A Wireless Sensor MAC Protocol for Bursty Data Traffic and Its Use in a Fire Monitoring Application

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SIGAPANO: Recolha de Informação Sensorial com "Nós Patrulha"

POSC/EIA/62199/2004

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RTCM – Nov. 28, 2007

Outline

- Motivation and WSN MAC protocol brief overview
- MH-MAC presentation
- MH-MAC performance evaluation
- Alarm application overview
- Conclusions

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Outline

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Motivation

- Standard WSN MAC protocols are usually designed under the assumptions of **periodic traffic**, or **seldom traffic**, but not for applications where both characteristics are needed at different instants :
  - B-MAC and X-MAC were designed for seldom traffic:
    - Nodes run independent asynchronous duty cycles
    - Low Power Listening bind sender and receiver using a large preamble
  - S-MAC, T-MAC, and Z-MAC were designed for periodic traffic:
    - Nodes run synchronized duty cycles
    - T-MAC introduced abbreviated awake periods due to inactivity
    - Z-MAC changes to TDMA fallback during load peaks, maximizing throughput
  - **B-MAC/X-MAC maximum throughput is low**
  - **S-MAC/T-MAC/Z-MAC energy consumption for idle periods is high**

Motivation

- Application requirements change
  - e.g. Forest monitoring with mobile patrol nodes
    - Energy consumption must be minimized when the patrol node is away
    - Throughput must be maximized when the patrol node is present
  - e.g. Alarm application for large forest with mobile patrol nodes
    - The two requirements above …
    - Delay must be minimized during a fire

- The existing protocols are too static

➔ **a new MAC protocol is needed to handle both periodic and seldom traffic, accordingly to the application needs**

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Objectives

- **Propose a Multimode Hybrid MAC protocol (MH-MAC) for packetizing radios (e.g. CC2420) that can be in one of three states:**
  - **Asynchronous**
  - **Synchronous**
  - **Full-on**
- Provide applications an API to control the state
- Develop an alarm application using MH-MAC API
  - **Large forest** (e.g. Peneda-Gerês national park, with 72000 ha) **with sparse WSN coverage**

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1. Motivation

2. **MH-MAC Protocol**

3. Performance Evaluation

4. Alarm Application

5. Conclusions

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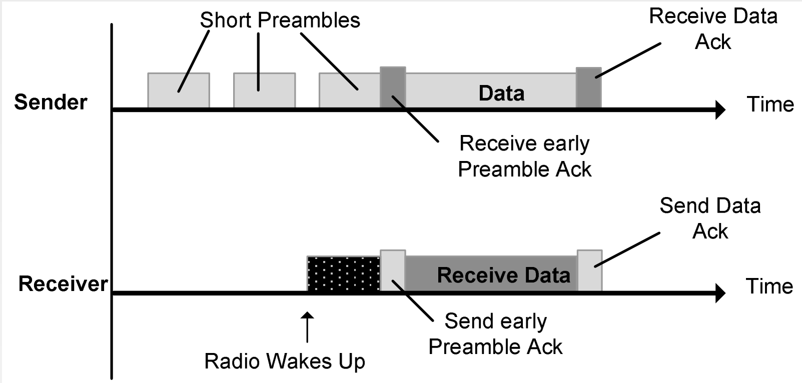
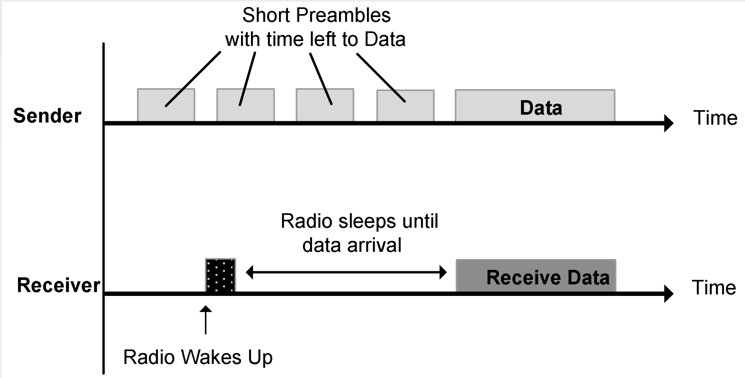
MH-MAC asynchronous mode



Unicast asynchronous transmission

- Based on X-MAC unicast mode
- *Low Power Listening*
  - Sender sends a sequence of short preambles with a duration up to $2 * T_{DutyCycle}$ before the data frames
  - Receivers send an **Early Preamble ACK** when they awake up
- Collision receivers send **SHUT-UP packets**, with probability *p*

MH-MAC asynchronous mode



Broadcast asynchronous transmission

- Sender sends a sequence of short preambles with a duration of $2x\ T_{DutyCycle}$ before the data frames
- **Receivers** receive the remaining preamble time in the preamble packet, and **sleep until near the data reception time**
- Collision receivers send SHUT-UP packets, with probability p

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MH-MAC synchronous mode

- Nodes run synchronized **duty-cycle periods**: a fixed length (11) sequence of slots.
- **Slots** have a fixed duration (100 ms)
  - Carry an average of 11,87 data frames (112 Bytes) on 802.15.4 radios
- Slots can be **public** or **private**
- **SYNC packets** synchronize the nodes and publicize the slot allocation map

Private slot

- **Reserved slot** for unicast traffic between two nodes.
- No collisions (differentiated backoffs)
- Unicast traffic is acknowledged
- SYNC packets include the local slot allocation map
- **After 25ms of inactivity** nodes go into sleep

Public slot (slot ALL)

- **Shared by all nodes**, used for broadcast traffic, or casual unicast traffic exchange.
- **First 15 ms reserved** for MAC signaling and application premium packets
  - SYNC packets
- **After 25ms of inactivity** nodes go into sleep
- Unicast traffic is acknowledged and run a contention-based protocol, preceded by a RTS/CTS exchange (above a threshold length).

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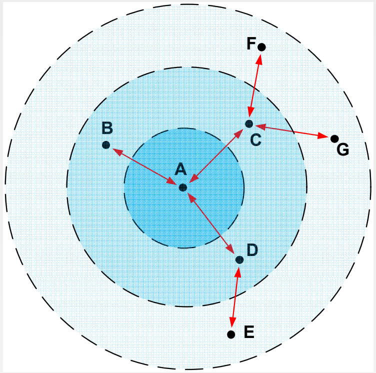
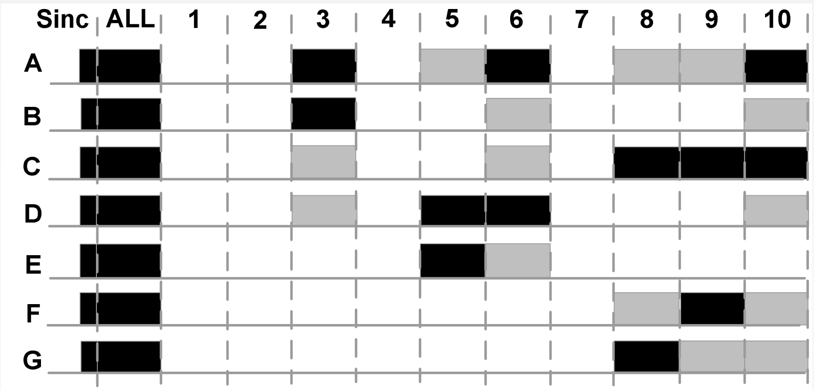
MH-MAC synchronous mode

Example of a slot allocation





- **Synchronous mode was designed for data collection over a sink tree**
- MH-MAC API only handles one hop interactions, but allows applications to create a multi-hop sink tree that
  - allocates multiple private slots to links proportional to the traffic
  - minimizes source-sink delay, organizing the private slots into a staggered wakeup schedule

- Delay in minimized in the figure
  - free slots are searched starting from the slot connecting to the sink
  - e.g. from F to A (slot 9 - 10)

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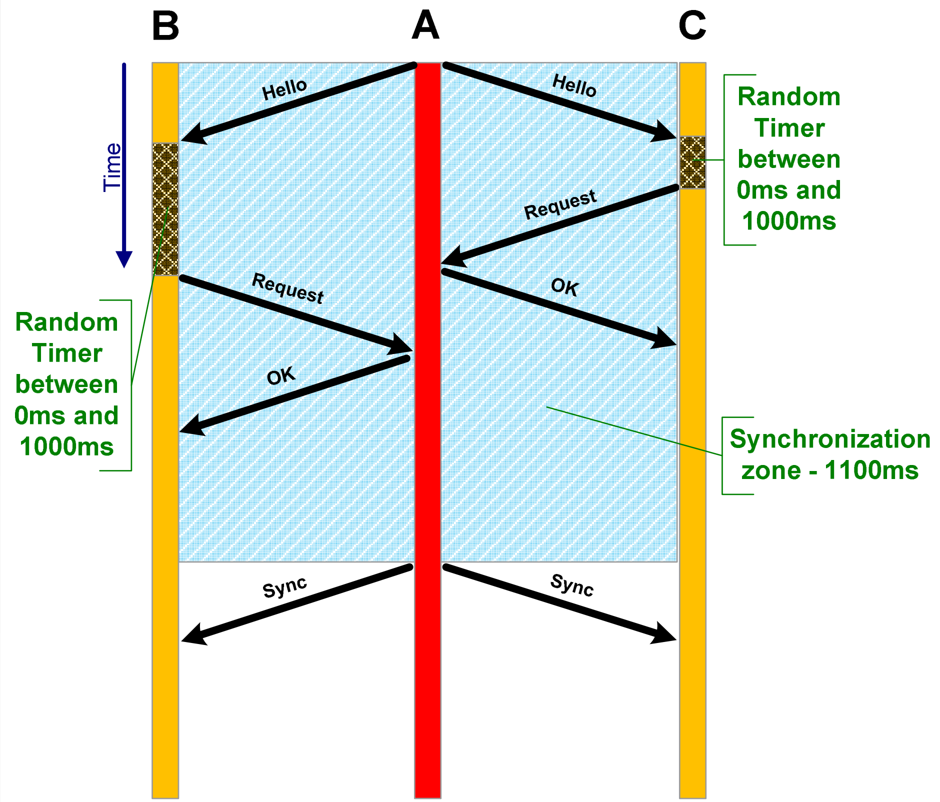
MH-MAC mode swapping



Total synchronization time

- Tree shaped network
  - Depth r; Neighbors $\leq v_{max}$
- Time per node
  - Jitter before Hello $\leq$ T
  - 2T preamble + 1100 ms
- Hypothesis:
  - Above 2 hops, nodes do not interfere
  - It may fail for normal topologies

$$TotalSyncTime \leq (2 + r(v_{max} - 1)) \times (3T + 1100)[ms]$$

Performance evaluation

Outline

- We use TOSSIM simulator
  - Run MH-MAC nesC code
  - CC2420 radio stack modified
  - Additional meters measure active time/sleep time/tx time/rcv time
- Single hop scenarios:
  - multiple senders to a single receiver
  - 100 Bytes / packet
  - Variable average IPT (Inter Packet Time)
- Energy Estimation : Xbow Telos B current consumption

Operation	**Current**
Mote Standby (RTC on)	5,1 μ A
MCU Idle (DCO on)	54,5 μ A
MCU Active	1,8 mA
MCU + Radio RX	21.8 mA
MCU + Radio TX (0dBm)	19,5 mA

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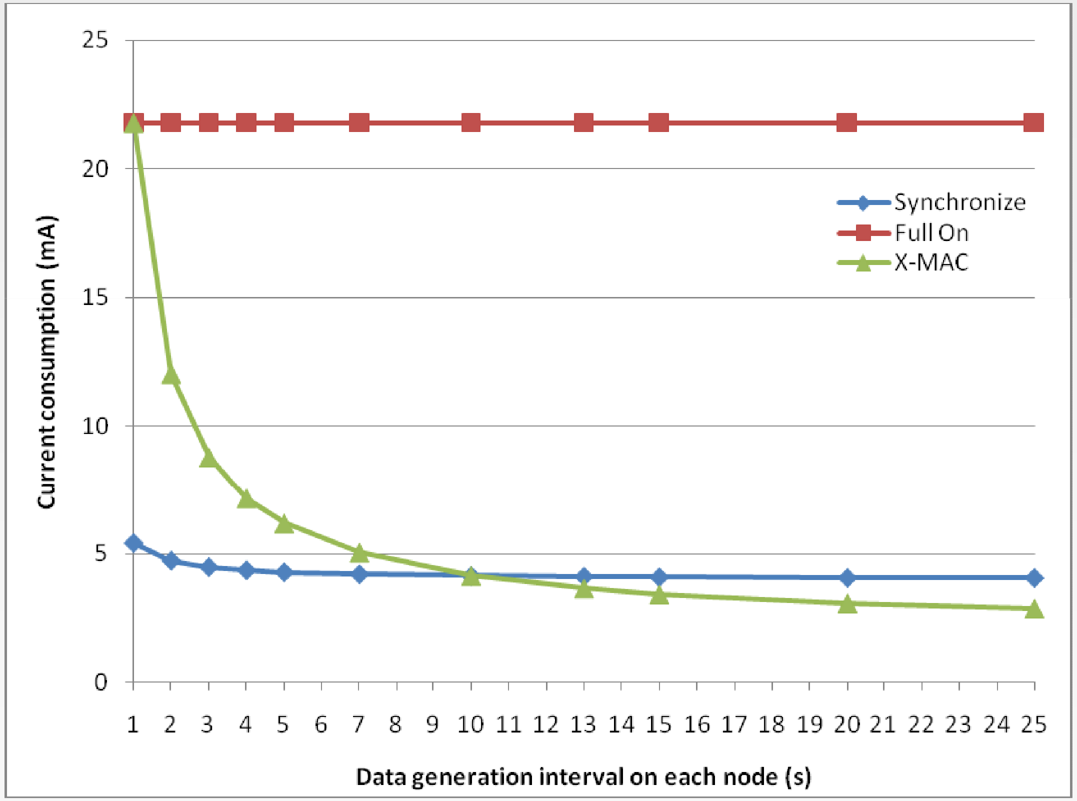
Current consumption



- 4 senders / 1 receiver
- Energy consumption is minimized for
- *Asynchronous mode* (X-MAC) for IPT above 10 s
- *Synchronous mode* for IPT below 10s

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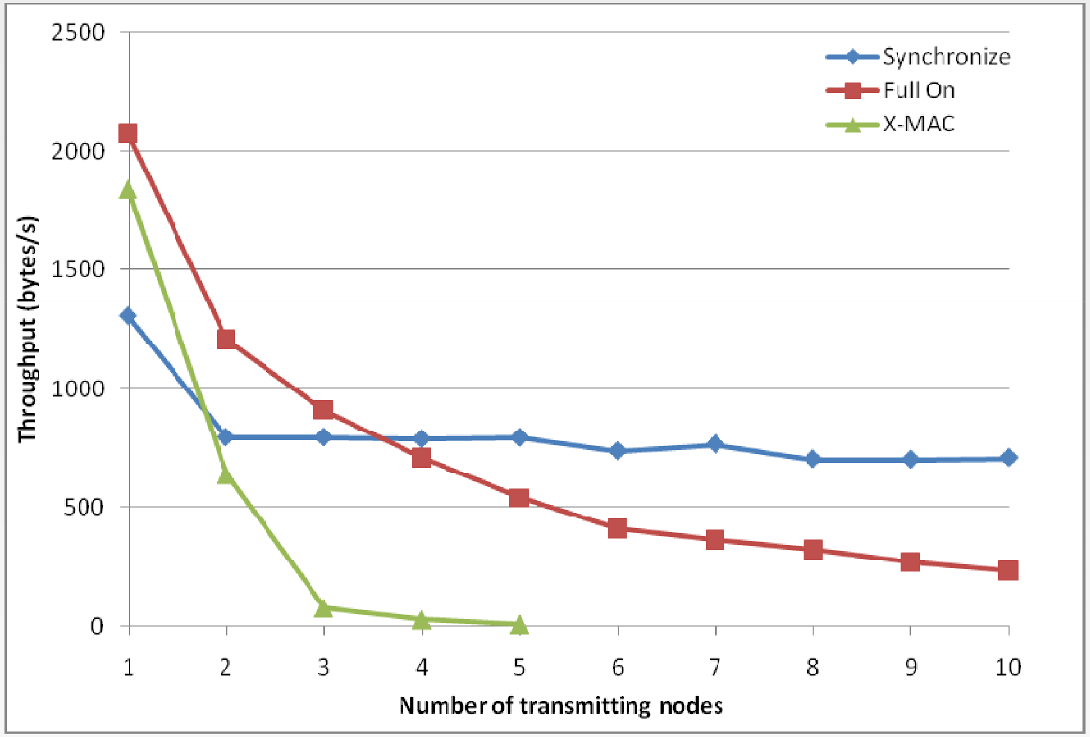
Throughput



- N nodes transmit a burst of 20 packets, with IPT=0

- Throughput is maximized for
- *Full On mode* (no sleep) for $N \leq 3$
- *Synchronous mode* for $N > 3$

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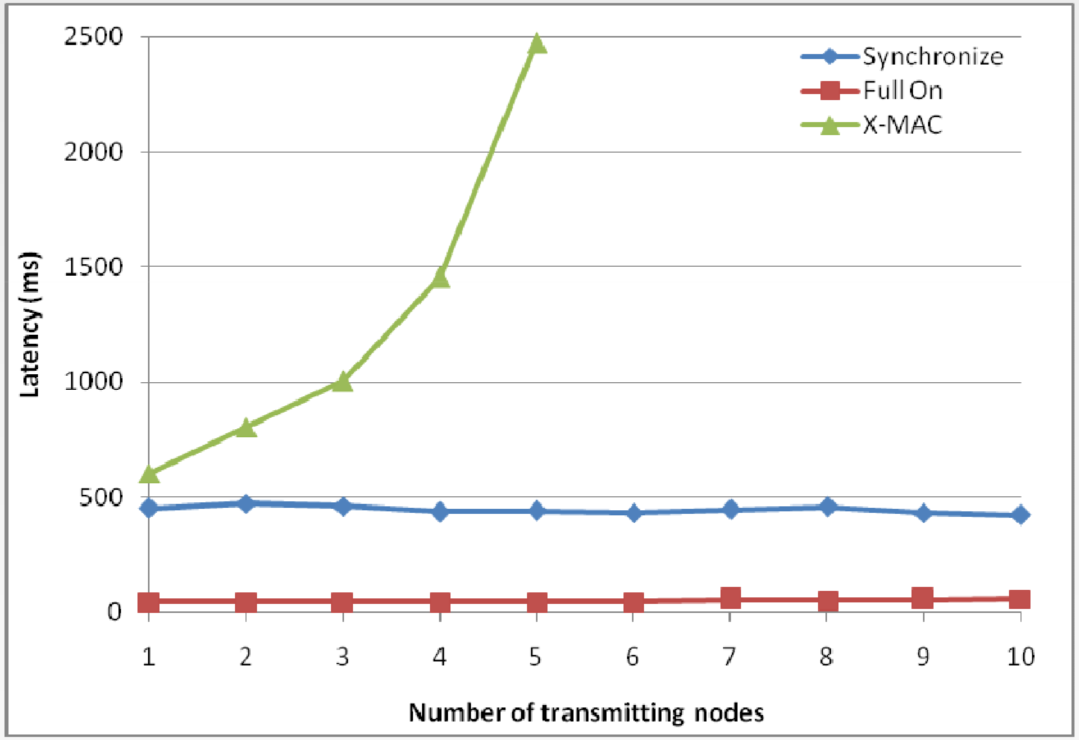
Latency



- IPT=1s

- Latency is minimized for
- *Full On mode* (no sleep)

- **Asynchronous mode introduces a huge delay for more than 2 senders**
- B-MAC/X-MAC reported good results only for 2 senders

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Application overview

- Cross layering application, transport and MAC layer
  - Configure MH-MAC and transport level accordingly to the alarm level
- Mobile patrol nodes (laptop or PDA) roam the forest connecting to the scattered WSN:
  - Set and collect alarms
  - Motes run autonomously, when the patrol node is not present
- Two alarm thresholds
  - Yellow alarm – possible fire
  - Red alarm – imminent fire (high probability of mote destruction)
- Motes store the alarm record is safe motes (when possible)
  - Patrol nodes read the alarms from the storing motes

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Application overview

- The application has three phases
  - Alarm deployment
  - Alarm handling
  - Alarm recovering

- Fast lookup operation for searching safe motes and stored records
  - Run a **peer-to-peer (p2p) lookup service** on the motes

    •**Clustering**

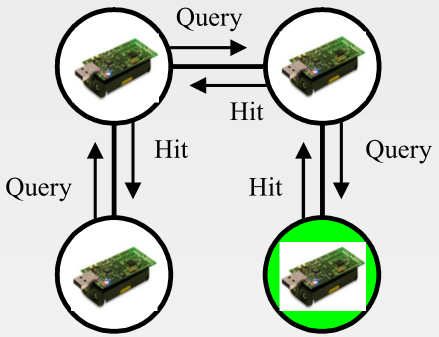
    •Run on a Virtual Overlay Network (VON) composed by a Minimum Connected Dominant Set (MCDS) covering the WSN

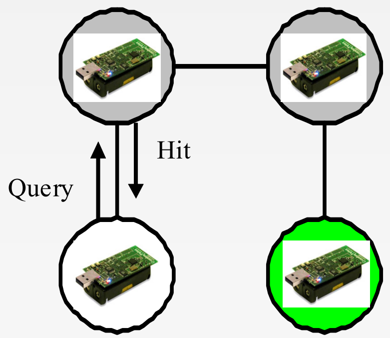
    •**QUERY flooding**

    • **HIT caching with invalidation mechanisms**

Outline

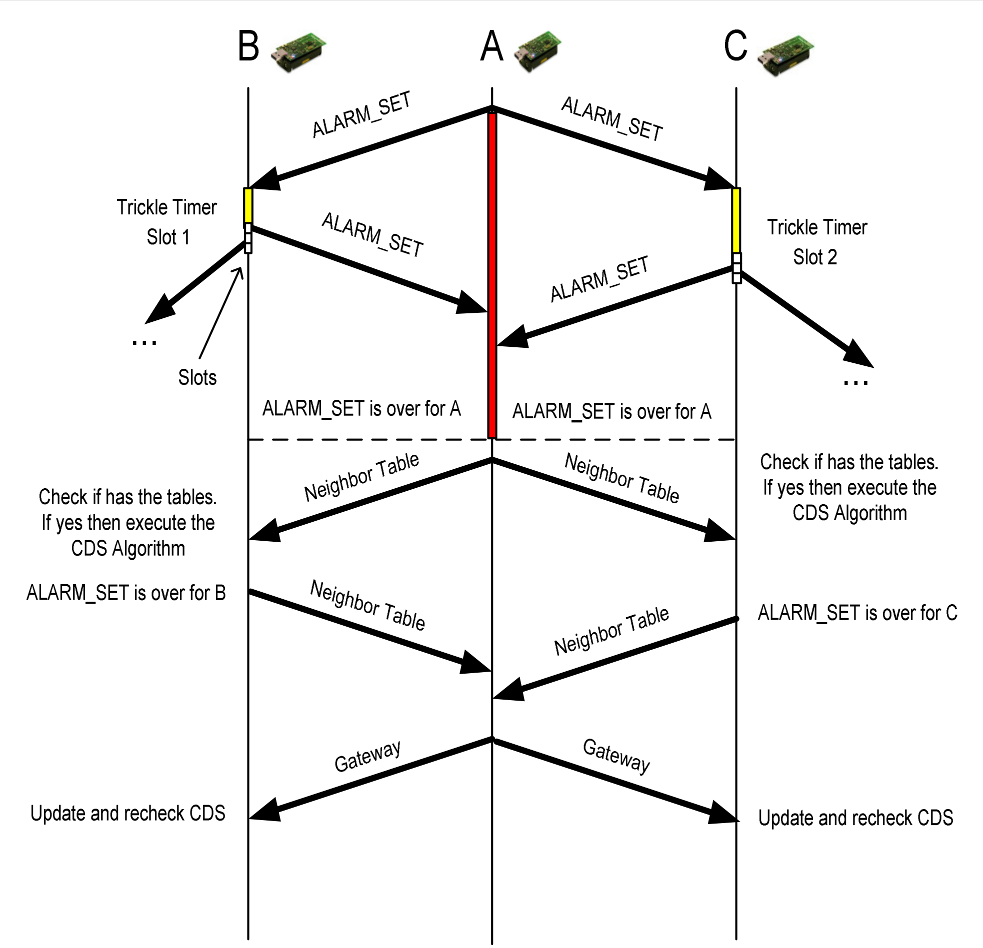
P2P searching algorithm





- Virtual Overlay Network of MCDS
  - MCDS motes act as ultra-peers
  - Classical Query flooding/Hit
    - Delay sensitive
  - Active Query Table
    - Cache of Hits forwarded
    - Forwarding motes p/Hit
- Hit carry two alarm levels
    - Sender alarm level
    - Maximum forwarding alarm level
- Forwarding nodes update the Hits when any of the alarm level changes

Alarm deployment



Total deployment time

- Tree shaped network
  - Depth r; Neighbors $\leq K$
- Time per node
  - T_{SLOT} per ALARM-SET
- Hypothesis:
  - No empty slots after trickle timer
  - Above 2 hops, motes do not interfere

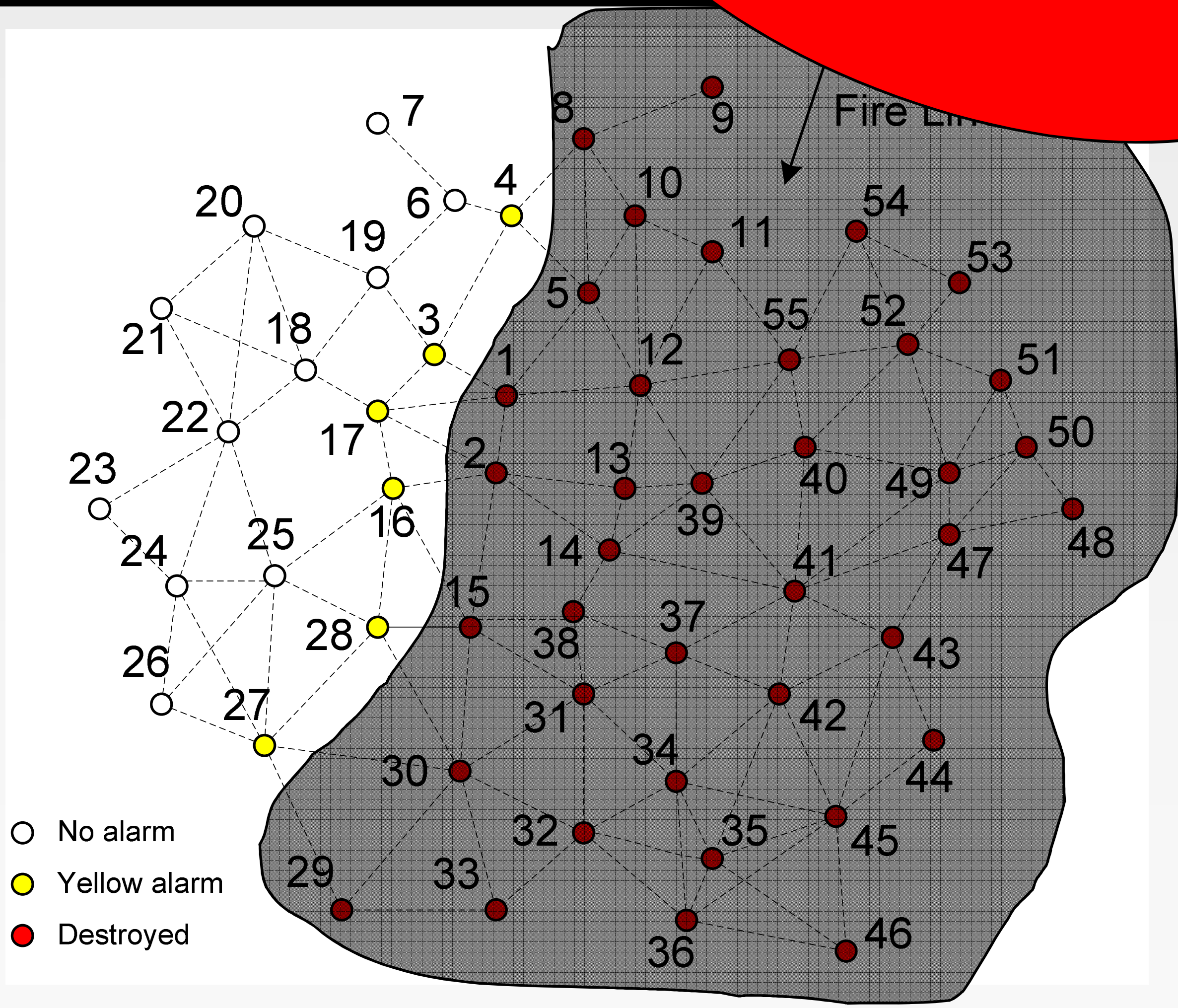
$$DeploymentTime \geq (r-1)((2K-1)T_{SLOT} + T_{IDLE}) + 2T_{SLOT} + T_{IDLE}$$

Outline

Alarm handling

- When an alarm is detected
  - MH-MAC changes to **Full-on**
    - Yellow alarm, red alarm and active CH motes
  - Motes record sensor measurement changes above a threshold limit to a repository mote located on a safe CH
  - return into no alarm state when the alarm thresholds are not exceeded for $T_{NO\text{-}ALARM}$ time
- Patrol nodes can receive ALARM-RECORD
  - asynchronously – CH store the ALARM-RECORD in the flash
  - real-time – CH forward the ALARM-RECORD it receives

Simulation s



- A fire front crosses a subset of the WSN
- Variable front velocity
- Constant temperature increase speed
- Red alarm (72 msgs)
  - t_{yellow}+120s – red
  - t_{yellow}+240s – destroy
- Yellow alarm (48 msgs)
  - during 360s
- **MEASUREMENT**
  - Percentage of saved ALARM-RECORD

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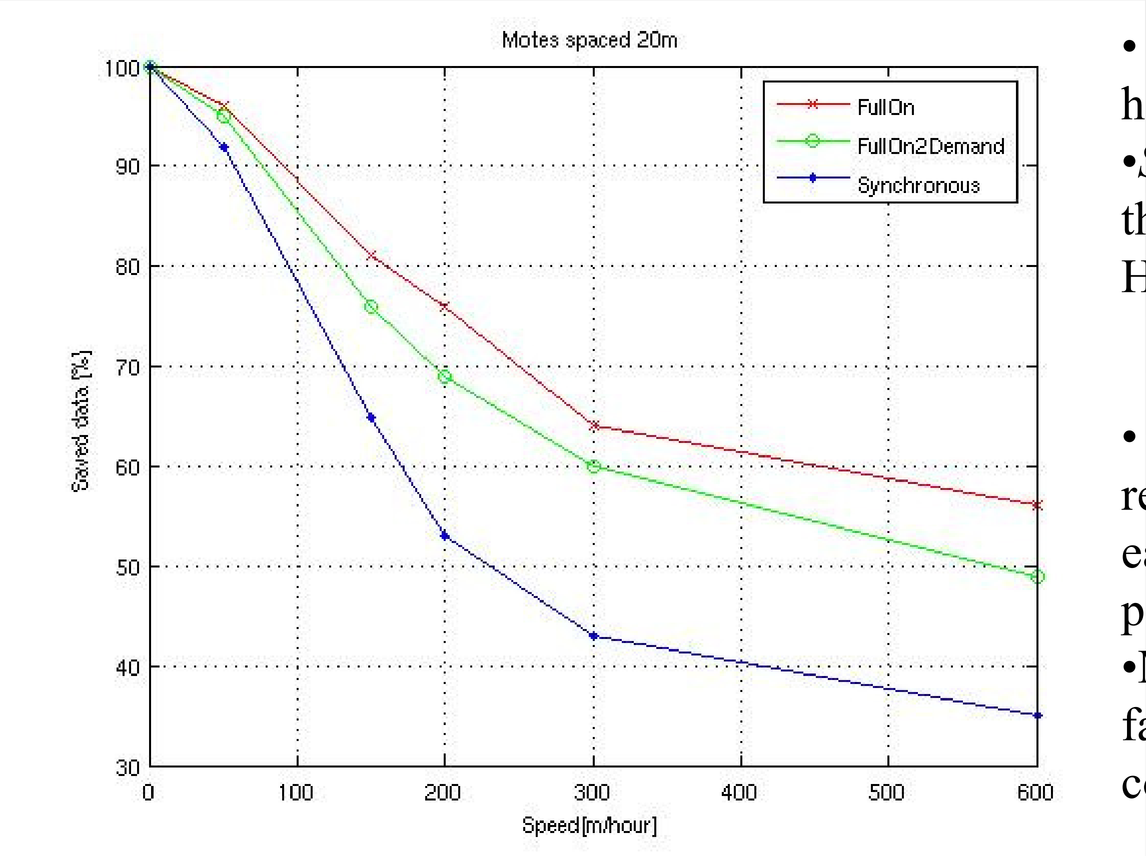
Simulation Scenario

- We evaluated three scenarios:
  - **FullOn2Demand**
    - MAC is asynchronous for no alarm situations and set to Full on when an alarm is detected
  - **Synchronous**
    - MAC is always in synchronous mode
  - **FullOn**
    - MAC is always Full on (minimum delay)
      - a benchmark for evaluating the other two approaches

P2P without HIT invalidation



- loss occurs for 2.5 WSN hops / hour
- *Synchronous* fails because the p2p search delay is HIGH
  - delay per hop = $T_{DUTY\_CYCLE}/2$
- *FullOn* fails because repository CH do not receive early warning of dangerous paths
- MH-MAC state transition is fast enough for the tested conditions
  - *FullOn2Demand* is slightly below *FullOn*

P2P with HIT invalidation

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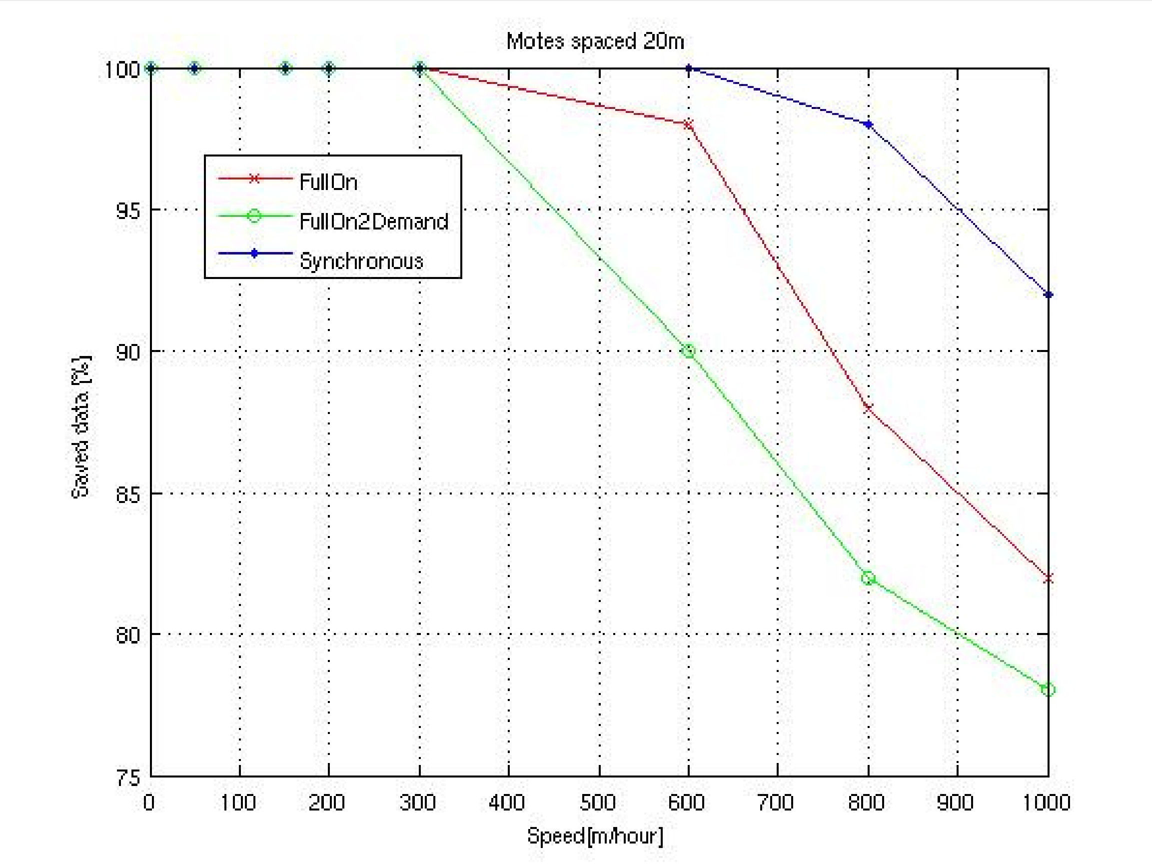

- P2P search is anticipated, recording paths are safer
  - loss occurs for 15 WSN hops / hour

- I_{FullOn}= 21.80 mA
- $I_{FullOn2Demand}$= 10.62 mA
- I_{Sync}= 10.78 mA
- SYNC costs on idle time

- Synchronous maximizes throughput (**no collisions**)
- MH-MAC state transition is fast enough for the tested conditions
  - *FullOn2Demand* is slightly below *FullOn*

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Conclusions

- MH-MAC allows applications to choose the mode, with three possible objectives:
- **Asynchronous mode** for minimizing energy consumption;
- **Synchronous mode** for maximizing throughput for convergecast traffic
- **Full On mode** for minimizing latency
- State transition incurs in energy costs and delay – applications must use it conscientiously
  - Alarm application shows that it can be used in real-time scenarios

Future Work

-WSN mobility support (Mobile MH-MAC is being developed)

- Improves radio interference handling and reduced state transition overhead

- Thorough testing of MH-MAC and the applications on a physical WSN

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More information can be downloaded from:

http://tele1.dee.fct.unl.pt

L. Bernardo, R. Oliveira, M. Pereira, M. Macedo, P. Pinto, "A Wireless Sensor MAC Protocol for Bursty Data Traffic", in IEEE PIMRC'07, September 2007.

L. Bernardo, R. Oliveira, R. Tiago, P. Pinto, "A Fire Monitoring Application for Scattered Wireless Sensor Networks: A peer-to-peer cross-layering approach", in WINSYS'07 (part of ICETE'07), July 2007.

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Thanks for your attention.

Q&A …