A COMPREHENSIVE ANALYSIS OF THE MAC UNRELIABILITY PROBLEM IN IEEE 802.15.4. WIRELESS SENSOR NETWORKS

Real-time networks midterm presentation

Supervisor: Decotignie Jean-Dominique

Students: Stojanov Marica
           Takyar Uday
           Agrafiotis Vasileios
           Tsavliri Ypatia

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Roadmap

- WSNs
- Introduction to the research and main results
- Related work
- IEEE 802.15.4 standard
- Performance indices
- MAC unrealibility problem
- CSMA/CA algorithm
- Impact of CSMA/CA parameters
- Problem Mitigation
- Simulation Analysis
- Experimental Analysis
- Conclusions
Wireless sensor networks

- the most promising solution for wireless technologies
- consists of tiny sensor nodes and base stations
- distributed sensing system
Wireless sensor networks

- four key requirements:
  1. energy efficiency
  2. scalability
  3. reliability
  4. timeliness

- predictability = meeting specific deadlines
IEEE 802.15.4 WSNs suffer from a serious unreliability problem, when:
- the power management mechanism is enabled
- the number of sensor nodes in the network is very low

The result: very low packet delivery ratio

caused by the contention based MAC protocol (specifically CSMA/CA algorithm) used for channel access and its default parameter values
The research and main results

- appropriate MAC parameters setting
- achieve a delivery ratio up to 100%
- cost of an increased latency
Related work

- have covered only specific scenarios:
  - no acknowledgments and retransmissions
  - infinitive number of packets to send
  - saturated traffic not concerned, ideal wireless channel
  - focus on CSMA/CA prioritization and only few parameters

- their results:
  - fundamental reasons for MAC unreliability problem
  - proposed solution that does not change standard MAC protocol
  - realistic scenarios concerned
IEEE 802.15.4. standard

- Low-rate, low-power and low-cost PAN
IEEE 802.15.4. standard

2 channel access methods:

- beacon-enabled mode
- nonbeacon-enabled mode

- power management mechanism based on a duty cycle
- superframe structure bounded by beacons
- no superframe
- nodes always active
- unslotted CSMA/CA algorithm for channel access
IEEE 802.15.4. standard

SUPERFRAME

- beacon Interval (BI) – defined by parameter BO
- superframe duration (SD) – defined by parameter SO

active period

- Contention Access Period (CAP)
  - slotted CSMA/CA alg for channel access

inactive period

- Collision Free Period (CFP)
  - Time Division Multiple Access for communication

idle mode
In our analysis, we considered the following indices:

- Delivery Ratio
- Latency
- On-time delivery ratio
- Average energy per packet
Delivery Ratio

- Delivery Ratio =
  Number of data packets correctly received by sink
  -----------------------------
  Total number of data packets generated by all sensor nodes

- Represents network reliability of data collection process
Latency

- Time from when packet transmission started at source node to when same packet is correctly received by the sink.

- Characterises timeliness of the system
On-Time delivery ratio

- Percentage of packets received correctly and within a certain predefined deadline.

- Tells about both reliability and predictability
Average energy per packet

Total energy consumed by each sensor node

Number of data packets correctly delivered to sink

- Measures energy efficiency of WSN
MAC Unreliability Problem

- Analyse performance of 802.15.4 MAC protocol in star network
- Packet Error Rate: 10%, unless specified otherwise
- We compare performance under

  - Traffic
    - Poisson
    - Periodic
  - Power Management
    - Enabled (PMan: On)
    - Disabled (Pman: Off)
Analysis 1: Under different traffic and power management modes
MAC Unreliability Problem

- 802.15.4 MAC protocol, when power management is enabled, is not able to manage contentions efficiently, even when limited number of nodes try to access the wireless channel simultaneously.

- This issue is referred to as MAC unreliability problem.

- Unreliability increases as number of simultaneously contending nodes increases.
PMan: Off  Traffic: Poisson

- **ACK: Off**
  - Delivery Ratio: 90%
  - Due to effect of packet errors (PER equals 10%)

- **ACK: On**
  - Delivery Ratio: Approx 100%
  - Retransmission recover almost all corrupted packets
Traffic: Poisson ACK:Off

- **PMan: Off**
  - ACTIVE
  - Generation
  - Transmission
  - Deferred

- **PMan: On**
  - ACTIVE
  - SLEEP
  - Generation
  - Transmission
  - Deferred

5/23/2011
Traffic: Poisson ACK: Off

<table>
<thead>
<tr>
<th></th>
<th>PMan: Off</th>
<th>PMan: On</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery Ratio</td>
<td>Around 90%</td>
<td>Drops sharply with number of nodes</td>
</tr>
<tr>
<td>Reason</td>
<td>Nodes always active</td>
<td>Packets generated during sleeping time, deferred to beginning of next active period.</td>
</tr>
<tr>
<td></td>
<td>Packets transmitted immediate after generation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Generation time spread along Beacon Interval</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No contention among sensor nodes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>All nodes wake up at the same time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Channel Access attempts tend to become synchronized. Hence contention</td>
</tr>
</tbody>
</table>
Traffic: Periodic PMan: On

- Performance lower than poisson
- When ACK:On, delivery ratio increases for both periodic and poisson case
Analysis 2: Different Beacon Intervals/Duty Cycles

- Different Beacon Intervals (Bl)
- Constant Active Period
- Implies Duty Cycle varies
- Small Bl => Large duty cycle and vice versa
Effect of Beacon Interval

Beacon Interval Increases
Active Period remains same
Duty Cycle Decreases
## Analysis2: Different Beacon Intervals / Duty Cycles

<table>
<thead>
<tr>
<th></th>
<th><strong>Traffic: Poisson</strong></th>
<th><strong>Traffic: Periodic</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delivery Ratio</strong></td>
<td>Close to 100%/90%(ACK On/Off) for fixed no. of nodes when BI small and decreases as BI increases</td>
<td>Independent of BI</td>
</tr>
<tr>
<td><strong>Reason</strong></td>
<td>Packet arrivals spread along beacon interval</td>
<td>All nodes contend for channel access at beginning of active period</td>
</tr>
<tr>
<td></td>
<td>Only nodes which generated packets during their sleeping time, contend simultaneously at beginning of active period</td>
<td></td>
</tr>
<tr>
<td></td>
<td>This is more likely to happen when relative duration of Active period with respect to Beacon Interval is low.</td>
<td></td>
</tr>
</tbody>
</table>
Impact of other parameters on MAC unreliability problem

- Packet Generation Rate
- Packet Size
- Packet error rate
- Periodic packet generation (more realistic than poisson for reporting applications)
- ACK: On
Impact of Packet Generation Rate/Packet Size (Offered load)

- Packet Generation Rate and Packet Size are directly linked to the offered load

- And as we increase the offered load the delivery ratio decreases

- Hence MAC unreliability problem increases
Impact of Packet Error Rate

![Graph showing the impact of Packet Error Rate on delivery ratio versus number of nodes. Different lines represent PER 0%, PER 10%, PER 20%, and PER 30%, with delivery ratio (%) on the y-axis and number of nodes on the x-axis.](image-url)
Impact of Packet Error Rate

- MAC unreliability increases as PER increases
- Since source sensor nodes have to retransmit more frames
- Impact of transmission errors much more apparent when number of sensor nodes low.
- Since when number of nodes is large, the effects of contention predominate over the effect of transmission errors
How to proceed for solution

- MAC unreliability in 802.15.4 WSNs is much more severe than in other contention-based WSNs
- We need to understand fundamental reasons of this behavior, to mitigate negative effects.
- CSMA/CA Algorithm
- Impact of CSMA/CA parameters
CSMA/CA in 3 steps:

Step 1: Initialization of state variables
- contention window, CA=2, only for the slotted variant
- number of backoff stages(NB)
- backoff exponent(BE), BE=macMinBE

Step 2: Initialization of backoff timer
- random time uniformly distributed in the range $[0, 320 \cdot (2^{BE} - 1) \mu s]$
CSMA/CA algorithm

Step 3: Wireless medium state checked by a Clear Channel Assessment (CCA)

- **Medium busy**
  - update of state variables CW, BE and NB,
  - frame dropped if max number of backoff stages exceeded,
  - back to step 2

- **Medium free and unslotted mode**
  - Immediate transmission

- **Medium free and slotted variant**
  - $cw = cw - 1$, transmission only when $cw = 0$ otherwise CCA again
CSMA/CA algorithm

- Unlike 802.11 transmission, not guaranteed at the end of the backoff time if channel is idle.
- Optional retransmission scheme based on acknowledgement and timeouts until the maximum number of retransmissions is reached, `macMaxFrameRetries`.

![Diagram](image.png)
Impact of CSMA/CA parameters

- Impact of each parameter in terms of delivery ratio, energy efficiency and latency

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>macMaxFrameRetries</td>
<td>Constant: 3</td>
<td>Range: 0-7</td>
<td>Maximum number of retransmissions</td>
</tr>
<tr>
<td></td>
<td>(aMaxFrameRetries)</td>
<td>Default: 3</td>
<td></td>
</tr>
<tr>
<td>macMaxCSMABackoffs</td>
<td>Range: 0-5</td>
<td>Range: 0-5</td>
<td>Maximum number of backoff stages</td>
</tr>
<tr>
<td></td>
<td>Default: 4</td>
<td>Default: 4</td>
<td></td>
</tr>
<tr>
<td>macMaxBE</td>
<td>Constant: 5</td>
<td>Range: 3-8</td>
<td>Maximum backoff window exponent</td>
</tr>
<tr>
<td></td>
<td>(aMaxBE)</td>
<td>Default: 5</td>
<td></td>
</tr>
<tr>
<td>macMinBE</td>
<td>Range: 0-3</td>
<td>Range: 0-7</td>
<td>Minimum backoff window exponent</td>
</tr>
<tr>
<td></td>
<td>Default: 3</td>
<td>Default: 3</td>
<td></td>
</tr>
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</table>
Impact of CSMA/CA parameters

- `macMaxFrameRetries` parameter
  - Increasing the parameter values larger than one has no significant effect to the delivery ration unless PER is very high (> 30%)
Impact of CSMA/CA parameters

- `macMaxCSMABackoffs` parameter
  - linear increase in the delivery ratio, a better energy efficiency and increase in latency
Impact of CSMA/CA parameters

- **macMaxBE parameter**
  - delivery ratio increases up to values close to 100%
  - packet latency increases and energy consumption decrease
Impact of CSMA/CA parameters

- macMinBE parameter
  - delivery ratio increases up to values close to 100%
  - packet latency increases and energy consumption decrease
Problem Mitigation

 Serious MAC unreliability problem due to CSMA/CA
 CSMA/CA protocol parameter values directly affect:
   Delivery ratio
   Latency
   Power Consumption

 Question:
   Can a more appropriate CSMA/CA parameters setting mitigate the problem without unacceptable side effects?
Simulation Analysis (1)

- 3 different sets of CSMA/CA parameter values:
  - Default Parameters Set (DPS)
  - Standard Parameters Set (SPS)
    - Maximum values compliant with 802.15.4
  - Non-standard Parameters Set (NPS)
    - Non compliant with 802.15.4
- Star Network, PER Values : 0%, 30%

<table>
<thead>
<tr>
<th>Parameter set</th>
<th>macMinBE</th>
<th>macMaxBE</th>
<th>macMaxCSMABackoffs</th>
<th>macMaxFrameRetries</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPS</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>SPS</td>
<td>7</td>
<td>8</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>NPS</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Simulation Analysis (2)

- DPS -> SPS: dramatic increase
- SPS << 100% when:
  - Many nodes
  - Unreliable channel
- NPS ~ 100% in all cases

- Large average packet latency for SPS, NPS
- 99th percentile of latency distribution:
  - 0.7s for SPS
  - 1.2s for NPS
Simulation Analysis (3)

- Energy consumption trend:
  - DPS $\to$ SPS: significant decrease
  - Reason: Increase in delivery ratio
  - Extra energy consumption is largely compensated
First Conclusions

1. Severe MAC unreliability problem when default parameter values (DPS) are used.

2. Problem mitigated when setting more appropriate parameter values
   - Delivery ratio up to 100%
   - Higher latency

3. Reliability and timeliness in the same time cannot be guaranteed.

Need for problem and proposed solution validation
- Measurements on a real Wireless Sensor Network (WSN)
Experimental Analysis (1)

- Same star network scenario
- Tmote Sky sensor nodes
  - Chipcon CC2420 radio transceiver
  - 250 Kbps bit rate, 2.4 GHz ISM band
  - TinyOS 2.x
  - TKN15.4 802.15.4 MAC protocol implementation

- Working environment with sources of interfering signals (e.g. WiFi)
- PER estimate = beacon loss rate
Experimental Analysis (2)

- Retransmission Mechanism ON/OFF
- Same trend of simulation and experiment curves
Experimental Analysis (3)

- SPS, NPS ~ 100% Delivery ratio
- Only small WSN analyzed (up to 16 nodes)
- Simulation trend confirmed
- Slightly higher packet latency in experimental results (*clock misalignment*)
Experimental Analysis (4)

- Again WSN more efficient for SPS and NPS
- Energy consumption worse in experimental
  - Due to worse packet latency
Experiment confirmed simulation conclusions:

1. CSMA/CA parameter setting suggested by IEEE 802.15.4 render the WSN unreliable when:
   - Power management in enabled
   - Many nodes are simultaneously contending

2. Appropriate parameter setting can bring up to 100% delivery ratio. But:
   - Higher latency => Inappropriate for industrial applications with stringent latency requirements

Future research: Adaptive scheme to dynamically tune MAC parameters to meet each application requirements
References

- http://www.escotal.com/networking.html
- http://users.crhc.illinois.edu/thkim/pub/CL07.pdf
Questions?