Energy Efficient MAC Protocols Design for Wireless Sensor Networks

Francesco Chiti, Michele Ciabatti*, Giovanni Collodi§, Davide Di Palma*, Romano Fantacci *, Antonio Manes▲*

**Dipartimento di Elettronica e Telecomunicazioni,*
▲Dipartimento di Energetica, §Consorzio MIDRA
Università di Firenze -Via di S. Marta, 3 - 50139 Firenze, Italy

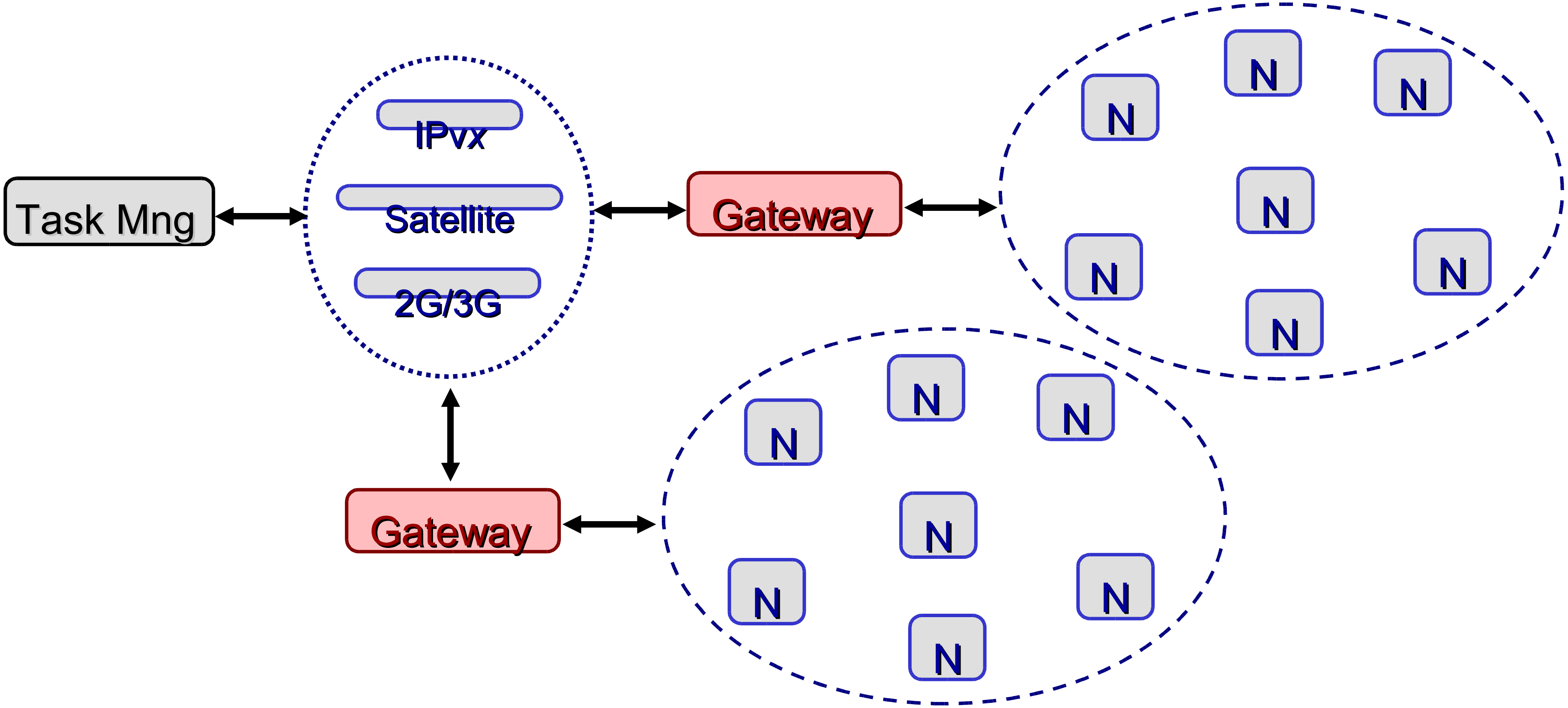
chiti@lenst.det.unfi.it, michele.ciabatti@unifi.it, collodi@ing.unifi.it, davide.dipalma@unifi.it, fantacci@lenst.det.unfi.it, antonio.manes@unifi.it

Outline

3. MAC protocols overview
    - Scheduled based
    - Contention based
4. Proposed MAC schemes
    - ATSR
    - STAR
    - STAR+
5. Performance evaluation:
    - Cost
    - Drift
6. Conclusions and further developments

Definition

Wireless Sensor Network (WSN) is composed of a large number of sensor nodes (N) that are densely deployed either inside the investigated phenomenon or very close to it.

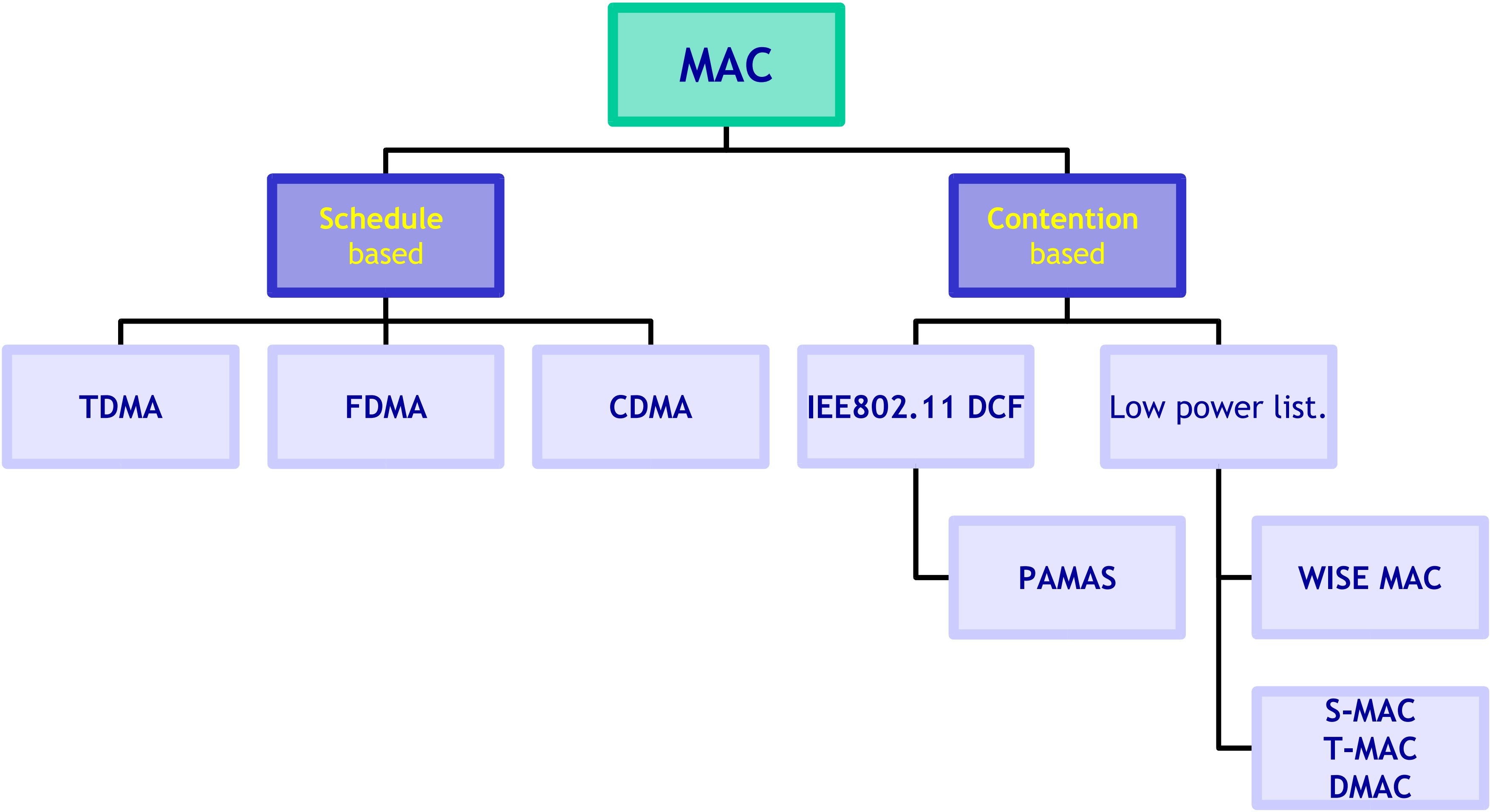


WSN MAC protocols

- *Tasks:*
  - To realize a self-organizing network “infrastructure”
  - To fairly and efficiently share communication resources
- *Requirements:*
  - Unique destination (*Sink*)
  - High nodes density
  - Low nodes mobility
  - Limited resources (bandwidth, battery, processing and storage)
  - *Data centric*
  - *Application oriented*

⇨ Ad Hoc networks approaches are not merely applicable

MAC protocols overview



Schedule-Based MAC protocols

- *TDMA, FDMA, CDMA:*

  Resources reservation and scheduling.

  - energy conserving, since overhead and collisions due to contention processes are not further introduced;
  - the nodes are required to form real communication clusters, like in *Low-Energy Adaptive Clustering Hierarchy* (*LEACH*) and to control:
    - the *intra-cluster* communications;
    - the *inter-cluster* communications that is difficult in time varying topology regime.
  - lower scalability.

Contention-Based MAC protocols

- IEEE 802.11 *Distributed Coordination Function* (*DCF*):

  based on *Media Access with Collision Avoidance Wireless* (*MACAW*)

  - widely applied in ad hoc wireless networks because of its simplicity and robustness with respect to the hidden terminal problem;
  - high energy consumption when nodes are in idle mode due to the idle listening mode (*power-save mode*) of CSMA/CA.

- *Power Aware Multi Access Protocol with Signaling* (*PAMAS*)
  - improvement in energy saving by avoiding the overhearing effects among neighboring nodes;
  - requires two independent radio channels, thus implying in most of the cases two independent radio systems on each node;
  - does not attempt to reduce idle listening.

Contention-Based MAC protocols

- *Low Power Listening and Preamble Sampling* protocols:

  based on listening (part of) the packet *preamble* to:

  - notify receivers of the upcoming transfer;
  - to adjust accordingly the circuitry.

  The receiver can periodically turn on the radio to sample for incoming data (*duty cycle*). If it detects a preamble, it will continue listening until the start-symbol arriving, conversely, the radio is turned-off again.

  👍Energy saving for the sender who waits instead of transmitting a preamble,

  👍Energy saving for the receiver, since the time until the start symbol occurs is reduced in length considerably

Contention-Based MAC protocols

- *WiseMAC*:

  nodes maintain the *schedule offsets* (*phase*) of their neighbors through piggy backed information on the ACK of the underlying CSMA protocol. Offset is used to determine when to start transmitting the preamble.

  adapts automatically to traffic fluctuations:

  - under low load it uses long preambles and consumes low power (receiver costs dominate);
  - under high loads, it uses short preambles and operates energy-efficiently (overheads are minimized).

  not well suited for message broadcasting as the preamble length must span the sampling points of all neighbors accounting for drift, so it is often maximized.

Contention-Based MAC protocols

- *S-MAC*, *T-MAC*, *DMAC*:

  They introduce a *duty cycle* within each *slot* thus synchronizing the nodes. At the beginning of a slot, <u>all</u> nodes wakeup and any node wishing to transmit a message must contend for the channel. These approaches differ in their way of deciding when and how to switch back from active to sleep.

  This increases the collision probability in comparison to energy-efficient CSMA protocols.

  To mitigate the increased collision overheads S-MAC and TMAC include an RTS/CTS handshake, while DMAC avoids this protocol overhead.

System requirements for MAC protocols design

- **Power consumption issues** to make the system able to run unattended;
- **Optimal energy management**;
- **Network life-time** to avoid the whole network to get partitioned;
- Capability of **quickly set-up** an end-to-end communication infrastructure;
- Support both to **synchronous** (*source-initiated*) and **asynchronous** (*event-based*) sensing;
- **Quality of Service** (*QoS*) provisioning;

MAC layer optimization ensuring that the spent energy is directly related to the amount of traffic. Trade off between:

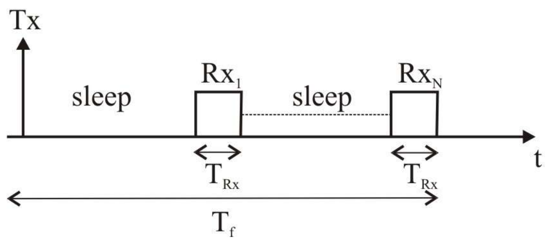
- ✓ performance (latency, throughput, fairness);
- ✓ cost (energy efficiency, algorithmic complexity, signaling overhead).

ATSR

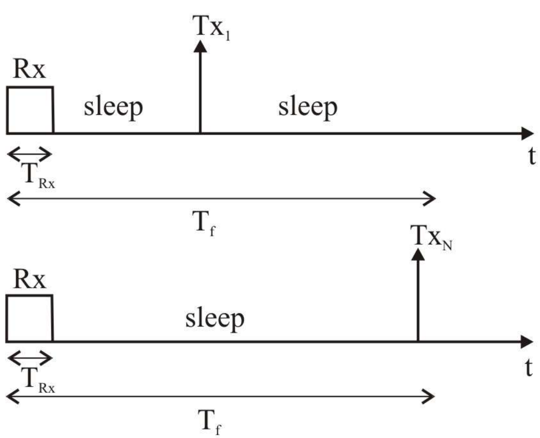
Asynchronous **T**ransmission **S**ynchronous **R**eception

Maximize node life-time → **sleep status**

node



neighbour node



<u>Synchronization message</u>

- **`ID`**: unique identifier
- **`Phase`**: relative time offset to the next listening state

→ **≈ S-MAC**

STAR MAC

Synchronous **T**ransmission **A**synchronous **R**eception

Background:

- WISE MAC: nodes maintain the schedule offsets of their neighbors
- S-MAC: nodes regularly broadcast SYNC packets (*duty cycle*)

Drawbacks (related to our application):

- WISE MAC: offset information is transmitted within ACK messages, then its update depends on traffic load
- S-MAC: clustered nodes are strictly synchronized and must have the same duty cycle and frame time

Proposed approach:

STAR protocol does not require strict node synchronization: each node can adjust its duty cycle and frame period independently.

Nodes periodically send their offsets to neighbors through a MAC layer signaling.

As a result, the network topology is flat.

STAR MAC

Synchronous **T**ransmission **A**synchronous **R**eception

1. Completely **novel** approach effectively joining:
   - WISE MAC (*phase* based transmission scheduling)
   - S-MAC (*duty cycle*)
2. Efficient **power management** (*<u>stable</u> low power state* + *duty cycle*)

Sleep status (T_S , c_{sleep}= 0.01 mA):

- RF OFF
- Micro & Sensor board: power save mode

MAC frame period ($T_f = T_l + T_S$)

Duty cycle

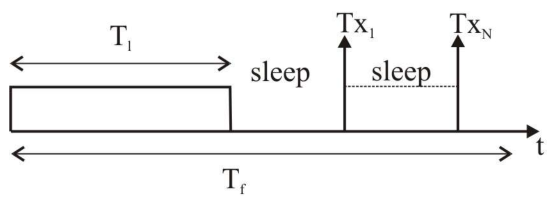
$$\boxed{d_{\%} = \frac{T_l}{T_f} 100 = \frac{T_l}{T_l + T_s} 100}$$

STAR MAC

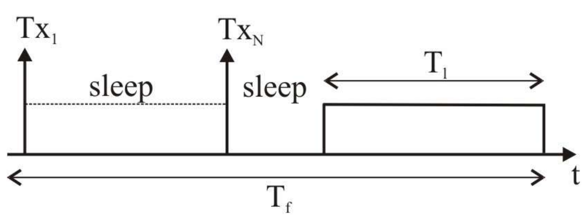
Synchronous **T**ransmission **A**synchronous **R**eception

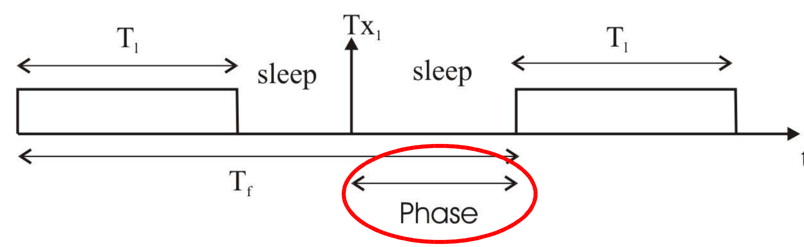
- **Sleep status** (T_S , c_{sleep}=0.01 mA):
  - RF OFF
  - Micro power save mode
  - Sensor board power save mode
- **Listening status** (T_l, c_{Tl}=10-40 mA):
  - RF ON (*Rx or Tx*)
  - Micro ON
  - Sensor board ON only when triggered

node



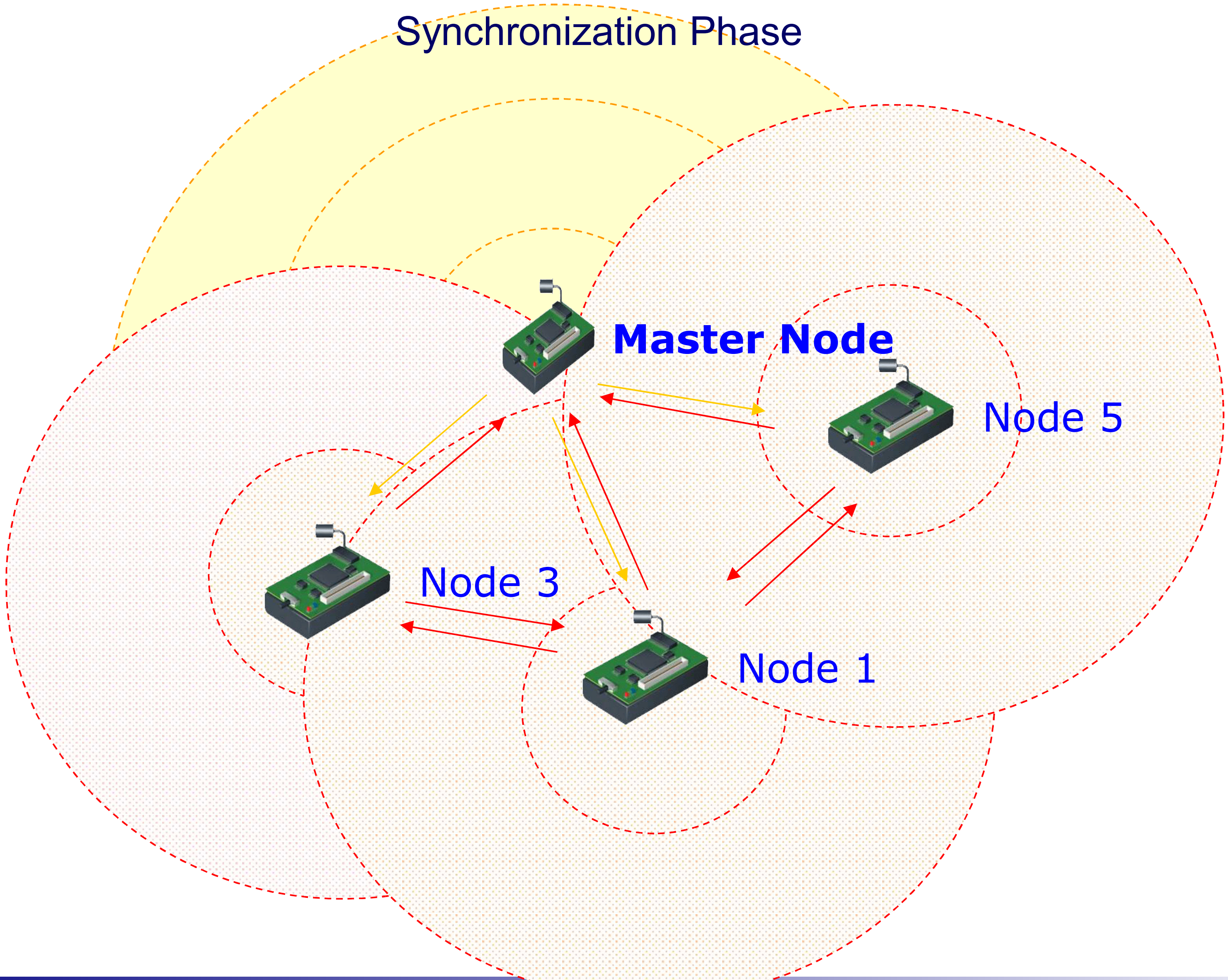
neighbour node





STAR MAC

Synchronization Phase



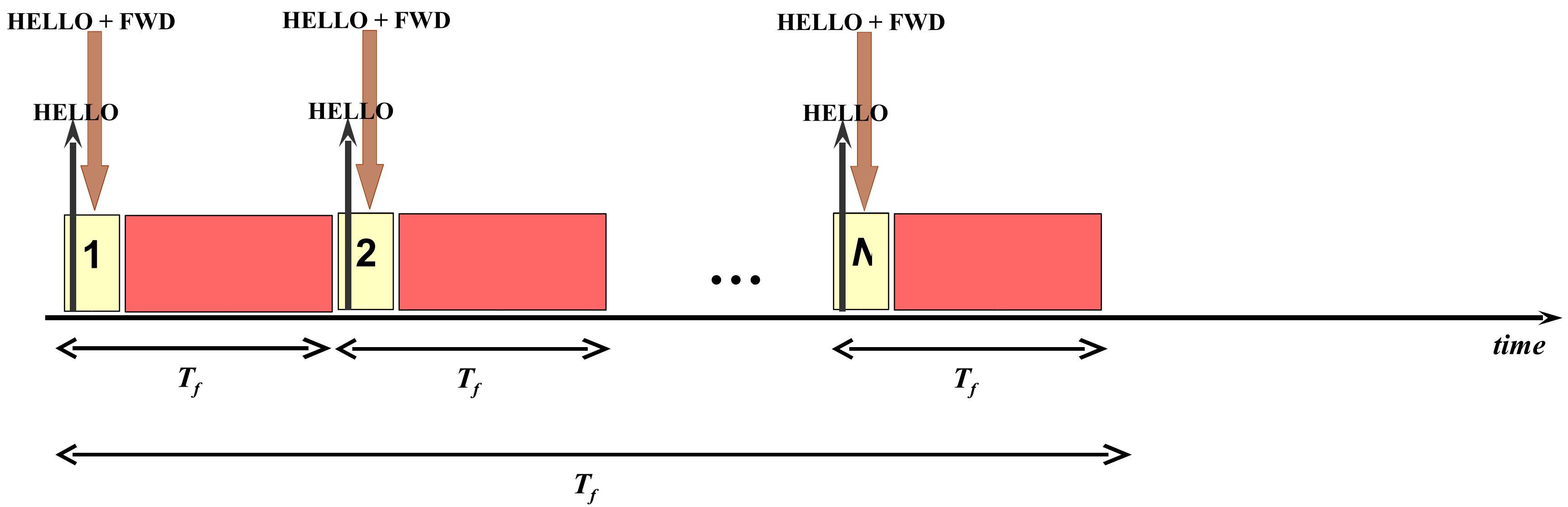
STAR MAC

Set-up Phase

2. Beacon broadcasting (starting from Gateway)
3. Neighbors list assessment within at least 1 period (T_f)
4. Duty cycle operation mode with semi duplex communications (independently each other)
5. Mote's phase transmission (time to the next awakening)
6. Weak and distributed synchronization scheme (*rendez vous* like)

STAR MAC

Regime Phase



Network status updating frame-by-frame with HELLO mesasages:

- n_i++ (incoming neighbor)
- n_i --or (node failure)
- additional parameters (Hop Counter, Battery Level, Link Quality)

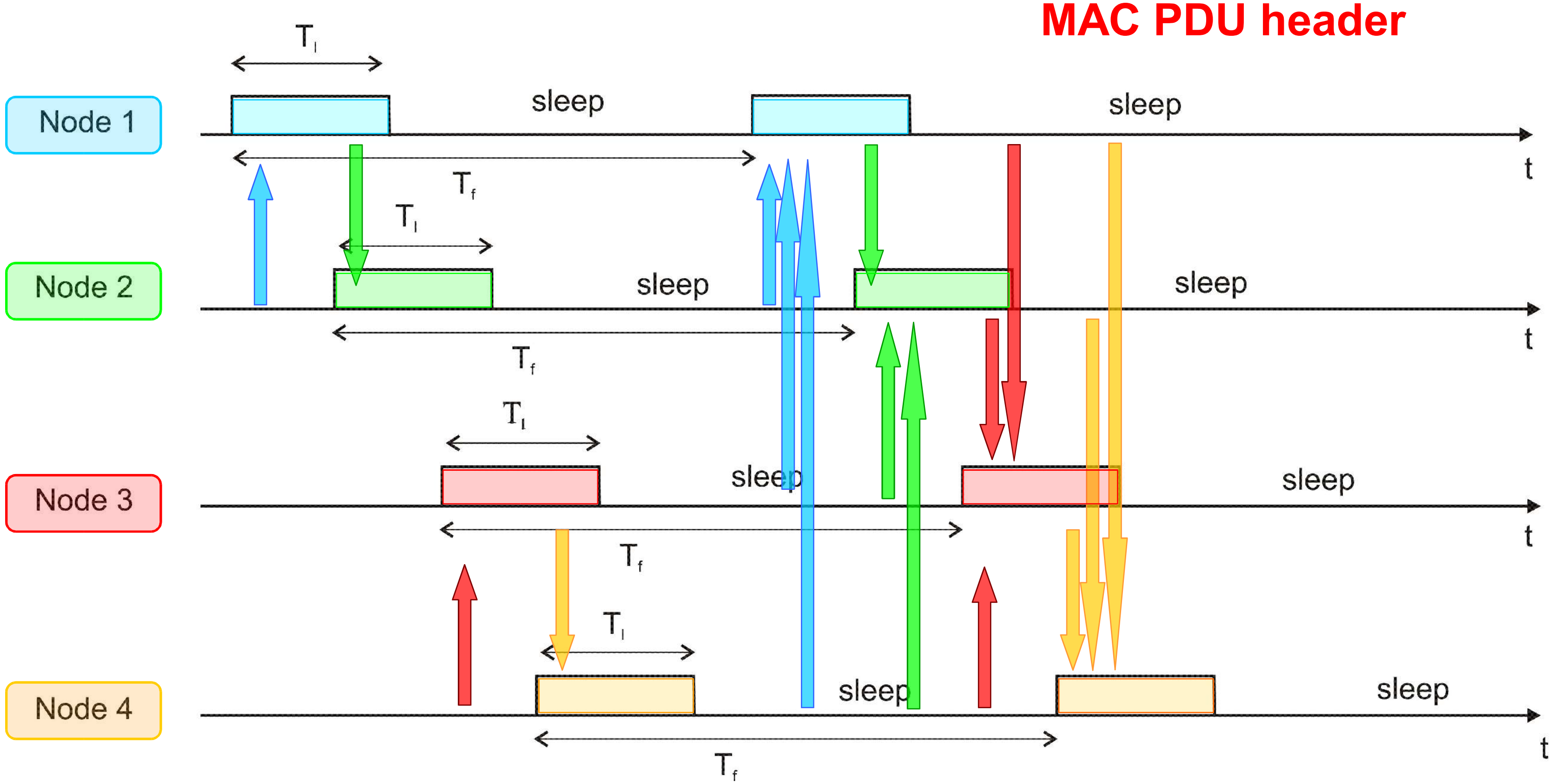
STAR MAC

Regime Phase

1. **Weak** nodes synchronization (*2 way handshake*)
   - Set up + recovery procedures

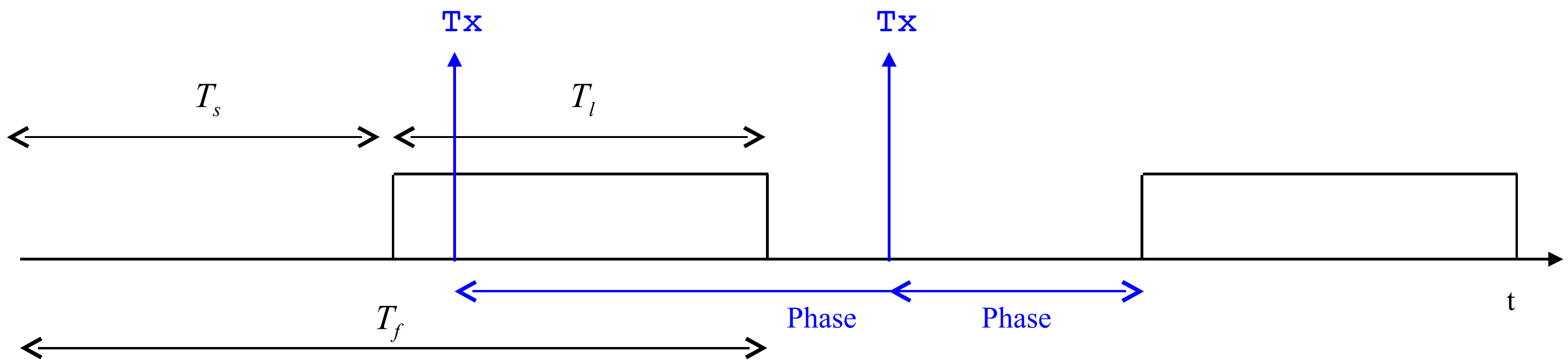
ID	Phase	Hop counter	Sequence Number

MAC PDU header



STAR MAC

Phase evaluation procedure



MAC PDU header

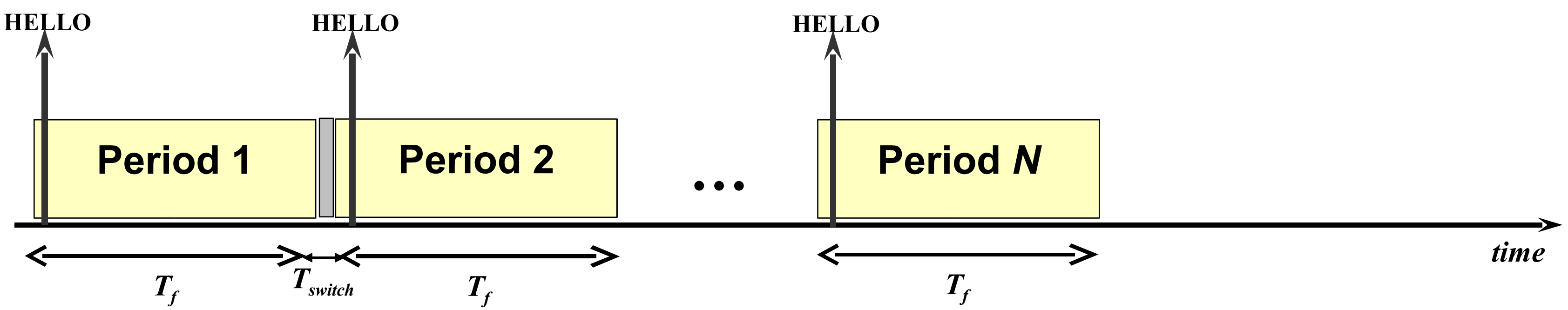
ID	Phase	Hop counter	Sequence Number

- **Phase evaluation**

```
if (STATE == LISTEN)
        { Phase = Ticksleft + SleepTime }
else if (STATE == SLEEP)
        { Phase = Ticksleft - ListeningTime }
```

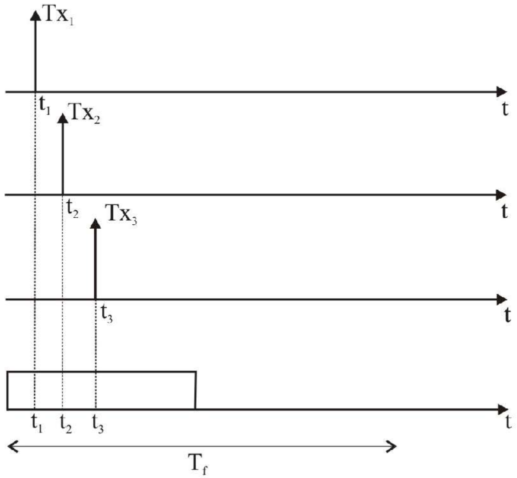
STAR MAC

Recovery Phase



- Orphanage management
- Beacon broadcasting
- Neighbors list assessment within *N* period (*N* T_f)
- Own HELLO messages broadcasting in search of connectivity

Enhanced STAR (STAR+)



Subset:

set of neighbor nodes jointly awake for a time interval greater than the time necessary for receiving a message (T_{Rx})

Only one synchronization message is *multicasted* to all the neighbor nodes belonging to a *subset*

↓

Lower number of synchronization messages (*multicasting gain*)

Normalized Cost:

ATSR (≈S-MAC)

$$\frac{C}{T_f} = \frac{C_{Tx} + N c_{Rx} T_{Rx}}{T_f} + c_{sleep}\left(1 - \frac{N T_{Rx}}{T_f}\right) [mA]$$

STAR

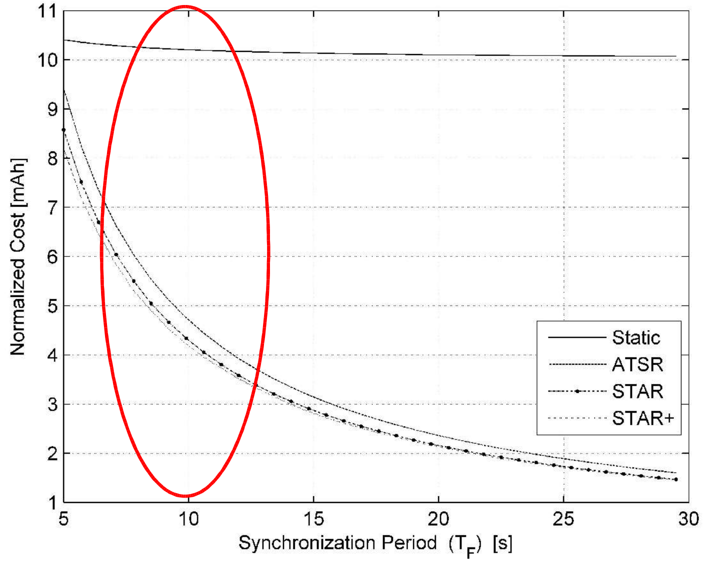
$$\frac{C}{T_f} = c_{Rx} d + c_{sleep}(1-d) + \frac{N C_{Tx}}{T_f} [mA]$$

STAR +

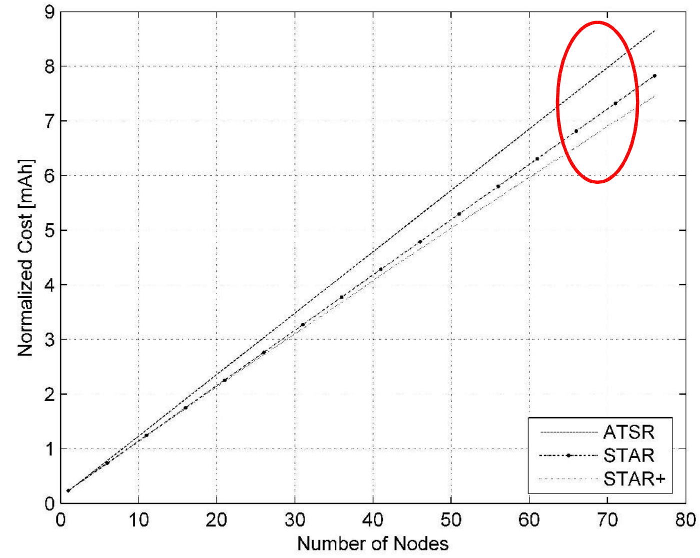
$$\frac{C}{T_f} = c_{Rx} d + c_{sleep}(1-d) + \frac{K C_{Tx}}{T_f} [mA]$$

Parameter	Value
Cost of receiving status (c_{Rx})	10 mA
Cost of transmitting status (C_{Tx})	30 mAh
Cost of sleep status (c_{sleep})	0.01 mA
number of neighbor nodes (N)	1-80
Synchronization period (T_F)	5-30 s

Normalized Cost vs T_F



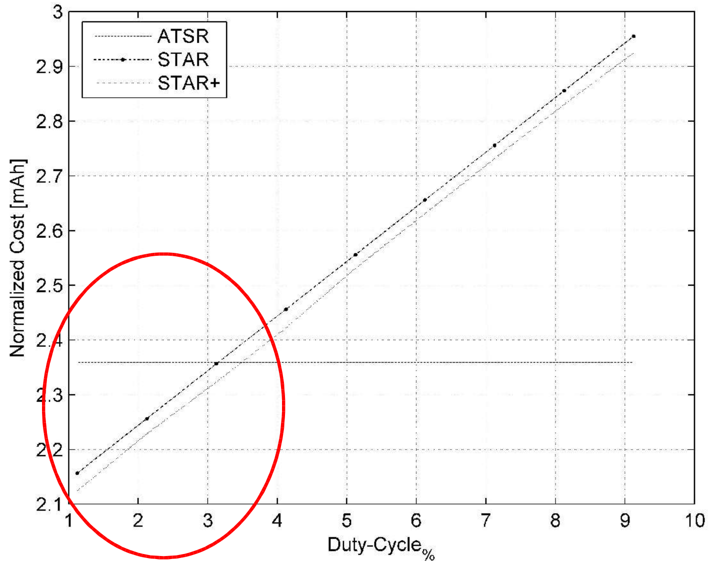
Normalized Cost vs N



Cut-off time for T_F (floor effect)

$$K = \left\lceil \frac{N}{\bar{n}} \right\rceil \qquad \bar{n} = \sum_{n=2}^{N-1} n \left[\frac{2}{T_f} \left(T_l - T_{Rx} \right) \right]^{n-1}$$

Normalized Cost vs Duty-Cycle%



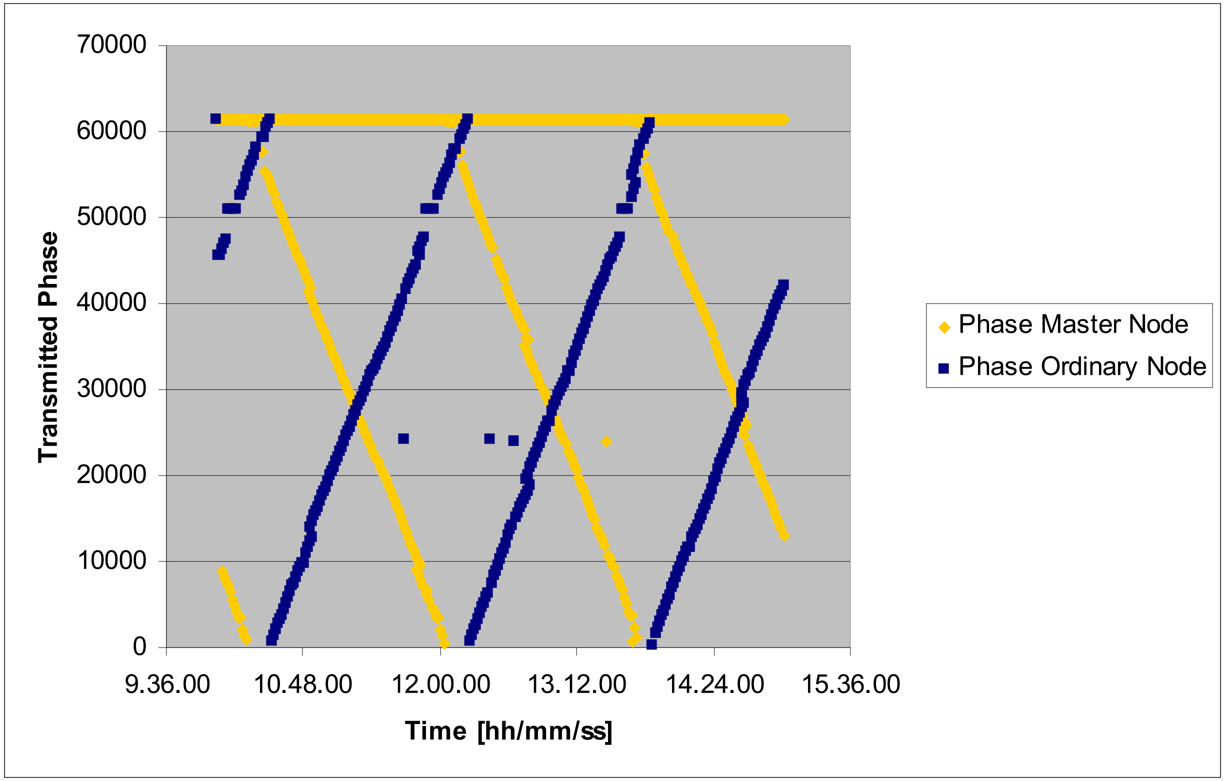
- Duty-cycle dimensioning according to scenario and topology

- **Performance of STAR and STAR+ protocols is better than ATSR**

STAR MAC

Impact evaluation of Phase drift

Master Node vs Ordinary Node (different drift)

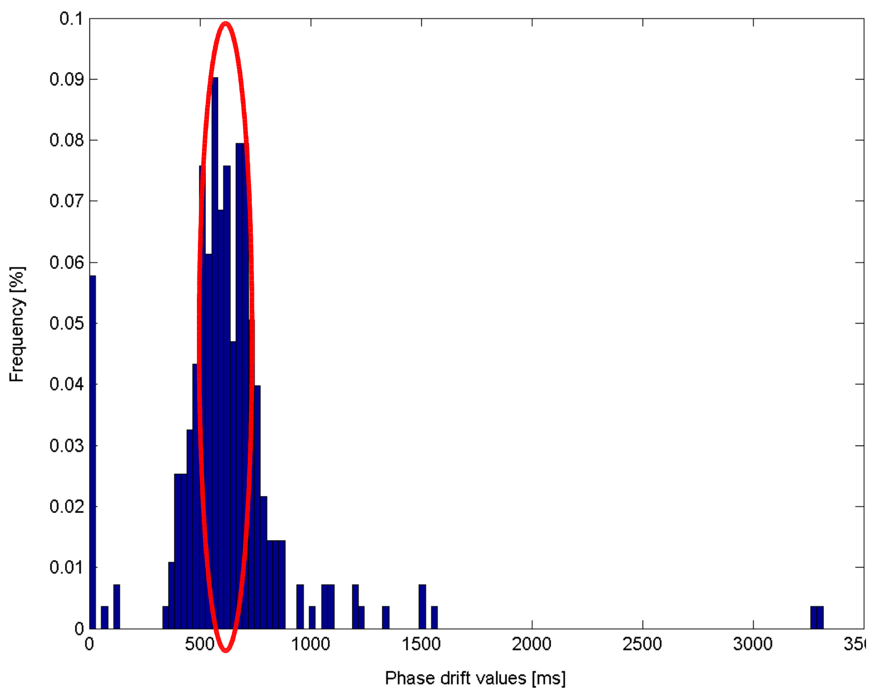


Joint phase drift time diagrams

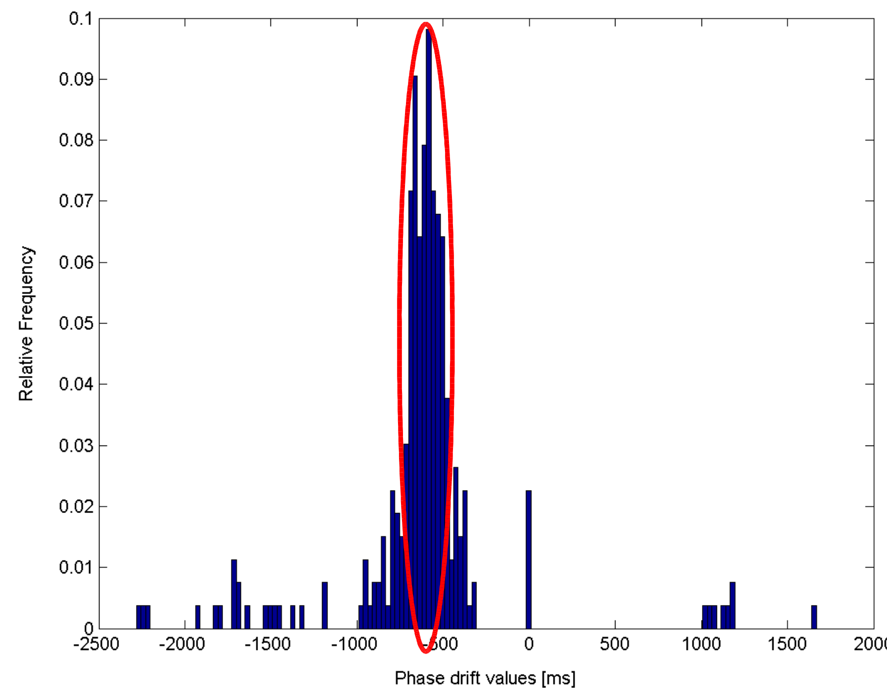
STAR MAC

Impact evaluation of Phase drift

Master Node vs Ordinary Node (different drift)



Ordinary Node Phase drift PDF



Master Node Phase drift PDF

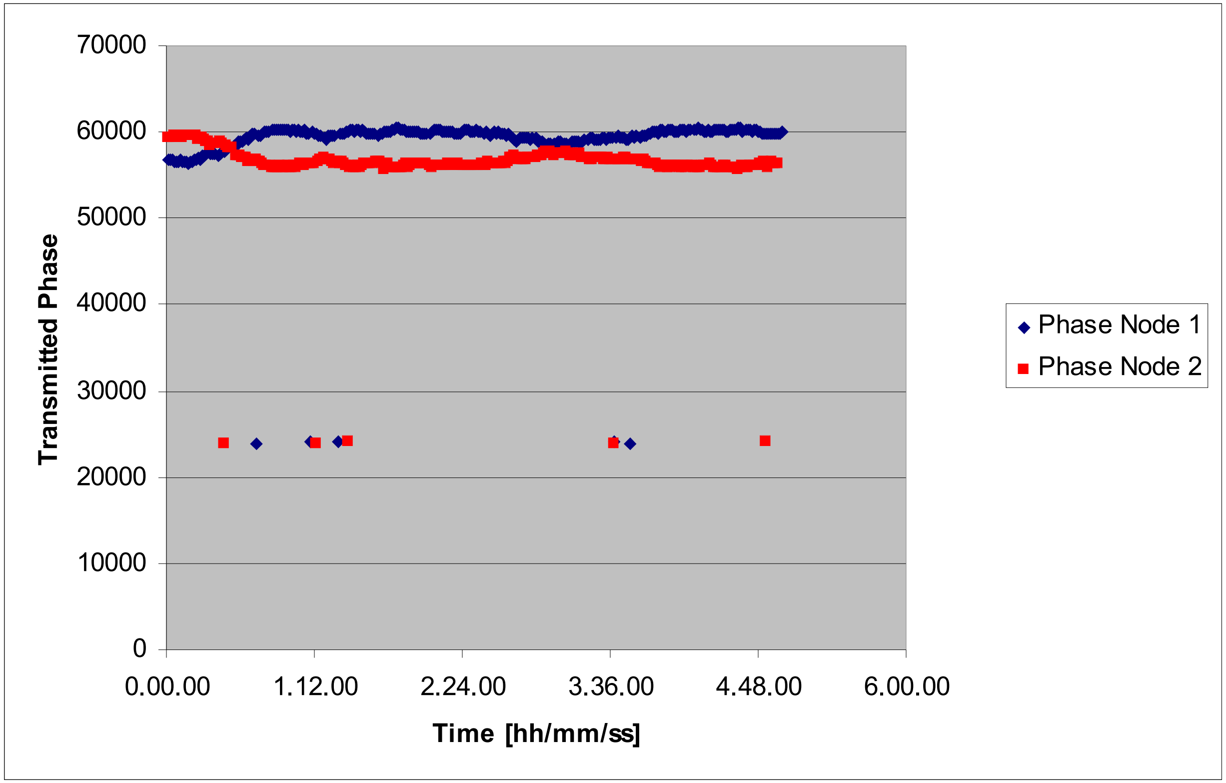
Mean drift (Δ) = 500 ms $\Rightarrow \Delta/T_f = 10\%$

$\Rightarrow$ Node lack after $\lceil \delta/\Delta \rceil T_f$ without STAR MAC synchronization

STAR MAC

Impact evaluation of Phase drift

Ordinary Node vs Ordinary Node (comparable drift)

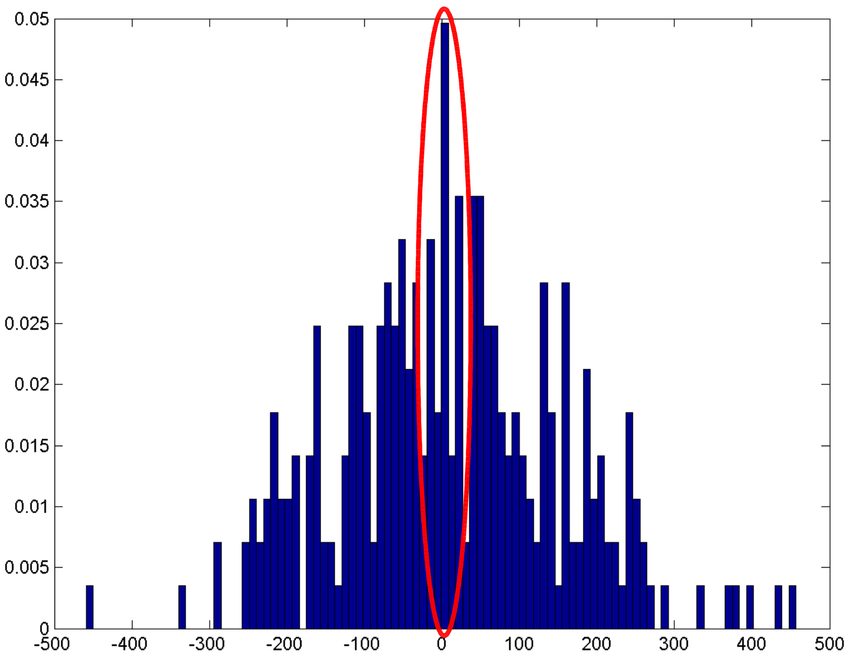


Joint phase drift time diagrams

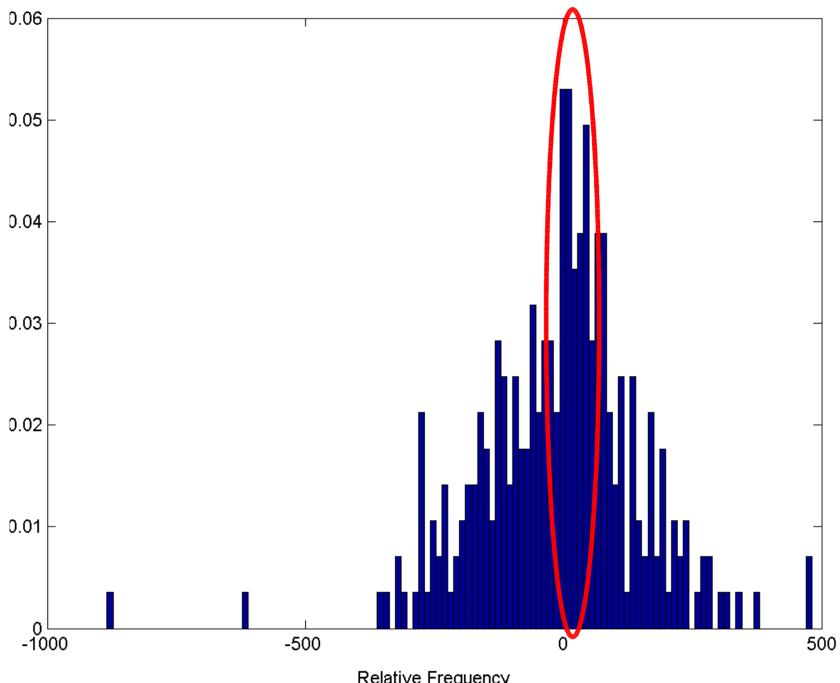
STAR MAC

Impact evaluation of Phase drift

Ordinary Node vs Ordinary Node (comparable drift)



Ordinary Node Phase drift PDF



Master Node Phase drift PDF

Mean drift (Δ) = 0 ms $\Rightarrow \Delta/T_f = 0\%$

Achieved results

- Energy efficient MAC protocols proposal
  - ✓ Analytical modeling and rationales
  - ✓ Parameters tuning
- Object oriented simulator:
  - ✓ Traffic Generators and Map
  - ✓ MAC module
  - ✓ Routing module
- Implementation on MICA2 motes
  - ✓ Stable low power state (10 μA)
  - ✓ STAR MAC implementation
  - ✓ Test bed (3 motes) monitored along 72 h
  - ✓ Test bed (3 motes and traffic generators) monitored along 12 h

Conclusions

Energy efficient MAC protocols proposal (analytical modeling & rationales)

- ✓ **STAR (duty cycle)**
- ✓ **STAR + (multicasting)**

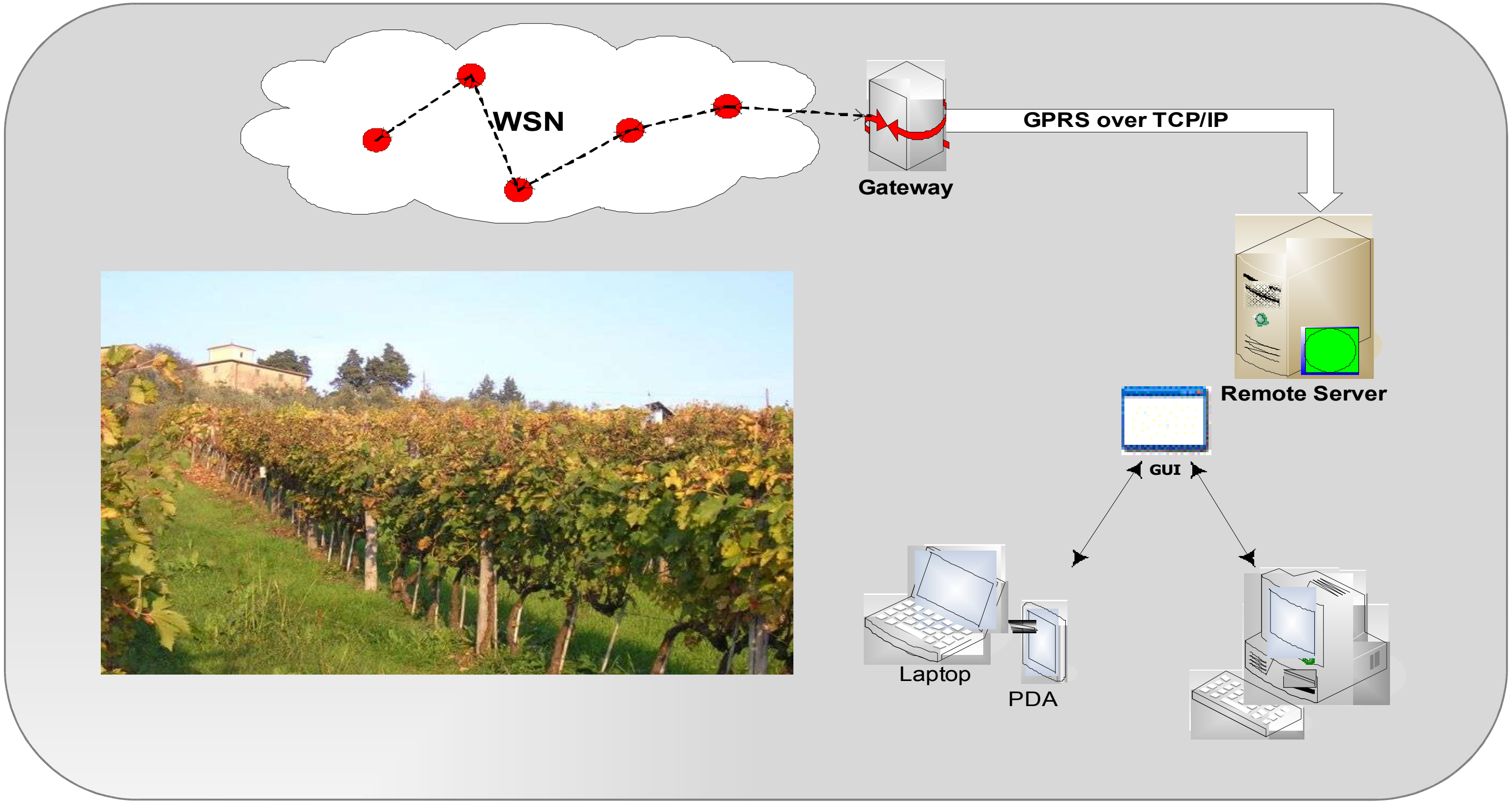
- **Power saving by introducing a sleep state;**
- **Optimization of Frame period;**
- **Duty cycle tuning dependently from the number of neighbors;**
- **Traffic load balancing resorting to multicasting effect (robustness and scalability);**
- **Better self-adaptability and re-configurability;**
- **Higher end-to-end delay.**

Further developments

- ✓ **STAR MAC integration with smart antennas**
- ✓ **Mobile node management**
- ✓ **Basic χ-layer routing protocol implementation:**
  - **synchronous (downstream) sensing**
  - **asynchronous or event-based sensing (upstream + downstream)**
- ✓ **Enhanced routing protocols:**
  - **QoS oriented**
  - **Differentiated services**

Acknowledgments

- FP6-IST-1-508744-IP ***GoodFood***
- FP6-IST-1-507325-NoE ***NEWCOM*** - ***N****etwork of* ***E****xcellence in* ***W****ireless* ***COM****munications*
- FP6-IST-4-027738-NoE ***CRUISE*** - ***CR****eating* ***U****biquitous* ***I****ntelligent* ***S****ensing* ***E****nvironments*



Energy Efficient MAC Protocols Design for Wireless Sensor Networks

Francesco Chiti, Michele Ciabatti*, Giovanni Collodi§, Davide Di Palma*, Romano Fantacci *, Antonio Manes▲*

**Dipartimento di Elettronica e Telecomunicazioni,*
▲Dipartimento di Energetica, §Consorzio MIDRA
Università di Firenze -Via di S. Marta, 3 - 50139 Firenze, Italy

chiti@lenst.det.unfi.it, michele.ciabatti@unifi.it, collodi@ing.unifi.it, davide.dipalma@unifi.it, fantacci@lenst.det.unfi.it, antonio.manes@unifi.it

STAR MAC

Synchronization messages exchange

Master to Ordinary Node (different drift)