Energy Efficient Scheduling for Two-Tier CDMA Sensor Networks

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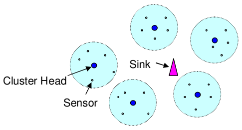
Introduction

- Efficient transmission strategies are essential in wireless sensor networks (WSNs) due to limited battery energy.
- CDMA WSN: applications with high data bandwidth
- Scheduling -- careful coordination of the sensor data transmissions to achieve efficient data collection.
- Objective: Energy efficient scheduling for CDMA WSNs
  - ✓Reliable communications: SINR requirement
  - ✓Delay requirement: data collection is complete in a number of time slots
  - ✓Fairness: a short term average throughput guarantee at each sensor node

Two-Tier CDMA WSN Model



- Passive clusters: clusters are triggered by the sink
- Two consecutive phases for the data collection:
  - ✓*Ph1*: Intra-cluster communications, sensors => CH
  - ✓*Ph2*: Inter-cluster communications, CHs => sink
- Multi-rate CDMA WSN
  Multiple spreading codes at each node -> virtual sensor

Scheduling for Intra-Cluster Communications

- *K* sensor nodes communicate with the CH in *n* time slots
- Aim: minimize the total power expenditure while satisfying the received SINR target and the short term throughput requirement.

$$
\begin{aligned}
\min_{\{K_{il},\,p_{i_k l}\}} \quad & \sum_{l=1}^{n}\sum_{i=1}^{K}\sum_{i_k=1}^{K_{il}} p_{i_k l} \\
s.t. \quad & SINR_{i_k l} \ge SINR_{target}, \forall i_k, l \text{ such that } p_{i_k l} > 0 \\
& R_i = R_{i_{target}}, \ \forall i \\
& p_{i_k l} \ge 0, \ \forall i_k, l
\end{aligned}
$$

$$
\text{where} \quad SINR_{i_k l} = \frac{p_{i_k l}\,|g_i|^2}{\frac{1}{N}\left(\sum_{j=1}^{K}\sum_{j_k=1}^{K_{jl}} p_{i_k l}\,|g_j|^2 - p_{i_k l}\,|g_i|^2\right) + \sigma^2} \quad \text{and} \quad R_i = \frac{\sum_{l=1}^{n} K_{il} R_{base}}{n}, \quad R_{base} = W/N
$$

g_i : channel fading; $p_{j_k l}$: transmit power;

K_{jl} : the number of virtual sensors of node j in slot l;

N : the processing gain; W : spreading bandwidth.

Observations

- Equal optimum received power for each virtual sensor in the same slot *l* $$q_l^* = \frac{I\gamma}{(1+\gamma) - |s_l|\gamma}$$
- The optimum policy always schedules a virtual sensor with a lower channel gain to a slot with fewer virtual sensors.
- Any schedule can be reordered such that $$|s_1| \le |s_2| \le \cdots \le |s_n|$$
- The optimum policy schedules the virtual sensors in the order of increasing channel gains.

$$
\underbrace{|g_K|^2,\ldots|g_K|^2}_{T_k},\underbrace{|g_{K-1}|^2,\ldots|g_{K-1}|^2}_{T_{k-1}},\ldots,\underbrace{|g_1|^2,\ldots|g_1|^2}_{T_1}
$$

$$
|g_K|^2 \le |g_{K-1}|^2 \le \ldots \le |g_1|^2
$$

Optimum Schedule

- Map the reordered virtual sensors to the vertices *V* along a string *G* from the left to the right.
- $\{s_1, s_2, \ldots, s_n\}$ represents the partition of *V* into *n* subsets

=> An equivalent n-partition problem

$$
\min_{\{s_1,\ldots,s_n\}} \quad \sum_{l=1}^{n} q_l^* \sum_{i \in s_l} \frac{1}{|g_i|^2}
$$

$$
s.t. \quad |s_1| \le |s_2| \le \cdots \le |s_n|
$$

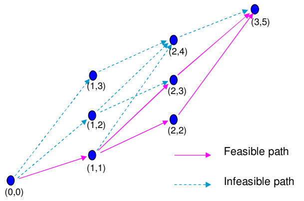
- This problem can be solved in polynomial time.

Optimum Schedule (Cont'd)

- Step 1: Construct a network from the string G
  - ✓Node: $\{(i,j): 1 \le i \le n-1; i \le j \le T-n-1\}$
    i: index of the time slot; j: index of the virtual sensor.
  - ✓An edge is placed from (i1,j1) to (i2,j2) if $i2 = i1+1$ and $j2 > j1$
  - ✓Map the cost function from the string G to the constructed network
    Infeasible path if it violates
    $|s_1| \le |s_2| \le \cdots \le |s_n|$ or $|s_l| < \lfloor (1+\gamma)/\gamma \rfloor$
- Step 2: Find the shortest path with minimum cost by a shortest path algorithm such as Dijkstra's algorithm.

Shortest path => optimum partition => optimum schedule

An Example Network



A network constructed from a 5-vertex string with 3 partition sets

Scheduling for Inter-Cluster Communications

- *Kc* CHs communicate with the sink in *m* time slots
- Each cluster: two antennas and Alamouti Scheme
- Transmission scheme of CH i

		slot m_1	slot m_2
CH i	Antenna 1 (g_{i1})	$s_{i1}c_i$	$-s_{i2}^*c_i$
	Antenna 2 (g_{i2})	$s_{i2}c_i$	$s_{i1}^*c_i$
		T_i	T_i^*

- Four possible schedule schemes of CHs

	Other slot	slot m_1	slot m_2	Other slot
CH i		T_i	T_i^*	
CH j: case 1		T_j	T_j^*	
CH j: case 2		T_j		T_j^*
CH j: case 3	T_j		T_j^*	
CH j: case 4	T_j			T_j^*

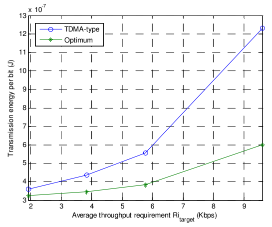
Near-Optimum Schedule

- In case 1, the SINR of CH *i* is $$SINR_{s_{i1}} = SINR_{s_{i2}} = \frac{N|g_i|^2\ p_i}{\sum_{j \in F_i} |g_j|^2\ p_j + I}$$
- Scheduling *2Kc* super transmissions of CHs into *m* slots

  = Scheduling *Kc* sensors into *m/2* slots

  given that each CH is considered as a single-antenna node with a channel gain $|g_i|^2 = |g_{i1}|^2 + |g_{i2}|^2$, and the two time slots it takes are bounded into one.
- The computational cost is largely reduced with a modest performance penalty.
- Same results can be applied to multi-rate CDMA CHs.

Average Energy Consumption: Intra-Cluster



- Optimum schedule: big energy savings
- Sensor load ⬆ => energy savings ⬆

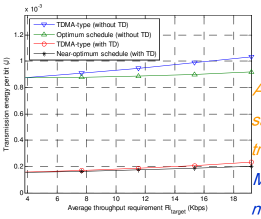
Benefit of the optimum schedule for a loaded CDMA WSN

Average Energy Consumption: Inter-Cluster

User number	Optimum $(10^{-5} J/Bit)$	Near-optimum $(10^{-5} J/Bit)$	Penalty
4	4.3091	4.4826	4.03%
5	4.3217	4.6165	6.28%
6	4.3267	4.6839	8.26%

{4,5,6} CHs,6 slots, $R_{i_{target}} = 9.6kbps$

The near-optimum schedule: Polynomial complexity with (<10%) penalty



$R_{i_{target}} = \{3.84, 7.68, 11.52, 15.36, 19.2\}kbps$

A large amount of energy is saved by exploiting transmit diversity (TD).

More energy is saved by the near-optimum schedule.

Conclusions

- Short term average throughput requirements are imposed in addition to the QoS requirements when designing the energy efficient scheduling strategies.
- Optimum and near-optimum scheduling algorithms with polynomial complexity are proposed for intra- and inter-cluster communications.
- Significant energy savings is achieved by proposes schemes.

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