Adaptive Modulation for Coded Cooperative Systems

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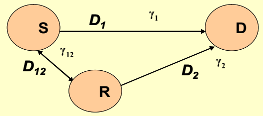
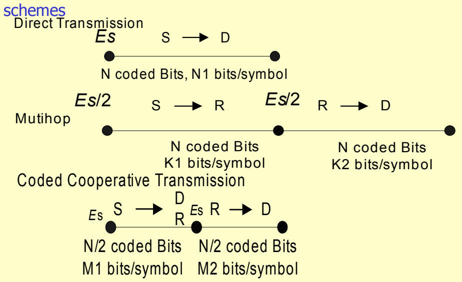
Motivation and System Model

- Throughput: Performance measure for data communications
- Wireless LAN standard IEEE 802.11 uses adaptive modulation and coding to obtain high data rates
- Previous work on user cooperation:
  - Focus on error rates/outage probability
  - Use fixed (common) modulation for all users
- We consider adaptive modulation to maximize data throughput



Quasi-static channel for S and R; block-fading channel codes designed for cooperation to obtain diversity gains

- Assume: the transmitted energy per symbol is fixed as *Es*; Compare: three types of transmission schemes



- Adaptive modulation: modulation modes N1, K1, K2, M1, M2 are adapted to maximize throughput.

Throughput Analysis

- **Assumptions:**
  - When the receiver detects an error in a packet, the system uses ARQ to resend the packet until the packet is successfully delivered to the receiver.
  - R_s: symbol transmission rate; R_c: convolutional code rate; B: number of data bits in each packet.
  - N = B/ R_c: number of coded bits in each packet (ignore the overhead bits);
  - Throughput: the number of payload bits per second received correctly

$$\Gamma = \frac{B}{E(T)}$$

where E(T) is the total expected time for each packet to be received at the destination successfully

- **Direct Transmission:** S re-sends each packet directly to the destination until the destination receives it correctly.

$$\Gamma_{direct} = N_1 R_s R_c (1 - P_{d,1}^{QS})$$

$P^{QS}_{d,1}$: Average FER for direct transmission; N_1: The number of bits per symbol transmitted by *S* to the destination

- **Multihop:** S retransmits the coded packet to R until the packet is successfully received by R; R relays the packet to destination until the destination gets it correctly.

$$\Gamma_{mhop} = \frac{R_s R_c}{\frac{1}{(1-P_{m,12}^{QS})K_1} + \frac{1}{(1-P_{m,2}^{QS})K_2}}$$

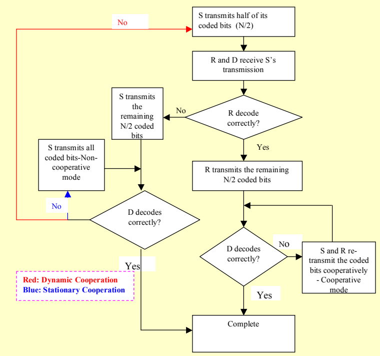
$P^{QS}_{m,12}$ and $P^{QS}_{m,2}$: Average FER of the channel code for the quasi-static **S**-to-**R** channel and **R**-to-**D** channel; K_1 and K_2: The number of bits per symbol for **S** and **R** respectively for the multihop mode respectively during cooperation

***S* and *R* adapt their modulation rates *K1* and *K2* based on qualities of *S-R* and *R-D* channels respectively.**

Coded Cooperative Transmission

- **S** transmits half of the coded bits to the destination and **R**.
- If **R** decodes the information correctly, **R** sends the other half of the coded bits, and **S** and **R** cooperate until the destination receives the packet successfully.
- If **R** cannot decode:
  - **Stationary Cooperation: S** transmits the remaining coded bits, and if necessary repeats the whole packet until successful reception at the destination.

    Limited use of relay: if **R** doesn't decode in the first transmission, it doesn't listen to retransmissions from **S**.
  - **Dynamic Cooperation: R** continues hearing the signal from **S** and helps **S** transmit the remaining coded bits to the destination until successful reception once it decodes correctly



Throughput for Coded Cooperation

- Stationary Cooperation:

$$\Gamma_{s\_coop} = \frac{R_s R_c}{\frac{(1-P_{c,12}^{QS})}{(1-P_c^{BF})}\left(\frac{1}{2M_1}+\frac{1}{2M_2}\right) + \frac{P_{c,12}^{QS}}{(1-P_{c,1}^{QS})}\frac{1}{M_1}}$$

- Dynamic Cooperation:

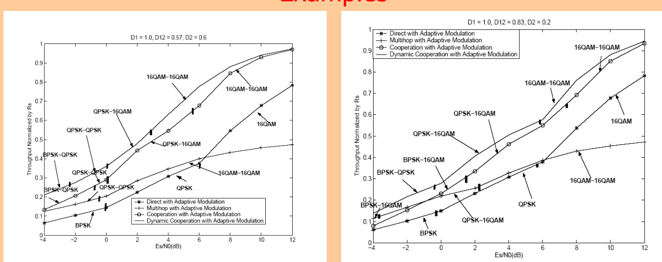
$$\Gamma_{d\_coop} = \frac{R_s R_c}{\frac{1}{(1-P_c^{BF})}\frac{(1-P_{c,12}^{QS})}{(1-P_{c,1}^{QS}P_{c,12}^{QS})}\left(\frac{1}{2M_1}+\frac{1}{2M_2}\right) + \frac{P_{c,12}^{QS}}{(1-P_{c,1}^{QS})}\frac{(1-P_{c,12}^{QS})}{(1-P_{c,1}^{QS}P_{c,12}^{QS})}\frac{1}{M_1}}$$

- $P^{QS}_{c,12}$: Average FER of channel code for inter-user channel;
- $P^{QS}_{c,1}$: Average FER for the quasi-static **S**-to-**D** channel in the non-cooperative case;
- P^{BF}_{c}: FER for the block fading channel when cooperation takes place;
- M_1, M_2 : bits per symbol for **S** and **R** respectively during cooperation

Discussions:

- $P^{QS}_{c,1}$ and $P^{QS}_{d,1}$ are not necessarily equal as **S** may have a different optimal modulation scheme for direct transmission and cooperative scheme;
- $P^{QS}_{m,12}$ is different from $P^{QS}_{c,12}$ since **S** only uses half transmitted energy per symbol in multihop as in cooperative transmission;
- We find from Γ_{s_coop} and Γ_{d_coop} that the throughputs of **S** in coded cooperation depend on all three link SNRs, γ_1, γ_2 and γ_{12} ; to optimize Γ_{coop}, **S** and **R** should base their modulation modes on all these three links.

Examples



[5, 7, 5, 7] convolutional code

- Cooperation with adaptive modulation leads to higher throughput than multihop and direct transmission with adaptive modulation. The gains associated with cooperation are many fold:
  - Gain due to diversity at the receiver;
  - Gain due to channel coding cooperatively;
  - Gain due to multihop
- Multihop with adaptive modulation improves the throughput over direct transmission with adaptive modulation in low and medium SNR.
- Modulation mode selection of the relay in coded cooperation not only depends on its own channel quality but also is determined by the source's channel quality.
- When D12 is large, the throughput of stationary cooperative transmission is less than that of multihop in low SNR as the inter-user channel is not very reliable and cooperation occurs less often. Dynamic cooperative transmission remedies this disadvantage as relay updates when it hears more and provides higher throughput than the other three transmission schemes.

Ongoing Work

- Throughput maximization using joint adaptation of modulation, code rate and level of cooperation.
  - Use high rate codes (rates 1/2, 2/3 and 3/4) as in 802.11 standard and adjust the level of cooperation by puncturing the mother code.
- Information theoretic approach:
  - Provide a bound on the throughput achievable by finite rate codes.
  - Use outage probability instead of frame error rates.
  - For M-level modulation, use M'ary symmetric channel with average symbol error rate to upper bound the outage probability.
  - Optimize throughput over all modulation modes, code rates in bits/channel use, and levels of cooperation.

Conclusion

- Cooperative schemes incorporating adaptive modulation at both the source and the relay are proposed.
- Analytical throughput expressions for direct transmission, multihop, stationary and dynamic coded cooperative transmission are derived.
- The effects of channel qualities on the throughput performance of the four schemes are investigated.
- Joint adaptation of modulation modes is essential to maximize the throughput of cooperative system.
- Adaptive modulation coupled with diversity and multihop gains provided by cooperation improves the throughput over direct transmission and multihop.
- Dynamic coded cooperation provides the highest throughput among the four schemes.