From Outage Probability to ALOHA MAC Layer Performance Analysis in Distributed Wireless Sensor Networks

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Outline

Introduction: Wireless Sensor Networks (WSNs)

Problem Statement & Outage Probability

Slotted-ALOHA with Channel Reservation and Without Interferences

Slotted-ALOHA with Channel Reservation and Interferences

Experimental Analysis and Main Result
Introduction: Wireless Sensor Networks (WSNs)
Nowadays, WSNs are everywhere!

- Environmental applications.
- Home applications.
- Medical applications, etc.
LIRIMA PREDNET Project

- Even Rhinos need smartphones!
Challenges behind WSNs

- Keep the network up for several years (5-10 years).
- Generally the deployed architectures are distributed
  ⇒ Interferences! (partially responsible for the loss of energy).
To face these challenges

Two directions are natural:

▶ Use different sources of energy (solar for example).
▶ Optimizing the hardware and the software.

The software concerns essentially:

▶ The physical layers.
▶ The Medium Access Control (MAC) Layer.

In this work, we study:

▶ The influence of the MAC layer on the network performance.
▶ In particular, we address the following question:

How many channels do we need to achieve high performance distributed wireless sensor network?
Problem Statement & Outage Probability
MAC Protocol: Slotted-ALOHA

- Multiple nodes and a unique BTS.
- Distributed access policy ⇒ the nodes make the decision (randomly) to transmit on their own (e.g. Slotted-ALOHA MAC protocol).

Multiple nodes could choose the same channel ⇒ Interferences!
Outage Probability

The probability that the signal-to-interference-plus-noise-ratio (SINR) is less than a given threshold \( \tau > 0 \),

\[
Op = \mathbb{P}\{\text{SINR} < \tau\},
\]

where, \( \text{SINR}(o, r) = \frac{S(o, r)}{I(o) + N_0} \).
Assumptions

- $\Pi_\lambda \subset \mathbb{R}^2$ Homogeneous Poisson Point Process (HPPP) spatial distribution of the nodes with density $\lambda$.
- The wireless channel consists of path loss attenuation with no fading:

$$\forall X_i \in \Pi_\lambda, P_i = P_e \|X_i\|^{-\alpha},$$

where $\alpha, P_e > 0$.
- The Medium Access Control strategy is a Slotted-ALOHA, the communicating nodes have a density $\lambda^*$ s.t.

$$\lambda^* = \frac{2 T_s}{T} \frac{1}{N_c} \lambda.$$
Expression of Op

Proposition

The Outage probability for Slotted-ALOHA MAC protocol is given by the following expression:

\[
\text{Op}^{SA} \equiv \lim_{N \to +\infty} \frac{1}{N} \sum_{j=1}^{N} \mathbb{I}(\Sigma_{\alpha}^j > \frac{\xi}{(\lambda^* \pi)^{\alpha/2}}) \\
\text{where } \mathbb{I}(\cdot) \text{ is the indicator function, } \xi = \frac{r^{-\alpha}}{\tau} - \frac{N_0}{P_e} \text{ and}
\]

\[
\Sigma_{\alpha}^j = \log \left( \frac{1}{1 - U_0^j} \right)^{-\alpha/2} \\
+ \sum_{k=1}^{+\infty} \left( -kW_0 \left[ -\frac{1}{k} \exp \left( \log \left( \frac{(1 - U_k^j)k!}{k} \right) \right) \right] \right)^{-\alpha/2}.
\]
Slotted-ALOHA with Channel Reservation and Without Interferences
MAC Protocol Description: Slotted-ALOHA with Channel Reservation (SACR)

Assuming $N \sim \text{Poiss}(\mu = \frac{N_n}{N_{ts} N_{fc}})$, the reservation probability is

$$Rp = \mathbb{P}\{N = 0\} = e^{-\mu}$$
SACR Strategy Illustration

- **BTS**
- Communicating node
- Inactive nodes
Communicating Node States Modeling: Markov Chain
Given its transition matrix $\Gamma$, the distribution over states is given by a stochastic row vector $\pi$ s.t. $\pi^{(k+1)} = \pi^{(k)} \Gamma$ and so $\pi^{(k)} = \pi^{(0)} \Gamma^k$, thus $\pi^\infty = \pi^{(0)} \lim_{k \to \infty} \Gamma^k$. In particular the success transmission likelihood is given by

$$T_{xi} = \left[ \lim_{k \to \infty} \Gamma^k \right]_{(1,4i)}$$
Figure 1: Curves of $Tx_i$'s.
Slotted-ALOHA with Channel Reservation and Interferences
When interfering nodes in the *out range* of the BTS

\[ \text{Op} \|X_0\| > R = \mathbb{P} \left\{ \sum_\alpha > \frac{\xi}{(\lambda^* \pi)^{\alpha/2}} \left\| X_0 \right\| > R \right\}, \]

where \( R \) denotes the range of the BTS.
When interfering nodes in the *out range* of the BTS

![Graph showing transmission success likelihood](image)

**Figure 2:** Comparison of the transmission success likelihood after one trial with no interfering nodes (in blue) and with interference (in black).

*TX1* vs. *Number of nodes*
Experimental Analysis and Main Result
Experiment using Fit-IoT-Lab platform

IoT experimentation at a large scale
Automatic, in a few click!

IoT-LAB: a very large scale open testbed
IoT-LAB provides a very large scale infrastructure facility suitable for testing small wireless sensor devices and heterogeneous communicating objects.
### Experiment details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of nodes</td>
<td>$\lambda = 1.7 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>Attenuation coeff.</td>
<td>$\alpha = 2.2$</td>
</tr>
<tr>
<td>Noise power</td>
<td>$N_0 = -100, \text{dBm}$</td>
</tr>
<tr>
<td>Trans. power</td>
<td>$P_e = 25, \text{dBm}$</td>
</tr>
<tr>
<td>SINR thresh.</td>
<td>$\tau = -10, \text{dB}$</td>
</tr>
<tr>
<td>Dist. node</td>
<td>$r = 50, \text{m}$</td>
</tr>
<tr>
<td>Numb. nodes</td>
<td>$N_n = 40$</td>
</tr>
<tr>
<td>Numb. channels</td>
<td>$N_c = 5$</td>
</tr>
<tr>
<td>Numb. time-slots</td>
<td>$N_{ts} = 4$</td>
</tr>
</tbody>
</table>

[Diagram showing various wireless technologies and data rates]

Contiki

MATLAB
Figure 3: Comparison between the theoretical transmission likelihood and its practical estimation for 20 channels. Best view in color.
Main result: How many channels do we need to achieve high performance distributed wireless sensor network?

Figure 4: Transmission success likelihood in terms of number of nodes in the network and number of channels assuming the presence of interfering nodes in the out range of the BTS.
Thank you for your attention!