Recent results on successive interference cancellation for CDMA cellular and ad hoc networks

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Talk Outline

- Brief Introduction/Motivation
- Optimum power control for Successive Interference Cancellation (SIC)
- Achieving the optimum solution using 3G-compatible iterative power control
- Capacity of wireless ad hoc networks, with CDMA and SIC

Introduction - Motivation

- Code-Division Multiple Access (CDMA) is the dominant air interface for USA 2G and worldwide 3G cellular

  Increasing CDMA cellular capacity is a very relevant topic

- A limiting factor in ad hoc networks is self-interference. Typically, collisions cannot be tolerated.

  Can CDMA help?

Introduction – CDMA

In (non-orthogonal) CDMA, achieved throughput is limited by the amount of total interference, rather than by the available number of time slots, orthogonal codes, or frequency slots.

The CDMA Philosophy:

In the presence of unpredictable interference, it is preferable to design for robustness to interference than for multiple access orthogonality.

Introduction – CDMA Cellular

- CDMA's current advantages come principally from two important side-effects, due to the manner in which cellular systems are used and deployed:
  - Voice Activity: users don't waste bandwidth when silent
  - Frequency Reuse: since designed for robustness, much more resistant to interference from other cells.

- An intriguing aspect of CDMA is that any technique that reduces interference increases capacity proportionally $\Rightarrow$ Multiuser Detection

Multiuser Detection?

- Multiuser detection has been intensely researched for the past 10-15 years
- 1000’s of papers and 1,000,000’s of equations later, industry still predominately uses the single-user matched filter. **Why?**
  - Concerns about robustness of techniques to a realistic multi-cell environment with other-cell interference, doppler, Rayleigh fading, multipath propagation
  - Reduced complexity techniques are still quite complex
  - Design sacrifices often must be made for reduced complexity techniques:
    - short PN codes
    - ECC separate (low input SNR makes estimation difficult)
    - Synchronous operation often required

Introduction – Successive Interference Cancellation

- Successive Interference Cancellation (SIC) is a “flavor” of MUD that is potentially more appealing for a few reasons:
  - Powerful error correcting codes easily integrated
  - Long PN sequence poses no problem
  - No orthogonality or synchronization is required
  - Linear complexity increase with number of users
  - Based on the conventional single-user receiver that has proven robustness and everyone’s faith
  - Approaches Shannon capacity, assuming perfect channel estimation [Viterbi, 1990].

Historical Problems with SIC

Several crucial unresolved problems have plagued SIC:

1. Channel estimation error can easily cause catastrophic error propagation
2. Highly-complicated power control distribution required, and the optimal form was unknown
3. Multipath channel introduces large problem as all paths must be cancelled
4. Latency is proportional to K (the number of users)

Recent Progress on SIC

Recent research has developed solutions for three of these shortcomings:

1. **Estimation-Error Resistant Power Control**

   J. Andrews and T.H. Meng, "Optimum Power Control for Successive Interference Cancellation with Imperfect Channel Estimation" *IEEE Trans. on Wireless Communications*, Mar. 2003. [AndMen03]

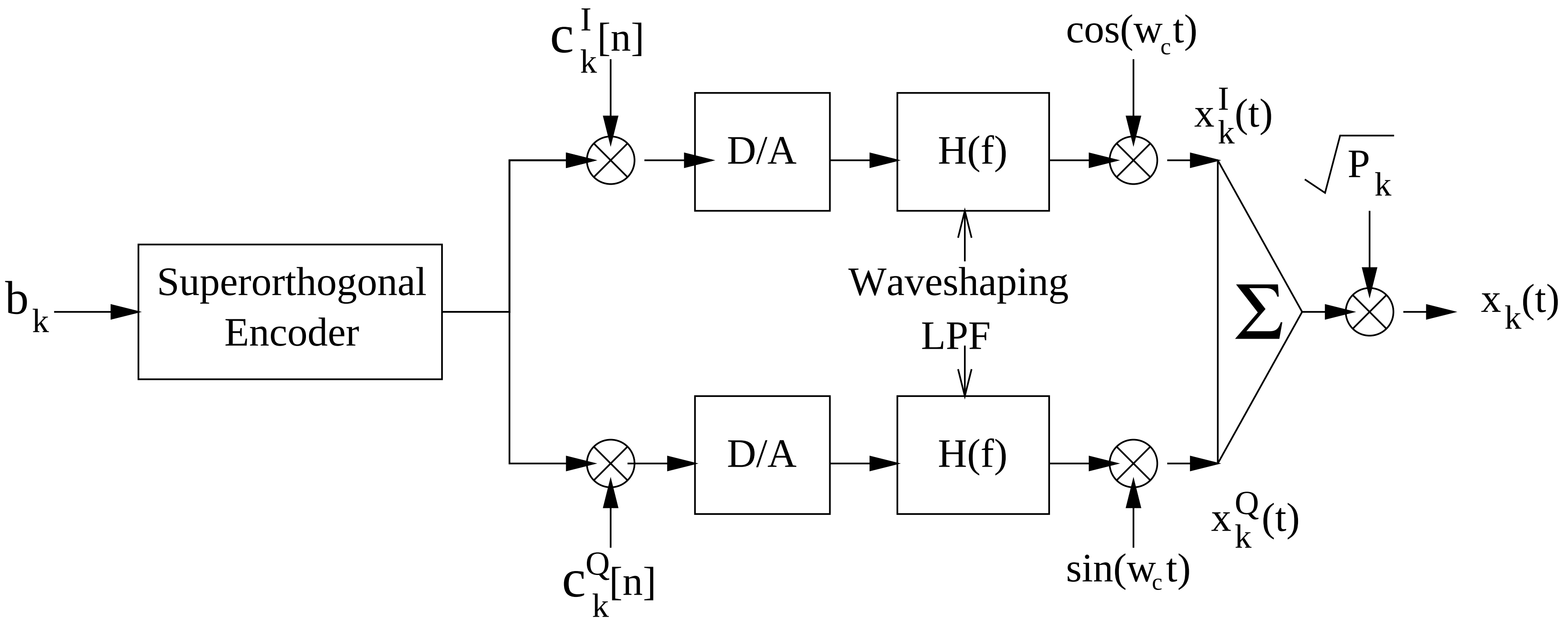
2. **Iterative Power Control**

   A. Agrawal, J. Andrews, J. Cioffi and T. Meng, "Iterative Power Control for Successive Interference Cancellation", to appear, *IEEE Trans. on Wireless Communications.* [AgrAndCioMen03]

3. **Multicarrier-CDMA with SIC** (not discussed today)

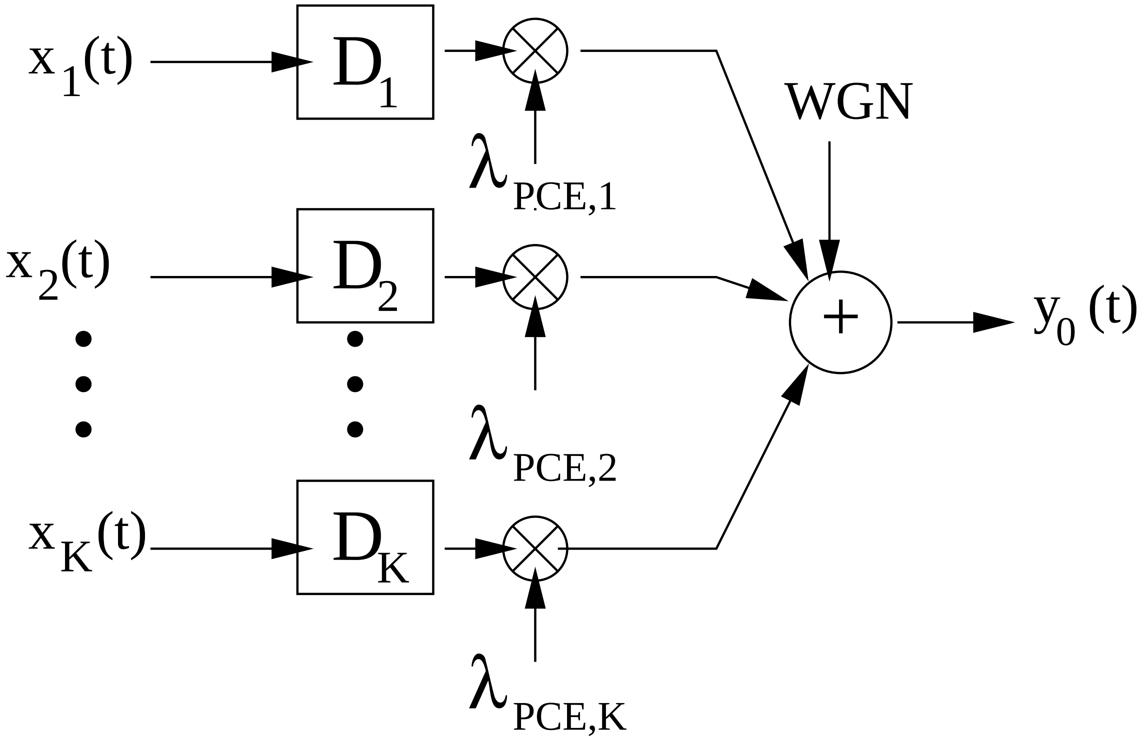
   J. Andrews and T.H. Meng, "Performance of MC-CDMA with Successive Interference Cancellation in a Multipath Fading Channel", to appear, *IEEE Trans. on Communications*, May 2004.

Transmitter Block Diagram



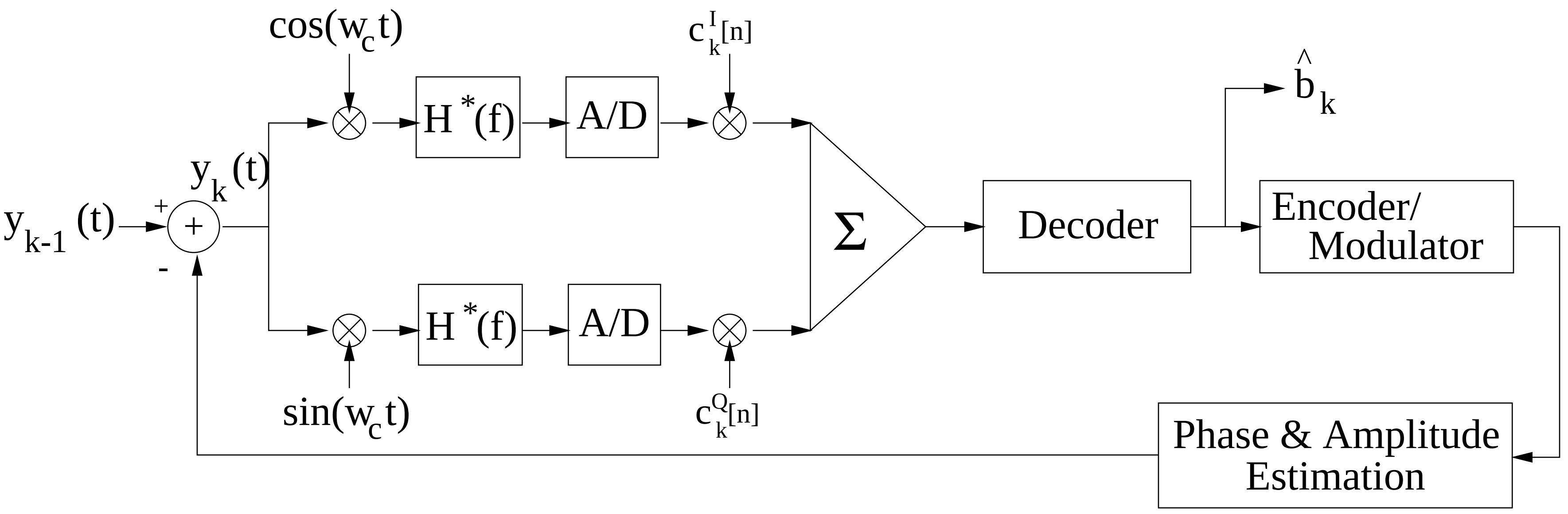
- Superorthogonal Code provides spreading
- I & Q spreading for diversity and noncoherent reception
- Power control adjusted to equalize BERs at receiver for all users

Channel Model – Flat Fading



- Flat-fading channel with random delay
- Power control error $\lambda_{PCE,k}$ models unmitigated fading
- The PCE is lognormally distributed

Receiver Block Diagram



- Standard correlating receiver and Viterbi decoder
- Accurate channel estimation is required. How accurate?

Optimum Power Control for SIC

For SIC with imperfect cancellation, the following set of equations equalize the BERs (maximizes capacity):

$$\Gamma_1 = \frac{P_1}{\sum_{k=2}^{K} P_k + N} = \Gamma_2 = \frac{P_2}{\sum_{k=3}^{K} P_k + \varepsilon_1 P_1 + N} = \Gamma_K = \frac{P_K}{\sum_{k=1}^{K-1} \varepsilon_k P_k + N}$$

Γ_k : Signal-to-Interference plus Noise Ratio (SINR) for user *k*

P_k : Received Power for user *k*

N : Noise power

ε_k : Residual fractional interference for user *k*

Optimum Power Control for SIC

- Solving the SIR equations results in a recursive relationship of:

$$P_k = P_{k-1} - \frac{(1-\varepsilon_{k-1})P_{k-1}^2}{I_{k-1} + N}$$

$$I_k = \sum_{i=1}^{K} P_i - \sum_{i=1}^{k-1} (1-\varepsilon_i) P_i$$

- This is a general solution for CDMA power control:

$$\varepsilon_k \to 0 \Rightarrow \text{Perfect Cancellation}$$

$$\varepsilon_k \to 1 \Rightarrow \text{Single User Detection}$$

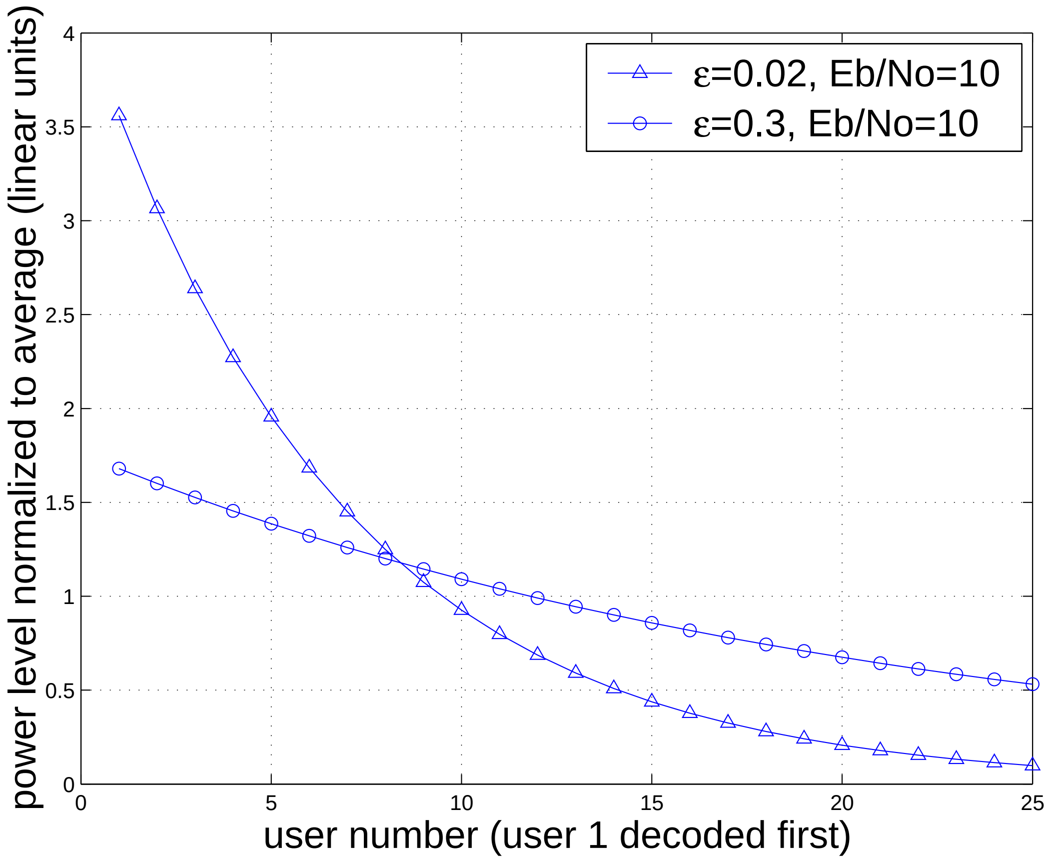
Power Control (PC)

- This solution suggests that modified power control is the key to mitigating imperfect cancellation in SIC
- Conventional systems attempt to equalize the power of all users at the receiver.
- In a SIC system, **unequal powers are actually desirable**: the strongest user is decoded first and subtracted out of the composite signal – the weakest user is decoded last.

Estimation Error and Residual Interference – Definitions

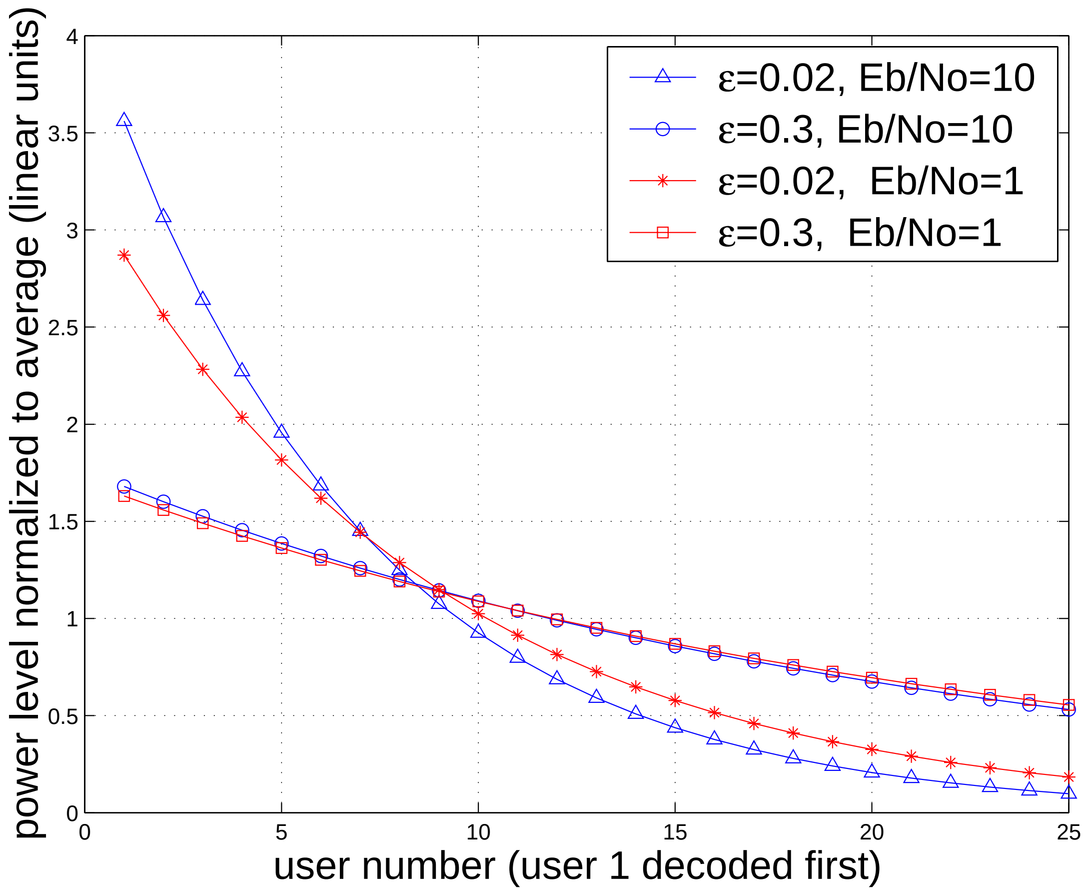
- The fractional amount of interference power left after cancellation for user *k* is ε_k.
- The two sources of ε_k:
  1. Channel estimation error
  2. Bit decision errors
- Estimation error dominates when BER is low ($< 10^{-3}$)
- Estimation error is modeled as a lognormal random variable with normalized standard deviation σ_ε
- Hence ε_k is approximately lognormal, but we'll need to choose a value for power control implementation

Sample Power Distributions



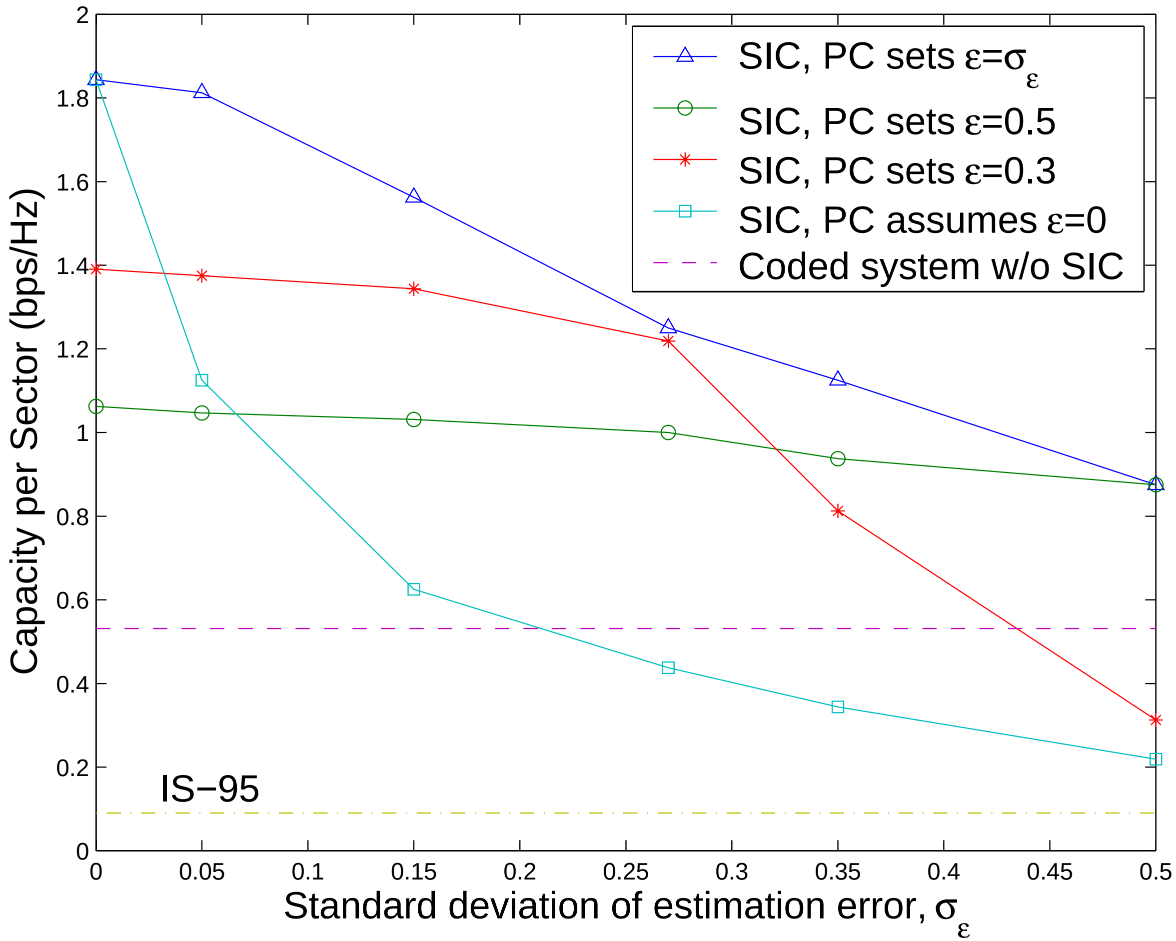
- Highly dependent on estimation error

Sample Power Distributions



- Not very dependent on Eb/No

Capacity per sector (bps/Hz)



Capacity is defined as the data rate achievable per Hz at a specified BER. ($BER=10^{-4}$, Eb/No=10dB)

Performance Results

- Optimal power control makes a huge difference in robustness of system to estimation error
- For estimation error > 20%, no interference cancellation at all is better than cancellation with the commonly used suboptimal algorithm
- Even w/ 50% estimation error, SIC with the optimal power control algorithm doubles non-SIC capacity

Update

- The derived power control algorithm maximizes capacity for a given amount of estimation error:

$$P_k = P_{k-1} - \frac{(1-\varepsilon_{k-1})P_{k-1}^2}{I_{k-1} + N}$$

- But how do the users actually know how much power to transmit?

Iterative Power Control

- Optimal power control algorithm requires each user to have a specific power level for robust operation
- Iterative power control, as in 3G CDMA, is desirable.
- Iterative PC sends one-bit commands at a rate of ~1000 Hz – power is adjusted UP or DOWN by δ dB
- Is the optimal SIC power control distribution achievable with existing (iterative) industry schemes?

Iterative PC for SIC – How it works (1)

- Description of one-bit UP/DOWN power control:

$$p_k(n+1) = \begin{cases} \delta p_k(n), & \text{if } \hat{\gamma}_k(n) \le \gamma_k \\ \delta^{-1} p_k(n), & \text{if } \hat{\gamma}_k(n) > \gamma_k \end{cases}$$

- Target SINR γ_k is set by an outer PC loop
- Received SINR is estimated at base station as:

$$\hat{\gamma}_k = \frac{p_k(n)}{i_{est,k}(n)}$$

$p_k(n) =$ received power for user k, time n

$i_{est,k}(n) =$ estimated interference for user k, time n

Iterative PC for SIC – How it works (2)

- Received interference power is:

$$\mathbf{i}_{est}(n) = (\mathbf{F} + \mathbf{E}_{est})\mathbf{p}(n) + \mathbf{n}_0$$

$$\mathbf{F}_{ij} = \begin{cases} 0 & i \geq j \\ 1 & \text{otherwise} \end{cases}$$

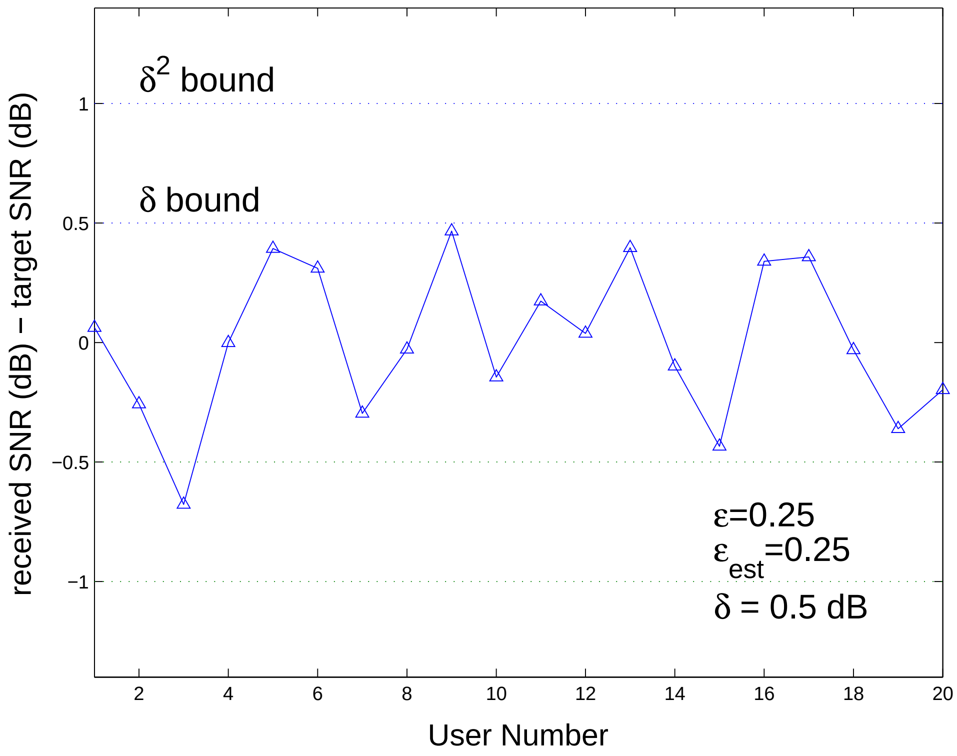
(Upper Triangular)

$$\mathbf{E}_{est,ij} = \begin{cases} \hat{\varepsilon}_j & i > j \\ 0 & \text{otherwise} \end{cases}$$

(Lower Triangular)

$$\mathbf{n}_0 = \text{noise vector}$$

Iterative PC Convergence



- Convergence to within δ^2 of the optimum solution was proven.
- Convergence is typically with δ of the optimum for SIC.

Summary of Results on Iterative PC

- Properties previously known on one-bit iterative PC:
  - Convergence to $\mathcal{S}^2$ for a matched filter receiver [D. Kim, 2001]
  - Convergence for *all* "Standard interference functions" [Yates 1995, Herdtner and Chong 2000]
- Our results [AgrAndCioMen03]:
  - Imperfect SIC has a Standard interference function
  - Convergence proven both in SINR and power
  - Proved that active links are protected
  - Results are applicable to multipath channels

Update

1. Special power control is required for SIC to function properly

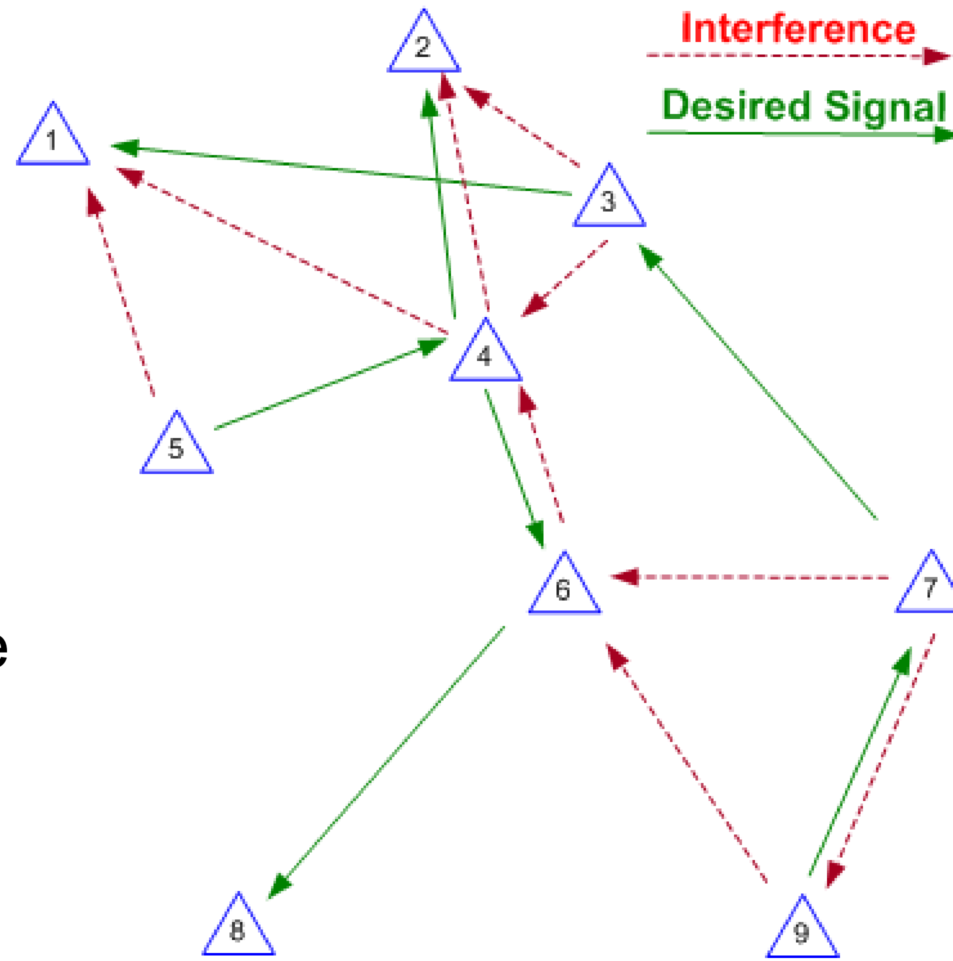
2. This special power control distribution is not to be feared, it can be implemented just as easily as current commercial CDMA power control.

3. A order 2-4 increase in capacity is a reasonable expectation in a cellular environment

– Can CDMA with (or without) SIC also help in an **ad hoc network?**

Ad Hoc Networks

- Ideally, would allow simultaneous transmissions in a given area
- Time/Frequency duplexing is not generally possible
- Interference may come from many sources



Potential Solutions

- Time division in the form of CSMA
  - Users only transmit when no one else is using the channel
  - Avoids most collisions
  - **Problem:** No one else can transmit in an often quite large geographic area
  - **Problem:** spatial reuse follows "worst-case" scenario
  - **Problem:** capacity per node goes to zero as number of nodes increases (GupKum00)
- Spatial separation techniques also will play a role
- What about CDMA?

CDMA allows interference averaging

- CDMA is intuitively appealing:
  - Can tolerate potentially numerous “collisions”
  - Allows high degrees of spatial reuse
  - Tolerant to narrowband interference
- BUT:
  - Still have the duplex issue (can’t Tx/Rx at same time)
  - Synchronization might be hard
  - Power control looks undoable
  - Spreading factor comes with a big capacity penalty
- Some work indicates best capacity is for CDMA + successive interference cancellation [TouGol02]

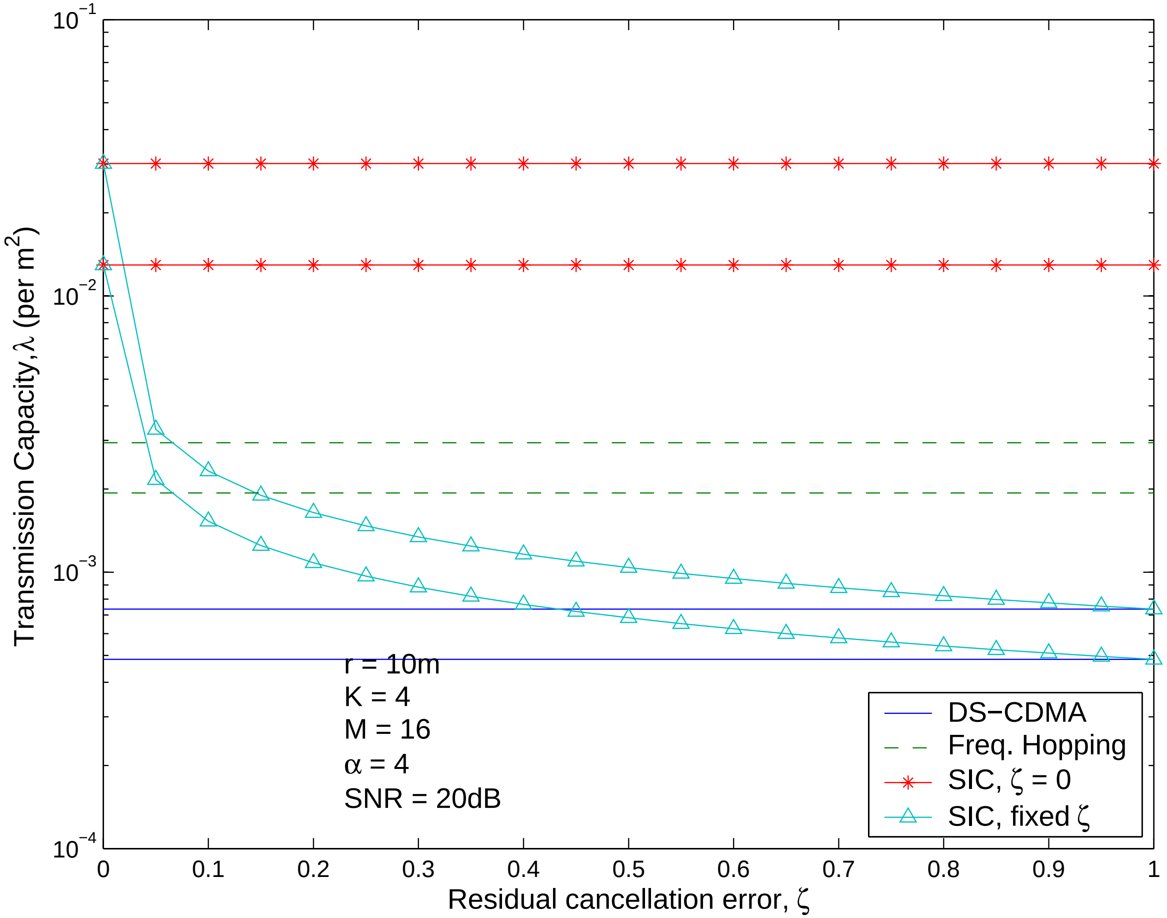
“Transmission Capacity”

- Model the node locations as a Poisson Point Process
- Use stochastic geometry to determine the maximum allowable intensity λ of the PPP under different multiple access and power control setups
- λ corresponds to “transmissions per area”
- Joint ongoing work with:
  - Prof. Steven Weber (Drexel)
  - Prof. Gustavo de Veciana (UT Austin)
  - Mr. Xiangying Yang (UT Austin)

Capacity Bounds

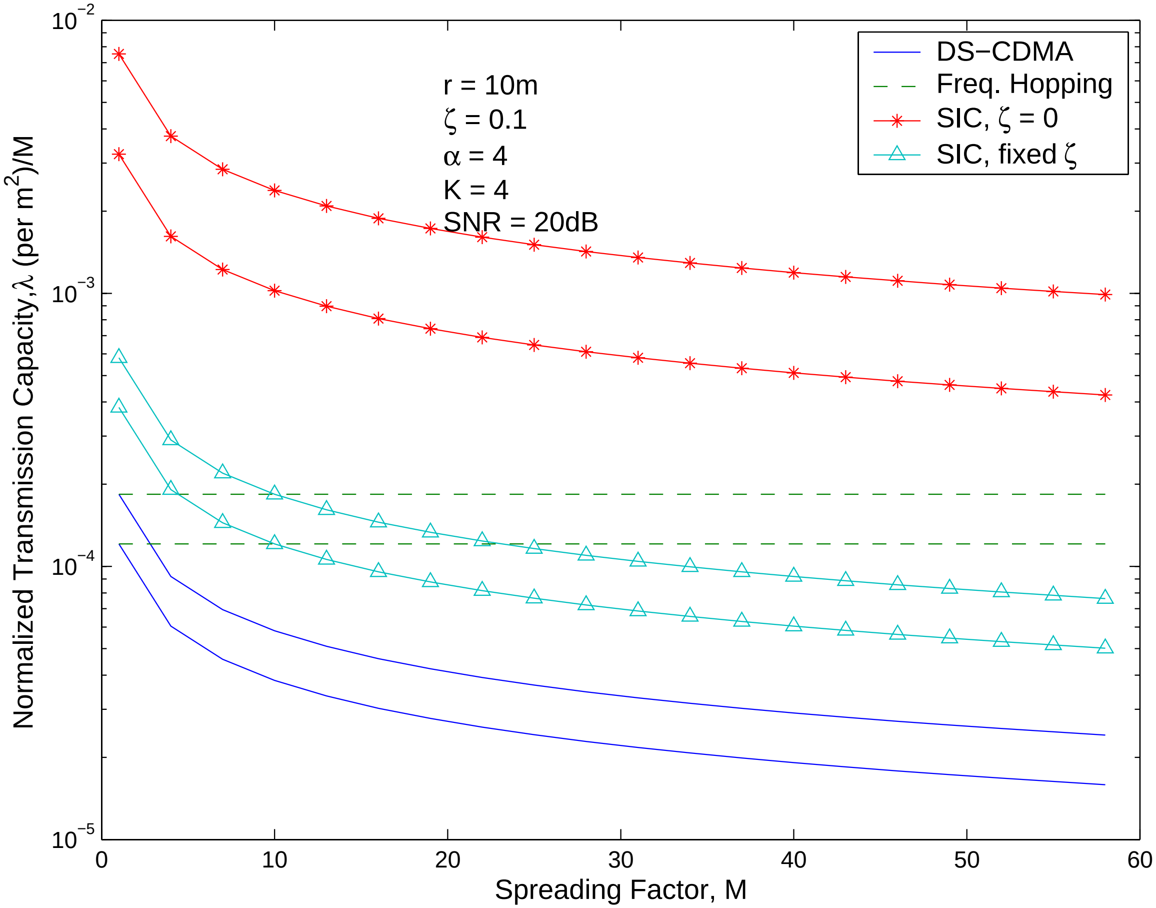
- We have recently proven upper and lower bounds on ad hoc network transmission capacity for the following scenarios:
  - Frequency Hopped Spread Spectrum (FHSS)
  - Direct Sequence Spread Spectrum (DSSS)
  - DSSS with (imperfect) successive interference cancellation
  - CSMA can be considered an optimistic special case of DSSS/FH with spreading factor = 1.
- Initial work has been submitted to ISSSTA and Globecom – Information Theory Transactions paper will be forthcoming soon with all proofs.

Capacity vs. Cancellation Error



- Ideal SIC increases capacity by nearly 100x!
- Results are a bit discouraging for imperfect SIC
- Frequency hopping is *much* better than DS (power control not important)

Normalized Capacity vs. Spreading



- Strictly speaking, no spreading is best
- But this is also true in theory for cellular – practical issues may tip in favor of CDMA
- Interestingly, frequency hopping capacity is not a function of spreading factor

Conclusions

- SIC is an interesting technology for both cellular and ad hoc networks
- Old arguments against SIC (propagation errors and power control complexity) do not hold water
- We have developed a new framework for ad hoc network capacity analysis and seen that frequency hopping is a promising CDMA technique
- SIC also can dramatically increase the capacity by canceling nearby nodes, but cancellation error must be small