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Examples of WSNs

- Wireless Sensor Networks (WSNs) are widely used to monitor the physical environment.
Comparison with Traditional Networks

- Unlike traditional networks, wireless sensor networks are often resource limited
  - Limited power supply
  - Limited computational capability
  - Limited communication capability

- Developing an effective sensor network must take into account its Quality-of-Monitoring (QoM)
  - Avoid redundant sensor readings
  - Leverage the statistical correlations among sensor nodes
System Overview

Quality of Monitoring

- Sensing rate allocation
- Routing plan

Sensing

Networking
The readings among neighboring nodes are often spatially correlated.

- The degree of correlation depends on the internode separation
- Those sensors with similar readings naturally form a component or cluster.
Correlation Model

- A correlation component is a subset of sensors where the sensor nodes within one component have similar sensing values.

- Communication graph and correlation components.
How to Represent Quality of Monitoring?

- We define a general **submodular** function to quantify the Quality-of-Monitoring (QoM) under different sensing rate allocations.

We say a function is submodular if it satisfies a natural “diminishing returns” property:

\[
\begin{align*}
U_i(\emptyset) &= 0, \\
U_i(S_1) &\leq U_i(S_2), \text{ if } S_1 \subseteq S_2, \text{ and} \\
U_i(S_1 \cup A) - U_i(S_1) &\geq U_i(S_2 \cup A) - U_i(S_2), S_1 \subseteq S_2
\end{align*}
\]
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How to Represent Quality of Monitoring?

- We define a general **submodular** function to quantify the Quality-of-Monitoring (QoM) under different sensing rate allocations.

Let $p_j$ be the probability that the sensor $v_j$ will detect a certain event happened at a component. Then the utility function gained from that component can be defined as

$$U_i(S) = 1 - \prod_{v_j \in S}(1 - p_j)$$
How to Represent Quality of Monitoring?

The overall utility is defined by summing utilities over all correlation components:

$$U = \sum_{c_i \in C} U^{c_i} = \sum_{c_i \in C} U(\sum_{v \in c_i} s_v)$$
Problem Formulation

- We assume that there is a set of sensor nodes deployed over a two-dimensional area.
- In addition, there is one sink node to collect all sensing data from the network.

**Problem:** QoM-aware Rate Allocation

**Objective:** Maximize \( U = \sum_{c_i \in C} U(\sum_{v \in c_i} s_v) \)

subject to:

1. \( s_u + \sum_{v \in N_u} f_{vu} = \sum_{v \in N_u} f_{uv}, \forall u \neq \text{sink} \)
2. \( \sum_{v \in N_u} f_{vu} \delta_r + \sum_{v \in N_u} f_{vu} \delta_t + s_u \delta_s \leq B_u, \forall u \neq \text{sink} \)
3. \( f_{uv} \geq 0, \forall u, v \in \mathcal{V} \)
System Flow

Initial Input & Final Output
- Communication Graph
- Correlation Component

Intermediate Stage
- Communication-Correlation Graph
- QoM-aware Rate Allocation
- Fair Rate Allocation
Two-layered Communication-Correlation Graph

- Two-layered Communication-Correlation Graph based on the example in Figure 2.
Let $s_c$ represent the total sensing rate from component $c$.

Therefore, the overall utility function can be rewritten as:

$$U = \sum_{c \in C} U(\sum_{v \in c} s_v) = \sum_{c \in C} U(s_c)$$
The new problem formulation is similar to the original one, except for some additional constraints on the virtual node.

**Problem:** QoM-Aware Rate Allocation based on CCG

**Objective:** Maximize $U = \sum_{c \in C} U(s_c)$

subject to:

\[
\begin{align*}
(1) \quad s_c &= \sum_{v \in N_c} f_{cv}, \quad \forall c \in C \\
(2) \quad \sum_{u \in N_v} f_{uv} + \sum_{c: N_c \ni v} f_{cv} &= \sum_{u \in N_v} f_{vu} \\
(3) \quad \sum_{c: N_c \ni v} \delta_s + \sum_{v' \in N_v} f_{vu} \delta_t + \sum_{u \in N_v} f_{uv} \delta_r &\leq B_v \\
(4) \quad f_{vu} &\geq 0, \quad \forall v, u \in V
\end{align*}
\]
**Optimal Fair Rate Allocation**

- *Fair rate allocation* problem seeks a rate allocation which can maximize the minimum sensing rate among all components.
- We show that both problems share the common optimal solution under some settings.

**Definition 3 (Fair Rate Allocation).** Given two feasible sensing rate allocations $S_a$ and $S_b$, we sort them in non-decreasing order, and obtain two non-decreasing rate vectors $Q_a$ and $Q_b$. Let $Q^i_a$ and $Q^i_b$ represent the $i$-th rate in $Q_a$ and $Q_b$, respectively. We define $S_a = S_b$ if, and only if, $Q_a = Q_b$; $S_a > S_b$ if, and only if, there exists an $i$ such that $Q^i_a > Q^i_b$ and for all $j < i$, $Q^j_a = Q^j_b$. We say a rate allocation $S$ is an optimal fair rate allocation if, and only if, there exists no other rate allocation $S'$ such that $S' > S$. 
Optimal Fair Rate Allocation

- We modify a classic two phase approach to solve this problem
  
  1. Maximum Common Rate Computation: compute a maximum common rate \( s \) that satisfies all energy constraints and flow conservation; and
  
  2. Maximum Individual Rate Computation: calculate the maximum rate for each component by assuming the sensing rate of all the other components is \( s \).
To compute the maximum common rate, we formulate it as a linear programming problem.

**Problem: Maximum Common Rate Computation**

**Objective:** Maximize $\bar{s}$

**subject to:**

1. $\bar{s} = \sum_{v \in N_c} f_{cv}, \forall c \in C$
2. $\sum_{u \in N_v} f_{uv} + \sum_{c : N_c \ni v} f_{cv} = \sum_{u \in N_v} f_{vu}$
3. $\sum_{c : N_c \ni v} \delta_s + \sum_{u \in N_v} f_{vu} \delta_t + \sum_{u \in N_v} f_{vu} \delta_r \leq B_v$
4. $f_{vu} \geq 0, \forall v, u \in V$
Maximum Individual Rate Computation

- Compute the maximum individual sensing rate that can be achieved for each component by assuming all the other components take the same sensing rate.

**Problem:** Maximum Individual Rate Computation

**Objective:** Maximize $s_c$

subject to:

1. $s_c = \sum_{v \in N_c} f_{cv}$;
2. $s_c' = \sum_{v \in N_c'} f_{c'v} = \bar{s}, \forall c' \in C \setminus \{c\}$
3. $\sum_{u \in N_v} f_{uv} + \sum_{c : N_c \ni v} f_{cv} = \sum_{u \in N_v} f_{vu}$
4. $\sum_{c : N_c \ni v} f_{cv} \delta_s + \sum_{u \in N_v} f_{vu} \delta_t + \sum_{u \in N_v} f_{uv} \delta_r \leq B_v$
5. $f_{vu} \geq 0, \forall v, u \in V$
Optimal Fair Rate Allocation

- This algorithm returns the optimal fair rate allocation.

Algorithm 1 Optimal Fair Rate Allocation (FRA)

Input: CCG and associated energy constraint & flow conservation.
Output: Sensing rate for each component and flow assignment on each link.

1: while $C \neq \emptyset$ do
2:    Compute the maximum common sensing rate $\bar{s}$ in $C$;
3:    for each component $c$ in $C$ do
4:        Compute the maximum individual sensing rate $s_c$ by assuming the sensing rate of all other components is $\bar{s}$;
5:        if $s_c = \bar{s}$ then $C \leftarrow C - c$
6:    return the rate allocation.
QoM-aware Rate Allocation

- If the per unit data sensing cost is no less than the per unit data receiving cost, then the optimal fair rate allocation is also an optimal QoM-aware rate allocation.
QoM-aware Rate Allocation

- Given any feasible rate allocation, in order to increase the sensing rate of some component by $c$, we only need to decrease the total sensing rate of the other components by at most $c$.
  - This can be shown through construction.
  - For any given feasible rate adjustment, we can always modify it to achieve this goal without violating the energy budget constraint.
QoM-aware Rate Allocation

- Given any optimal fair rate allocation, we cannot increase the sensing rate of a correlation component without reducing the sensing rate of another component with a lower sensing rate.
- this can be shown through contradiction
QoM-aware Rate Allocation

- Any optimal QoM-aware rate allocation must also be an optimal fair rate allocation if the sensing cost is no less than the receiving cost.

  - Given any feasible rate allocation, in order to increase the sensing rate of some component by $c$, we only need to decrease the total sensing rate of the other components by at most $c$.

  - Given any optimal fair rate allocation, we cannot increase the sensing rate of a correlation component without reducing the sensing rate of another component with a lower sensing rate.
QoM-aware Rate Allocation

- If optimal fair rate allocation is not an optimal QoM-aware rate allocation, we can increase the sensing rate of some component while decreasing the total sensing rate of some other components with a higher rate by at most the same amount.

- This leads to a better QoM-aware rate allocation due to its submodularity.
  - It contradicts to the assumption that the original rate allocation is optimal.
QoM-aware Rate Allocation

- This algorithm also returns the optimal QoM-aware rate allocation.

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5: if $s_c = \bar{s}$ then $C \leftarrow C - c$
6: return the rate allocation.
Experimental Results

- We adopt the TelosB Mote with a MSP430 processor and CC2420 transceiver.
- Each mote is equipped with 2 AA batteries.
Experimental Results

![Graph showing the relationship between the number of correlation components and the dissimilarity threshold. The x-axis represents the dissimilarity threshold (m) ranging from 0 to 2, and the y-axis represents the number of correlation components ranging from 0 to 70. The graph includes points at (0.1, 68), (0.2, 34), (0.3, 22), (0.6, 11), (0.9, 7), (1.2, 5), (1.5, 4), and (1.8, 3).]
Experimental Results
Experimental Results
Future Work

- The per unit data sensing cost is less than the per unit data receiving cost.

- The utility function $U()$ is heterogeneous to different correlation components.

- Taking wireless interference into account.

- Distributed implementation.
• Thanks!