Harmonizing MAC and Routing in Low Power and Lossy Networks

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Outline

• Low power and lossy networks

• MAC and routing interaction

• Analytical model of IEEE 802.15.4 MAC and RPL

• MAC-aware routing metrics

• Experimental validation
Low power and lossy networks (LLNs)

- Networks of embedded devices with limited power, memory, and processing resources wirelessly interconnected.
- Wide range of applications in multi-hop scenarios.
  - Industrial and building automation, smart cities...
- Different applications with different requirements on the same infrastructure.
  - High reliability, low latency, energy efficiency, flexibility...
  - Dynamic routing and channel access.
- Understanding routing and MAC interactions is fundamental for efficient network operations [IETF 6TiSCH WG 2013].
Protocol interactions

- **CoAP** - Constrained Application Protocol
- **IETF RPL** - Routing over low power and lossy networks
  - DODAG (Destination-oriented Directed Acyclic Graph) structure
  - Multipoint-to-point communication
- **Unslotted IEEE 802.15.4 MAC**
  - Random access based on CSMA/CA with binary exponential backoff (BEB)

Diagram:

- Application
  - Traffic generation rate
  - Performance requirements
- Routing
  - Traffic pattern
  - Routing metrics
- MAC
  - Contention level
  - Channel losses
- Physical
  - Link performance
  - End-to-end performance indicators
IEEE 802.15.4 MAC model

**Idle state** → the node is in low power listening mode and it generates a packet with probability $q_i$.

**Backoff state** → the node delays for a random number of backoff units.

**Carrier sensing state** → the node performs a clear channel assessment (CCA).
- Busy channel ($a_i$) → the node increases the backoff exponent and go back to backoff state.
- Clear channel ($1-a_i$) → the node goes to TX state.

**TX state** → the node sends the packet and waits for an ACK
- Packet not acknowledged ($y_{i,j}$) → the node restarts the transmission process.
- Packet acknowledged ($1-y_{i,j}$) → the node returns to idle state and waits for the next packet generation.

After a maximum number of backoffs (m) and retransmissions (n) the packet is discarded.
MAC reliability

- The link reliability $R_{i,j}$ is typically estimated based on the number of received ACKs.

**IDEA:**
- Each node estimates its busy channel probability $a_i$ during the CCA, and the bad link probability $p_{i,j}$ from link quality indicator (LQI) and received signal strength index (RSSI).
- The packet loss probability $\gamma_{i,j}$ is obtained as

$$\gamma_{i,j} = p_{\text{coll},i} + (1 - p_{\text{coll},i})p_{i,j}$$

$$p_{\text{coll},i} = \frac{\alpha_i}{T_s}$$

- Then, the reliability is calculated as

$$R_{i,j} = 1 - p_{cf} - p_{cr}$$

$$p_{cf} = \alpha_i^{m+1} \sum_{k=0}^{n} (\gamma_{i,j}^k (1 - \alpha_i^{m+1}))$$

$$p_{cr} = (\gamma_{i,j} (1 - \alpha_i^{m+1}))^{n+1}$$
Joint MAC and routing model

- The traffic distribution is the solution of a system of flow balance equations

\[ Q = QT + \lambda \]

- \( T \) is the routing matrix such that

\[ T_{i,j} = M_{i,j}R_{i,j} \]

\[ M_{i,j} = \Pr \left[ \pi_{i,j} = \max_{V_h \in \Gamma_i} \pi_{i,h} \right] \]

- Nodes know the value of the metric of candidate parents through local communication (DIO messages).
Routing metrics

- **Reliability / throughput** metrics: distribute the traffic through the paths with the highest successful reception probability / throughput.
  - **ETX** selects the path with the minimum expected number of retransmissions.
- **Load balancing** metrics: distribute the traffic along various paths to maximize the network lifetime.
  - **Back-pressure** routing uses information on local queues and link state.

- The presence of contention based MAC and low data-rates affect the performance of the metrics.
ETX over IEEE 802.15.4

- ETX selects the path with the minimum total expected number of retransmissions (path $V_3-V_1-V_0$).
- The IEEE 802.15.4 MAC sets a maximum number of retransmissions $n$ allowed in each link, and the end-to-end delivery ratio is affected.

<table>
<thead>
<tr>
<th>Path</th>
<th>n=0</th>
<th>n=1</th>
<th>n=2</th>
<th>n=3</th>
<th>n=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_3-V_1-V_0$</td>
<td>50%</td>
<td>75%</td>
<td>87%</td>
<td>93%</td>
<td>97%</td>
</tr>
<tr>
<td>$V_3-V_2-V_0$</td>
<td>39%</td>
<td>74%</td>
<td>89%</td>
<td>96%</td>
<td>99%</td>
</tr>
</tbody>
</table>
Proposed routing metrics

• **R-metric** extend the ETX metric to account for losses due to contention and limited number of retransmissions at MAC layer.
  - Nodes forwards their packets by selecting a parent such that
    \[
    \max_{j \in \Gamma_i} R_{i,j} \cdot R(j) \quad \text{subject to} \quad R_{i,j} \cdot R(j) \geq R_{\min},
    \]
    \[R(i) = R_{i,0}\]
    - The set of candidate receivers is composed by the set of nodes that can guarantee a progress towards the destination, according to RPL.

• **Q-metric** distributes the forwarded traffic to provide load balancing in the network.
  - Nodes forwards their packets by selecting a parent such that
    \[
    \min_{j \in \Gamma_i} P_i Q_j + P_r (Q_j - \lambda_j)
    \]
    \[P_i \quad \text{TX power consumption} \]
    \[P_r \quad \text{RX power consumption} \]
    \[Q_j \quad \text{forwarded traffic} \]
Experimental validation

- The R-metric achieves the best average performance from a network perspective.
- The Q-metric is preferable if a guaranteed reliability is required for all paths in the network (which is desired in LLN applications).
ETX estimates the reliability based on the ACKs received.
R-metric estimates the reliability based on the busy channel probability.
ETX shows larger variability and slower convergence speed.
Reliability

- R-metric maximizes the average and peak end-to-end reliability and outperforms the back-pressure metric.
- Q-metric guarantees a minimum reliability and outperforms the back-pressure metric.
With the Q-metric, the power consumption is balanced among nodes and the maximum consumption, crucial for the network lifetime, decreases of 15% with respect to the R-metric and 10% with respect to backpressure.
Conclusions

- Analytical model of RPL and IEEE 802.15.4 protocol interactions.
- Novel metrics that take into account the combined behavior of MAC and routing:
  - R-metric extends the ETX to maximize the reliability including the effects of contention-based channel access.
  - Q-metric guarantees minimum requirements by balancing the contention level in the network.
- Experimental evaluation
  - Comparison with ETX and back-pressure routing
  - MAC and routing parameter selection.
thanks for the attention
Protocol parameters selection mechanism

- We consider the analytical model of the IEEE 802.15.4 MAC and we let the mechanism select
  - the initial backoff exponent \( m_0 = [3−8] \),
  - the maximum backoff exponent \( m_b = [m_0 −8] \)
  - the maximum number of backoffs \( m = [0−4] \).
- We implement RPL and we let the mechanism choose between R-metric and Q-metric.

The objective is the minimization of the energy consumption subject to reliability and delay constraints.

- The Q-metric is always preferred to the R-metric, whenever the solution is feasible.
- Depending on the constraints, the node energy consumption can be 20\% lower than the consumption with default parameters.
Node performance

- The R-metric tends to distribute the traffic to the dominant node $V_2$.
- With the Q-metric, the maximum power consumption decreases of at least a factor 2 with respect to the R-metric and 70% with respect to backpressure.
R-metric tends to distribute the traffic to the dominant node $V_2$, reducing the level of contention at MAC layer.

Q-metric distributes the traffic uniformly among nodes with lower traffic.

For the proposed scenario, the routes are more stable than the back-pressure approach.