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

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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 if \(i \geq k\) 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
  - 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
- $p = [p_1 \ p_2 \ \ldots \ p_C]$ 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)

\[
\begin{align*}
G & \quad \text{G} \quad \text{B} \\
1-P_e & \quad P_e & \quad 1-P_b & \quad P_b
\end{align*}
\]

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 \( P_{\text{suc}}(N,k) \)
  - It takes \( N \) “time units” to transmit each block
- Define the Effective Rate (ER) as

\[
ER_A(N,k) = \frac{k \cdot P_{\text{suc}}^A(N,k)}{N} = \frac{k}{N} \cdot P_{\text{suc}}^A(N,k)
\]
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 $P^*_s(N,k)$ 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*
  ⇒ 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) won’t use both channels equally
  - But then the two users don’t get treated the same way (need to switch “roles” ⇒ 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)

- 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 $P_{\text{min}}$
  - 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 $P_{\text{min}}$

- Potential for improvement increases as
  - $P_{\text{min}}$ 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 $P_{\text{min}}$ 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 ($\geq 40\%$ in both $EBL$ and $LTER$)

Trading-Off Performance for Robustness

<table>
<thead>
<tr>
<th>System</th>
<th>$D_{ER}$ compared to a no diversity system</th>
<th>Percent increase in both $LTER$ and $EBL$ so that $P_{nit}$ is not satisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>No diversity ($N = 19$)</td>
<td>0%</td>
<td>2%</td>
</tr>
<tr>
<td>Diversity ($N = 15$)</td>
<td>27.6%</td>
<td>16%</td>
</tr>
<tr>
<td>Diversity ($N = 16$)</td>
<td>20.7%</td>
<td>37%</td>
</tr>
<tr>
<td>Diversity ($N = 17$)</td>
<td>14.2%</td>
<td>63%</td>
</tr>
<tr>
<td>Diversity ($N = 18$)</td>
<td>8.2%</td>
<td>92%</td>
</tr>
<tr>
<td>Diversity ($N = 19$)</td>
<td>2.7%</td>
<td>$&gt; 100%$</td>
</tr>
</tbody>
</table>

• 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

We use three users and three GSM channels with $P_{\text{min}} = 0.97$

- 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

<table>
<thead>
<tr>
<th>Variance Multiplier</th>
<th>No Diversity</th>
<th></th>
<th>Channel Diversity</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N = 19$</td>
<td>$N = 16$</td>
<td>$N = 15$</td>
<td>$N = 19$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ER$</td>
<td>$P_{\text{succ}}$</td>
<td>$ER$</td>
<td>$P_{\text{succ}}$</td>
<td>$ER$</td>
<td>$P_{\text{succ}}$</td>
<td>$ER$</td>
<td>$P_{\text{succ}}$</td>
</tr>
<tr>
<td>Original</td>
<td>1.534</td>
<td>0.971</td>
<td>1.956</td>
<td>0.978</td>
<td>1.850</td>
<td>0.987</td>
<td>1.574</td>
</tr>
<tr>
<td>x 0.25</td>
<td>1.555</td>
<td>0.985</td>
<td>1.947</td>
<td>0.973</td>
<td>1.840</td>
<td>0.982</td>
<td>1.574</td>
</tr>
<tr>
<td>x 0.5</td>
<td>1.547</td>
<td>0.980</td>
<td>1.942</td>
<td>0.971</td>
<td>1.837</td>
<td>0.980</td>
<td>1.568</td>
</tr>
<tr>
<td>x 1</td>
<td>1.538</td>
<td>0.974</td>
<td>0</td>
<td>0.968</td>
<td>1.83</td>
<td>0.976</td>
<td>1.562</td>
</tr>
<tr>
<td>x 2</td>
<td>0</td>
<td>0.963</td>
<td>0</td>
<td>0.962</td>
<td>0</td>
<td>0.968</td>
<td>1.552</td>
</tr>
<tr>
<td>x 4</td>
<td>0</td>
<td>0.961</td>
<td>0</td>
<td>0.949</td>
<td>0</td>
<td>0.957</td>
<td>1.538</td>
</tr>
<tr>
<td>x 8</td>
<td>0</td>
<td>0.953</td>
<td>0</td>
<td>0.941</td>
<td>0</td>
<td>0.949</td>
<td>0</td>
</tr>
</tbody>
</table>

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