Time-triggered communication protocols modeling IEEE 802.15.4/ZigBee

Experimental evaluation in:

Hanzálek, Z. - Jurčík, P.: Energy efficient scheduling for cluster-tree Wireless Sensor Networks with time-bounded data flows: application to IEEE 802.15.4/ZigBee. IEEE Transactions on Industrial Informatics. doi: 10.1109/TII.2010.2050144, Volume 6, Number 3, Pages 438 - 450, August 2010.

Cyclic Scheduling

Algorithm representation by **oriented graph *G:***

- vertex ~ instruction ~ task
- arc ~ precedence relation
- arc height h_{ij} ~ shift of the iteration index
- arc length l_{ij} ~ **positive (input-output latency) and negative (deadline) time lags**

for k=1 **to** N **do**

T_1: $a(k) = X(k) - c(k-2)$

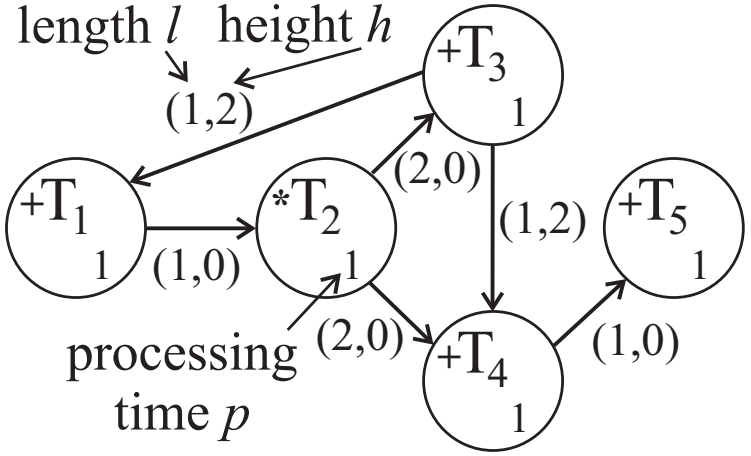
T_2: $b(k) = a(k) * \alpha$

T_3: $c(k) = b(k) + X(k)$

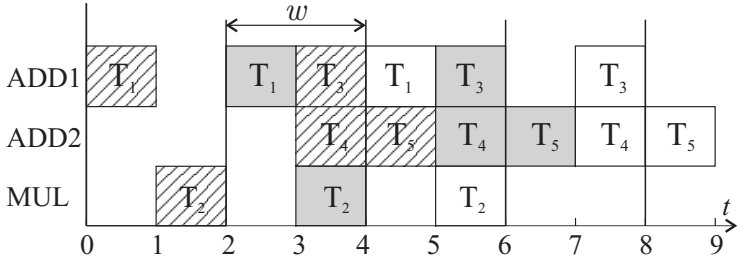
T_4: $d(k) = b(k) + c(k-2)$

T_8: $Y(k) = X(k-1) + d(k)$

end



Objective: to find an overlapped periodic schedule with the **minimum period** (**NP-hard**)



New Application - WSN

To find a static schedule for static Wireless Sensor Network (IEEE 802.15.4/ZigBee) which specifies when the clusters are active while:

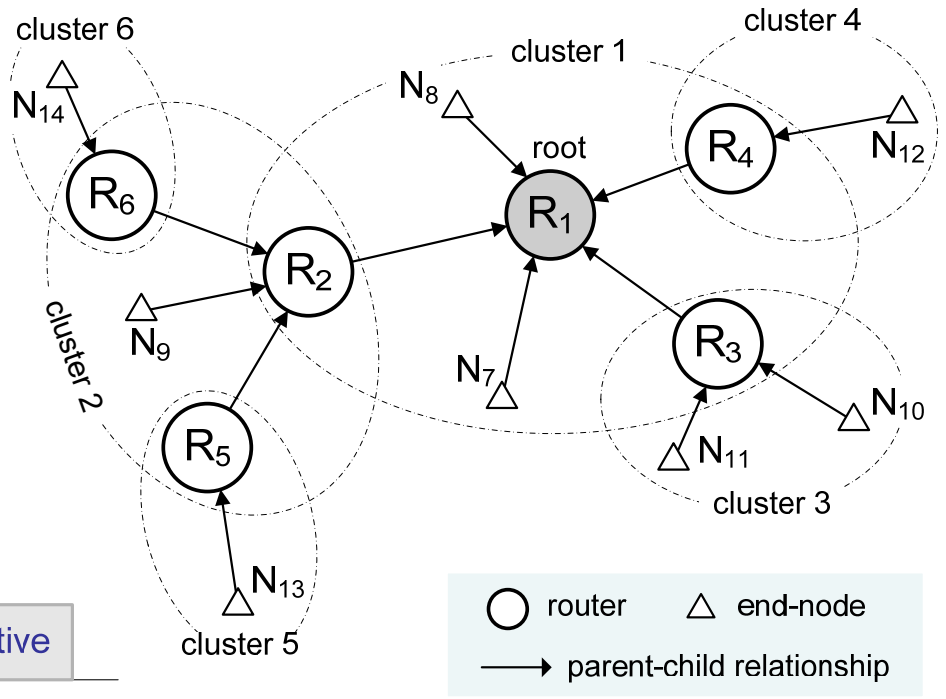
- communicating all data flows
- avoiding possible cluster collisions
- meeting all data flows' end-to-end deadlines
- minimize the energy consumption of the nodes

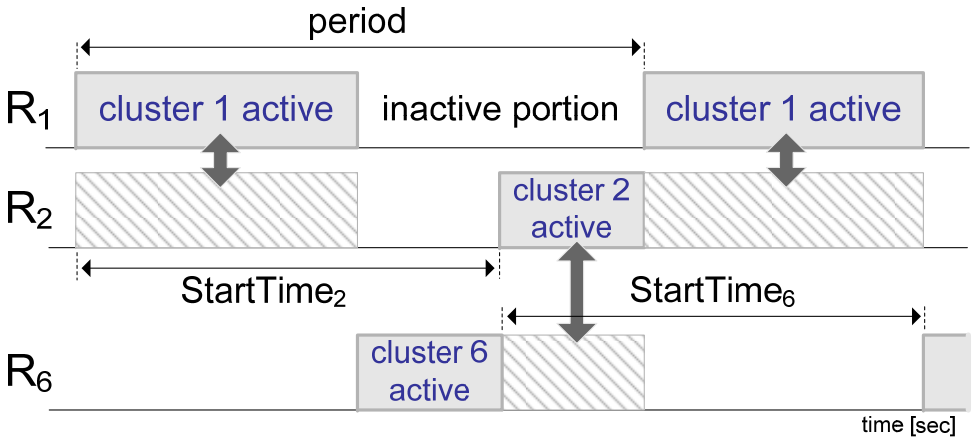
Cluster-Tree Sensor Networks

- Koubaa, A. Cunha, M. Alves, and E. Tovar, "TDBS: a time division beacon scheduling mechanism for ZigBee cluster-tree wireless sensor networks," Real-Time Systems Journal, 2008. – uniform flows – topological order

Cluster-tree topology

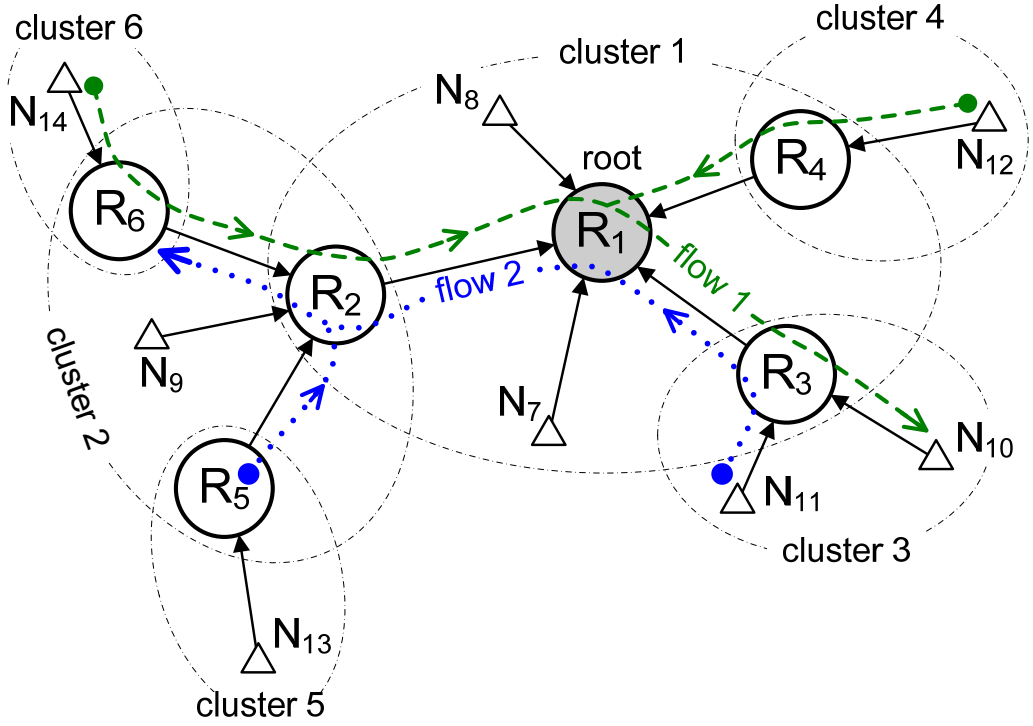
- static wireless sensor networks (WSNs)
  - cluster-tree topology
    - in-tree
    - deterministic routing
- cluster
  - star sub-network
  - cluster-head
  - active & inactive portions
- collision domains





Data flow model

- data flows
  - predefined
  - time-bounded
  - multi-source mono-sink
  - periodic data
  - parameters: [flow 1]
    - sources [N14, N12]
    - sink [N10]
    - required period [0.4]
    - sample size [64]
    - end-to-end deadline [0.2, 0.1]

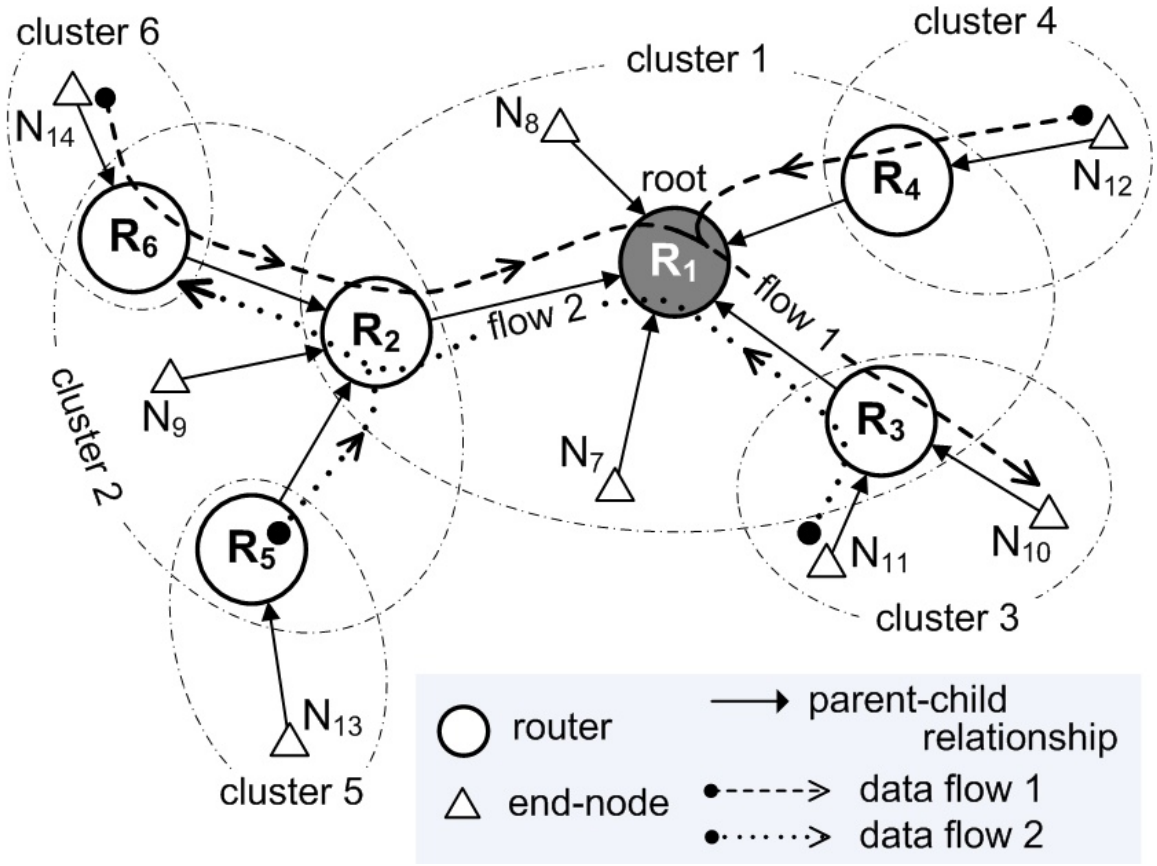


- communication errors
  - bounded number of retransmissions

Time-bounded data flows

Problem is to find a periodic schedule which specifies when the clusters are active while:

- communicating all data flows
- avoiding possible cluster collisions
- meeting all data flows' e2e deadlines



flow ID	sources	sink	*e2e_deadline*		*req_period*	*sample_size*	*sample_ack*
			[sec]	[ptu]	[sec]	[bit]	
1	$\{N_{12}, N_{14}\}$	N_{10}	$\{0.05, 0.61\}$	$\{52, 635\}$	0.5	64	0
2	$\{R_5, N_{11}\}$	R_6	$\{0.01, 0.75\}$	$\{10, 781\}$	1	16	0

Cyclic nature of the scheduling problem

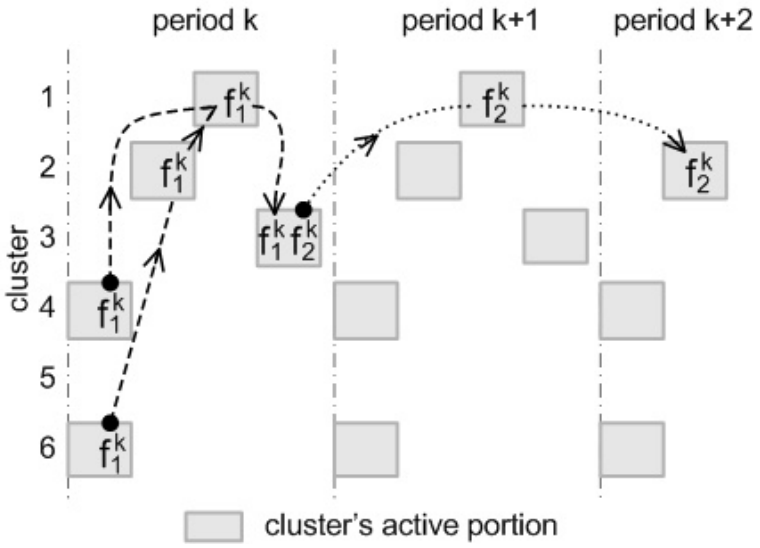
One wave of the flow may go over several periods

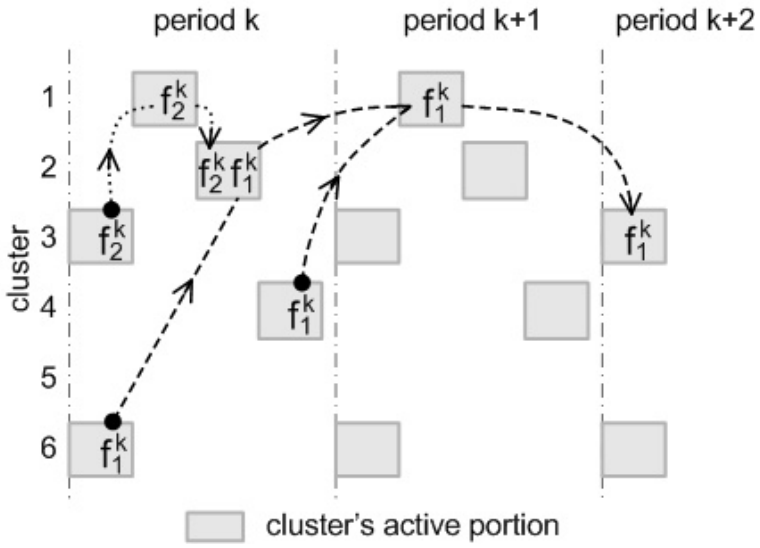
$$s_i = \hat{s}_i + \hat{q}_i \cdot \mathrm{BI}$$

start time of the occurence

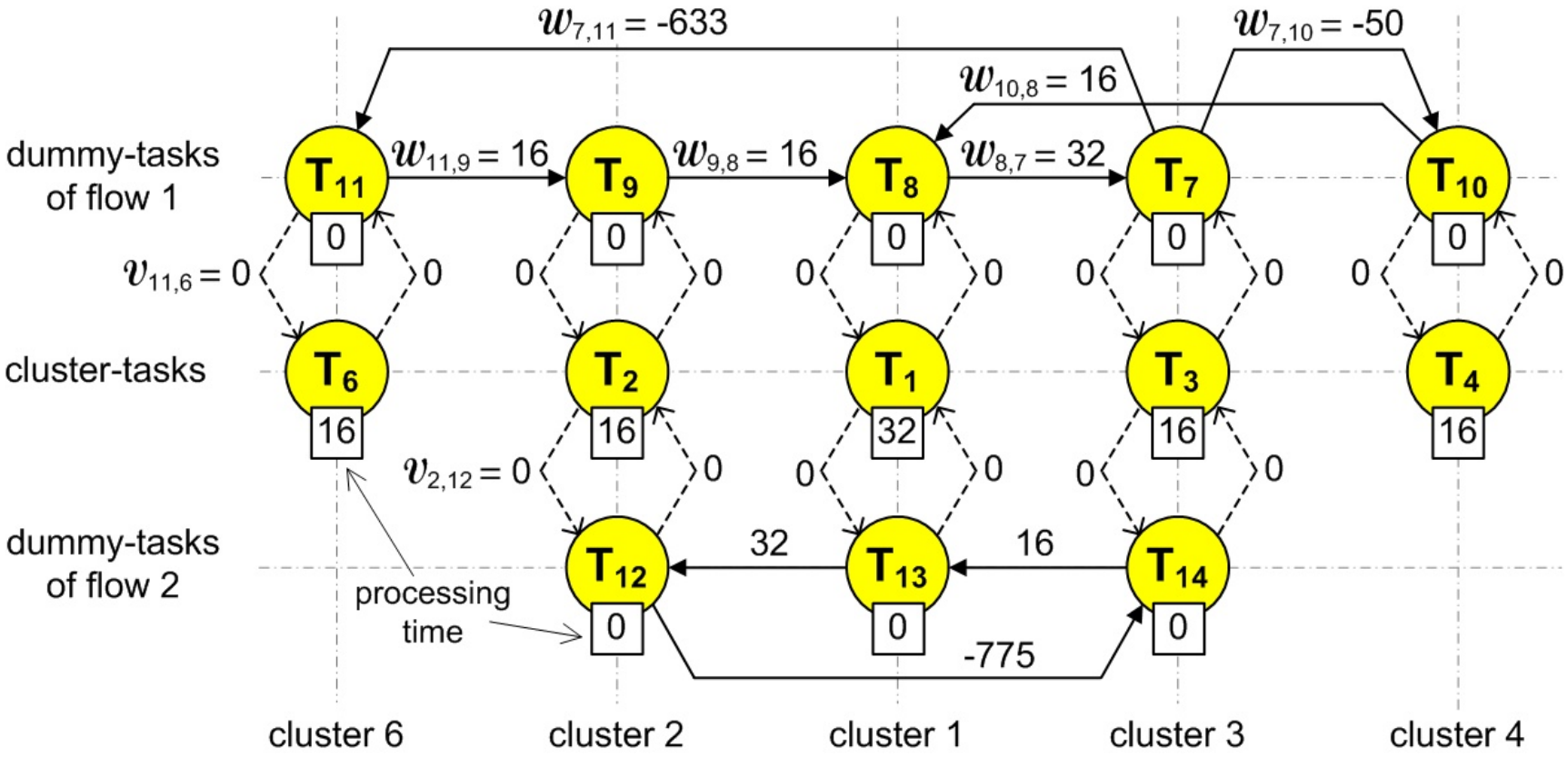
It is cyclic scheduling problem due to the three aspects:

- the cluster is active only once during the period, i.e. all the flows in a given cluster are bound together
- the flows are deadline constrained
- the flows have opposite directions





Graph of the tasks



precedence constraints - positive edges

negative edges – end-to-end deadlines

synchronization with cluster task - core constraints - dashed edges

ILP formulation
cyclic extension of PSm,1|temp|C_{max}

$$\min \sum_{i=1}^{n} \hat{s}_i + \hat{q}_i \cdot \mathrm{BI} \tag{8}$$

subject to:

$$\hat{s}_j + \mathrm{BI} \cdot \hat{q}_j - \hat{s}_i - \mathrm{BI} \cdot \hat{q}_i \geq w_{ij} \qquad \forall (i,j); i \neq j, w_{ij} \neq -\infty \tag{9}$$

$$\hat{s}_j - \hat{s}_i \geq v_{ij} \qquad \forall (i,j); i \neq j, v_{ij} \neq -\infty \tag{10}$$

$$\hat{s}_i - \hat{s}_j + \mathrm{BI} \cdot x_{ij} \geq p_j \qquad \forall \{i,j\} \in \mathcal{M}; i < j \tag{11}$$

$$\hat{s}_i - \hat{s}_j + \mathrm{BI} \cdot x_{ij} \leq \mathrm{BI} - p_i \qquad \forall \{i,j\} \in \mathcal{M}; i < j \tag{12}$$

where: $\hat{s}_i \in \langle 0, \mathrm{BI} - p_i \rangle$; $\hat{q}_i \geq 0$; $\hat{s}_i, \hat{q}_i \in \mathbb{Z}$; $x_i \in \{0,1\}$

Pseudo code of the TDCS algorithm

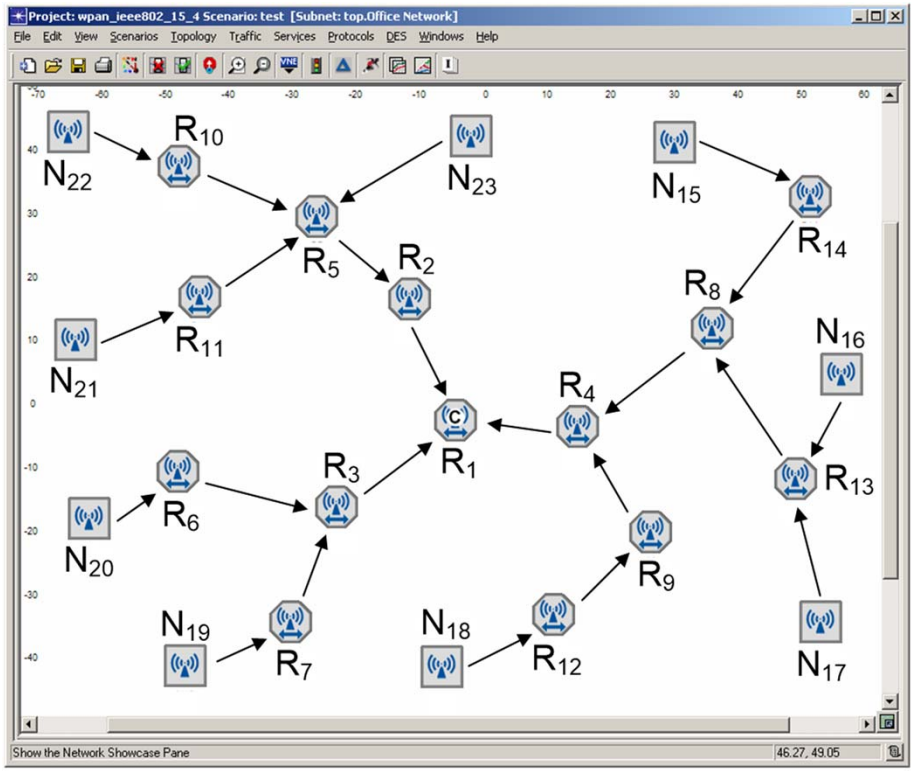
```
(BO, SO, StartTime, GTS_params) = TDCS(C, A, flows)
01 begin
02   (BO_min, BO_max, p, SO, V, W, GTS_params) =
                                   init(C, A, flows)
03   BO = BO_min
04   while BO ≤ BO_max
05     (ŝ, q̂, feasible) = ilp_solve(V, W, BO, p)
06     if feasible
07       BO = BO + 1
08     else
09       break
10     end
11   end
12   /* calculate the StartTime parameter
                              of each cluster */
13   StartTime = config_params(ŝ, BO)
14 end
```

A – adjacency matrix of cluster-tree topology;
C – matrix of collision domains

Simulation study

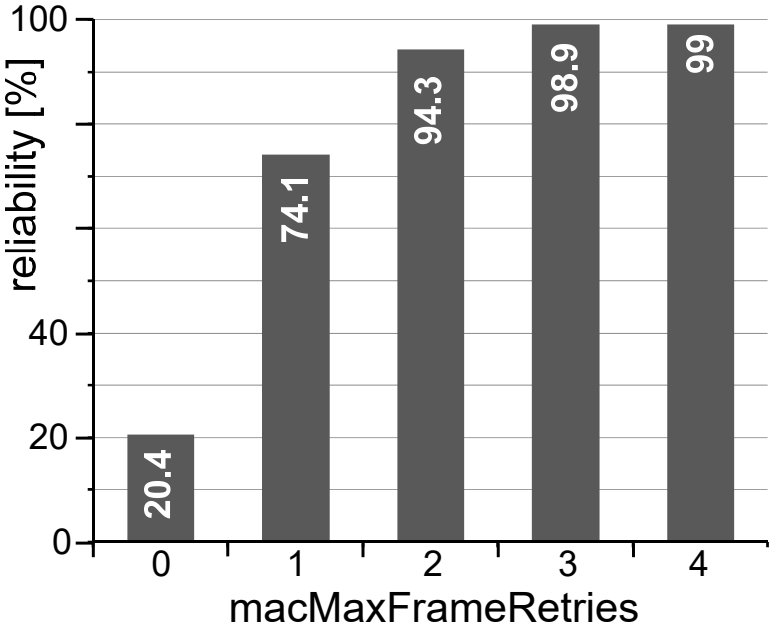
- How the maximum **number of retransmissions** impacts the **reliability** of data transmission, **energy** consumption of the nodes, **end-to-end** communication delay in IEEE 802.15.5 cluster-tree WSN?

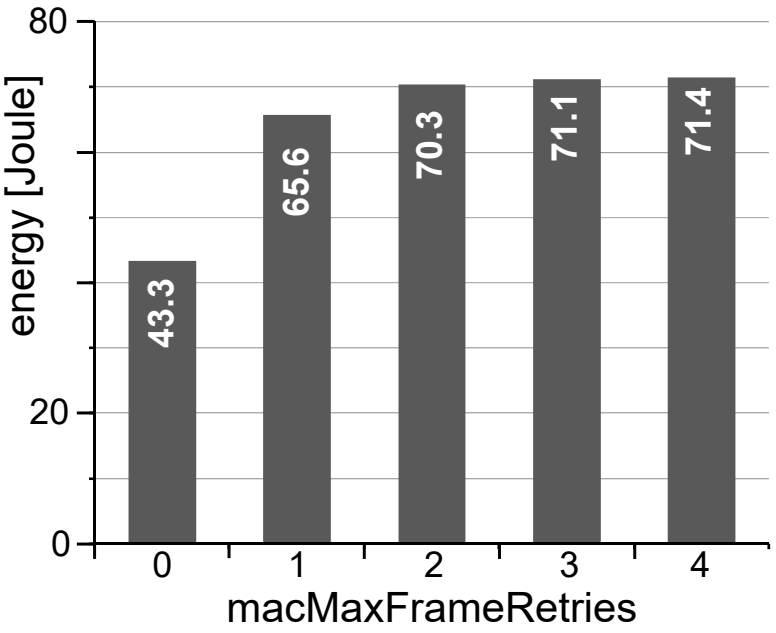
- setup
  - 14 clusters
  - 23 TelosB motes
  - 3 data flows
  - homogenous channel
  - error rate = 20%
  - one run = 20 minutes



Impact of number of retransmissions on reliability and energy

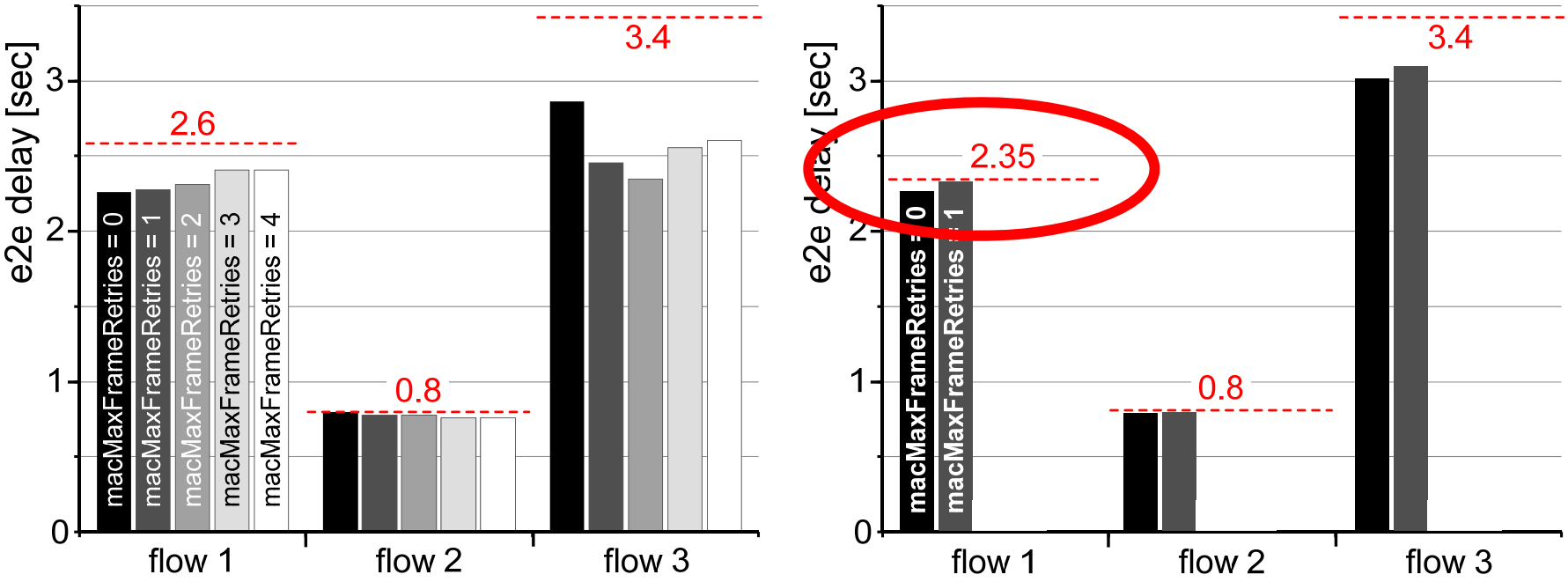
- reliability = dispatched frames/received frames
- sum of the energy consumption of all nodes





Number of max retransmissions given by required end-to-end delay

Maximum e2e delay as a function of the maximum number of retransmissions



- flow 1
  - e2e deadline = 2.6 sec leads to *macMaxFrameRetries* = 4
  - e2e deadline = 2.35 sec leads to *macMaxFrameRetries* = 1