Collaborative Signal Processing for Energy-Efficient Self-Organizing Wireless Sensor Network

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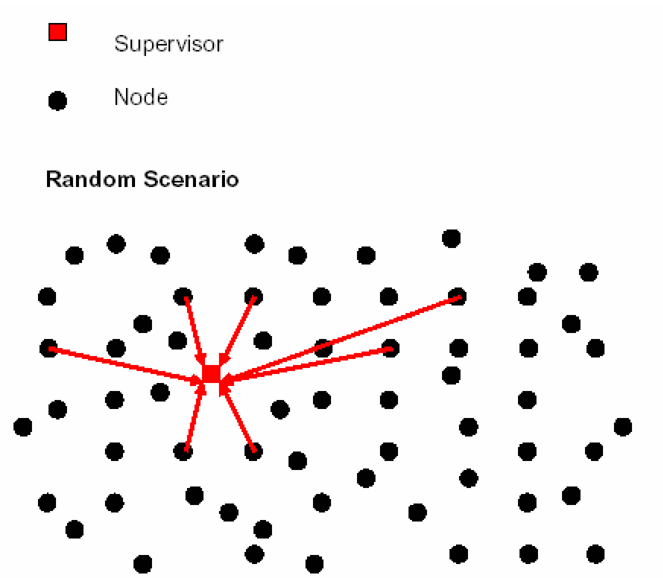
Introduction

- We analyze the performance of a dense energy-efficient Wireless Sensor Network for distributed collaborative environment monitoring

- The target multi-dim process is estimate from samples captured by nodes (sensor+wireless transceiver) randomly uniformly distributed

- We evaluate the impact of Collaborative Signal Processing on both – estimation error
  – lifetime



Motivations of the work

- Many applications require sensing from random node's position

- Many papers in the literature are based on simulations or consider deterministic channels → analytical framework for WSN design in realistic wireless medium

- WSN design aspects:

- Channel model → path-loss + shadowing
- Connectivity
- Energy consumption
- Information routing
- Process estimation quality
- Node's density
- Localization (centralized or distributed)
- MAC protocol
- System and process parameters

Low-cost device → proper balance between communication capabilities and signal processing

Self-organized WSN

Supervisor more capable (in processing and transmission) than other nodes that are typically in sleep mode and periodically commute in rx mode

round

SV triggers

↓

triggered nodes organize thamselves into cluster with random selection of the node Cluster Head

↓

each node sent its sample to its CH

No CSP ↙ ↘ CSP

No CSP: each CH sends the aggregate information of its cluster to the SV that estimate the process

CSP: each CH sends a properly processed information to the SV that estimate the process

↘ ↙

SV estimates the process

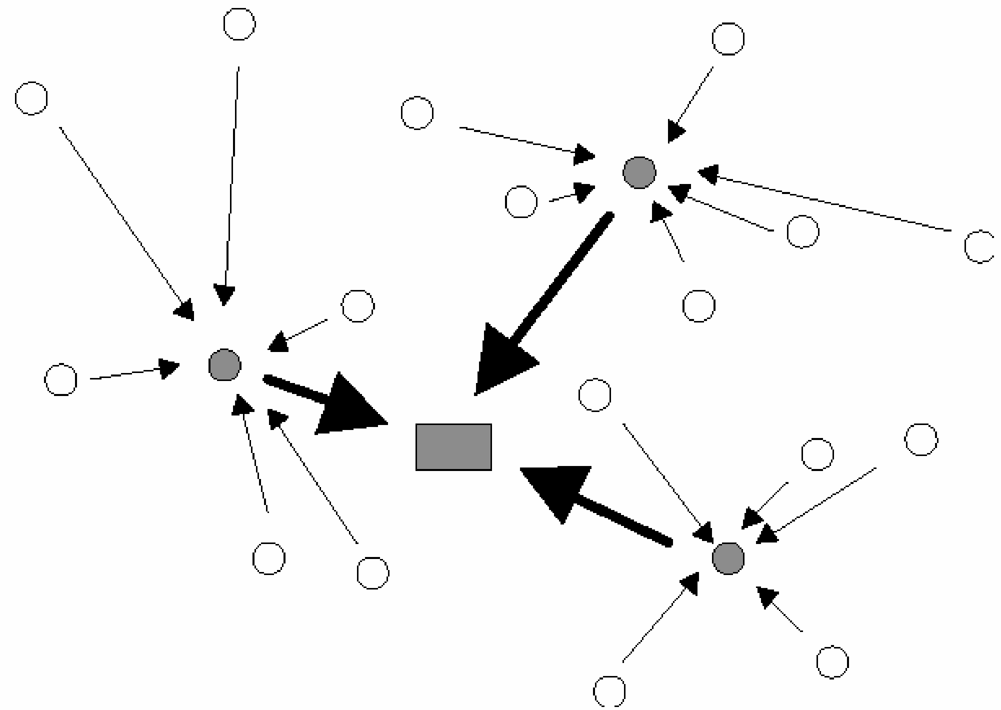


Fig. 1. Transmission flow with the clustered algorithm. Filled box: supervisor; filled circle: cluster heads; circle: nodes non-cluster head.

LEACH-based alg.

More information to be transmitted from CH (greater energy consumption)

Random election of CH at each trigger with prob. **x**

Statistical analysis of connectivity

Propagation-loss (dB) $L = K_0 + K_1 \cdot ln(d) + s$ ← shadowing $\sim N(0,\sigma^2)$

Readapting theory in [12][13] to WSN: …infinite plane of Poisson distributed nodes with density ρ

- The number of nodes triggered by SV is Poisson distr. with mean

$$N_t = \mathbb{E}\{n_t\} = \pi\ \rho\ e^{2(\sigma^2/K_1^2 - K_0/K_1 + L_{su}/K_1)}$$

- Self-election of CH $N_{ch}=x\ N_t$ $\rho_{ch}=x\ \rho$

- Broadcasting to notify CH's election $P_t=\alpha\ P_{su}$

- Cluster selection (each nonCH node associates itself to the strongest rx CH)

$$N_{ach} = \mathbb{E}\{n_{ach}\} = \pi\ \rho_{ch}\ e^{2(\sigma^2/K_1^2 - K_0/K_1 + L_p/K_1)}$$

- Mean cluster dimension, n_p Poisson distributed with mean

$$N_p = \mathbb{E}\{n_p\} = \pi\ \rho_{nch}\ e^{2(\sigma^2/K_1^2 - K_0/K_1 + L_p/K_1)} \cdot \frac{1 - e^{-N_{ach}}}{N_{ach}}$$

$$N_p^{(\infty)} = \rho_{nch}/\rho_{ch} = (1-x)/x$$

- Probability to have triggered but isolated nodes

$$p = e^{-N_{ach}}$$

- Energy spent by the CH to tx information

  - no CSP → $(np+1)\ E_H/T$

  - CSP → $m\ E_H/T$

    ↘ + energy spent for signal processing E_{csp}

- Energy spent by a nonCH

  $E_H\ \alpha\ /T$

⇓

Energy budget

Target Process Estimation

Sample space limited by SV tx range

$$x(\mathbf{s}) = z(\mathbf{s}) \cdot r_A(\mathbf{s})$$

x(**s**) has finite energy with bandwidth per dimension B and

$$dim(\mathcal{S}) = \beta \qquad \beta = (2B)^l$$

Sequence of spatial samples is an Homogeneous Poisson point process

$$H(\mathbf{s}) = \sum_n \delta(\mathbf{s} - \mathbf{s}_n)$$

With linear interpolation of sampled version of the target process we estimate

$$\hat{X}(\mathbf{s}) = \phi(\mathbf{s}) \otimes Y(\mathbf{s})$$

$$\Phi(\nu) = \begin{cases} 1/\mu_\phi & \nu \in \mathcal{S}^* \\ 0 & \text{otherwise}. \end{cases}$$

Normalized Estimation Error

$$\varepsilon = \frac{1}{E_0}\mathbb{E}\left\{\int_{\Re^l}\left(\hat{X}(\mathbf{s}) - x(\mathbf{s})\right)^2 d\mathbf{s}\right\}$$

$$\varepsilon = p^2 + (1-p)\beta\zeta/\rho$$

Without CSP → ς=1, oversampling factor $\eta = \rho/\beta$

With CSP → the CH estimate the process in its cluster and re-sample @ Nyquist frequency to tx to the SV only M samples

ς=Nch $M = \frac{(N_p+1)\beta}{\rho} = (N_p+1)/\eta$

Energy Budget

Mean energy/round spent by a node.

Without CSP

$$E_{round} = x\ E_H (N_p + 1) + E_H\ \alpha\ (1 - x)$$

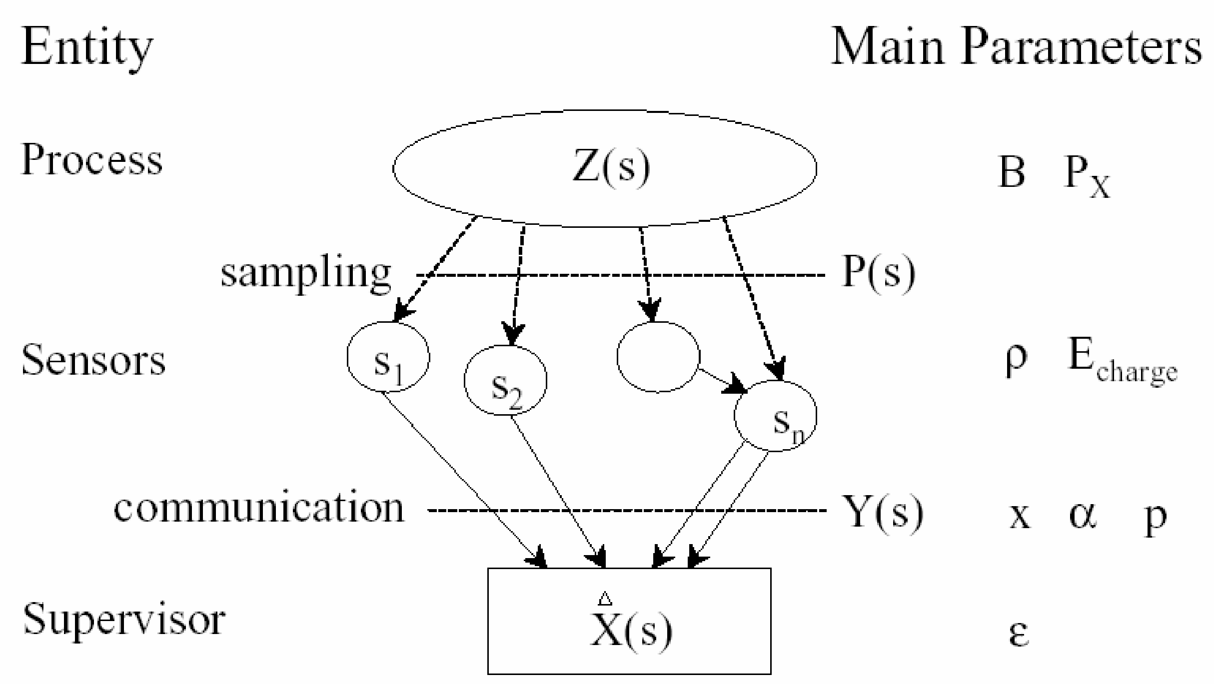
With CSP

$$E_{round} = x\ \left[E_{csp} + E_H (N_p + 1)/\eta\right] + E_H\ \alpha\ (1 - x)$$

$$E_{csp} = E_H\ \gamma\ (N_p + 1)$$

WSN lifetime

$$N_{round} = \frac{E_{charge}}{E_{round}}$$



By playing with the parameters and CSP different trade-offs between WSN lifetime and process estimation quality are possible, e.g.,

$K_0 = 40$, $K_1 = 13.03$, $\sigma = 8$, $\beta = 4\ 10^{-4}\ \mathrm{m}^{-2}$, $L_{su} = 100$, $E_{charge} = 5$ J, $E_H = 10^{-4}$ J, and $\gamma = 0.01$.

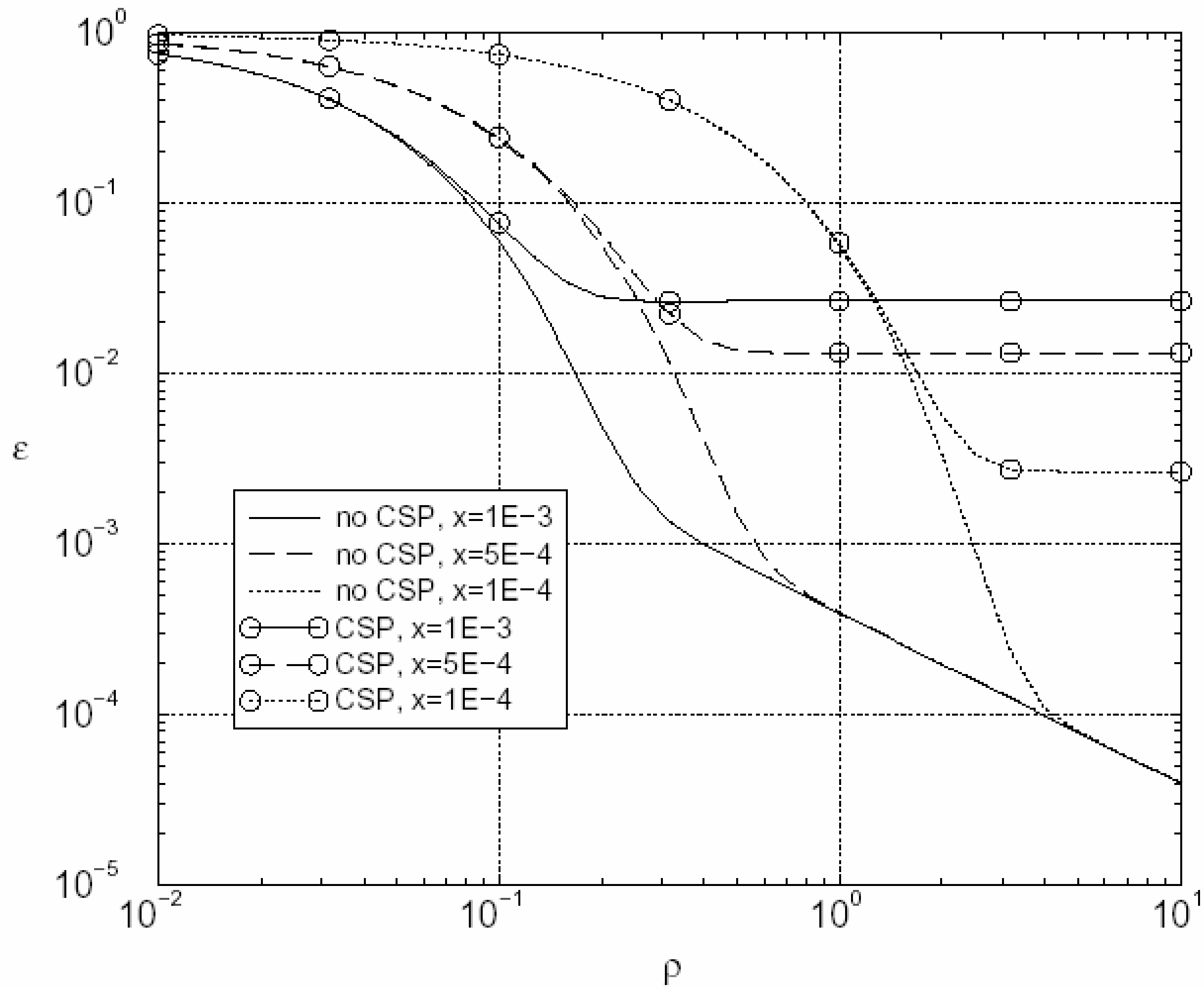


Fig. 2. Normalized process estimation error with and without CSP as a function of the node density for different values of x for $\alpha = 0.1$.

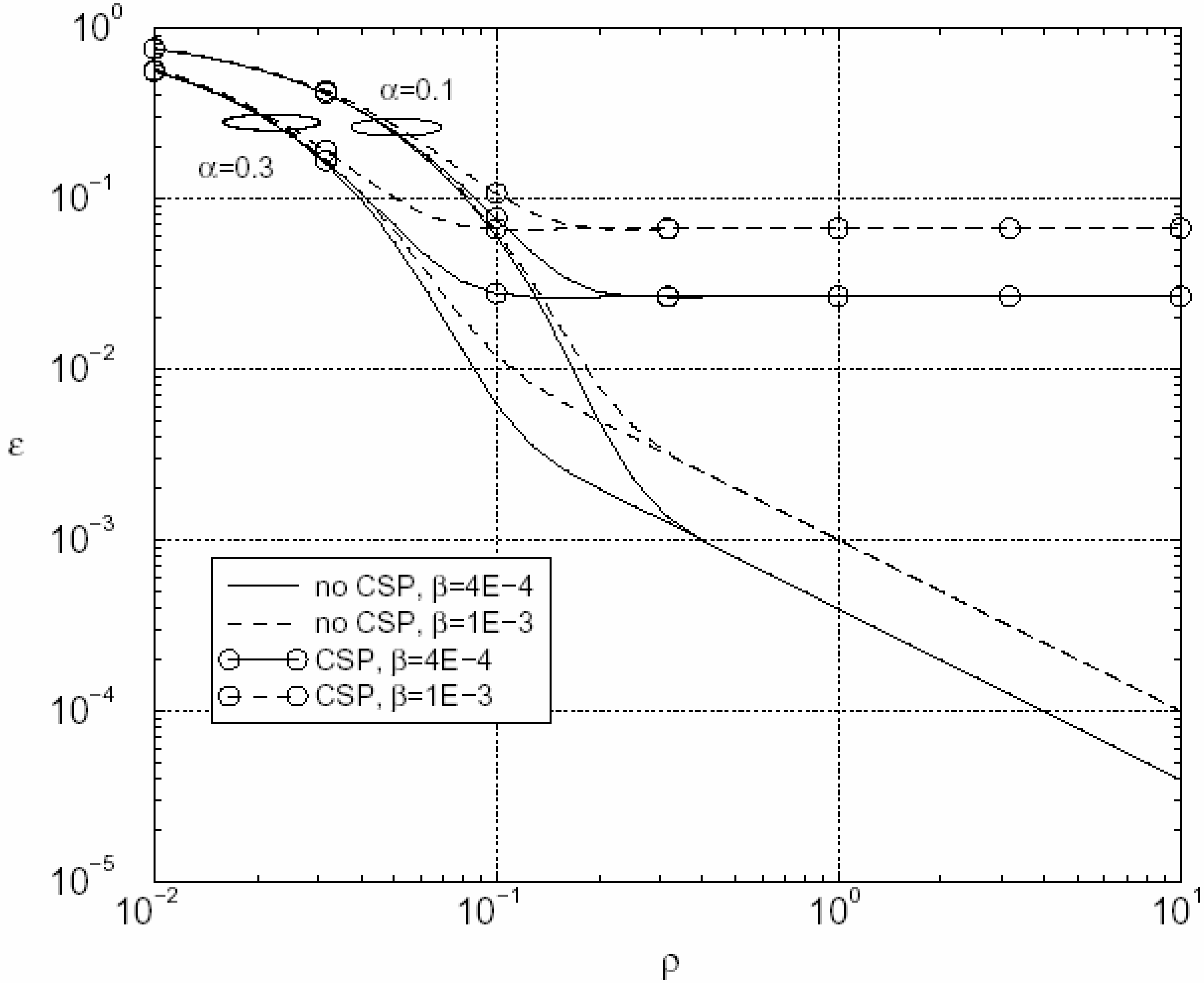


Fig. 3. Normalized process estimation error with and without CSP as a function of the node density for different values of β and α with $x = 0.001$.

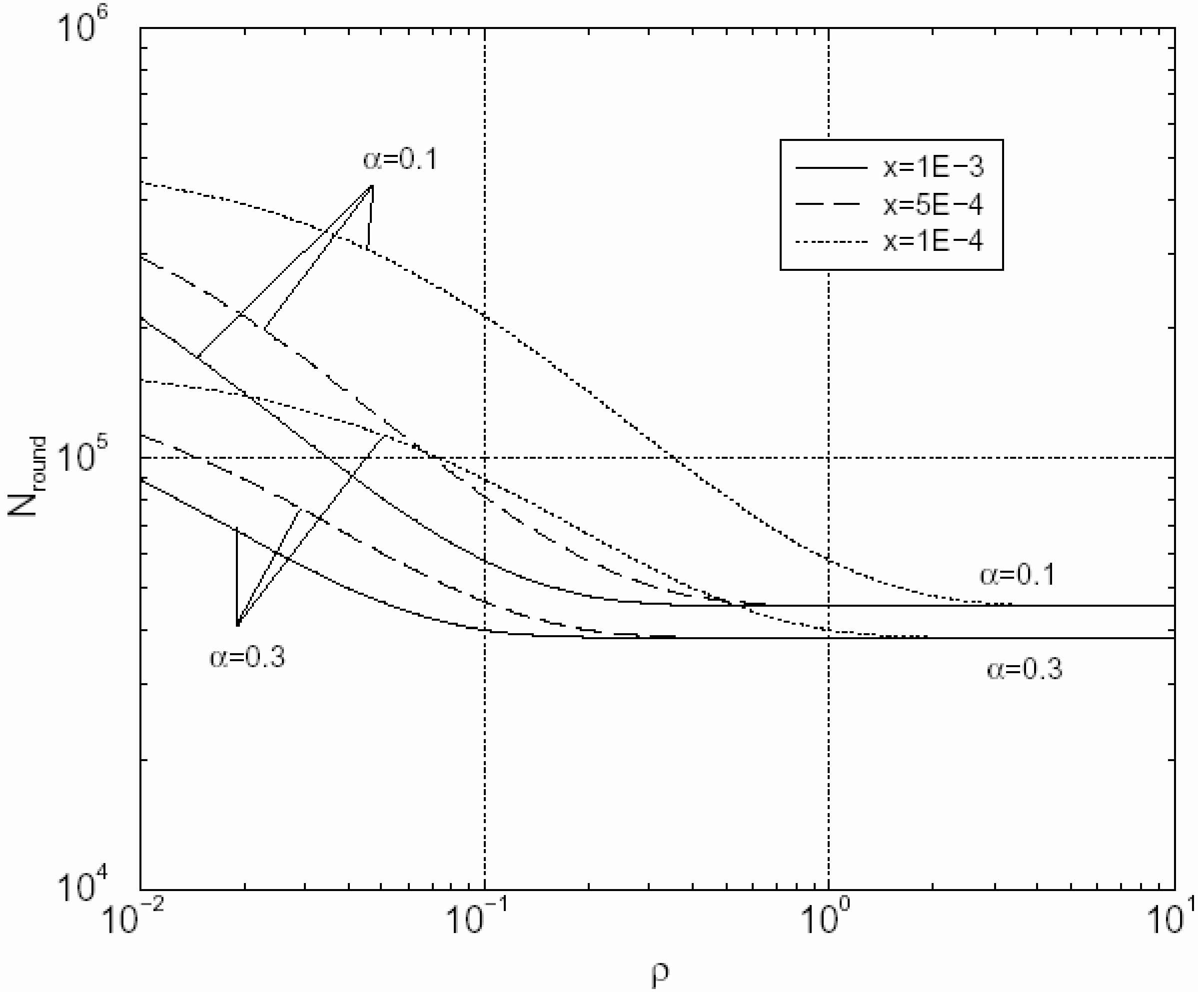


Fig. 4. Mean node's life duration (in terms of number of transmissions) as a function of the node's density for different values of parameters x and α in the absence of CSP.

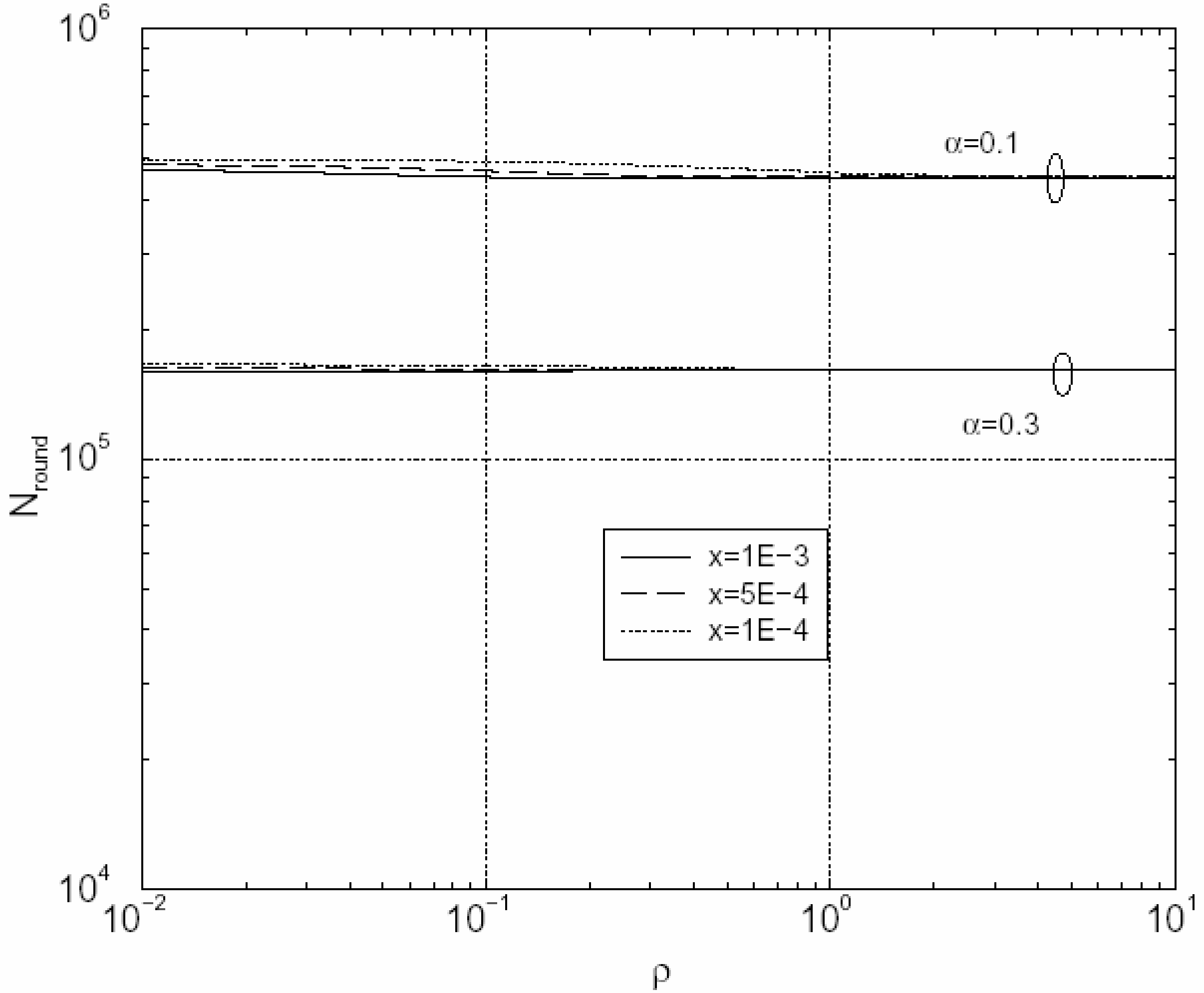


Fig. 5. Mean node's life duration (in terms of number of transmissions) as a function of the node's density for different values of parameters x and α in the presence of CSP.

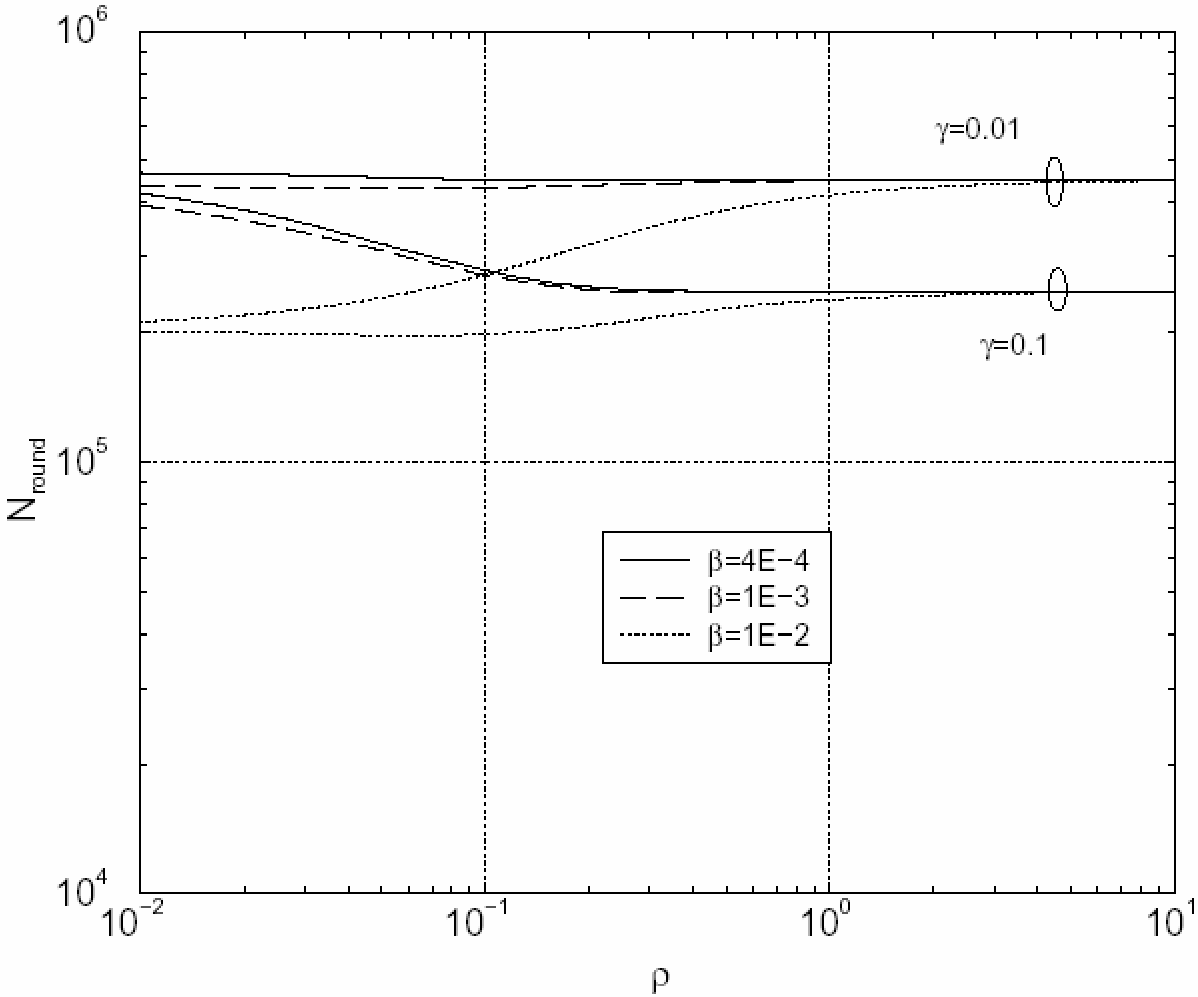


Fig. 6. Mean node's life duration (in terms of number of transmissions) as a function of the node's density for different values of parameters β and γ in the presence of CSP with $x = 0.001$ and $\alpha = 0.1$.

Conclusions

We addressed interdependent aspects for WSN design by developing an analytical framework

The trade-off between process estimation quality and life-time can evaluated

The adoption of CSP can strongly improve the network life-time