Wireless Sensor Networks

Roberto Verdone
www.robertoverdone.org
roberto.verdone@unibo.it
+39 051 20 93817

Office Hours:
Monday 4 – 6 pm @ “CSITE” Building within main campus, first floor

Credits: 6

Outline

1. Random Access
2. 802.15.4 MAC
3. 802.15.4 MAC Performance
Section 1
Random Access

Random Access: ALOHA and CSMA

ALOHA
S-ALOHA

CSMA
CSMA/CA
CSMA/CA with RTS/CTS
Random Access: ALOHA

Whenever a node has a packet put in the data link layer buffer, it broadcasts it. Collisions (i.e. partial or total overlap between packet transmissions by separate sources) may occur, with probability $P_{\text{collA}}$. In an interference-limited environment, packet losses (i.e. events of packets not captured by the receiver because of C/I below capture threshold) may occur, with probability $P_{\text{lossA}} < P_{\text{collA}}$.

Random Access: Slotted ALOHA

Time is slotted. Whenever a node has a packet put in the data link layer buffer, it broadcasts it starting from instant when next slot initiates. Collisions (i.e. total overlap between packet transmissions by separate sources) may occur, with probability $P_{\text{collSA}}$. In an interference-limited environment, packet losses (i.e. events of packets not captured by the receiver because of C/I below capture threshold) may occur, with probability $P_{\text{lossSA}} < P_{\text{collSA}}$.
Random Access: CSMA

Whenever a node has a packet put in the data link layer buffer, it starts sensing the carrier. When it detects the channel is free, it broadcasts the packet. Collisions may occur if two nodes stop sensing the carrier simultaneously, with probability $P_{\text{coll}}$.

$P_{\text{coll}}$ can not be reduced to zero unless collision resolution algorithms are used. In an interference-limited environment, packet losses may occur, with probability $P_{\text{loss}} < P_{\text{coll}}$.

Random Access: CSMA/CA

Whenever a node has a packet put in the data link layer buffer, it starts sensing the carrier. When it detects the channel is free, a backoff phase (i.e. transmission is deferred by a random delay) is initiated; at its end, the node broadcasts the packet. Collisions may occur with probability $P_{\text{coll}}$.

Large backoffs can reduce collisions deliberately ($P_{\text{coll}}$ can be reduced to zero). In an interference-limited environment, packet losses may occur, with probability $P_{\text{loss}} < P_{\text{coll}}$.
Random Access: CSMA – Hidden Terminal Problem

Even if backoff could solve collision problems in a perfect broadcast channel (every node is within range of all others), hidden nodes might cause collisions in an environment where transmission ranges do not cover the whole network. An hidden node (Z) is a node, willing to transmit to a given terminal (Y), which does not sense the transmission from a given source (A) to an other node (B) because received power (from A) is too small, but the node receiving both packets (B) is within range of both transmitting nodes (A and Z) and detects a collision.

Random Access: CSMA with CTS/RTS

Whenever a node has a packet put in the data link layer buffer, it starts sensing the carrier. When it detects the channel is free, a backoff phase is initiated; at its end, the node sends a short RTS packet informing everyone within its range to avoid transmission for a packet time. The receiver responds with a short CTS packet allowing transmission and informing everyone within its range to avoid transmission for a packet time. Upon reception of the CTS, the source node broadcasts the packet. All nodes within range of receiver know that have to wait before transmitting a RTS.
Random Access: CSMA – Exposed Terminal Problem

If a node (A) willing to transmit a packet to a given sink (B), broadcasts the RTS, all other nodes within its range will refrain from transmitting. On the other hand, there might be a node (Y) willing to transmit to a sink (Z) which would not detect a collision because it is not within range of the interferer (A), which refrains from transmitting though its transmission would not be a problem because its (Y’s) range does not include the other link’s sink (B). CSMA would work better in this case. CSMA/CA with RTS/CTS reduces throughput.

Random Access: CSMA with CTS/RTS

RTS / CTS mode is a powerful tool but must be used with care, dimensioning the transmit power of such short packets so as to keep refrained from transmitting only those nodes that would really cause packet loss.

Particular problems may arise in multi hop networks. Case study follows.
Section 2
802.15.4 MAC

IEEE 802.15.4 - MAC

Beacon-Enabled Mode

- Approx. duration: 15 ms – 250 s

- Superframe
  - Frame Beacons
  - 16 slots, 960 * 2^SO µs each

- Contention Access Period
- Contention Free Period

SO = 0, 1, …, 14
[Superframe Order]

Non Beacon-Enabled Mode

- Maximum 7 GTSs
  - (Granted Time Slots)

- Only CAP, with (unslotted) CSMA/CA
IEEE 802.15.4 – Network Topologies

A Network (PAN) is managed by a coordinator

RFD
Reduced function device
• Reduced functionalities
• Battery – powered
• No forwarding

FFD
Full function device
• All functionalities implemented
• Forwarding
• Can play the role of coordinators

IEEE 802.15.4 – Network Topologies

Star

Mesh

Tree

PAN Coordinator
Full Function Device
Reduced Function Device
IEEE 802.15.4 – Network Topologies

- PAN Coordinator
- Full Function Device
- Reduced Function Device

Tree

IEEE 802.15.4 - MAC (Beacon Enabled Mode)

- A number $N_{GTS}$ (maximum 7) of Guaranteed Time Slots (GTSs)

- Superframe duration: 16 slots, $960 \times 2^{SO}$ us each

- Beacon Interval: $BO = 0, 1, \ldots, 14$ [Beacon Order]

- Inactive part

- Beacon Order $BO$

- Superframe Order $SO$

- Guaranteed Time Slots $GTS$
IEEE 802.15.4 - MAC (Beacon Enabled Mode)

Superframe duration

Parent

Beacon Interval

Child

Beacon tracking

Beacon Tx offset

IEEE 802.15.4 - MAC (Beacon Enabled Mode)

PAN Coordinator

$N_R$ routers

Level 1 nodes

$2^{BO} \geq (N_R + 1) \cdot 2^{SO}.$
IEEE 802.15.4 – Addressing

**ADDRESSES**

Extended, 64 bits  
(more than 128 billion devices).  
Short, 16 bits  
(more than 65000 devices connected to one coordinator)

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IEEE 802.15.4 – Network Topologies

- **Star**
- PAN Coordinator
- Full Function Device
- Reduced Function Device
Wireless Sensor Networks

IEEE 802.15.4 – Data Exchange

Beacon-Enabled Net

Coordinator

Network Device

Beacon

Data

Acknowledgment (optional)

Non Beacon-Enabled Net

Coordinator

Network Device

Data

Acknowledgment (optional)

IEEE 802.15.4 – Data Exchange

Beacon-Enabled Net

Coordinator

Network Device

Beacon

Data Request

Acknowledgment

Data

Acknowledgment

Non Beacon-Enabled Net

Coordinator

Network Device

Data Request

Acknowledgment

Data

Acknowledgment
**Beacon-Enabled Mode:** slotted CSMA/CA

- NB counts the number of times the node tries to access the channel
- BE used to derive the backoff time
- CW used so that two sensing phases are performed before the transmission

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**Beacon-Enabled Mode:** slotted CSMA/CA

- **Beacon**
  - Back-off
  - Sensing
  - Transmission

- Back-off Time = random $[0, 2^{BE-1}] \times$ Back-off Period
- Back-off Period = 20 $T_S$
- Sensing Period = 20 $T_S$

$T_S$ (symbol period) = 16 $\mu$s.
Non Beacon-Enabled Mode: unslotted CSMA/CA

- NB=0, BE=BEmax
- Delay for max \((2^{\text{BE}} - 1)\) backoff periods
- Perform sensing
- Channel idle?
  - Y: Success
  - N: NB=NB+1, BE=min(BE+1, BEmax)
- NB>NBmax?
  - Y: Failure
  - N: Continue

Section 3
802.15.4 MAC Performance
Scenario studied

Assumptions:
- Star topology
- No hidden terminal node problem
- Query-Based traffic
- Both BE and non-BE modes are considered

Objective

Evaluation of statistics of the arrival times of packets received by the sink in the IEEE 802.15.4 network (Non Beacon Enabled Mode)
CSMA/CA: Non Beacon-Enabled mode

Query

BO  S  BO  BO  S  Tx  Tx  Idle

T  T  D * T

T_q

T = 320 μs → SLOT

Packet size = D * 10 Bytes (D integer)

Performance Metrics

\[ P(T_i) := \text{Probability that a node transmits its packet in slot } j \]

\[ P(Z_i) := \text{Probability that a node transmits its packet with success in slot } j \]

Cumulative Functions:

\[ F_T(j) := \text{Probability that a node transmits its packet within slot } j \]

\[ F_Z(j) := \text{Probability that a node transmits its packet with success within slot } j \]
Generic state: $Q(t) = \{BO_c, BO_s, t\}$

- **$BO_c$** → Backoff Counter
  (initial value uniformly distributed in $(0, W_i = 2^{BE_i} - 1)$)

- **$BO_s$** → Backoff Stage $\rightarrow$ Different $W_i$

- $t$ → Time expressed in number of slots, having size $20T_s$

<table>
<thead>
<tr>
<th>$BO_s$</th>
<th>$NB$</th>
<th>$BE$</th>
<th>$W_{NB} = 2^{BE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$BE_{min}$</td>
<td>$W_0 = 2^{BE_{min}}$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$BE_{min} + 1$</td>
<td>$W_1 = 2^{BE_{min}+1}$</td>
</tr>
<tr>
<td>$NB_{max}$</td>
<td>$NB_{max}$</td>
<td>$BE_{max}$</td>
<td>$W_{NB_{max}} = 2^{BE_{max}}$</td>
</tr>
</tbody>
</table>

$P(C_j)$ := Probability of being in sensing in slot $j$

$P(S_{ij}) = P(0, i, j)$ := Probability of being in sensing in slot $j$ at the $i$-th backoff stage

$p_j^b :=$ Probability that the channel is busy in slot $j$
Transition Diagram (BO_s=0)

Transition Diagram (BO_s=1)
… the probabilities $P(S_i)$ and the probabilities $P(C_j)$ given by:

$$P(C^j) = \sum_{i=0}^{NB_{max}} P(S_i^j).$$

... and the probabilities $p_b^j$ given by:

$$p_b^j = 1 - \left[p_b^{j-1} + (1 - p_b^{j-1}) \prod_{i=0}^{NB_{max}} (1 - P(S_i^{j-1}))^{N_b-1}\right]$$
Traffic statistic

\[ P[Z_j] := \text{Probability that a node transmits its packet with success in slot } j \]

\[
P[Z_j] = (1 - p_j)^{Z_j} \prod_{i=0}^{N_{\text{max}}} (1 - P[S_i^{j-1}])^{N_i - 1}
\]

Non Beacon-Enabled: \( P(T) \)

j = 10 equivalent to 3.2 ms
Non Beacon-Enabled: $P(T'_j)$

\[ P(T'_j) = 10 \text{ equivalent to 3.2 ms} \]

Non Beacon-Enabled: $P(Z'_j)$

\[ P(Z'_j) = 10 \text{ equivalent to 3.2 ms} \]
Non Beacon-Enabled: $F_r(j)$

![Graph showing the comparison between simulation and model results for different values of N and D.

Objective

Evaluation of the trade-off between success probability and energy consumption (Non Beacon-Enabled Mode)
Performance Metrics

\[ p_s = \text{Probability that a packet is correctly received by the PAN coordinator} \]

\[ E_{\text{mean}} = \text{Mean Energy spent by a node in } T_q \]

\[ E^j_q = P_t \cdot \frac{D \cdot N_{\text{lat}}}{R_b} \cdot P(T^j) \]

\[ E^{(\text{mean})}_q = \sum_{k=0}^{\ell_{\text{max}}+D-1} E^j_q + E^j_q + E^j_q \]

\[ E^j_q = P_s \cdot \frac{N_{\text{lat}}}{R_b} \cdot (1 - b^{-D}) \sum_{k=0}^{N_{\text{ran}} - D} (j - k - D) \cdot P(S^j_k - D) \]

\[ E^j_q = P_s \cdot \frac{N_{\text{lat}}}{R_b} \cdot (1 - b^{-D}) \sum_{k=0}^{N_{\text{ran}} - D} (k + 1) \cdot P(S^j_k - D) \]

Success Probability

\[ W_i \text{ increases} \]

\[ W_i \text{ standard} \]

Non exponential BO

Exponential BO

\[ P_s \]

\[ W_{\text{exp}} W=16 \]

\[ W=16 \]

\[ W_{\text{exp}} W=8 \text{ (default)} \]

\[ W=8 \]

\[ W_{\text{exp}} W=4 \]

\[ W=4 \]
Mean Energy spent

![Graph showing energy spent vs. N with different W parameters]

**Objective**

Comparison between Beacon-Enabled and Non Beacon-Enabled Modes
Performance Metrics

\[ p_s = \text{Probability that a packet is correctly received by the PAN coordinator} \]
Non Beacon-Enabled Mode: $p_s$

$N$ = number of nodes in the network

$D = 2$ or 10