Multi-Objective Routing Optimisation for Battery-Powered Wireless Sensor Mesh Networks

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Wireless Sensors

- Autonomous devices
- Environmental or process monitoring
  - Industrial
  - Heritage
  - Pharmaceuticals
  - Health-care
- Battery powered
  - Monitor locations that are difficult to access
  - Typically left unattended for long periods of time
Point-to-Point Networks

- Sensors and Gateway
Point-to-Point Networks

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- Direct connections between Sensor and Gateway
Point-to-Point Networks

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Challenges
- Limited Range
Point-to-Point Networks

- Sensors and Gateway
- Direct connections between Sensor and Gateway

Challenges
- Limited Range
- Vulnerable to dynamic radio environment
Mesh Networks

- Sensor nodes relay their adjacent nodes’ data to the gateway
Mesh Networks

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  - Range extension
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  - Alternative routes - resilience to changes in radio environment
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Maximise

- Average battery lifetime
- Minimum time before one node expires
Routing Scheme

- Network connectivity map

A route for node $v_3$: $S_3 = \langle v_3, v_1, v_G \rangle$

A routing scheme for the network: $R = \{S_1, S_2, S_3, S_4, S_5\}$
Routing Scheme

- Network connectivity map
- A route for node $v_3$:

$$S_3 = \langle v_3, v_1, v_G \rangle$$
Routing Scheme

- Network connectivity map
- A route for node $v_3$:
  \[ S_3 = \langle v_3, v_1, v_G \rangle \]
- A routing scheme for the network:
  \[ \mathcal{R} = \{ S_1, S_2, S_3, S_4, S_5 \} \]
Node Costs

- Node’s cost due to a routing scheme $\mathcal{R}$:

$$C_1 = T_{1,G} + (R_{1,2} + T_{1,G}) + (R_{1,3} + T_{1,G})$$

For a transmission from $v_i$ to $v_j$:
- $T_{i,j}$ Transmission cost at node $v_i$
- $R_{j,i}$ Reception cost at node $v_j$
Node Costs

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Node Costs

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For a transmission from $v_i$ to $v_j$:

$T_{i,j}$ Transmission cost at node $v_i$

$R_{j,i}$ Reception cost at node $v_j$
Objectives

- Lifetime for node $v_i$:

$$L_i(R) = \frac{Q_i}{E_i + C_i}$$

- $Q_i$: battery charge
- $E_i$: quiescent current
- $C_i$: radio communication current
Objectives

- Lifetime for node $v_i$:

$$L_i(\mathcal{R}) = \frac{Q_i}{E_i + C_i}$$

$Q_i$  battery charge
$E_i$  quiescent current
$C_i$  radio communication current

Maximise

Average lifetime:
$$f_1(\mathcal{R}) = \frac{1}{n} \sum_{i=1}^{n} L_i(\mathcal{R})$$

Minimum lifetime:
$$f_2(\mathcal{R}) = \min_{i \in [1,n]} L_i(\mathcal{R})$$
Search Space Size

- How big is the search space?

Number of possible routing schemes: \( n \prod_{i=1}^{a_i} \)

- Limit the number of paths available to each node by using \( k \)-shortest paths algorithm [Yen, 1972; Eppstein, 1999]

Maximum search space size: \( k n \)

Quicker approximation of Pareto Front

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Search Space Size

- Number of possible loopless paths for node $v_3$: 1

Limit the number of paths available to each node by using $k$-shortest paths algorithm [Yen, 1972; Eppstein, 1999].

Maximum search space size: $k n$
Number of possible loopless paths for node $v_3$: 2

Maximum search space size: $k n$

Quicker approximation of Pareto Front

Limit the number of paths available to each node by using $k$-shortest paths algorithm [Yen, 1972; Eppstein, 1999]

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Search Space Size

- Number of possible loopless paths for node $v_3$: 3
Search Space Size

- Number of possible loopless paths for node $v_3$: 4
Number of possible loopless paths for node $v_3$: 5
Search Space Size

- Number of possible loopless paths for node $v_3$: 6
Search Space Size

- Number of possible loopless paths for node $v_3$: 7

Limit the number of paths available to each node by using $k$-shortest paths algorithm [Yen, 1972; Eppstein, 1999]
Search Space Size

- Number of possible loopless paths for node $v_3$: 7
- Number of possible routing schemes:

$$\prod_{i=1}^{n} a_i$$

$a_i$: Number of available routes from $v_i$ to $v_G$
Search Space Size

- Number of possible loopless paths for node $v_3$: 7
- Number of possible routing schemes:

$$\prod_{i=1}^{n} a_i$$

$a_i$: Number of available routes from $v_i$ to $v_G$

- 4032 solutions
Search Space Size

- Number of possible loopless paths for node $v_3$: 7
- Number of possible routing schemes:

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$a_i$: Number of available routes from $v_i$ to $v_G$

- 243 solutions
Search Space Size

- Number of possible loopless paths for node $v_3$: 7
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- $a_i$: Number of available routes from $v_i$ to $v_G$
- 243 solutions

- Limit the number of paths available to each node by using $k$-shortest paths algorithm [Yen, 1972; Eppstein, 1999]
- Maximum search space size: $k^n$
- Quicker approximation of Pareto Front
Multi-Objective Evolutionary Algorithm

1: $A \leftarrow InitialiseArchive()$ $\triangleright$ Initialise elite archive randomly
2: for $i \leftarrow 1 : T$ do
3: $\mathcal{R}_1, \mathcal{R}_2 \leftarrow Select(A)$ $\triangleright$ Select two parent solutions
4: $\mathcal{R}' \leftarrow UniformCrossOver(\mathcal{R}_1, \mathcal{R}_2)$
5: $\mathcal{R}'' \leftarrow Mutate(\mathcal{R}')$
6: $A \leftarrow NonDominated(A \cup \mathcal{R}'')$ $\triangleright$ Update archive
7: end for
8: return $A$ $\triangleright$ Approximation of the Pareto set

**Crossover** Select paths for each node from parents

**Mutation** Replace paths randomly from $k$-shortest paths for some nodes
Real Network: The Victoria & Albert Museum
Real Network: The Victoria & Albert Museum

Basement

Ground

First

Second

Third
Real Network: The Victoria & Albert Museum

- 30 nodes + gateway
- $k = 10$; search space is limited to $10^{30}$ solutions.
- Initial population size: 100
- Mutation and crossover rate: 0.1
- Number of iterations: 150,000
- Run time: 2 minutes
30 nodes + gateway

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Initial population size: 100

Mutation and crossover rate: 0.1

Number of iterations: 150,000

Run time: 2 minutes
Real Network: The Victoria & Albert Museum

Average lifetime: 2 years
Minimum lifetime: 0.75 years (node v_{19})
Real Network: The Victoria & Albert Museum

Average lifetime: 1.93 years
Minimum lifetime: 1.12 years (node v21)
Real Network: The Victoria & Albert Museum

Average lifetime: 1.97 years
Minimum lifetime: 0.97 years (node v_{19})
Recovering from Link Failure

- Select operating point from estimated Pareto front
- Simulate radio activity for 6 months
- Simulate link failure
Recovering from Link Failure

- Select operating point from estimated Pareto front ✓
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Recovering from Link Failure

- Select operating point from estimated Pareto front ✓
- Simulate radio activity for 6 months ✓
- Simulate link failure

![Graph showing lifetime analysis](image)
Recovering from Link Failure

- Select operating point from estimated Pareto front ✓
- Simulate radio activity for 6 months ✓
- Simulate link failure ✓
Recovering from Link Failure

- Reoptimize with aged front

![Graph showing Minimum Lifetime vs. Average Lifetime (years)]
Recovering from Link Failure

- Reoptimise with aged front

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Recovering from Link Failure

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Recovering from Link Failure

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![Graph showing Minimum Lifetime vs. Average Lifetime with indicated fronts.](image-url)
Extending Minimum Lifetime
Extending Minimum Lifetime

Node 1

Node 5

Charge

Time

\( \mathcal{R}_1 \)

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Extending Minimum Lifetime

Node 1

Node 5

Charge

Time

$\mathcal{R}_2$

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$\mathcal{R}_1$

Charge vs. Time for Nodes 1 and 5

Graph 1: Charge vs. Time for Node 1
Graph 2: Charge vs. Time for Node 5
Extending Minimum Lifetime

\[ R_1 + R_2 \]

Node 1

Node 5

\[ R_2 \]

Charge

Time
Extending Minimum Lifetime

\[ \langle R_1, R_2, R_3 \rangle \]
Extending Minimum Lifetime

![Graph showing the relationship between average lifetime and minimum lifetime](image)

- Average Lifetime (years)
- Minimum Lifetime (years)

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Extending Minimum Lifetime
Extending Minimum Lifetime

Average Lifetime (years) vs. Minimum Lifetime (years)
Extending Minimum Lifetime

Multiple Routing Scheme

Single Routing Scheme

Average Lifetime (years)

Minimum Lifetime (years)
Summary

- Multi-objective optimisation of routing schemes to extend battery powered mesh network lifetime
- Novel $k$-shortest path search space pruning enables rapid optimisation
- Dynamic reoptimisation allows recovery from node or link failure
- Novel temporal load balancing to improve performance
- Patent applied for with the IMC Group Ltd.

Current Work

- Find optimum time span for component routing schemes
- Protect a group of nodes