Optimization and Evaluation of an Energy-Efficient MAC protocol for WASNs

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Joint work with
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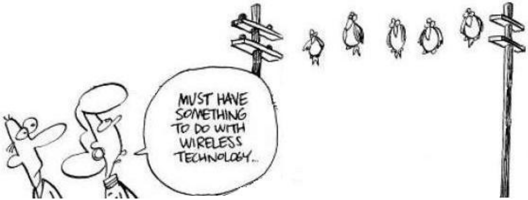
Outline

1. Introduction
   - Context
   - Problem
   - Related Works
   - Objective
2. Our contribution
   - Protocol overview
   - Protocol Analysis
3. Experimental results

Outline

What is a WASN?

- A Wireless Ad hoc Sensor Network (WASN) is a collection of devices (nodes) sensing the physical environment
- It is a kind of wireless network operating in absence of a preexisting communication infrastructure
- WASN are decentralized and all network activities are executed by nodes themselves (e.g. routing)



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The energy problem

- Devices are typically powered by batteries and devices running out of battery power impact network functionalities
- The main sources of energy waste are:
  - Collision
    - two or more packets are transmitted at the same time
  - Overhearing
    - a node receives packets intended for other nodes
  - Overhead
    - energy consumed in transmitting and receiving control messages
  - Idle Listening
    - Listening when there is no activity in the radio channel

The latency problem

- In a WASN, nodes use multi-hop communication to forward their data
- Several MAC protocols have employed low duty cycle operations with a sleep/wake-up scheduling to save energy
- This increases latency for the nodes on the communication path
  - when a packet arrives at a sensor node it must be queued if the next-hop is sleeping

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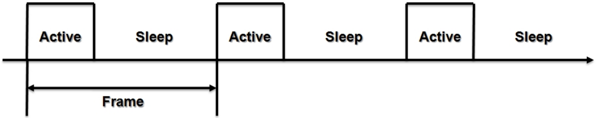
Low duty cycle protocols

- Low duty cycle protocols are essential for efficient long-term functioning of WASNs
  - Each node goes to periodic sleep mode for some time during which it turns off its radio off
  - When the time expires, it wakes up and listens to see if any other node wants to communicate
  - The ratio of wake-up duration to the whole duration of a frame is called duty cycle
    - Setting a low duty cycle is possible to save energy.



S-MAC

- S-MAC is a well known energy efficient MAC for wireless sensor networks
  - Nodes go to sleep periodically by using a fixed duty cycle
  - Neighboring nodes synchronize their schedules to reduce the control overhead
  - Message passing is used to reduce the contention latency and control overhead
- Major drawbacks:
  - high latency if the traffic is high: nodes cannot forward all the messages in their wake-up period
  - energy waste if the traffic is low: nodes stay in idle listening

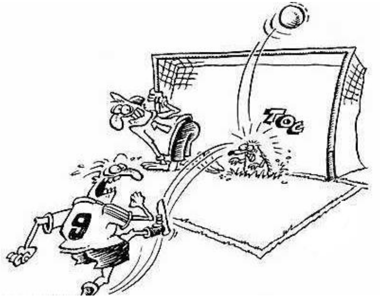
T-MAC

- Timeout-MAC (T-MAC) introduces the adaptive duty-cycle by dynamically setting the wake-up period:
  - At every frame the node wakes up only for a very short time (15ms vs 300ms of S-MAC)
  - If nothing happen nodes go back to sleep state
  - If an activation event (e.g. communication) is detected, nodes remain in the wake-up mode for other 15ms
- Main drawbacks:
  - T-MAC is subject at the early sleeping problem where a node goes to sleep when a neighbor still has messages for it
  - T-MAC suffers the same high latency as S-MAC when the duty-cycle is very low

Outline

Goal

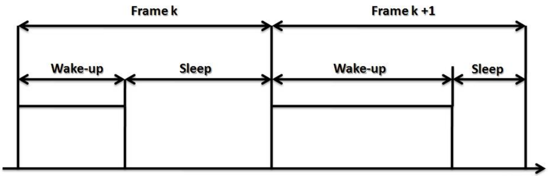
- The aim of this work is to develop a novel MAC protocol:
  - using only local neighborhood information
  - reducing the energy waste due to collision and overhearing
  - using traffic information in order to adapt the duty-cycle
  - improving the balance between end-to-end latency and energy consumption



Outline

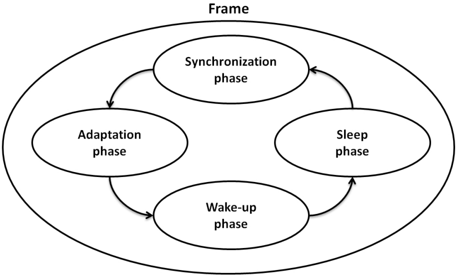
Basic Idea

- A wake-up adaptation scheme based on model-based predictive control is developed
  - During periods of regular activity, nodes produce less traffic as compared to periods of abnormal signal activity
  - By scaling down the wake-up time at regular periods, we expect a lower energy consumption while limiting latency
  - At each frame, the optimal duty-cycle is calculated by predicting future traffic conditions



Protocol phases

- The protocol is characterized by the following phases:
  - synchronization phase
  - adaptation phase
  - wake-up phase
  - sleep phase



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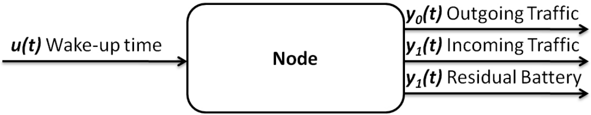
Synchronization

- The synchronization phase is inspired by the virtual clustering algorithm used in S-MAC and T-MAC.
- All nodes maintain and synchronize on schedules of their neighbors
  - SYNC packets are exchanged to keep the nodes schedules synchronized and compensate for clock drifts
  - Each node listens the channel for a while waiting for a SYNC packet from its neighbors
  - The node receives and follows its neighbor's schedule by setting its schedule to be the same.
  - If the node receives a different schedule after it chooses its own schedule, it adopts both schedules

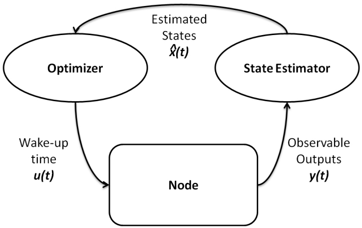
Wake-up adaptation

- The protocol uses a wake-up time adaptation strategy based on model-based predictive control
    - a dynamic model of the node is used to predict and guide the node behavior in terms of remaining energy and incoming/outgoing traffic
    - schedule is calculated in such a way to optimize a cost objective function over a future horizon
- We characterize the dynamic node model using an input-output black-box modeling technique



Wake-up time calculation

- A learned node model is used by a Sate Estimator to estimate the node state
- An optimizer computes the optimal sequence of wake-up time by solving an optimization problem in order to trace the desired node behavior
- The first value of the computed sequence is injected into the sensor node



System Model

- We assume that the node dynamics are unknown and so we apply an off-line system identification approach
- A mathematical model is derived by analyzing input-output relationship of a proper experimental data set:

$$\begin{aligned} x(t+1) &= Ax(t) + Bu(t) + w(t) \\ y(t) &= Cx(t) + v(t) \end{aligned}$$

  - $x(t)$ is the internal state of the node
  - $u(t)$ is the wake-up time - input
  - $y(t)$ is the outgoing traffic, incoming traffic and the residual battery - outputs
  - $w(t)$ and $v(t)$ are disturbance due to the use of partial information on the neighbors state

State Estimation

- In the black-box approach, the node state $x(t)$ is not directly measurable
- We need to estimate the internal state of the node given only the observable outputs $y(t)$
- The Estimator is based on the Kalman filter
    - it is an efficient recursive filter that estimates the state of a dynamic system from a series of incomplete and noisy measurements
- The estimator uses the learned state space model in order to derive the node state

Optimizer

- Assuming that the estimates of $x(t)$ are available at time t, the optimal wake-up time is obtained by solving the following optimization problem

$$\min_{\Delta u(t),\ldots,\Delta u(t+C-1)} \sum_{l=1}^{P} \|\hat{y}(t+l|t)-r(t+l)\|_R^2+\|\Delta u(t+l-1)\|_Q^2$$

  - $\Delta u(t) = u(t) - u(t-1)$ is the wake up time adjustment
  - $r(t)$ is the reference trajectories of the system and we use it to steer the behavior of the node
  - Q and R are weighting matrices
  - $\hat{y}(t+l|t)$ is the predicted value of y at time $t+l$ based on the information available at time t

Simulation environment

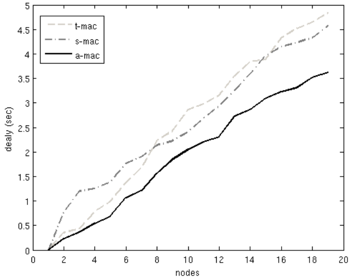
- We compared our protocol with S-MAC and T-MAC:
  - We have implemented our MAC protocol, called A-MAC, in the Castalia
  - Our simulation model captures a wireless ad hoc sensor network of Mica2 motes using Chipcon CC1100
  - We use a grid topology of 100 nodes separated by a distance of 30m
  - The size of packets is setted to 100 bytes

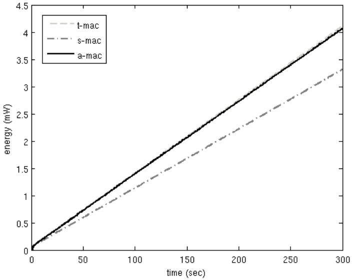
Optimization Problem

Reference Points	Residual energy	max
	Queue packets	0
	Neighbour queue packets	0
Output Weights	Residual energy	2
	Queue packets	1
	Neighbour queue packets	1
Input Weights	Wake-up time	1

Simulation 1: high traffic load

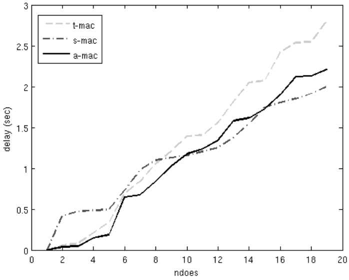
- All nodes generate packets with a random delay comprised between 0.1s and 2 s

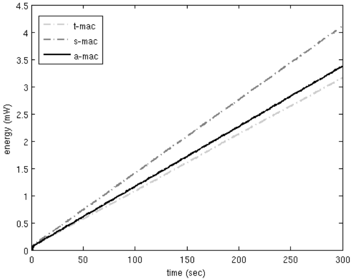




Simulation 2: low traffic load

- All nodes generate packets with a random delay comprised between 10 s and 15 s





Conclusion

- The results of the experimentation showed an improvment in the balance between end-to-end latency and energy consumption in WASNs
- Future work will involve the development of
  - an adaptive on-line system identification process in order to capture changing dynamics in the application context
  - an efficient mechanism with low control overhead in networks with high mobility

Thank You for Your Attention