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1. Motivation - Energy efficiency

Nodes with limited capabilities
• batteries
• processing
• memory

Managing communication is key
• collaboration is essential
• radio is power hungry

transmit: 10 mA
receive: 4 mA
sleep: 20 μA
Medium Access Control

Reduce overheads:
- idle listening
- collisions
- overhearing
- protocol overhead

CSMA

idle listening time
transmitting time
receiving time
2. Related work: S-MAC

- synchronize clocks
- divide time into frames
- implement duty cycle
  - fixed active period
  - variable frame length
- trade-off: energy vs. throughput/latency

CSMA  
\[ t \rightarrow \]

S-MAC  

: sleeping time
S-MAC problems

- Manual tuning of duty cycle

- Under traffic fluctuations conditions:
  - Too much idle listening
  - Too low throughput
3. Communication patterns

Characteristics:
• little traffic
• fluctuations in time and location
4. Time-out MAC (T-MAC)

Simple policy
- fixed frames
- variable active period
  - time-out interval (TA)

Advantages
- automatic adaptation
- handles traffic fluctuations
4. Time-out MAC (T-MAC)

Basic Protocol

- Periodical wake up and sleep
- Communicating with RTS, CTS and ACK
- A special scheme to decide when should an active period end- no *activation event* has occurred for TA
  - Firing of a periodic timer
  - Reception of any data
  - End-of-transmission or ACK
  - Knowledge of neighbor's transmission has ended
Additional features of T-MAC

- **Fixed contention interval**

  - Transmitting queued msg. in a burst
  - Load is mostly high and does not change
  - RTS starts by waiting a random time within a **fixed** contention interval
Additional features of T-MAC

• RTS Retries

Three causes of no CTS:

- Receiving node misses RTS due to collision
- Receiving node overheard RTS or CTS from others
- The receiving node is asleep

A node should retry by re-sending RTS if it receives no answer. (times of retry=2 in this paper)
Determining of TA

- TA > C+R+T (must be long enough to receive at least the start of the CTS packet)
5. Early-sleeping Problem

Diagram showing the order of events in a protocol, with states such as 'contend', 'RTS', 'CTS', 'DATA', 'ACK', 'active', and 'sleep'. The diagram also includes a label 'TA' and a question mark at the end.
Solution 1: Future request-to-send
Solution 2: Taking priority on full buffer
Solutions Evaluation

FRTS:

• Overhead of DS and FRTS
• More suitable for a reasonably high load and unidirectional communication pattern

Priority on full buffer:

• reduce the prob. Of early sleeping problem
• a limited form of flow control
• Dangerous in a high-load situation
Homogeneous unicast, msglen=20

Load [bytes/node/sec] vs. Energy used [avg. mA/node]

- CSMA: 839 ms, 686 ms, 534 ms, 305 ms, 183 ms
- S-MAC: 3.5, 3, 2.5, 2, 1.5, 1, 0.5
- T-MAC: 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5
Event-based unicast, msglen=100

- CSMA
- S-MAC
- T-MAC

energy used [avg. mA/node]

peak load [bytes/node/sec]
Nodes-to-sink, msglen=20

Energy used [avg. mA/node] vs. load [bytes/node/sec]

- CSMA
- S-MAC
- T-MAC

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Real implementation

CPU: TI MSP490F149 (16 bit, 5MHz)
- 60 KB Flash (code)
- 2 KB RAM (data)

Radio: RFM TR1001 (115 kbps)
- transmit 10 mA
- receive: 4 mA
- sleep: 20 μA
Conclusions

T-MAC
• duty cycle: reduce idle listening
• time-out policy: adapt to traffic fluctuations

Results
• simulations: T-MAC < S-MAC < CSMA
• measurements: up to 96% energy savings

Problems
• Early sleeping problem need new more efficient solutions
• comparison/combination with low-power listening