Modèles pour le calcul du délai pire-cas de communication dans les réseaux IoT industriels

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Wireless networking and real-time

- Wireless multi-hop networks are appealing to real-time industry
  - It can carry soft real-time flows
  - Versatile deployment and scalability
  - Reduces weight
- But : real-time applications necessitate <u>delay guarantees</u>
  - Critical flows have to arrive within a fixed delay bound.

Manufacturing (FAL)
Skywise
(~ 1sec.)
Flight test
(128 Hz ~ 7.8ms)
Avionics (down to 1ms)

Mature technologies and protocols

- Multiple access methods
  - TDMA: a time-triggered approach
    - high determinism, but reduced scalability in number of nodes
    - WirelessHART, ISA100.11a, IEEE802.15.4e,…
  - CSMA/CA: an event-triggered approach
    - non-determinism, but high scalability in number of nodes
    - suffers from heavy load
    - IEEE802.11 DCF, S-MAC, F-MAC, RTXP, …
  - Combination of both
    - IQueueMac, MaCARI, IEEE802.15.4, ContikiMAC…

Worst-case delay for wireless

- Deterministic bounds
  - Network calculus: sensor network calculus [Schmitt & Roedig, 05]
    - Perfect TDMA, no losses, perfect synchronization
  - Model checking
    - Link error probabilities [Mouradian & Augé-Blum, 14], but scaling still an issue
- Probabilistic bounds
  - Probabilistic network calculus [Fidler, 06]
    - Gilbert-Elliott channel model and moment generating functions
  - Reliability calculus [He et al., 10]
    - Stochastic network model and Laplace transform
  - Process mining to retrieve a Markov chain for ContikiMAC [Despaux et al., 14]

Worst-case delay for wireless

- Calculating the worst-case delay (WCD) for wireless is complicated
- It has to account for :
  - A valid and realistic PHY layer channel model
  - Fine-grained MAC protocol model that accounts for PHY layer model
    - Cross-layer interactions : MAC decisions impact channel model
  - Routing / forwarding decision for end-to-end flows

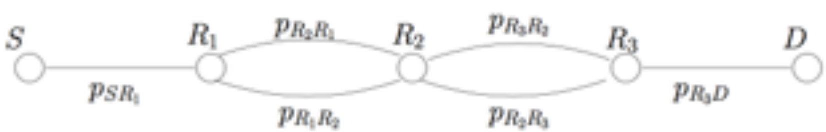
- In this talk, a small piece of this complex problem is investigated:
  - Two probabilistic models for WCD calculation for TDMA and CSMA/CA are introduced
    - They account for a link channel probability
    - Assume a basic TDMA / legacy CSMA/CA DCF protocol
  - Both bounds are compared and validated by extensive simulations

Outline

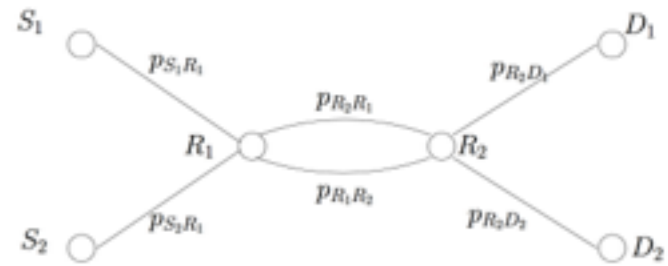
- System model and protocols
  - For CMSA/CA
  - For TDMA
- Probabilistic worst case delay definition
- Analytical delay distribution and worst-case delay models
  - For CMSA/CA
  - For TDMA
- Results for investigated topologies
- Conclusions

System models and protocols

- Considered multi hop / multi flow topologies



(a) 3-relay/1-flow topology

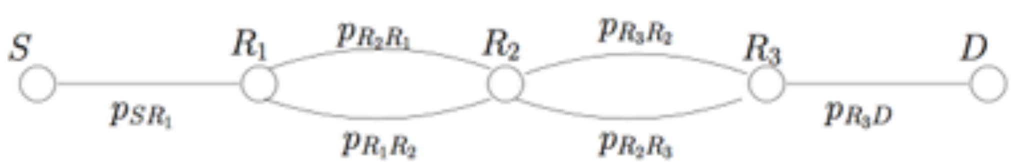


(b) 2-relay/2-flow topology

- Periodic flows
  - Packet emission rate is controlled to have a single packet in the queue at all times
  - Only MAC delay, no queuing delay
  - MAC delay : time for a frame to access the channel

System model for CSMA/CA

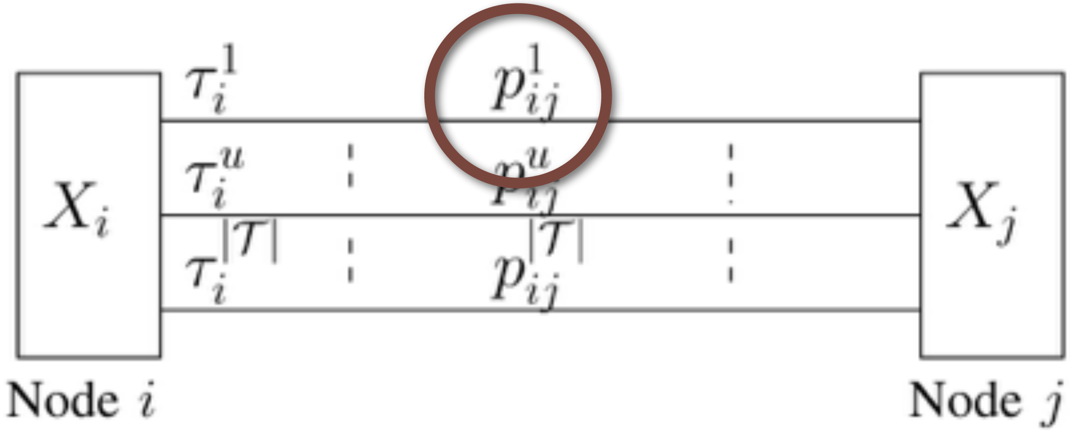
- IEEE802.11 DCF protocol
  - RTS/CTS mechanism
- N stationary nodes constantly contending for channel
  - Worst case scenario
  - N nodes include the nodes of considered topologies
  - For instance, if N=5, we assume there are
    - 2 additional nodes emitting at the same time than R1, R2 or R3,
    - and 3 more nodes at the same time than S.



(a) 3-relay/1-flow topology

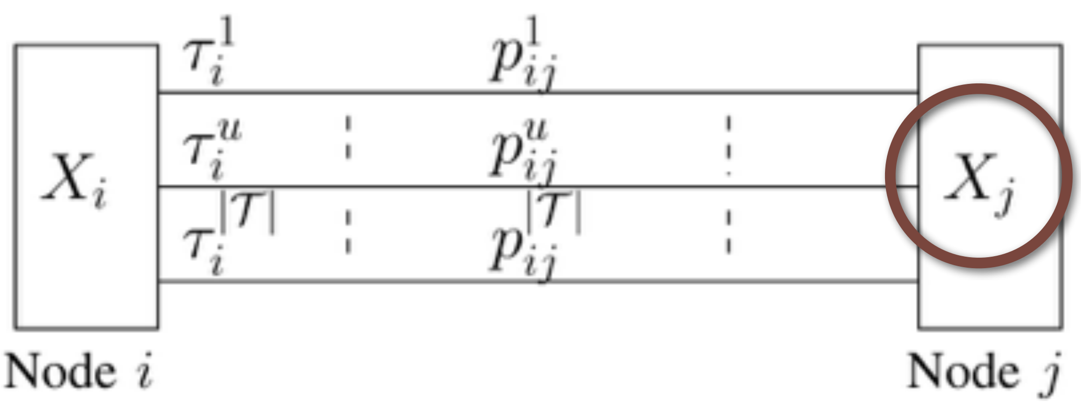
System model for TDMA

- A perfectly synchronized TDMA
  - A frame of |T| time slots
  - At most one packet emitted per frame
  - Channel model :
    - packet error probability p_{ij}^u between nodes *i* and *j*, in time slot u



System model for TDMA

- A perfectly synchronized TDMA
  - Channel model :
    - packet error probability p_{ij}^{u} between nodes *i* and *j*, in time slot u
  - Forwarding decisions :
    - forwarding probability x_{ij}^{uv} probability node *j* emits on slot *v* a packet coming from *i* on slot *u.*

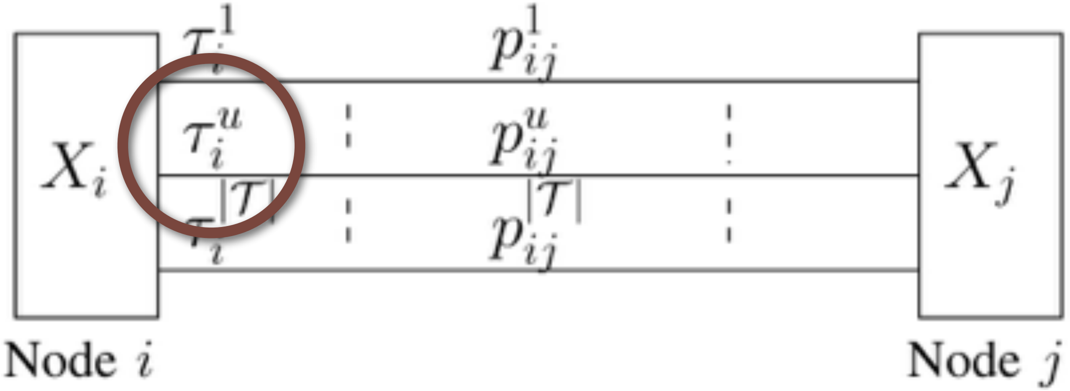


$$\sum_v x_{ij}^{uv} \leq 1$$

Node *j* re-emits message of *j* in slot *u* at most once in next frame

System model for TDMA

- A perfectly synchronized TDMA
  - Channel model :
    - packet error probability p_{ij}^{u} between nodes *i* and *j*, in time slot u
  - Forwarding decisions :
    - forwarding probability x_{ij}^{uv} decision to send to node *j* in slot *v* a packet coming from *i* on slot *u.*
  - Emission rate :
    - emission rate defined for each slot τ_j^v
    - if τ_j^v = 0,5 node emits a packet every two frames in slot v.



$$\sum_v x_{ij}^{uv} \leq 1$$

Node *j* re-emits message of *j* in slot *u* at most once in next frame

System model for TDMA

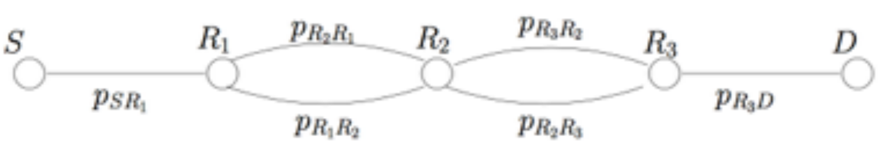
- Cross-layer constraint
  - Emission rates are required to calculate the packet error probability
  - This emission rate τ_j^v depends on the emission rates of neighbor nodes, and incoming link packet error probabilities
- Flow conservation at each node

$$\sum_{(i,j)\in\overrightarrow{\mathcal{N}_j^u}} \sum_{u\in\mathcal{T}} \tau_i^u P_{ij}^u x_{ij}^{uv} = \tau_j^v$$

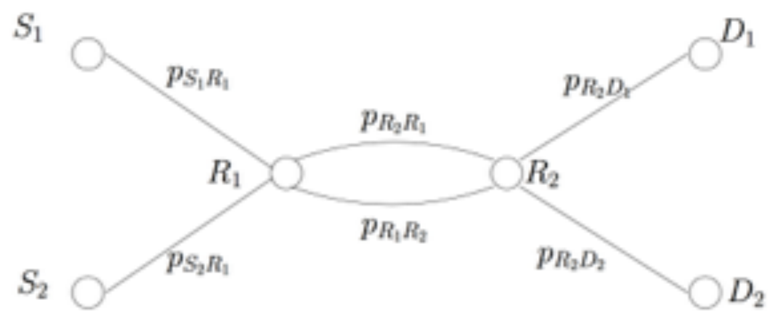
- Forwarding probabilities can be optimized
  - s.t. flow conservation constraints (at all nodes, all slots)
  - Metrics : average delay minimization, average energy minimization, maximum capacity

TDMA model for our topologies

- Packet error probability:
  - AWGN channel + BPSK
- Memory at each node:
  - 1-packet size memory per slot



(a) 3-relay/1-flow topology



(b) 2-relay/2-flow topology

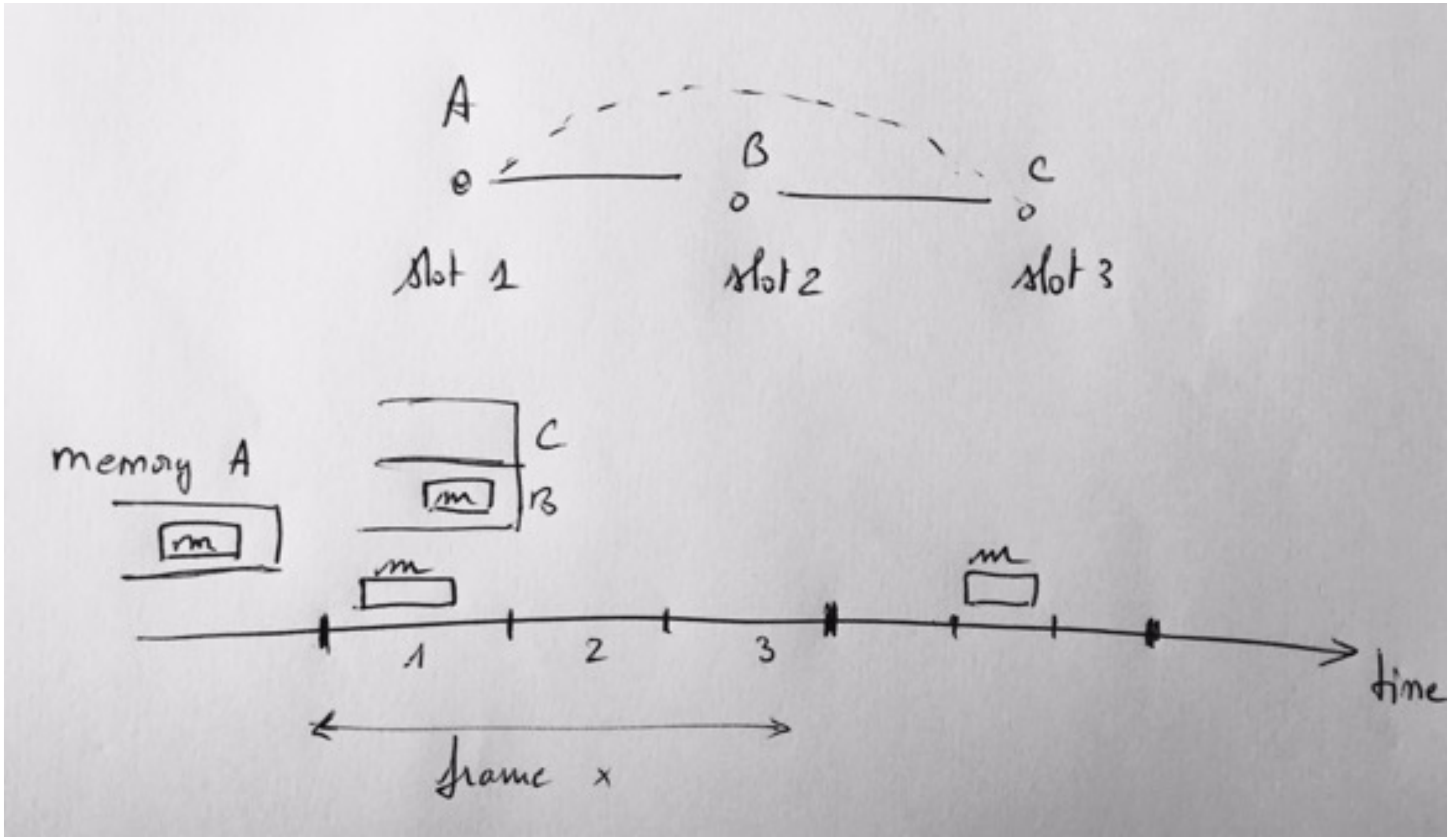
- A frame of 4 time slots
  - S emits in slot 1,
  - R1 emits in slot 2,
  - R2 emits in slot 3,
  - R3 emits in slot 4.
- A frame of 4 time slots
  - S1 emits in slot 1,
  - S2 emits in slot 2,
  - R1 emits in slot 3,
  - R2 emits in slot 4.

TDMA scheduling algorithm

Algorithm 1 TDMA scheduling algorithm of relay node j in time slot u.

```
if memory of slot u not empty then
    Send the packet;
else
    if Relay j receives a packet p from i in slot u then
        Generate a random value x ∈ [0, 1];
        for each time slot v ∈ T do
            if v==1 and forwarding decision x ≤ x_ij^{u1} then
                Store the packet p into memory of slot 1;
            else
                if forwarding decision x_ij^{u(v-1)} ≤ x ≤ x_ij^{uv} then
                    Store the packet p into memory of slot v;
                end if
            end if
        end for
    end if
end if
```

Example

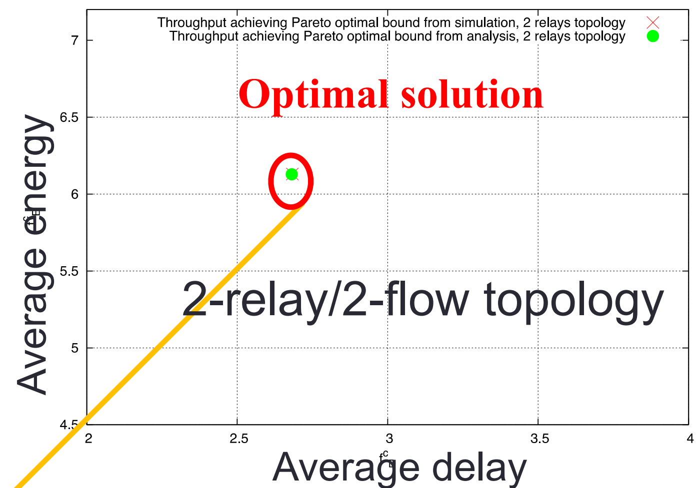


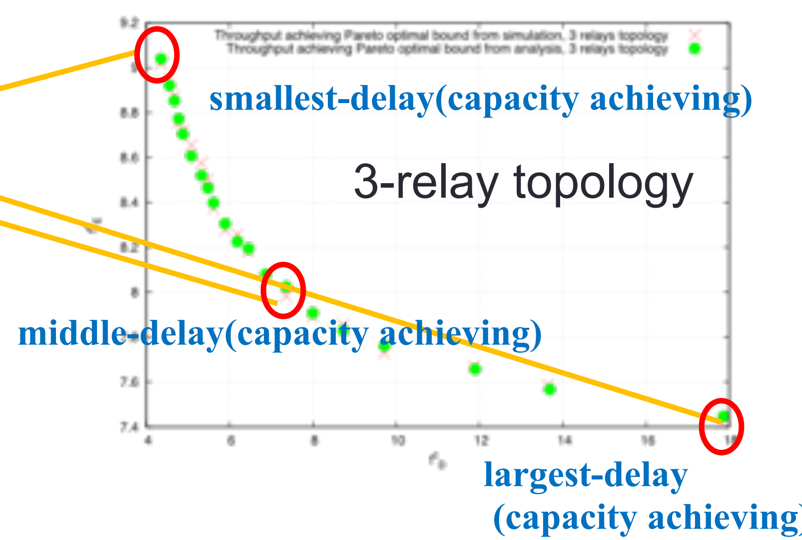
Delay and energy optimization

Optimisation for capacity-achieving average delay and energy criteria

Algorithm 1 TDMA scheduling algorithm of relay node j in time slot u.

if memory of slot u not empty **then**
  Send the packet;
else
  if Relay j receives a packet p from i in slot u **then**
    Generate a random value $x \in [0, 1]$;
    for each time slot $v \in \mathcal{T}$ **do**
      if v==1 **and** forwarding decision $x \leq x_{ij}^{u1}$ **then**
        Store the packet p into memory of slot 1;
      else
        if forwarding decision $x_{ij}^{u(v-1)} \leq x \leq x_{ij}^{uv}$ **then**
          Store the packet p into memory of slot v;
        end if
      end if
    end for
  end if
end if



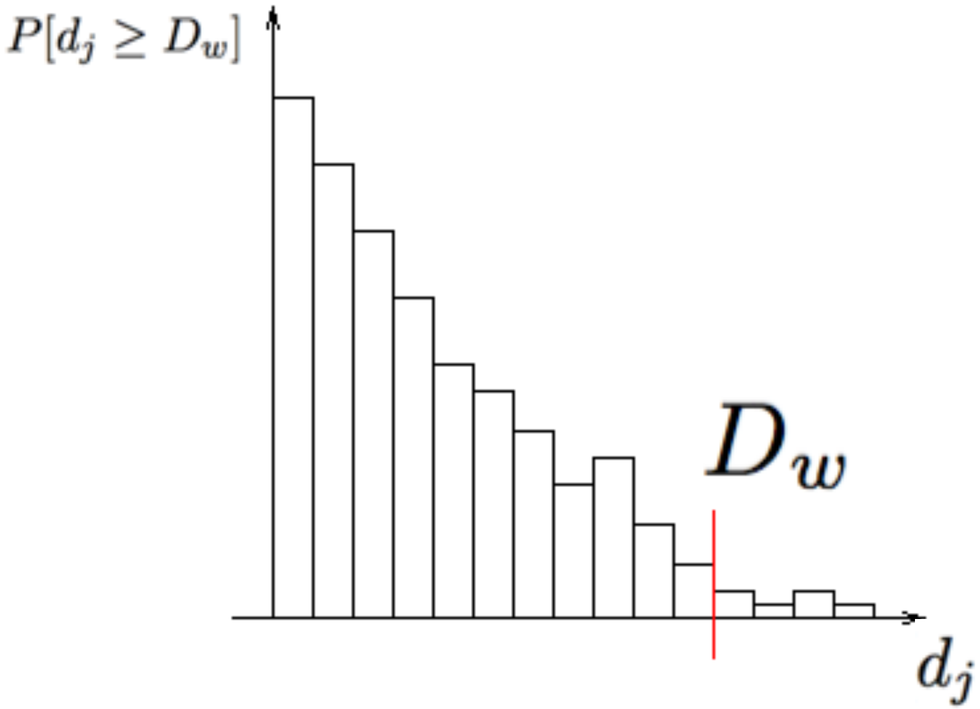


Worst case delay definition

- Probabilistic definition

$$\max \quad D_w \qquad s.t. \quad P[d_j \geq D_w] \leq \delta$$

  - with delta arbitrarily small (e.g. smaller 10e-9)



Delay distribution for CSMA/CA

- Markov model
  - [Bianchi, 00] extended by [Zhai et al., 04] and [Vardakas et al., 08] to derive the delay distribution.
  - RTS/CTS mechanism.
  - **Single hop** delay distribution
    - Probability generating function $D_m(Z)$
  - **Multihop delay** distribution (independence of delay between hops)

$$D_{multi}(Z) = D_{m1}(Z)*D_{m2}(Z)* \dots * D_{mN}(Z)$$

  for N hops

- Inversion to get the distribution using the numerical Lattice-Poisson methods with 10^-8 accuracy.

Delay distribution for TDMA

- Assume that
  - 1 hop = 1 time unit
  - Delay distribution is the probability for a transmission towards the destination to be done in *h* hops

$$P[d_j = h] = \begin{cases} \frac{\mathcal{A}_S \cdot I_D(D_j)}{f(D_j)} & h = 1 \\ \frac{\mathcal{Q}_S \cdot \mathcal{Q}^{h-2} \cdot \mathcal{A} \cdot I_D(D_j)}{f(D_j)} & \forall h \geq 2 \end{cases}$$

- Absorbing Markov chain model with

$$Q = \begin{bmatrix} 0 & Q_{12} & \cdots & Q_{1N} \\ Q_{21} & 0 & \cdots & Q_{2N} \\ \vdots & & & \vdots \\ Q_{N1} & \cdots & Q_{N-1N} & 0 \end{bmatrix} \quad Q_{ij} = \begin{bmatrix} Q_{ij}^{11} & \cdots & Q_{ij}^{1|\mathcal{T}|} \\ \vdots & & \vdots \\ Q_{ij}^{|\mathcal{T}|1} & \cdots & Q_{ij}^{|\mathcal{T}||\mathcal{T}|} \end{bmatrix} \quad D = \begin{bmatrix} D_{1D_1} & \cdots & D_{1D_{|\mathcal{D}|}} \\ \vdots & & \vdots \\ D_{ND_1} & \cdots & D_{ND_{|\mathcal{D}|}} \end{bmatrix}$$

Relay matrix Q

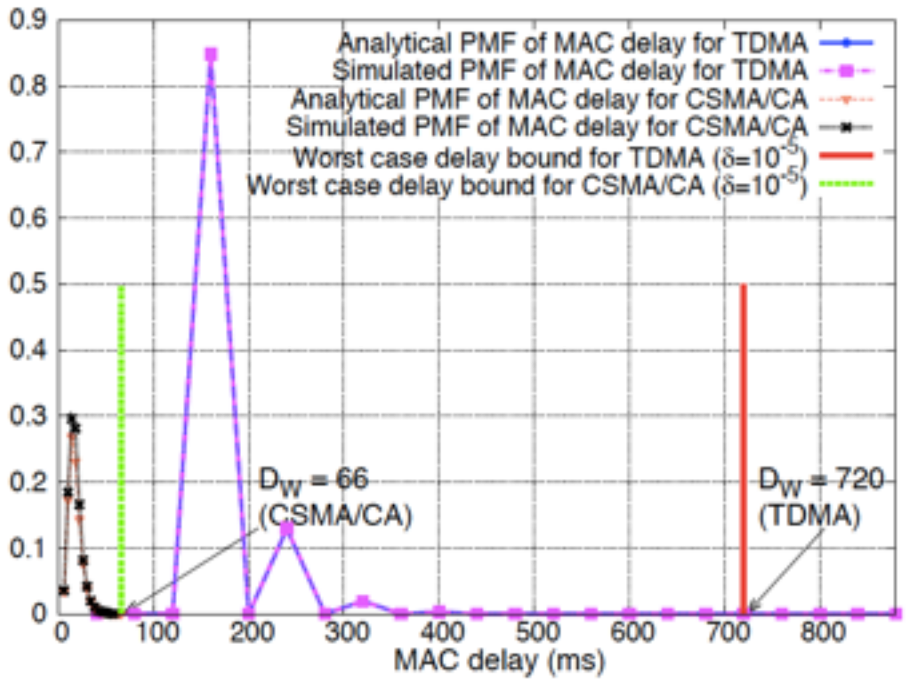
$$Q_{ij}^{uv} = p_{ij}^{u} x_{ij}^{uv}$$

Arrival matrix D

Results

- Settings
  - AWGN channel with BPSK modulation, no coding.
  - Perfect TDMA - no synchronization errors
  - Time slot duration to emit and ACK a 127 byte frame
    - Tslot = 0.29ms @ 11Mbps
    - Tslot = 10ms @ 250kbps
    - Tslot = 2.1ms @ 11Mbps, max WiFi frame size (2560 bytes)
  - Slotframe of 4 slots: in the worst case, a node waits for a slotframe at each hop.
- Simulations
  - With WSNet
  - Source period set to the worst case end-to-end delay of CSMA/CA Markov model
  - CSMA/CA: any node in range of 4 constantly emitting nodes.

Linear topology



3-relay topology (5 hop path)
10 ms slots, 4 slots per frame, delta = 10^{-5}
CSMA/CA with 127 byte frame

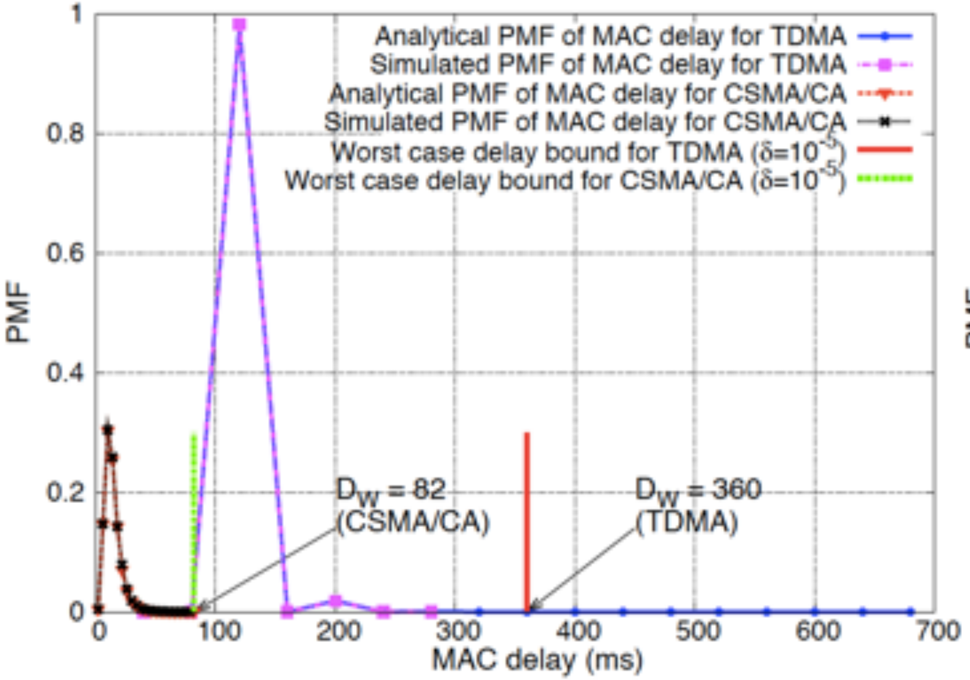
Bound precision delta
3-relay topology

D_w	TDMA #hops	10ms slots	0.29ms slots	CSMA/CA
10^{-5}	18	720	20.9	66
10^{-6}	20	800	23.2	74
10^{-7}	22	880	25.5	78

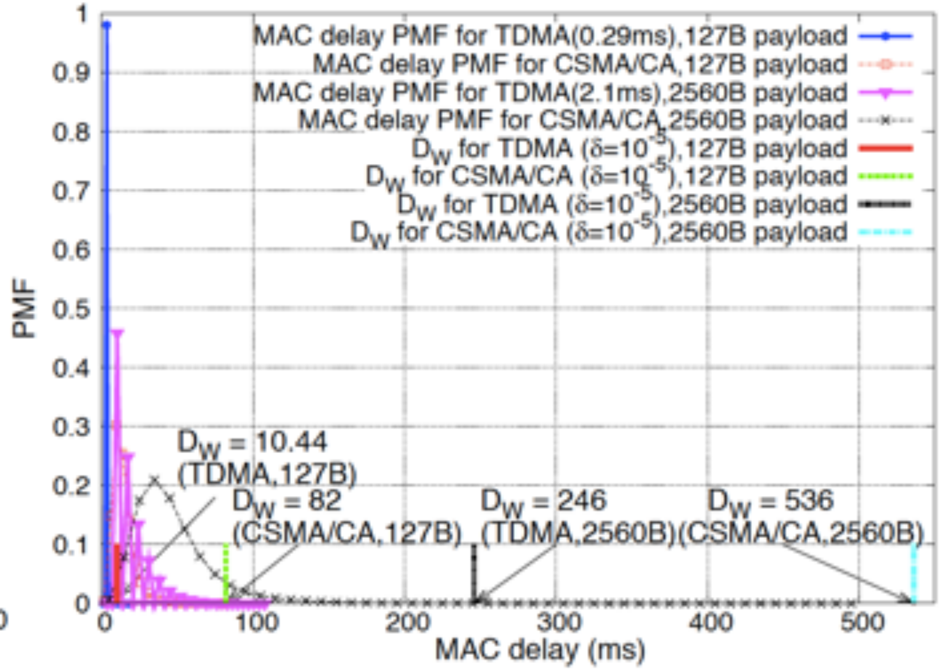
Number of relays
delta = 10^{-5}

# relays	TDMA #hops	10ms slots	0.29ms slots	CSMA/CA
3	18	720	20.9	66
4	19	950	27.6	132
5	20	1200	34.8	152

Cross flow topology



Impact of payload size



Worst case for delta=10^{-5}
Slot duration of 10ms

In TDMA, worst case represents 9 hops
only 3-hop paths

Worst case for delta=10^{-5}
Slot duration of 0.29ms, 2.1ms (x7)

Big impact of payload on TDMA D_w
(TDMA x51 while CSMA x7)

Worst case bounds

- Lightly loaded network with simple TDMA scheme, reminiscent of TSCH slot frames
- The choice of TDMA slot duration impacts the worst case bound performance of TDMA, as expected.
  - A lower slot duration is of course beneficial for TDMA
  - Requires good synchronization of node
- The overhearing (i.e. the loop in the forwarding probability) increases robustness, but introduces longer delays.

Conclusions

- This work presents two worst case delay bound calculation for TDMA and CSMA/CA based wireless multi-hop networks.
  - Both models are validated by extensive simulations for two elementary topologies
  - Worst case delay bounds for TDMA and CSMA/CA are compared considering the impact of different TDMA time slot durations.

- Future works will leverage the performance evaluation
  - Add synchronization overhead into out TDMA model
  - Calculate bounds for more complex topologies
  - Better capture the physical layer of mainstream sensors.

Thank you for your attention

Q & A

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