A Simple Wake-Up Scheme Based on Ultra-Wideband Beamforming

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Motivation

- **Ultra-Wideband Impulse Radio (UWB-IR)** is a promising candidate for Low-Data-Rate/Location-Tracking (LDR/LT) sensor networks:
  - Low power
  - Low complexity
  - Good localization capabilities

- Stringent constraints on hardware and **power consumption** of sensor nodes:

  ⇒ Investigation of simplified sensor network scenario for **semi-active sensor nodes** with significantly reduced power consumption
Scenario:

- **Circular room** of radius $R_D$:
  - Wireless backbone statically mounted on the wall
  - Many distributed sensor nodes in the room

- **Wireless backbone** consists of distributed UWB-IR devices:
  - Perfectly synchronized
  - With global positioning and beamforming information
  - Coordinates sensors by means of beamforming.

- **Semi-active sensor nodes**:
  - All identical
  - No position nor channel state information
  - Only a low power wake-up detector is active, during idle times and triggers active mode, if received energy exceeds a threshold.
System Model: Backbone and Channel Model

- The wake-up signal from the **wireless backbone** steered to position $i$ is described by

$$s(t, i) = \sqrt{E_p} \sum_{a=0}^{N_a-1} w(t - \delta_{a,i}),$$

with $N_a$ the number of backbone devices, $w(t)$ a short pulse, and $\delta_{a,i}$ the beamform delays.

- The **channel impulse response** between antenna $a$ and position $j$ is modeled deterministically as

$$h_{a,j}(t) = \sqrt{\frac{1}{\Psi_{a,j}}} \delta(t - \tau_{a,j}) \quad \text{with} \quad \Psi_{a,j} = (Ad_{a,j}^{-\gamma})^{-1} = \left(\frac{1}{B} \int_1^{f_a} \frac{c^2}{(4\pi f)^2 d_{a,j}^{\gamma}} df\right)^{-1},$$

and $\tau_{a,j}$, the corresponding linear path loss factor and propagation delay, respectively.
System Model: Wake-Up Detector

- Non-coherent threshold receiver
- It periodically scans the environment by sampling an observation window much larger than the pulse width.
- The observation window is synchronized to the backbone.
- As system performance is dominated by the strongest sample within each window, an approximate signal model can be applied:

\[ y(i,j) = \frac{E_p}{\psi_{a,j}} \int_{t_j}^{t_j+T_j} \left| \sum_{a=0}^{N_a-1} w(t - \tau_{a,j} - \delta_{a,i}) \right|^2 \, dt. \]

- \( t_j \) is the corresponding sampling instance.

\[ \hat{y}(i,j) \]

with \( \hat{y}(i,j) \), the sample with the strongest signal component.
Energy at Beamed and Non-Beamed Positions for $N_a=10$, 3GHz and $\gamma = 2$

Beam pattern over disc [dBJ], if beamforming is done to position [-1,1]  

All beamed (blue) and non-beamed samples (green) plotted over disc radius
Threshold:

- Ideal threshold $\eta$ satisfies:
  - Condition 1: $\eta \leq \eta_{\text{max}} = \min_{\forall i} y(i, i)$
  - Condition 2: $\eta > \eta_{\text{min}} = \max_{\forall i} \left\{ \max_{\forall j \neq i} y(i, j) \right\}$

- If Condition 1 is violated, there exist sensors which can not be triggered. If Condition 2 is violated, there exist sensors which often are triggered erroneously.

- Due to path loss effects the ideal threshold does not exist and there is a clear trade-off between the two conditions.

- By choosing the threshold equal or smaller than the maximal feasible threshold, Condition 1 is always satisfied:
  $$\eta \leq \eta_{\text{max}} = \min_{\forall i} y(i, i)$$

  $\rightarrow$ Non-feasible regions appear only at the edge of the disc due to Condition 2.
Minimal Beamed Energy for $N_a = 4$ and $N_a = 5$
Feasibility of Threshold System:

- Approximation of minimal beamed energy \( \min_{\forall i} y(i, i) \) by the beamed energy at disc center leads to:

\[
E_{\text{rx}} = N_a^2 E_p A R_D^{\gamma}, \quad \text{with} \quad A = \frac{1}{B} \int_{f_l}^{f_u} \frac{c^2}{(4\pi f)^2} df.
\]

- We define the feasible area as the area, where the beamformed energy exceeds maximal single pulse energy from the nearest antenna:

\[
E_{\text{Single}} < E_{\text{rx}} \quad \iff \quad E_p A d_{a,j}^{-\gamma} < N_a^2 E_p A R_D^{\gamma}.
\]

- Simple approximation of feasibility coverage can be derived:

\[
\mathcal{F} = \pi R_D^2 - \frac{1}{2} N_a \pi \left( N_a^{\gamma - 2/\gamma} R_D \right)^2.
\]
Feasible Areas and Feasibility Coverage:

Significant coverage improvement is achieved with increased number of antennas.
Probability of False Alarm and Missed Detection (1)

\[ p_{FA} = \sum_{\forall i} \sum_{\forall j \neq i} P(y > \eta_{\text{min}} | i, j) \cdot P(i, j) \]

\[ p_{MD} = \sum_{\forall i} P(y \leq \eta_{\text{min}} | i, i) \cdot P(i, i), \]

Integration duration approximately equals Rx pulse width

⇒ Wake-up detector can be modeled as one-tap receiver.
Probability of False Alarm and Missed Detection (2)

- Sample after bandpass filter is modeled as:
  \[ b(i, j) = \sqrt{y(i, j)} + \tilde{n}, \]
  with \( \tilde{n} = N(0, 2N_0). \)

- With \( Z = b^2(i, j), \) \( Z \) has non-central chi-square distribution and:
  \[
  P(\hat{y} > \eta | i, j) = Q_1 \left( \sqrt{y(i, j)}/N_E, \sqrt{\eta}/N_E \right)
  \]
  \[
  P(\hat{y} \leq \eta | i, i) = 1 - Q_1 \left( \sqrt{y(i, i)}/N_E, \sqrt{\eta}/N_E \right),
  \]
  with \( Q_1 \) the generalized Marcum-Q function.
Probability of False Alarm and Missed Detection (3)

For SNR=85dB, promising wake-up performance is achieved!

\[ R_D = 100\, \text{m}, \quad \gamma = 2, \quad N_a = 10, \quad \tilde{\eta} = 0.7 \]

\[ \text{SNR} = \frac{E_p}{N_E} \]

\[ N_E = N_0 G_{\text{Amp}} L_{\text{Ant}} L_{\text{Imp}} \]
A Link Budget Example:

- With: $L_{\text{Imp}} = 3\, \text{dB}$, $L_{\text{Ant}} = 3\, \text{dB}$, $G_{\text{Amp}} = 17\, \text{dB}$, we have $N_E = -181\, \text{dBW/Hz}$
- Assuming Tx pulse band from 3.1GHz to 6.1GHz:
  
  $$E_{p}^{tx} = -96\, \text{dBJ} \text{ and } PL(dB,100\, \text{m}) = 85\, \text{dB}$$

**Calculations:****

SNR(dB) = $E_{p}^{tx}$ (dB) − $N_E$ (dB)

= $-96\, \text{dB} + 181\, \text{dB} = 85\, \text{dB}$

$$\text{SNR}_{Rx} \text{ (cntr,dB)} = \left( \frac{N_{a}^{2} E_{p}^{tx} AR_{D}^{-\gamma}}{N_{E}} \right)$$

= $20 \log \left( N_{a} \right) + E_{p}^{tx} \text{ (dB)} - PL(dB) - N_{E} \text{ (dB)}$

= $20 - 96 - 85 + 181 = 20\, \text{dB}$
Conclusions:

- We proposed a very simple wake-up scheme for UWB-IR, significantly reducing power consumption at sensor side.
- Scaling of non-feasible regions as a function of number of antennas was investigated:
  - Non-feasible regions strongly decrease with increasing number of backbone antennas.
- Within feasible region promising performance results were shown.
Thank You!

Questions & Answers