On Energy Efficiency of Routing with Cooperative Transmissions

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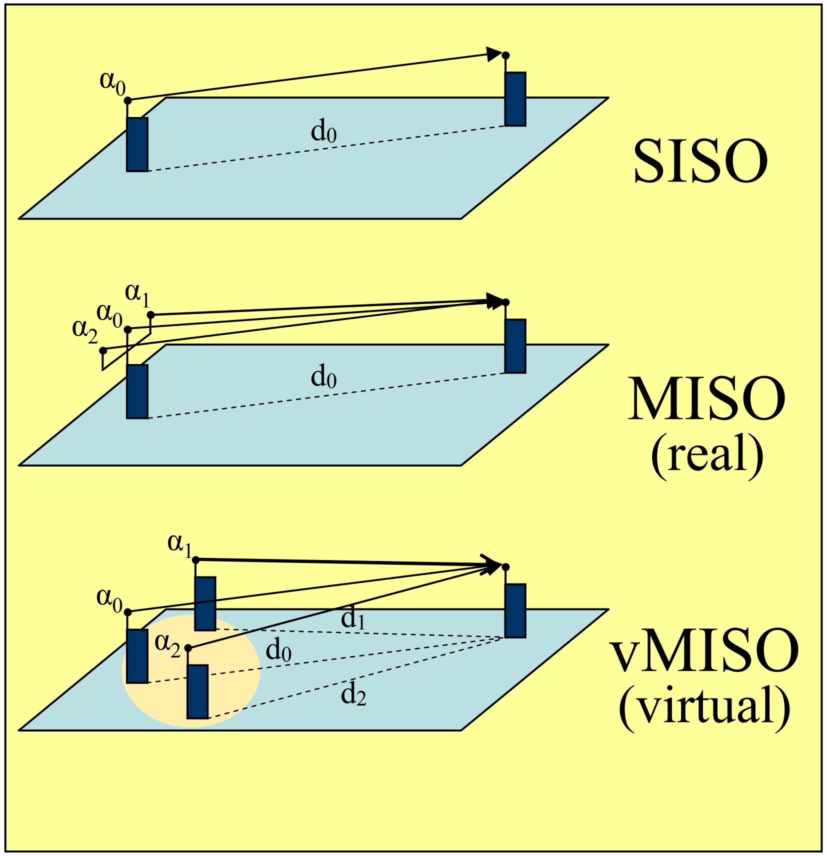
1. Our Motivation

- **Wireless sensor networks**
  - Limited battery capacities, multi-hop wireless communications
  - Signal attenuations and channel fading
- **In order to mitigate the effects of fading;**
  - ✗ Increasing transmission power → Energy consuming
  - ✗ Antenna arrays → Size restriction
  - ✓ Cooperative diversity
    - Spatial diversity
    - Improved quality of point-to-point transmissions
    - Energy efficient long-haul wireless links

Can we utilize the advantages of cooperative transmissions to prolong the network lifetime of wireless sensor networks?

2. Physical layer properties of vMISO links



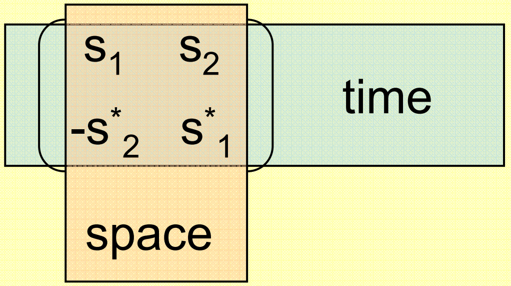
Virtual MISO (vMISO) links:

- Multiple transmitters transmit the same symbols to a common destination
- Joint transmission improves the signal quality and reliability of information at the destination
- The symbols are *replicated* in
  - Space
  - Time
- Destination node combines the received symbols with linear combination

Space-time block coding can provide large diversity gains

Complex orthogonal design

- Alamouti codes
- Generalized form



$$r_1 = h_1 s_1 + h_2 s_2$$

$$r_2 = -h_1 s_2^* + h_2 s_1^*$$

Energy consumption model:

QoS measure→Average SNR

- For an average **SNR** $\geq \gamma$, the energy to send a bit of information in each case is at least;

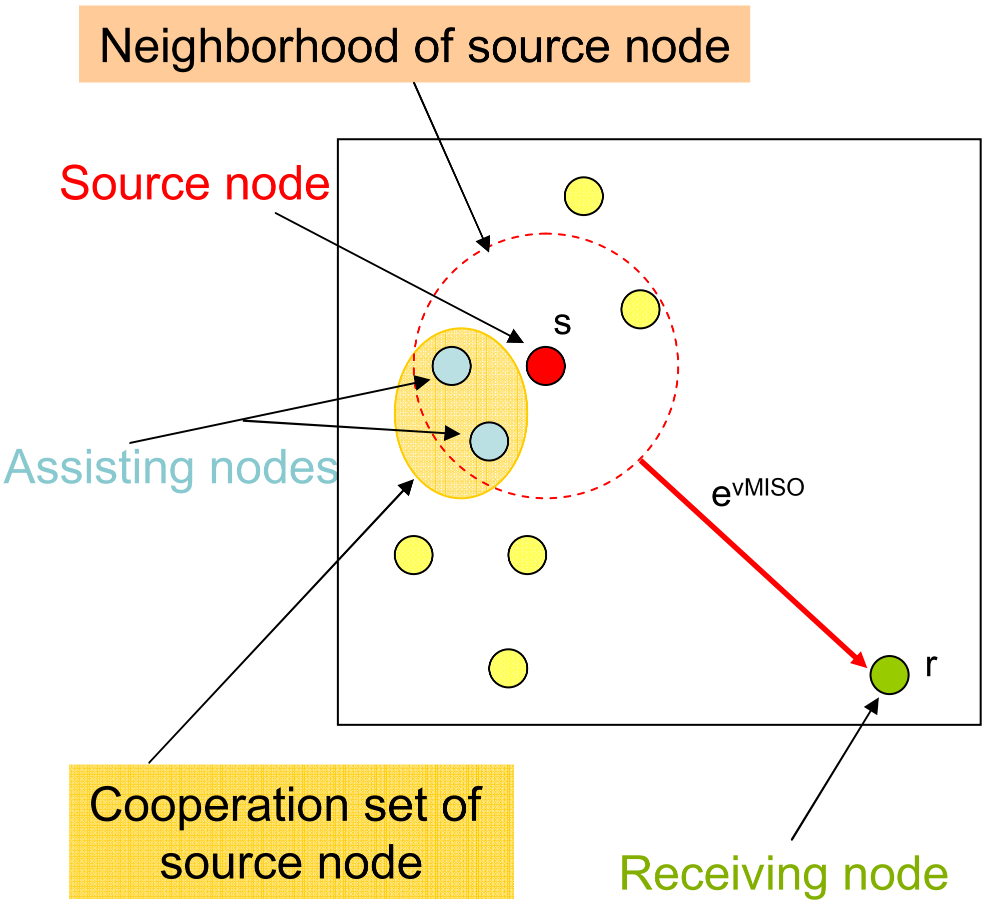
$$e^{SISO} = \frac{\gamma N_0}{\mathrm{E}\left[\alpha_0^2\right]} d_0^{\beta}$$

$$e^{vMISO} = \frac{\gamma N_0}{\mathrm{E}\left[\alpha_0^2\right]\sum_{i=0}^{N-1} d_i^{-\beta}}$$

- Each vMISO cooperating node should transmit with at least R_{ij}^{c} times less power than the power required for SISO transmission

$$R_{ij}^{c} = 1 + \frac{\sum_{k \in V_{ij}^{c}} d_{kj}^{-\beta}}{d_{ij}^{-\beta}}$$

Three states of nodes in vMISO:



3. Network Lifetime Maximization

Lifetime of node i:

$$T_i(\text{q}) = \frac{E_i}{e_i^{source} + e_i^{coop} + e_i^{receive}}$$

System lifetime: $T_{sys}(\text{q}) = \min_{i \in N} T_i(\text{q})$

Nonlinear Optimization Problem

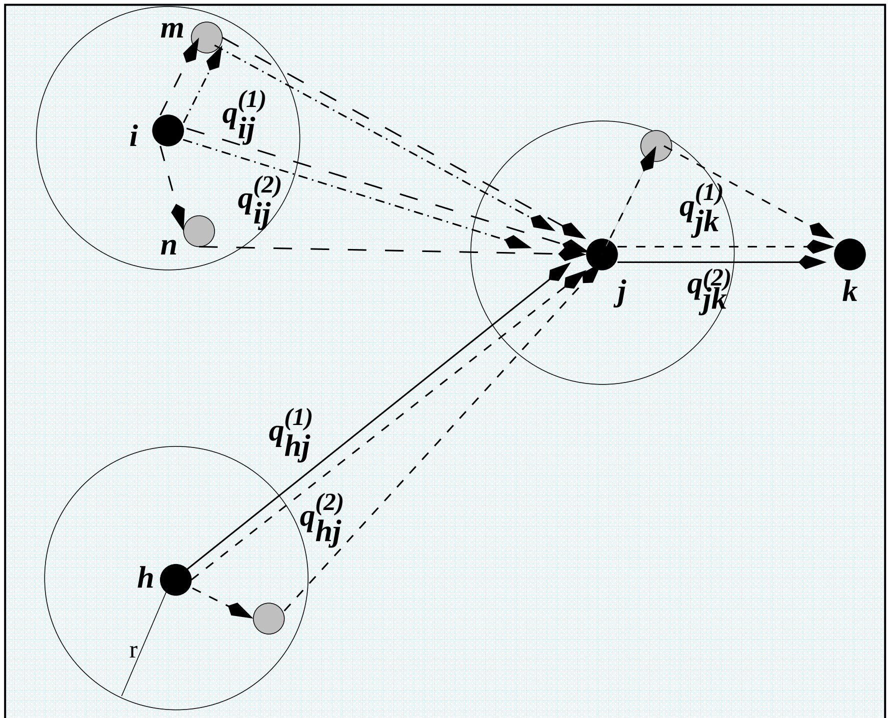
max T,

$$\sum_{i \in N} \left[\sum_{c=1}^{M_{ij}} e_{ij}^{c} \hat{q}_{ij}^{(c)} + \sum_{(c,k):i \in v_{kj}^{c}} \tilde{e}_{kj}^{c} \hat{q}_{kj}^{(c)} + \sum_{c=1}^{M_{ij}} e_r \hat{q}_{ij}^{(c)} \right] \le E_i$$

$$, \forall i \in N$$

$$\sum_{i \in N, i \neq j} \sum_{c=1}^{M_{ij}} \hat{q}_{ij}^{(c)} = \sum_{k \in N, k \neq j} \sum_{c=1}^{M_{jk}} \hat{q}_{jk}^{(c)}, \forall j \in N$$

$$s.t.\ \hat{q}_{ij}^{(c)} \ge 0, \forall_i \in N$$



Flow conservation condition at node j:

$$\sum_{i \in N, i \neq j} \sum_{c=1}^{M_{ij}} q_{ij}^{(c)} = \sum_{k \in N, k \neq j} \sum_{c=1}^{M_{jk}} q_{jk}^{(c)}$$

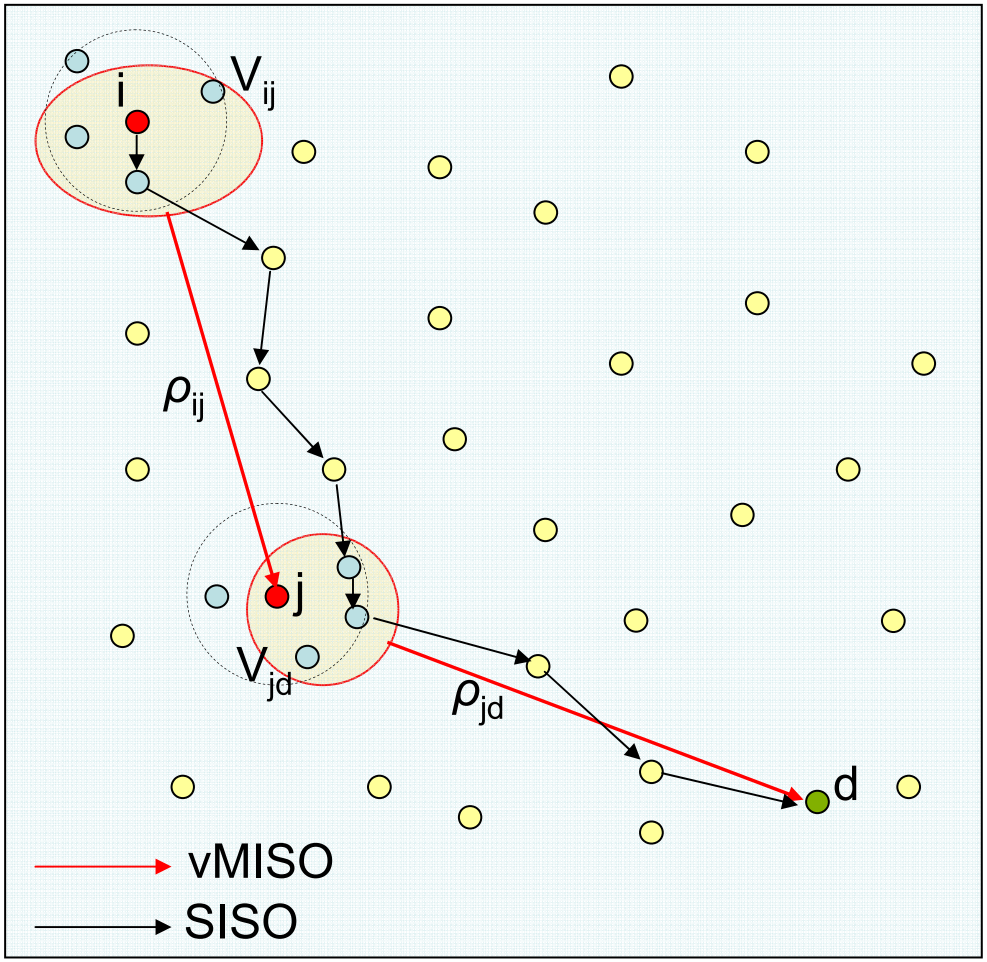
4. vMISO Routing Algorithm

A flow augmentation algorithm

At each iteration:

- For each transmitter-receiver pair *(i, j)*, the best cooperation set V_{ij}^{c} is selected
- Assign a cost $\boldsymbol{\rho}$ to each edge (vMISO links) between the cooperation set and the next node *j*
- Shortest cost paths from origin nodes to destination nodes are calculated using vMISO links

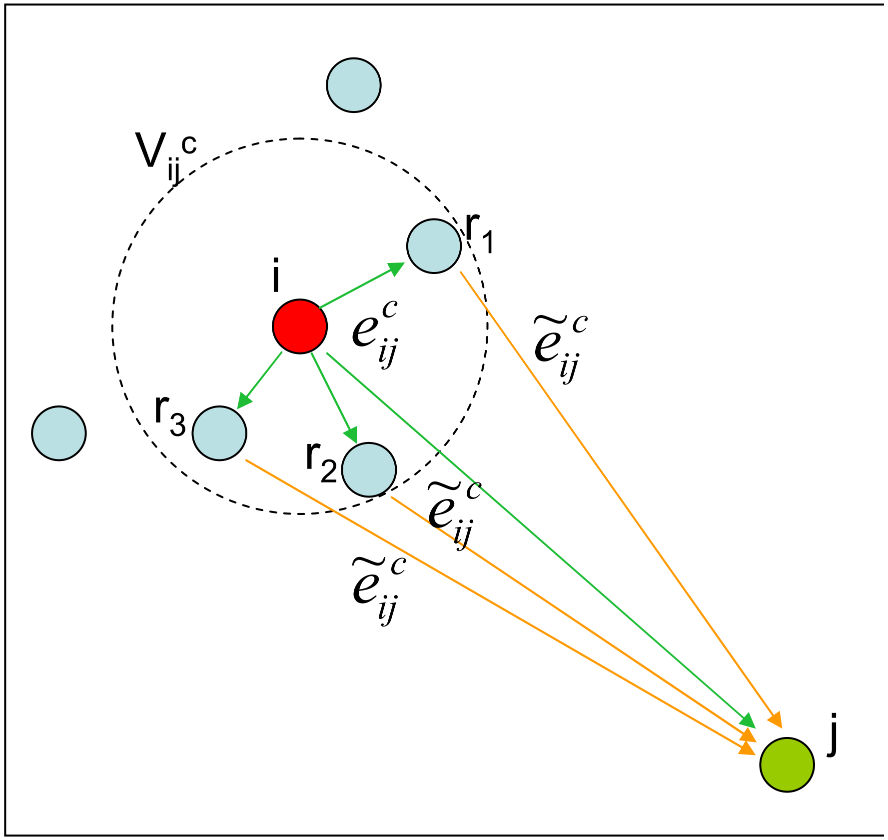
After each augmentation shortest cost paths are recalculated. The procedure repeats until any node in the network runs out of its initial total energy.



As a result, we obtain the flow used in each node to properly split the incoming traffic.

Selection of cooperation set

- Energy expenditure per bit of data flowing from the cooperation set to the next node
- Minimum of the residual energies of the nodes in the cooperation set
- A **good candidate** for cooperation set should:
  - Consume low energy
  - Avoid nodes with small residual energy
- The cost function is $\rho_{ij}^{c} = \dfrac{e_{ij}^{c} + \sum_{k\in V_{ij}^{c}} \tilde{e}_{ij}^{c}}{\min_{k\in V_{ij}^{c}}\left[E_k\right]}$



$$\tilde{e}_{ij}^{c} = e_r + \frac{\hat{e}_{ij}}{R_{ij}^{c}}\xi\left(\left|V_{ij}^{c}\right|\right)$$

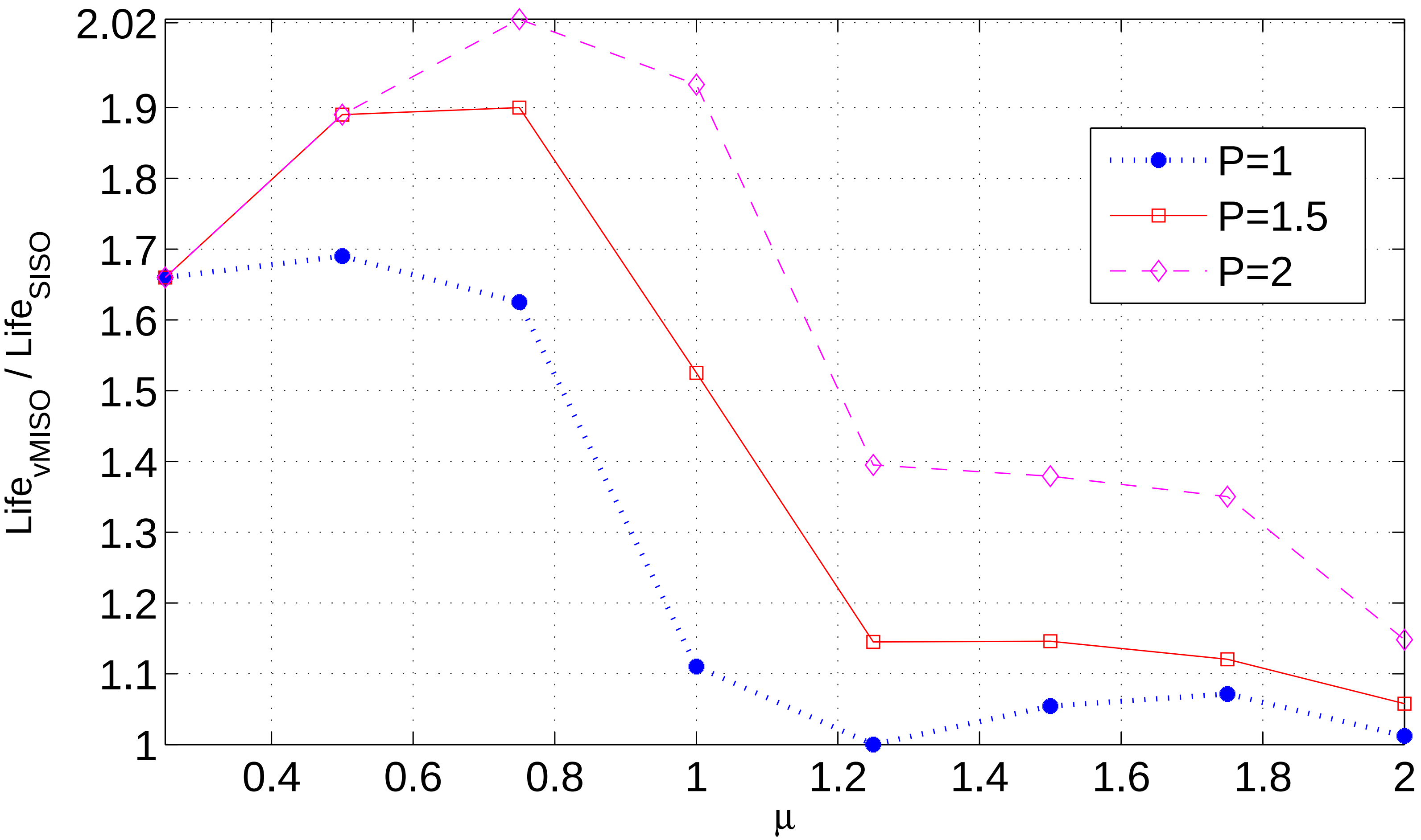
$$e_{ij}^{c} = \sum_{k\in V_{ij}^{c}} \hat{e}_{ik} + \frac{\hat{e}_{ij}}{R_{ij}^{c}}\xi\left(\left|V_{ij}^{c}\right|\right)$$

$$e_i^{source} = \sum_{j\in N}\sum_{c=1}^{M_{ij}} q_{ij}^{(c)} e_{ij}^{c}$$

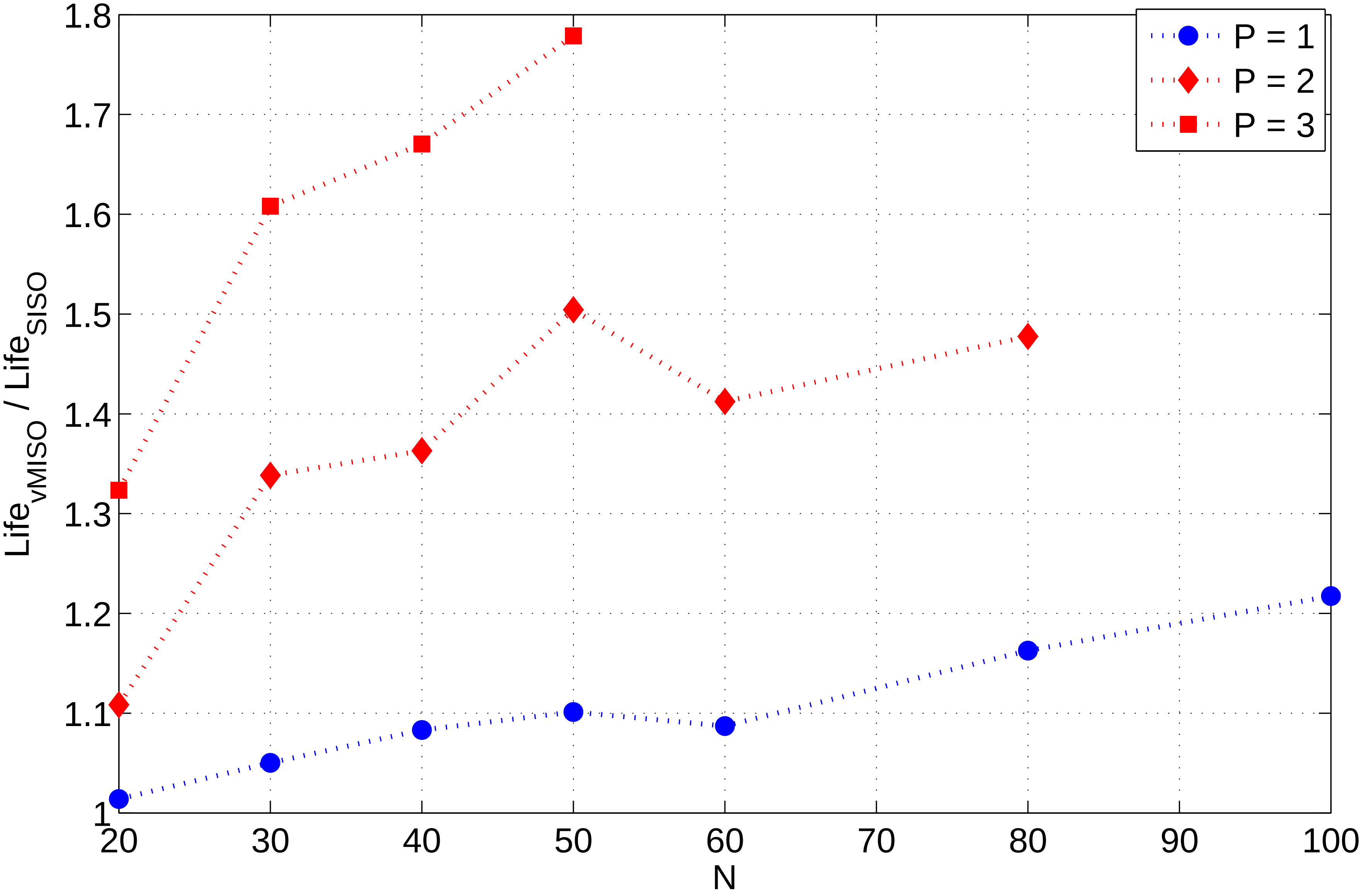
$$e_i^{coop} = \sum_{j\in N}\sum_{(c,k):i\in V_{kj}^{c}} q_{kj}^{(c)} \tilde{e}_{kj}^{c}$$

$$e_i^{source} = \sum_{j\in N}\sum_{c=1}^{M_{ij}} q_{ij}^{(c)} e_r$$

5. Preliminary Results



Effect of clustering on network lifetime, *P: neighborhood radius



Effect of node density on the network lifetime