Projects

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1 Project 1. duty-cycle MAC protocols - Energy conservation

The objective of this project is to optimize a duty-cycle MAC protocol in order to minimize energy consumption and e2e delay.

1.1 Network Model

Let us consider an unsaturated network with low traffic, which is typical of WSN applications. For a sake of simplicity, a ring topology is adopted following the same analysis as in [3], although our modeling can be easily adapted to other network topologies, e.g. random topology or grid topology. A spanning tree is constructed, where nodes are static and maintain a unique path to the sink and use the shortest path routing with a maximum length of D hops; the depth or number of rings of the tree. We assume a network with size of N nodes, a uniform node density on the plane and a unit disk graph communication model. There are C+1 nodes, in average, on the unit disk. Hence, all nodes are in communication range with an average number of neighbors, C, except the leaf nodes. The nodes are layered into levels according to their distance to the sink in terms of minimal hop count, d (d=1,...,D), where d =0 is reserved for the sink.

Let us consider periodic traffic generation. That is to say, every source node generates traffic with frequency F_s. According to this, we will use in our modeling the same input F_I^d, output F_{out}^d, background F_B^d traffic and input links I^d equations for every node as derived in [3]. The different symbols introduced in the analysis related to network and traffic model are summarized in Table 1 with typical values. The neighboring nodes, then, can be classified as the set of children (input) nodes I and the set of overheard (background) nodes, B, such that, $C = |I| + |B|$.

Assuming a ring topology, let us define the following parameters; N_d is the number of nodes in ring d:

$$N_d = \begin{cases} 1 & \text{if d=0,} \\ Cd^2 - C(d-1)^2 = (2d-1)C & \text{otherwise.} \end{cases} \quad (1)$$

The average number of input links at a node at level d is:

$$I_d = \begin{cases} 0 & \text{if d=D,} \\ C & \text{if d=0,} \\ \frac{N_{d+1}}{N_d} = \frac{2d+1}{2d-1} & \text{otherwise.} \end{cases} \quad (2)$$

Assuming a sampling rate of F_s, the output frequency defined as the number of packets that leaves a node is:

$$F^d_{out} = \begin{cases} F_s & \text{if d=D,} \\ F^d_I + F_s = I_d F^{d+1}_{out} + F_s = F_s \frac{(D^2-d^2+2d-1)}{(2d-1)} & \text{otherwise.} \end{cases} \quad (3)$$

and thus the input frequency, F^d_I, defined as the number of packets that enter a node is:

$$F^d_I = \begin{cases} F_s D^2 C & \text{if d=0,} \\ I_d F^{d+1}_{out} = F_s \frac{(D^2-d^2)}{(2d-1)} & \text{otherwise.} \end{cases} \quad (4)$$

Finally, the aggregated background traffic frequency is: $F^d_B = B^d F^d_{out} = (C - I_d) F^d_{out}$, where B^d is the average number of background nodes. Table 1 summarizes the different parameters.

(a)

CC2420 Radio	**Parameter Description**	**Values**
R	Rate [kbyte/s]	31.25
T_{cs}	Time [ms] to turn the radio on and probe the channel (carrier sense)	2.60
T_{up}	Time [ms] to turn the radio on into RX or TX	2.40
L_{pbl}	Packet preamble length [byte]	4
Traffic & Network	**Parameter Description**	**Values**
P	data payload [byte]	32
F_s	Sampling rate [pkt/node/min]	F^*_s
F^d_I	Node's Input Traffic Frequency at level d	$F^d_{out} - F_s{=}F_s \frac{D^2-d^2}{2d-1}$
F^d_{out}	Node's Output Traffic Frequency at level d	$F_s \frac{D^2-d^2+2d-1}{2d-1}$
F^d_B	Background Node's Traffic Frequency at level d	$\lvert B^d \rvert F^d_{out} {=} C - \lvert I_d \rvert F^d_{out}$
N	Network Size (number of nodes) [#nodes]	200-512
D	Network Depth [#levels]	5-8
C	Network Density (Connectivity) [#neighbors]	4-8

(b)

MAC	**Parameter & Description**	**Values**
	T_w X-MAC wake-up period [ms]	T^*_w
	T_{al} Acknowledgement listen period [ms]	0.95
X-MAC	T_{ps} Strobe preamble duration [ms]	$\frac{5+L_{pbl}}{R}$
	T_{cw} Contention window size [ms]	15 * 0.62
	T_{hdr}, T_{ack} pkt header & Ack duration [ms]	$\frac{9+L_{pbl}}{R}$

Table 1: (a) CC2420 Radio Constants [1], Network and Traffic Model with Typical Parameter Values. (b) X-MAC, DMAC, and LMAC Symbols used in Energy & Delay Equations

1.2 XMAC: a duty-cycle MAC protocol

X-MAC [2] is an asynchronous preamble sampling based protocol where nodes wake up periodically every T_w seconds to perform carrier sensing for, $T_{cs} + T_{al}$, (1) as depicted in Fig. 1. To send a packet, a node first contends to access the channel within the contention window T_{cw}, and it transmits a sequence of strobe preambles of duration T_{ps}, which are short packets containing the identifier of the receiver. It

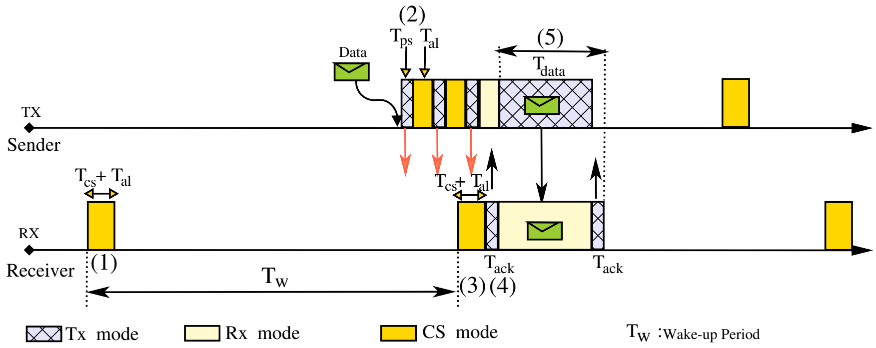

Figure 1: X-MAC's carrier sensing, transmission, and receiving modes.

then listens to an acknowledgment for T_{al} (2). Strobes continue for a period sufficient to make at least one strobe overlap with a receiver wake-up (3). The receiver replies with an acknowledgment of duration T_{ack} (4) and keeps the radio on. After that, the sender transmits the data packet, T_{data}, which spans for the transmission of the header and the payload (5). The main adjustable parameter that affects the energy and delay performance is mainly the wake-up period, T_w, and hence the vector parameter for X-MAC protocol is given by X_{XMAC}=$[T_w]$. The per-node energy consumption based on the protocol operation modes, the e2e packet delay, and the bottleneck constraint are given in the following:

a) The Energy of node n:

$$E^n = E^n_{cs} + E^n_{tx} + E^n_{rx} + E^n_{ovr} \tag{5}$$

where

$$E^n_{\text{cs}}=\frac{(T_{cs}+T_{al})}{T_w},$$
$$E^n_{\text{tx}}=(T_{cs}+T_{al}+T_{tx})\, F^n_{\text{out}},$$
$$E^n_{rx} = (\tfrac{3}{2}T_{ps}+ T_{\text{ack}}+T_{\text{data}})\, F^n_I,$$
$$E^n_{\text{ovr}}=(\tfrac{3}{2}\tfrac{T_{\text{tx}}}{T_w}T_{ps})\, F^n_B.$$

and

$$T_{tx}=\lceil \frac{T_w}{T_{ps}+T_{al}} \rceil \frac{T_{ps}+T_{al}}{2}+T_{\text{ack}}+T_{\text{data}}.$$

b) The delay of node n at level d^n:

$$L^n_{d^n} = \sum_{i=1}^{d^n} \left(\frac{T_w}{2} + \frac{T_{cw}}{2} + T_{\text{data}} \right) \tag{6}$$

where T_{data}=T_{hdr}+P/R+T_{ack}.

c) The bottleneck constraint:

$$|I^0|\, E^1_{tx} < 1/4 \tag{7}$$

The energy and e2e delay formulas are summarized in Table 2.

Table 2: Eenrgy consumption and e2e delay formulas for XMAC.

Network Energy consumption	End-to-End Delay
$E^{\text{XMAC}} = \max\limits_{n \in N}(\frac{\alpha_1}{T_w} + \alpha_2 T_w + \alpha_3)$	$L^{\text{XMAC}} = \max\limits_{n \in N}(\beta_1 T_w + \beta_2)$
$\alpha_1 = T_{cs} + T_{al} + \frac{3}{2}T_{ps}(\frac{T_{ps}+T_{al}}{2} + T_{ack} + T_{data})F_B^{d^n}$	$\beta_1 = \sum_{i=1}^{d^n} 1/2$
$\alpha_2 = \frac{F_{out}^{d^n}}{2}$	
$\alpha_3 = (\frac{T_{ps}+T_{al}}{2} + T_{cs} + T_{al} + T_{ack} + T_{data})F_{out}^{d^n} + (\frac{3}{2}T_{ps} + T_{ack} + T_{data})F_I^{d^n} + \frac{3}{4}T_{ps}F_B^{d^n}$	$\beta_2 = \sum_{i=1}^{d^n}(\frac{T_{cw}}{2} + T_{data})$

1.3 Project Realization

Since we want to optimize energy consumption and delay, we will take worst case conditions. That means, that for energy we will consider the worst case as the energy of a node at ring d=1 (e.g., E=E^n, with n such n is in d=1). That means that related to equations of Table 2, in the energy equations, $F_{out}^{d^n}$, $F_{in}^{d^n}$ and $F_B^{d^n}$ have to be accorded to d^n=1. On other hand, for the e2e delay, we will consider a node in the outer ring d=D (e.g., L=L^n, with n such that n is in d^n=D).

1. Fix a topology, e.g. N, C, and D, and for that topology, draw the energy consumption for several sampling rates, E, and delay, L, curve for the worst case assumption. For that purpose, fix the sampling rate between some value in the interval $F_s \in [0.005, 5]$ $[pkt/node/min]$ and for several T_w, obtain the correspondent E and L values using the formulas of Table 2. Then plot the curve E-L. Repeat the process for several sampling rates.

2. Using a solver (e.g. use geometric programming provided in CVX), obtain the minimum energy consumption (Optimization Problem 1) and delay (Optimization Problem 2) for several values of L_{max} and E_{budget}. Draw plots showing the behaviour of such parameters in energy consumption and delay optimal values. $L_{max} \in [0.1, 5]$ seconds and $E_{budget} \in [0.5, 5]$ Joules.

$$\begin{array}{lll} (P1) & Minimize & E^{XMAC}(T_w) \\ & s.t. & L^{XMAC}(T_w) \leqslant L_{max} \\ & & T_w \geqslant T_w^{min} \\ & & \left|I^0\right| E_{tx}^1 \leqslant 1/4 \\ & Var. & T_w \end{array} \tag{8}$$

$$\begin{array}{lll} (P2) & Minimize & L^{XMAC}(T_w) \\ & s.t. & E^{XMAC}(T_w) \leqslant E_{budget} \\ & & T_w \geqslant T_w^{min} \\ & & \left|I^0\right| E_{tx}^1 \leqslant 1/4 \\ & Var. & T_w \end{array} \tag{9}$$

3. Using the Nash Bargaining scheme, find the trade-off between energy conservation and latency. The problem is expressed as:

$$
\begin{array}{lll}
\text{(NBS)} & \max & (E_{\text{worst}} - E(T_w))(L_{\text{worst}} - L(T_w)) \\
& \text{s. t.} & (E_{\text{budget}}, L_{\text{max}}) \geq E(T_w), L(T_w) \\
& & (E_{\text{worst}}, L_{\text{worst}}) \geq E(T_w), L(T_w) \\
& & E(T_w), L(T_w) \in S \\
& \text{var.} & T_w
\end{array}
$$

where the $E(T_w)$,$L(T_w)$∈S means that we have to include the MAC protocol intrinsic conditions and where the point $(E_{\text{worst}}, L_{\text{worst}})$ is the disagreement point. The problem (NBS) is non-linear non-convex, but this kind of problems can be transformed into a standard convex optimization problem without changing its solution. The idea is to define auxiliary variables E_1 and L_1 such that $E_1 \geq E(T_w)$ and $L_1 \geq L(T_w)$, which should be satisfied by the optimal solution. Whenever the problem (NBS) is feasible, $E(T_w) \leq E_{\text{worst}}$, $L(T_w) \leq L_{\text{worst}}$, and application of (NBS) to the MAC protocols yields a concave problem.

$$
\begin{array}{lll}
\text{(NBS*)} & \max & log(E_{\text{worst}} - E_1) + log(L_{\text{worst}} - L_1) \\
& \text{s. t.} & (E_{\text{worst}}, L_{\text{worst}}) \geqslant (E(T_w), L(T_w)) \\
& & (E_1, L_1) \geqslant (E(T_w), L(T_w)) \\
& & (E_1, L_1) \leq (E_{\text{budget}}, L_{\text{max}}) \\
& & (E_1, L_1) \in S \\
& \text{var.} & E_1, L_1, T_w
\end{array}
$$

Consequently, the equivalent concave problem for XMAC is:

$$
\begin{array}{lll}
\text{(NBS-XMAC*)} & \max & log(E^{\text{XMAC}}_{\text{worst}} - E_1) + log(L^{\text{XMAC}}_{\text{worst}} - L_1) \\
& \text{s. t.} & E^{\text{XMAC}}_{\text{worst}} \geqslant E^{\text{XMAC}}(T_w) \\
& & E_1 \geqslant E^{\text{XMAC}}(T_w) \\
& & L^{\text{XMAC}}_{\text{worst}} \geqslant L^{\text{XMAC}}(T_w) \\
& & L_1 \geqslant L^{\text{XMAC}}(T_w) \\
& & T_w \geqslant T_w^{\text{min}} \\
& & |I^0|\, E^1_{tx} \leqslant 1/4 \\
& \text{var.} & E_1, L_1, T_w
\end{array}
$$

References

[1] *CC2420 Single-Chip 2.4 GHz RF Transceiver, Texas Instruments*, March 2010.

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