Opportunistic Relaying vs. Selective Cooperation

Analyzing the Occurrence-Conditioned Outage Capacity

MSWiM 2008

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What is this talk about?

• Performance bounds: Two opposed design approaches for
  • Cooperative relaying protocols, i.e. Opportunistic relaying vs. Selection decode-and-forward
  • Degrade performance bounds according to practice

• Maximum data rate (end-to-end capacity) given that:
  • Error (outage) probability bound is not exceeded, e.g. such that: PER ≤ 10% (IEEE 802.11)
  • Control feedback is required and may be in erroneous
  • Relay(s) occur, i.e., can be employed beneficially
⇒ Occurrence-conditioned outage capacity

⇒ Protocol designers: Select approach & benchmark
  • Find region of operation; compare actual protocol to upper bounds

Outline

• Basics: Cooperative relaying & performance measures
• Outage probability: From 1 to N relays
• Outage capacity: N relays & feedback costs
• Beneficial configurations: Occurrence & resulting capacity

When to choose which cooperation protocol design approach?
... and how “good” is it compared to the ideal case?
Compared cooperative relaying approaches

- Both: Relays regenerate and forward only correct messages
- BUT fundamental differences: Used channels and feedback

- Opportunistic relaying (OR):
  - Only single "best" relay forwards, no combining
  - Full diversity requires: End-to-end channel knowledge at a or relays ⇒ Feedback from d needed

- Selection Decode & Forward (SDF):
  - All relays forward, d combines signals
  - Full diversity requires: No feedback, only local channel knowledge needed

Assumptions and end-to-end performance measures

- Assumptions: High SNR, i.i.d. Rayleigh fading & noise are only error events, all codes and combining equal & ideal
- Outage event: Channel capacity falls below a selected spectral efficiency $R$ (bit/s/Hz); Single channel: $\gamma_{a,d} < 2^R - 1$
- Outage probability $P_{\text{out}}$:

$$P_{\text{out}} = \Pr(\gamma_{a,d} < 2^R - 1) \approx \frac{1}{\Gamma_{a,d}} \frac{2^R - 1}{\Gamma}$$

- High SNR approximation: Only mean SNR
- Notation: Channel $(a,d)$’s mean SNR: $\Gamma_{a,d}$
- Outage capacity $C^*$: Maximum spectral efficiency supported at given outage probability bound $\epsilon$
  - Solve $P_{\text{out}}(R) = \epsilon$, in $R$; Define $C^* := R$
  - E.g. WLAN standard $\epsilon = 0.1$: Do not exceed 10% packet error rate

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Outage probability: From 1 to $N$ relays

- Cooperative triangle: 1 hop, 1 relay

$$P_{\text{out}}^C \sim \frac{1}{\Gamma_{a,d}} \left( \frac{1}{\Gamma_{a,b}} + \frac{1}{\Gamma_{a,d}} \right) \left( \frac{2^R - 1}{\Gamma} \right)^\Theta$$

- General form – 3 factors depending on:
  1. Diversity order $L$
  2. $\Theta$: Channel gains $\Gamma_{a,b}$...
  3. No. channels $K$, $L$, reference mean SNR $\Gamma$

- Derive:
  - Count $K$
  - Obtain $\Theta$ and $L$ by cut set method [5]
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Feedback: Impact on OR’s outage capacity

- For any feedback scheme:
  \[ C_{\text{OR,FB}} := C' \cdot R_{\text{FB}}(C_{\text{FB}}^\epsilon) \]
  with \(R_{\text{FB}} \in [0,1]\) utilization of feedback channel’s capacity \(C_{\text{FB}}^\epsilon\)
- Examples:
  - \(R_{\text{FB}}=0\): Require complete or more feedback channel capacity \(C_{\text{FB}}^\epsilon\)
    Assumption: Without signaling OR gives up
  - \(R_{\text{FB}}=1\): Require no portion of \(C_{\text{FB}}^\epsilon\)
    \[ R_{\text{FB}}(C_{\text{FB}}^\epsilon, b_{\text{FB}}, T) := \begin{cases} \frac{C_{\text{FB}}^\epsilon b_{\text{FB}}}{T} & \text{if } b_{\text{FB}}/T < C_{\text{FB}}^\epsilon \\ 0 & \text{otherwise} \end{cases} \]
  - 1/T feedback frequency: E.g. T=1 feedback in each Tx cycle
- Consequence, if \(C_{\text{FB}}^\epsilon < C'\): Feedback channel’s capacity bounds OR’s end-to-end capacity

Outage capacity in closed form: \(N\) relays or hops

- Apply outage probability results; Solve \(P_{\text{out}}(R) = \epsilon\) in \(R\)
  \[
  C'^\epsilon := R = \frac{L}{R} \log_2 \left( \frac{L+1}{\epsilon} \right)
  \]
  Multiplexing loss
- With \(\log_2(L) \approx \int_1^L \log_2 x \, dx = L \log_2 L - L\)
  we obtain
  \[
  C'^\epsilon \approx \frac{1}{K} \left( \log_2(L) \cdot \frac{1}{L} \log_2 \epsilon - \frac{1}{L} \right) \]
  \(\Rightarrow\) Outage capacity of cooperative relaying is fraction of:
  - \(C_{\text{AWGN}}^\epsilon\): AWGN capacity of \(L\)-antenna MISO system degraded by \(\epsilon\) and channel-dependent terms
  - Valid for:
    - SDF: 1 hop, \(K\) relays; OR: \(K\) hops, per hop: 1 out of \(N\) relays

Numerical results: Assumptions & parameters

- Assumed feedback scheme: \(d\) assigns the best relay
  - Once per \(T\) cycles: Broadcast \(b_{\text{FB}}\) bits from \(d\) to all relays
  - Minimal costs: \(b_{\text{FB}}=\log(N+1)\) bits and \(K=1\)
  - BUT: Only direct channel to each relay; \(L=1\)
  - Feedback frequency: \(T=57\) phases
    Coherence time in .11a WLAN with \(v=1\) m/s
- Scenario:
  - All possible configurations with: 2 relay, 1 hop
  - Symmetrical: Equal mean channel gains
  - Two error rate bounds: \(\epsilon=10^{-3}, \epsilon=0.1\)
**Numerical results: High robustness $\varepsilon=10^{-3}$**

- Maximum: ~ $1/4$ of MISO capacity
- SDF: Best performance if all relays and all channels are employed
- OR: Performance highly degraded with feedback

**Numerical results: Low robustness $\varepsilon=0.1$**

- Maximum: $1/2$ of MISO capacity
- Situation reversed:
  - SDF: Poor performance, especially with many relays
  - OR: High performance, only slightly degraded by feedback

**Outage capacity: Range of operation**

- At which SNR and error bound $\varepsilon$ does SDF outperform OR?
  - Search crossing points – For many $\varepsilon$: Solve $C_{\text{SDF}}(\Gamma) = C_{\text{OR}}(\Gamma)$ in $\Gamma$

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Can we find beneficial relays? How likely?

- In practice: Can we really use all relays and all channels?
- Studied: How likely do beneficial 1 and 2-relay configurations occur?

Effect of network density:
- Can employ: Always a single relay
- For more relays: No high density required

Occurrence: Impact on outage capacity

Occurrence-conditioned outage capacity: $C_{\varepsilon,o} = P_0 \cdot C_{\varepsilon}$

- Manhattan: Capacity decreases for both approaches
- Stronger effect: $\varepsilon$ defines if SDF or OR is beneficial

Conclusion

- SDF: Highest capacity if all channels can be employed
  - Without all channels: Employ fewer relays
  - Limit multiplexing loss: Mostly 1 or 2 relays suffice
- OR: Control feedback channel bounds end-to-end capacity
  - Even for control data: Cooperation required
- Protocol choice: Error rate bound defines if OR or SDF reach maximum outage capacity
  - Low robustness, stable channels (WLANs): Choose OR
  - High robustness, unstable channels (speech, vehicular): SDF
  - Occurrence: Manhattan decreases OR and SDF’s capacity

Future of cooperative protocol design is “gray”:
- Choose any no. $K \geq 1$ out of $N$ relays; Optimize $K$

Thank you! – Any questions?

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