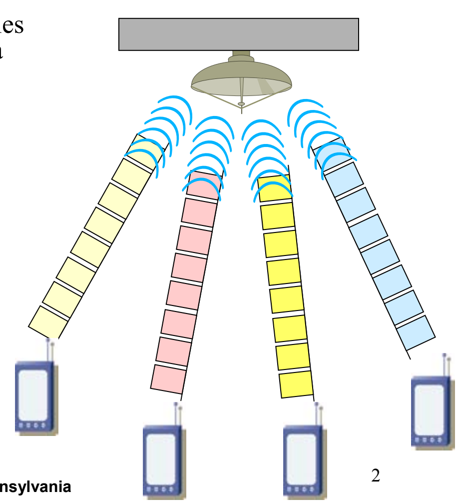
Exploring the Benefits of Channel Diversity in a Multi-User Environment*

R. Guérin
University of Pennsylvania

* joint work with S. Sarkar and E. Vergetis

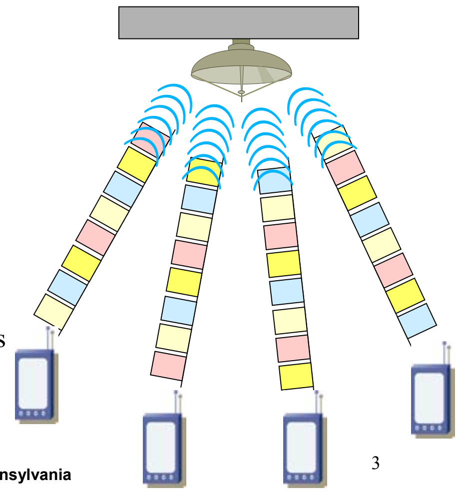
Broad Problem Setting (1)

- Channel definition
  - Distinct physical resource that enables transmission between a sender and a receiver, e.g., a frequency band
- Many users – many channels
  - How do we share channels between users to maximize "performance"?
- Two basic options
  - One user → one channel
  - One user → many channels
    - Leverage diversity
    - Many examples where this helps
      - Physical layer
      - Routing layer



Broad Problem Setting – (2)

- Many users – many channels
  - How do we share channels between users to maximize "performance"?
- Two basic options
  - One user → one channel
  - One user → many channels
    - Leverage diversity
    - Many examples where this helps
      - Physical layer
      - Routing layer



Scoping/Refining the Problem

- Channels are assumed independent and their performance is unaffected by user behavior
  - Multipath interference, Raleigh fading, etc.
- Focus is on open-loop systems
  - Channel "characteristics" are known
  - But, no active monitoring of channel state (no feedback)
- Users can distribute packet transmissions across channels
  - Multiple transmitters/antennas, frequency agile, etc.
- Channel access is synchronized across users
  - No collisions due to simultaneous use of same channel
  - E.g., access point distributes disjoint channel transmission schedules

Some Basic Questions

- When does channel diversity yield meaningful benefits?
  - What channel characteristics?
  - What channel combinations?
- What is the "best" way to use the available channels?
  - What transmission policies?
  - What channel grouping strategies?
- What types of benefits does channel diversity afford?
  - Higher throughput,
  - Robustness to channel variations
- How sensitive are those benefits?
  - To errors in estimating channel characteristics?
  - To deviations from the optimal policy?

Focus of This Talk

- Assume bursty channels.
  - Common in wireless (and wireline) settings
  - At the heart of diversity is the avoidance of long error bursts
- Rely on (N,k) diversity code
  - k data packets are encoded into N transmission packets
  - Transmission is successful is $i \geq k$ out of N packets are correctly received
  - Other types of erasure correction codes are possible
- Simple probabilistic and deterministic policies
  - Keep complexity low
  - Keep analysis tractable
  - Provide insight into the benefits of diversity

Related Work

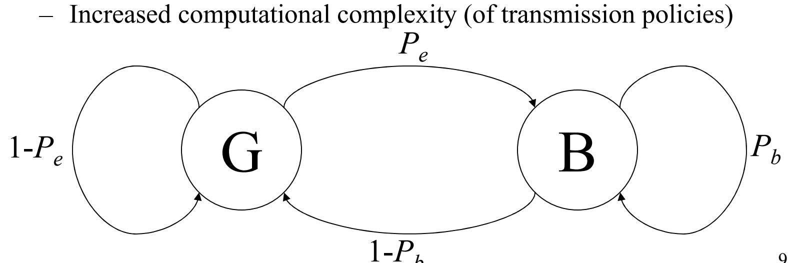
- Golubchik et al., 2002
  - Similar motivations
  - Different performance metrics
- Tsirigos & Haas, 2004.
  - Shares the goal of identifying the optimal transmission policy
  - Paths either succeed or fail for an entire transmission block of *N* packets (total erasure channel)
- Video applications
  - Apostolopoulos, Miu et al., Mao et al., Nguyen & Zakhor
  - Design of codes
  - Identify the best set of channels
- Information Theory
  - Laneman et al. (2004), Pradhan et al. (2004/2005)

Some Definitions

- Channel characteristics
  - Long-term error rate (*LTER*)
  - Expected burst length (*EBL*)
- k = data-frame size (fixed)
- N = code length (variable)
  - The bigger N, the greater the overhead
- P_{min} = Required probability of frame transmission success
- $\underline{p} = [p_1\ p_2\ \ldots\ p_C]$ characterizes the channel selection policy for C channels

Channel Model

- Simplest bursty model due to Gilbert (1960)
  - Basic ON-OFF behavior allows tuning of *EBL* and *LTER*
  - A reasonable first step (decent approximation of GSM and other wireless channels)
- Main limitations
  - Only two levels of channel quality
  - Exponential distribution of Good and Bad periods
- More complex channel models can be constructed using higher order Markov chains
  - Increased computational complexity (of transmission policies)



Performance Metrics – (1)

- Amount of information transmitted per unit time
  - *k* packets of information in each *N*-block
  - These *k* packets are correctly transmitted with probability $P_{succ}(N,k)$
  - It takes *N* “time units” to transmit each block
- Define the **Effective Rate** (*ER*) as

$$ER_A(N,k) = \frac{k \cdot P_{succ}^A(N,k)}{N} = \frac{k}{N} \cdot P_{succ}^A(N,k)$$

Performance Metrics – (2)

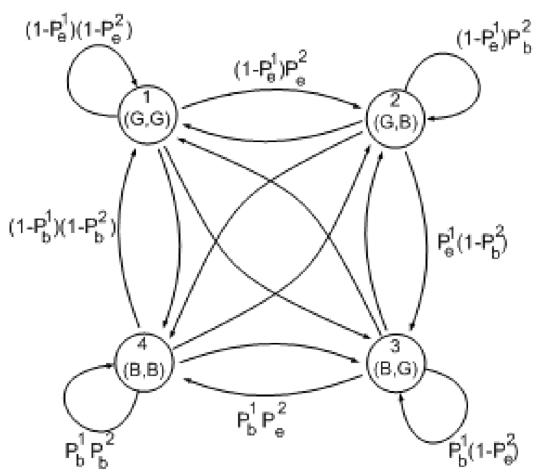
- Let A and B denote two arbitrary transmission policies
- The **relative gain** in ER is then given by

$$G_{ER}(A,B) = \frac{ER_B(N_B, k_B) - ER_A(N_A, k_A)}{ER_A(N_A, k_A)}$$

- The maximum possible gain by using diversity:
  - Policy A uses only one channel
  - Policy B is the optimal way of using the available channels

Computing the Optimal Policy

- Need to calculate $P^A_{succ}(N,k)$ given the channel characteristics
  - Recursive solution
- 4-state Markov Chain corresponding to two *independent* Gilbert channels
- For C independent channels, the MC has 2^C states



When Can We Increase *ER*?

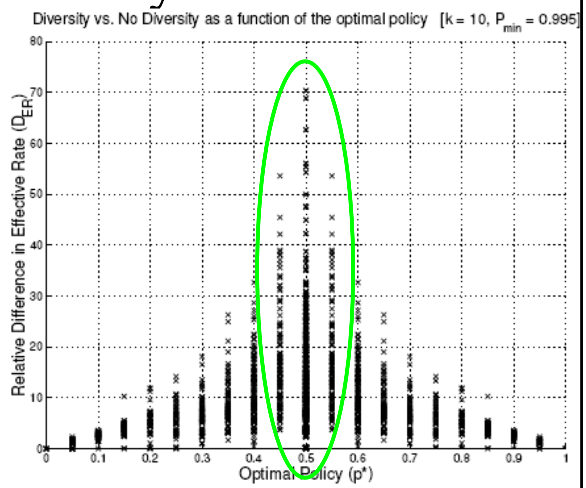
- What combinations of (possibly different) channels yield meaningful improvements in *ER*?
  - Consider wide range of channel combinations with different *EBL* and *LTER* values
- Comparison methodology
  - Single channel setting as a reference
    - Pick the best channel and (N,k) code combination that maximizes *ER* while still satisfying P_{min}
  - Path diversity setting
    - Pick the best code and policy combination that maximizes *ER* when using all channels

Intuition

- Channel diversity allows the break-up of extended periods of error bursts
  - Even a relatively bad channel can accomplish this goal
- Using multiple channels results in
  - A higher probability of success
  - A smaller code length N that satisfies P_{min}
- Most of the gains arise from reducing the code length N needed to satisfy P_{min}

When Is Diversity Beneficial?

- Exploring a broad range of channel combinations
  - Focus on 2-channel scenarios first
  - *LTER* ranges from 1% to 9%
  - *EBL* ranges from 1.01 to 20 packets



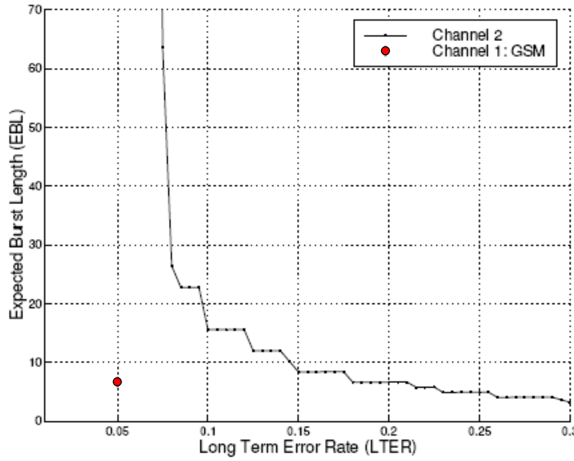
- Max. benefits when channels are used roughly *equally*

$\Rightarrow$ We will concentrate on such scenarios

But Before We Move On…

- When I share two very different channels across two users
  - The optimal strategy (for one user) wont use both channels equally
  - But then the two users don’t get treated the same way (need to switch “roles” $\Rightarrow$ added complexity…)
  - And ideally they should use different codes
    - Does this really matter?
- In general, when does a “bad” channel help?

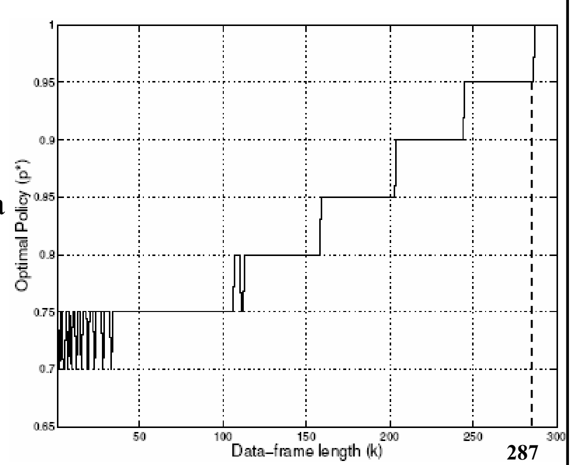
Can a "Bad" Channel Help?



- Channels that when used together with a GSM channel improve performance by 25%.

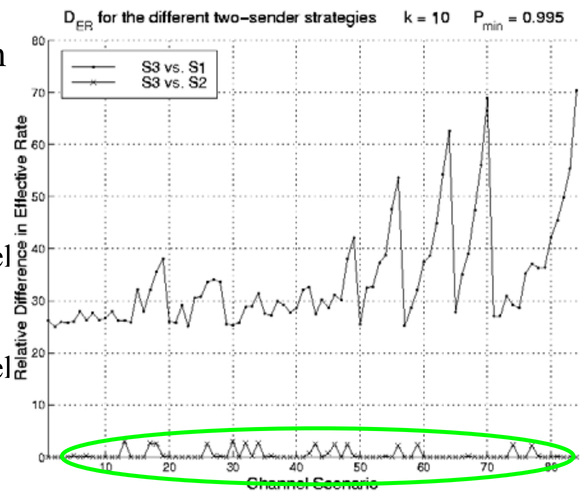
How Often Would I Use a Bad Channel?

- Configuration
  - 2 channels with same *EBL*
  - 1st channel has *LTER*=1%
  - 2nd channel has *LTER*=9%
- Optimal policy varies as a function of the maximum allowable code length
  - As expected, when increasing *k* (and *N*) for a given *EBL*, even a bursty channel ultimately looks like a Bernoulli channel



Do I Really Need Different Codes?

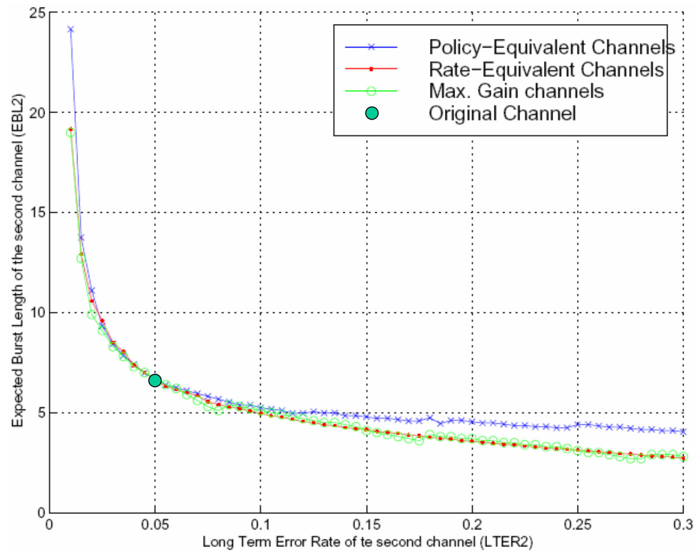
- Scenarios for which *ER* improvement exceeds 25%
  – S1: No channel diversity
  – S2: Optimal channel diversity with *identical* codes
  – S3: Optimal channel diversity with *distinct* codes
- No I don't!



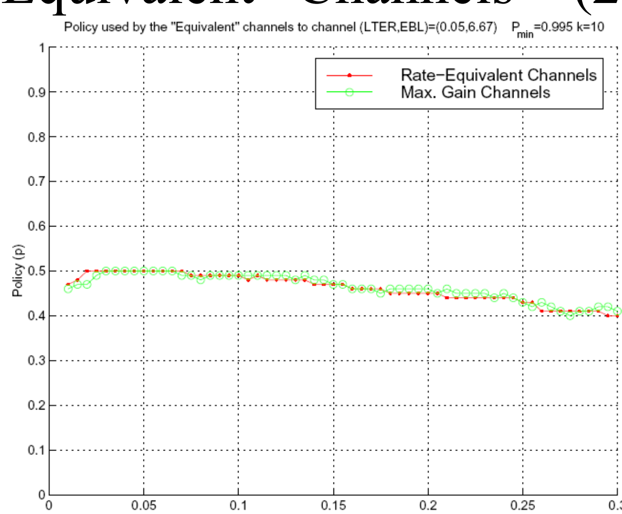
Coming Back to Scenarios Where Improvement Is Large

- We saw that improvement was large mostly when channels are used more or less equally
  – Note: When channels are used equally, we can use deterministic (round-robin) policies that actually perform better than probabilistic ones (they maximize spacing between consecutive channel uses)
- When is it the case that the optimal policy uses channels equally?
  – Obviously this holds for identical channels
    - A sufficient but probably not a necessary condition
- Three possible perspectives
  – Channels that when used individually have the same performance (*ER*)
  – Channels that are used equally under the optimal policy
  – Channels that when combined yield the maximum improvement
- Interestingly all three perspectives are nearly identical, although not entirely

“Equivalent” Channels – (1)

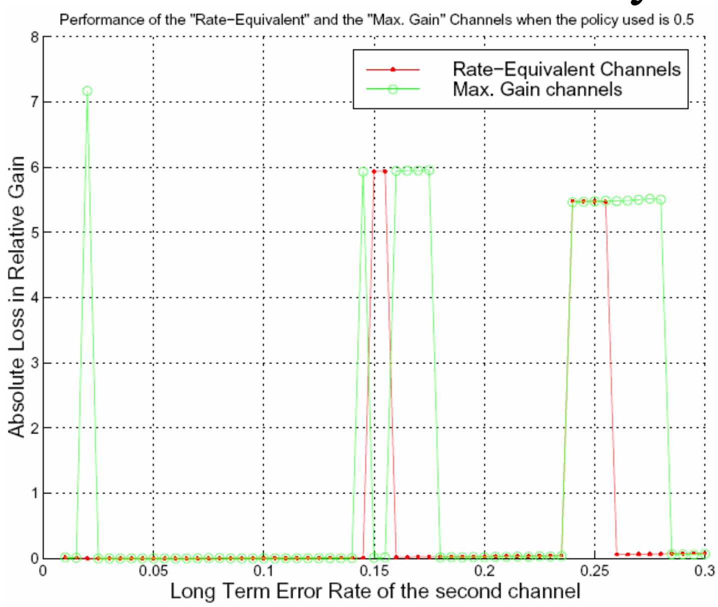


“Equivalent” Channels – (2)



- The optimal policy for rate-equivalent channels is close to 0.5.

The Price of Uniformity

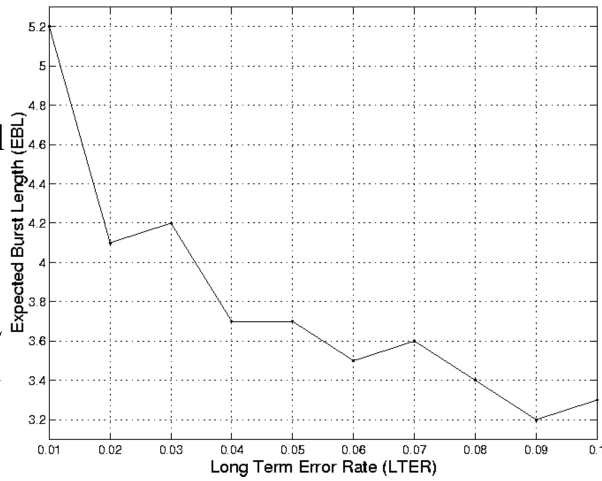


Focusing on "Equivalent" Channels

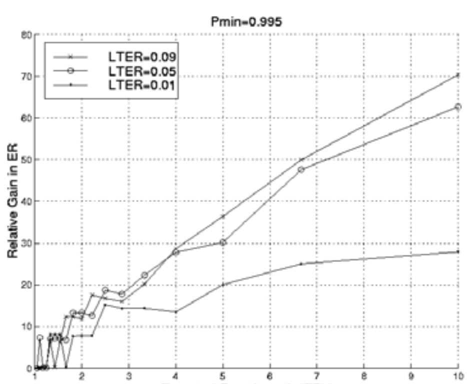
- Lets understand better what influences the potential for *ER* improvements
  - Channel characteristics, i.e., *EBL* and *LTER*
  - Performance target P_{min}
  - Number of channels available

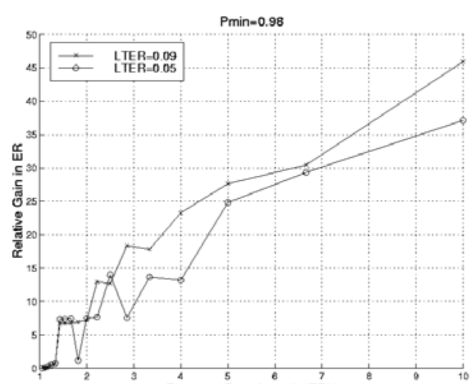
Impact of Channel Characteristics

- 25% performance improvement when combining identical channels with these characteristics
- The higher *LTER*, the smaller the *EBL* needed to achieve a given level of improvement



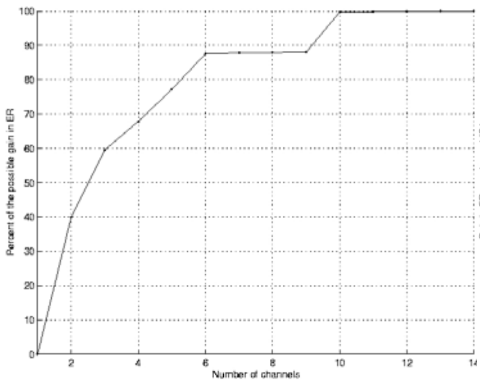
Sensitivity to P_{min}

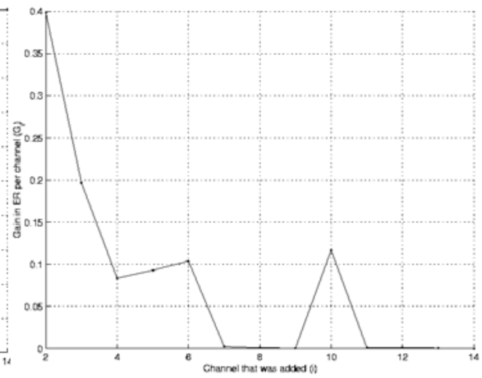




- Potential for improvement increases as
  - P_{min} gets tighter
  - *EBL* and *LTER* increase

Impact of Number of Channels



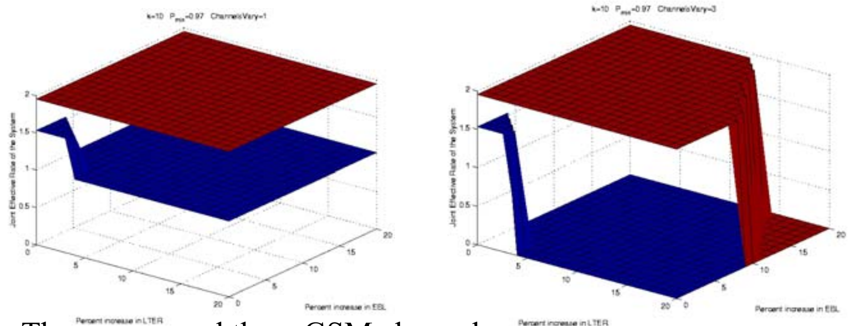


- Focus on GSM channel scenario
  - Benefits quickly taper off after 2 or 3 channels
  - Non-monotonous behavior because of discrete nature of transitions (when can I use a smaller *N*)

Sensitivity Analysis

- Two concerns
  1. Are we optimizing ourselves into a corner?
     - Quality of channels can change over time
     - Measurements might be inaccurate
  2. Can I trade-off performance improvements for robustness against channel degradations
- Explore sensitivity to
  - Changes in channel parameters (*EBL* and *LTER*)
  - Changes in distribution of duration of error bursts
     - Impact of the GE channel model
- Investigate relationship between performance improvements and ability to maintain $P_{\min}$ over degraded channels

Impact of Channel Degradations



- Three users and three GSM channels
  - Two scenarios: (1) each user is assigned one channel; (2) all three users (optimally) share the three channels
  - Both *EBL* and *LTER* are progressively made worse
    - First on only one channel (left), then on all three channels (right)
- Use of diversity helps improve both performance and robustness
  - There some loss of “isolation” in the single bad channel case, but it happens quite late (≥ 40% in both *EBL* and *LTER*)

Trading-Off Performance for Robustness

System	D_{ER} compared to a no diversity system	Percent increase in *both* LTER and EBL so that P_{min} is not satisfied
No diversity ($N = 19$)	0%	2%
Diversity ($N = 15$)	27.6%	16%
Diversity ($N = 16$)	20.7%	37%
Diversity ($N = 17$)	14.2%	63%
Diversity ($N = 18$)	8.2%	92%
Diversity ($N = 19$)	2.7%	$> 100\%$

- We use one of the scenarios of the previous slide
  - *EBL* and *LTER* are made progressively worse on all three channels
- We vary the code length *N* that the diversity system uses
  - A larger *N* makes the system more robust to errors, but lessens the potential performance improvement under “normal” conditions
- We assess the trade-off between the two

Impact of Changes in Channel Statistics

Variance Multiplier	No Diversity		Channel Diversity					
	$N = 19$		$N = 15$		$N = 16$		$N = 19$	
	ER	P_{succ}	ER	P_{succ}	ER	P_{succ}	ER	P_{succ}
Original	1.534	0.971	1.956	0.978	1.850	0.987	1.574	0.997
x 0.25	1.555	0.985	1.947	0.973	1.840	0.982	1.574	0.997
x 0.5	1.547	0.980	1.942	0.971	1.837	0.980	1.568	0.993
x 1	1.538	0.974	0	0.968	1.83	0.976	1.562	0.989
x 2	0	0.963	0	0.962	0	0.968	1.552	0.986
x 4	0	0.961	0	0.949	0	0.957	1.538	0.974
x 8	0	0.953	0	0.941	0	0.949	0	0.966

- We use three users and three GSM channels with $P_{\min} = 0.97$
  - The variance of the error burst periods is varied from 0.25 to 8 times that of the GSM channel using a Gamma distribution (non-Markovian)
- Again diversity allows trading-off performance for robustness

What Have We Learned?

- Path diversity can offers substantial benefits in both performance and robustness
  - It is possible to trade-off one for the other
- The biggest gains are when channels are "equivalent", but adding one bad channel can often still help
- Gains are higher when performance requirements are tight and increase as the channels get worse
- We don't need too many channels to reap the bulk of the benefits
  - Smaller groups of users makes for simpler coordination

Some Ongoing/Future Work

- Investigate impact of channel "stickiness"
  - Make transmission decisions for a block of *b* packets
  - Reduces the channel switching overhead
  - But, also reduces the ability to avoid bursts
- Impact of packet size
  - Bigger packets incur less overhead
  - But, same problem as with channel stickiness
- Exploring more general channel models
  - Hybrid time/frequency channel definition
  - More complex channel statistics, e.g., an 8-state Markov Chain
  - Correlated channels
    - How does the optimal policy change?
    - How quickly do performance improvements vanish?
- Accounting for possible collisions when sharing is not coordinated
  - Access point association scenario
    - Users register with multiple access points (to implement transmission diversity)
    - More users per access point $\Rightarrow$ greater potential for collision, but
    - More access points per user $\Rightarrow$ lesser load per user on a given access point
- Experimental validation (802.11 testbed)
  - Channel modeling (from bits to packets)
  - Evaluation of path switching overhead