When Does Cooperation Have Better Performance in Sensor Networks?

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Outline

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Introduction

“Diversity”= “state of being varied, variety”

The basic concept of diversity: transmit the signal via several independent diversity branches to get independent signal replicas via

- time diversity
- frequency diversity
- space diversity
- polarization diversity
Introduction

- Frequency diversity
  - Multi-carrier communications
  - Multi-path diversity in spread spectrum communications.

- Space diversity
  - Antenna diversity
    E.g. Multiple-Input Multiple-Output (MIMO)
Introduction

- Original MIMO

- Cooperative diversity

Virtual antenna array
Introduction

- Cooperation takes the advantage of the broadcast nature of the wireless channel
  - Overhearing

- The previous works studies the gain of cooperation diversity under ideal model of negligible *listening* and *computing power*.
  - In WSNs, these two power are the same order as the transmit power.
Introduction

- This paper takes into account the extra:
  - processing
  - receiving
  - power consumption at relay and destination.

- There will be a tradeoff between the gains in the transmit power and the loses when applying cooperation.
System Model

- Considering a single hop in the network between two nodes.
- Three node model
System Model

- Direct transmission
  - Source → Destination

- Cooperative transmission
  - Phase 1: Source → Relay
    Success → ACK
    Failure → NACK → phase 2
  - Phase 2: Relay → Destination
System Model

- Outage Probability

\[ P_O = P(\text{SNR} \leq \beta). \]

- \( \beta \) is a threshold which depends on the QoS requirement.
System Model

- Wireless channel
  - Narrow band Rayleigh fading
  - Propagation loss
  - AWGN
  - Channel fades are independent for different links

- Antenna
  - One antenna
  - Half-duplex mode
System Model

- **Power consumption**
  - Transmitting power: $P$
    - $P(1-\alpha)$ is actually used for RF transmission
    - $\alpha$: power amplifier loss
  - Processing power: $P_c$
  - Receiving power: $P_r$
System Model

- The received signal strength

1. Direct mode

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

2. Cooperative mode

\[ y_{sd} = \sqrt{P_s^c (1 - \alpha) r_{sd}^{-\gamma} h_{sd} x + n_{sd}}, \]
\[ y_{ld} = \sqrt{P_l (1 - \alpha) r_{ld}^{-\gamma} h_{ld} x + n_{ld}}. \]
Summary

- Cooperation provides a new means to achieve signal reliability via spatial diversity.

- The **drawback** of the cooperation mode is the extra **processing** and **receiving** power required at the **relay** and **destination**.
Performance Analysis

This paper formulates a constrained optimization problem to minimize the total consumed power subject to a given outage performance.
Direct Transmission

\[ SNR(r_{sd}) = \frac{y^2_{sd}}{N_0} = \frac{|h_{sd}|^2 r^{-\gamma}_{sd} P^D_s (1 - \alpha)}{N_0} \] (5)
Direct Transmission

- Outage probability

\[ P_{OD} = P(SNR(r_{sd}) \leq \beta) = 1 - \exp\left(-\frac{N_0 r_{sd}^\gamma}{(1-\alpha)P_s^D}\right) \tag{6} \]

- Total transmission power

\[ P_{tot}^D = P_s^D + P_c + P_r \]
Direct Transmission

- Optimization problem

$$\min_{P_{out}^D} P_{tot}^D, \quad s.t. \quad P_{OD} \leq P_{out}^*$$

- Let $P_{OD} = P_{out}^*$

$$P_{sd}^D = -\frac{\beta N_0 \gamma}{(1-\alpha)\ln(1-P_{out}^*)}$$
Direct Transmission

The minimum total power required for direct transmission:

\[ P_{\text{tot}}^* = P_c + P_r - \frac{\beta N_0 r_{sd}^{\gamma}}{(1 - \alpha) \ln(1 - P_{\text{out}}^*)} \]
Cooperative Transmission

- Two possible power allocation scenarios
  1. Source and Relay have different transmission powers
     - Complex and infeasible
  2. Source and Relay have equal transmission powers
Cooperative Transmission

Calculate each SNR value in each phase

- Phase 1: $\text{SNR}_{sd}, \text{SNR}_{sl}$ (11)
- Phase 2: $\text{SNR}_{ld}$ (12)
Cooperative Transmission

- Outage conditions
Cooperative Transmission

\[ P_{OC} = \mathcal{P} \left( (\text{SNR}_{sd} \leq \beta) \cap (\text{SNR}_{sl} \leq \beta) \right) + \mathcal{P} \left( (\text{SNR}_{sd} \leq \beta) \cap (\text{SNR}_{ld} \leq \beta) \cap (\text{SNR}_{sl} > \beta) \right) \]

\[ = \left( 1 - f(r_{sd}, P_s^C) \right) \left( 1 - f(r_{sl}, P_s^C) \right) + \left( 1 - f(r_{sd}, P_s^C) \right) \left( 1 - f(r_{ld}, P_l) \right) f(r_{sl}, P_s^C) \]

\[ f(x, y) = \exp \left( -\frac{N_0 \beta x^\gamma}{y(1-\alpha)} \right) \]
Cooperative Transmission

### Simplification

\[ P_{OC} = \left( 1 - f(r_{sd}, P_s^C) \right) \left( 1 - f(r_{sd}, P_l) f(r_{sl}, P_l) \right) \]

### The total consumption power

\[
P_{tot}^C = (P_s^C + P_c + 2P_r) P(SNR_{sd} \geq \beta)
+ (P_s^C + P_c + 2P_r) P(SNR_{sd} < \beta) P(SNR_{sl} < \beta)
+ (P_s^C + P_l + 2P_c + 2P_r)
\times P(SNR_{sd} < \beta) P(SNR_{sl} > \beta),
\]

(15)
Cooperative Transmission

- **Simplification**

\[
P_{tot}^C = (P_s^C + P_c + 2P_r)f(r_{sd}, P_s^C) + (P_s^C + P_c + 2P_r)(1 - f(r_{sd}, P_s^C))(1 - f(r_{sl}, P_s^C))
+ (P_s^C + P_l + 2P_c + 2P_r)(1 - f(r_{sd}, P_s^C))
\times f(r_{sl}, P_s^C).
\]

(16)
Cooperative Transmission

- Optimization problem

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

Let \( P_s^C = P_l = P_{CE} \)

\[
\min_{P_{CE}} P_{tot}^C(P_{CE}), \quad \text{s.t. } \mathcal{P}_{OC}(P_{CE}) \leq P_{out}^*.
\]
Cooperative Transmission

- The minimum total power required for direct transmission

\[(k_1 k_2 + k_1 k_3) x^2 - k_1 k_2 k_3 x^3 = P_{out}^*\]

where \(k_1 = \frac{\beta N_0 r_s^\gamma}{1-\alpha}\), \(k_2 = \frac{\beta N_0 r_s^\gamma}{1-\alpha}\), and \(k_3 = \frac{\beta N_0 r_{ld}^\gamma}{1-\alpha}\).
Experimental Results

- Assumptions
  - Channel independence
  - Channel error exhibits strong time correlation

Office Environment

source 5m 20cm 5m Receiver 1

Receiver 2

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Simulation Results

- **Parameters**
  - $\alpha = 0.3$, $\beta = 10$
  - $N_0 = 10^{-3}$
  - $P_c = 10^{-4}$ watts
  - $P_r = 5 \times 10^{-5}$ watts
  - $Qos = P_{outage} = 10^{-4}$
  - $Coop. \text{ Gain} = P_{coop.}/P_{direct}$
Simulation Results

- Different $P_r$

$\text{Gain(coop.)} > \text{Gain(direct)}$

$\text{Gain(coop.)} < \text{Gain(direct)}$

$G(\text{equal}) = G(\text{opt.})$

$G(\text{equal}) < G(\text{opt.})$
Simulation Results

- The effect of SNR threshold $\beta$

$\gamma_{sd} = 100m$

SNR Threshold 'Beta' vs Cooperation Gain
Simulation Results

- Power amplifier loss $\alpha$
- Direct transmission is more sensitive to variations in $\alpha$
Simulation Results

- The effect of the relay location
- 3 cases
  - Close to S: 1:4
  - Middle: 1:1
  - Close to D: 4:1

Close to S is better
Simulation Results

Equal power allocation

Middle is better
Summary

- The $r_{sd}$ will affect the cooperation gain
  - $<20\text{m}$, direct transmission is better
  - $<100\text{m}$, the equal power allocation can approximate the optimal power allocation

- The relay location also affects the cooperation gain.
  - Closing to the source has better performance
  - $<100\text{m}$, the relay location does not affect the performance much
Conclusions

- This paper investigates the gains of cooperation in WSNs by taking the extra overhead of cooperation into account.
- It formulates a constrained optimization problem to minimize the total consumed power.
- It shows that the distance between source and destination, and the relay location will affect the cooperation gain.