Harmonizing MAC and Routing in Low Power and Lossy Networks

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Outline

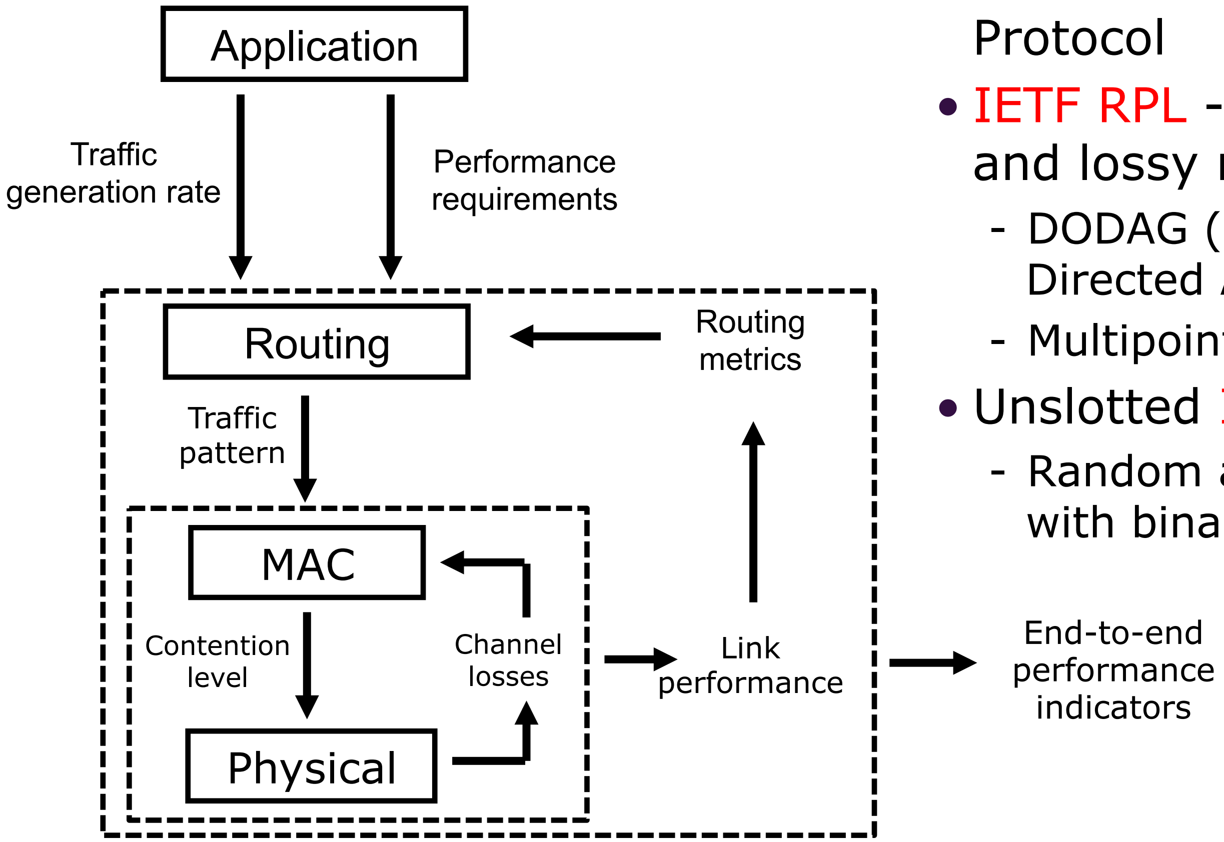
- Low power and lossy networks
- MAC and routing interaction
- Analytical model of IEEE 802.15.4 MAC and RPL
- MAC-aware routing metrics
- Experimental validation

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…

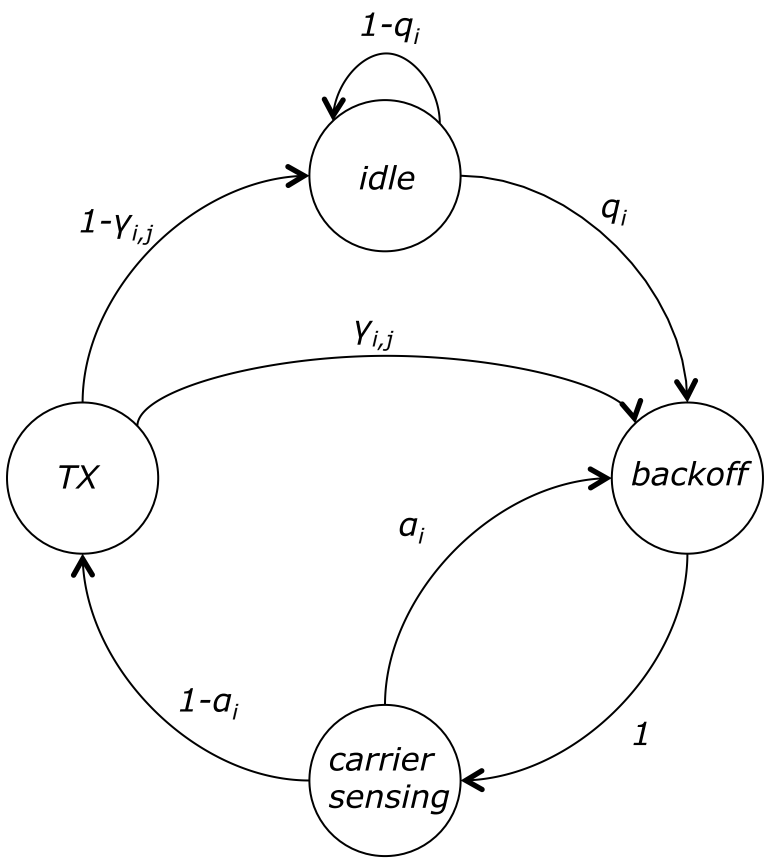
- Different applications with different requirements on the same infrastructure.
  - High reliability, low latency, energy efficiency, flexibility…
  - Dynamic routing and channel access.
- Understanding routing and MAC interactions is fundamental for efficient network operations [IETF 6TiSCH WG 2013].

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)

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 ($1\text{-}a_i$) → the node goes to TX state.

TX state → the node sends the packet and waits for an ACK

- Packet not acknowledged ($\gamma_{i,j}$) → the node restarts the transmission process.
- Packet acknowledged ($1\text{-}\gamma_{i,j}$) → 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 α_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

$$\gamma_{i,j} = p_{\mathrm{coll},i} + (1 - p_{\mathrm{coll},i})p_{i,j} \qquad p_{\mathrm{coll},i} = \alpha_i / T_s$$

collision probability

- Then, the reliability is calculated as

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

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

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

Joint MAC and routing model

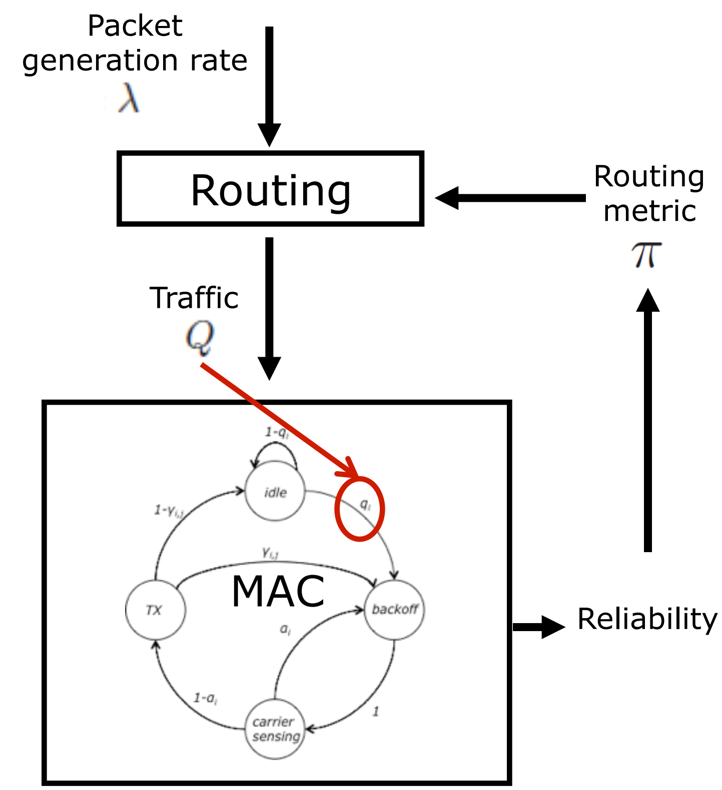
- The traffic distribution is the solution of a system of flow balance equations

$$Q = Q\,\mathrm{T} + \lambda$$

- T is the routing matrix such that

$$\begin{aligned} T_{i,j} &= M_{i,j} R_{i,j} \\ M_{i,j} &= \Pr\left[\pi_{i,j} = \max_{V_h \in \Gamma_i} \pi_{i,h}\right] \end{aligned}$$

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

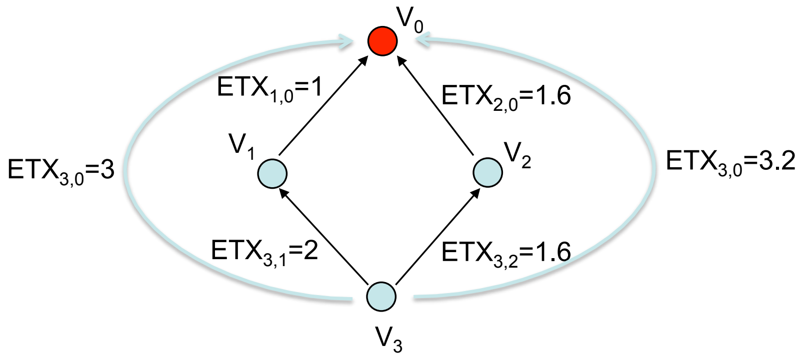


Routing metrics

- 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 re-transmissions *n* allowed in each link, and the end-to-end delivery ratio is affected.

End-to-end delivery ratio

	n=0	n=1	n=2	n=3	n=4
Path V_3-V_1-V_0	50%	75%	87%	93%	97%
Path V_3-V_2-V_0	39%	74%	89%	96%	99%

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

$$\underset{j \in \Gamma_i}{\text{maximize}} \quad R_{i,j} \cdot R(j) \qquad\qquad R(i) = R_{i,0}$$

  - 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

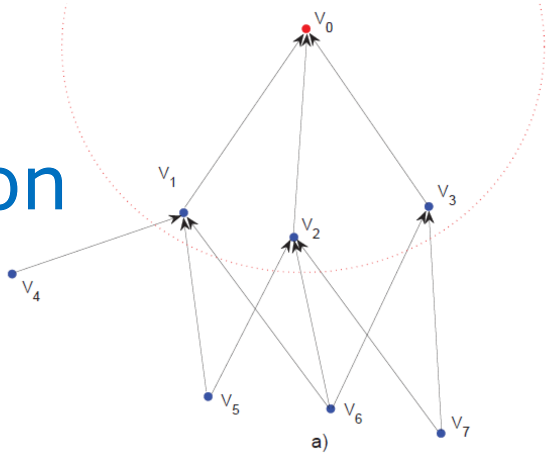
$$\begin{aligned} \underset{j \in \Gamma_i}{\text{minimize}} \quad & P_t Q_j + P_r (Q_j - \lambda_j) \\ \text{subject to} \quad & R_{i,j} \cdot R(j) \geq R_{\min}\,, \end{aligned}$$

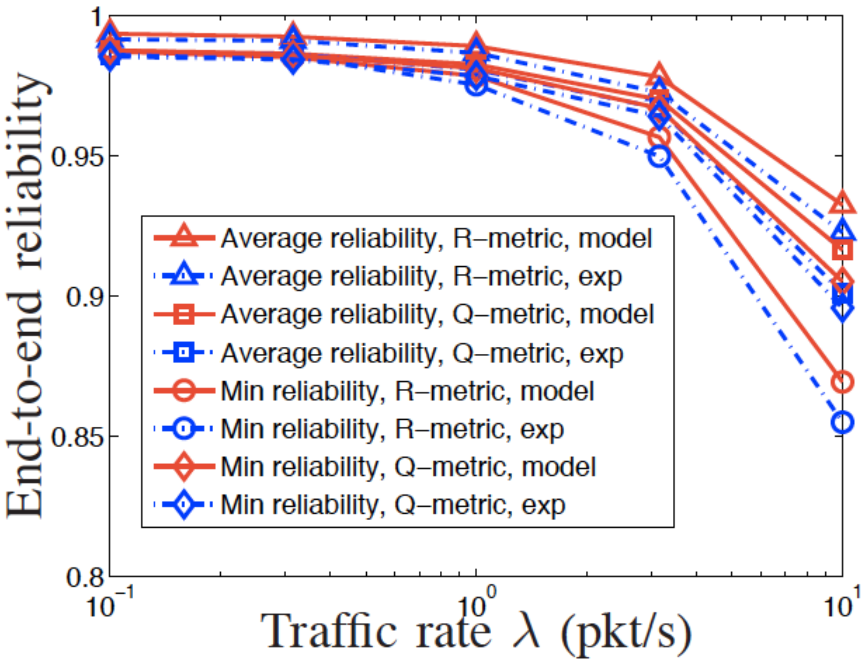
P_t TX power consumption

P_r RX power consumption

Q_j forwarded traffic

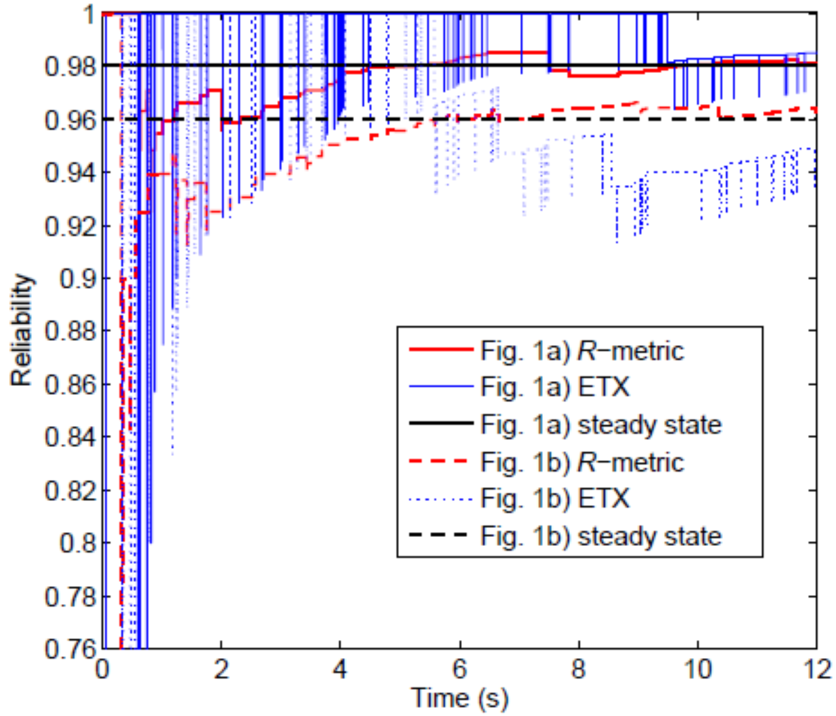
Experimental validation

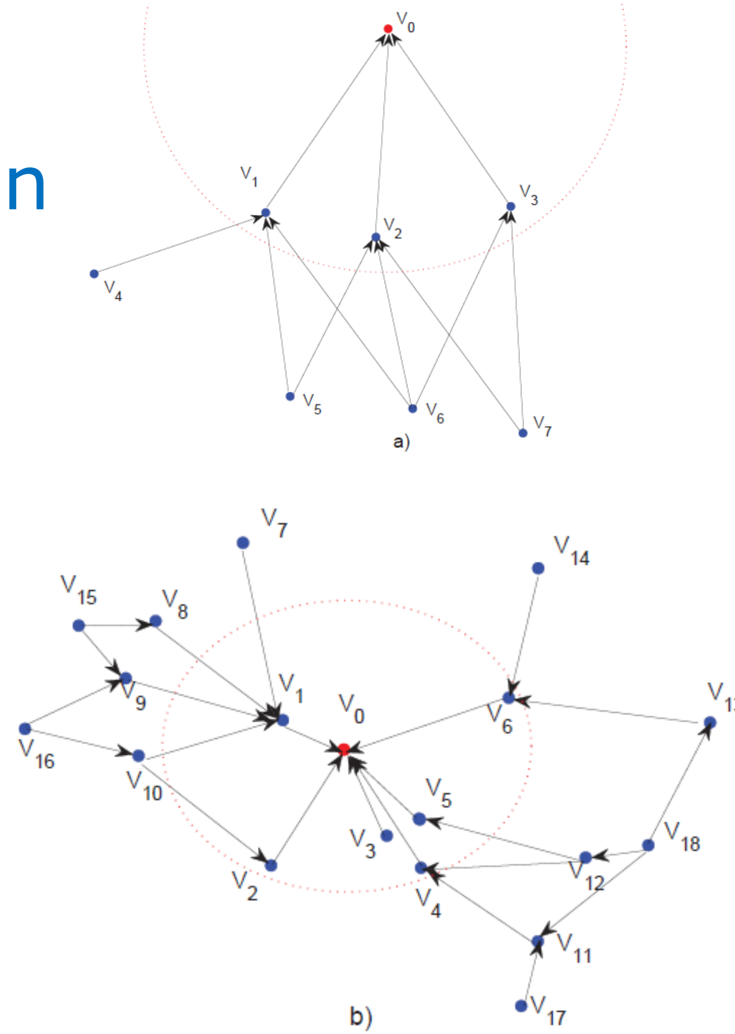




- The R-metric achieves the best average performance from a network perspective.
- The Q-metric is preferable if a guaranteed reliability is required for all paths in the network (which is desired in LLN applications).

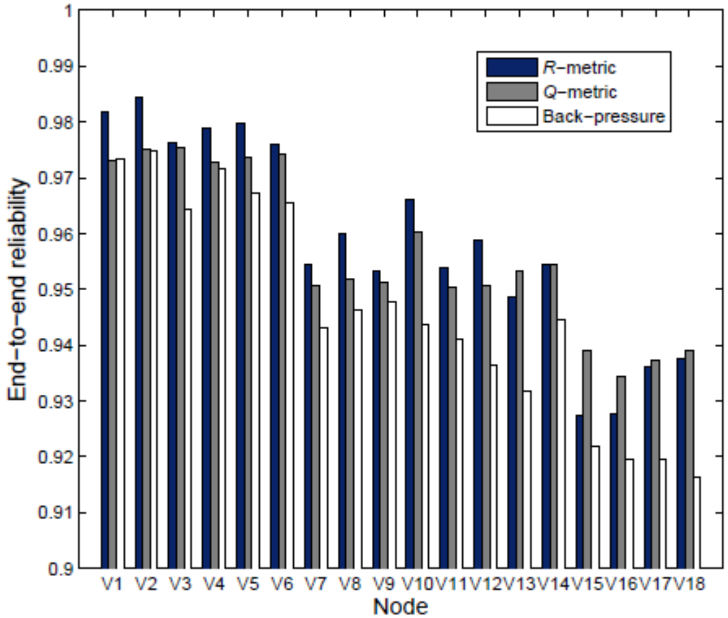
Reliability estimation

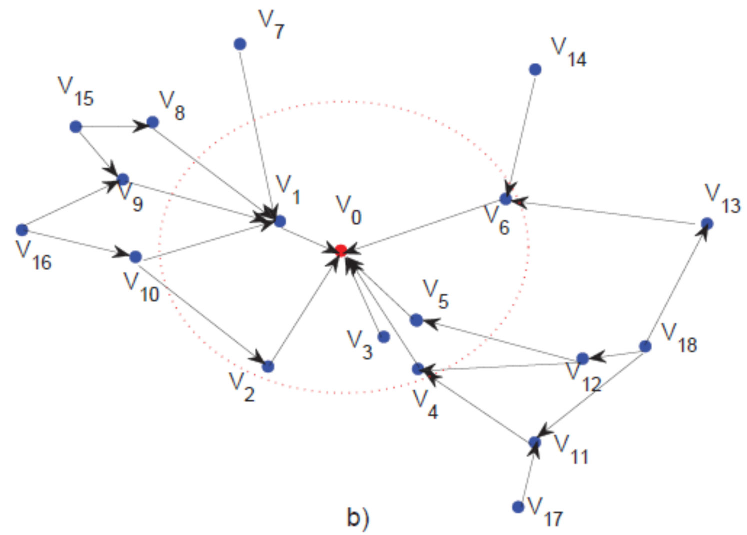




- ETX estimates the reliability based on the ACKs received.
- R-metric estimates the reliability based on the busy channel probability.
- ETX shows larger variability and slower convergence speed.

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.

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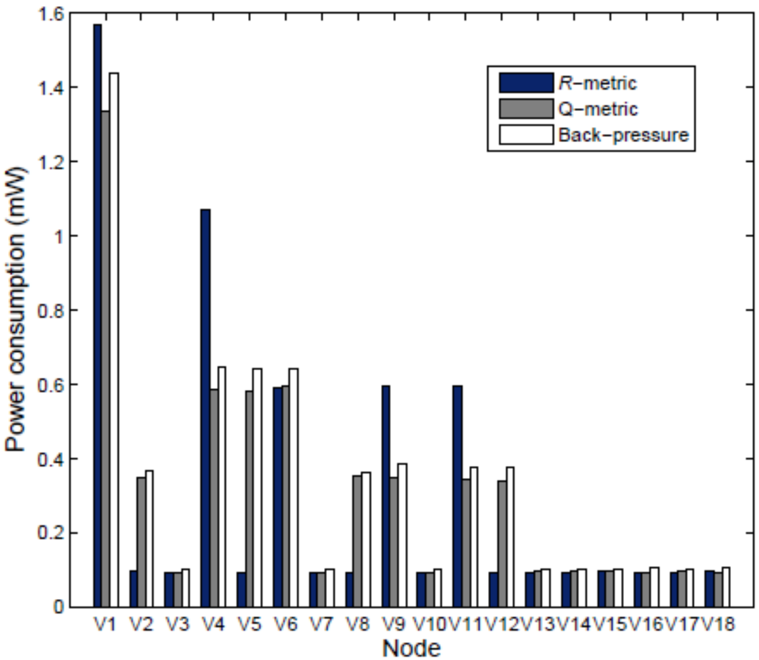
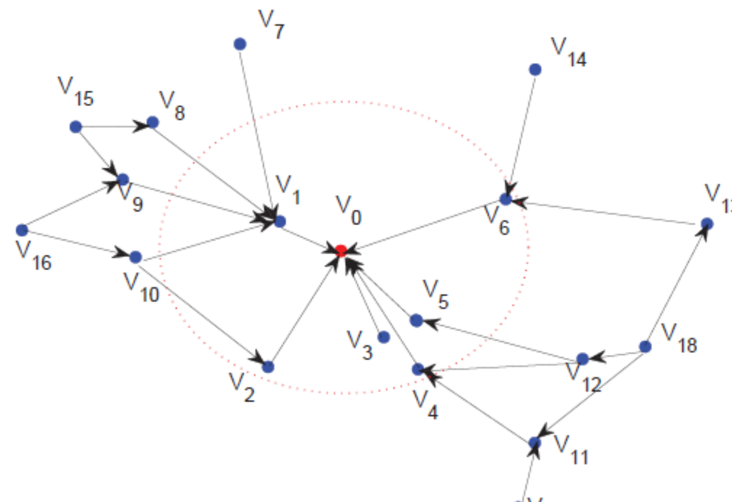
Power consumption





b)

- 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.

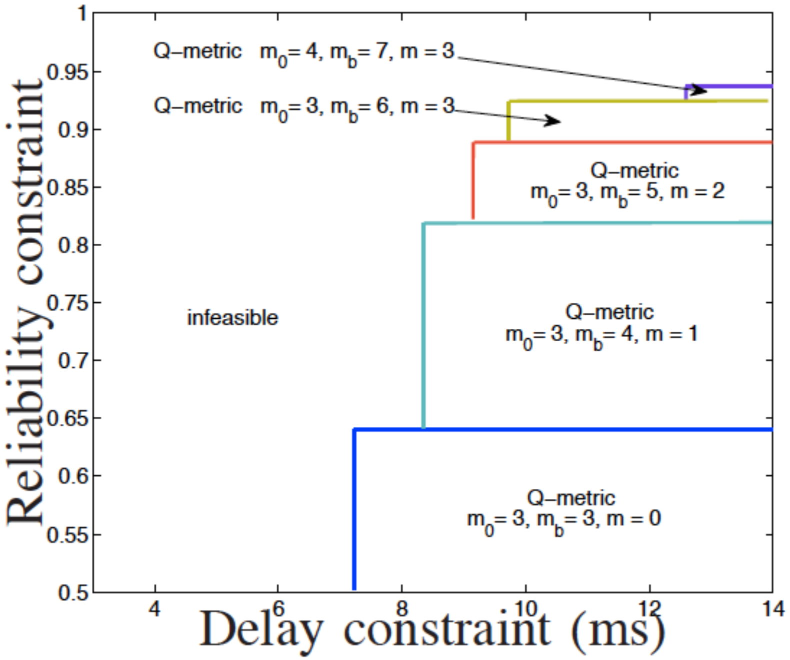
Conclusions

- 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.

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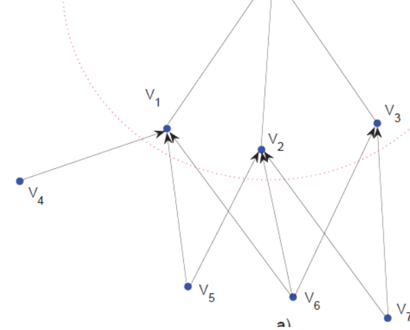
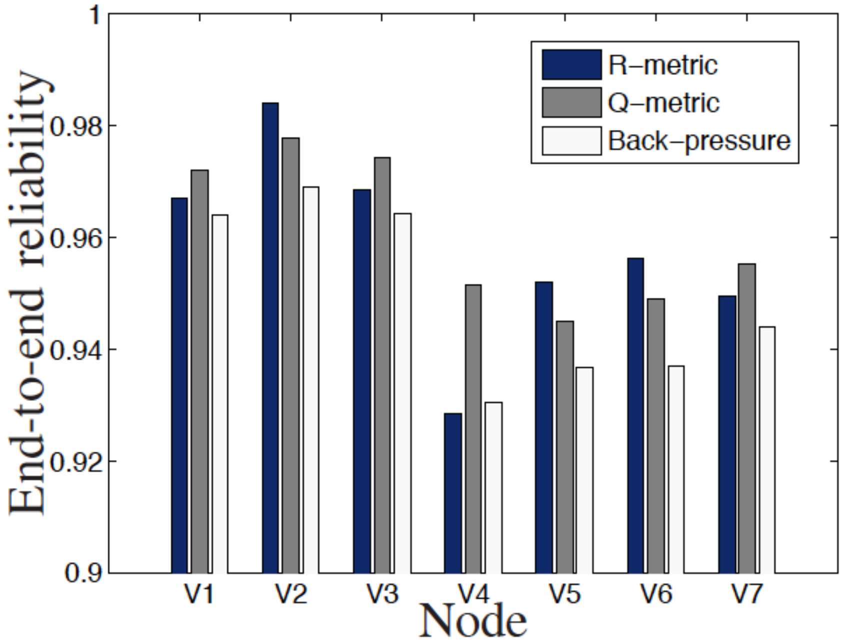
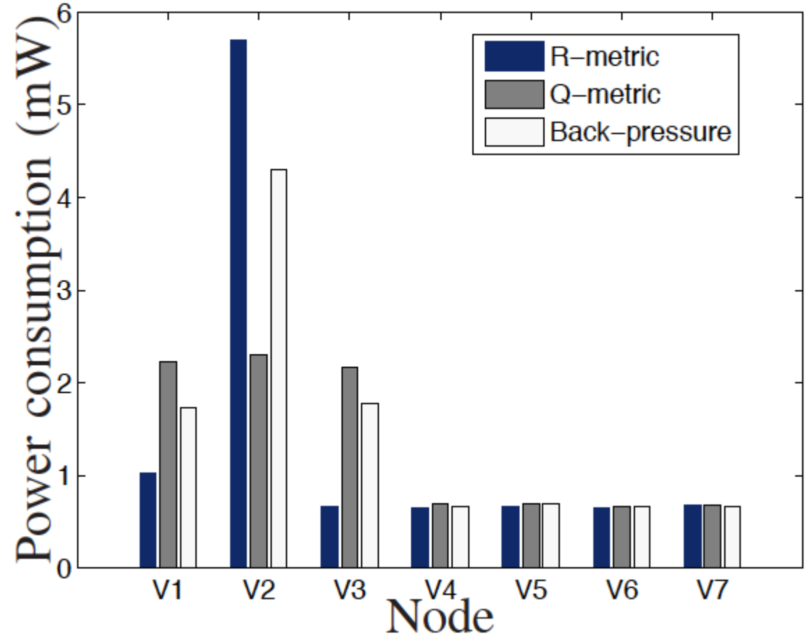
Node performance



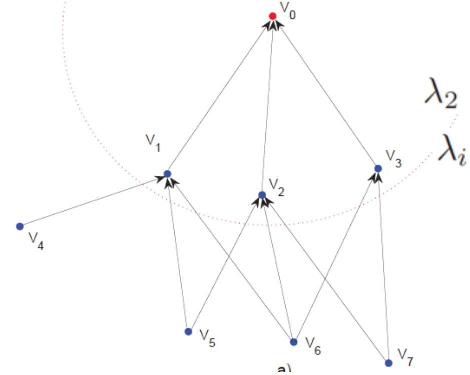
$$\lambda_2 = 20 \text{ pkt/s}$$
$$\lambda_i = 10 \text{ pkt/s}$$
$$i \neq 2$$





- 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.

Stability



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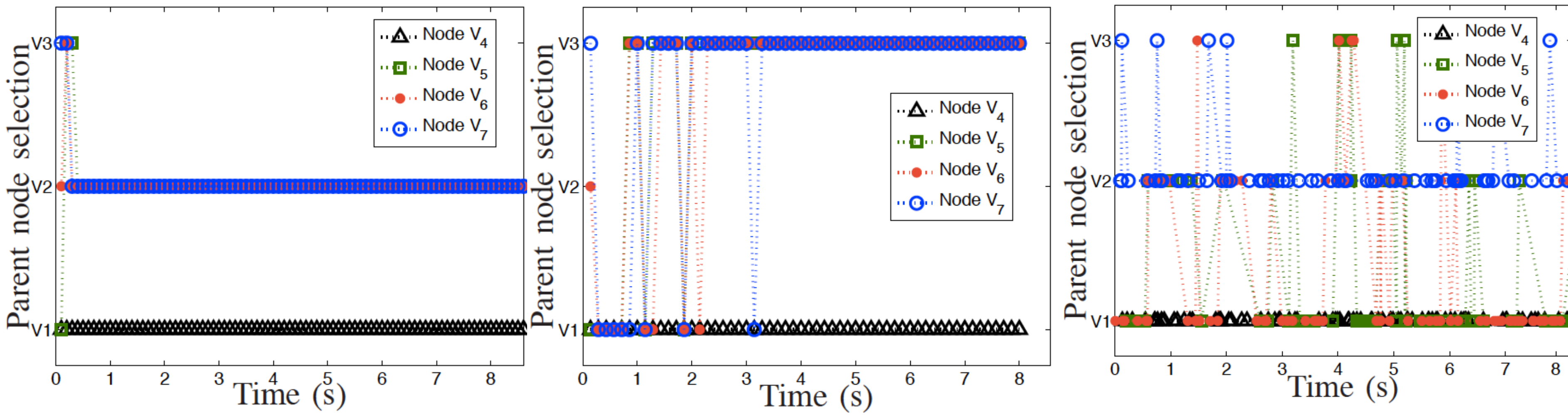

(a) R-metric (b) Q-metric (c) Back-pressure

- 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.