Energy-efficient Cooperative Broadcast in Fading Wireless Networks

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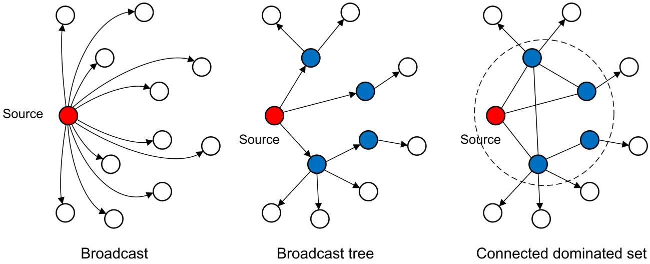
Outline

Background

Broadcast: disseminating a message from one source to all other nodes.

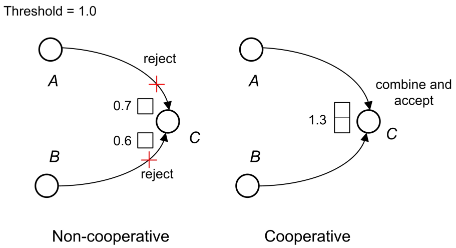
- Broadcast tree
- Connected Dominating Set



Background: Cooperative Communication

Cooperative communication (CC)

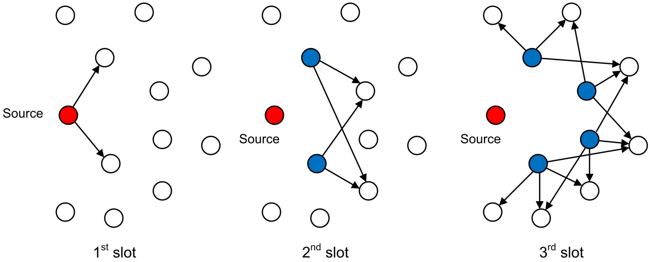
- Without CC, the receiver will directly drop the packet if the received Signal-to-noise ratio (SNR) is lower than a threshold.
- With CC, the receiver can combine weak SNRs from different senders to recover the original packet.



Background: Cooperative Broadcast

Cooperative broadcast: The efficiency of broadcasting is improved by combining weak signals rather than discarding them.

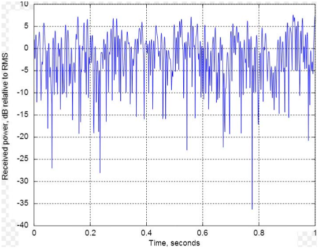
Example:



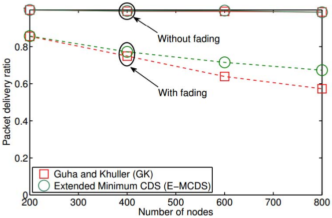
Problem: In each time slot, how to allocate the relay nodes to minimize the energy consumption, or minimize the broadcast delay, or both?

Background: Fading

Fading. In fading environments, the transmissions between relay nodes are susceptible to random fluctuations in signal strength.



Signal strength in fading



Delivery ratios deteriorate in fading [Lichte, Mobicom'12]

Problem: In cooperative broadcast, how to overcome fading?

Background: Related Work

Reduce energy cost, e.g., CIA/CSIA [Hong, TWC'06], EDS [Wu, TPDS'06], and MLAB [Maric, JASC'05]
Reduce delay e.g., EDS [Wu, TPDS'06] and PCDB [Lichte, Mobicom'12]
Both e.g., DMECB [Baghaie, Infocom'11].

Scheme	**Fading**	**Delay**	**Energy**
PCDB	√	√	
EDS		√	√
CIA/CSIA			√
MLAB			√
DMECB		√	√
Our work	√	√	√

Table 1

Our goal: to study the tradeoff between energy cost and delay in cooperative broadcast, with the consideration of fading.

Our contributions

Challenges:

- Problem formulation is more complicated.
- Algorithm design is more complicated.

Our contributions:

- Build a mathematical model for the cooperative broadcast problem considering fadings.
- Problem formulation: Fading-resistant Delay-constrained Minimum Energy Cooperative Broadcast (FDMECB) problem.
- Two algorithms: an approximation algorithm and a heuristic algorithm (FREEB).
- Experiments: demonstrate the efficiency of our new algorithm.

System Model

Network model

- The system has N nodes: $V = \{v_1, v_2, ..., v_N\}$ and one source node v_s, in 2D Euclidean plane;
- A packet is broadcasted from a source node v_s to all other nodes $(V - v_s)$;
- Time is assumed to be discretized into fixed duration time slots;
- K power levels $\mathcal{W} = \{w_1, ..., w_K\}$ for each node ($w_1 = 0$).

Channel model

- **Rayleigh fading**:
  $\Pr(\text{received signal power} \leq x) = 1 - e^{\frac{x}{\sigma^2}}$, where
  $\sigma^2 = E(\text{signal power}) \propto$ transmission power;
- **Maximal ratio combining**:
  Packet can be coded iff $\sum_i \text{signal power } i \geq \text{decoding threshold}$;
- **Requirement**:
  $\Pr(\sum_i \text{signal power } i < \text{decoding threshold}) < \text{acceptable error rate } \epsilon$;

Problem Formulation

Fading-resistant Delay-constrained Minimum Energy Cooperative Broadcast (FDMECB)

Instance: N nodes $V = \{v_1, ..., v_N\}$, including one source node v_s, K power levels $w_1, ..., w_K$, acceptable error rate ϵ, delay constraint T, and energy constraint W.

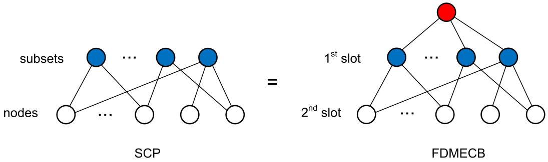
Question: Existence of a schedule such that:

- Each node v_j can forward packet only if it has been informed.
- By the end of the time slot T, all the nodes in V have been informed.
- By the end of the time slot T, the total energy consumption of all the nodes in V is no larger than W.

Theorem 1 (Hardness of FDMECB)

FDMECB is NP-hard.

Proof: Polynomial reduction from the set covering problem (SCP) to FDMECB.



Corollary 1

FDMECB is $o(\log N)$ inapproximable.

Algorithm Design: Approximation Algorithm

Definition 1

Integral version of FDMECB (FDMECB-int): does not allow signals to be combined at receivers.

Lemma 1

Denote the relay node set at time slot t by R_t. If the white noise follows exponential distribution with mean value μ_0, then v_j can be informed in time slot t iff

$$\sum_{v_i \in R_t} \delta_{i,j} \geq \ln(1/\varepsilon), \quad (1)$$

where $\delta_{i,j} = \frac{wd_{i,j}^{-\alpha}}{\gamma_{\mathrm{th}}\mu_0}$ is called *relative SNR* from v_i to v_j.

FDMECB-int loses a factor of $o(\log N)$ compared to the optimal FDMECB (can be mapped to weighted set cover problem).

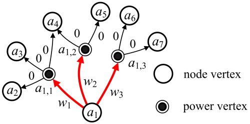
Algorithm Design: Approximation Algorithm

Steiner tree (ST) problem.

- Given a graph, a source node $a_{\rm s}$ and a set of destinations D
- Objective: construct a tree rooted at $a_{\rm s}$ and spanning all the destinations, with minimum cost.

Auxiliary graph. Construct two types of vertices: *node vertex* and *power vertex*.

- For each node v_i, construct in a node vertex a_i
- For each power level w_j of node v_i, construct a power vertex $a_{i,j}$.



Finding a feasible schedule for FDMECB-int = finding a ST on the auxiliary graph.

Using the existing method for ST, FDMECB can be solved with performance guarantee $O(N^{\varepsilon} \log N)$, which is asymptotically to $O(N^{\varepsilon})$.

Algorithm Design: Heuristic Algorithm

Definition 2

$$\text{Efficiency of } R_t = \frac{\#\text{ of newly informed nodes}}{\text{Total energy consumption of } R_t} \tag{2}$$

Fading-Resistant Energy-Efficient Broadcast (FREEB): in each time slot t, solve the following integer programming (IP) problem

$$\begin{aligned} \text{Maximize} \quad & \text{the efficiency of } R_t && (3) \\ \text{subject to} \quad & \#\text{ of nodes in } R_t \geq \frac{\#\text{ of uninformed nodes}}{T - t + 1} && (4) \end{aligned}$$

Proposition 1

If the constraint in Equ (4) can be satisfied in each time slot, all the nodes in V can be informed within T time slots.

Simulation

Settings

Path loss exponent	4.0
Data rate	1Mbit/s
Decoding threshold	25.8dB
Maximum transmit power	20dBm
Noise power density	$4.32 \times 10^{-18} W/Hz$
Adjustable power levels	5

Table 2

Compared algorithm

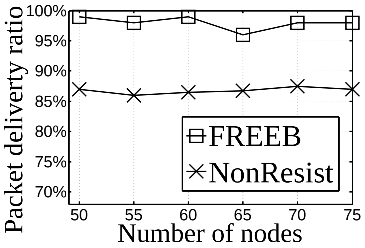
- Non-fading resistant delay constrained algorithm (denoted by *NonResist*) [Baghaie, Infocom'11].

Metrics

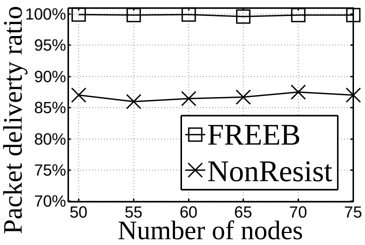
- Packet delivery ratio.
- Energy consumption.

Experimental results

Packet delivery ratio:



$\epsilon = 0.05$

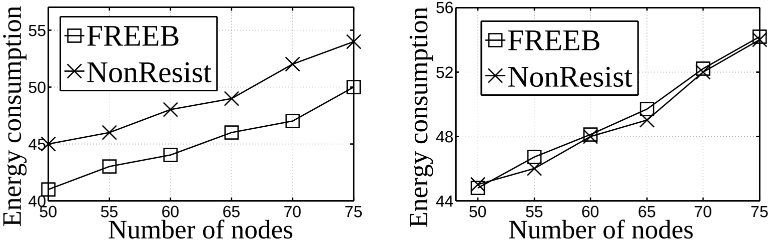


$\epsilon = 0.01$

1. FREEB $>$ NonResist
2. When ϵ is smaller, the packet delivery ratio of NonResist is higher

Experimental results

Energy consumption:

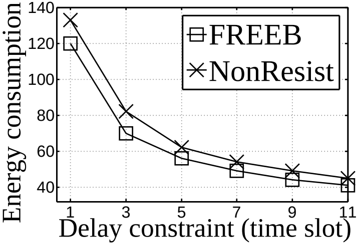


$\epsilon = 0.05$ $\epsilon = 0.01$

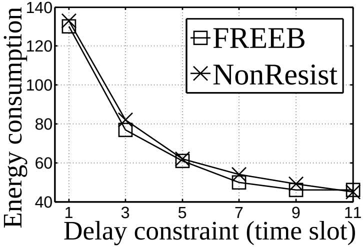
1. FREEB $<$ NonResist
2. When ϵ is smaller, the energy cost of FREEB is higher

Experimental results

Energy delay tradeoff:



$\epsilon = 0.05$



$\epsilon = 0.01$

When delay constraint is smaller, the energy consumption is higher

Conclusions

Our contributions:

- Math model: cooperative broadcast in fading environment.
- Problem formulation: Fading-resistant Delay-constrained Minimum Energy Cooperative Broadcast (FDMECB) problem.
- Two algorithms: an approximation algorithm and a heuristic algorithm (FREEB).
- Experiments.

Future work:

- Dynamic networks.
- Multi-flow broadcast.

Questions&Comments?

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