Signal Processing in Communications II: CDMA

Samuel Sheng, Ph.D.

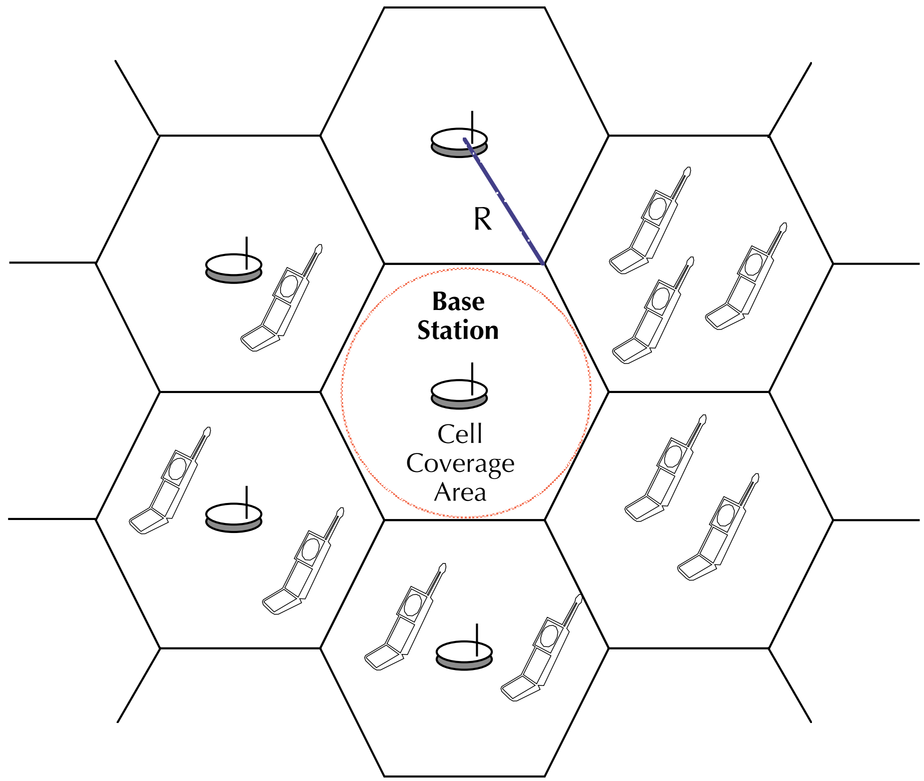
DataPath Systems, Inc.
ssheng@datapathsystems.com
408-366-3391

15 August 99

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



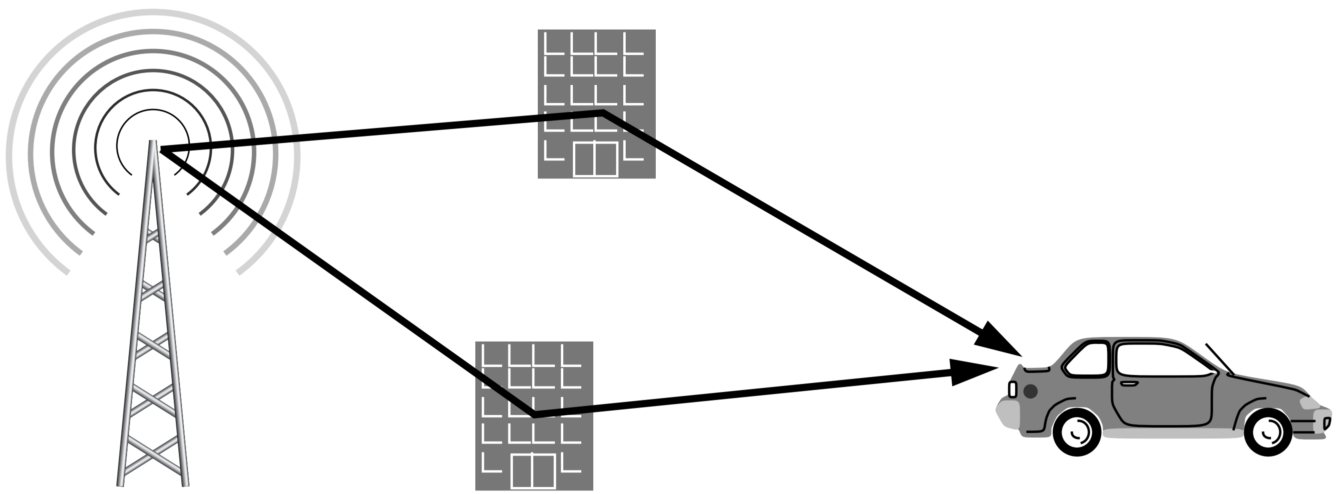
- Each cell is given a fraction of the available spectrum resources
- High dynamic range environment:
  Interference floor often well above the thermal limit!

    Intercell (cochannel/adjacent-channel) interference

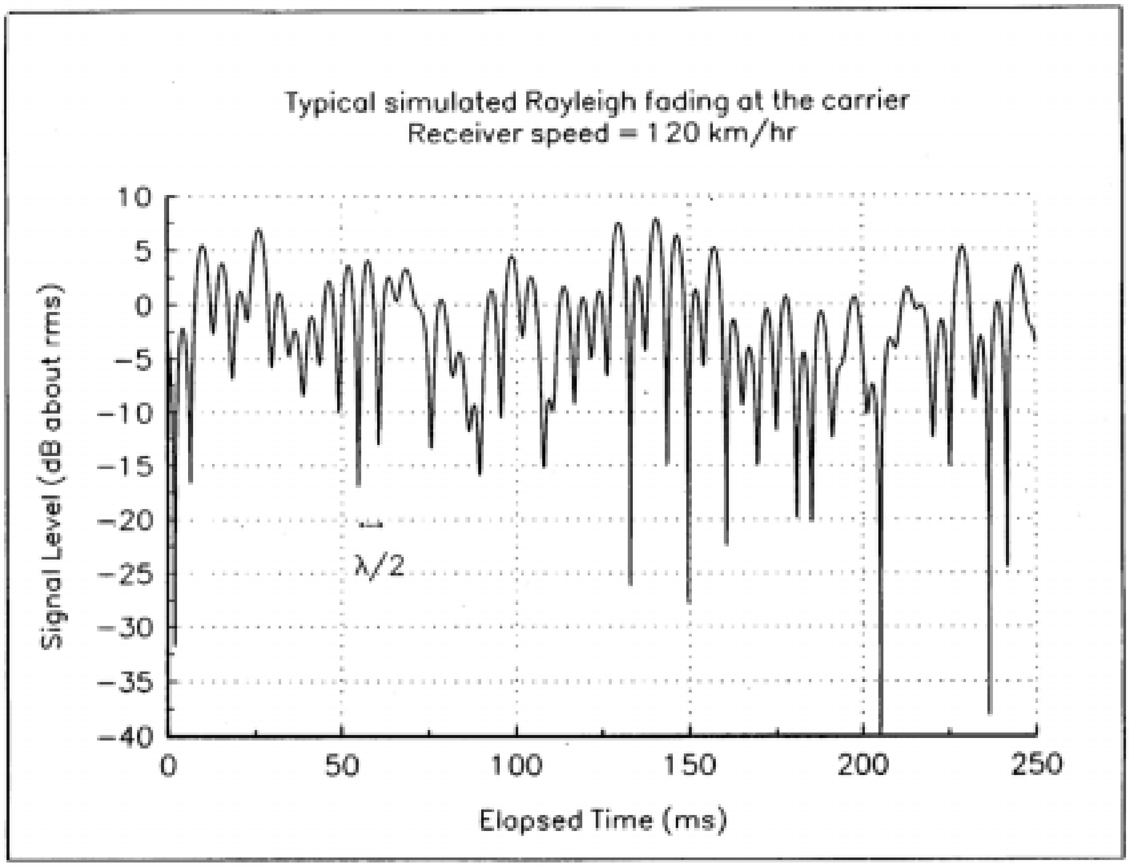
    Intracell ("self") interference

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:

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

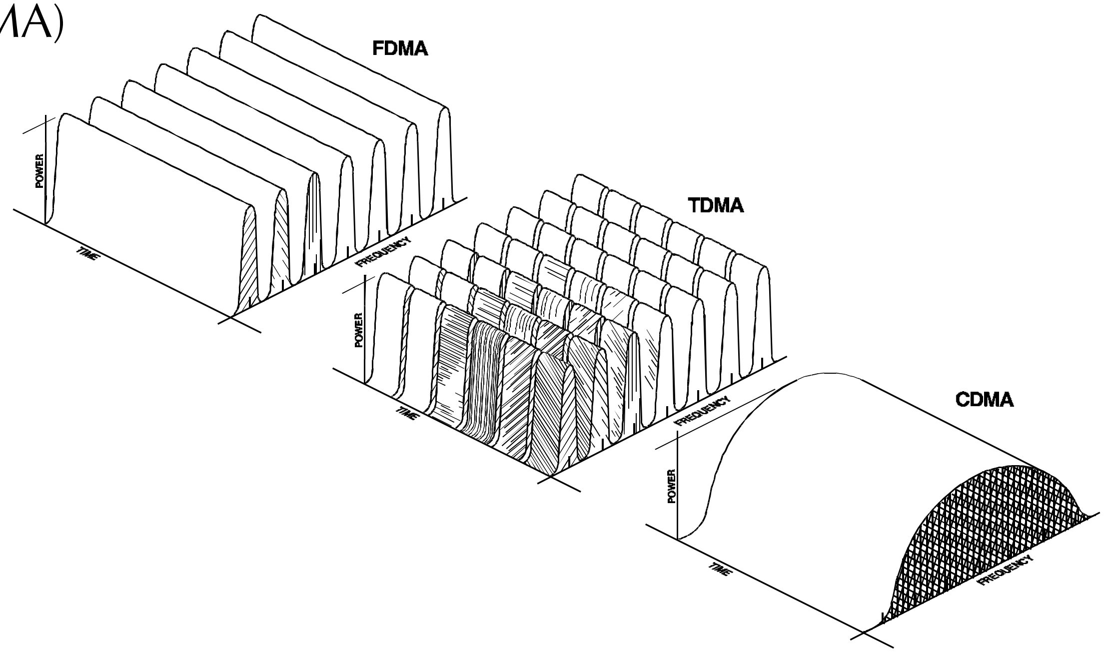
- Each $\delta(t\text{-}t_k)$ represents one received multipath arrival

- 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)



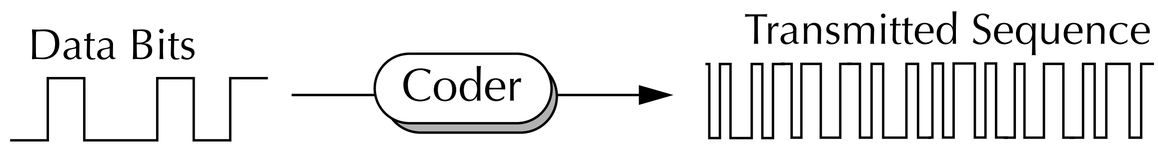
(Figure from [Qual92])

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

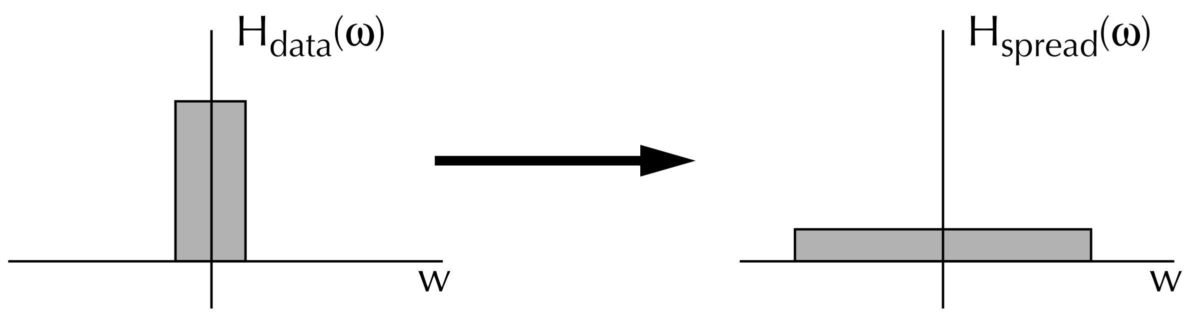
What is Direct-Sequence Spread-Spectrum?

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

  - Time Domain:
    Spread rate = N • Bit Rate



  - Frequency Domain:
    Transmit bandwidth = N • 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*(-1 1 -1 1). (-1 1 -1 1) is user 1's *signature sequence*

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

time →

So the receiver gets a sequence:

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

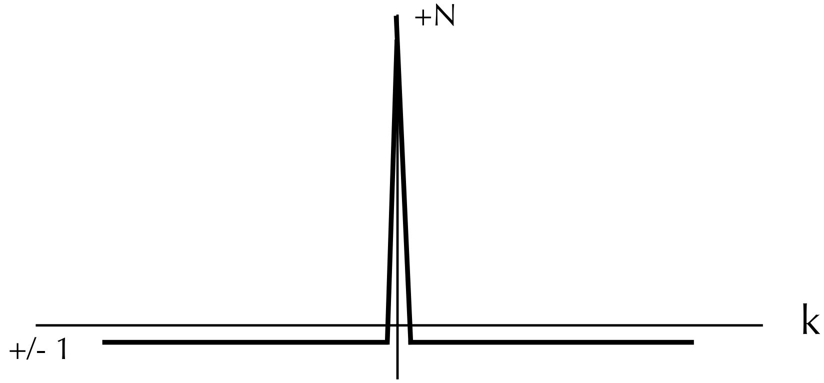
If we take an inner product of this with (-1, 1, -1, 1), we get (4*a)!

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):

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

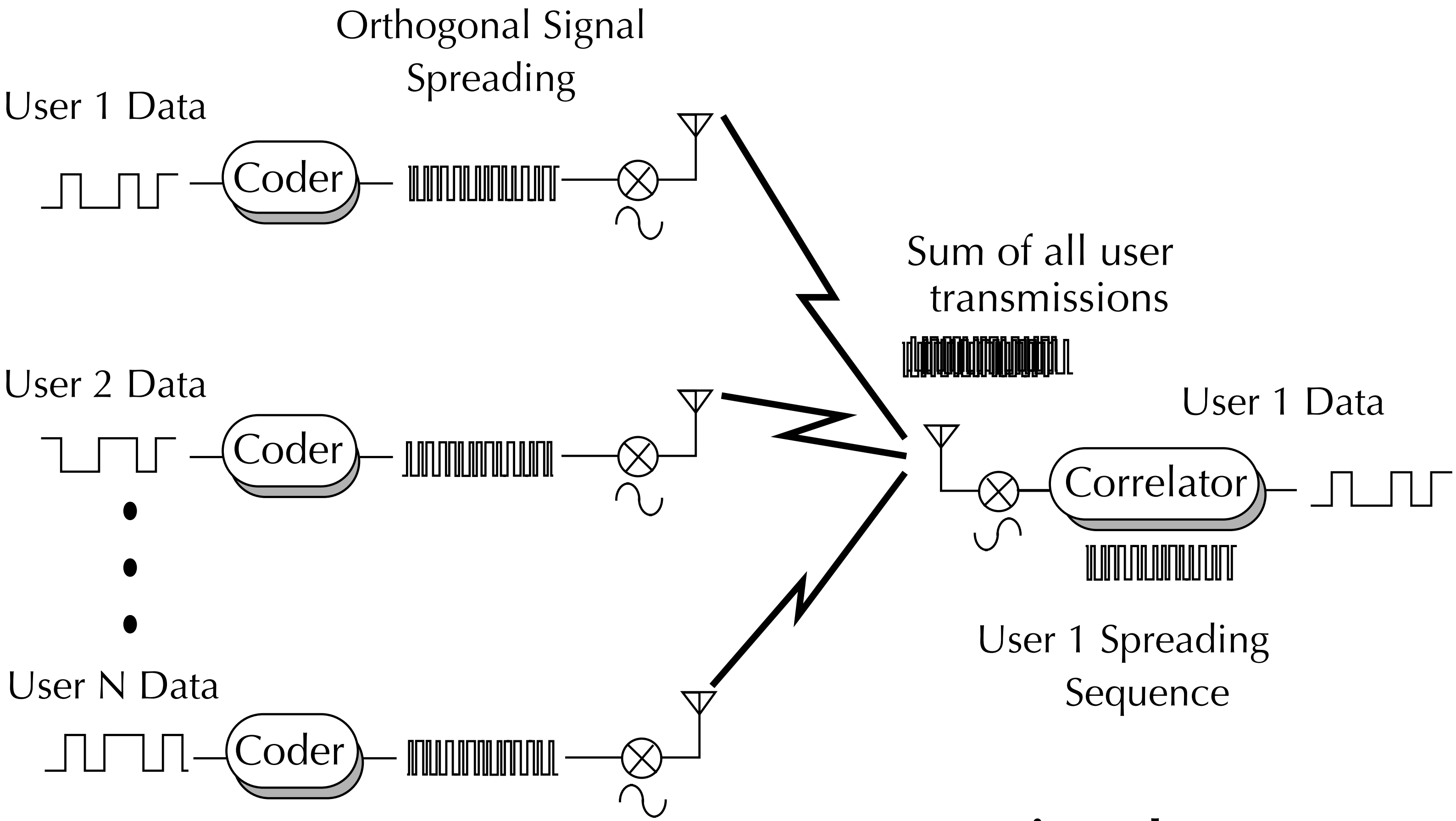


- Crosscorrelation: if $s_a(n)$ and $s_b(n)$ are both spreading sequences:

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

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

Direct-Sequence CDMA

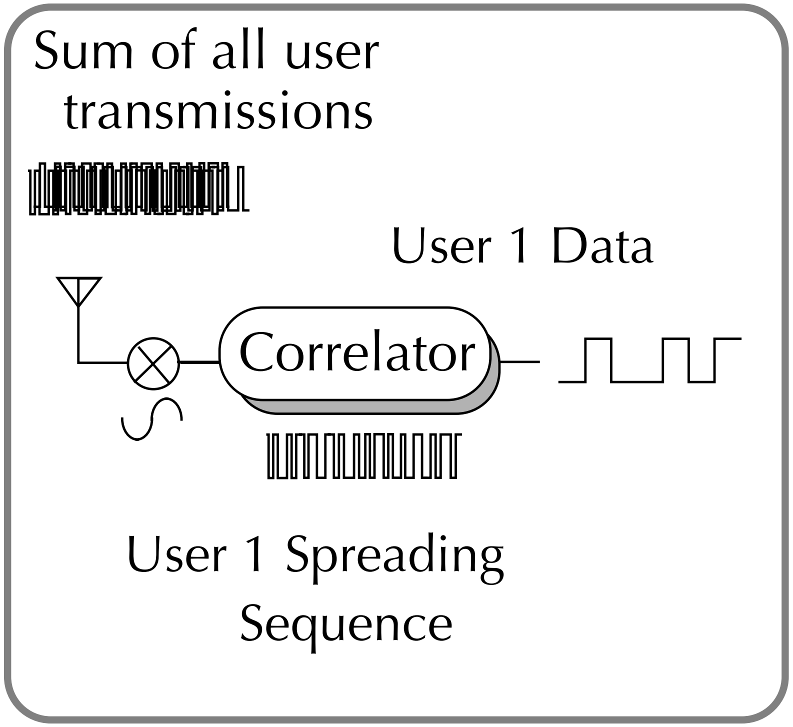


Users transmit at the same time, in the same frequency!

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

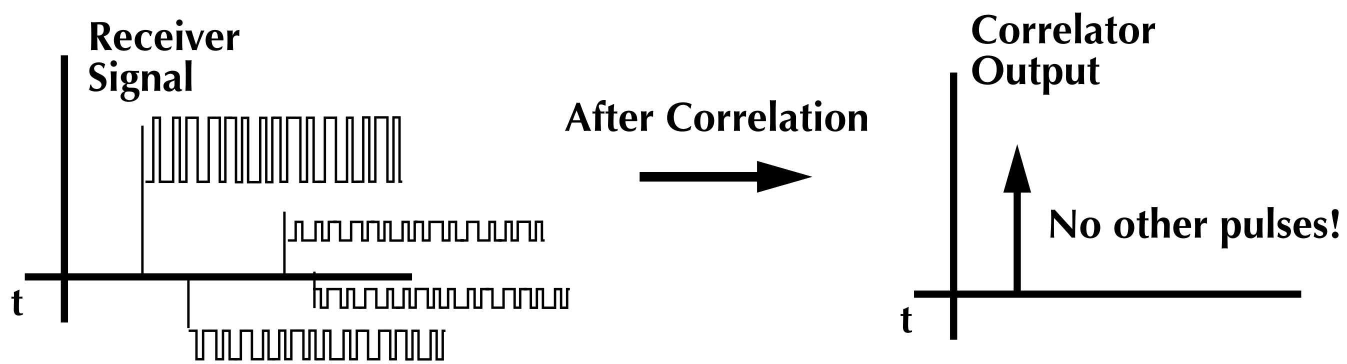
- The Near-Far Problem
  - Most codes have finite crosscorrelation performance (codes can "leak" into each other)
  - If one user close to antenna, one user far, the near user's crosscorrelation leakage can swamp out the far user
  - Extremely accurate power control is required

- Available code space
  - Sufficient codes must exist to support the desired number of users / difficult for large number of users

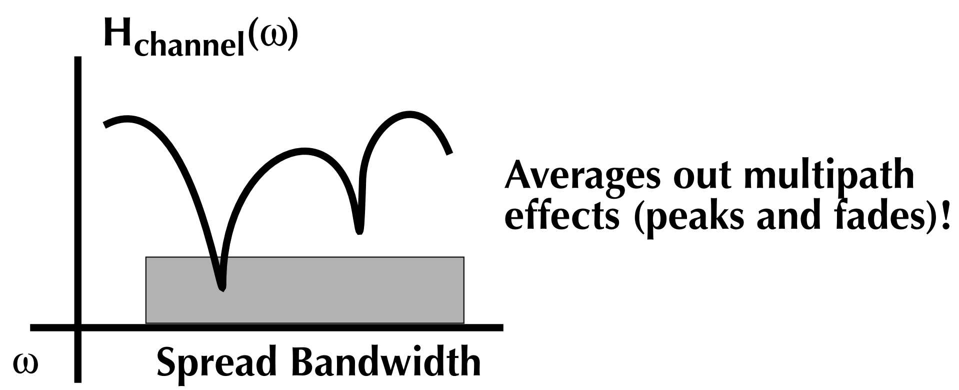
- Receiver Timing Recovery
  - Since we desire perfect autocorrelation (e.g, for multipath rejection), receiver timing is critical!
  - Very accurate receiver timing recovery needed

Multipath "Immunity"

- Time Domain

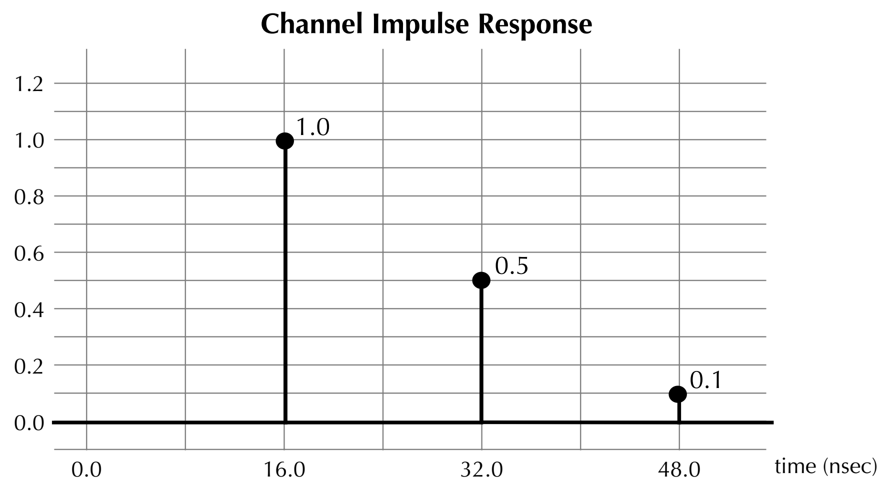


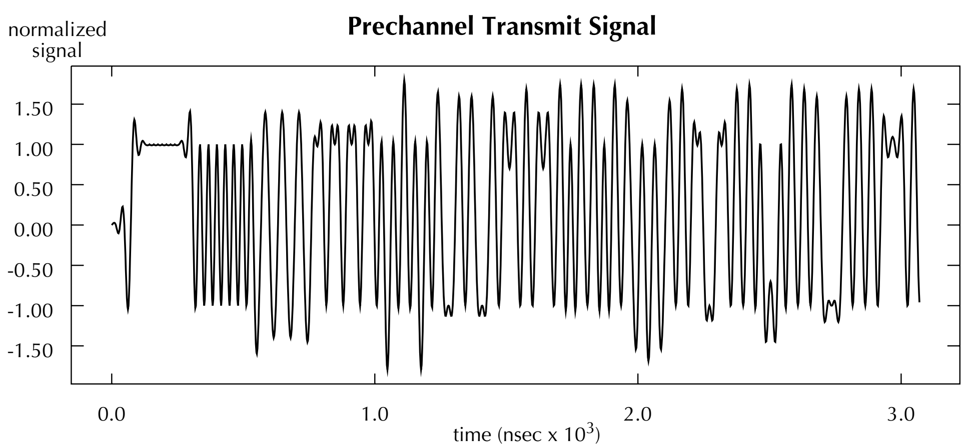
- Frequency Domain

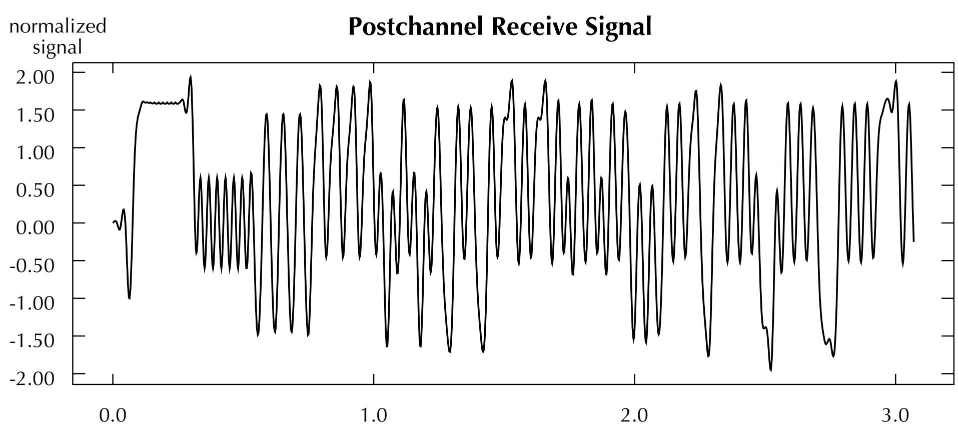


Resolving Multipath

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

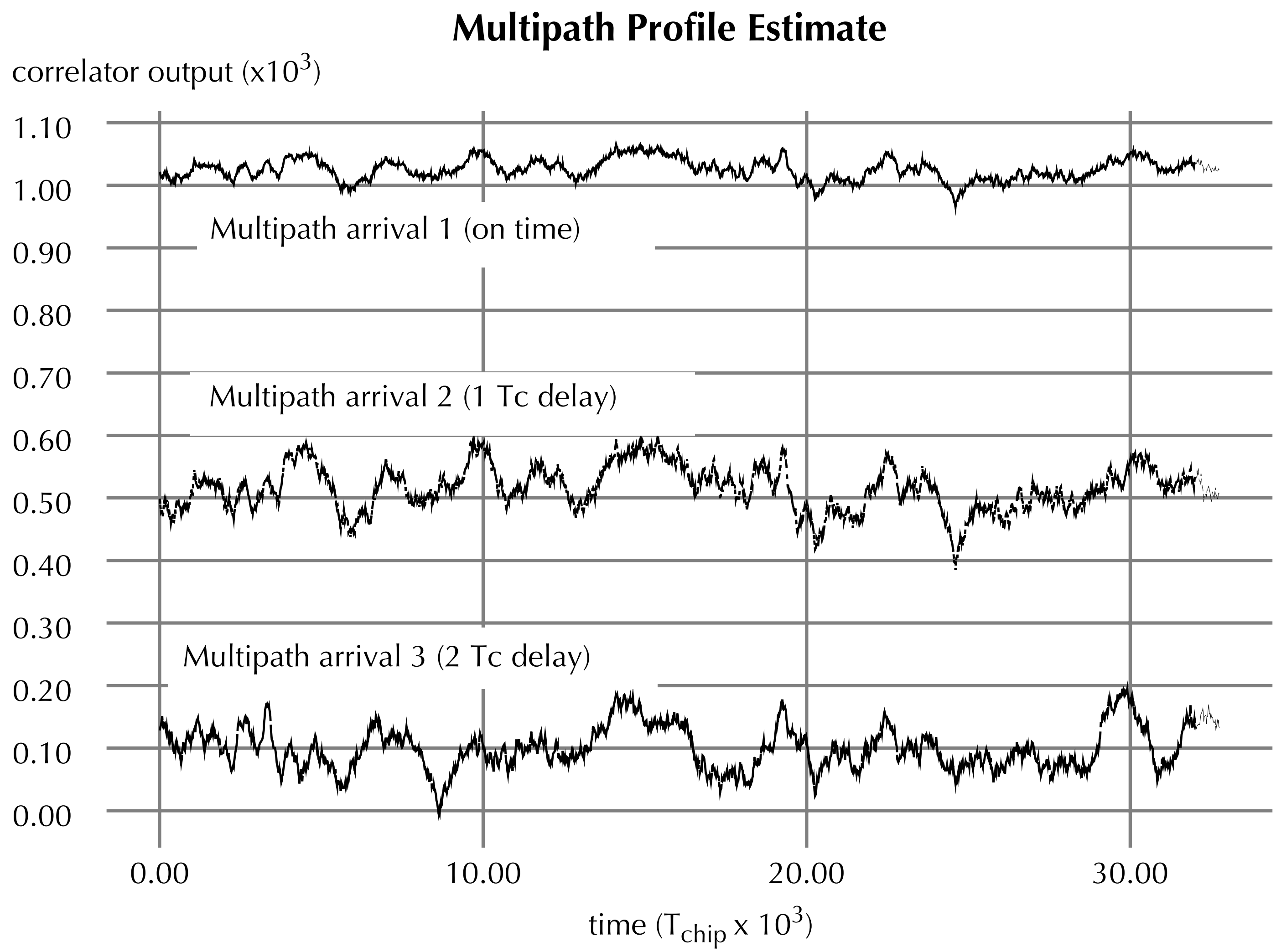






Resolving Multipath, cont.

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



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, $N_{resolvable}$ = (Delay spread/T_{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?

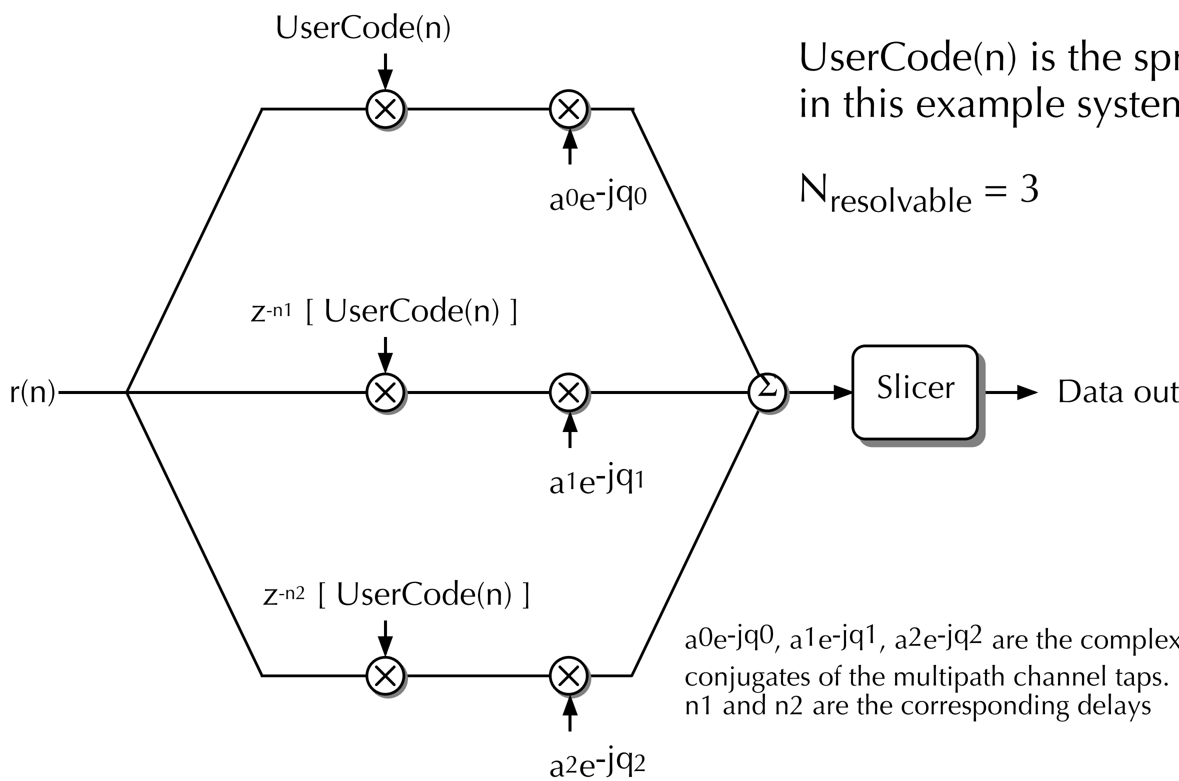
The RAKE Receiver

[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 $N_{resolvable}$ separate receivers (fingers):

UserCode(n) is the spreading sequence in this example system.

$N_{resolvable} = 3$



The RAKE Receiver, cont.

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

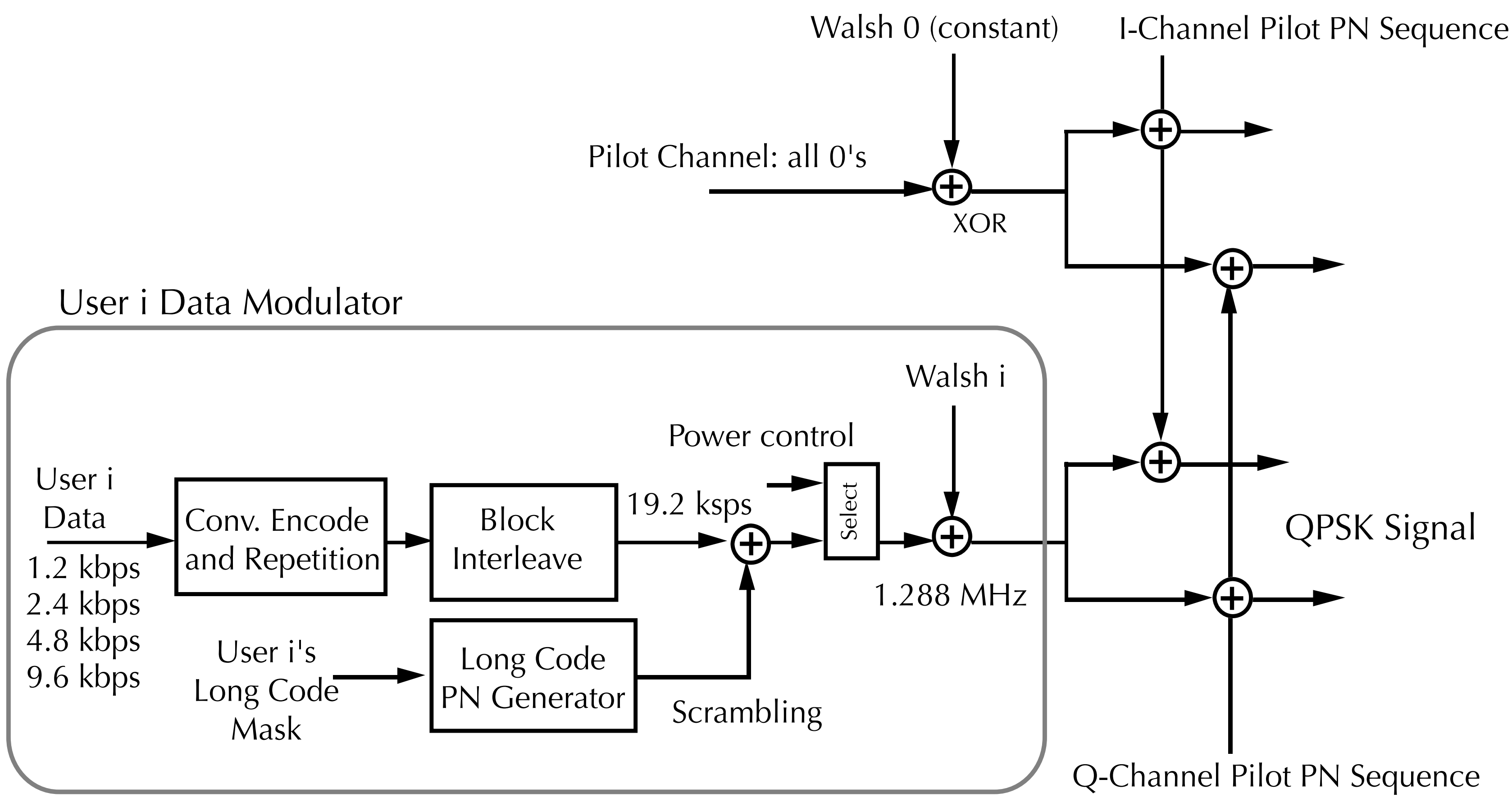
$$SNR_{increase}(dB) = 10\log\sum_{k}\left|\frac{a_k}{a_0}\right|^2$$

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

The IS-95 CDMA Digital Cellular System

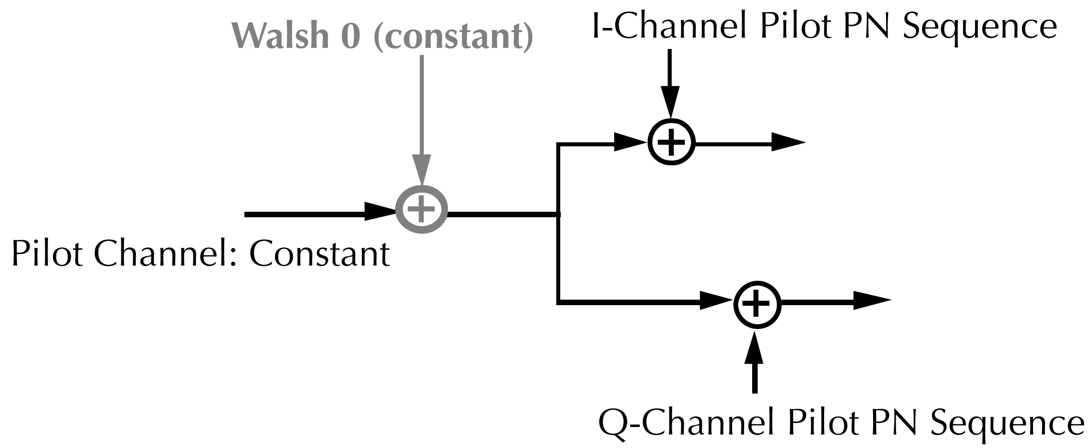
Specification	IS-95
Access Method	Combined CDMA / FDMA
Analog channel Bandwidth	1.25 MHz, + 270 kHz guardband
Channel Chip Rate	1.2288 MHz
Spreading Factor	64
Processing Gain	18.1 dB
Carrier Frequency Downlink (Base Station to Mobile) Uplink (Mobile to Base Station)	 869-894 MHz 824-849 MHz
Baseband 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

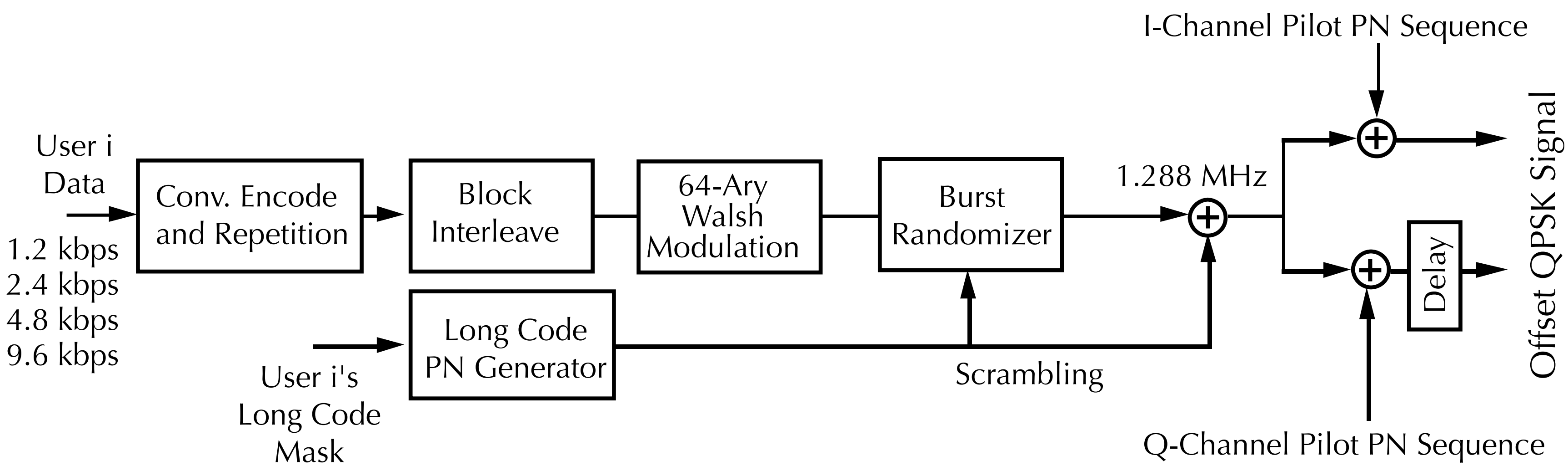
User Data Rate	9600	4800	2400	1200
ECC Coding Rate	1/2	1/2	1/2	1/2
Data Repetition	1	2	4	8
Baseband Coded Rate	19.2k	19.2k	19.2k	19.2k
PN chip rate	1.23 Mcps	1.23 Mcps	1.23 Mcps	1.23 Mcps
Coding • Spreading	128X	256X	512X	1024X

- 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

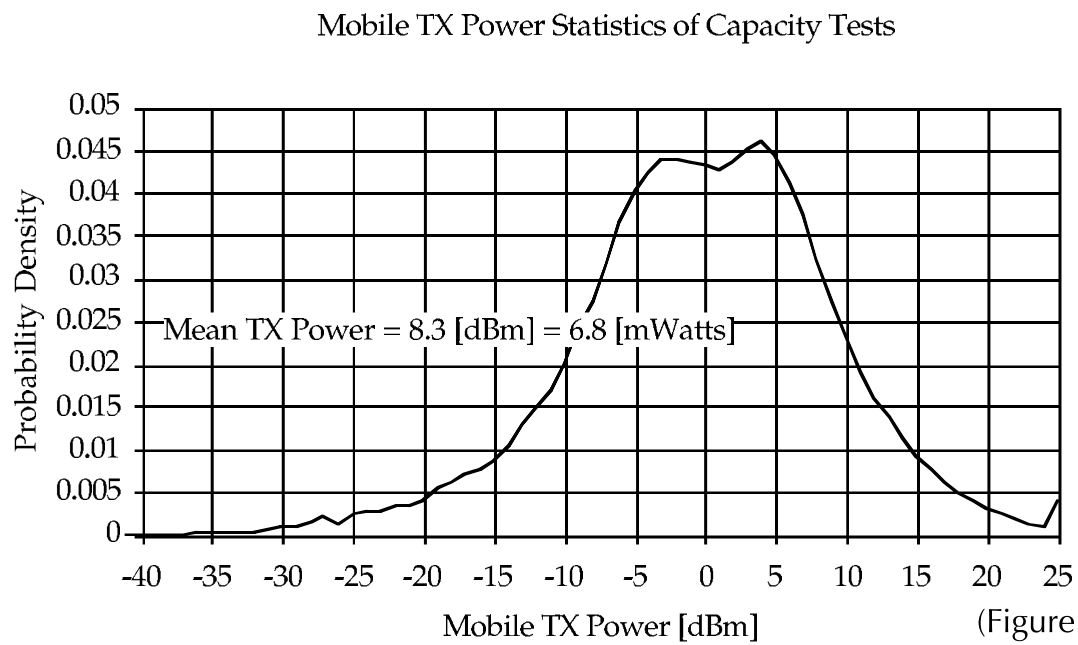
  Downlink: user number determines the Walsh code (spreading)
  Uplink: *data* determines the Walsh code (modulation)

- 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

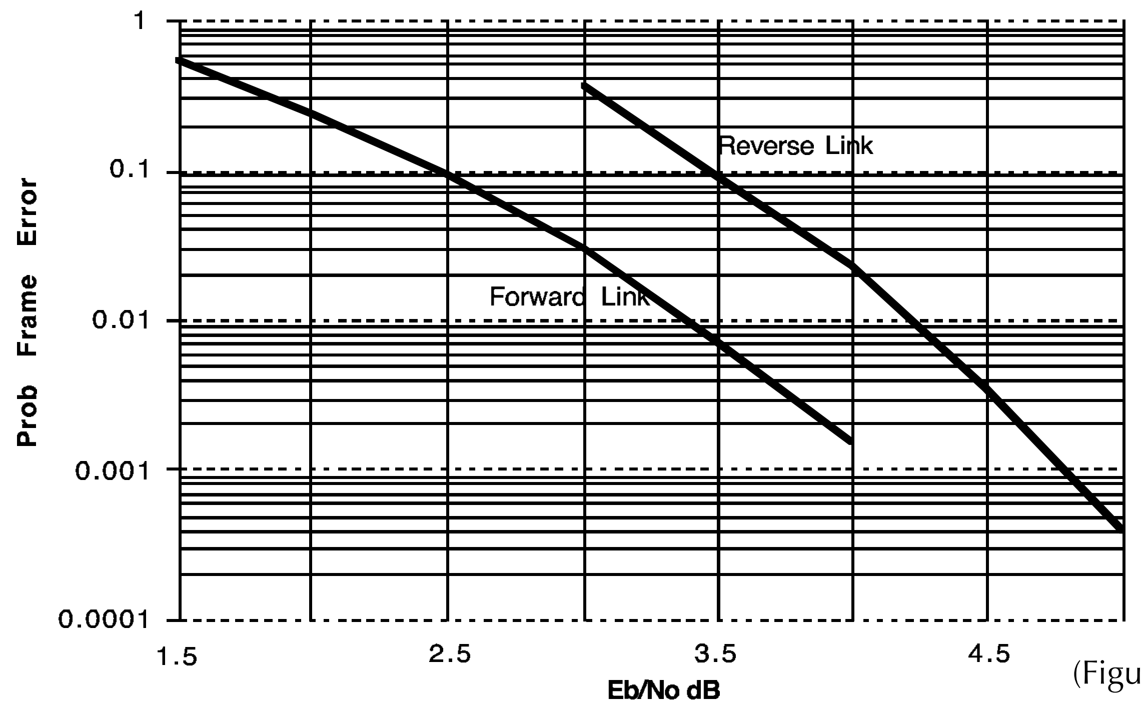
- One interesting aspect of IS-95: mobile uplinks only as much power is needed, and no more:



(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

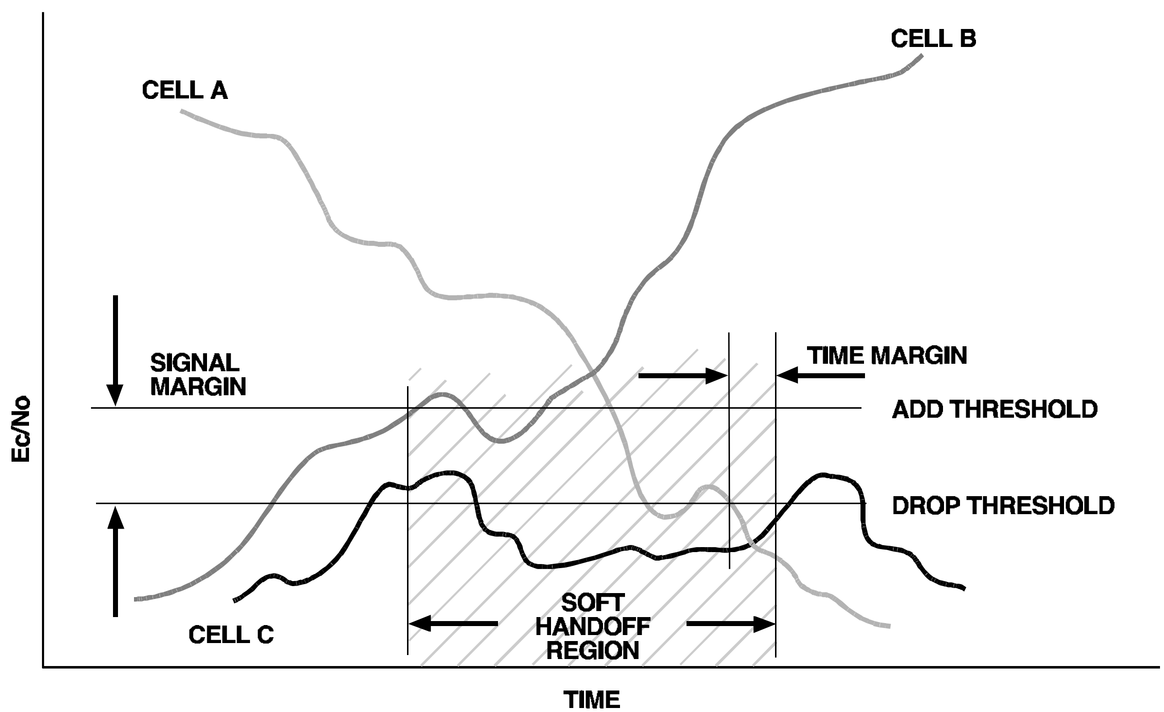
    Repetition overlay coding

    Walsh function
    data modulation

    20 msec block interleave

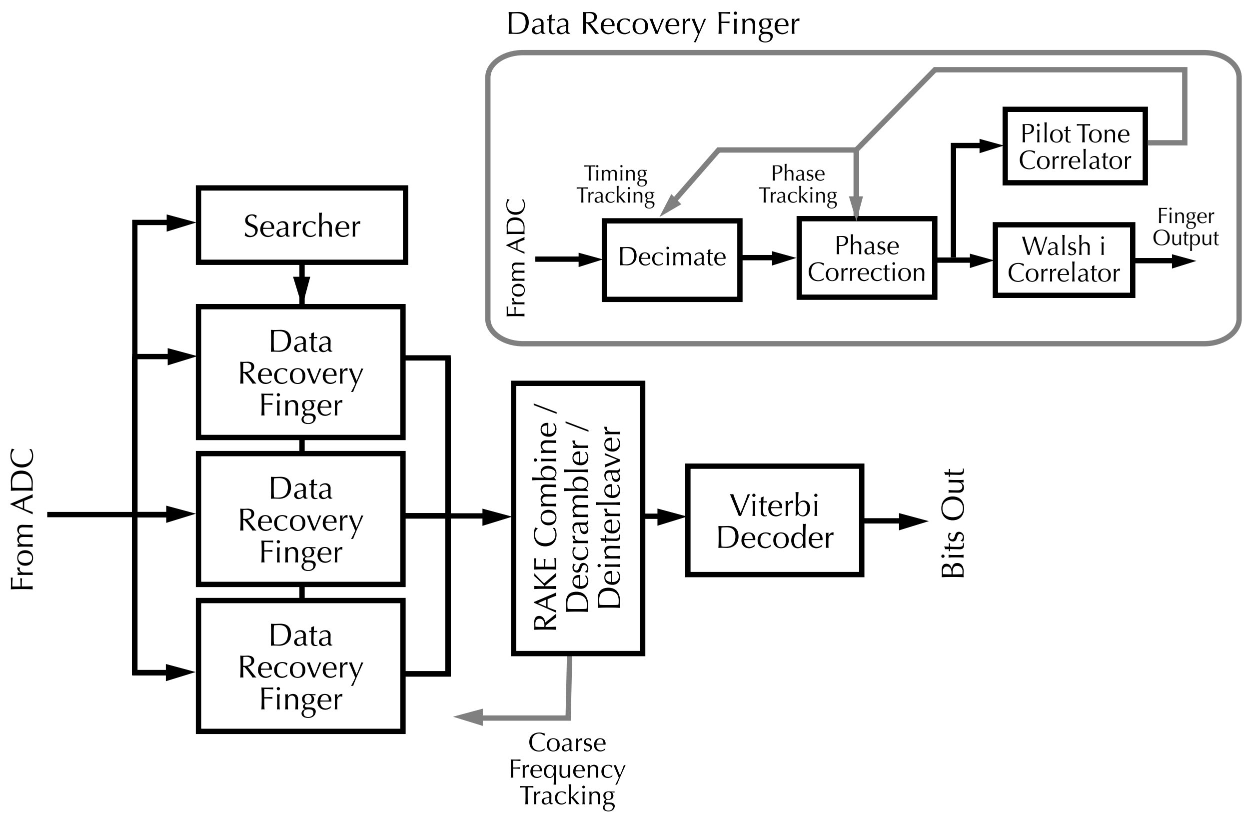
Mobile Assisted Soft Handoff

- 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



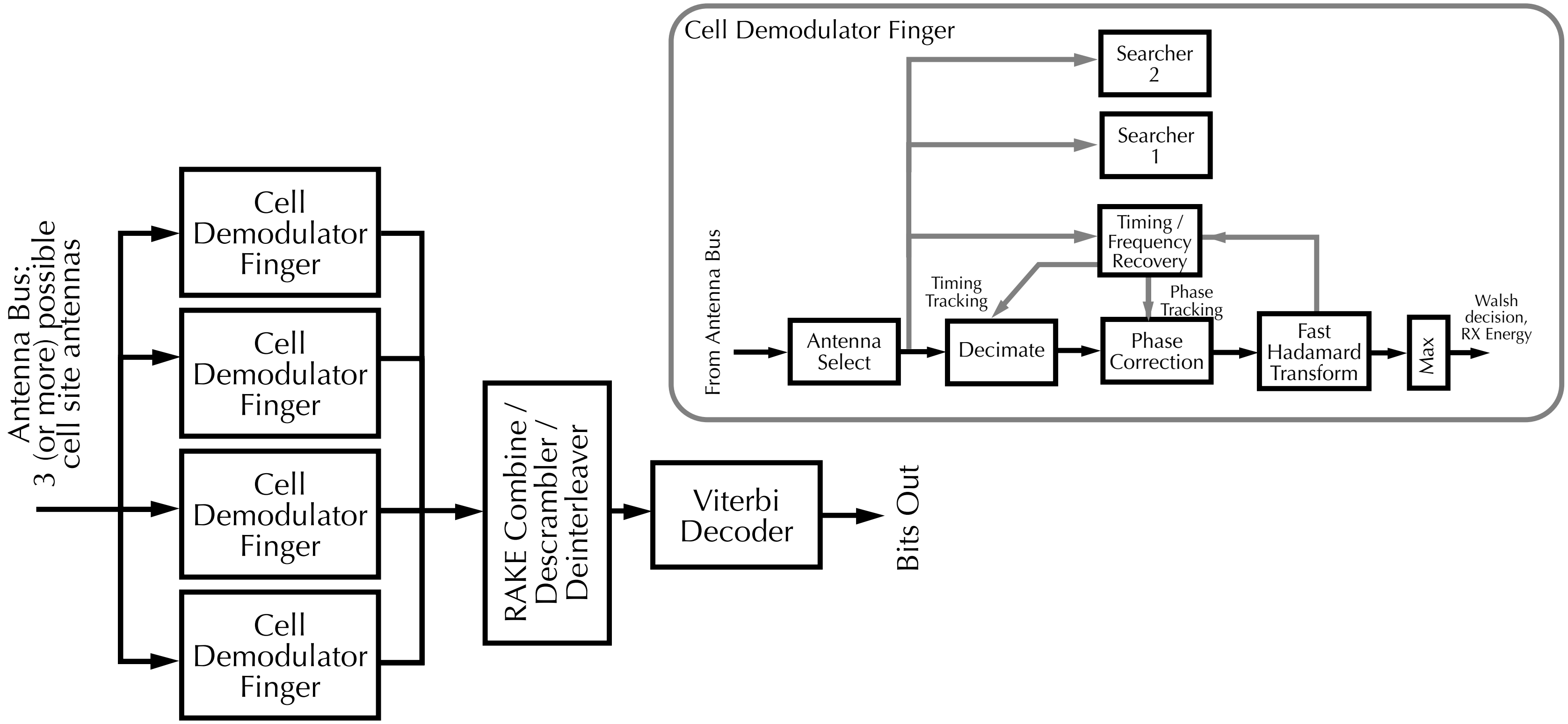
- Leverages timing recovery off of pilot tone detection
- Searcher block looks for:

  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

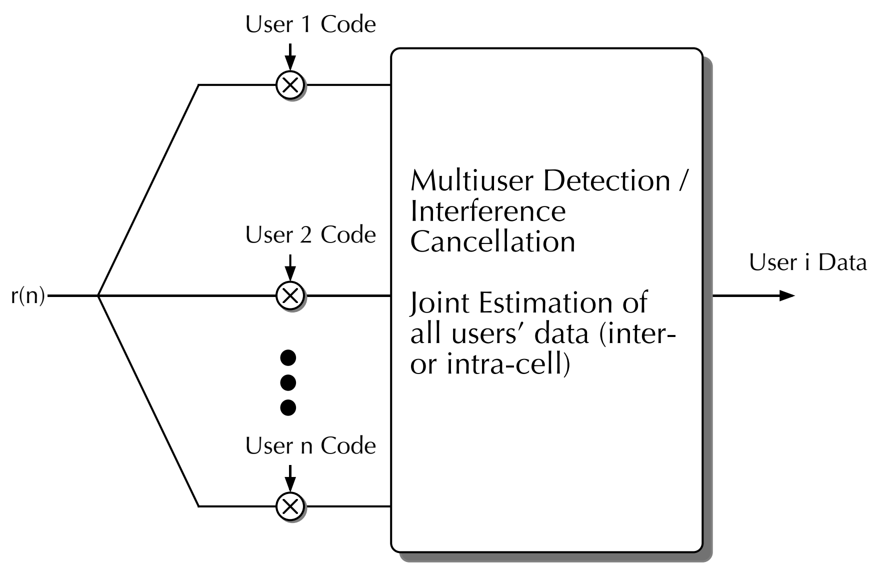
- How to achieve greater spectral capacity?
    - Use of more advanced spreading codes
        - Variable-rate Gold codes
        - Multicarrier methods
    - Error correction techniques
        - High complexity convolutional codes (constraint length 9)
        - Concatenated block/convolutional coding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

Multiuser 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!

Bibliography

[Cook83] C.E. Cook and H.S. Marsh. "An Introduction to Spread Spectrum," *IEEE Communications Magazine*, pp. 8-16. March 1983.

[Dixon84] R.C. Dixon. *Spread Spectrum Systems,2nd ed.*, New York: J. Wiley and Sons, 1984.

[Feher87] K. Feher. *Advanced Digital Communications.* New Jersey: Prentice-Hall Inc. 1987.

[Fun93] V. Fung, T.S. Rappaport, B. Thoma. "Bit-Error Simulation for p/4 DQPSK Mobile Radio Communication Using Two-Ray and Measurement-Based Impulse Response Models," *IEEE Journal on Selected Areas in Communications*, Vol. 11, No. 3, pp. 393-405, April 1993.

[Lee88] E.A. Lee and D.G. Messerschmitt. *Digital Communication.* New York: Kluwer Academic Publishers, 1988.

[Lee89] W. C-Y Lee. *Mobile Cellular Telecommunications Systems.* New York: McGraw-Hill Book Co., 1989

[Ojan98] T. Ojanpera, R. Prasad, ed. *Wideband CDMA for Third Generation Mobile Communications.* Boston, MA: Artech House, 1998

[Peroul94] J. Peroulas. *Design and implementation of a High-Speed CDMA Modulator for the INFOPAD Basestation.* M.S. Thesis, U.C. Berkeley, Berkeley, CA, 1996.

[Pick82] R.L. Pickholtz and D.L. Schilling. "Theory of Spread-Spectrum Communications - A Tutorial." *IEEE Transactions on Communications*, Vol. COM-30, No. 5, pp. 855-883. May 1982.

[ProakB83] J.G. Proakis. *Digital Communications.* New York: McGraw-Hill Book Co., 1983

[Qual92] *EIA/TIA IS-95 Interim Standard, Wideband Spread-Spectrum Digital Cellular Dual-Mode Mobile Station-Base station Compatibility Standard.* Telecommunications Industry Association, April 1992.

[QualC92] *An Overview of the Application of Code Division Multiple Access (CDMA) to Digital Cellular Systems and Personal Cellular Networks.* Qualcomm Inc., May 21, 1992.

[Rapp96] T.S Rappaport. *Wireless Communications: Principles and Practice*. New Jersey: Prentice-Hall PTR, 1996.

[Saleh87] A.M. Saleh and R. A. Valenzuela. "A Statistical Model for Indoor Multipath Propagation." *IEEE Journal of Selected Areas in Communications*, Vol. SAC-5, No. 2, pp. 128-137. February 1987.

[Schill90] D.L. Schilling, R.L. Pickholtz, and L.H Milstein, eds. "Spread-Spectrum Communications I and II." Special Issues of the *IEEE Journal of Selected Areas in Communications*, Vol. JSAC-8, No. 4-5. May-June 1990.

[Sheng96] S. Sheng, L. Lynn, J. Peroulas, K. Stone, et al. "A Low-Power CMOS Chipset for Spread-Spectrum Communications." IEEE 1996 International Solid-State Circuits Conference, San Francisco, CA Feb. 1996.

[Sheng98] S. Sheng. *Low-Power CMOS Wireless Communications*. Massachusetts: Kluwer Academic Publishers, 1998.

[Simon85] M.K. Simon, et al. *Spread-Spectrum Communications*, *Vol. 1-3*. New York: Computer Science Press Inc., 1985.

[Verdu98] S. Verdu. *Multiuser Detection.* New York: Cambridge University Press, 1998.

[Viter95] A.J. Viterbi. *CDMA: Principles of Spread Spectrum Communications*. Reading, MA: Addison-Wesley Pub. Co., 1995.