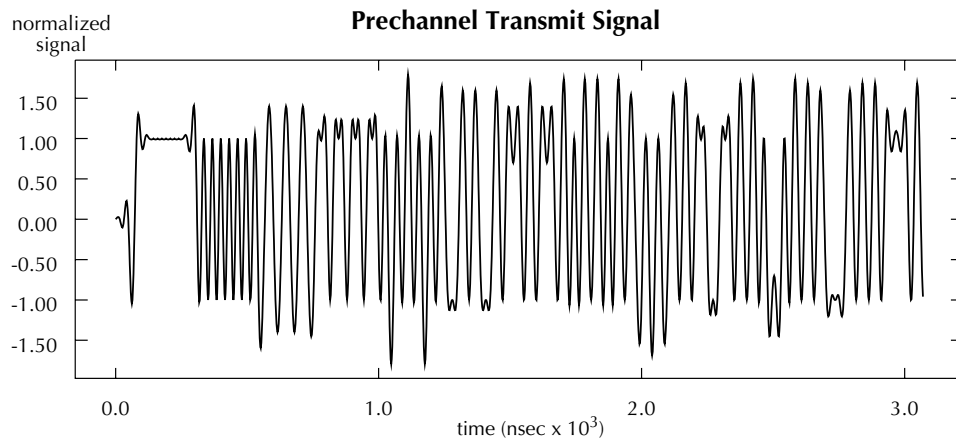
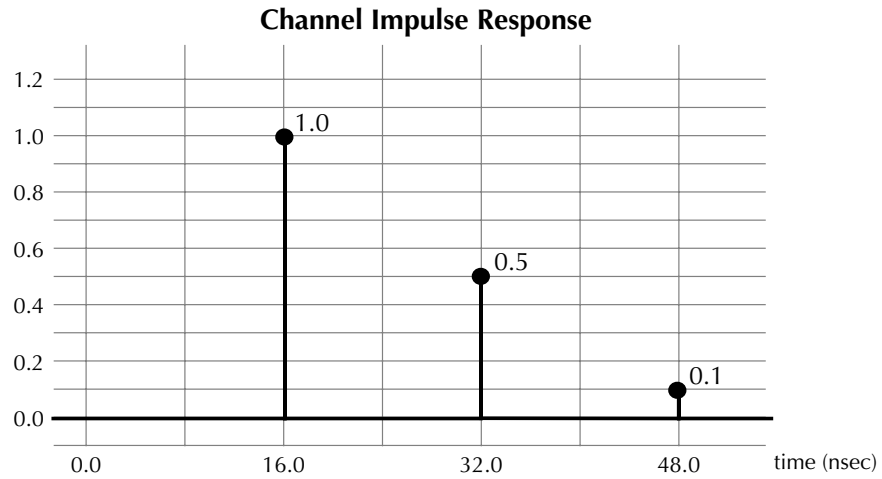


- Frequency Domain



Resolving Multipath

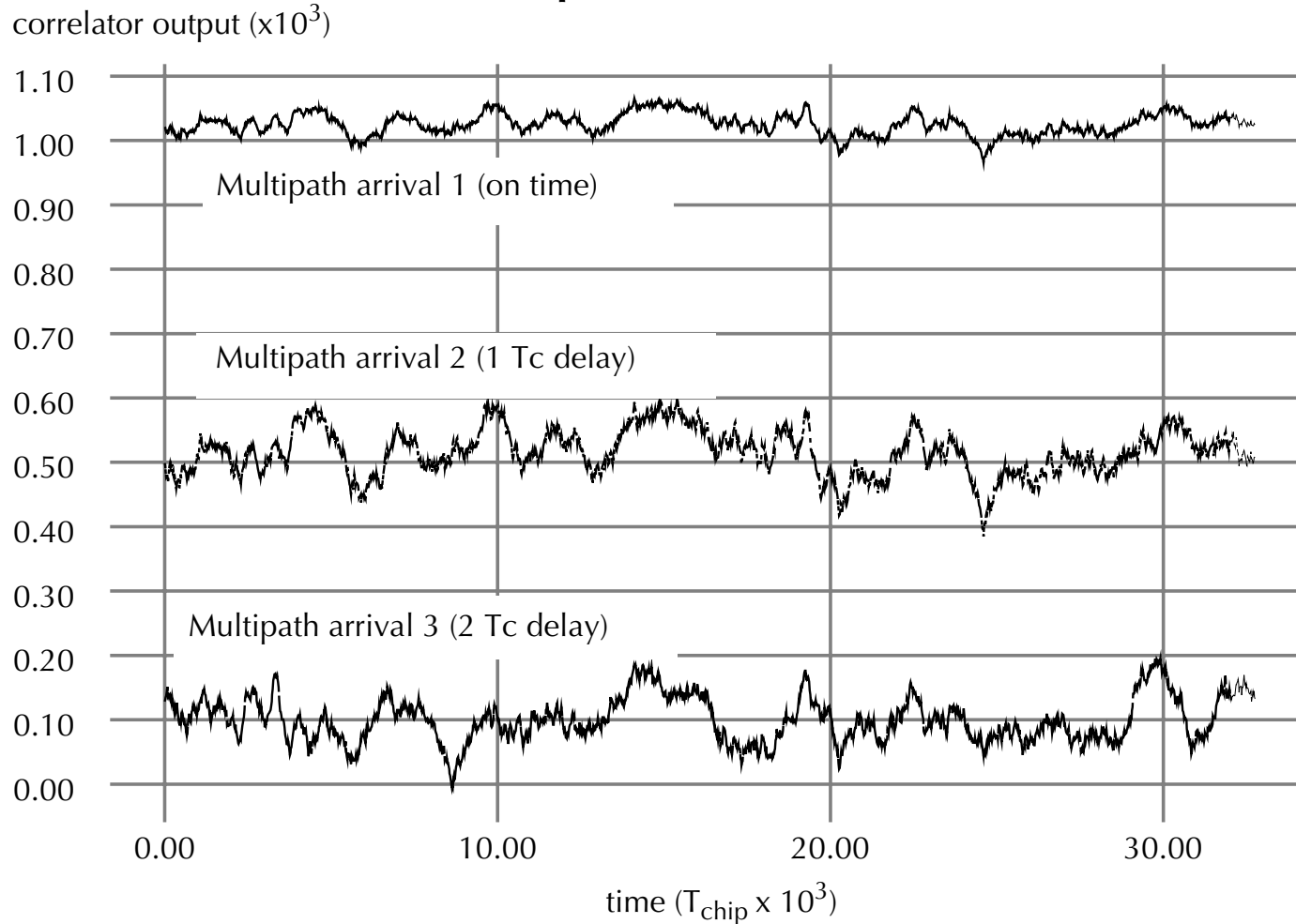
Idea: since we have nearly perfect autocorrelation, can “scan” for multipath arrivals and resolve them.



Resolving Multipath, cont.

Look at correlator outputs at $0, 1T_C, 2T_C$ ($T_C =$ chip time, 16 nsec in this case)

Multipath Profile Estimate



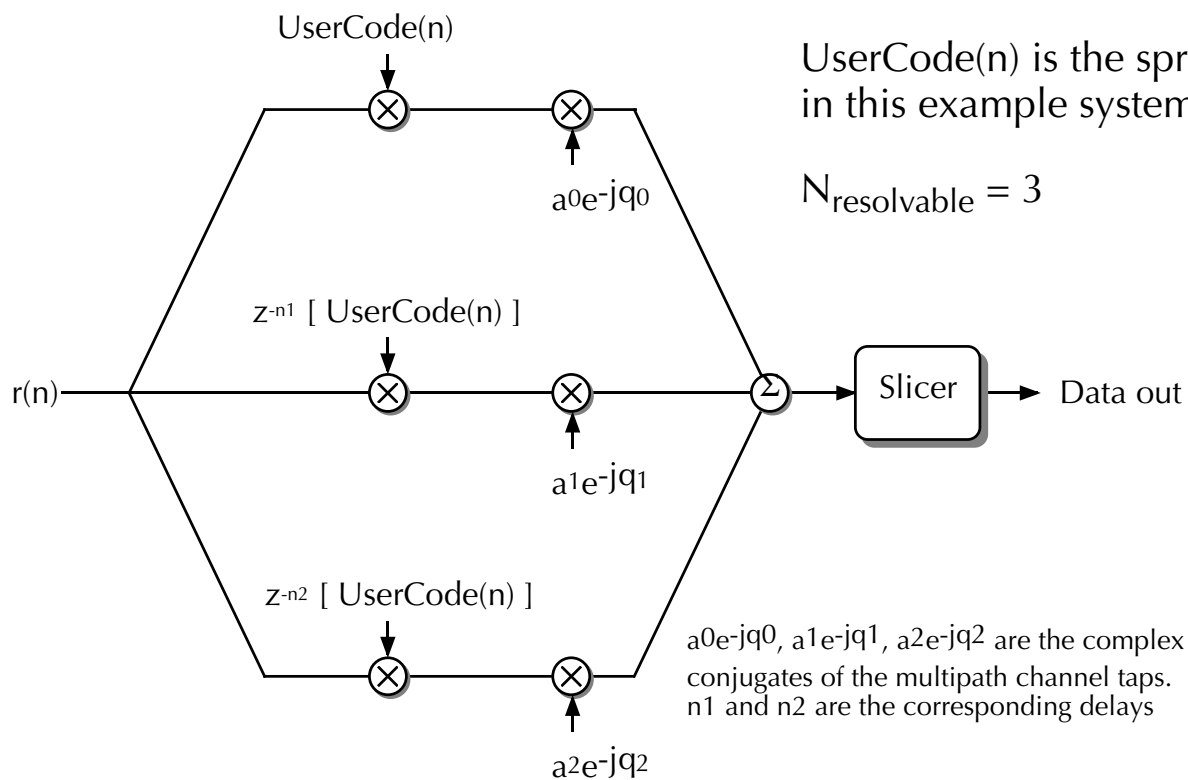
Comments

- Key point: *via signal processing, you can figure out what the channel looks like!*
- Intuitively, can only really “resolve” multipath arrivals to a time accuracy of T_{chip}
- The number of *resolvable paths* must be related to the multipath delay spread. In particular, $N_{\text{resolvable}} = (\text{Delay spread}/T_{\text{chip}}) + 1$
- The higher the spreading factor, the better resolvability/immunity you have
- “Time diversity” - transmit data is distinctly replicated in time by the multipath
- How to take advantage of this?

The RAKE Receiver

[ProakB83]

- Combine the information at each multipath arrival
 - Smaller multipath arrivals have worse SNR
 - Want to “weight” proportional to strength, and coherent in phase
- Use $N_{\text{resolvable}}$ separate receivers (fingers):



The RAKE Receiver, cont.

- How much SNR improvement?
- Assuming that the noise is uncorrelated and white in all fingers of the RAKE:

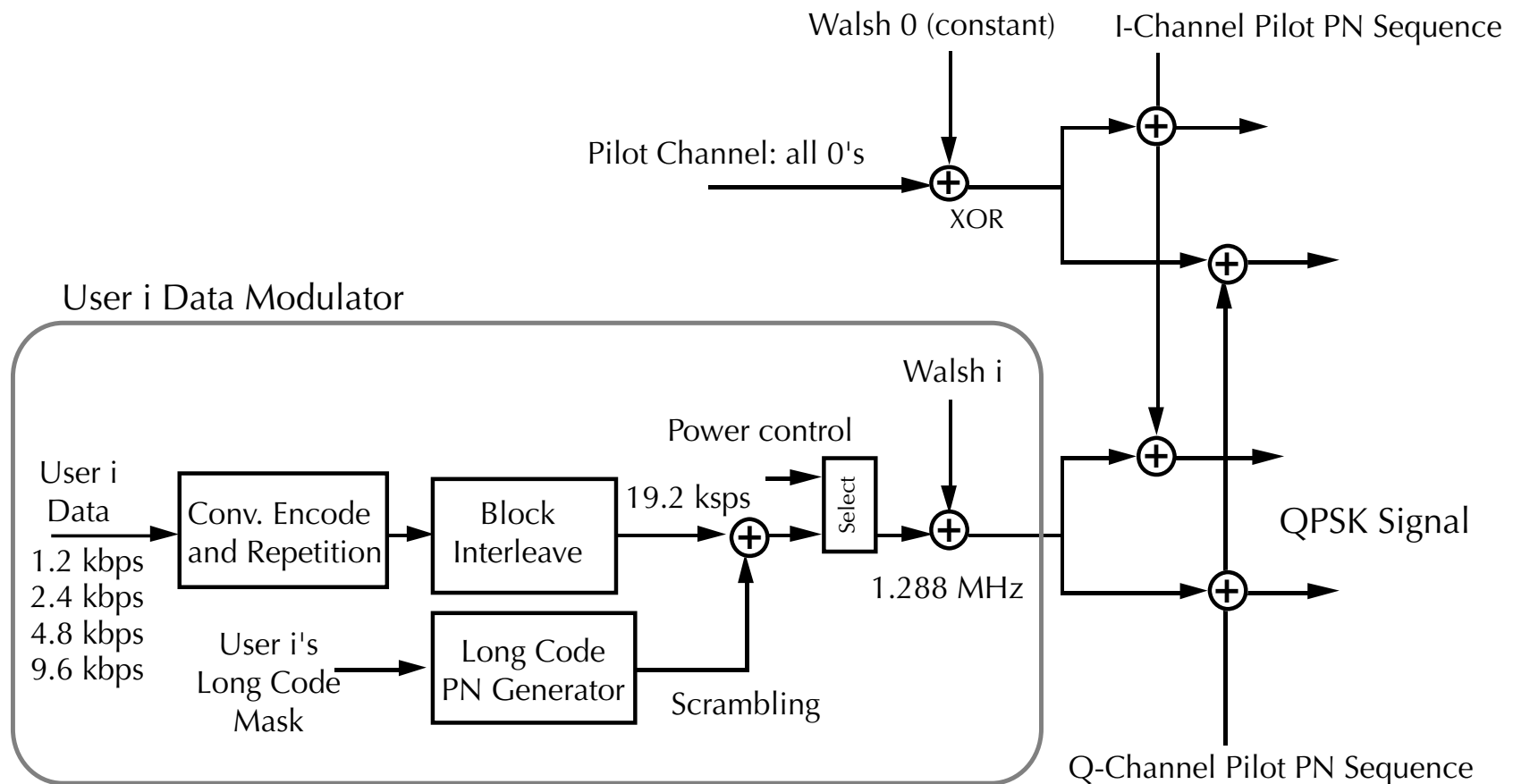
$$\text{SNR}_{\text{increase}}(\text{dB}) = 10 \log \sum_k \left| \frac{a_k}{a_0} \right|^2$$

(where $\{a_k e^{jq_k}\}$ are the complex-valued coefficients of the multipath arrivals, and k is summed from 0 to $(N_{\text{resolv}} - 1)$)

The IS-95 CDMA Digital Cellular System

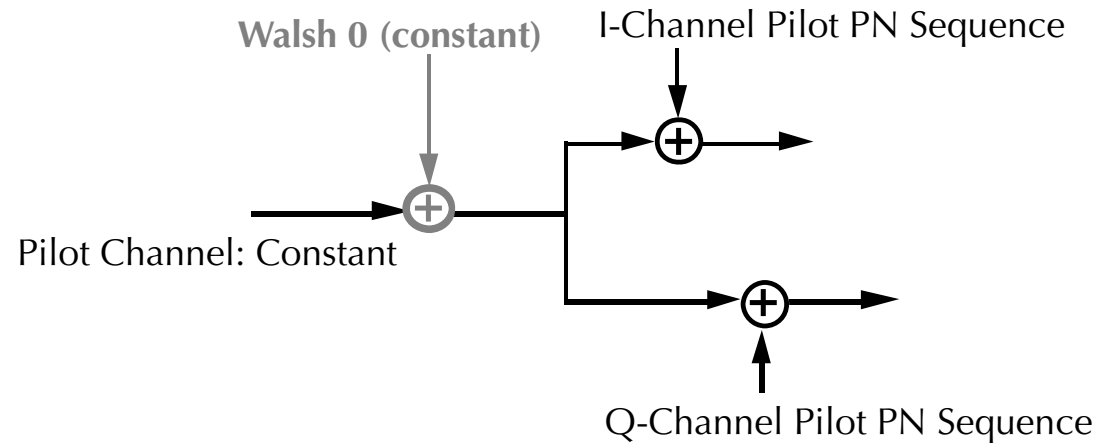
Specification	IS-95
Access Method	Combined CDMA / FDMA
Analog channel Bandwidth	1.25 MHz, + 270 kHz guardband
Channel Chip Rate	1.2288 MHz
Spreading Factor	64
Processing Gain	18.1 dB
Carrier Frequency Downlink (Base Station to Mobile) Uplink (Mobile to Base Station)	869-894 MHz 824-849 MHz
Baseband Modulation	QPSK (downlink) / Offset QPSK (uplink)
Users / Channel	Up to 62 (+1 pilot, +1 sync)
Total Available Frequency Channels	20 (however, only 10 available due to AMPS compatibility)
Spread-Spectrum Coding	Length 32768 PN (scrambling) Length 64 Walsh (per user) Pilot-assisted synchronization
Handoff	Mobile Assisted, Soft Handoff
Cell Structure	3 sectors/cell, offset PN code per cell

Forward Link Channelization



(Data & Pilot channels only)

The Pilot Tone



- Pilot tone consists of PN sequence only
- Leverage off of outstanding autocorrelation performance
 - Timing recovery
 - Adjacent cell detection
 - Multipath estimation
 - Precision power control/measurement
- Note that pilot tone detection/estimation can be done *independent* of data detection in the receiver!

Power Control for the Forward Link

- Achievable downlink system capacity a function of SNR
- How to accommodate variable user voice activity/data rate?

For lower data rate, use repetition coding:

9600 kbps = full rate voice

4800 kbps = half rate voice, repeat bits twice at lower tx power

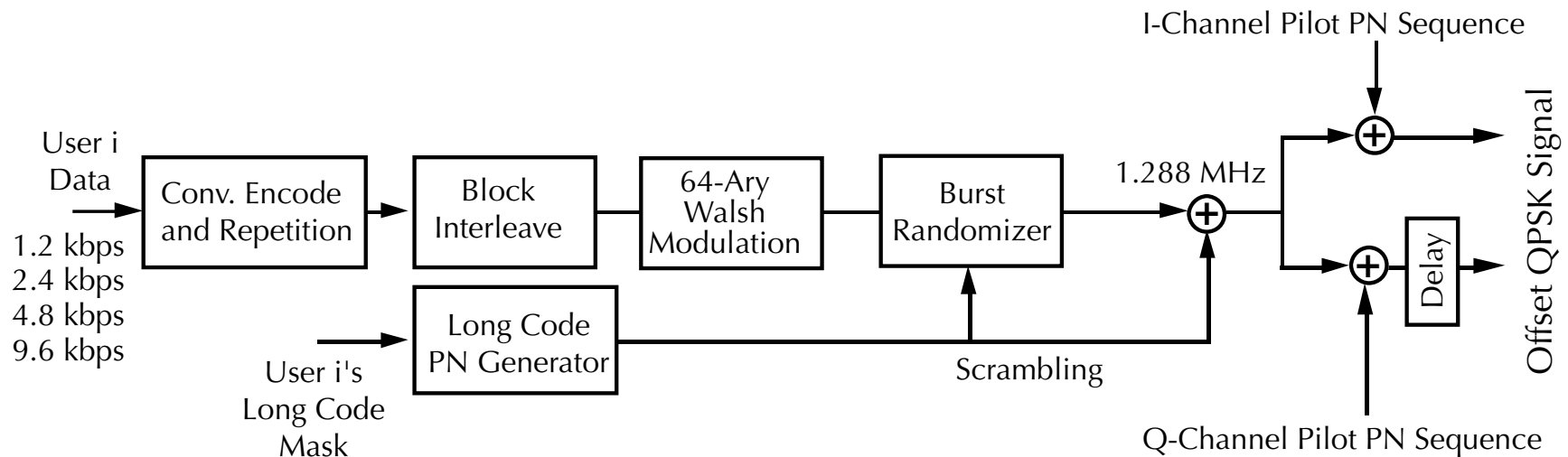
User Data Rate	9600	4800	2400	1200
ECC Coding Rate	1/2	1/2	1/2	1/2
Data Repetition	1	2	4	8
Baseband Coded Rate	19.2k	19.2k	19.2k	19.2k
PN chip rate	1.23 Mcps	1.23 Mcps	1.23 Mcps	1.23 Mcps
Coding • Spreading	128X	256X	512X	1024X

- Modulates transmit power as a function of:

Required data rate / voice activity

Mobile received signal quality (0.5 dB accurate power control)

Reverse Link Channelization

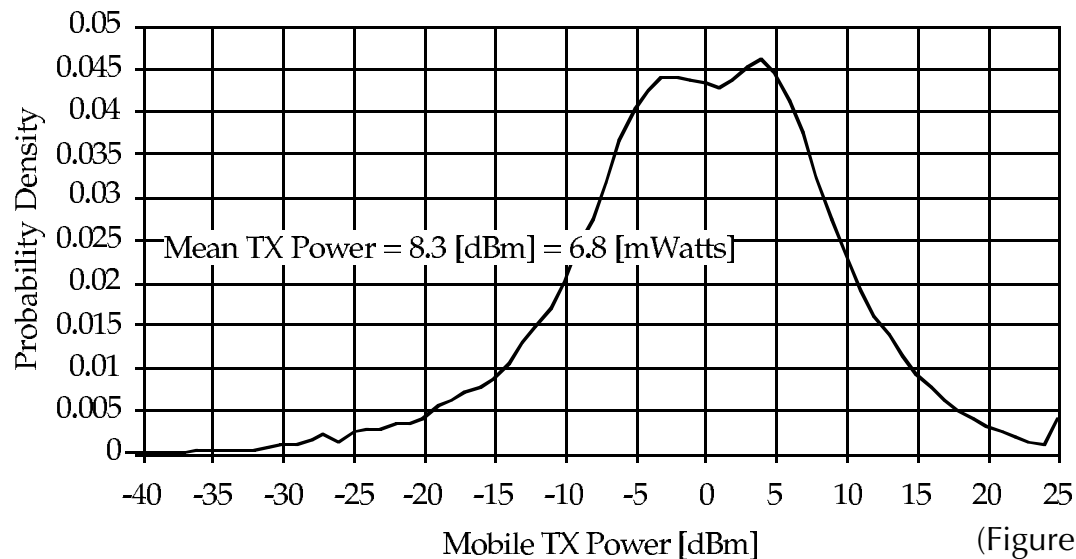


- Structurally very different from downlink
 - Downlink: user number determines the Walsh code (spreading)
 - Uplink: *data* determines the Walsh code (modulation)
- Reason for this asymmetry: difficult to synchronize the uplink
- Users are separated entirely by the long code
- Power control required for near-far avoidance at base station
 - Closed-loop control achieves 0.5 dB power accuracy

Measured Transmitted Power in Mobile

- One interesting aspect of IS-95: mobile uplinks only as much power is needed, and no more:

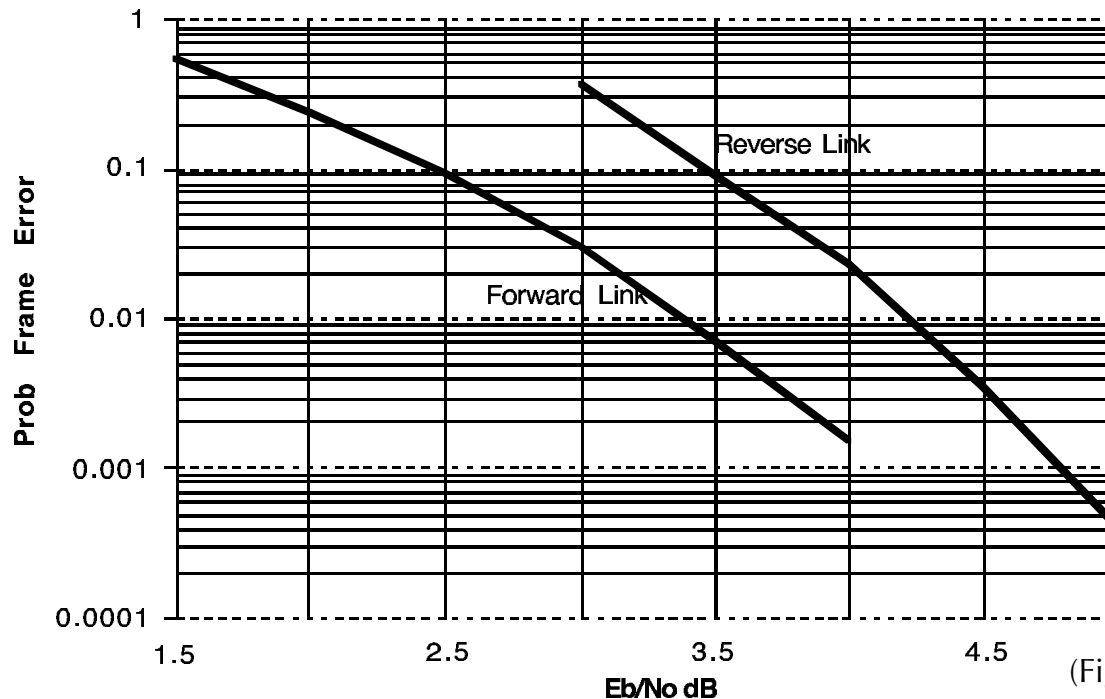
Mobile TX Power Statistics of Capacity Tests



(Figure from [QualC92])

- Can be extremely power efficient in the mobile!

Error Correction Coding



(Figure from [QualC92])

- Downlink

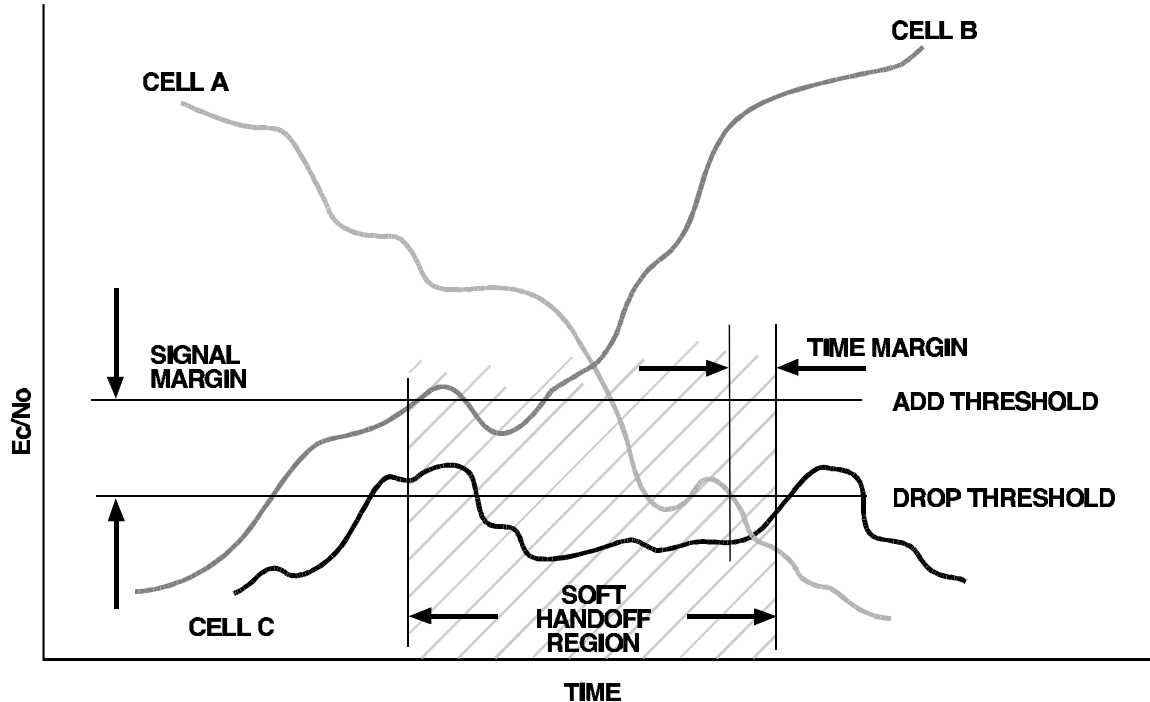
- Rate 1/2, K=9 convolutional coder
 - Repetition overlay coding
 - 20 msec block interleave

- Uplink

- Rate 1/3, K=9 convolutional coder
 - Repetition overlay coding
 - Walsh function data modulation
 - 20 msec block interleave

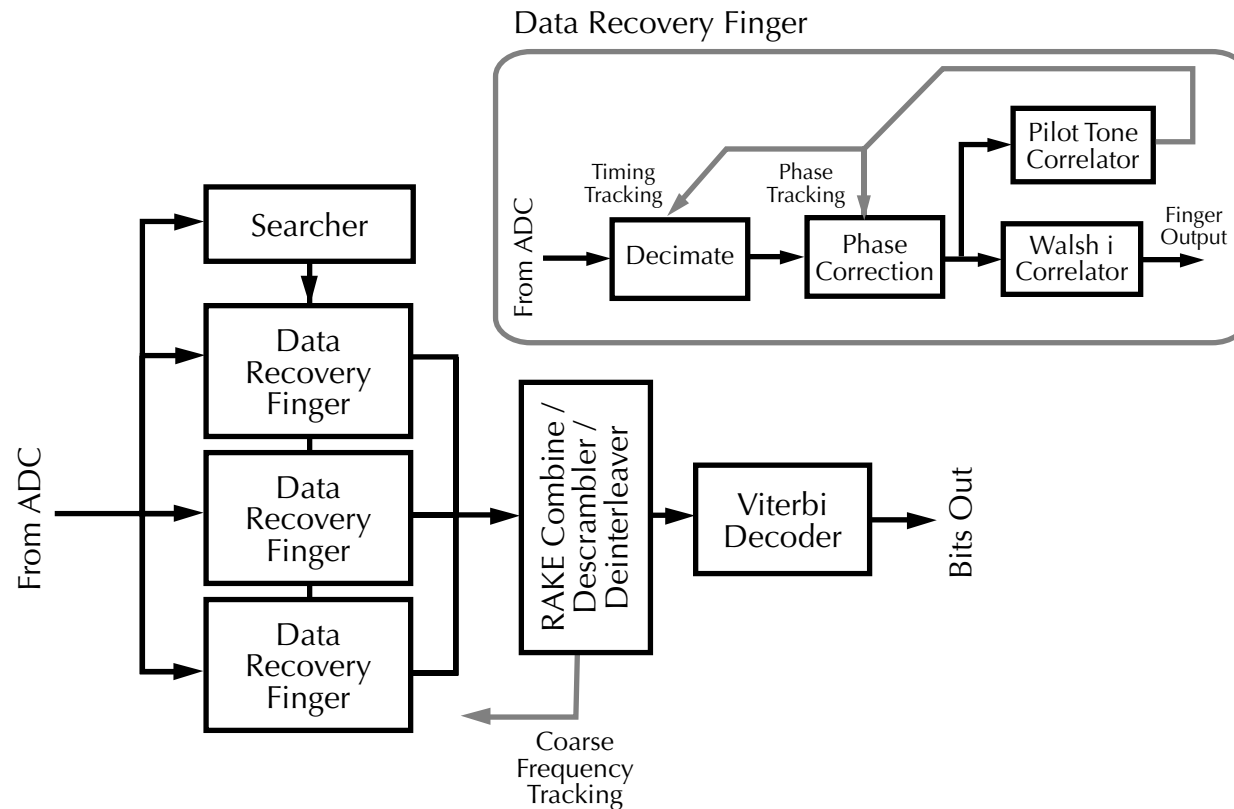
Mobile Assisted Soft Handoff

- Mobile can sense pilot tone / measure power of adjacent cells
- Handoff is “soft”: the mobile can establish link with the adjacent cell *before* full handoff is performed
- Mobile is effectively in both cells simultaneously



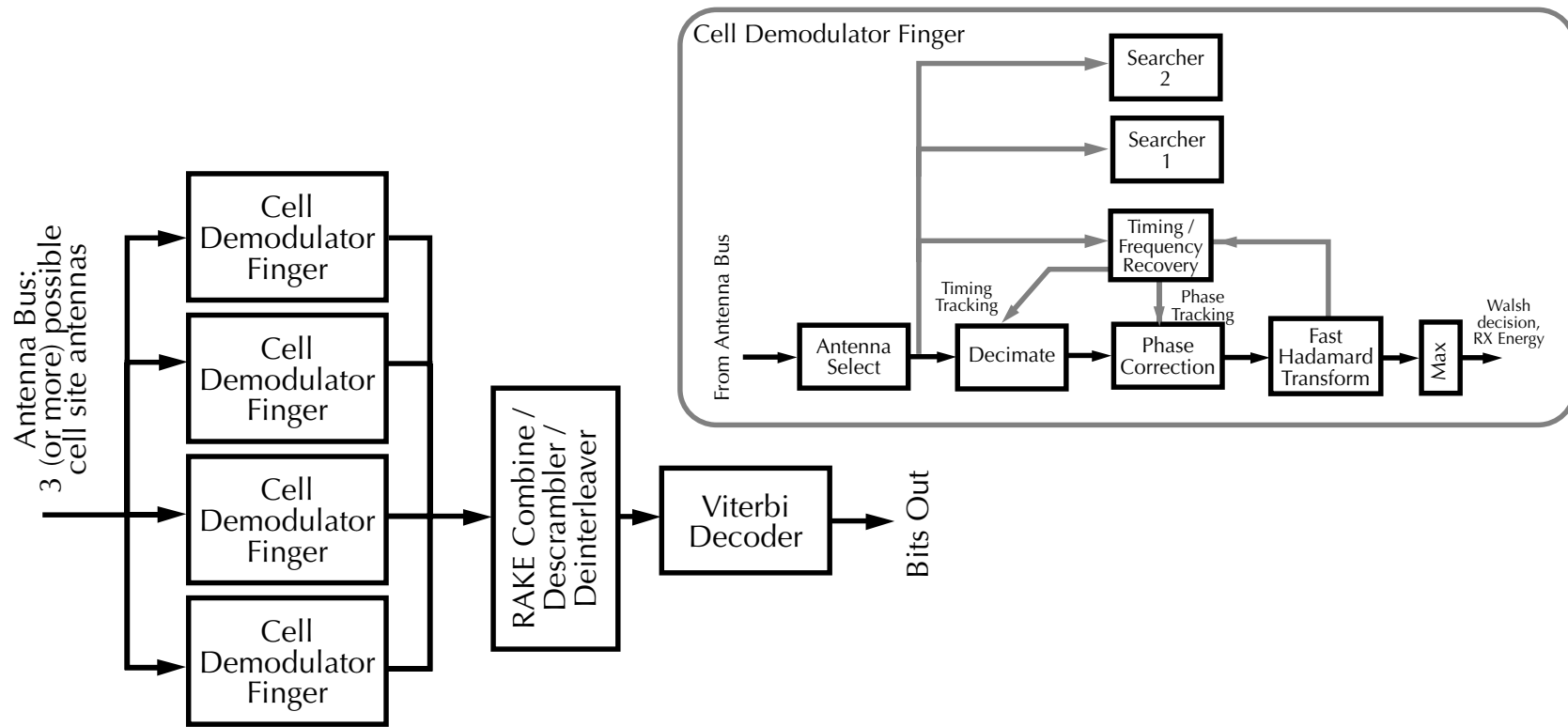
(Figure from [QualC92])

Forward-Link Receiver: DSP Architecture



- Leverages timing recovery off of pilot tone detection
- Searcher block looks for:
 - Adjacent cells
 - Stronger multipath arrivals
- Three independent fingers used for RAKE recovery

Reverse-Link Receiver: DSP Architecture



- Significantly more complex: no pilot tone available
- Antenna diversity
 - Multipath mitigation
 - Can perform “micro-handoffs” within a cell (sectorized)
- Four independent fingers used for RAKE recovery

Third-Generation Digital Cellular (3G) Systems

- Goals of 3G Systems

Advanced services (video, data) in addition to voice

Minimum of 144 kbps/user data access, up to 384 kbps/user

Provision for 2 Mbps data access (limited coverage/mobility)

High spectrum efficiency

- Need to coexist with existing PCS systems (1.9 GHz band)

- *Multiple* proposals / standards

Two major ones are WCDMA and cdma2000

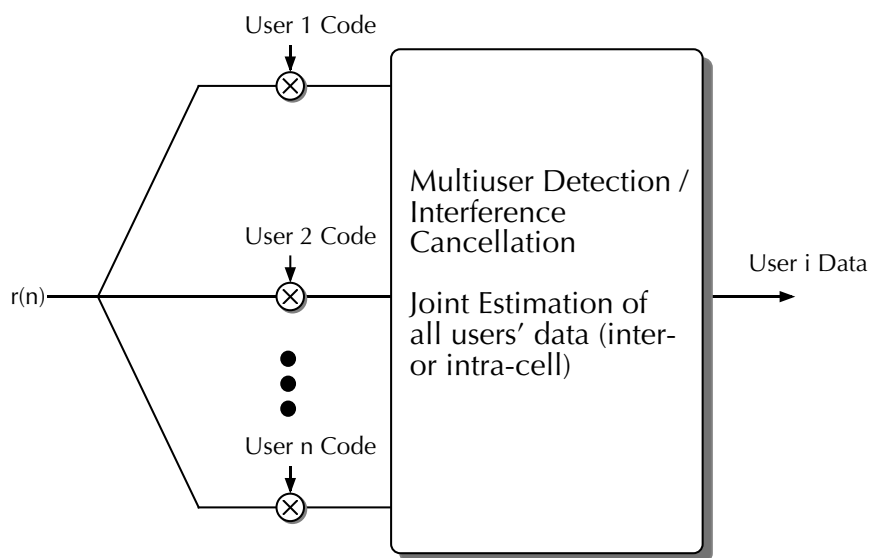
	WCDMA	cdma2000
Chip Rate	1.024, 4.096, 8.192, 16.384 Mcps direct spread	1.2288, 3.6864, 7.3728, 11.0593, 14.7456 (direct spread); n * 1.2288 Mcps (n = 1,3,6,9, 12) (multicarrier spread)
Carrier Spacing	1.25, 5, 10, 20 MHz	1.25, 5, 10, 15, 20 MHz
Inter-base station synchronization	Asynchronous	Synchronous
Pilot Tone	User dedicated time-interleaved pilot (both uplink and downlink); common pilot in downlink	Time-interleaved per-user pilot in uplink Common pilot in downlink

Signal Processing Aspects of 3G

- How to achieve greater spectral capacity?
 - Use of more advanced spreading codes
 - Variable-rate Gold codes
 - Multicarrier methods
 - Error correction techniques
 - High complexity convolutional codes (constraint length 9)
 - Concatenated block/convolutional coding
 - Turbo coding
 - Multiuser detection

Multuser Detection

- CDMA systems have proven to be self-interference limited
Codes are not perfectly orthogonal under multipath!
- Idea: improve system performance/capacity by detecting data from *all* users and cancelling interference



- Simple example:
With 70% intracell interference, maximum achievable capacity gain by MUD is $(1.3/0.3) = 3.9X!$
Limited by accuracy of multipath estimation, power control, etc.

Conclusions

- CDMA provides a multiple access strategy well-suited to the cellular transmission environment
- Achieves this robustness mainly due to signal processing
 - Channel estimation
 - RAKE reception
 - Availability of synchronous pilot tone
 - Advanced error correction
 - Multiuser detection
- Such flexibility has made it the technology of choice for 3G systems!

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