Minimum-Latency Aggregation Scheduling for Wireless Sensor Networks under the SINR Model

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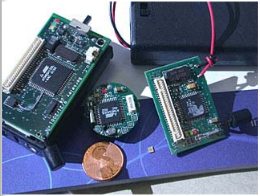
Wireless Sensor Network



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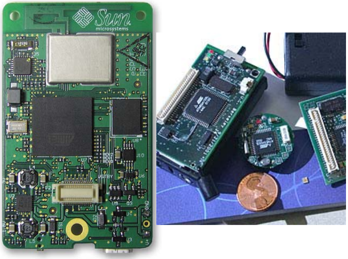

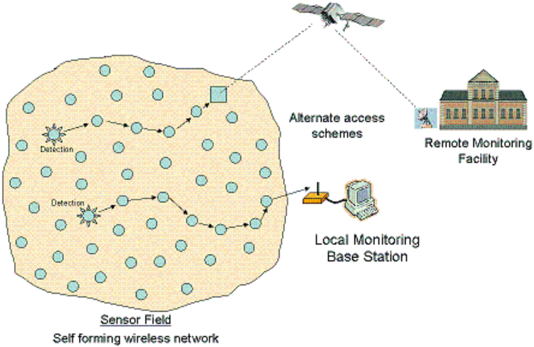

Applications of Wireless Sensor Networks

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- Others.

Data Aggregation in Wireless Sensor Networks

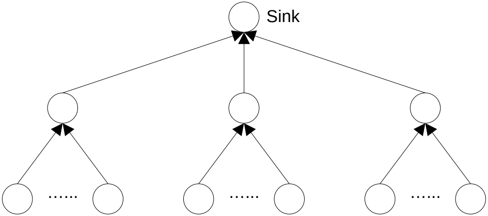

Figure: Data Aggregation.

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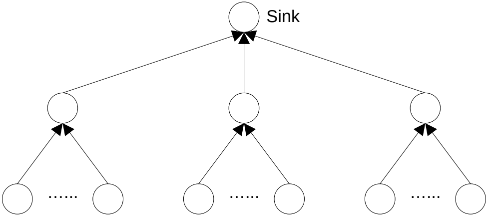

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Aggregation should be done in a timely fashion!

Definition (Minimum-Latency Aggregation Scheduling)

How shall one effectively schedule the aggregation transmissions in a wireless sensor network, such that no interference may occur and the total slots of time used for aggregation (referred to as *aggregation latency* hereinafter) is minimized?

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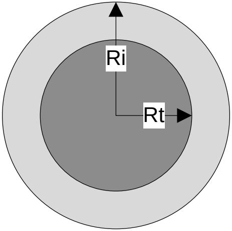
Graph Model

Binary interference relationship among concurrent transmitters: one transmission is successful if and only if its receiver is in the transmission range (R_t) of its transmitter and out of the interference range (R_i) of any other concurrent transmitter.



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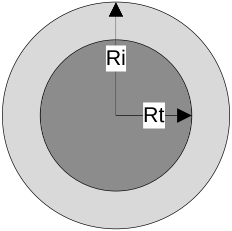

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Problem: Too ideal, not realistic!

Signal-to-Interference-plus-Noise-Ratio (SINR) Model

$$SINR_i = \frac{P_i/d_{ii}^{\alpha}}{N_0 + \sum_{e_j \in \Lambda - \{e_i\}} P_j/d_{ji}^{\alpha}} \geq \beta$$

Here, Λ denotes the set of links that transmit simultaneously with e_i. P_i and P_j denote the transmission power at the transmitters of link e_i and e_j, respectively. d_{ii} (d_{ji}) is the distance between transmitters of link e_i (e_j) and the receiver of link e_i. α represents the path loss ratio, with a typical value between 2 and 6. N_0 is the ambient noise. β is the SINR threshold for a successful transmission, which is at least 1.

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Challenge: Global information is required!

Current works on MLAS problem are all conducted on the basis of graph model.

- Chen et al. proved the NP-hardness of MLAS problem and proposed an aggregation scheduling algorithm with latency bound of $(\Lambda - 1)R$.
- Huang et al., for the first time, converted Λ from a multiplicative factor into an additive one. The scheduling algorithm builds on the basis of maximal independent set.
- Yu et al. presented the first distributed aggregation scheduling algorithm for MLAS problem. The aggregation latency is bounded by $O(\Lambda + R)$.

Here, Λ is the maximal node degree and R is the network radius.

Although there is no work on MLAS problem under the SINR model, there are a bunch of interesting results considering the Minimum-Length link Scheduling (MLS) problem with SINR constraints.

- Moscibroda, for the first time, gave a scaling law that describes the achievable data rate in worst-case sensor networks. A data gathering algorithm integrated with link scheduling, which maintains a $O(\log^2 n)$, is presented.
- In another work, Moscibroda et al. proposed a new measurement called "disturbance" to address the difficulty of finding a short schedule.
- Goussevskaia et al. proved the NP-completeness of a special case of the MLS problem.
- Fu. et al. introduced consecutive transmission constraints into MLS problem and proved the NP-hardness of that issue.

Problem Model

Definition (Minimum-Latency Aggregation Scheduling)

Given an arbitrarily located set of nodes V and sink node v_n, construct an aggregation tree $G = (V, E)$ and a link schedule $S = \{S_0, S_1, \ldots, S_{T-1}\}$, which meet the constraints that $\bigcup_{t=0}^{T-1} S_t = E$, for each $i \neq j$, $S_i \cap S_j = \emptyset$ and for each $i < j$, $T(S_i) \cap R(S_j) = \emptyset$, such that T is minimized and there is no collision under the SINR model.

The aggregation scheduling algorithm should be composed of two parts.

- Data aggregation tree construction.
- Link Scheduling.

Nearest-Neighbor Aggregation Scheduling (*NN-AS*) algorithm

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  - Otherwise, add link e_{ij} into E.
- At the end of each phase, all nodes been selected as transmitter in this phase are removed from V.

Algorithm 1 Centralized Aggregation Scheduling (NN-AS)

Input: Node set V with sink v_n.
Output: Set of link sets E and link schedule S.

$m := 1$; $E := S := \emptyset$;
while $(|V/\{v_n\}| \neq 1)$
  $E_m := \emptyset$;
  for$(\forall v_i \in V/\{v_n\})$
    Find v_i's nearest-neighbor $v_j \in V/\{v_n\}$;
    if$(v_j \in T(E_m) \cup R(E_m))$
      continue;
    $E_m := E_m \cup \{e_{ij}\}$;
  $V := V/T(E_m)$; $E := E \cup E_m$; $m := m + 1$;
  $S := S \cup$ Phase-Scheduler(E_m);
$v_i :=$ only node in $V/\{v_n\}$; $E := E \cup \{\{e_{in}\}\}$; $S := S \cup \{\{e_{in}\}\}$;
Return E and S;.

Figure: Phase by phase tree construction with nearest-neighbor mechanism: phase 1.

Figure: Phase by phase tree construction with nearest-neighbor mechanism: phase 2.

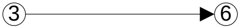

Figure: Phase by phase tree construction with nearest-neighbor mechanism: phase 3.

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    - One node is selected as head for each cell and all other nodes aggregation data to the head.
    - At the end of each phase, only head nodes remain in V for next phase.
    - In the very end, only one node is left and it aggregate all data to the sink.

Algorithm 2 Aggregation Scheduling (Cell-AS)

Input: Node set V with sink v_n.
Output: Set of link sets E and link schedule S.

$k := 0$; $V := V/\{v_n\}$;
while $(|V| \neq 1)$
  Cover the network with cells of side length 3^k and color them with 16 colors;
  for$(i := 1$ to $16)$
    $E_i := \emptyset$;
    for(Each cell j with color i)
      Randomly select one node v_h in cell j as head;
      Connect all other nodes in cell j to v_h, add links to E_i and E, remove all nodes but v_h from V;
    $S := S \cup$ Cell-Scheduler(E_i);
  $k := k + 1$;
$v_h :=$ only node in V; $E := E \cup \{\{e_{hn}\}\}$; $S := S \cup \{\{e_{hn}\}\}$;
Return E and S;.

Algorithm 3 Cell Scheduler

Input: Link Set E_i.

Output: Link schedule S_i.

```
Define constant c such that c := Nβ / (1 − I_sum 2^α β);
t := 1; S_i := ∅;
while (E_i ≠ ∅)
    S_t := ∅;
    for(Each cell j with color i)
        Choose one non-scheduled link e_l in cell j; S_t := S_t ∪ {e_l}; E_i := E_i/{e_l};
        P_l := c × d_ll^α;
    S_i := S_i ∪ {S_t}; t := t + 1;
Return S_i;.
```

Where: $c := \frac{N\beta}{1 - I_{sum} 2^{\alpha}\beta}$; $t := 1$; $S_i := \emptyset$; while $(E_i \neq \emptyset)$: $S_t := \emptyset$; for(Each cell j with color i): Choose one non-scheduled link e_l in cell j; $S_t := S_t \cup \{e_l\}$; $E_i := E_i/\{e_l\}$; $P_l := c \times d_{ll}^{\alpha}$; $S_i := S_i \cup \{S_t\}$; $t := t + 1$; **Return** S_i;.

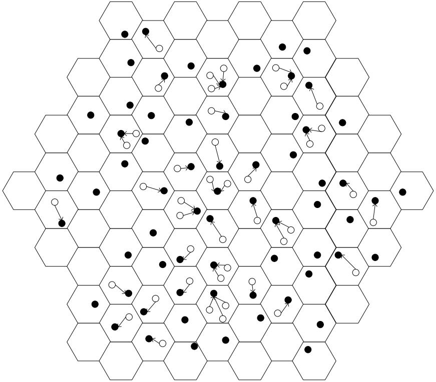
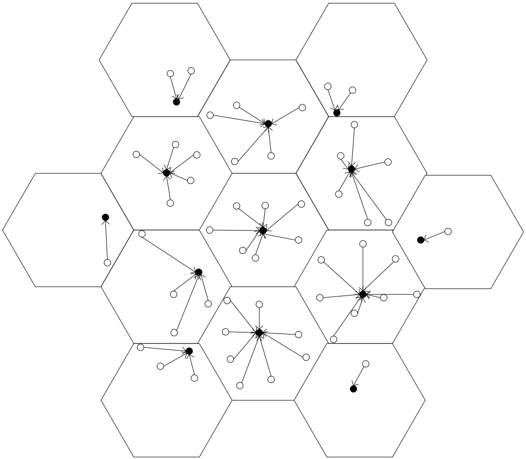


Figure: Tree construction with cells of different link length categories: category 0.



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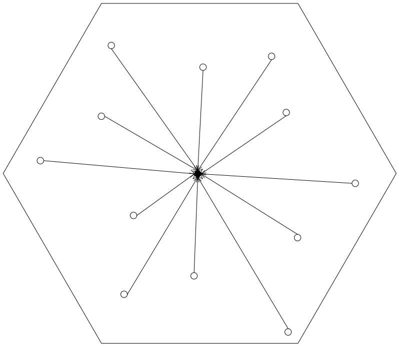


Figure: Tree construction with cells of different link length categories: category 2.

Theorem (Optimal Aggregation Scheduling Latency)

The optimal aggregation scheduling latency under any interference model is bounded by $\lceil \log n \rceil$.

Theorem (Centralized NN-AS Aggregation Latency)

The aggregation scheduling latency for centralized NN-AS is bounded by $O(\log^3 n)$ and the approximation ratio is bounded by $O(\log^2 n)$.

Theorem (Distributed Cell-AS Aggregation Latency)

The aggregation scheduling latency for distributed Cell-AS is bounded by $192K - 83$ and the approximation ratio is bounded by $(192K - 83)/\log n$.

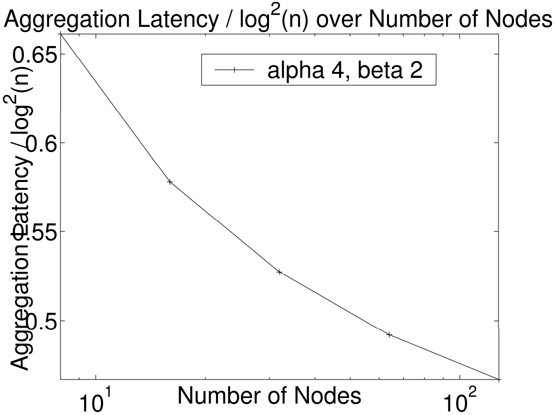
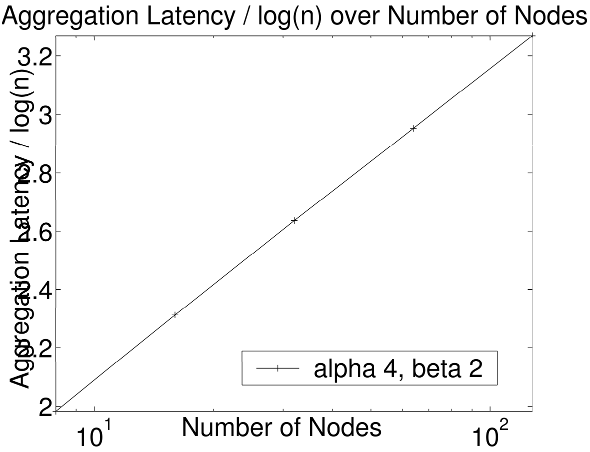


Figure: Aggregation Latency / $log^2 n$ over Number of Nodes (*NN-AS*).



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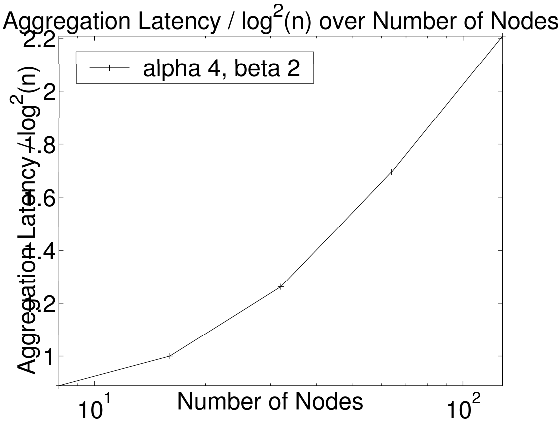

Figure: Aggregation Latency / $log^2 n$ over Number of Nodes (*Cell-AS*).

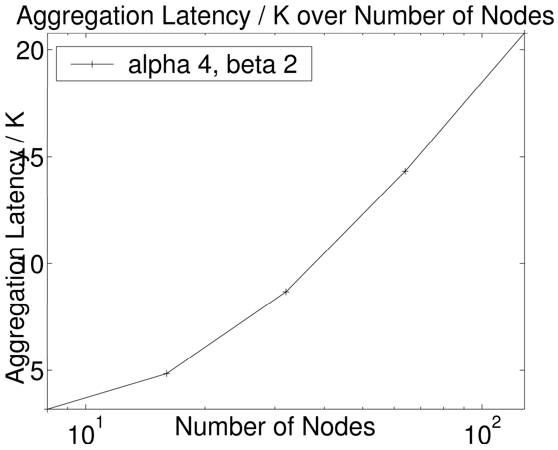

Figure: Aggregation Latency / $log^2 n$ over Number of Nodes (*Cell-AS*).

1. **Contributions:**
   - *Centralized joint aggregation tree construction and link scheduling algorithm*: Aggregation latency $O(\log^2 n)$, approximation ratio $O(\log^3 n)$.
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2. **Future Works:** Reduce the approximation ratio of centralized and distributed aggregation scheduling algorithms to $O(\log n)$ and $O(\log^2 n)$ respectively.

Thank You!