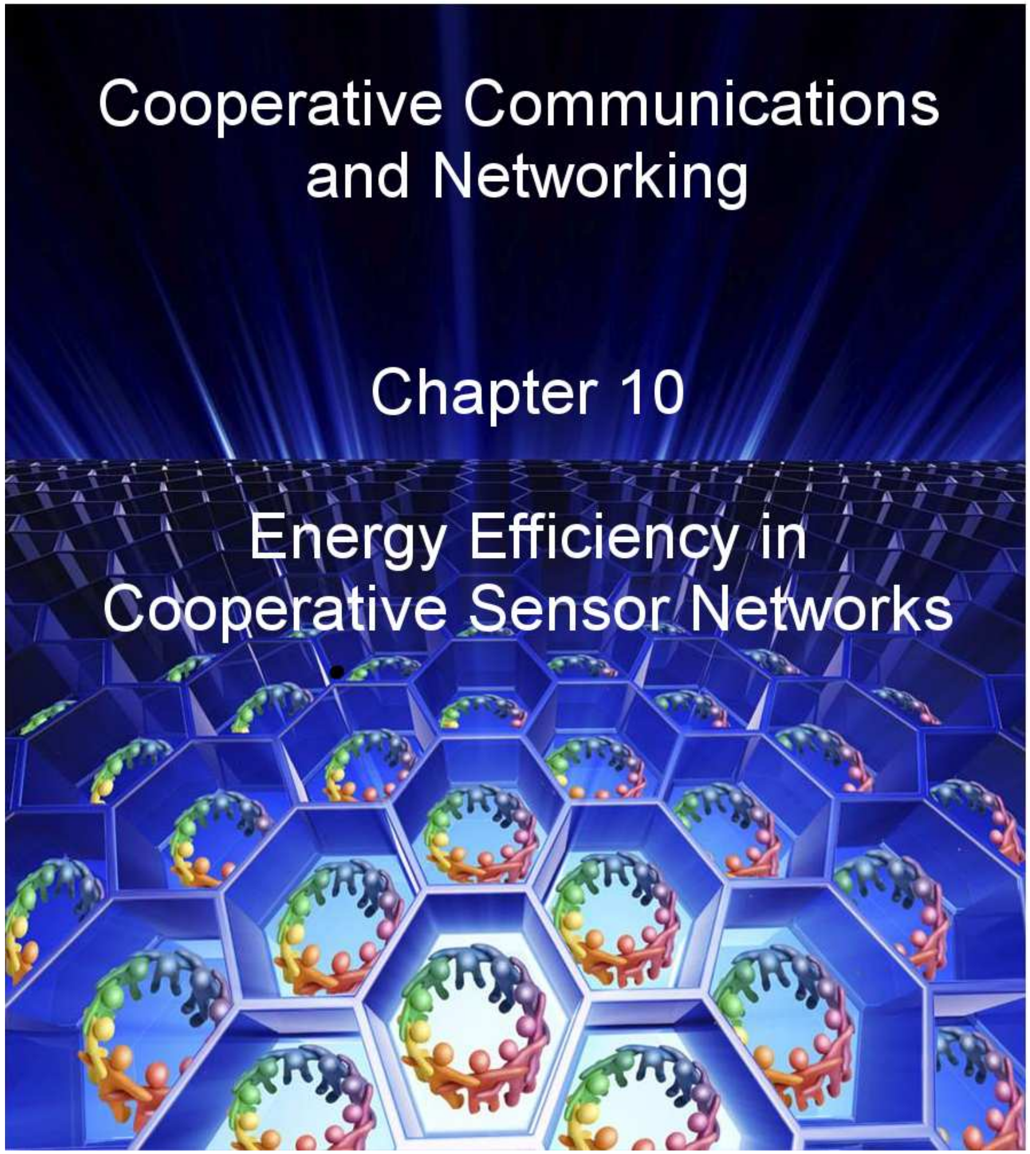

Cooperative Communications
and Networking
Chapter 10
Energy Efficiency in
Cooperative Sensor Networks

Outline

- Introduction and Motivation
- System Model
- Performance Analysis
- The Optimization Problem
- Experimental and Numerical Results

Introduction and Motivation

- Cooperative diversity: a new communication paradigm
- A lot of gains promised by enabling cooperation
- Note: Cooperation only saves in terms of the required transmit energy
- However, cooperation results in increases receive and processing power
- There is a Tradeoff!

System Model

- The received signal model for direct transmission

$$y_{sd} = \sqrt{P_s^D(1-\alpha)r_{sd}^{-\gamma}}h_{sd}x + n_{sd}$$

where α is the power amplifier loss.

- Received signal model for cooperative transmission

$$y_{sd} = \sqrt{P_s^c(1-\alpha)r_{sd}^{-\gamma}}h_{sd}x + n_{sd}$$
$$y_{sl} = \sqrt{P_s^c(1-\alpha)r_{sl}^{-\gamma}}h_{sl}x + n_{sl}$$

- If the destination fails to receive correctly, and the relay receives correctly

$$y_{ld} = \sqrt{P_l(1-\alpha)r_{ld}^{-\eta}}h_{ld}x + n_{ld}$$

Energy Tradeoff

- Significant gains in performance, e.g., throughput, coverage, capacity, and other aspects have been shown in a lot of works on cooperation.

- The rationale here is: cooperation results in spatial diversity which saves in terms of transmit power.

- However, there is extra power consumption in processing and receiving at the relay and destination!

Performance Analysis

- Outage is the event that the received SNR falls below some threshold β.

- For direct transmission

$$\text{SNR}(r_{sd}) = \frac{\mid h_{sd} \mid^2 r_{sd}^{-\gamma} P_s^D (1-\alpha)}{N_o}$$

- The outage probability for direct transmission is thus given by

$$\mathcal{P}_{OD} = \mathcal{P}\left(\text{SNR}(r_{sd}) \leq \gamma\right) = 1 - \exp(-\frac{N_o \gamma r_{sd}^{\eta}}{P_s^D})$$

- Similar calculations can be done for the received SNR for the cooperation mode, and the resulting outage probability

$$\begin{aligned}
&\mathcal{P}_{OC} = \mathcal{P}\left((\mathsf{SNR}_{sd} \leq \beta) \cap (\mathsf{SNR}_{sl} \leq \beta)\right) + \\
&\mathcal{P}\left((\mathsf{SNR}_{sd} \leq \beta) \cap (\mathsf{SNR}_{ld} \leq \beta) \cap (\mathsf{SNR}_{sl} > \beta)\right) = \\
&\left(1 - f(r_{sd}, P_s^C)\right)\left(1 - f(r_{sl}, P_s^C)\right) \\
&+ \left(1 - f(r_{sd}, P_s^C)\right)\left(1 - f(r_{ld}, P_l)\right) f(r_{sl}, P_s^C)
\end{aligned}$$

- where $f(x,y) = \exp(-\frac{N_o \beta x^\gamma}{y(1-\alpha)})$

- The above expression can be simplified as follows

$$\mathcal{P}_{OC} = \left(1 - f(r_{sd}, P_s^C)\right)\left(1 - f(r_{sd}, P_l) f(r_{sl}, P_l)\right)$$

Energy Optimization Problem: Direct Case

- The total consumed power for direct transmission

$$P_{tot}^{D} = P_s^D + P_c + P_r$$

  where P_c and P_r are the processing and receiving power, respectively

- The optimization problem can be formulated as follows

$$\min_{P_s^D} P_{tot}^{D}, \qquad \text{s.t. } \mathcal{P}_{OD} \leq P_{out}^{*}$$

- The optimal transmitting power is given by

$$P_s^{D*} = -\frac{\beta N_o r_{sd}^{\gamma}}{(1-\alpha)\ln(1-P_{out}^{*})}$$

Energy Optimization Problem: Cooperative Case

- We consider two scenarios
  - The source and the relay can use different power levels for transmission
  - Equal power allocation at all nodes
- The total consumed power for cooperative transmission to transmit a packet is given by

$$
\begin{aligned}
P_{tot}^{C} = & (P_s^C + P_c + 2P_r)\mathcal{P}(SNR_{sd} \geq \beta) \\
& + (P_s^C + P_c + 2P_r)\mathcal{P}(SNR_{sd} < \beta)\mathcal{P}(SNR_{sl} < \beta) \\
& + (P_s^C + P_l + 2P_c + 2P_r) \\
& \times \mathcal{P}(SNR_{sd} < \beta)\mathcal{P}(SNR_{sl} > \beta)
\end{aligned}
$$

- Using the Rayleigh fading channel model, the total consumed power can be given as follows

$$
\begin{aligned}
P_{tot}^{C} = & \,(P_s^C + P_c + 2P_r) f(r_{sd}, P_s^C) + (P_s^C + P_c \\
& + 2P_r) \left(1 - f(r_{sd}, P_s^C)\right) \left(1 - f(r_{sl}, P_s^C)\right) \\
& + (P_s^C + P_l + 2P_c + 2P_r) \left(1 - f(r_{sd}, P_s^C)\right) f(r_{sl}, P_s^C)
\end{aligned}
$$

- The optimization problem can be stated as follows

$$
\min_{P_s^C, P_l} P_{tot}^C(P_s^C, P_l), \qquad \text{s.t. } \mathcal{P}_{OC}(P_s^C, P_l) \leq P_{out}^*
$$

- Solving the above optimization problem yields optimal power allocation at the source and the relay nodes.

- This is, however, difficult to implement.

- Easier but suboptimal solution: equal power assignment at all nodes

- Denote the equal transmission power in this case by P_{CE}; the optimization problem in this case can be formulated as

$$\min_{P_{CE}} P_{tot}^{C}(P_{CE}), \qquad \text{s.t. } \mathcal{P}_{OC}(P_{CE}) \leq P_{out}^{*}$$

- This is just a one-dimensional optimization problem

- Can be relaxed as follows

- at enough high SNR the following approximation holds $\exp(-x) \simeq (1 - x)$

- The total consumed power can be approximated as follows

$$P_{tot}^{C} \simeq P_{CE} + P_c + 2P_r + (P_{CE} + P_c)\frac{k_1}{P_{CE}} - (P_{CE} + P_c)\frac{k_1 k_2}{P_{CE}^2}$$

- Similarly, the outage probability can be written as follows

$$P_{OC} \simeq \frac{k_1 k_2}{P_{CE}^2} + \frac{k_1 k_3}{P_{CE}^2} - \frac{k_1 k_2 k_3}{P_{CE}^3}$$

where $k_1 = \frac{\beta N_o r_{sd}^{\gamma}}{1-\alpha}$, $k_2 = \frac{\beta N_o r_{sl}^{\gamma}}{1-\alpha}$, and $k_3 = \frac{\beta N_o r_{ld}^{\gamma}}{1-\alpha}$.

- The lagrangian is given by

$$\frac{\partial P_{tot}^{C}}{\partial P_{CE}} + \lambda \frac{\partial P_{OC}}{\partial P_{CE}} = 0$$

- where

$$\frac{\partial P_{tot}^{C}}{\partial P_{CE}} = 1 + \frac{k_1k_2 - P_c k_1}{P_{CE}^2} + \frac{2k_1k_2P_c}{P_{CE}^3}$$
$$\frac{\partial P_{OC}}{\partial P_{CE}} = \frac{-2(k_1k_2 + k_1k_3)}{P_{CE}^3} + \frac{3k_1k_2k_3}{P_{CE}^4}$$

- The Lagrangian can be written in the following simple polynomial form

$$1 + (k_1k_2 - P_c k_1)x^2 + 2\left(k_1k_2P_c - \lambda(k_1k_2 + k_1k_3)\right)x^3 + 3\lambda k_1k_2k_3x^4 = 0$$

under the outage constraint

$$(k_1k_2 + k_1k_3)\,x^2 - k_1k_2k_3x^3 = P_{out}^{*}$$

Experimental Results to verify channel model

- Three wireless nodes in the experiments, one of them acts as the sender and the other two act as receivers.

- Each wireless node is computer equipped with a IEEE 802.11g wireless card

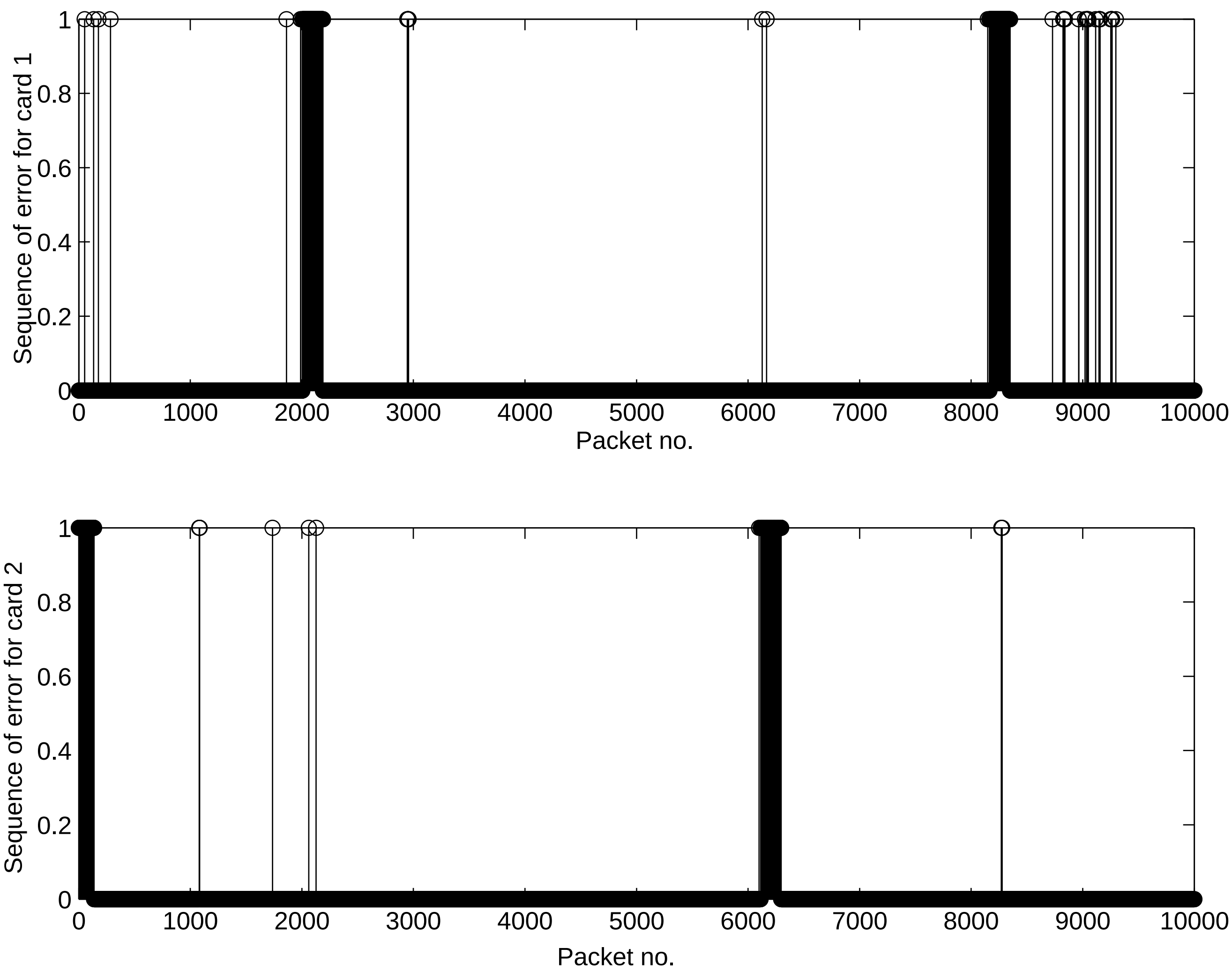
- The traffic rate is 100 packets per second, and the size of each packet is 554 bytes (including packet headers).

- The two receivers are placed together, with the distance between them being 20cm.

- The distance between the transmitter and the receiver is around 5 meters. The experiments have been mainly conducted in office environments.

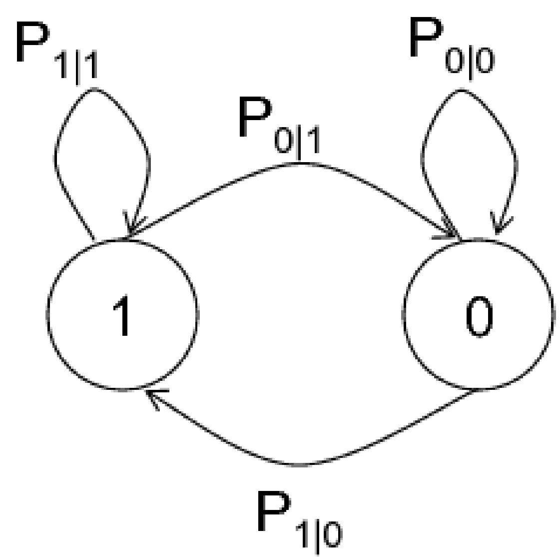
- The results have revealed two important observations: the channels exhibit strong time correlation for each receiver, while exhibit negligible dependence among the two receivers

Experimental Results to verify channel model



Experimental Results to verify channel model

- To better understand the temporal correlation behavior, we model the channel fades as a two-state Markov Chain.



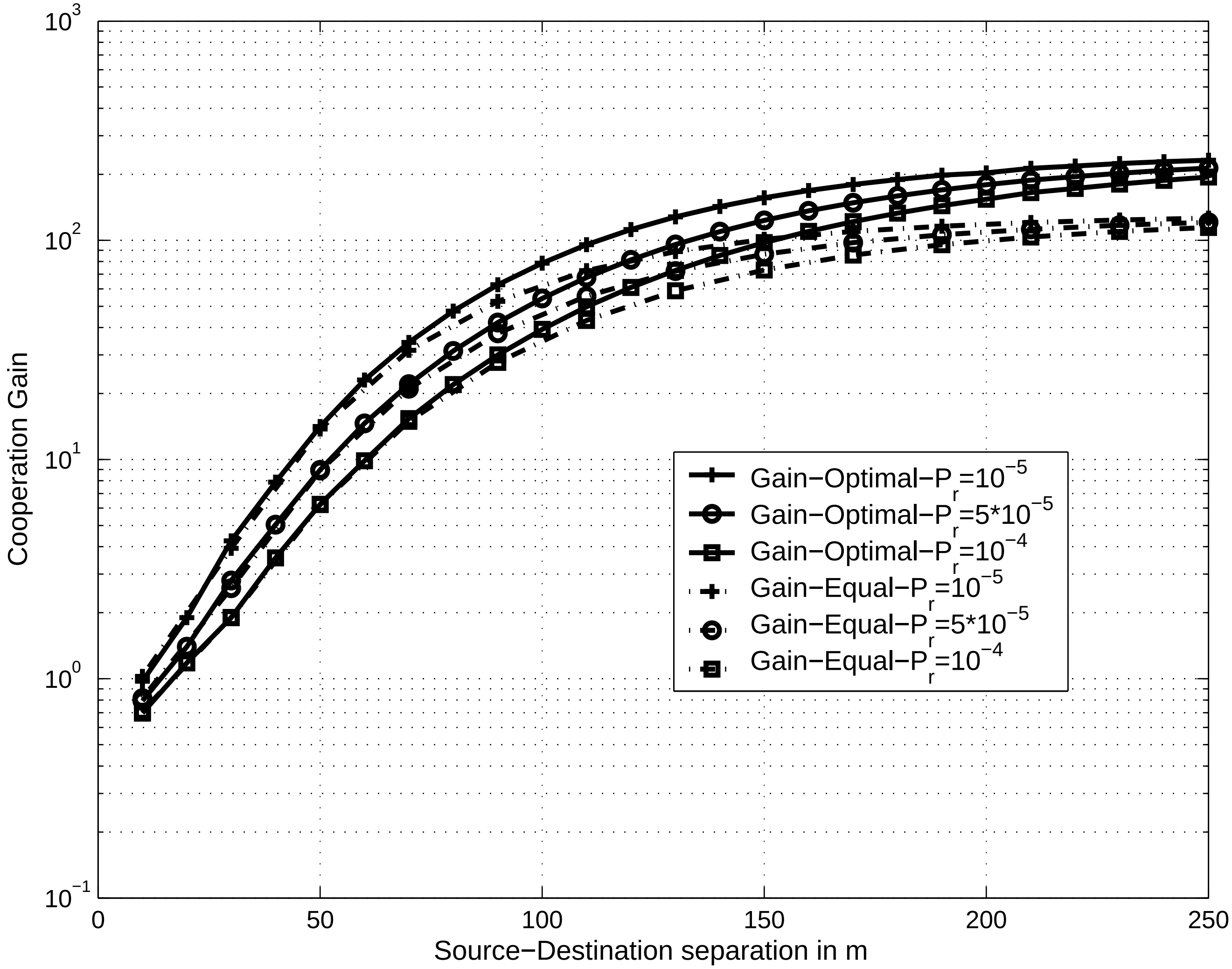
- The following transition probabilities have been obtained after using the experimental results to train the model: $P_{1|0} = 0.03$, $P_{1|1} = 0.999$, $P_{0|0} = 0.97$, $P_{0|1} = 0.001$.

Simulation Results

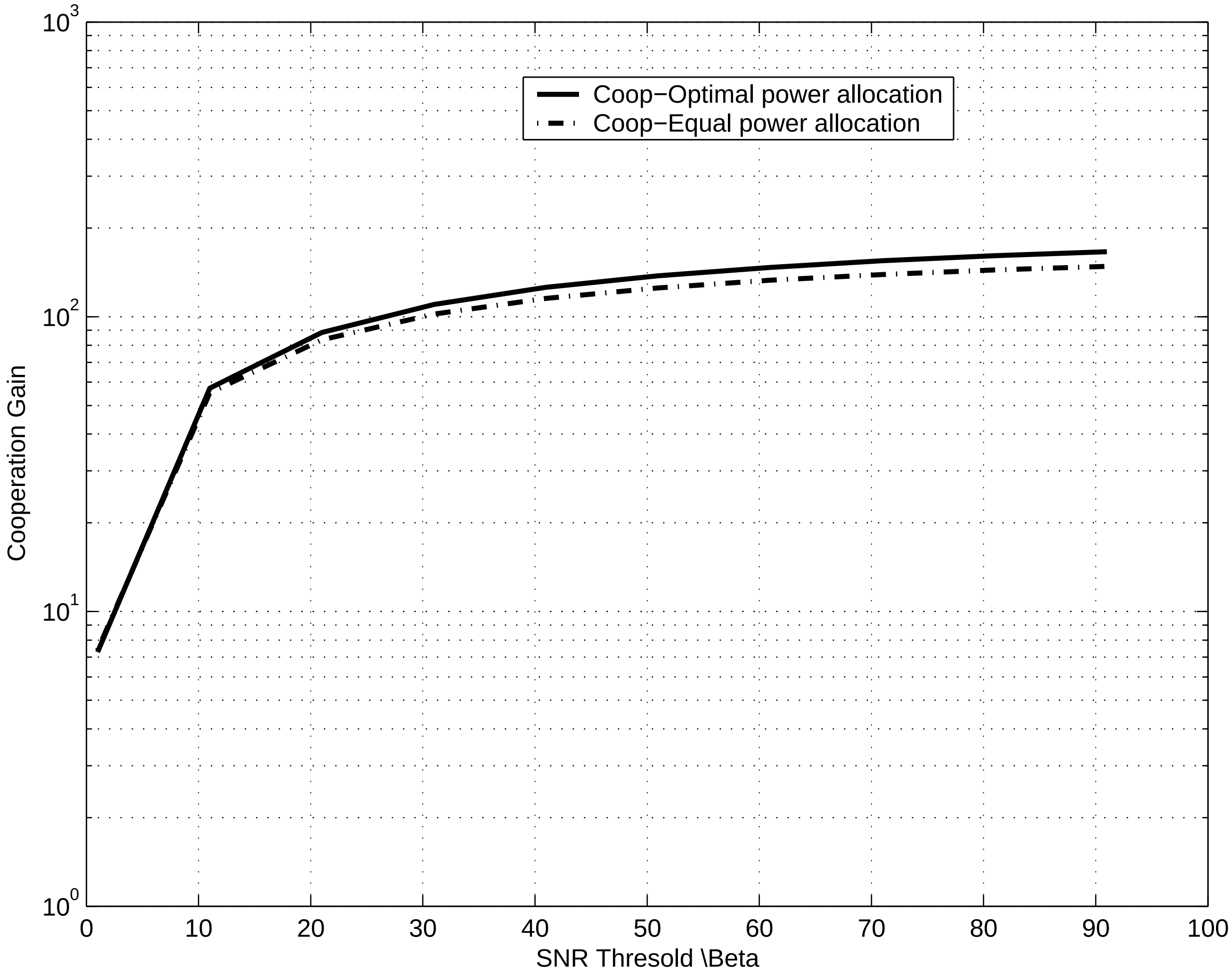
- There are different system parameters that can control whether we can gain from cooperation or not: the received power consumption, the processing power, the SNR threshold, the power amplifier loss, and the topology.

- In all of the simulations, the aforementioned parameters take the following values when considered fixed: $\alpha = 0.3$, $\beta = 10$, $N_o = 10^{-3}$, $P_c = 10^{-4}$ Watt, $P_r = 5 \times 10^{-5}$, $QoS = 10^{-4}$.

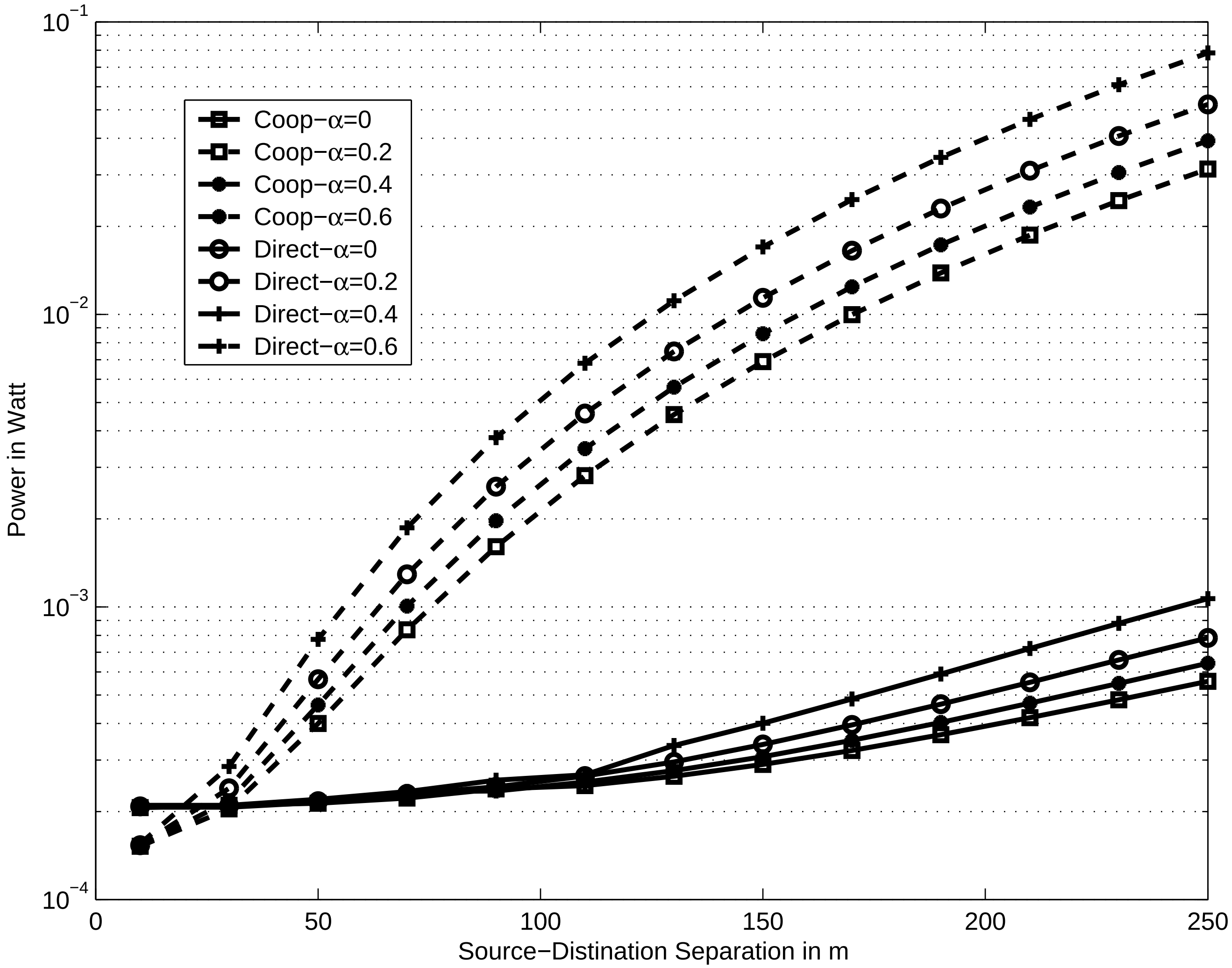
Effects of Varying the Received Power



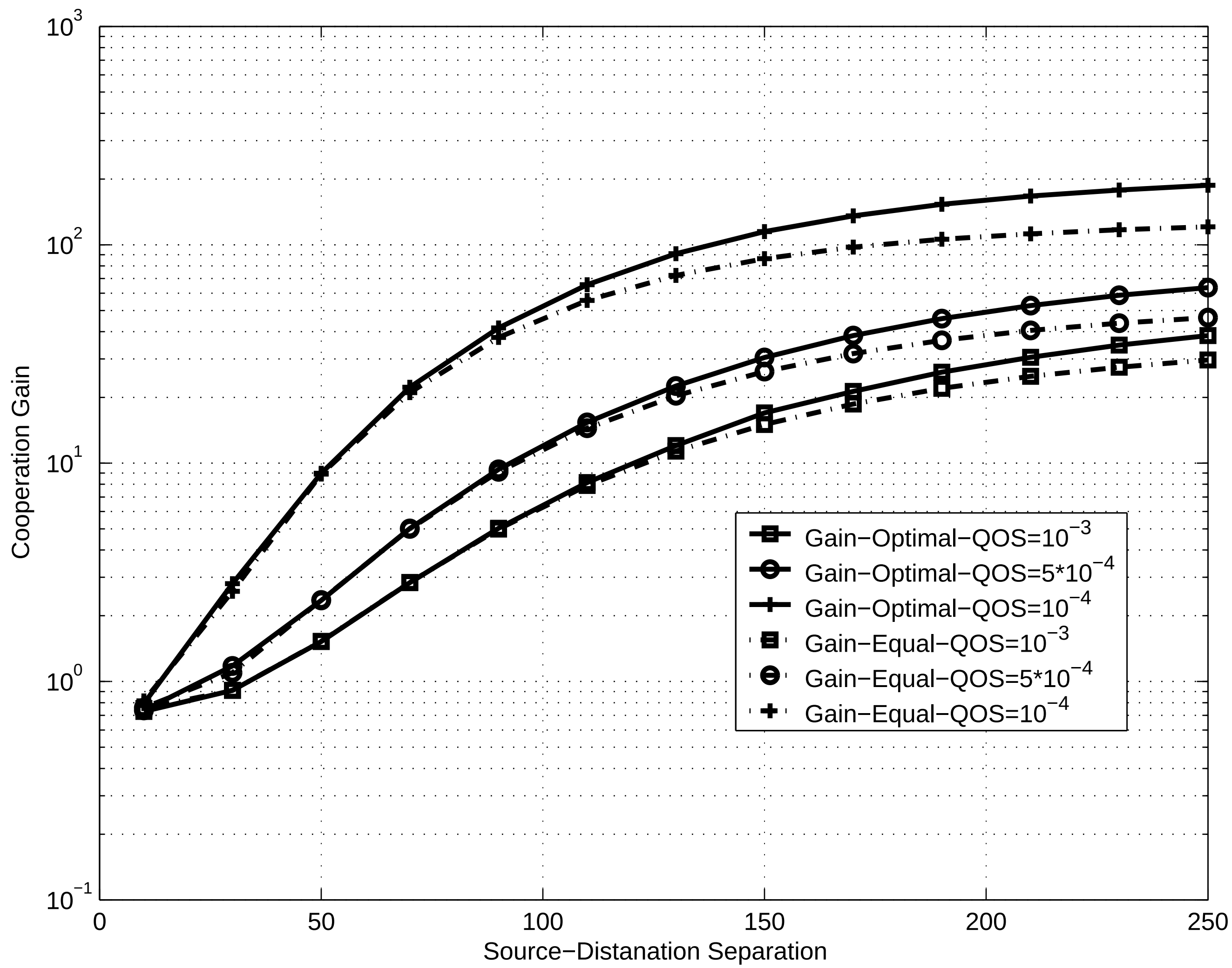
Effects of Varying the SNR Threshold



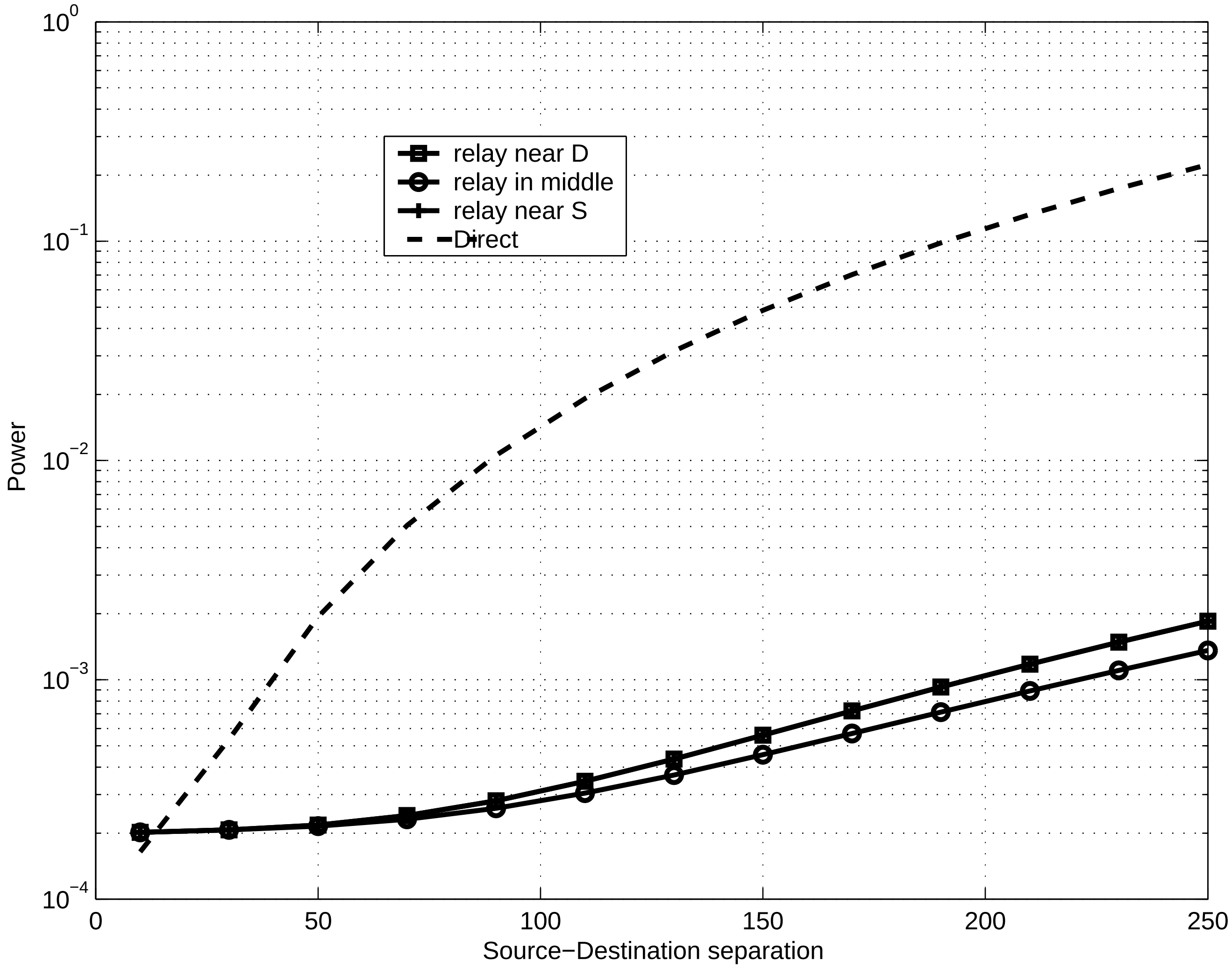
Effects of Varying the propagation path-loss



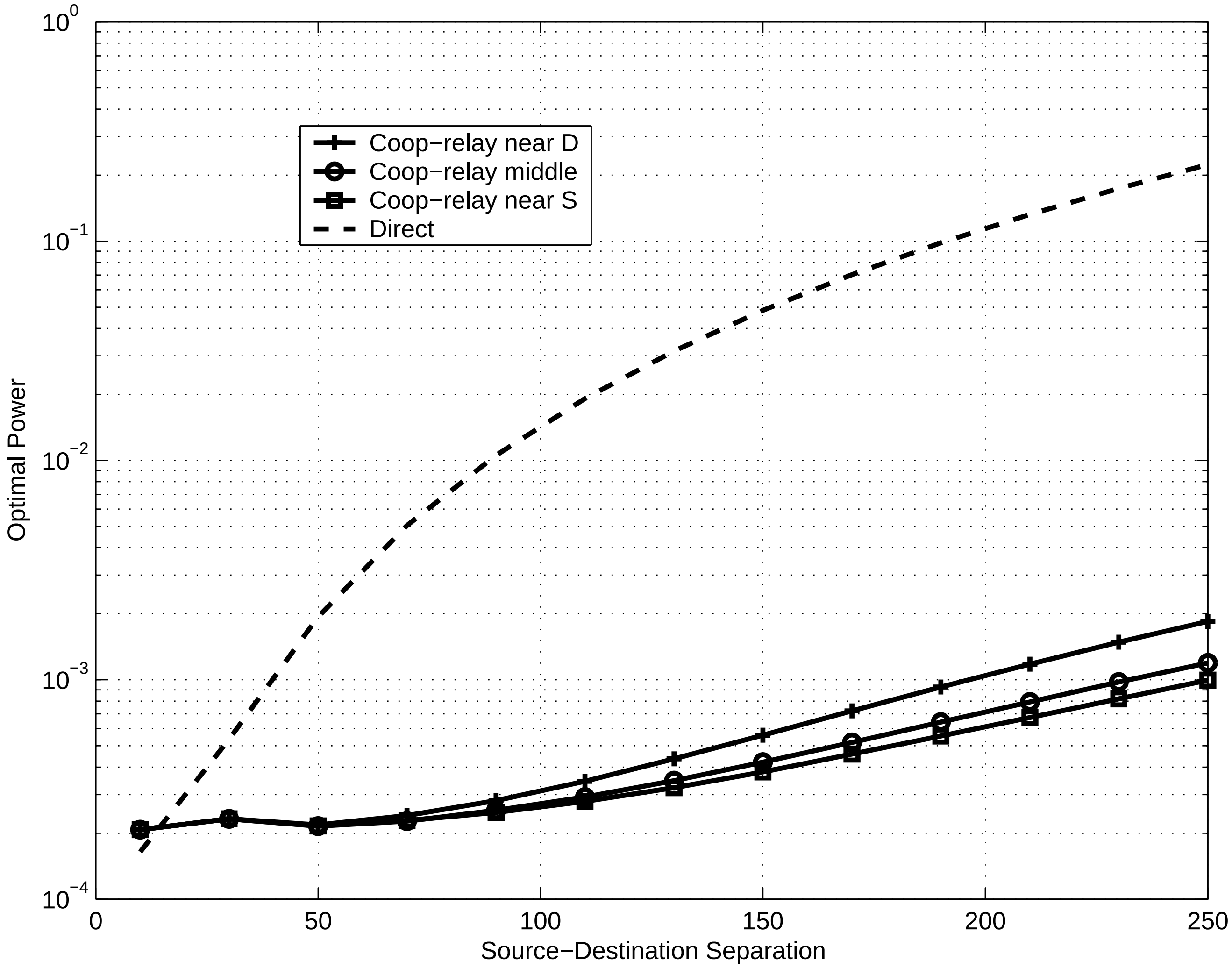
Effects of Varying Qos



Effect of Relay Location: Equal Power Allocation



Effect of Relay Location: Optimal Power Allocation



Conclusions

- We investigated the gains of cooperation in sensor networks under a practical setting

- For short distance separations and more specifically below a certain threshold between the source and the destination, the overhead of cooperation overweighs its gains and direct transmission is more efficient.

- It was also shown that simple equal power allocation at the source and the relay achieves almost the same gains as optimal power allocation at these two nodes for distances below 100m

Conclusions

- Choosing the optimal relay location for cooperation plays an important role above a certain threshold and the best relay location depends on the power allocation scheme, whether optimal or equal allocation

- The message: Caution must be taken before applying cooperative communications to sensor networks, in particular whether we should apply cooperation or not, whether equal power allocation is good enough, and how to choose a partner or a relay for cooperation.