A Novel Control Strategy for Fail-Safe Cyclic Data Exchange in Wireless Sensor Networks

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Wireless Sensor Networks Fundamentals

- Sensors are cheap, small and with little processing capacity
- Sensors are usually battery-powered or self-powered
- A Wireless Sensor Network typically consists of several hundreds of sensors
- In a multi-hop network, key nodes (gateways) are used to route data from one cluster to another
Wireless Sensor Networks Fundamentals

✓ Administering sensors’ energy enhances their lifetime and thus network availability

✓ The underlying problem is mathematically complex and requires proper modeling of physical and application layers

✓ Wireless Sensor Networks are a “hot topic” in both academia and industry

✓ “Fail-safe” is a hot topic in Wireless Sensor Networks
In this scenario, our goal is ...

✓ to propose a mathematical model that enables the designer to ensure a target network availability by trading off between message transmission rate and outage probability

• Outage Probability ($P_{out}$): probability that the signal quality received by a given node falls under a minimum acceptable threshold value (i.e., bad signal quality)
Definitions

One-Way Message Exchange Mechanism:

Node A transmits $m$ messages to node B through a wireless fading channel. Node B successfully receives $\tilde{m}$ messages.

- Under small-scale fading effects, the system’s performance is governed by the signal-to-noise ratio.
System Model

- \( s_1 \) and \( s_a \) are **Cluster Head Nodes** between **cluster 1** and **cluster 2**
- \( s_b \) and \( s_c \) are **Coordinator Nodes** control the quality of the communication links between nodes within a single broadcast domain, by overhearing messages during an observation **Window** \( T_w \)
- Remaining nodes are **Application Nodes** (e.g., sensing nodes)
- Nodes transmit data at **constant transmission rate** \( R \)
- Nodes are synchronized and use **TDMA** to avoid medium contention
Energy Function and Metrics

• Outage Probability ($P_{out}$):

\[
\hat{P}_{out} = 1 - \frac{\tilde{M}}{\hat{m}} \approx \frac{\gamma_0 \sigma_N^2}{S}
\]

- # of successfully received messages by the Coordinator Node from a Sensing Node over a $T_w$
- # of estimated transmitted messages from the sensing node

• Where:

\[
\hat{m} = T_w R
\]

- Transmitter Window
- Transmission Rate
- Receiver Sensitivity
- Channel Noise
- Transmit Power

• Expected number of successfully received messages:

\[
\tilde{m} = m (1 - P_{out})
\]
Control Loop Strategy

- **Control loop** runs on the **Coordinator Node** to regulate **Application Nodes** energy $S$

- The possible control actions are
  - regulate the **transmit power** of Application Nodes
  - reconfigure network to achieve a **target availability**
Node Energy and Lifetime

• The instantaneous energy of a node is defined by:

\[ E_T(t) = E_0 + E_H(t) - E_C(t) \]

• The consumed energy of a node can be defined as:

\[ E_C(t) = S_{avg} t + V_{dd} I_q t \]
\[ S_{avg} = T_m R \hat{S} \]

• Rewriting \( E_T(t) \):

\[ E_T(t) = E_0 + E_H(t) - (T_m R \hat{S} + V_{dd} I_q) t \]

• Therefore, the lifetime of a node is defined by:

\[ t_{lt} = \frac{E_0 + E_H - E_{min}}{T_m R \hat{S} + V_{dd} I_q} \]
Network Availability

• The network availability $\alpha$ is defined as the probability that the lifetime of a key node falls below a minimum value $t_{\text{min}}$

\[ P_r (t_{lt} < t_{\text{min}}) = 1 - \alpha \]

• The closed form of the network availability is given by the estimated transmitted messages and the outage probability in the form of a binomial probability as defined below:

\[ P_r (t_{lt} < t_{\text{min}}) = 1 - \sum_{k=0}^{\lfloor B(R) \rfloor} \binom{\hat{m}}{k} (1 - P_{\text{out}})^k (P_{\text{out}})^{\hat{m} - k} \]

with

\[ A(R) \triangleq \frac{1}{RT_m} \left( \frac{E_0 + E_H - E_{\text{min}}}{t_{\text{min}}} - V_{dd} I_q \right) \]

\[ B(R) \triangleq RT_w \left( 1 - \frac{\gamma_0 \sigma_N^2}{A(R)} \right) \]
Network Availability vs. Estimation Accuracy

• The estimation accuracy $\varepsilon$ of an application parameter must be guaranteed in order to meet the application’s demands

$$\sigma^2_\theta (\tilde{m}) \triangleq \frac{\sigma^2_V}{\tilde{m}} \leq \varepsilon$$

• Thus, for a target network availability $\alpha$, we can state:

$$\sum_{k=0}^{[B(R)]} \binom{\lceil (RT_w) \rceil}{k} \left( \frac{\sigma^2_V}{\varepsilon T_w R} \right)^k \left( 1 - \frac{\sigma^2_V}{\varepsilon T_w R} \right)^{\lceil (RT_w) \rceil - k} = \alpha$$

• The message rate $R_s$ that satisfied the previous equation defines the setpoint of $P_{\text{out}}$ as given by:

$$P_{\text{out}} \leq \left( 1 - \frac{\sigma^2_V}{\varepsilon R_s T_w} \right) H \left( 1 - \frac{\sigma^2_V}{\varepsilon R_s T_w} \right)$$

A target $\alpha$ can be achieved by tuning $R$, $P_{\text{out}}$, and trading $\varepsilon$
Simulation Results*

Increase of Sensor Lifetime due to the reduction of energy consumption

Increasing Transmission Rate (R)

Less transmit power (energy consumption) results in greater outage probability

* Proposed system modeled and simulated in MATLAB®
The message transmission rate that fulfills the target estimation accuracy requirement defines the outage probability setpoint. The greater $R$ and $P_{out}$, the greater the energy consumption.

Simulation Results (Cont’d)

As high is the expected availability (network lifetime), higher is the Outage Probability if the transmit power (energy consumption) is maintained constant.
Better (i.e., smaller) estimation accuracy implies worse (i.e., smaller) network availability due to increased power consumption, which reduces node lifetime.

Simulation Results (Cont’d)

Improving Estimation Accuracy

Increasing Transmission Rate

Degrading Network Availability due to the need to increase power consumption

Can be obtained by increasing R...
Questions?

Thanks for your kind attention!