Multilevel Coding Strategy for Two-Hop Single-User Networks

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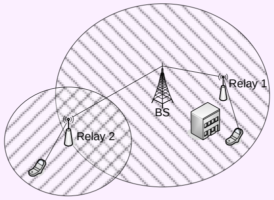
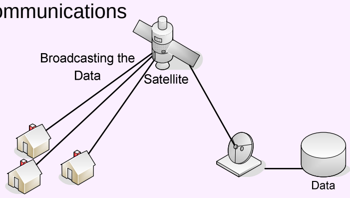
Introduction

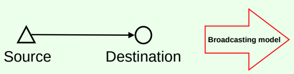
- **Relay node deployment**
  - Increasing the network coverage.
  - Improving the user's achievable data rate.

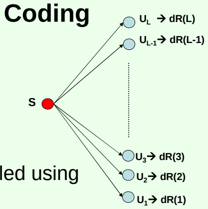


- **Example two-hop network applications**
  - TV Broadcasting
  - Satellite Communications



Notion of Multilevel Coding





- The single user fading link is modeled using a degraded broadcast channel.
- Source sends infinite layers of coded data with rate *dR(l)* and power *ρ(l)* to each of the virtual users.
- The sum-power of superior users acts as an interference.
- Therefore, each virtual user achievable data rate is

$$dR(l) = \log\left(1 + \frac{l\rho(l)dl}{1 + lI(l)}\right) \simeq \frac{l\rho(l)dl}{1 + lI(l)}$$

- As a result of the broadcast channel degradedness, each user can decode the data sent to the inferior users.
- Assuming *f(l)* as the *pdf* of the channel, *ρ(l)* should be found such that

$$\max_{\rho(l)} \quad R_{av} = \int_0^\infty dl\, f(l)R(l)$$
$$s.t. \quad \int_0^\infty \rho(l) = P$$

Single-Hop Networks

- **Original broadcasting strategy**
  - No CSI at the transmitter.
  - The source has a maximum power constraint.
  - Available data rate is unlimited.
  - Goal: Maximizing the average destination received data rate.

$$\max_{\rho(l)} \quad R_{av} = \int_0^\infty dl\, f(l)R(l) \qquad s.t. \quad \int_0^\infty \rho(l) = P$$

Fixed endpoints variation problem. →

$$I^*(l) = \begin{cases} P & l < l_0 \\ \frac{1-F(l)-lf(l)}{l^2 f(l)} & l_0 < l < l_1 \\ 0 & l_1 < l \end{cases} \qquad I^*(l_0) = P, \quad I^*(l_1) = 0$$

- **Rate-Limited broadcasting strategy**
  - The source has a maximum power constraint.
  - The available data rate is limited at the source.

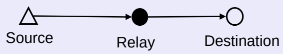
$$\max_{\rho(l)} \quad R_{av} = \int_0^\infty dl\, f(l)R(l) \qquad s.t. \quad \int_0^\infty \rho(l)dl = P, \quad \int_0^\infty dR(l) \leq R_{in}$$

Variation problem with fixed value constraint. →

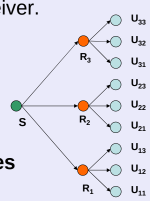
$$I^*(l) = \begin{cases} P & l < l_0 \\ \frac{1-F(l)+\lambda-lf(l)}{f(l)l^2} & l_0 < l < l_1 \\ 0 & l_1 < l \end{cases} \qquad I^*(l_0) = P, \quad I^*(l_1) = 0$$

λ is computed such that the rate condition holds.

Two-Hop Networks



- **Network Model**
  - No direct connection between the source and the destination (Two-hop settings).
  - Channel state information of each link is only available at its corresponding receiver.
  - Relay is simple. Not capable of:
    - Data buffering or rescheduling
  - Equivalent Broadcasting Model



- **Suboptimal Transmission Schemes**
  - Decode and Forward relaying
    - Outage approach at the source and the relay
    - Broadcasting at the source/ Outage at the relay ($DF_{1\text{-}bs}$)
    - Outage at the source/ Broadcasting at the relay
  - Amplify and Forward relaying
    - It was the best known high SNR transmission strategy.
- **Proposed Optimal Transmission Scheme**
  - Decode and Forward relaying
  - Broadcasting strategy at both of the source and relay

Multilevel DF Transmission

- **Transmission steps:**
  - The source constructs a multilevel code ($\rho_s^*(l)$):
    - Should satisfy the source total power constraint
  - Based on the first-hop realization, the relay receives:

$$R_r(x) = \int_{a=0}^{x} \frac{a\rho_s(a)da}{1 + aI_s(a)}$$

  - Knowing the first-hop channel, the relay designs a multilevel code for the second hop, ($\rho_r^*(l|\gamma = x)$):
    - Should satisfy the relay power and the rate constraints.
  - Condition on the second-hop channel, the receiver receives:

$$R_d(y|\gamma) = \int_0^y \frac{a\rho_r(a|\gamma)}{1 + aI_r(a|\gamma)}da$$

- **The Optimization problem would be**
  - Complexity: The rate constraint does not have a fixed value. Therefore, general variation methods can not be applied directly.

$$\max_{\rho_s(l),\ \rho_r(l|\gamma)} \int_0^\infty \int_0^\infty f_\gamma(x) f_\mu(y) R_d(y|\gamma = x)dydx$$
$$s.t. \quad \int_0^\infty \rho_s(a)da = P_s,$$
$$\forall x \in \gamma: \int_0^\infty \rho_r(a|\gamma = x)da = P_r,$$
$$\forall x \in \gamma: \int_0^\infty \frac{a\rho_r(a|\gamma = x)da}{1 + aI_r(a|\gamma = x)} \leq R_r(x).$$

Results

- Rewrite the optimization problem as a two-step problem:

$$\max_{\rho_s(l)} \int_0^\infty dx f_\gamma(x) \left[\max_{\rho_r(l|R_r(x)=i)} \int_0^\infty dy f_\mu(y) \int_0^y \frac{a\rho_r(a|R_r(x))}{1 + aI_r(a|R_r(x) = i)}da \right]$$

  - The inner optimization can be modeled as a rate-limited broadcasting problem.
  - Using the optimal results of the inner part, fixed endpoints variation method can be used to solve the outer problem.
- Figures depict the average received data rate for the flowing cases and show the superiority of the multilevel DF.

1) The cut-set bound
2) AF scheme
3) $DF_{1\text{-}BS}$ method
4) The proposed multilevel DF scheme