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Power Management

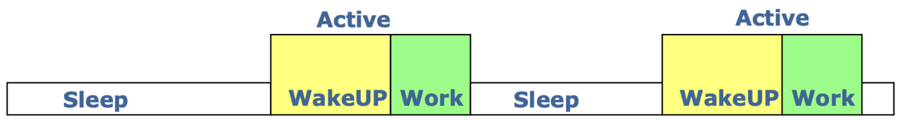


Figure 1: power-model-of-operation

- $T_{active} = T_{wakeup} + T_{work}$
- $\delta = f_{active} = \frac{T_{active}}{T_{cycle}}$
- $T_{sleep} = T_{cycle} - T_{active}$
- $P_{AVG} = f_{sleep} \cdot P_{sleep} + f_{wakeup} \cdot P_{wakeup} + f_{work} \cdot P_{work}$
- $LIFETIME = \frac{ENERGYSTORE}{P_{AVG} - P_{GEN}}$
- $E_{TX/RX} = P_{TX} \cdot (T_{wakeup} + T_{tx}) + [P_o T_{tx}]$

  We have the optional component only if we're transmitting, since P_o is the output power of the transmitter.

If we want to find the energy required to transmit a packet of L bits and if we define T_L the time needed to transmit a single packet:

- $E_c = E_{TX} = E_{RX} = P_{TX/RX}(T_{wakeup} + T_{TX/RX})$

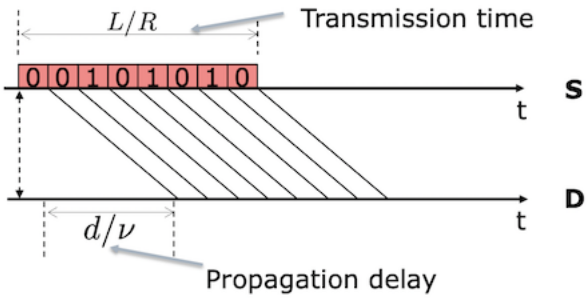
  E_c is the energy required to operate the TX/RX circuitry.
- $E_o = P_o T_L$
- $E_{wakeup} = P_{TX} T_{wakeup}$
- $E_{TX} = P_{TX} T_L$
- $E_{per\ BIT} = P_{TX} T_L$

Packet Error Rate (PER):

$PER = 1 - (1 - BER)^l$

Where $1 - BER$ is the probability to transmit correctly one bit.

COAP/MQTT



T: Delivery time, it depends on transmission time (L/R) and on propagation time (d/v):

$T = L/R + d/v$

Where:

- L: packet size [bits]
- R: throughput [bits/sec]
- d: distance between nodes [m]
- v: propagation speed [m/sec]

ZigBee

$$A(d) = \begin{cases} 1 + D_{\mathrm{m}} + R_{\mathrm{m}} & \text{if } d = L_{\mathrm{m}} - 1 \\ 1 + D_{\mathrm{m}} + R_{\mathrm{m}} A(d+1) & \text{if } 0 \leqslant d < L_{\mathrm{m}} - 1 \end{cases}$$

Where:

- L_m : maximum depth of the tree.
- R_m : maximum number of child routers;
- D_m : maximum number of child end-devices;

From the formula we can see that we start counting addresses starting from the second-last level of tree. For example, given $L_m = 3$:

$$A(2) = 1 + D_m + R_m A(1) = 1 + D_m + R_m \cdot A(2) A(0) = 1 + D_m + R_m \cdot A(1)$$

Notice that $A(0)$ device are the child nodes of the PAN coordinator.

MAC Layer Access (Beacon Enabled Mode)

1. **Collision Access Part** (**CAP**): random access through CSMA/CA;

2. **Collision Free Part** (**CFP**): access guaranteed via two groups of time slots, called **GTS**(**Guaranteed Time Slots**), one for uplink transmission and one for downink transmission.

During the inactive part nodes are sleeping.

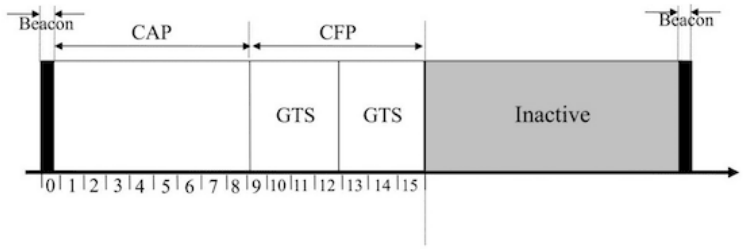


Figure 2: Beacon Interval

CSMA/CA

The procedure

- **NB**: number of consecutive times a device backoffs, which means that the device tried to access the channel but it was busy (initialized to zero before every transmission attempt);
- **CW**: Contention window length, tells how long carrier sensing should be performed. It defines the number of consecutive backoff periods that need to be sensed before some devices access the channel. Note that it is initialized to 2 (so the device will need to wait for 2 CW Consecutive time-slots, also called **backoff periods**) and only taken into account by **Slotted CSMA/CA**.
- **BE**: backoff exponent, how long to wait between each failed channel access attempt.

Procedure in case a node wants to transmit:

1. $NB = 0$, $CW = 2$, the node that wants to transmit before starting the transmission waits a random number of **backoff periods** between $[0, 2^{BE} - 1]$.
2. After the initial random delay the device performs carrier sensing: if the channel is free for CW consecutive backoff periods, node transmits and waits for an ACK.
3. If the channel is not free, both BE and NB are incremented and the procedure is repeated.
4. If the number of attempts is greater than NB_{max} the packet is discarded.

Formulas

1. **Probability of accessing the channel under CSMA/CA**

   - p_{busy}: probability of finding the channel busy at each backoff period;
   - $P_{idle} = (1 - p_{busy})^2$: probability that the channel is idle two times in a row, given that CW is initialized to 2.

     Since if the channel is sensed free for CW (which is initialized to 2) consecutive backoff periods the station accesses the channel, P_{succ} is also the probability of accessing successfully the channel within the first try.

   - $P_{succ}(i)$: The probability that the backoff procedure ends at the $i - th$ attempt:
     $$P_{succ}(i) = P_{idle}(1 - P_{idle})^{(i-1)}$$
     Which is the conditioned probability that the i-th attempt is succesful and the $i - 1$ attempts before went wrong. Note that CW remains the same after each failed attempt, while BE and NB gets increased.

2. **Average time after which a sensor access the channel (given ∞ possible backoff attempts)**

   $$E[T] = 2P_{idle} + \sum_{i=2}^{\infty} (1 - P_{idle})^{i-1} P_{idle} \left[2 + (i-1)1.5 + \sum_{k=2}^{i} \frac{2^k - 1}{2} \right]$$

3. **Transmission Time**: $T_{tx} = \frac{L}{R}$ (L packet length[bit], R throughput [bit/s])

4. **number of slots needed by a generic mote i:**

   $n_i = \frac{R_{mote}}{R_{min}}$

   As a consequence the total number of slots needed in a BI is the sum of all the slots needed by individual motes in the network.

5. **Slot Size**: $T_s = \frac{L}{R}$ (L packet length, R nominal data rate)

6. **Beacon Interval**: $BI = \frac{L}{r_{\min}}$ ($r_{\min}$ = minimum rate among all motes of the PAN)

7. **Energy Consumption**

   Usually motes generates packets according to a Poisson process with a rate of λ [packets/s]. To find out the energy consumed by a specific mote we need to find out if the mote is idle or if it's transmitting. Let's define with P_1 the probability that a generic mote has no packet ready:

   $$P_0 = P(N(BI) = 0) = e^{-\lambda \cdot BI}$$

Where $N(BI)$ is the number of packets generated by that mote in that specific beacon interval. The to find the power consumption of that mote, when it comes to taking into account the time slots (assuming it only has one time slot available) in which the mote is supposed to transmit we'll do the following:

$$E_{AVG} = \cdots + P_0 \cdot E_{idle} + (1 - P_0) \cdot E_{tx} + \ldots$$

This works in case the mote has one slot assigned for transmitting.

If for example the mote has 2 slots available at each BI, we need to sum the probability of having zero packet ready (idle in both slots), just one packet ready (idle in one slot, transmitting in the other one), or two packets ready (transmitting in both slots):

$P_0 = P(N(BI) = 0) = e^{-\lambda \cdot BI}$

$P_1 = P(N(BI) = 1) = -\lambda e^{-\lambda \cdot BI}$

$P_2 = P(N(BI) = 2) = 1 - P_0 - P_1 = 1 - e^{-\lambda \cdot BI} + \lambda e^{-\lambda \cdot BI}$

$E_{AVG} = \cdots + 2P_0 E_{idle} + P_1(E_{idle} + E_{tx}) + 2P_2 E_{tx} + \ldots$

6LowPan

1. **ETX**: Average number of transmission attempt to successfully transmit a packet.

$$ETX = \frac{1}{(1-p)(1-q)}$$

- p: packet error probability from A to B
- q: packet error probability from B to A

Moreover $ETX = \frac{1}{1-BER}$. This means that both ETX and ETT are directly proportional to the BER.

ETT: average time required to send a packet over a link.

$$ETT = ETX \cdot RTT$$

RFID

1. **Tag Arbitration Efficiency**

   $\eta = \frac{N}{L_N}$

   Where N = tag population size, L_N length of the arbitration period (i.e. the number of slots needed for all the tags to transmit without conflicts).

2. **Average throughput** (single frame ALOHA):

   - $E[S] = n\left(1 - \frac{1}{r}\right)^{n-1}$, maximum for $r = n$

- $\eta = \frac{E[S]}{r}$

3. **Schoute's Estimate**

   $H = \frac{\left(1-e^{-1}\right)}{1-2e^{-1}} = 2.39 \rightarrow n_{est} = \text{round}(2.39 \cdot c)$

   Where c is the number of collided slots.

4. **Dynamic Frame Aloha**

   λ is the number of tags that transmits in a slot, approximated by a Poisson distribution. The average tag resolution process can be recursively calculated as:

$$L_n = r + \sum_{i=0}^{N-1} P(S = i) L_{N-i}$$

   which leads to:

$$L_n = \frac{r + \sum_{i=1}^{n-1} P(S = i) L_{n-i}}{1 - P(S = 0)}$$

The probability that given X tags, they transmit in a colliding slot is:

$$P(X = i \mid X \geq 2) = \frac{\lambda}{i!} e^{-\lambda} \frac{1}{1 - \lambda e^{-\lambda} - e^{-\lambda}}$$

And the expected value of transmitting tags in a colliding slot is given by:

$$E[X \mid X \geq 2] = \sum_{i=0}^{\infty} i \frac{\lambda}{i!} e^{-\lambda} \frac{1}{1 - \lambda e^{-\lambda} - e^{-\lambda}} = \frac{\lambda - \lambda e^{-\lambda}}{1 - \lambda e^{-\lambda} - e^{-\lambda}} = H$$

If we consider $\lambda \neq 1$ [terminal/slot] :

$$P(X = i \mid X \geq 2) = \frac{P(X \geq 2 \mid X = i) P(X = i)}{P(X \geq 2)}$$

Where:

- $P(X \geq 2 \mid X = i) = \begin{cases} 1 & \text{if } i \geq 2 \\ 0 & \text{else} \end{cases}$
- $P(X = i) = \frac{1^i}{i!} e^{-1}$
- $P(X \geq 2) = 1 - 2e^{-1}$

And:

$$\hat{H} = E[X \mid X \geq 2] = \sum_{i=0}^{\infty} i \cdot P(X = i \mid X \geq 2) = \frac{1 - e^{-1}}{1 - 2e^{-1}}$$