# Qute: Quality-of-Monitoring Aware Sensing and Routing Strategy in Wireless Sensor Networks

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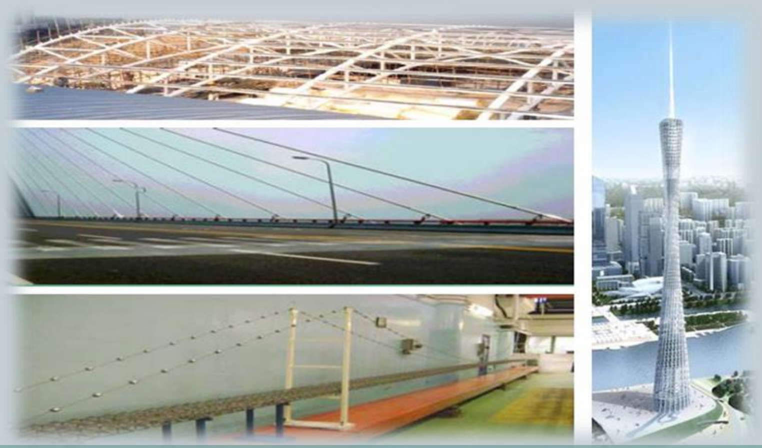
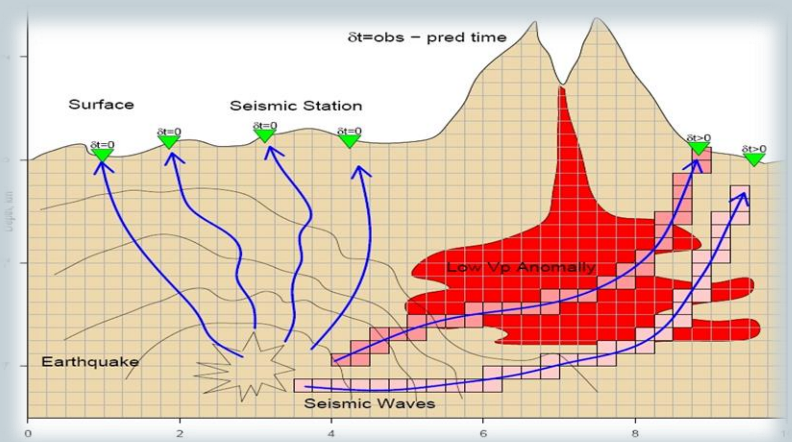
# Examples of WSNs

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

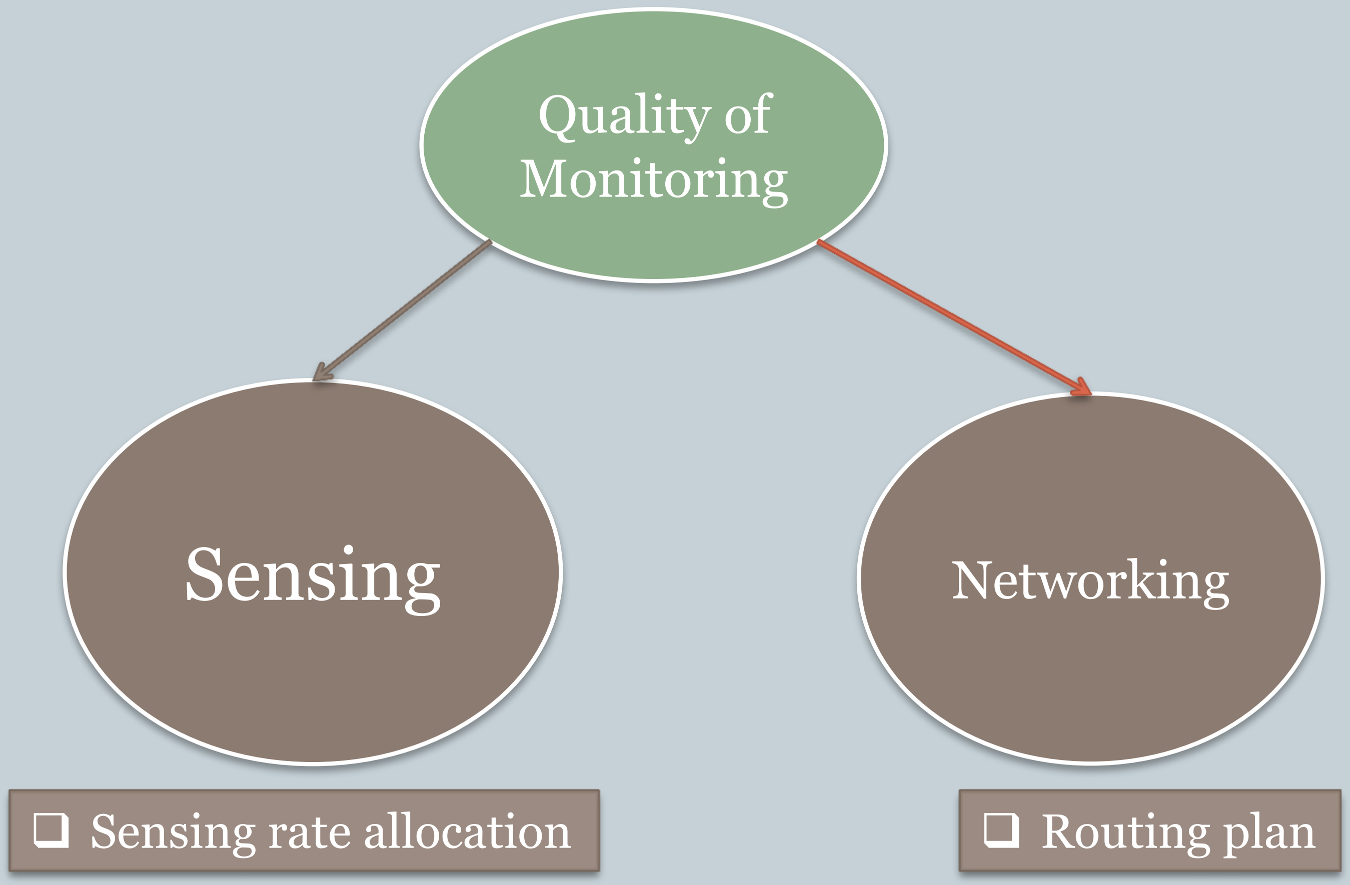




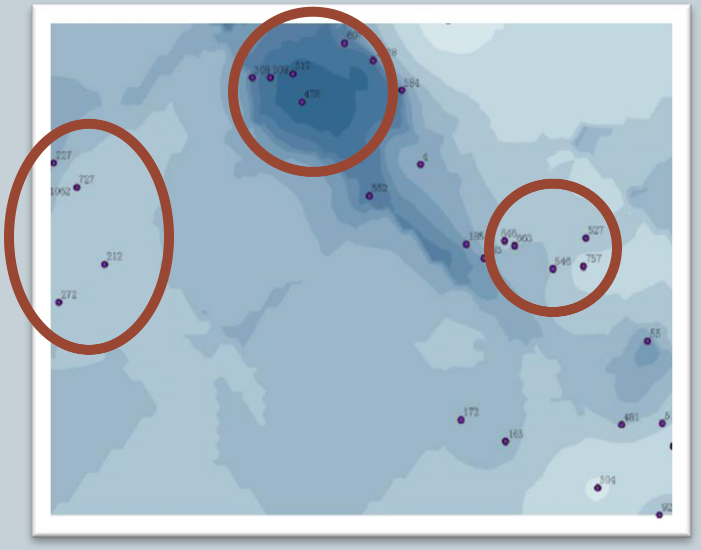
# Comparison with Traditional Networks

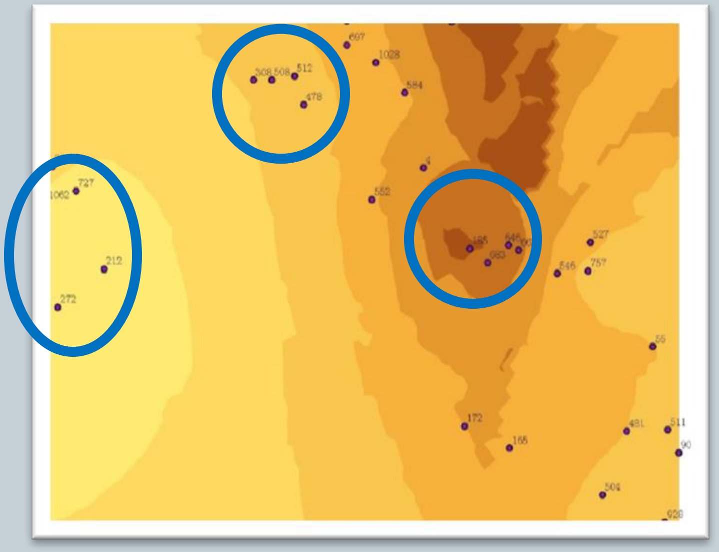
- Unlike traditional networks, wireless sensor networks are often resource limited
  - Limited power supply
  - Limited computational capability
  - Limited communication capability
- Developing an effective sensor network must take into account its Quality-of-Monitoring (QoM)
  - Avoid redundant sensor readings
  - Leverage the statistical correlations among sensor nodes

# System Overview



# Statistical Correlations

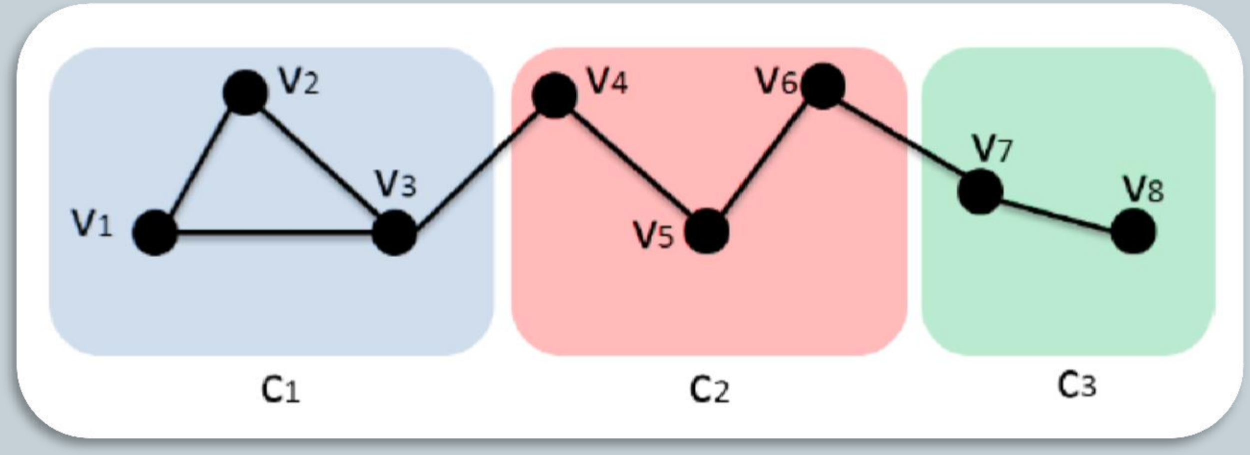




- The readings among neighboring nodes are often spatially correlated.
  - The degree of correlation depends on the internode separation
  - Those sensors with similar readings naturally form a component or cluster.

# 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

$$\begin{cases} U_i(\emptyset) = 0, \\ U_i(S_1) \leq U_i(S_2), \text{ if } S_1 \subseteq S_2, \text{ and} \\ U_i(S_1 \cup A) - U_i(S_1) \geq U_i(S_2 \cup A) - U_i(S_2), S_1 \subseteq S_2 \end{cases}$$

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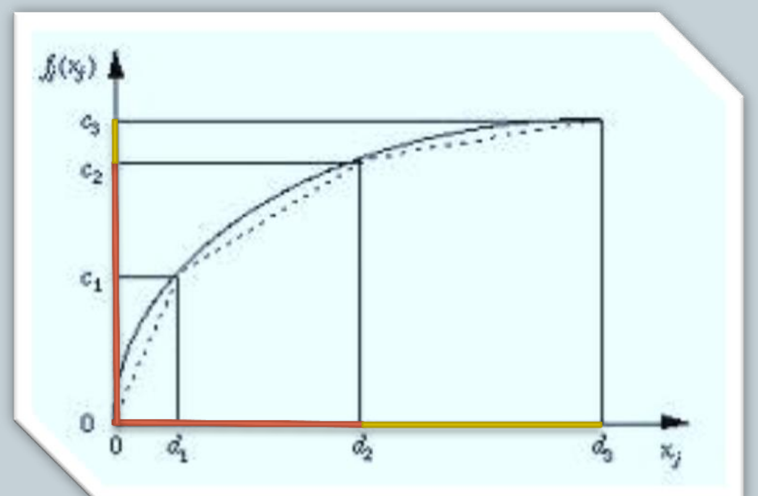
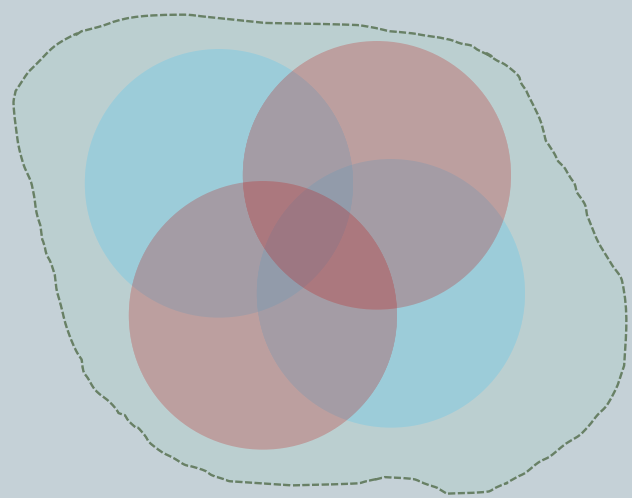


# How to Represent Quality of Monitoring?

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

Let $\mathbf{p_j}$ be the probability that the sensor $\mathbf{v_j}$ 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:

$$\mathbf{U} = \sum_{\mathbf{c}_i \in \mathcal{C}} \mathcal{U}^{\mathbf{c}_i} = \sum_{\mathbf{c}_i \in \mathcal{C}} \mathcal{U}\left(\sum_{v \in \mathbf{c}_i} s_v\right)$$

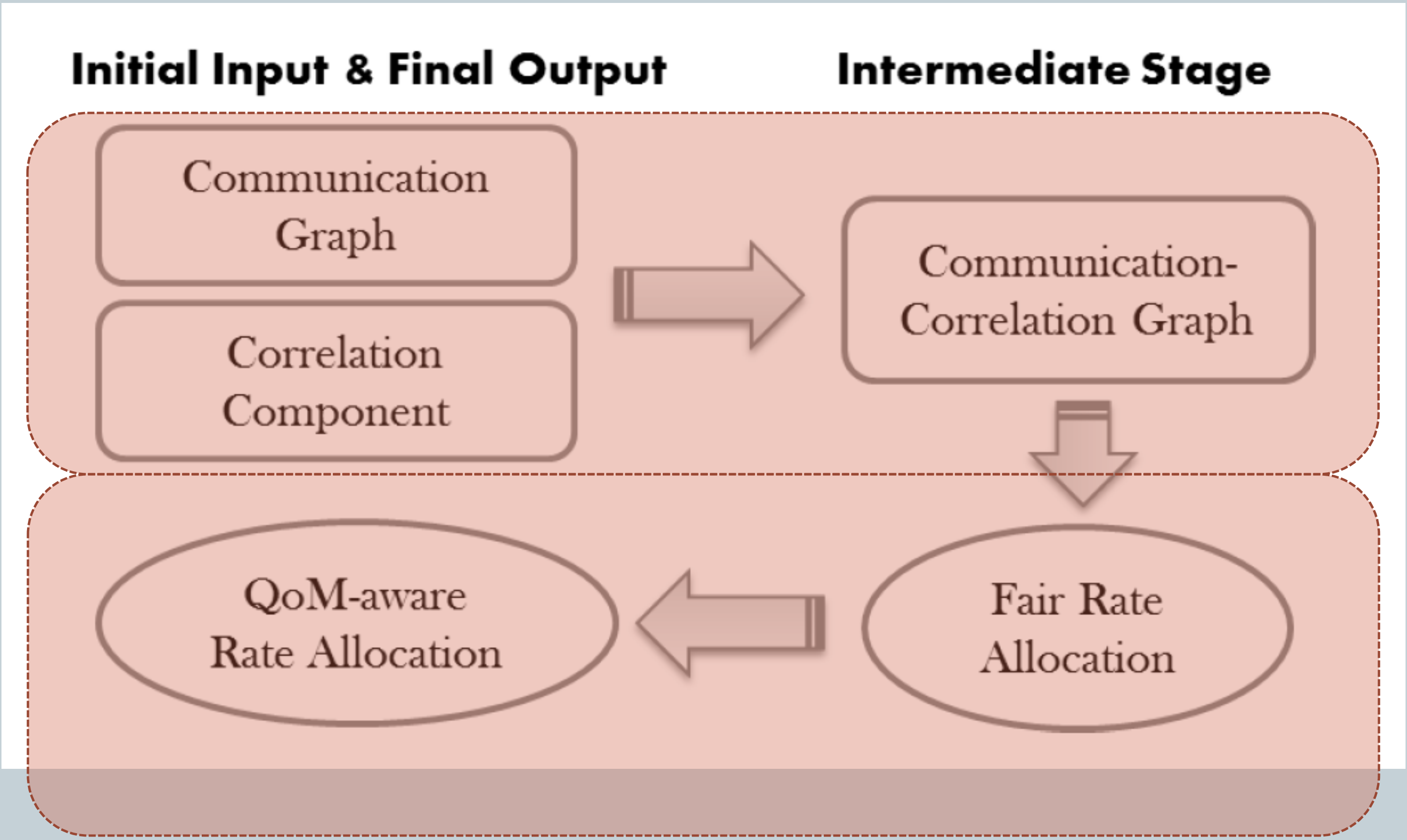
# Problem Formulation

- 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.

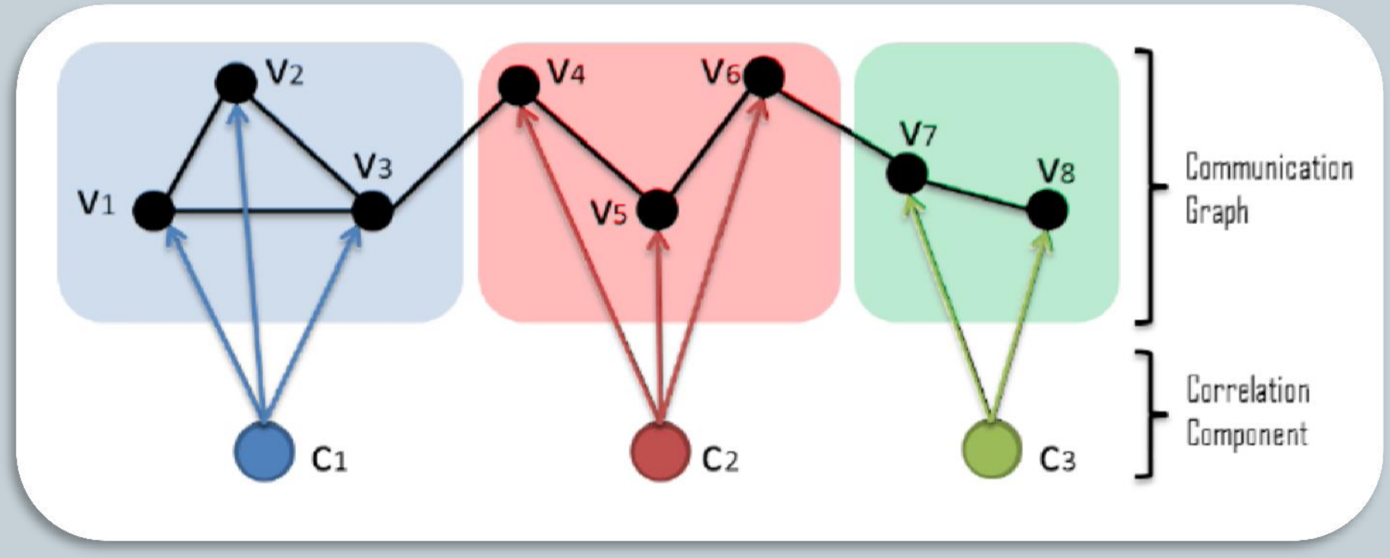
**Problem:** *QoM-aware Rate Allocation*
**Objective:** Maximize $\mathbf{U} = \sum_{\mathbf{c}_i \in \mathcal{C}} \mathcal{U}(\sum_{v \in \mathbf{c}_i} s_v)$
**subject to:**

$$\begin{cases} (1)\ \ s_u + \sum_{v \in N_u} f_{vu} = \sum_{v \in N_u} f_{uv}, \forall u \neq \text{ sink} \\ (2)\ \ \sum_{v \in N_u} f_{vu}\delta_r + \sum_{v \in N_u} f_{vu}\delta_t + s_u\delta_s \leq \mathbf{B}_u, \forall u \neq \text{ sink} \\ (3)\ \ f_{uv} \geq 0, \forall u, v \in \mathcal{V} \end{cases}$$

# System Flow


Initial Input & Final Output
Intermediate Stage
Communication Graph
Correlation Component
Communication-Correlation Graph
Fair Rate Allocation
QoM-aware Rate Allocation

# Two-layered Communication-Correlation Graph




- Two-layered Communication-Correlation Graph based on the example in Figure 2.

# CCG-based Formulation

- Let $s_{\mathbf{c}}$ represent the total sensing rate from component **c**.

- Therefore, the overall utility function can be rewritten as:

$$\mathbf{U} = \sum_{\mathbf{c} \in \mathcal{C}} \mathcal{U}\Big(\sum_{v \in \mathbf{c}} s_v\Big) = \sum_{\mathbf{c} \in \mathcal{C}} \mathcal{U}(s_{\mathbf{c}})$$

# CCG-based Formulation

- 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 $\mathbf{U} = \sum_{\mathbf{c} \in \mathcal{C}} \mathcal{U}(s_{\mathbf{c}})$
**subject to:**

$$\begin{cases} (1) & s_{\mathbf{c}} = \sum_{v \in N_c} f_{cv}, \forall \mathbf{c} \in \mathcal{C} \\ (2) & \sum_{u \in N_v} f_{uv} + \underset{\mathbf{c}:N_{\mathbf{c}} \ni v}{f_{cv}} = \sum_{u \in N_v} f_{vu} \\ (3) & \underset{\mathbf{c}:N_{\mathbf{c}} \ni v}{f_{cv}} \delta_s + \sum_{v' \in N_v} f_{vu} \delta_t + \sum_{u \in N_v} f_{uv} \delta_r \leq \mathbf{B}_v \\ (4) & f_{vu} \geq 0, \forall v, u \in \mathcal{V} \end{cases}$$

# 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 $Q_a^i$ and $Q_b^i$ 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 $Q_a^i > Q_b^i$ and for all $j < i$, $Q_a^j = Q_b^j$. We say a rate allocation $S$ is an optimal* fair rate allocation *if, and only if, there exists no other rate allocation $S' > S$.*

# 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.

# Maximum Common Rate Computation

- To compute the maximum common rate, we formulate it as a linear programming problem.

**Problem:** *Maximum Common Rate Computation*
**Objective:** Maximize $\overline{s}$
**subject to:**

$$
\begin{cases}
(1)\ \ \overline{s} = \sum_{v \in N_{\mathbf{c}}} f_{\mathbf{c}v}, \forall \mathbf{c} \in \mathcal{C} \\
(2)\ \ \sum_{u \in N_v} f_{uv} + \underset{\mathbf{c}:N_{\mathbf{c}} \ni v}{f_{\mathbf{c}v}} = \sum_{u \in N_v} f_{vu} \\
(3)\ \ \underset{c:N_{\mathbf{c}} \ni v}{f_{\mathbf{c}v}} \delta_s + \sum_{u \in N_v} f_{vu}\delta_t + \sum_{u \in N_v} f_{uv}\delta_r \leq \mathbf{B}_v \\
(4)\ \ f_{vu} \geq 0, \forall v, u \in \mathcal{V}
\end{cases}
$$

# 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 $s_{\mathbf{c}}$
**subject to:**

$$
\begin{cases}
(1) \;\; s_{\mathbf{c}} = \sum_{v \in N_{\mathbf{c}}} f_{\mathbf{c}v}; \\
(2) \;\; s_{\mathbf{c}'} = \sum_{v \in N_{\mathbf{c}'}} f_{\mathbf{c}'v} = \overline{s}, \forall \mathbf{c}' \in \mathcal{C} \setminus \{\mathbf{c}\} \\
(3) \;\; \sum_{u \in N_v} f_{uv} + \underset{c:N_c \ni v}{f_{cv}} = \sum_{u \in N_v} f_{vu} \\
(4) \;\; \underset{\mathbf{c}:N_{\mathbf{c}} \ni v}{f_{cv}} \delta_s + \sum_{u \in N_v} f_{vu} \delta_t + \sum_{u \in N_v} f_{uv} \delta_r \le \mathbf{B}_v \\
(5) \;\; f_{vu} \ge 0, \forall v, u \in \mathcal{V}
\end{cases}
$$

# Optimal Fair Rate Allocation

- This algorithm returns the optimal fair rate allocation.

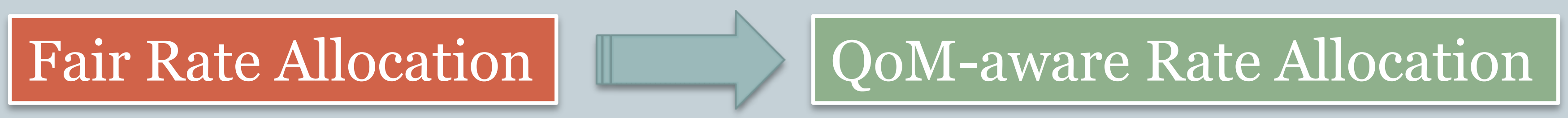
**Algorithm 1** Optimal Fair Rate Allocation (FRA)

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

```
while 𝒞 ≠ ∅ do
    Compute the maximum common sensing rate s̄ in 𝒞;
    for each component c in 𝒞 do
        Compute the maximum individual sensing rate s_c by assuming the sensing rate of all other components is s̄;
        if s_c = s̄ then 𝒞 ⟵ 𝒞 − c
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, <u>then the optimal fair rate allocation is also an optimal QoM-aware rate allocation</u>.



# 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 contradication

# 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.

**Algorithm 1** Optimal Fair Rate Allocation (FRA)

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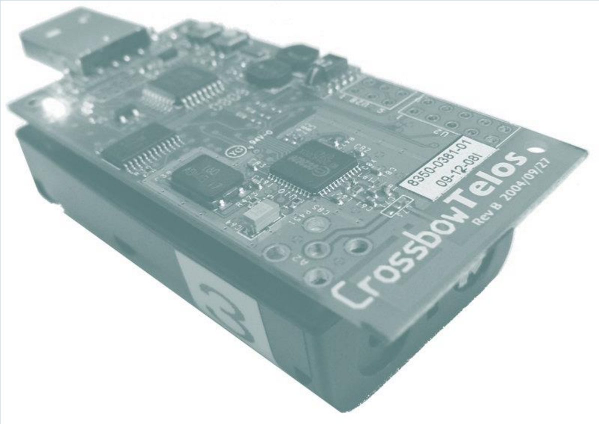
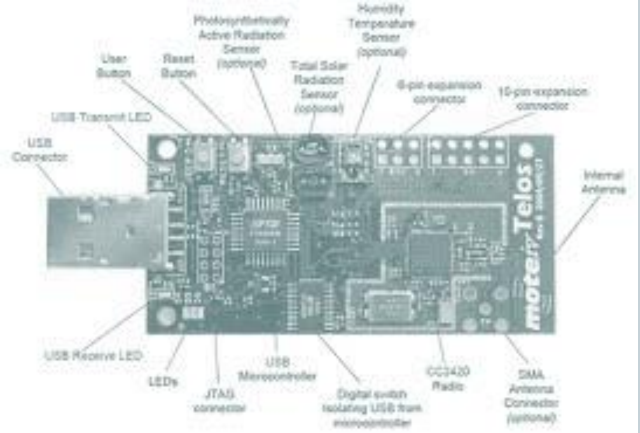
        if s_c = s̄ then 𝒞 ⟵ 𝒞 − c
return the rate allocation.
```

# Experimental Results

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



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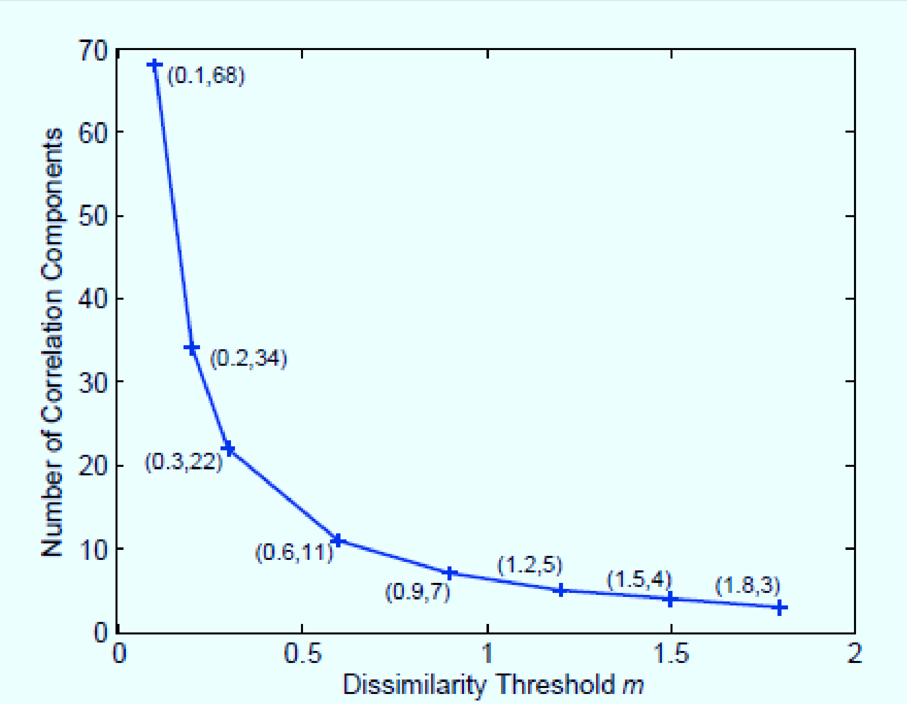

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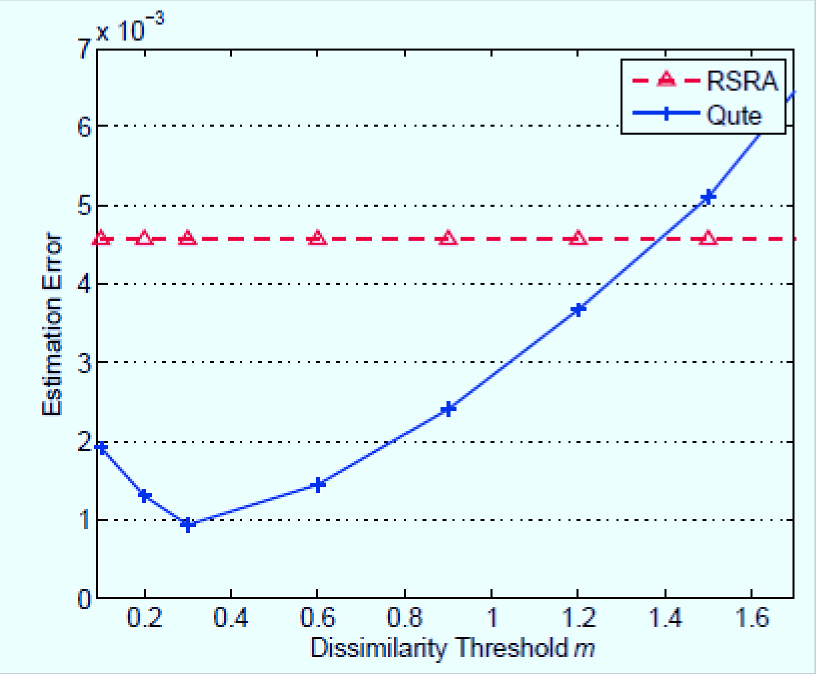

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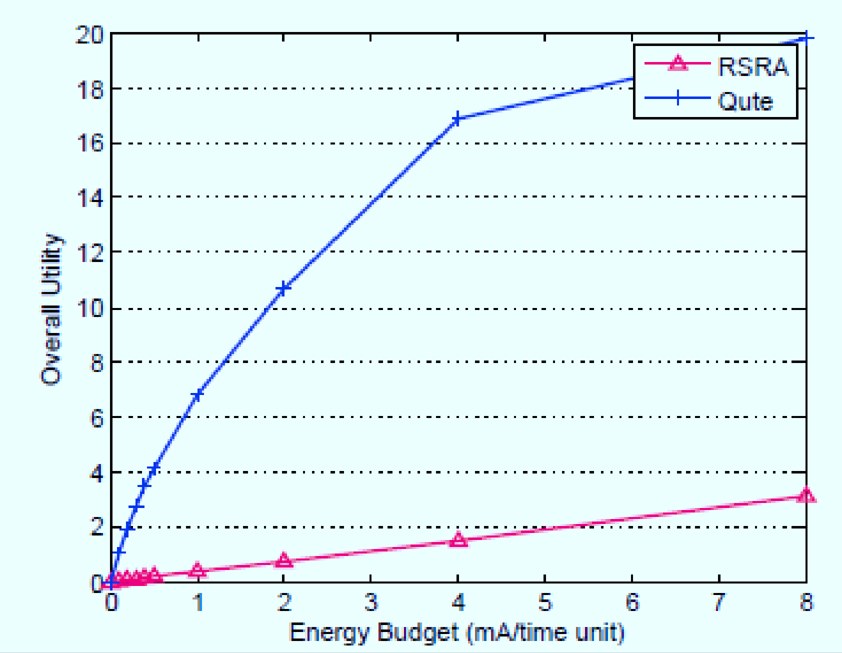

# Future Work

- 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!