Reducing Energy Consumption in Wireless Sensor Networks

CHESS seminar

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Introductory Overview

Minimum Energy Coding

Radio Power Control

Bit Error Rate

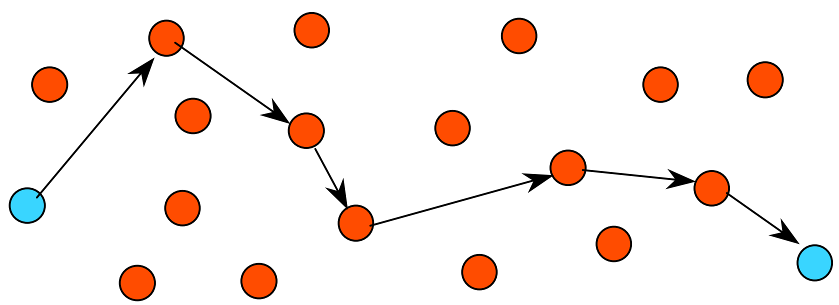
Energy Consumption

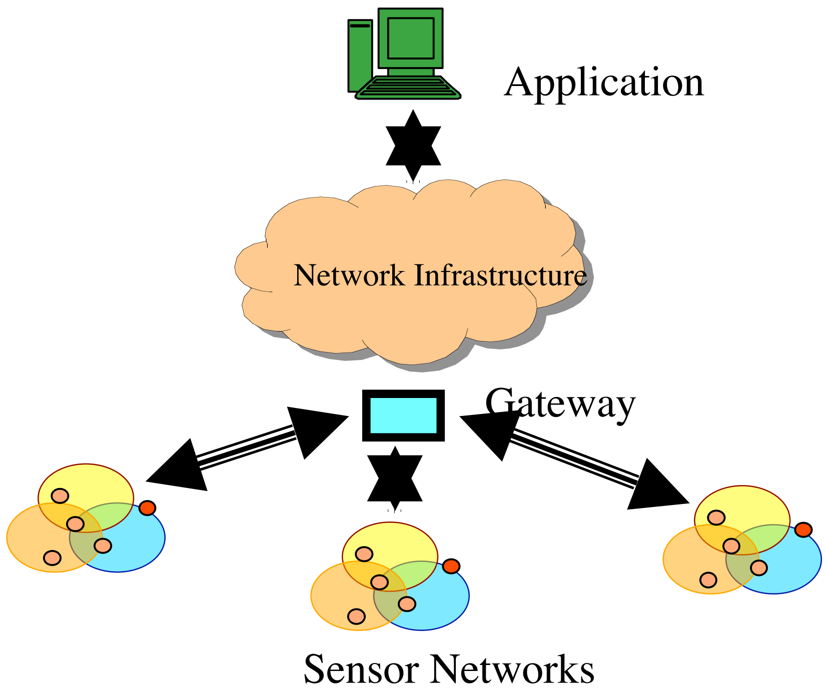
Numerical Results

Conclusions and Future Work

Definition of WSNs

"Wireless Sensor Networks (WSNs) are networks for communication, control, sensing and actuation by small nodes communicating through wireless links"

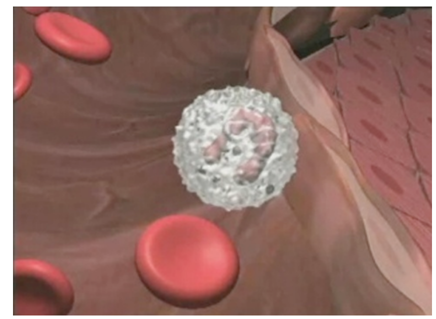


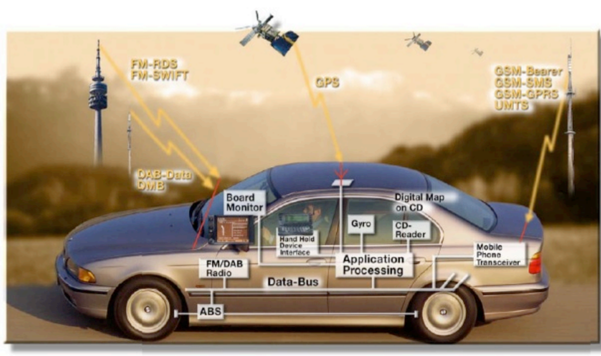


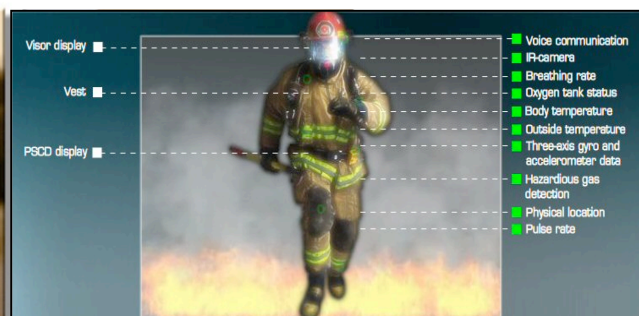
Applications

Tremendous space of applications:

- Monitoring space: ocean water, pollution, ...
- Monitoring things: robots, human body,…

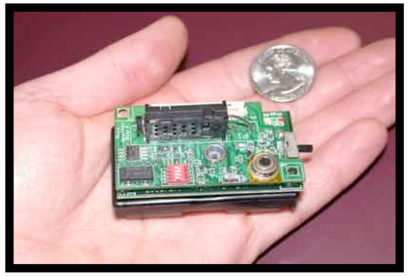




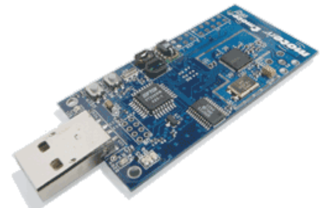


History of WSNs

DARPA DSN node (~1960)

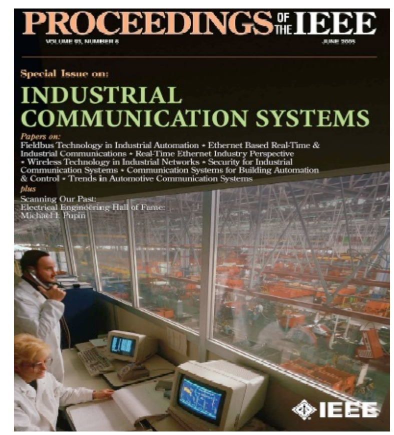


Mica node (~2000)

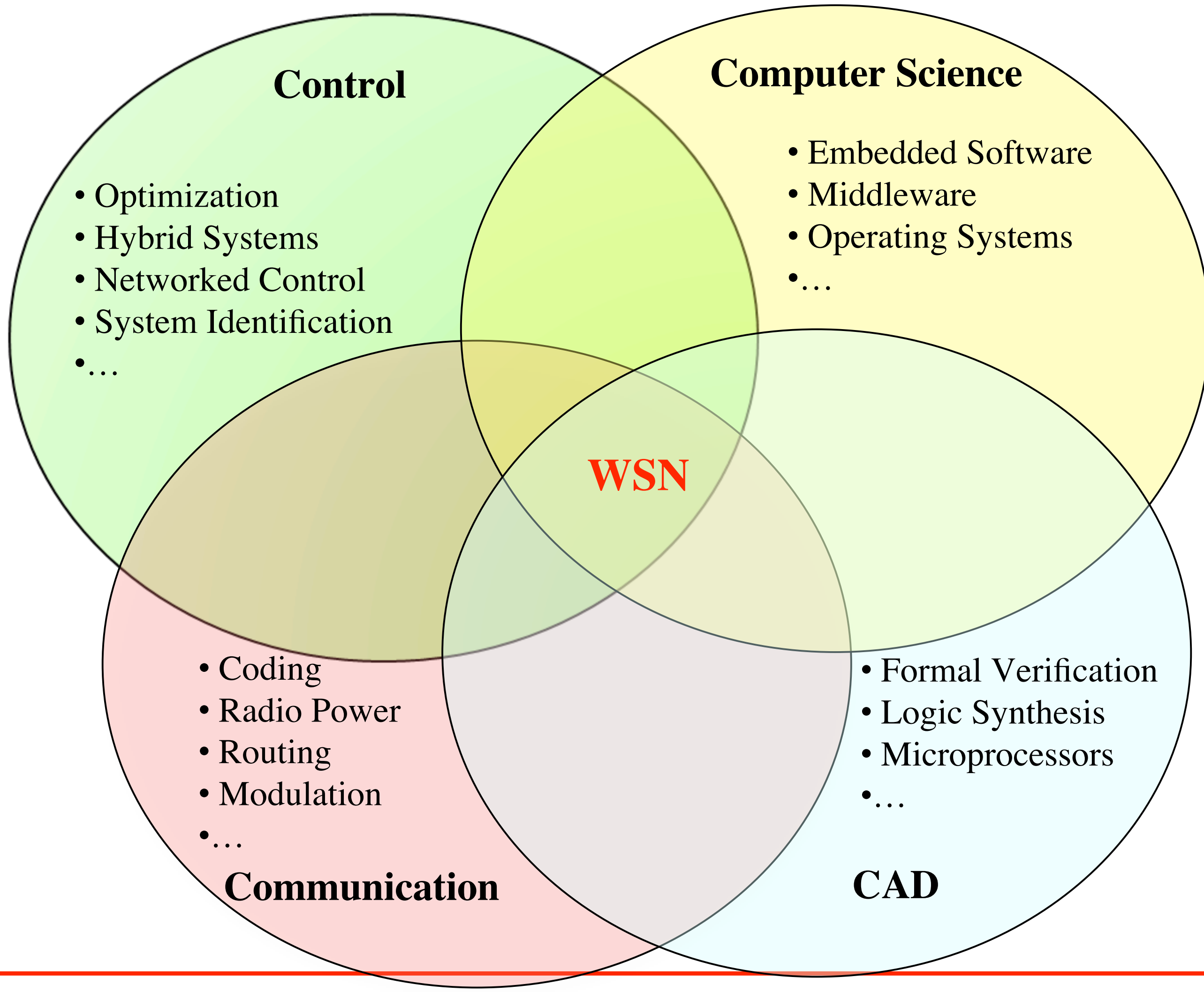


Tmote-sky node (~2003)

- WSNs are an area of active research from electronic to computer science since few years.
- Many industries are now investing in this new technology:
  - ABB
  - Fiat
  - Pirelli
  - Siemens
  - United Technology
  - …

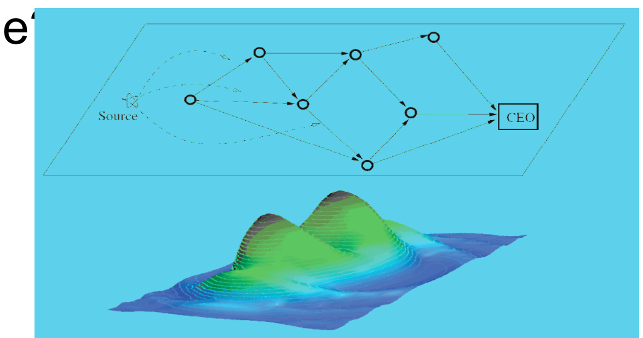


Design Principles of WSNs

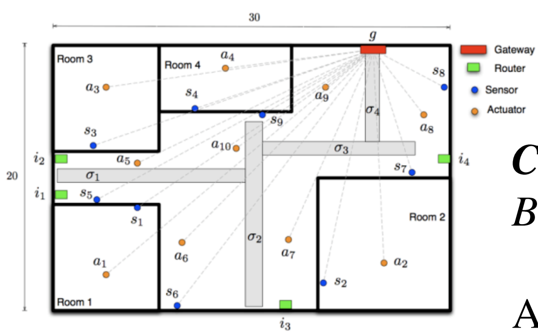


Some Challenges...

- How to schedule the link each node should select to forward packets?
- How to quantize the measurements to transmit the minimum amount of information in the presence of uncertainties of the network?
- How to do radio power and rate control, when neither accurate channel models and channel state information are available?



- How to access to the channel?

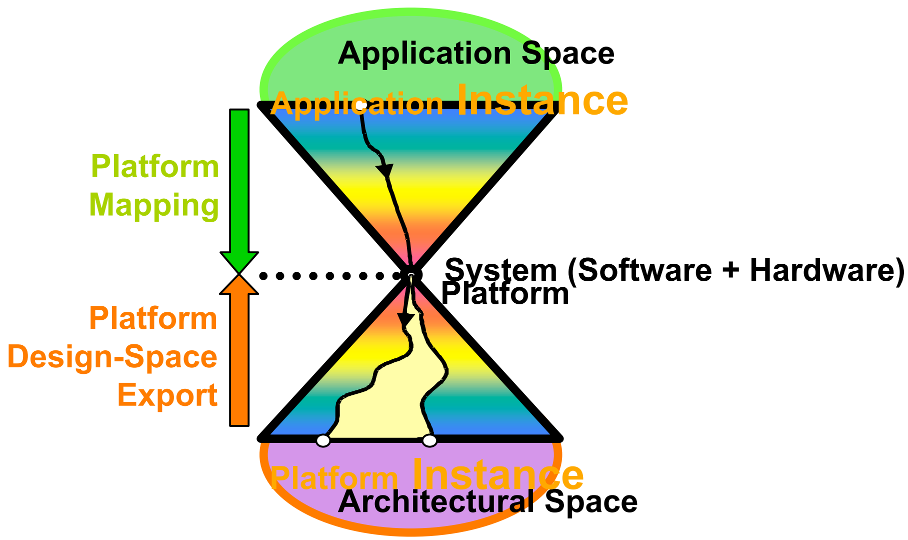


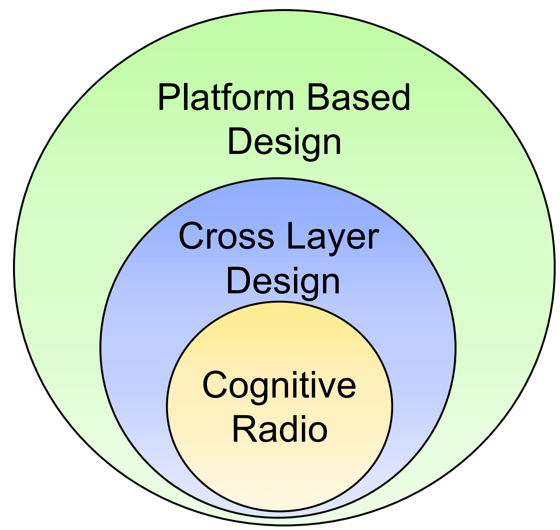
***COSI** project: Synthesis of Embedded Networks for Building Automation and Control*

A. Pinto & A. Sangivanni-Vincentelli, UC Berkeley

Design Principles of WSNs…

- ♣ Design of WSNs includes several techniques (distributed computation, distributed source coding, distributed control,...).
- ♣ Cross-layer approaches are necessary to take into account several interacting techniques and protocols.





A. Sangiovanni-Vincentelli et al.

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Minimum Energy Coding

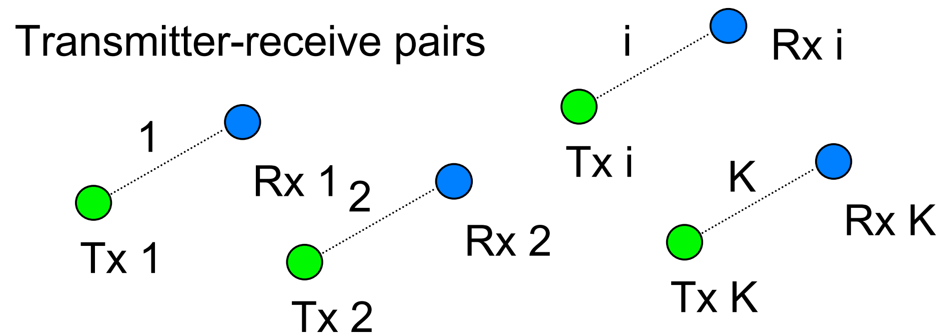
- Performance analysis of minimum energy coding schemes in Coded Division Multiple Access (CDMA) wireless sensor networks:

  1. **Minimum Energy coding** (ME);

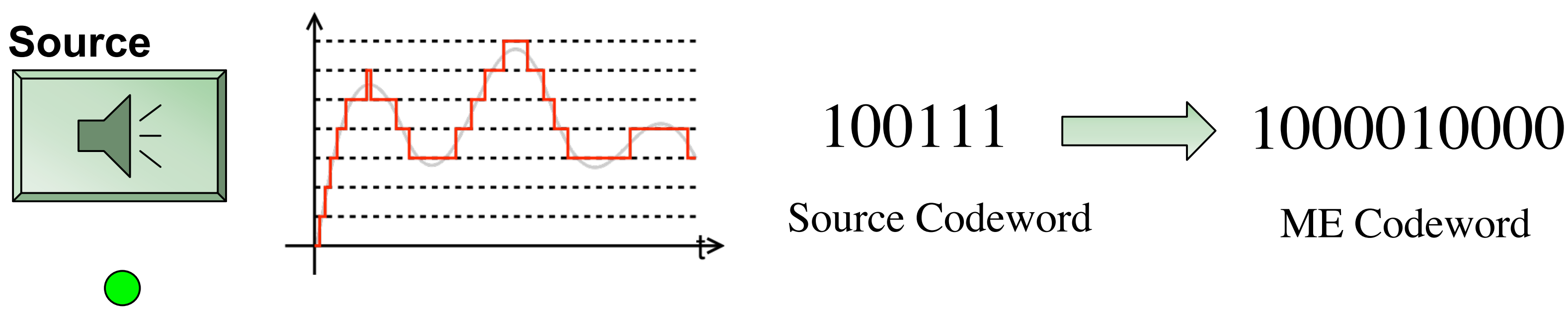
  2. **Modified Minimum Energy coding** (MME).

- Detailed models of the **energy consumption** and **bit error rate:**
  1. coding schemes;
  2. wireless channel;
  3. power control;
  4. hardware characteristics of the transceivers.

System Description

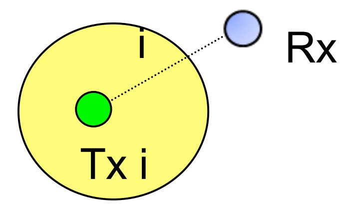


- Data sensed by a node are coded with a Minimum Energy coding scheme.
- The bits of the ME coded data are OOK modulated: only bits having value 1 are transmitted after a DS-CDMA spreading operation.



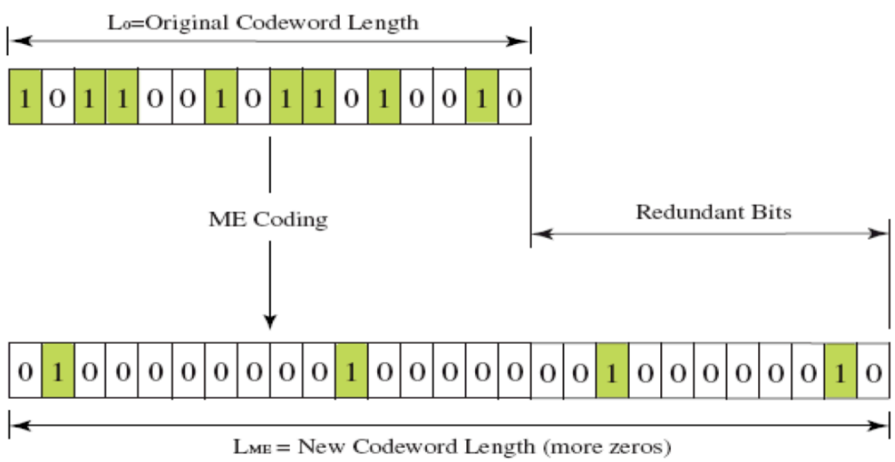
ME Coding

- In ME Coding (Erin and Asada: *"Energy Optimal Codes for Wireless Communications"* in 38th IEEE CDC 99) a source codeword is mapped into a new codeword having larger length but less number of 1 (or high) bits.



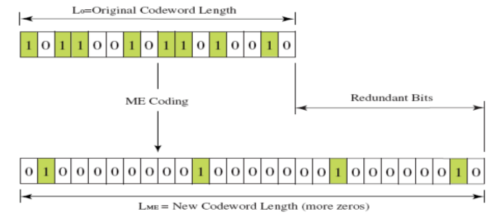
Source codeword

ME codeword

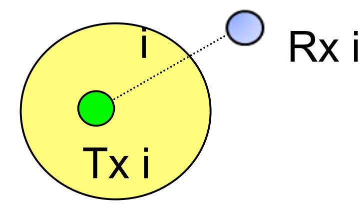


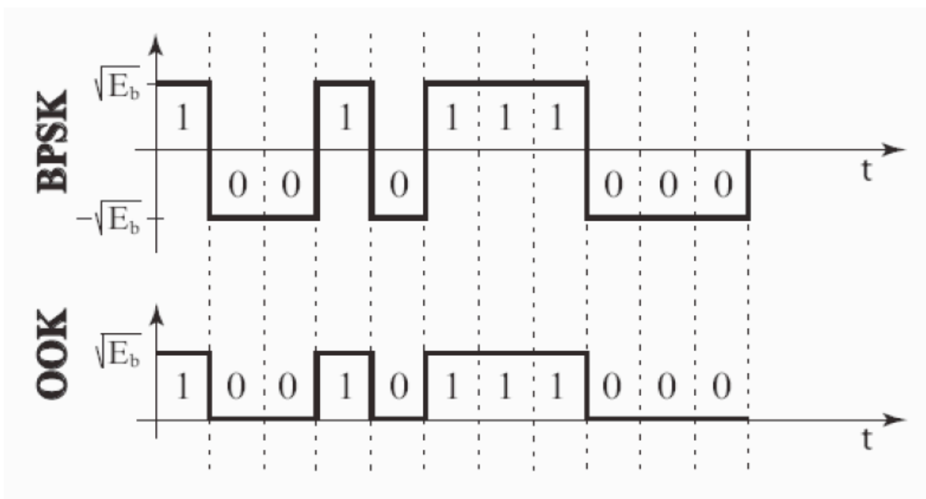
- Source codewords having large probability of occurrence are associated to ME codewords with less high bits.
- Only high bits are transmitted with OOK modulation.

OOK Modulation



♣ Only bits having value 1 are transmitted





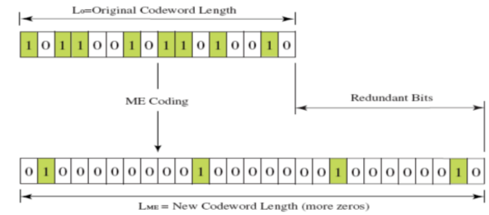
$\alpha = 1$

$\alpha < 1$

- Lower Activity
- Lower interference
- Higher bit error rate

♣ α is the average transmit time per codeword.

ME Coding (2)



- Energy consumption per ME codeword

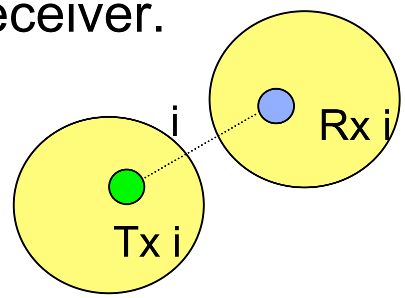
$$E_i^{(ME)} = E_i^{(tx)} + E_i^{(rx)}$$
$$= P^{(tx,ckt)}\left(T^{(on,tx,ME)} + T_s\right) + \alpha_{ME} P_i T^{(on,tx,ME)} + P^{(rx,ckt)}\left(T^{(on,rx,ME)} + T_s\right)$$

- ME coding increases the value of three system parameters:
  1. the codeword length;
  2. the Transmitter active time (it is negligible with respect to the radio power consumption);
  3. the Receiver active time: it is not negligible, the power spent to receive is approximately the same as that used to transmit.

MME Coding

- MME coding exploits a structure of the codeword that allows the **receiver to go in a sleep state:** Kim and Andrews: "*An Energy Efficient Source Coding and Modulation Scheme for Wireless Sensor Networks*". In IEEE WSPAWC, 2005.

- In MME coding, energy is saved not only at the transmitter as ME coding, but also at the receiver.

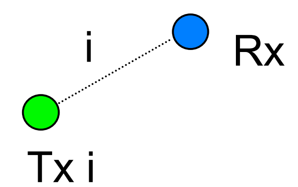


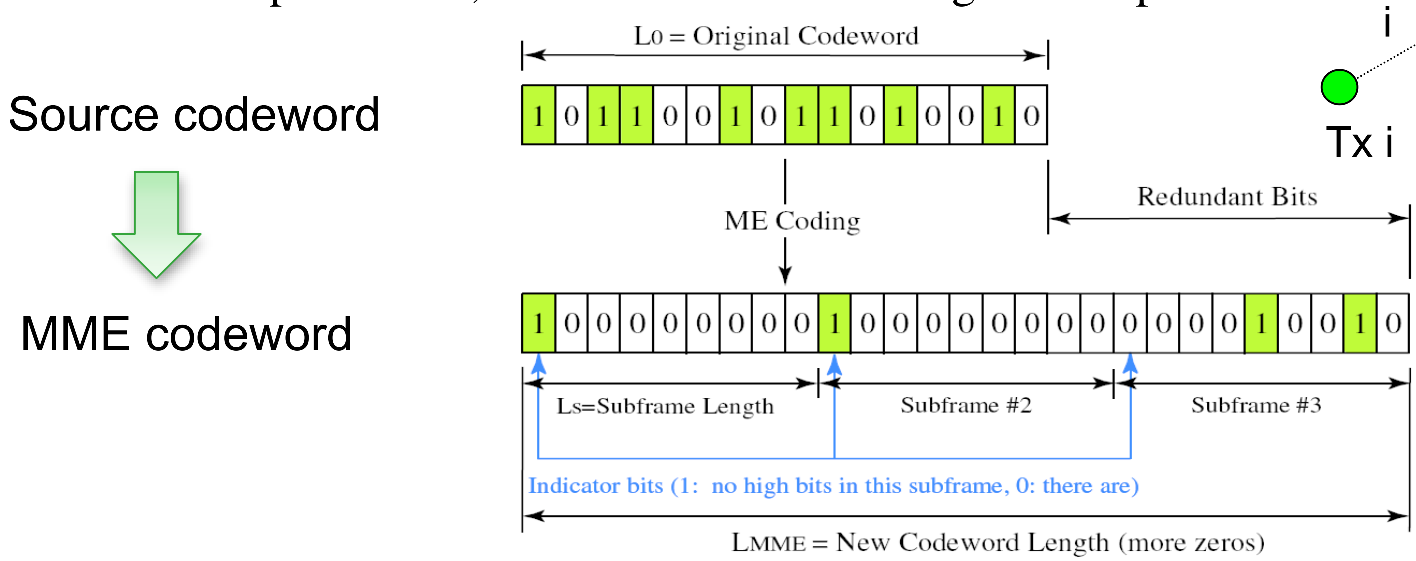
MME Coding (2)

MME coding: the ME codewords are partitioned into sub-frames starting with an indicator bit.

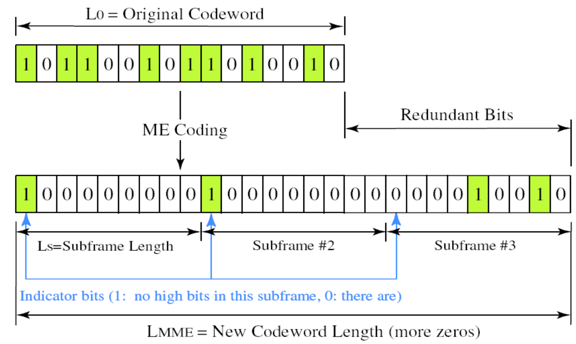
Indicator bit = 1 => there are not high bits in the sub-frame, there is no need for decoding, and the receiver goes to sleep.

Indicator bit = 0 => there are high bits in the sub-frame, so the decoding operation must be performed, and the receiver cannot go to sleep.





MME Coding (3)

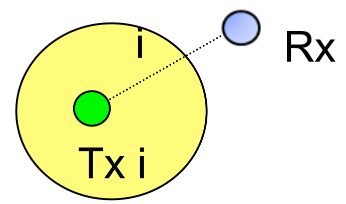


- MEE energy consumption per codeword:

$$
\begin{aligned}
E_i^{(MME)} &= E_i^{(tx)} + E_i^{(rx)} \\
&= P^{(tx,ckt)} \left[T^{(on,tx,MME)} + T_s \right] + \alpha_{MME} P_i T^{(on,tx,MME)} + \\
&\quad + P^{(rx,ckt)} \left[T^{(on,rx,MME)} + (N_i + 1)\, T_s \right] .
\end{aligned}
$$

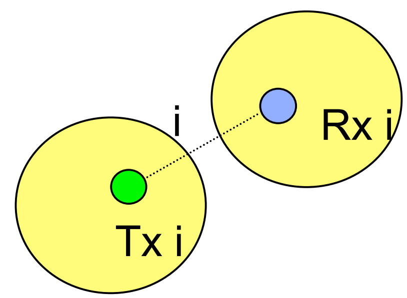
- N_i: average receiver activity (it is a function of the number of sub-frames, and bit error rate)

Energy of ME and MME



$$E_i^{(ME)} = E_i^{(tx)} + E_i^{(rx)}$$
$$= P^{(tx,ckt)} \left(T^{(on,tx,ME)} + T_s \right) + \alpha_{ME} P_i T^{(on,tx,ME)} + P^{(rx,ckt)} \left(T^{(on,rx,ME)} + T_s \right)$$

$$E_i^{(MME)} = E_i^{(tx)} + E_i^{(rx)}$$
$$= P^{(tx,ckt)} \left[T^{(on,tx,MME)} + T_s \right] + \alpha_{MME} P_i T^{(on,tx,MME)} +$$
$$+ P^{(rx,ckt)} \left[T^{(on,rx,MME)} + (N_i + 1) T_s \right] .$$



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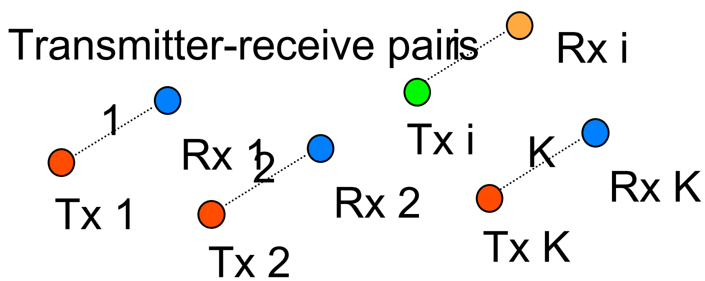
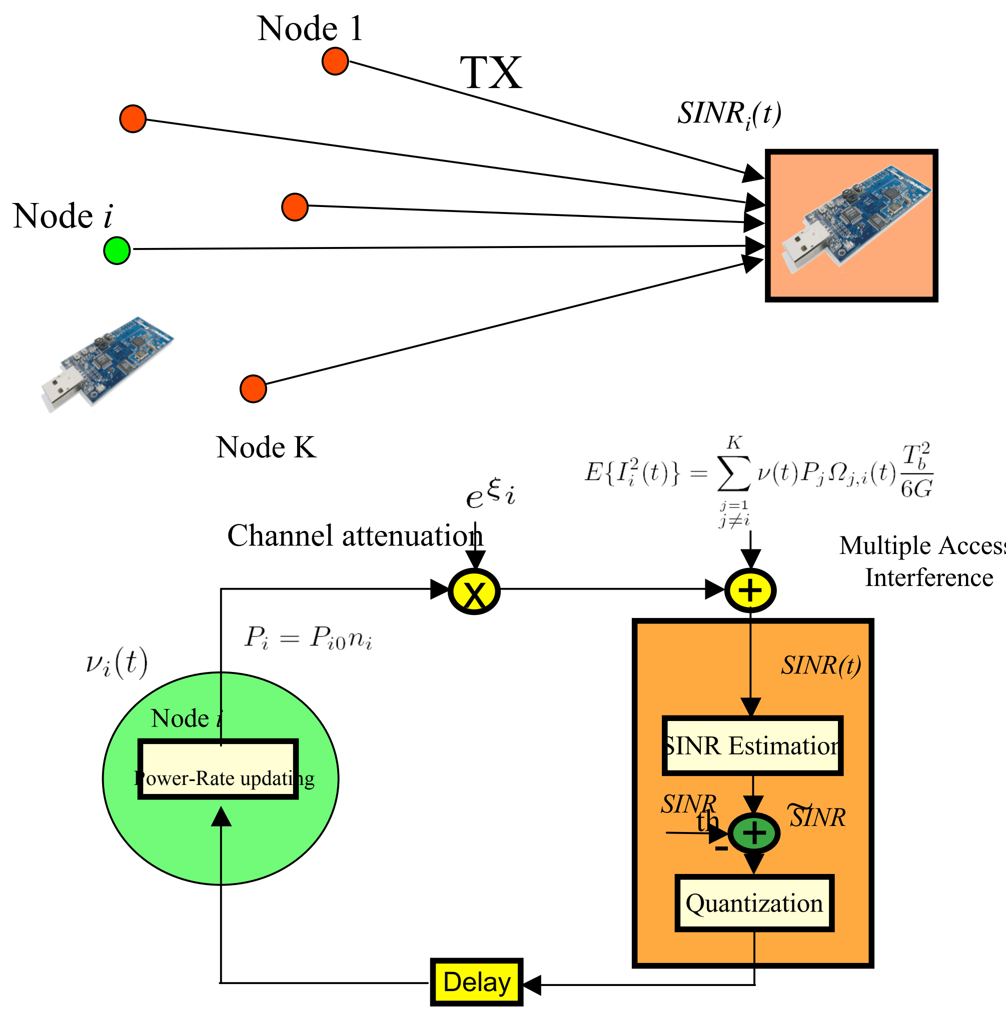
Radio Power Control

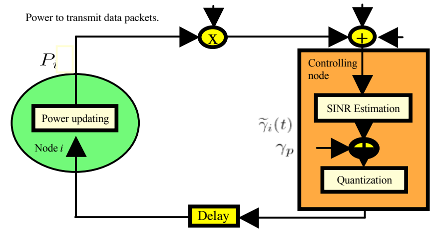
- Efficient power control algorithms for wireless sensor networks (WSNs) are crucial to **reduce energy consumption**.
  - **Lifetime**: in scenario where recharging is not possible, radio power control is very important to increase the network lifetime.
  - **Collisions**: power control is beneficial to reduce packet collisions (more retransmitted packets means wasting energy), and increase throughput.
- Energy for radio power is responsible from **37%** up to **85%** of the **total Energy** consumption for off-the-shelf sensor nodes.

Radio Power Control (2)

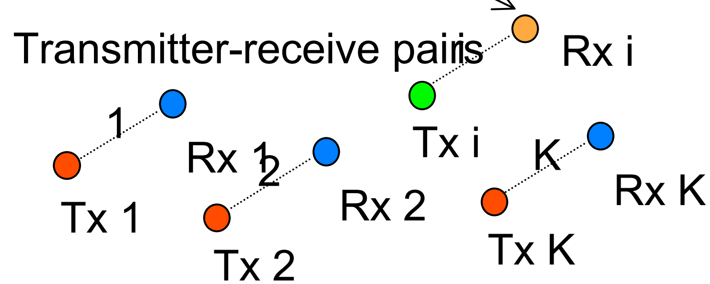




Radio Power Control (3)



♣ Received signal $$Z_i(t) = D_i(t) + I_i(t) + N_g(t)$$



$$D_i(t) \quad = \quad \sqrt{\frac{h_{i,i}(t)P_i}{2}}T_b b_i(t)$$ Desired Signal

$$E\{I_i^2(t)\} = \sum_{\substack{j=1 \\ j\neq i}}^{K} \nu(t) P_j \Omega_{j,i}(t) \frac{T_b^2}{6G}$$ MAI

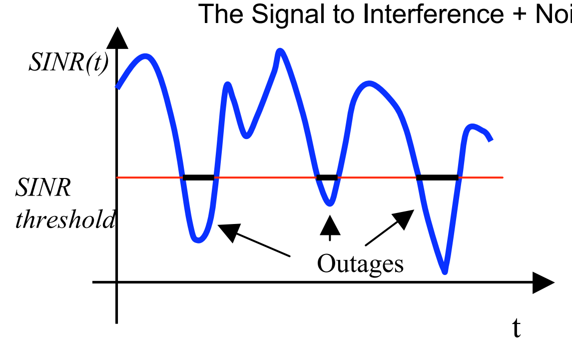
$$N_g(t)$$ Thermal Noise

$$\Pr(\nu(t) = 1) = \alpha$$ Transmitter Activity (ME or MME)

The SINR

- The SINR of the signal of a node is expressed as

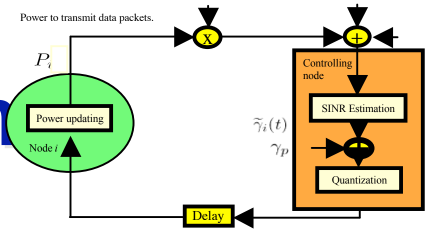
$$\mathrm{SINR}_i(t) = \frac{b_i(t)h_{i,i}(t)P_i}{\frac{N_0}{2T_b} + \frac{1}{3G}\sum_{\substack{j=1 \\ j\neq i}}^{K} \nu_j(t)h_{ji}(t)P_j}$$



$$\boldsymbol{\nu}(t) = [\nu_1(t), \ldots, \nu_K(t)]^T$$

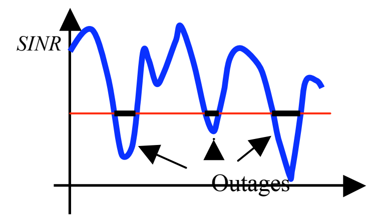
Vector of Binary on/off Processes: ME and MME coding

The Optimization Problem



♣ Mixed integer-real optimization problem

$$
\begin{aligned}
\max_{\mathbf{n},\mathbf{P}} \quad & \textstyle\sum_{i=1}^{K} n_i \\
\text{s.t.} \quad & \Pr\left[SINR_i(\boldsymbol{\xi},\boldsymbol{\nu}) < \gamma_i\right] \leq \bar{P}^i_{out} \\
& \textstyle\sum_{i=1}^{K} P_i \leq P_T \\
& 0 < P_{i0} \\
& 1 \leq n_i \leq G_{i0}, \quad n_i \in \mathbb{N} \ , i = 1, \ldots, K
\end{aligned}
$$

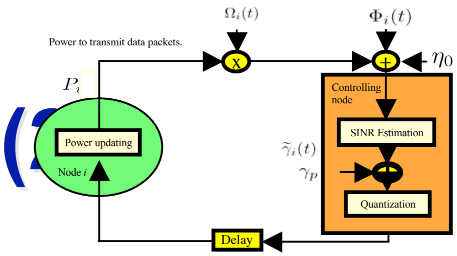


$$\mathbf{P} = [P_{01}, \ldots, P_{0K}]^T \qquad P_i = P_{i0} n_i, \;\; i = 0, ..., K$$

$$\mathbf{n} = [n_1, n_2, \ldots, n_K]^T$$

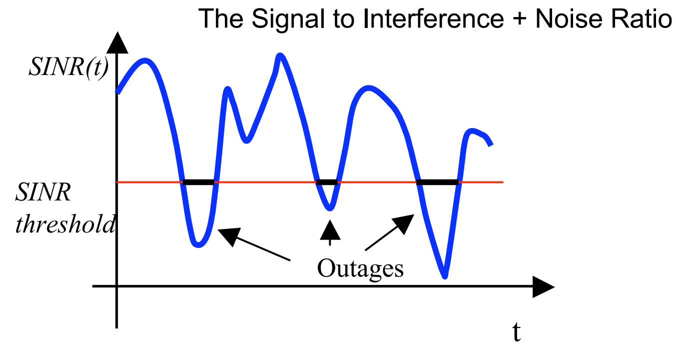
- K-L. Hsiung, S-J. Kim, S. Boyd, "Power Control in Lognormal Fading Wireless Channel with Uptime Probability Specifications via Robust Geometric Programming", ACC 2005.
- J. Papandriopoulos, J. Evans, S. Dey, "Outage-Based Power Control for Generalized Multiuser Fading Channels", IEEE Trans. Comm. 2006.

The Optimization Problem (2



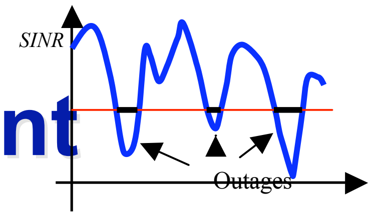
- How to express the constraints on the outage probability?

$$Pr\left[SINR_i(\boldsymbol{\xi},\boldsymbol{\nu}) < \gamma_i\right] = \int_0^{\gamma_i} f_{SINR_i}(x)dx$$



- How to solve efficiently the problem?
  - good precision of the solution (otherwise waste of resources);
  - computationally affordable (WSNs have limited processing capabilities).

Outage Probability Constraint



- The SINR is a combination of log-normal processes weighted with on/off binary random processes, it is approximated with an overall Log-normal:

$$SINR_i(\boldsymbol{\xi}(t),\boldsymbol{\nu}(t)) = L_i(\boldsymbol{\xi}(t),\boldsymbol{\nu}(t))^{-\frac{1}{2}} \Rightarrow \boxed{L_i(\boldsymbol{\xi}(t),\boldsymbol{\nu}(t)) \cong e^{Z_i(t)}} \Rightarrow Z_i \in G(m_{Z_i},\sigma_{Z_i})$$

$$m_{Z_i} = \ln\left[\frac{M_{m1}^2}{\sqrt{M_{m2}}}\right] \quad M_{m1} \triangleq E_{\boldsymbol{\xi}(t),\boldsymbol{\nu}(t)}\{SINR(\boldsymbol{\xi}(t),\boldsymbol{\nu}(t))\} \ ,$$

$$\sigma_{Z_i}^2 = \ln\left[\frac{M_{m2}}{M_{m1}^2}\right] \quad M_{m2} \triangleq E_{\boldsymbol{\xi}(t),\boldsymbol{\nu}(t)}\{SINR^2(\boldsymbol{\xi}(t),\boldsymbol{\nu}(t))\}$$

Fischione, Graziosi, Santucci,
IEEE Trans. Comm., October 2007

$$Pr[SINR_i(\boldsymbol{\xi},\boldsymbol{\nu}) < \gamma_i] = Q\left(\frac{-2ln\gamma_i - m_{Z_i}}{\sigma_{Z_i}}\right) \qquad Q(x) = 1/\sqrt{2\pi}\int_x^\infty e^{-t^2/2}dt$$

Interference Function

$$\boxed{\frac{P_{i0}}{I_i(\mathbf{n},\mathbf{P}_{-i})} \geq \gamma_i^2} \qquad I_i(\mathbf{n},\mathbf{P}_{-i}) = \frac{G_i(\mathbf{P}_{-i})^{q_i-\frac{1}{2}}}{H_i(\mathbf{P}_{-i})^{2q_i-2}}$$

$$q_i = Q^{-1}(\bar{P}_{out}^i)$$

$$H_i(\mathbf{n},\mathbf{P}_{-i}) = M_{m1}P_{i0}$$

$$G_i(\mathbf{n},\mathbf{P}_{-i}) = M_{m2}P_{i0}^2$$

Relaxation Problem

- Main Problem

$$\max_{\mathbf{n},\mathbf{P}} \sum_{i=1}^{K} n_i$$

$$s.t \quad \frac{P_{i0}}{I_i(\mathbf{n},\mathbf{P}_{-i})} \geq \gamma_i^2 \quad \forall\, i = 1,\ldots,K$$

$$\sum_{i=1}^{K} n_i P_{i0} \leq P_T$$

$$P_{i0} > 0 \quad \forall\, i = 1,\ldots,K$$

$$1 \leq n_i \leq G_i, \quad n_i \in \mathbb{N}^+ \quad \forall\, i = 1,\ldots,K$$

The Relaxation Problem

$$\min_{\mathbf{P}} \sum_{i=1}^{K} n_i P_{i0}$$

$$s.t. \quad \frac{P_{i0}}{I_i(\mathbf{n},\mathbf{P}_{-i})} \geq \gamma_i^2 \quad \forall\, i = 1,\ldots,K$$

$$P_{i0} > 0 \quad \forall\, i = 1,\ldots,K$$

$$1 \leq n_i \leq G_i, \quad n_i \in \mathbb{N}^+ \quad \forall\, i = 1,\ldots,K$$

- Any pair of vector $\bar{\mathbf{P}}$ a $\bar{\mathbf{n}}$ that solves the relaxation problem, with a cost function P_T s then , provides a feasible solution of the original problem.

- **Proposition 1:** *i* $\bar{\mathbf{n}} \leq \tilde{\mathbf{n}}$ *tł* $I_i(\bar{\mathbf{n}},\mathbf{P}) \leq I_i(\tilde{\mathbf{n}},\mathbf{P})$ *for* $\mathbf{P}$ *i and* *.*

- **Theorem:** *If the pa* $(\mathbf{n},\mathbf{P})$ *is a solution of the relaxation problem, then it verifies the following equations.*

$$\frac{P_{i0}}{I_i(\mathbf{n},\mathbf{P}_{-i})} = \gamma_i^2 \quad \forall\, i = 1,\ldots,K$$

Branch-and-bound Solution

- **Proposition 2**: $\bar{\mathbf{n}}$ *is feasible* $(\mathbf{n}, \mathbf{P})$ *pair can be a solution of the original problem only if* $\|\mathbf{n}\|_1 \geq \|\bar{\mathbf{n}}\|_1$

  The proposition says that, given a feasible vector $\bar{\mathbf{n}}$, the search for the feasible solutions can be restricted to the set

  $$\mathcal{N}_\Sigma(\bar{\mathbf{n}}) = \mathcal{N} \setminus \{\ \mathbf{n} \quad \text{such that} \quad \|\mathbf{n}\|_1 \leq \|\bar{\mathbf{n}}\|_1\ \}$$

- **Proposition 3**: *if* $\bar{\mathbf{n}}$ *is unfeasible, then any* $\|\mathbf{n}\|_1 \leq \|\bar{\mathbf{n}}\|_1$ *is unfeasible as well*.

  The proposition says that, if $\bar{\mathbf{n}}$ is unfeasible, the set of unfeasible solutions can be reduced as follows:

  $$\mathcal{N}_\mathcal{I}(\bar{\mathbf{n}}) = \mathcal{N} \setminus \{\ \mathbf{n} \quad \text{such that} \quad \|\mathbf{n}\|_1 \geq \|\bar{\mathbf{n}}\|_1\ \}$$

Radio Power Control (4)

- T Relaxation Problem in solved by contraction mappings (Fischione, Butussi, IEEE ICC 2007)

$$
\begin{aligned}
&\min_{\mathbf{P}} \sum_{i=1}^{K} n_i P_{i0} \\
s.t. \quad & \frac{P_{i0}}{I_i(\mathbf{n}, \mathbf{P}_{-i})} = \gamma_i^2 \quad \forall\, i = 1, \ldots, K \\
& P_{i0} > 0 \quad \forall\, i = 1, \ldots, K \\
& 1 \le n_i \le G_i, \quad n_i \in \mathbb{N}^+ \quad \forall\, i = 1, \ldots, K
\end{aligned}
$$

Algorithm *Relaxation Problem*

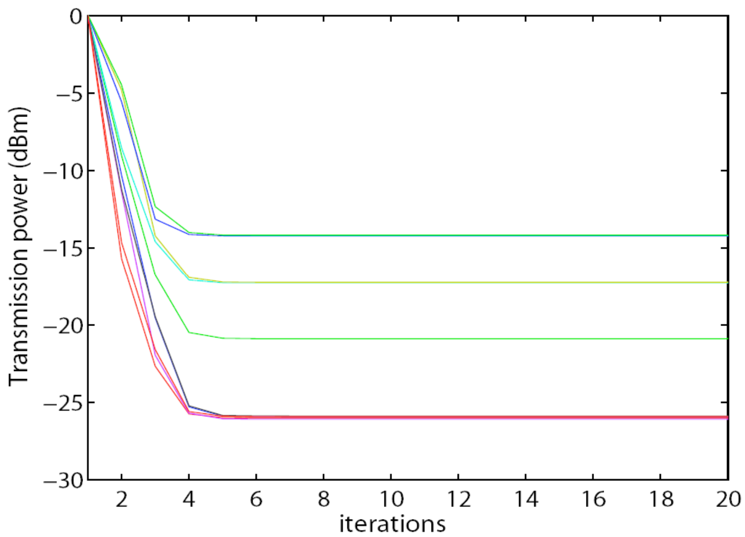
$t := 0;$
$\mathbf{n}(t-1) := \mathbb{1}\,;$
$\mathbf{p}(t-1) := 0;$
$\mathbf{n}(t) := \mathbb{1}\,;$
$\mathbf{p}(t) := \mathbf{p}_0\,;$
while $\|\mathbf{p}(t) - \mathbf{p}(t-1)\|_2 \ge \varepsilon$ **do**
  for $i := 1 : K$ **do**
    $p_i(t) := I_i(\mathbf{n}_{-i}(t-1), \mathbf{p}_{-i}(t-1))\gamma_i$
  end for;
  $t := t + 1;$
end while;

- A branch-and-bound algorithm builds the set of feasible and unfeasible rates by solving the Relaxation Problem, collecting feasible solutions, and reducing the candidate solutions via Proposition 2 and 3.

- It can be proved that the algorithm converges within a random time shorter then an exhaustive search over the initial set of possible rates.

Numerical Results for Power Control

Scenario	σ_{ξ_i}	α_i
A	0.5, 0.5, 0.5, 0.5	0.4, 0.4, 0.4, 0.4
B	0.5, 0.5, 0.5, 0.5	0.2, 0.2, 0.2, 0.2
C	0.5, 0.5, 0.5, 0.5	0.7, 0.7, 0.7, 0.7
D	0.4, 0.4, 0.4, 0.4	0.4, 0.4, 0.4, 0.4
E	0.6, 0.6, 0.6, 0.6	0.4, 0.4, 0.4, 0.4
M	0.5, 0.6, 0.4, 0.6	0.2, 0.4, 0.2, 0.7



Convergence of the Relaxation Problem

Number of rate vectors explored (solutions of the Relaxation Problem) to get the optimal solution with our proposed method:

Scenario	min	max	average
A	46	247	150
B	84	247	153
C	47	238	137
D	84	247	149
E	47	247	141
M	31	222	103

An exhaustive search over all rate vectors would have required $9^4 = 6561$ solutions of the relaxation problem.

Introductory Overview

Minimum Energy Coding

Radio Power Control

Bit Error Rate

Energy Consumption

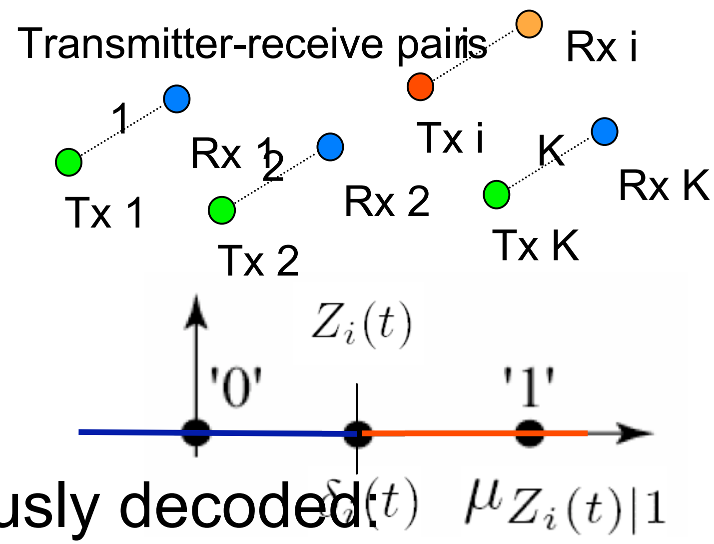
Numerical Results

Conclusions and Future Work

Bit Error Rate

- ♣ Decision variable at the receiver

$$Z_i(t) = D_i(t) + I_i(t) + N_g(t)$$



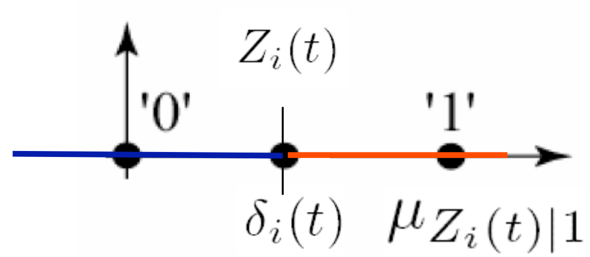
- ♣ The decision variable is erroneously decoded:
  - ¬ as a high bit, when a low bit was transmitted:

$$p_{i|0} = \Pr\left[Z_i(t) \geq \delta_i | b_i(t) = 0, \mathbf{h}_i(t), \nu_j(t)\right]$$

  - ¬ as a low bit when a high bit was transmitted:

$$p_{i|1} = \Pr\left[Z_i(t) < \delta_i | b_i(t) = 1, \mathbf{h}_i(t), \nu_j(t)\right]$$

Bit Error Rate (2)



- The probabilities are computed adopting the usual standard Gaussian approximation, where $Z_i(t)$ is modelled as a Gaussian random variable conditioned to the distribution of the channel coefficients and coding.

$$Z_i(t) \sim \mathcal{N}\left(\mu_{Z_i(t)}, \sigma_{Z_i(t)}\right)$$

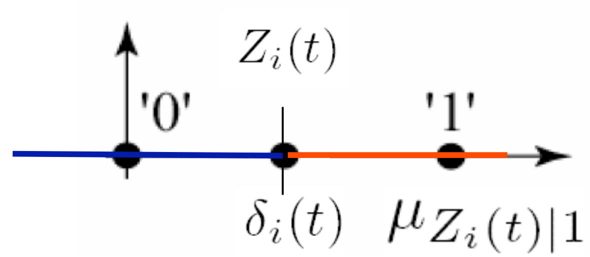
$$p_{i|0} = Q\left(\frac{\delta_i(t)}{\sigma_{Z_i(t)}}\right) ,$$

$$p_{i|1} = Q\left(\frac{\mu_{Z_i(t)|1} - \delta_i(t)}{\sigma_{Z_i(t)}}\right)$$

$$\mu_{Z_i(t)} = \begin{cases} \mu_{Z_i(t)|0} = 0 & \text{if } b_i(t) = 0 \\ \mu_{Z_i(t)|1} = \sqrt{\frac{P_i \Omega_{i,i}(t)}{2} T_b^2} & \text{if } b_i(t) = 1 \end{cases}$$

$$\sigma_{Z_i(t)} = \sqrt{\frac{N_0 T_b}{4} + \sum_{\substack{j=1 \\ j \neq i}}^{K} \nu(t) P_j \Omega_{j,i}(t) \frac{T_b^2}{6G}} .$$

Bit Error Rate (4)



- The Bit error probability is computed using the Log Normal SINR expression, and the Stirling approximation for the statistical Expectation:

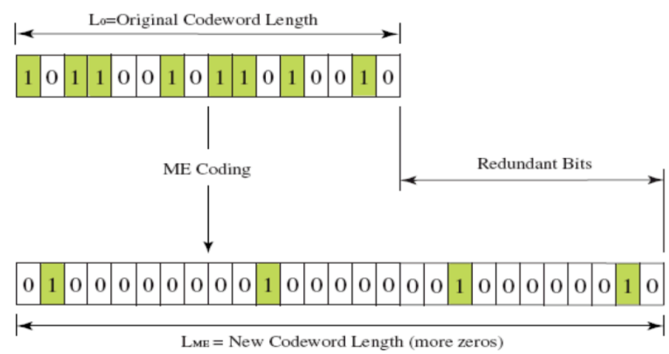
$$\Phi_i(\delta_i) \approx \frac{2}{3}\left[(1-\alpha_i)Q\left(\mu_{\zeta_{i0}}\right) + \alpha_i Q\left(\mu_{\zeta_{i1}}\right)\right] + \frac{1}{6}\left[(1-\alpha_i)Q\left(\mu_{\zeta_{i0}} + \sqrt{3}\sigma_{\zeta_{i0}}\right) + \right.$$
$$\left. + (1-\alpha_i)Q\left(\mu_{\zeta_{i0}} - \sqrt{3}\sigma_{\zeta_{i0}}\right) + \alpha_i\right] .$$

- It can be proved that the BER is a convex function.
  - The gradient method is used to derive the **optimal decision threshold**.

Bit Error Rate of ME and MME

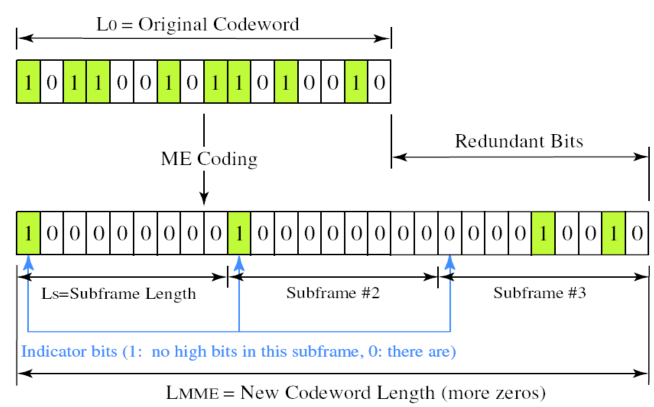
The characterization of Φ_i can be used to compute the BER of

1. ME: $\alpha = \alpha_{ME}$



2. MME: the coding structure,

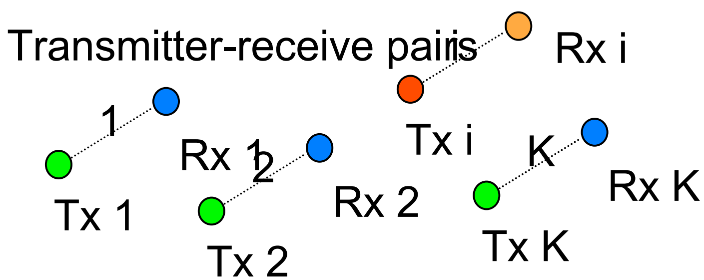
$$\alpha = \alpha_{MME}$$



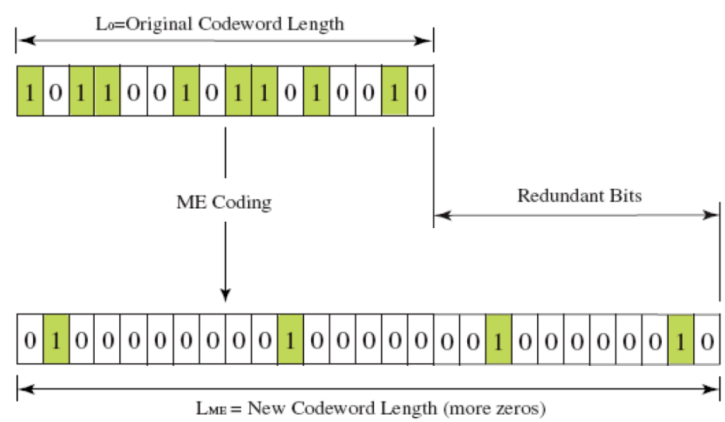
- Introductory Overview
- Main Contribution
- System Description
- Radio Power Control
- Bit Error Rate
- **Energy Consumption**
- Numerical Results
- Conclusions and Future Work

Average ME Energy Consumption

$$E_i^{(ME)} = E_i^{(tx)} + E_i^{(rx)}$$
$$= P^{(tx,ckt)}\left(T^{(on,tx,ME)} + T_s\right) + \alpha_{ME} P_i T^{(on,tx,ME)} + P^{(rx,ckt)}\left(T^{(on,rx,ME)} + T_s\right)$$

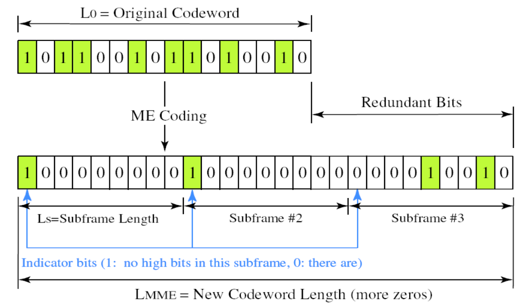


$$E^{(ME)} = \frac{1}{K}\sum_{i=1}^{K} E_i^{(ME)}$$



Average Energy MME Consumption

♣ The energy is function of the BER



$$E_i^{(MME)} = E_i^{(tx)} + E_i^{(rx)}$$
$$= P^{(tx,ckt)}\left[T^{(on,tx,MME)} + T_s\right] + \alpha_{MME} P_i T^{(on,tx,MME)} +$$
$$+ P^{(rx,ckt)}\left[T^{(on,rx,MME)} + (N_i + 1)\, T_s\right] .$$

$$N_i = N_s \left[1 - \Pr\left(b_{ind} = 0\right)\left(1 - \Phi_i\right) - \Pr\left(b_{ind} = 1\right)\Phi_i\right]$$

Receiver activity per MME codeword

$$E^{(MME)} = \frac{1}{K}\sum_{i=1}^{K} E_i^{(MME)}$$

$$\rho_{dB} = \left(\frac{E^{ME}}{E^{MME}}\right)_{dB}$$

MME Energy Gain

- ♣ Introductory Overview
- ♣ Main Contribution
- ♣ System Description
- ♣ Radio Power Control
- ♣ Bit Error Rate
- ♣ Energy Consumption
- ♣ **Numerical Results**
- ♣ Conclusions and Future Work

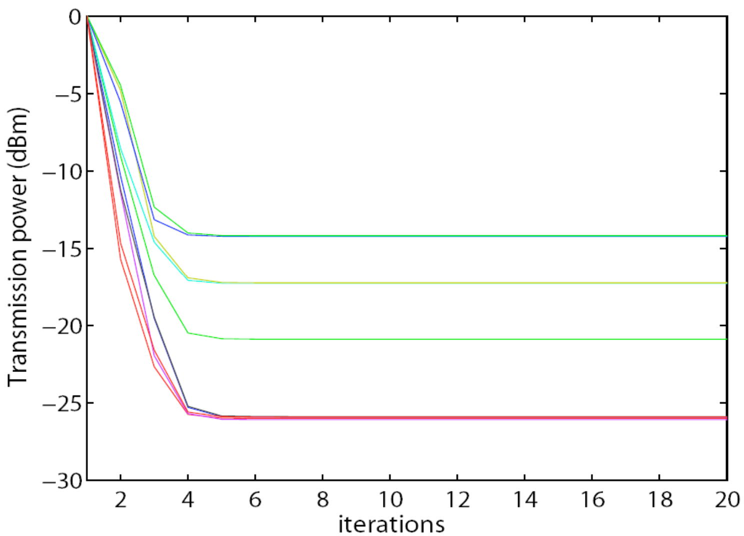
Numerical Results

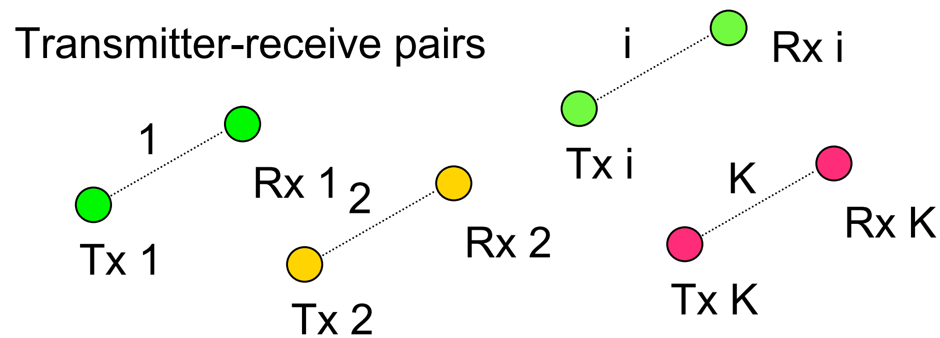
CC2420 was taken as reference for the energy parameters

$K = 10$	Number of transmitter receiver pairs
$P_l\left(d_r\right)\rvert_{\mathrm{dB}} = -55\ \mathrm{dB}$	Path loss at reference distance
$G = 64$	Spreading gain
$N_0/2\rvert_{\mathrm{dB}} = -174\mathrm{dBm}$	Noise Variance
SINR $\gamma = 3.1\ \mathrm{dB}$	SINR Threshold
$R_b = 250\mathrm{Kbps}$	Bit rate

Radio Power Optimization

- Convergence of the power minimization algorithm. On the x-axis is reported the number of iterations.



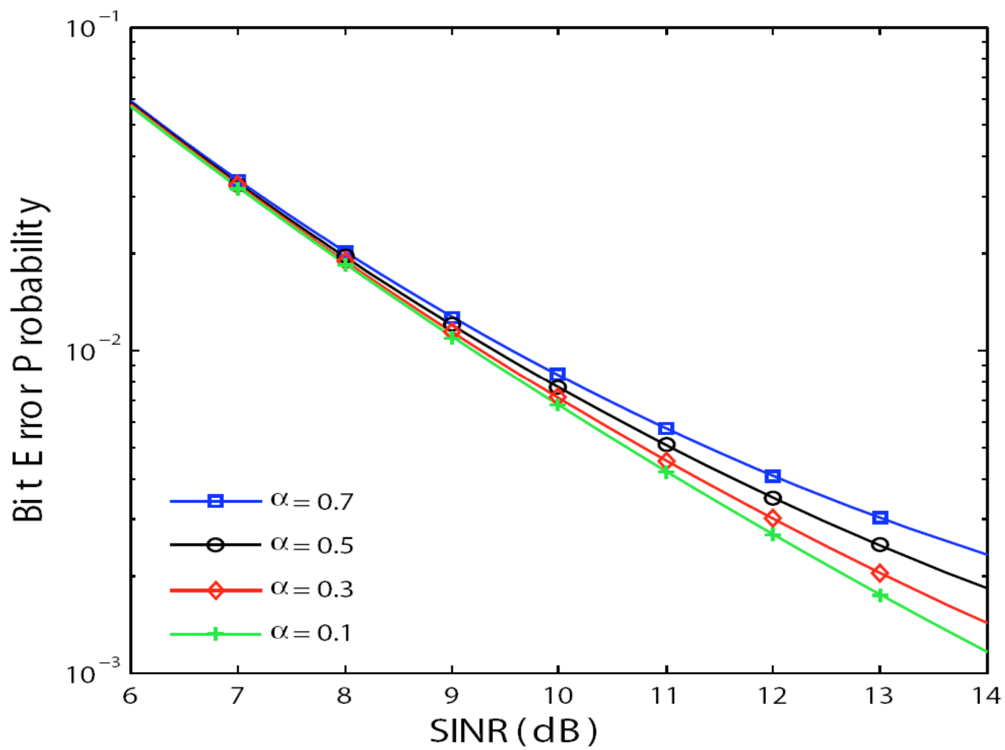


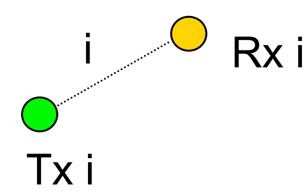
Algorithm *Relaxation Problem*

$t := 0;$
$\mathbf{n}(t-1) := \mathbb{1}\,;$
$\mathbf{p}(t-1) := 0;$
$\mathbf{n}(t) := \mathbb{1}\,;$
$\mathbf{p}(t) := \mathbf{p}_0\,;$
while $\|\mathbf{p}(t) - \mathbf{p}(t-1)\|_2 \geq \varepsilon$ **do**
  for $i := 1 : K$ **do**
    $p_i(t) := I_i(\mathbf{n}_{-i}(t-1), \mathbf{p}_{-i}(t-1))\gamma_i$
  end for;
  $t := t + 1;$
end while;

BER

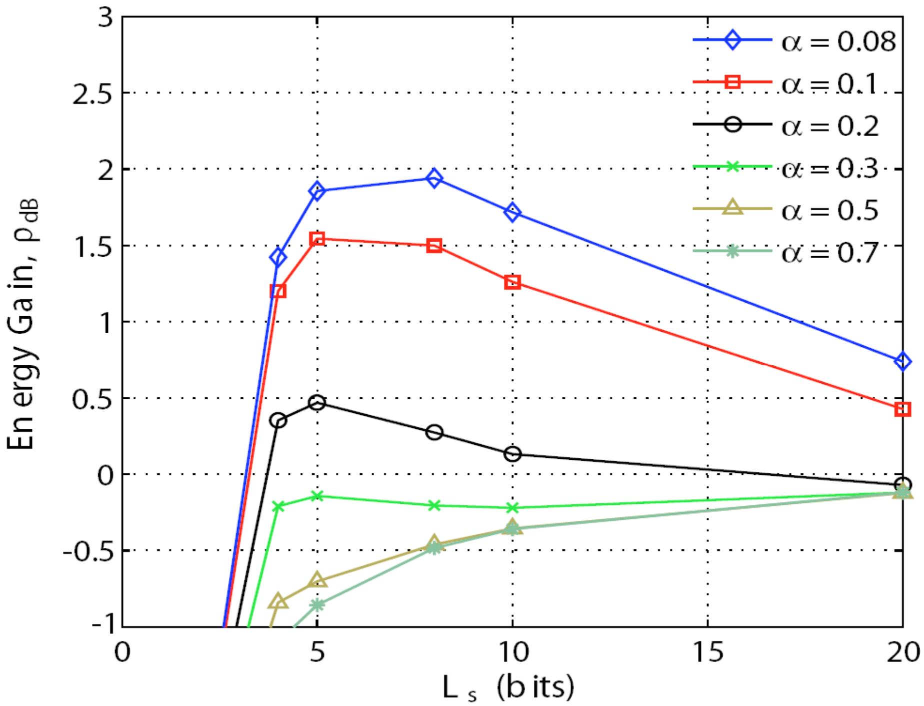
- Bit error probability for the ME and MME cases (note that they overlap).

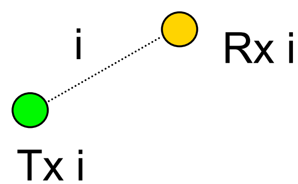




Energy Consumption

- MME Energy Gain as function of the sub-frame length, for different values of the transmitter activity





$$\rho_{dB} = \left(\frac{E^{ME}}{E^{MME}} \right)_{dB}$$

Conclusions and Future Work

- A general framework for accurate analysis of the Energy Consumption of ME and MME coding has been proposed.
  - Accurate Energy model and wireless propagation scenario.
  - Distributed power minimization strategy.
  - Optimal decision thresholds.
- Future studies
  - delay characterization.
  - distributed estimation.
  - simpler power control (geometric programming...)

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Questions

Thank you for your attention!

Any questions?