Cross-Layer Optimization for Wireless Sensor Network with Multi-Packet Reception

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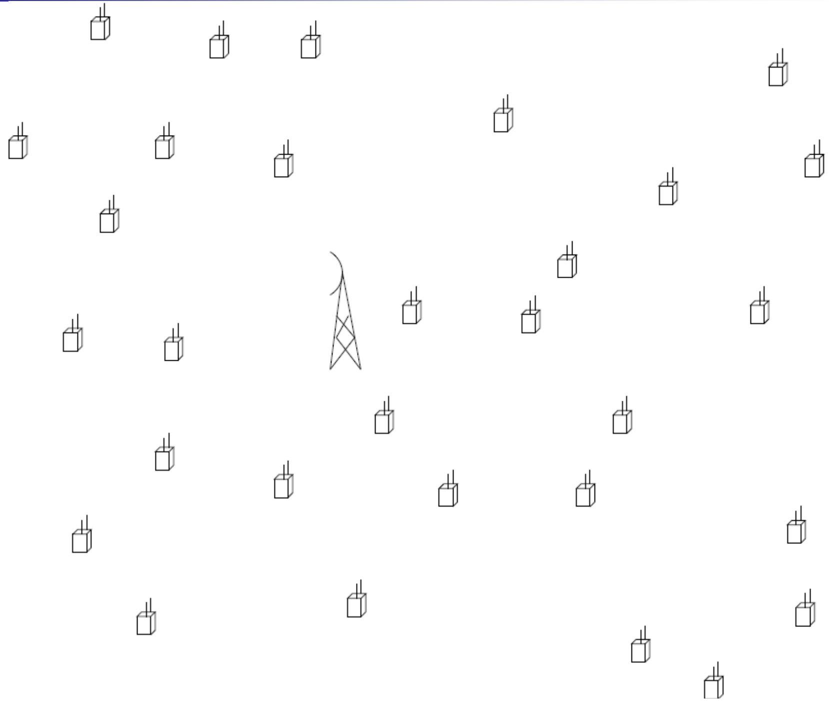
Outline

- Problem and background
- Optimizations without MPR
- Optimizations with MPR
- Numerical result

Wireless Sensor Networks

- **The WSNs features**
  - Wireless transmissions to the base station
  - May transmit a lot of sensed data

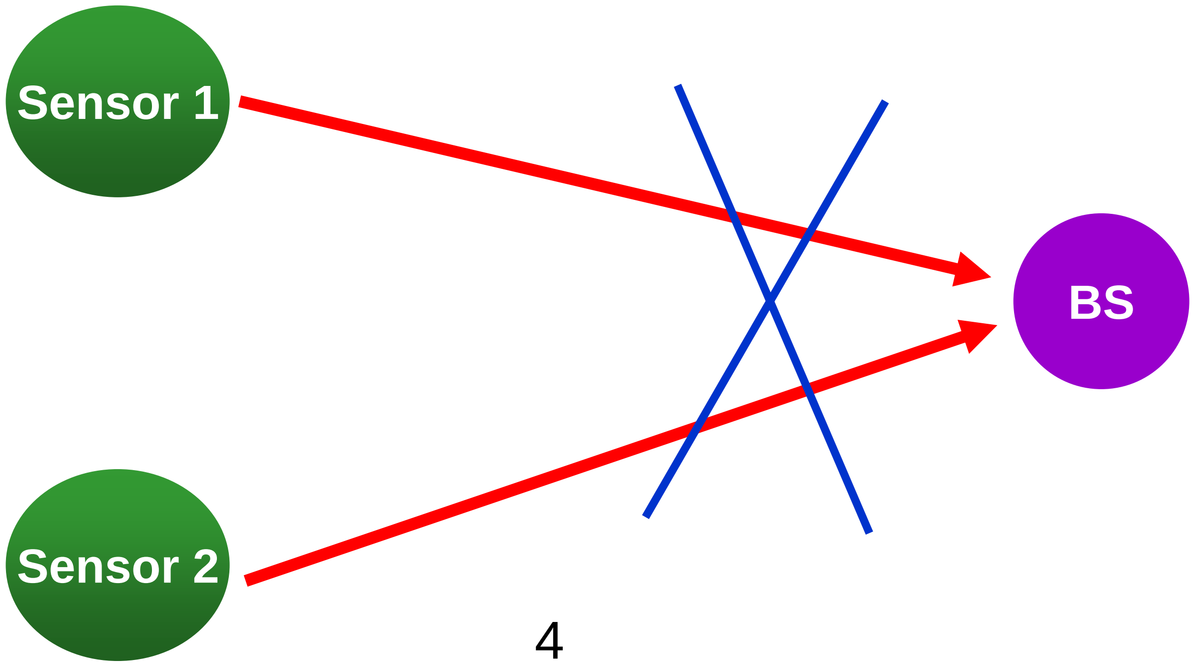


Our research focus on the capacity.

Traditional Transmission Scheme

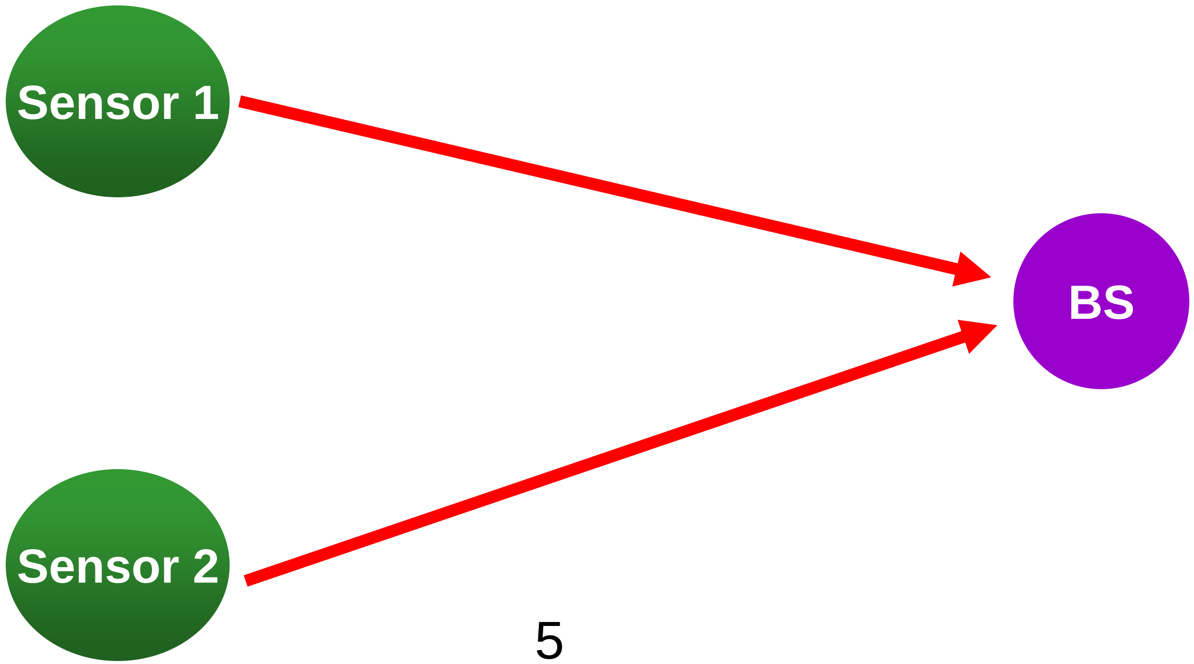
- The BS can receive one packet from a sensor node at any time
  - The achievable data rate depends on SNR

- Collision happens when several nodes transmit at the same time



MPR Transmission Scheme

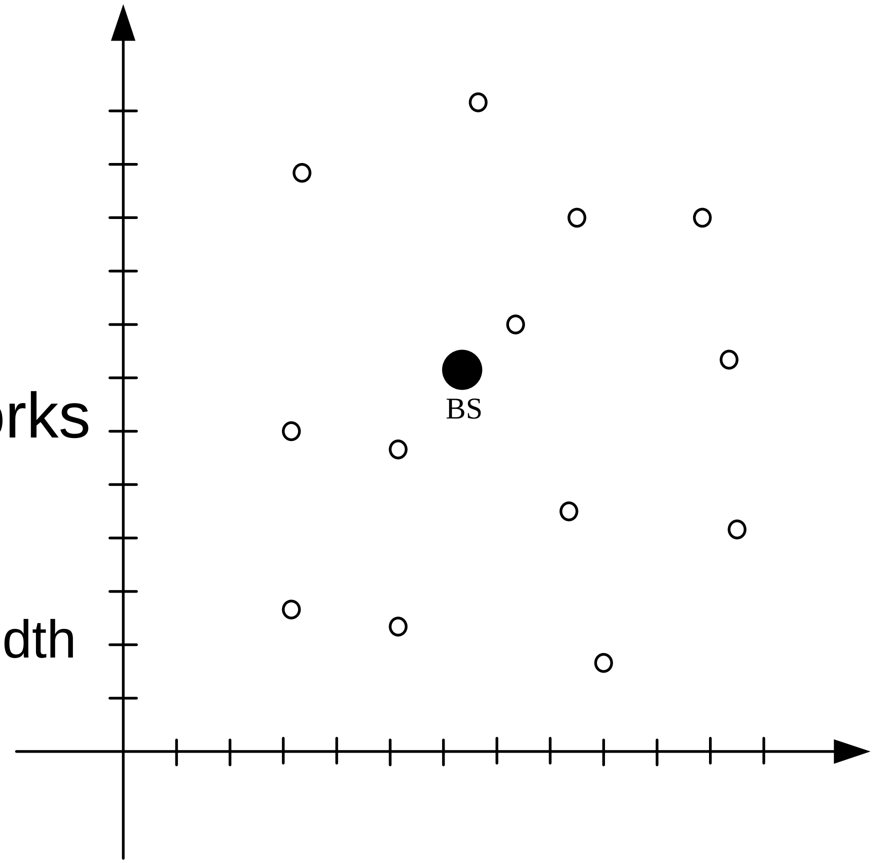
- BS can receive multiple data packets from several nodes at the same time.
  - Multi-Packet Reception (MPR)
  - Can be achieved by several techniques, e.g., SIC.
- In a networking environment the MPR behavior is complex.



Challenge and Problem Setting

- Challenge
  - Several BS
  - Multi-hop
  - Power control

- Single-hop wireless sensor networks
  - A WSN consisting of *n* sensor nodes and a base station.
  - Each node uses power *P* and bandwidth *W* to transmit data to the base station directly.



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SNR at the physical layer

- Denote g_i the channel gain from the node s_i to base station and λ as the path loss index.

$$SNR_i = \frac{g_i P}{N_0} \text{, where } g_i = a \cdot d_i^{-\lambda}$$

- For a successful transmission, $SNR > \beta > 1$
- The peak data rate is $W \log_2(1 + SNR_i)$

Time slot based scheduling

- *Denote n* time slot, $t_1, t_2 \ldots t_n$

$$T = \sum_{i=1\cdots n} t_i$$

- The average data rate is no more than

$$\frac{t_i W}{T} \log_2(1 + SNR_i)$$

Problem formulation

- Denote node s_i has a minimum rate requirement $r(i)$
- Denote a common scaling factor K , such that each node can transmit data to BS with rate $Kr(i)$

Max K

$$\begin{cases} Kr(i) \le t_i W \log_2(1 + SNR_i) & (1 \le i \le n) \\ \sum_{i=1\cdots n} t_i = 1, \end{cases}$$

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Our Approach

- Why challenge?
- Our approach
  - Build constraints for the signal-to-noise-ratio requirement under MPR.
  - Formulate the capacity problem as a linear program.
  - Propose a concept of maximum feasible set (MFS) to reduce the problem size.
- Our result: A cross-layer optimal solution on how to apply MPR to increase capacity

MPR can increase network capacity by about 100%.

SINR at the physical layer

- Denote

$$x_i^k = \begin{cases} 1 & \text{if node } i \text{ transmit data to the base station in time slot } k \\ 0 & \text{otherwire.} \end{cases}$$

$$SINR_i^k = \frac{g_i \cdot x_i^k P}{N_0 + \sum_{g_j < g_i} g_j \cdot x_j^k P}$$

$$W \log_2 (1 + SINR_i^k)$$

Optimizations with MPR

- Time slot based scheduling

$$\sum_{k \in F} t_k W \log_2(1 + SINR_i^k)$$

- Problem formulation

$$\text{Max } K$$

$$\begin{cases} Kr(i) \le \sum_{k \in F} t_k W \log_2(1 + SINR_i^k) & (1 \le i \le n) \\ \sum_{k \in F} t_k = 1, \end{cases}$$

A naïve approach

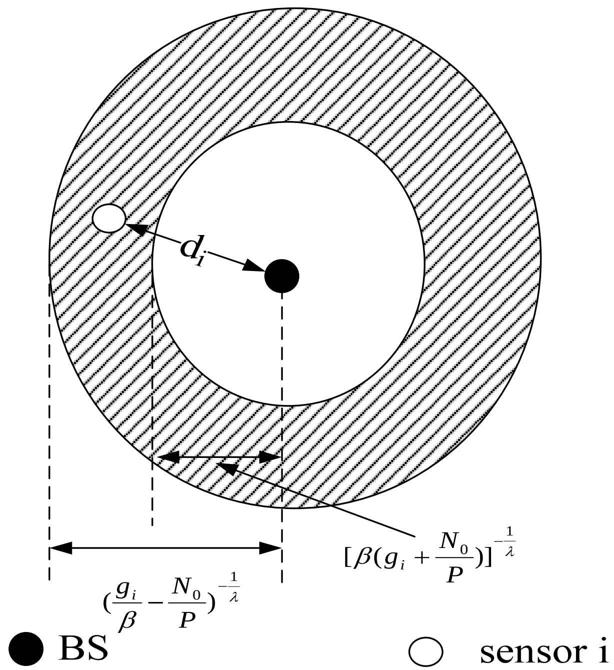
- *Check the feasibility for all possible sets.*
- *Solve the LP to obtain the optimal scheduling* t_k *for each feasible set*

complexity very high

Optimizations with MPR

- A Lemma
  - If nodes s_i and s_j transmit data to the base station in a time slot t_k and $d_i \le d_j$, then

$$d_j \ge (\frac{g_i}{\beta} - \frac{N_0}{P})^{-\frac{1}{\lambda}}$$



Optimizations with MPR

- From The Lemma
  - For a sorted feasible set with *h* nodes；
  - suppose the distances from these *h* nodes to the base station are

$$\hat{d}_1 < \hat{d}_2 < \ldots < \hat{d}_h$$

$$\hat{d}_2 > \beta^{\frac{1}{\lambda}} \cdot \hat{d}_1$$

$$\hat{d}_3 > \beta^{\frac{1}{\lambda}} \cdot \hat{d}_2 > \beta^{\frac{2}{\lambda}} \cdot \hat{d}_1$$

……………………

$$\hat{d}_h > \beta^{\frac{1}{\lambda}} \cdot \hat{d}_{h-1} > \ldots > \beta^{\frac{h-1}{\lambda}} \cdot \hat{d}_1$$

FS approach

- Theorem: The number of nodes in a feasible set (FS) is no more than a constant

$$l = \left\lfloor \log_{\beta^{\frac{1}{\lambda}}} \frac{d_{\max}}{d_{\min}} \right\rfloor + 1$$

- FS approach
  - Check the feasibility for all possible sets with no more than l nodes.
  - Solve the LP to obtain the optimal scheduling t_k for each feasible set.

- Complexity of the FS approach $\sum_{k=1\cdots l} C(n,k) = \Theta(n^l)$

MFS approach

- Maximum feasible set (MFS)
  - *A feasible set A is a maximum feasible set if for any node s that is closer to the base station than all nodes in A, $A \cup \{s\}$ is not a feasible set.*
- MFS approach
  - *Identify all MFS.*
  - *Solve the LP to obtain the optimal scheduling t_k for each MFS.*
- Complexity?

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Parameter Setting

- Bandwidth $W = 22$
- SINR threshold $\beta = 3$
- Gain model $g = d^{-4}$
- Minimum rate requirement in [10, 100]
- Transmission power P=1W

Numerical Results

Optimal Objective Value with and without MPR

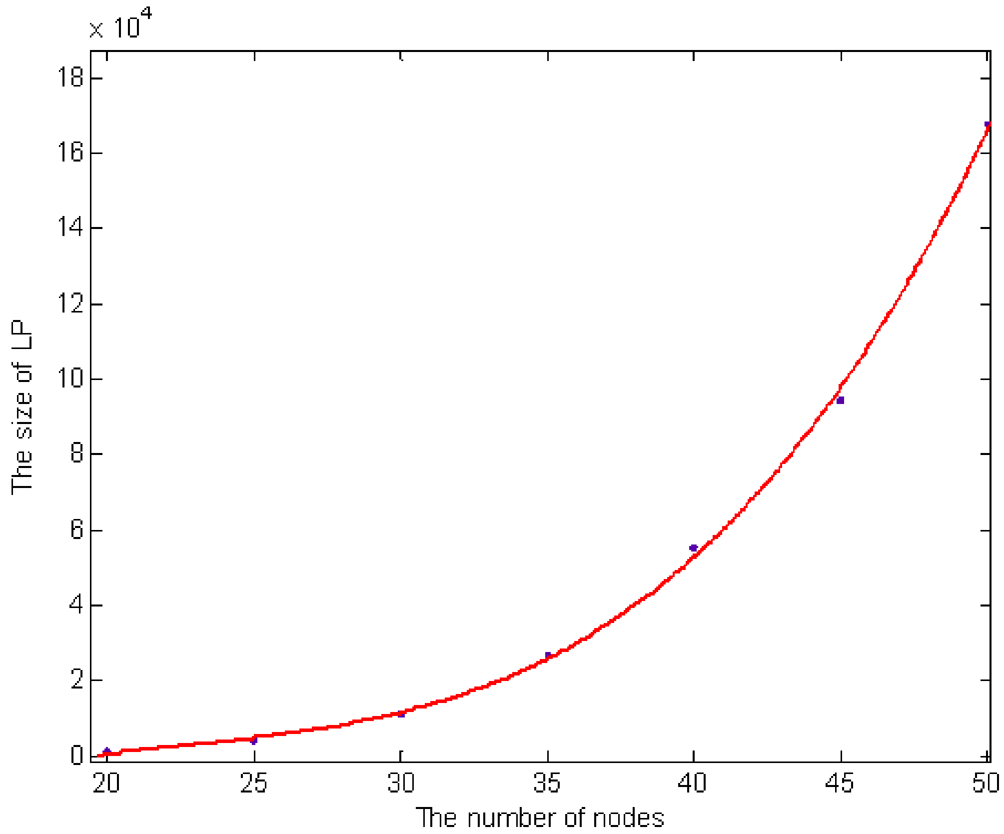
n	K (without MPR)	K (with MPR)	Improvement Ratio
20	11.62	20.83	79.19%
25	9.31	16.95	81.99%
30	7.18	14.67	104.28%
35	6.21	13.02	109.78%
40	5.25	10.84	106.42%
45	4.56	9.57	93.06%
50	4.50	8.69	93.03%

Numerical Results

Complexity Comparison

n	Complexity of the naive approach	Complexity of the FS approach	The size of LP in the MFS approach
20	1.04×10^{6}	9.1×10^{5}	1280.30
25	3.35×10^{7}	1.68×10^{7}	4067.75
30	1.07×10^{9}	1.94×10^{8}	11152.00
35	3.44×10^{10}	1.54×10^{9}	26722.25
40	1.10×10^{12}	2.55×10^{9}	55663.9
45	3.52×10^{13}	9.12×10^{9}	94613.55
50	1.13×10^{15}	1.72×10^{11}	167902.90

Numerical Results



The relationship between the size of the LP and the number of nodes is $\Theta(n^3)$ approximately.

$$y = 7.014x^3 - 480x^2 + 11780x - 98990$$

Summary

- Developed a cross-layer model for a single hop wireless sensor network (WSN) with MPR;
- Applied this model to solve a network capacity problem;
- Develop a polynomial time algorithm, which has a polynomial time complexity;
- Proposed a concept of maximum feasible set to further decrease the LP size;

- The developed MPR model can be extended for multi-hop networks. Optimal solutions for multi-hop WSNs will be addressed in our future work.