Probabilistic estimation of End-to-End Path Latency in Wireless Sensor Networks

C. Ferry, M. Zoveralli[1]

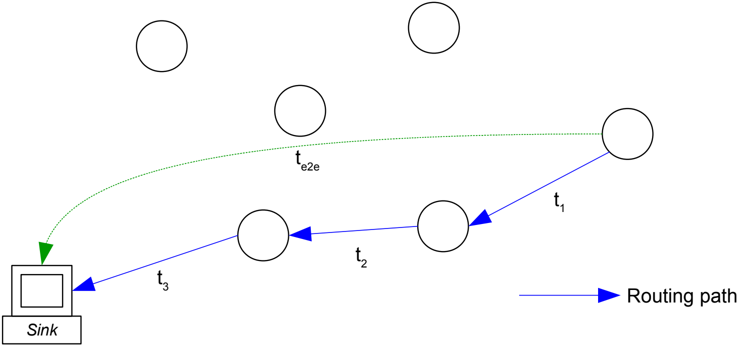
[1]Faculty of Computer Sciences and Communications
École polytechnique fédérale de Lausanne

May 22, 2017

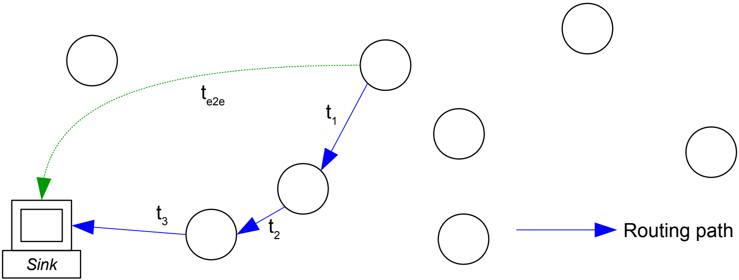
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Outline

Wireless Sensor Networks



Wireless Sensor Networks



Notion of timeliness

- The notion of timeliness defines a framework to guarantee **quality of service**
- Guarantees provided :
  - Time bounds for arrival between nodes, for each packet
  - Level of confidence
  - Quality of service indicator
- This doesn't fit WSNs...
  - Energy limits data rate
  - Its constraints are too strong

Related work

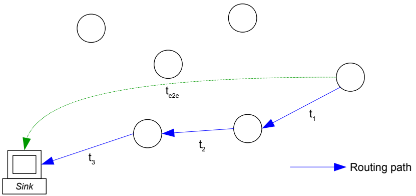
- O. Chipara [3], T. He [5], A. Sahoo [8] : assumptions on message speed and topology of the network to deduce hop number limits
- K. Karenos [6], L. Abeni [2], E. Felemban [4] : probailistically computed deadlines are strictly enforced by dropping out-of-time packets
- S. Gobriel [7] : use of TDMA (shedule construction), does not fit error-prone and mobile environments
- T. Abdelzaher [1] : exact computation of arrival times is not possible with WSNs

Outline

Outline

Hypotheses and constraints

- Our goal : a probabilistic estimation of the end-to-end latency
- WSN-related assumptions :
  - Packets dropped if their end-to-end deadline isn't met
  - No full connectivity, thus no bounded delays
  - Limited computational resources on each node
  - Variable network conditions (topology)
- We will do statistical analysis at each node instead



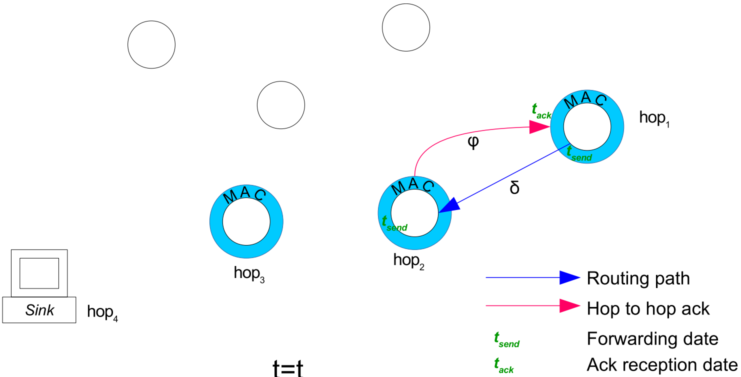
Requirements

- Performance should be achievable
  - i.e. applications should be have lighter demands than per-message
- The model should be more fine-grained than « success / failure »
  - i.e. we want a continuous function that models the probability of success
- A confidence indicator should be given with the estimated deadlines

Definitions

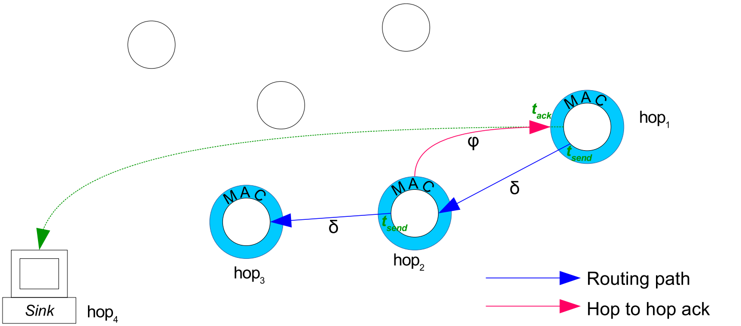
- Regular timeliness
  - applies to individual messages
  - sets hop-by-hop deadlines
- Generalized notion of timeliness
  - applies to a **sequence of messages** M
  - each sequence M has a **runtime interval** $[t_i, t_j]$ with **confidence** $p \in [0, 1]$ on its bounds
  - the **end-to-end delay** is a distribution function D_{e2e}

Wireless sensor networks (2)



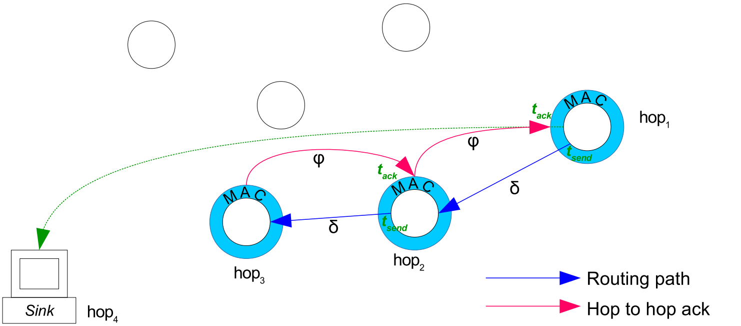
$t = t_{send}$

Wireless sensor networks (2)



$$t = t_{send} + \delta$$

Wireless sensor networks (2)



$t = t_{send} + \delta + \varphi = t_{ack}$ Thus $\delta = t_{ack} - t_{send} - \varphi$

Outline

Simple case : One single hop

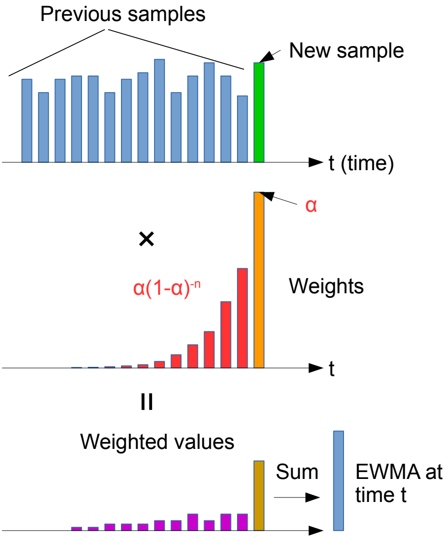
- The path $(\text{hop}_1, \text{hop}_2)$ is run with δ_{hop_1}
- Thus $D_{e2e} = \delta_{\text{hop}_1}$
  - D_{e2e} is a **random variable**
  - Assumption : D_{e2e} has a mean μ and a variance σ
  - We estimate with samples : mean $\overline{x}$, variance $\overline{s}^2$
- Exponential Weighted Moving Average estimator :

$$\overline{x}_t = \alpha\delta_t + (1-\alpha)\,\overline{x}_{t-1} \quad \overline{s}_t^2 = \tfrac{\alpha}{2-\alpha} s_t^2$$

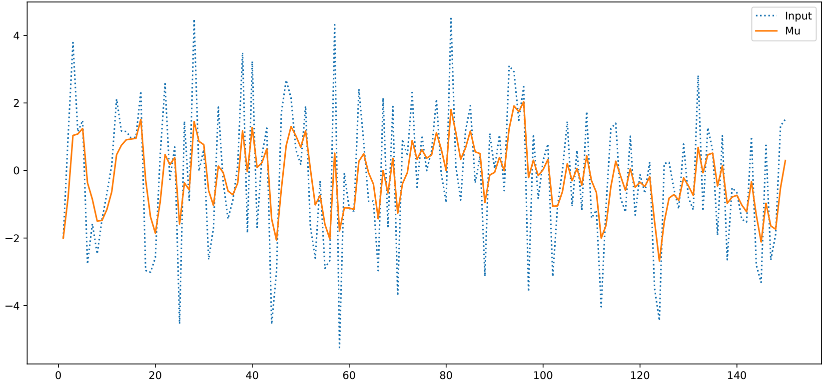
- EWMA requires no sample history

$$\begin{cases} \overline{x}_{t+1} = \alpha\delta_{t+1} + (1-\alpha)\,\overline{x}_t \\ s_{t+1}^2 = \tfrac{t}{t+1} s_t^2 + \tfrac{1}{t}\left(\delta_{t+1} - \overline{x}_{t+1}\right)^2 \end{cases}$$

Exponential Weighted Moving Average



Exponential Weighted Moving Average



Outline

General case : k-hop path

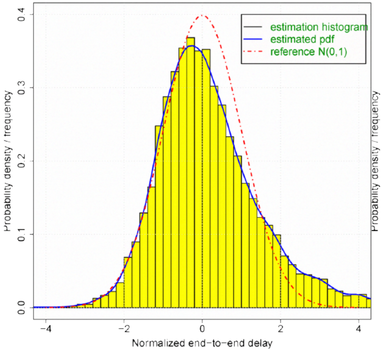
- We rely on the **central limit theorem**
- Suppose that we have a large number of samples of D_{e2e} : $(D_k)_{k=1\ldots N}$
- When $N \to \infty$, $\sum_{k=1}^{N} D_k = D_{rp} \sim \mathcal{N}\left(\mu, \sigma^2\right)$ for some μ, σ
    - By the CLT, μ is the same as the estimate from the samples
    - This is also valid for σ
- Hypotheses :
    - Quasi-independence of the samples of (D_{e2e})
    - All D_{e2e} samples follow the same distribution

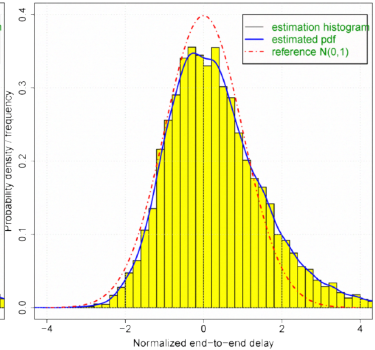
Outline

Experiment parameters

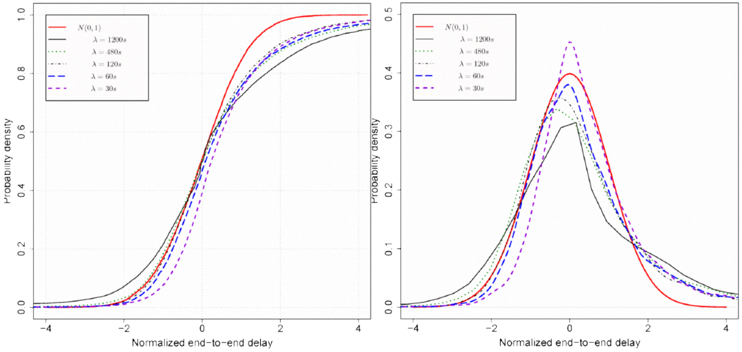
- Path length : $|rp| = 5, 10$
- One message sent into the network every $T = 30$ s
- Cross-traffic follows a Poisson distribution with $\lambda \in \{30 \text{ s}, 60 \text{ s}, 120 \text{ s}, 480 \text{ s}, 1200 \text{ s}\}$
- Distance between nodes : uniformly distributed in $[8 \text{ m}, 20 \text{ m}]$

Experimental results

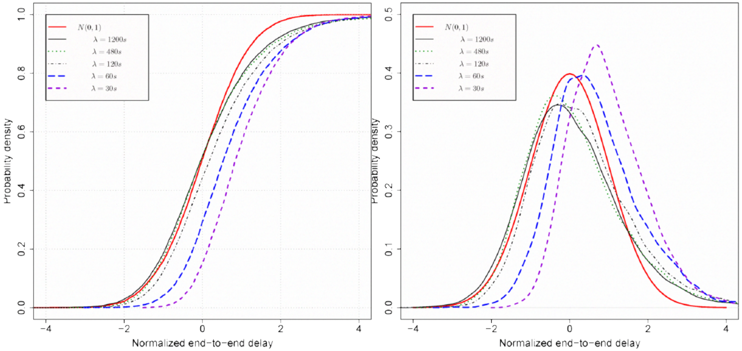




Experimental results



Experimental results (continued)



Experimental results (continued)

λ N(0,1)	I_1 (68%)	I_2 (27%)	I_3 (4.2%)	I_4 (0.2%)
30	66.5% (-1.5)	21.5% (-5.5)	6.8% (+2.6)	5.2% (+5)
60	62.2% (-5.8)	24.6% (-2.4)	7.1% (+2.9)	6.1% (+5.9)
120	61.1% (-6.9)	27.1% (+0.1)	7% (+2.8)	4.8% (+4.6)
480	53.3% (-14.7)	27% (=)	8% (+3.8)	7.7% (+7.5)
1200	50.8% (-17.2)	25.6%(-1.4)	11.9% (+7.7)	11.8% (+11.6)

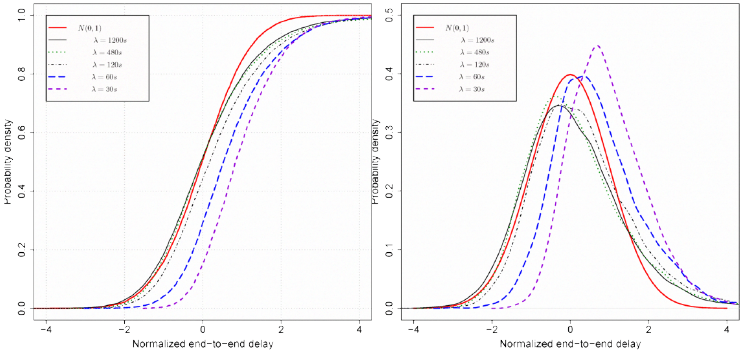
TABLE I
PERCENTAGE OF HITS PER σ-INTERVAL WITH PATH LENGTH 5. IN BRACKETS, DEVIATION WITH RESPECT TO $N(0,1)$.

λ N(0,1)	I_1 (68%)	I_2 (27%)	I_3 (4.2%)	I_4 (0.2%)
30	55.7% (-12.3)	30.1% (+3.1)	11% (+6.8)	3.2% (+3)
60	62.4% (-5.6)	24.9% (+2.1)	9.2% (+5)	3.5% (+3.3)
120	62% (-6)	27.1% (+0.1)	7.4% (+3.2)	3.6% (+3.4)
480	61.4% (-6.6)	28.5% (+1.5)	6.9% (+2.7)	3.2% (+3)
1200	60.7% (-7.3)	28.9% (+1.9)	7.6% (+3.4)	2.8% (+2.6)

TABLE II
PERCENTAGE OF HITS PER σ-INTERVAL WITH PATH LENGTH 10. IN BRACKETS, DEVIATION WITH RESPECT TO $N(0,1)$.

Discussion

- Heavy tail on PDFs / CDFs : the estimator gives good results, but...



Discussion

- Wrong formula on EWMA variance : if $s_t^2 = \sum_{i=0}^{t} x_i^2 - \frac{1}{t}\left(\sum_{i=0}^{t} x_i\right)^2$ then

$$s_{t+1}^2 = s_t^2 + \frac{t}{t-1}\left(\delta_t - \overline{x_t}\right)$$

- Determination of α : we have no quantitative metric
  - We'd like to compensate the « noise » (imprecision on measurement)
  - But at the same time, keep track of the time variations

Outline

Conclusion and further work

- **Probabilistic** approach to end-to-end time estimation
- Expense : no single-hop per-message deadline (but **per-group end-to-end**)
- Gain : **two models** (single-hop, multi-hop)
- Things that could be added :
    - Handling missed ACK packets
    - A clearer method for assessing α in EWMA

Bibliography I

T.F. Abdelzaher, S. Prabh, and R. Kiran.
On real-time capacity limits of multihop wireless sensor networks.
In *25th IEEE International Real-Time Systems Symposium*. IEEE.

L. Abeni and G. Buttazzo.
QoS guarantee using probabilistic deadlines.
In *Proceedings of 11th Euromicro Conference on Real-Time Systems. Euromicro RTS99*. IEEE Comput. Soc.

O. Chipara, Z. He, G. Xing, Q. Chen, X. Wang, C. Lu, J. Stankovic, and T. Abdelzaher.
Real-time power-aware routing in sensor networks.
In *200614th IEEE International Workshop on Quality of Service*, pages 83–92, June 2006.

Bibliography II

E. Felemban, Chan-Gun Lee, E. Ekici, R. Boder, and S. Vural.
Probabilistic qos guarantee in reliability and timeliness domains in wireless sensor networks.
In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.* IEEE.

Tian He, J.A. Stankovic, Chenyang Lu, and T. Abdelzaher.
SPEED : a stateless protocol for real-time communication in sensor networks.
In *23rd International Conference on Distributed Computing Systems, 2003. Proceedings.* IEEE.

Kyriakos Karenos and Vana Kalogeraki.
Real-time traffic management in sensor networks.
In *2006 27th IEEE International Real-Time Systems Symposium (RTSS06)*. IEEE, 2006.

Bibliography III

D. Mosse S. Gobriel, R. Cleric.
Adaptations of tdma scheduling for wireless sensor networks.
Proceedings of the 7th International Workshop on Real-time Networks (RTN), 2008.

Anirudha Sahoo and Prashant Baronia.
An energy efficient MAC in wireless sensor networks to provide delay guarantee.
In *2007 15th IEEE Workshop on Local & Metropolitan Area Networks*. IEEE, jun 2007.