An Optimized MAC Layer to Physical Device Mapping Methodology

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- Applications elaborated with energy consumption minimisation as primary goal
- The desired behaviour of embedded systems
  - subject to real-time constraints
  - involves interactions with physical devices with their own individual constraints

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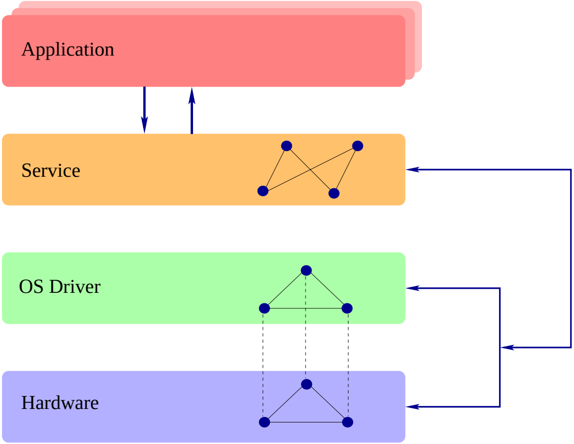


Figure: State machines and automata in systems

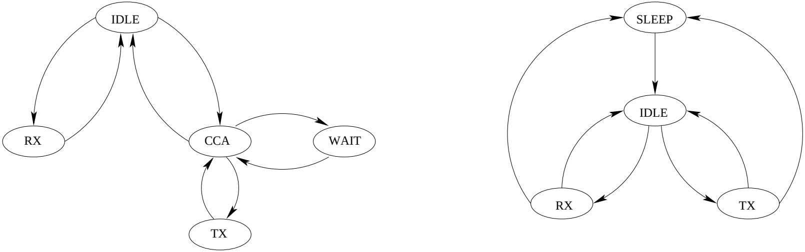
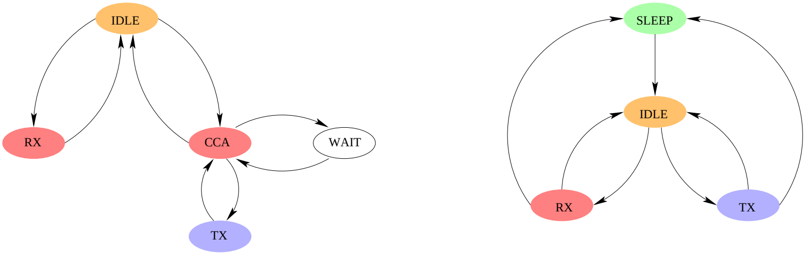


Figure: State machines mapping: simple network MAC protocol on physical device



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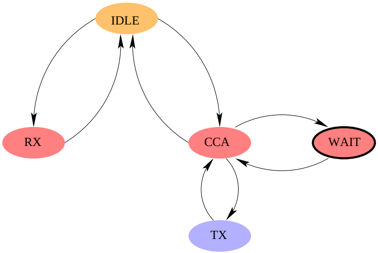

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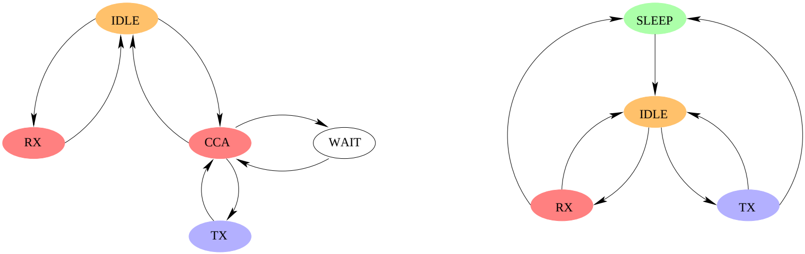

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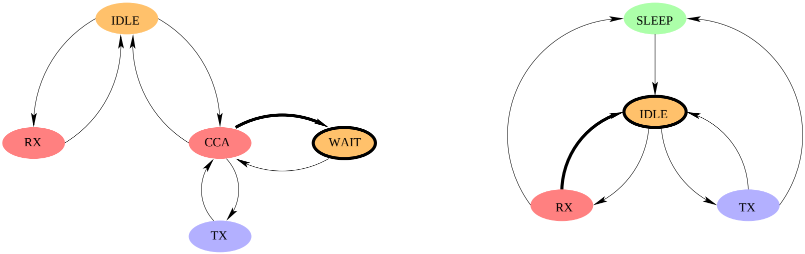

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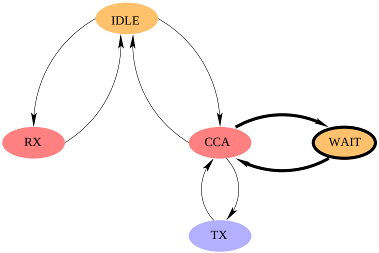

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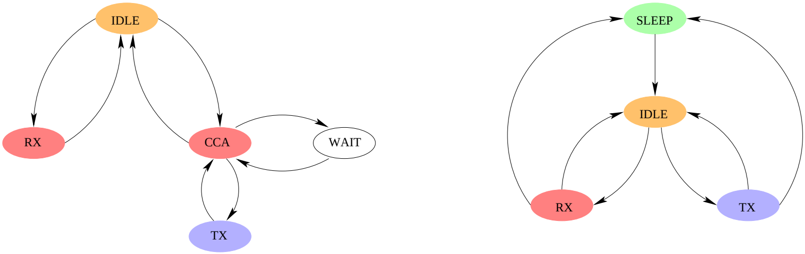

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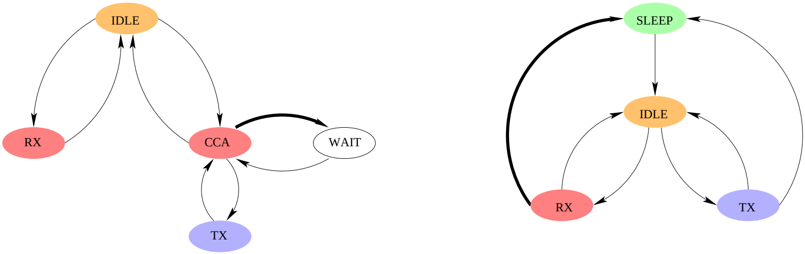

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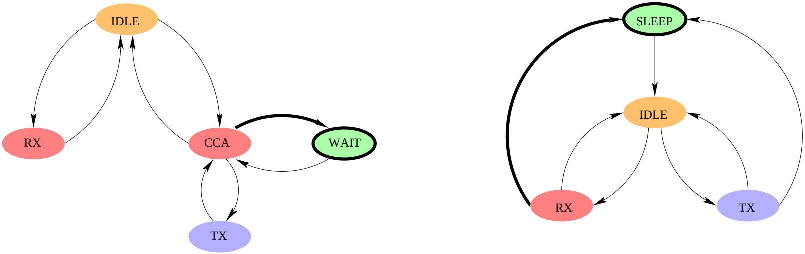

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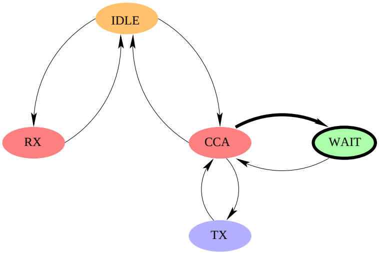

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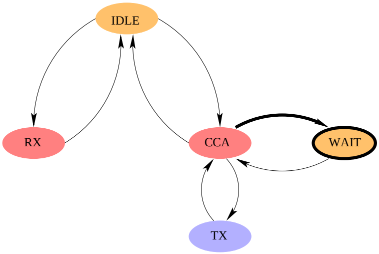

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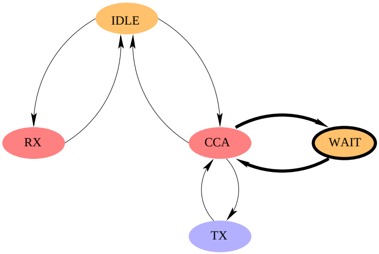

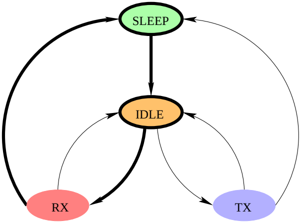

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  - optimal control synthesis for automata with acyclic control graphs

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We address the problem of mapping the *free states* of a software protocol (expressed as a TA) to unique states or paths in the device automaton (behaviour expressed as a TA) such that timing constraints are guaranteed while minimizing the energy consumed

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    - conditioned by logical expressions with clock variables and integer state variables

B-MAC protocol description

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    - low power operation
    - effective collision avoidance
    - simple implementation
    - efficiency in chanel utilization
    - reconfigurability
    - tolerance to changing network conditions
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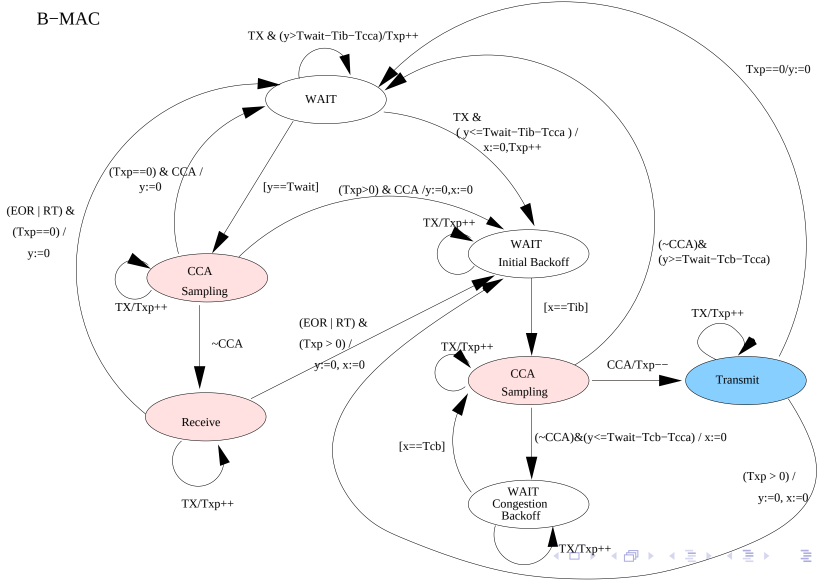
  - low power - low power listening


B−MAC
TX & (y>Twait−Tib−Tcca)/Txp++
WAIT
Txp==0/y:=0
TX &
(y<=Twait−Tib−Tcca) /
x:=0,Txp++
(Txp==0) & CCA /
y:=0
[y==Twait]
(Txp>0) & CCA /y:=0,x:=0
(EOR | RT) &
(Txp==0) /
y:=0
TX/Txp++
WAIT
Initial Backoff
(~CCA)&
(y>=Twait−Tcb−Tcca)
CCA
Sampling
TX/Txp++
[x==Tib]
TX/Txp++
(EOR | RT) &
(Txp > 0) /
y:=0, x:=0
~CCA
TX/Txp++
CCA/Txp−−
CCA
Sampling
Transmit
Receive
(~CCA)&(y<=Twait−Tcb−Tcca) / x:=0
[x==Tcb]
(Txp > 0) /
y:=0, x:=0
TX/Txp++
WAIT
Congestion
Backoff
TX/Txp++

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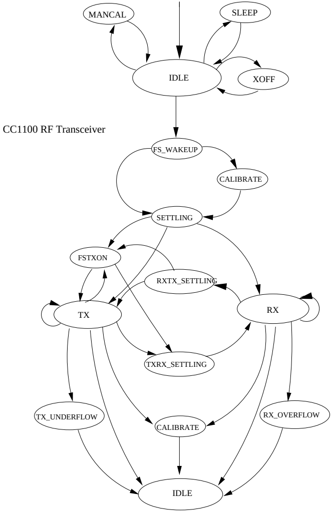
MANCAL
SLEEP
IDLE
XOFF
CC1100 RF Transceiver
FS_WAKEUP
CALIBRATE
SETTLING
FSTXON
RXTX_SETTLING
TX
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TX_UNDERFLOW
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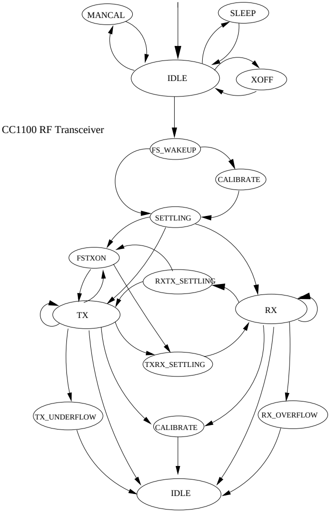
RX_OVERFLOW
IDLE



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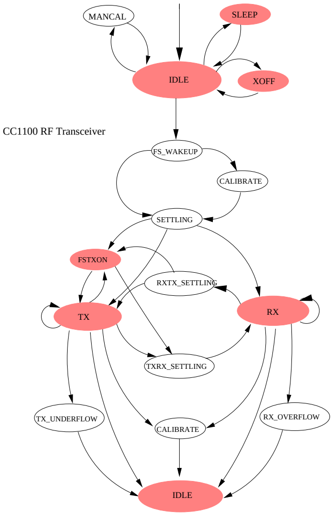

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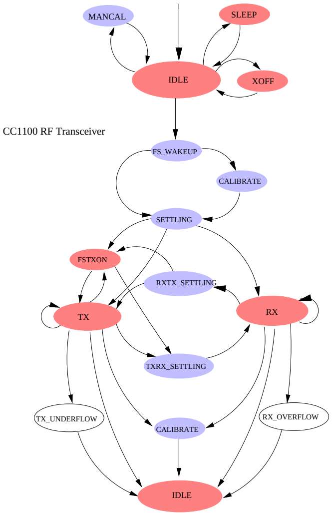

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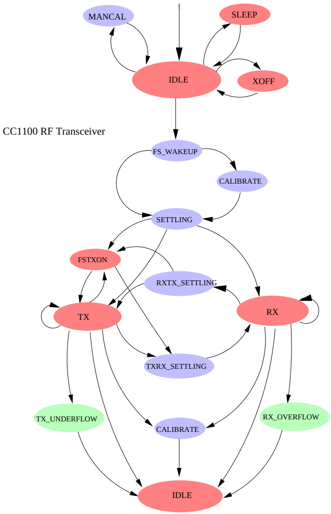

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  - error

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  - on **external signals**
    - from other layers in the protocol stack
    - not time correlated - such an external event can occur at any time while in the free state

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- Signal enabled transitions are assigned 0 weight
- Timer enabled transitions are assigned weight equal to the state duration
- Bottom Level computation - all pairs shortest paths having as intermediate nodes only free states

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$$\mathcal{E}[P]_{min} = \sum_{i=1}^{n} t_{i\_min} \times P_{s_i}$$

- For a timed path in the radio device automaton of duration t_{path} the extra time w.r.t the minimum transition time of the path t_{min} should be spent in the non-transitional state of the path with the minimum power consumption s_{min}

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- The distance $dist(S_1, S_2)$ in the physical device automaton - the minimum of all the lengths of the elementary paths leading from S_1 to S_2 in the duration-weighted device automaton

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$$offset(s, S_{MAC}) = \max\{0, \max_{S_{PHY} \in Reachable(S_{MAC})} \{dist(s, S_{PHY}) - BL(S_{MAC}, S_{PHY})\}\}$$

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- path duration $S_{MAC\,duration} - t_{rem} - offset(s, S)$.

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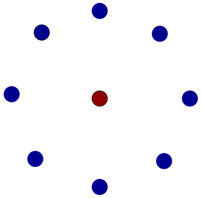

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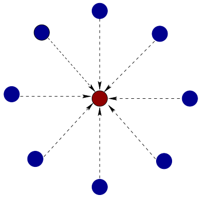

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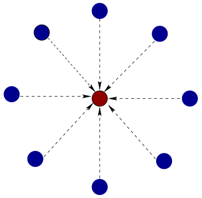

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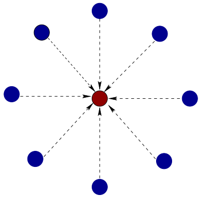

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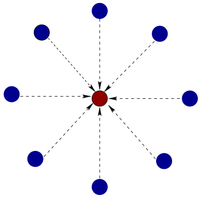

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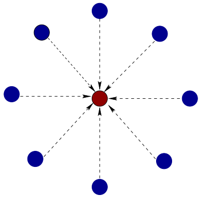

- Mappings for backoff states
  - map to RX device state
  - map to IDLE
  - optimized (IDLE, SLEEP and XOFF) according to the backoff value.

Energy Consumption Theoretical Analysis

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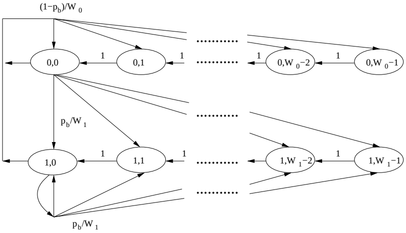
  - p_b probability of finding the medium busy when performing CCA

Energy Consumption Theoretical Analysis

Markov chain model for B-MAC backoffs



$$P\{i,k|i,k+1\} = 1 \qquad k \in (0, W_i - 2), i \in (0,1)$$

$$P\{0,k|i,0\} = \frac{(1-p_b)}{W_0}, \qquad k \in (0, W_0 - 1), i \in (0,1)$$

$$P\{1,k|0,0\} = p_b/W_1, \qquad k \in (0, W_1 - 1)$$

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- Non-linear system of equations in the two unknowns τ and p_b that can be solved using numerical techniques

Energy Consumption Theoretical Analysis

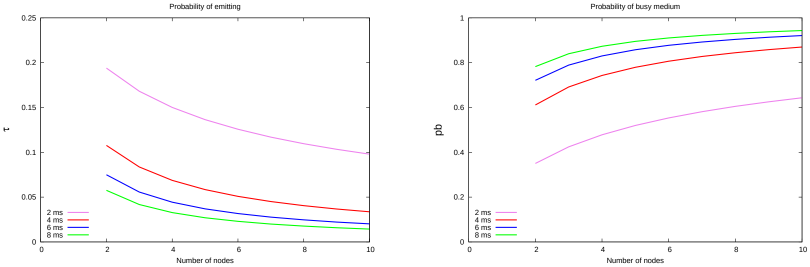

Figure: Transmission and busy medium probabilities for different packet lengths and number of nodes

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- In a randomly chosen slot time

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$$\begin{aligned} E[B] =& E[IB] + \\ & \sum_{i=1}^{\infty} {p_b}^{(i-1)} \times (1-p_b) \times [(i-1) \times E[CB] + i \times \mathcal{E}(CCA)]; \\ =& E[IB] + \frac{1}{1-p_b} \times \mathcal{E}(CCA) + \frac{pb}{1-pb} \times E[CB]; \end{aligned}$$

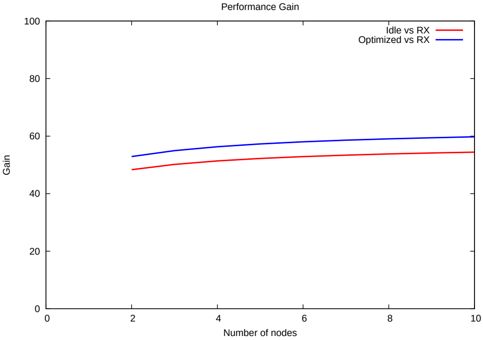
Performance Gain
Idle vs RX
Optimized vs RX
Gain
Number of nodes
0
20
40
60
80
100
0
2
4
6
8
10

Figure: Gain

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    - Long-term goal is to generate optimized device driver code.