# 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 …

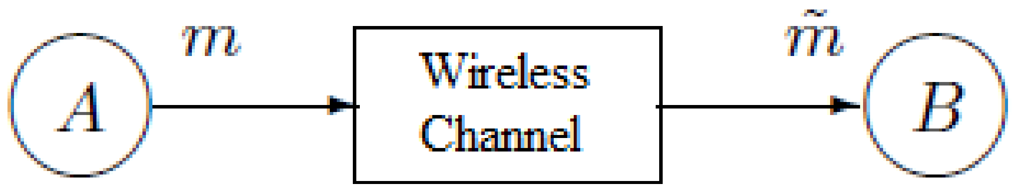
✓ to propose a **mathematical model** that enables the designer to ensure a **target network availability** by trading off between **message transmission rate** and **outage probability**

- **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

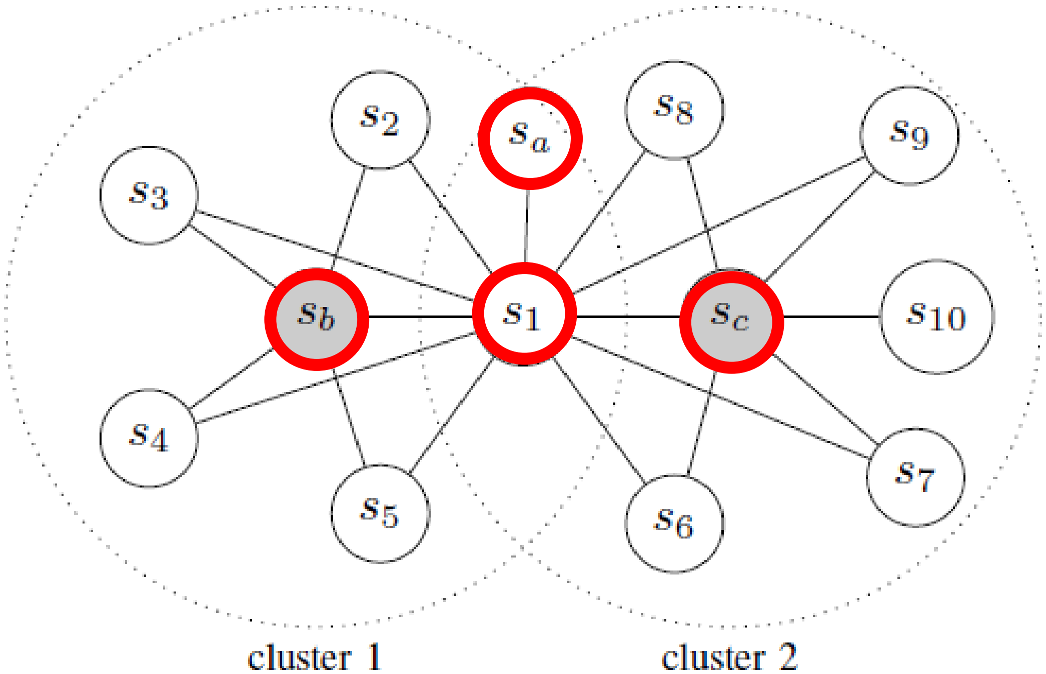
One-Way Message Exchange Mechanism:

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 ($P_{out}$):

# of **successfully received messages by the Coordinator Node from a Sensing Node** over a $T_w$

Receiver Sensitivity

Channel Noise

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

# of estimated **transmitted messages** from the sensing node

Transmit Power

- Where:

Transmission Window

Transmission Rate

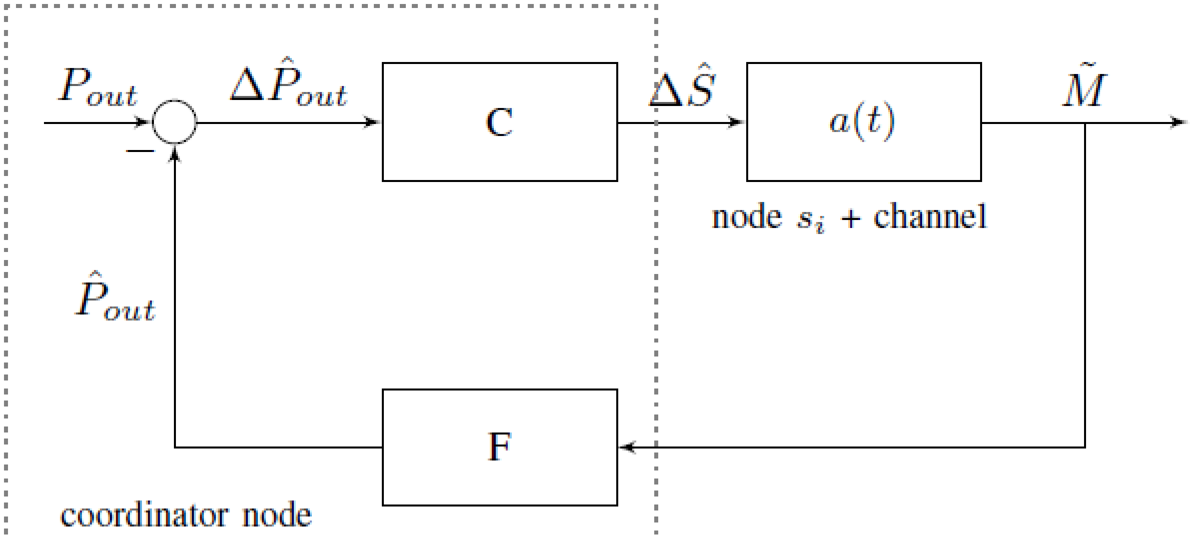
$$\hat{m} = T_w R$$

- Expected number of successfully received messages:

Outage Probability

$$\tilde{m} \Rightarrow = m\left(1 - P_{out}\right)$$

# 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 $t_{min}$

$$P_r\left(t_{lt} < t_{min}\right) = 1 - \alpha$$

• 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:

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

with

$$\begin{aligned} A(R) &\triangleq \frac{1}{RT_m}\left(\frac{E_0 + E_H - E_{min}}{t_{min}} - V_{dd}I_q\right) \\ B(R) &\triangleq RT_w\left(1 - \frac{\gamma_0 \sigma_N^2}{A(R)}\right) \end{aligned}$$

# Network Availability vs. Estimation Accuracy

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

$$\sigma_\theta^2(\tilde{m}) \triangleq \frac{\sigma_V^2}{\tilde{m}} \leq \epsilon$$

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

$$\sum_{k=0}^{\lfloor B(R) \rfloor} \binom{\lfloor (R\,T_w) \rfloor}{k} \left( \frac{\sigma_V^2}{\epsilon\, T_w\, R} \right)^k \left( 1 - \frac{\sigma_V^2}{\epsilon\, T_w\, R} \right)^{\lfloor (R\,T_w) \rfloor - k} = \alpha$$

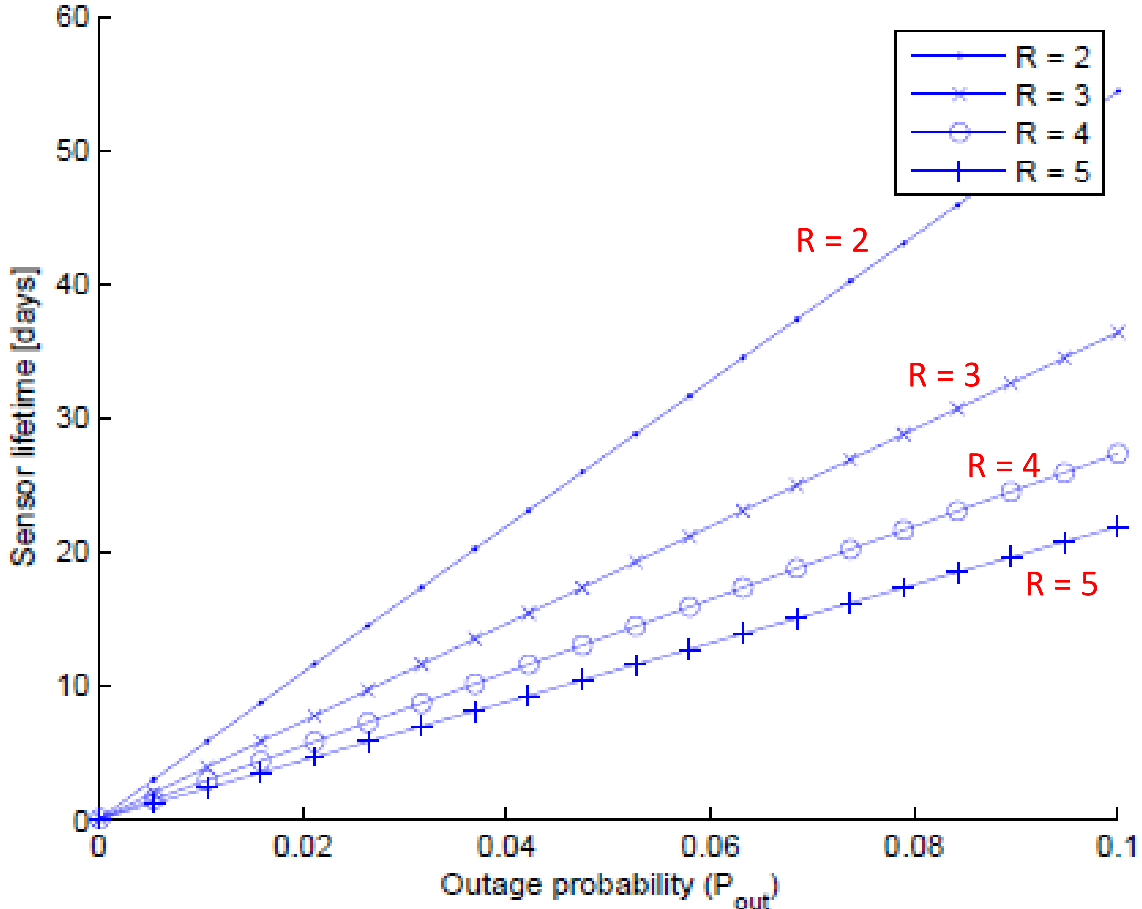
- The message rate $R_s$ that satisfied the previous equation defines the setpoint of $P_{out}$ as given by:

$$P_{out} \leq \left( 1 - \frac{\sigma_V^2}{\epsilon\, R_s\, T_w} \right) H \left( 1 - \frac{\sigma_V^2}{\epsilon\, R_s\, T_w} \right)$$

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

# Simulation Results*

Increase of Sensor Lifetime due to the reduction of energy consumption



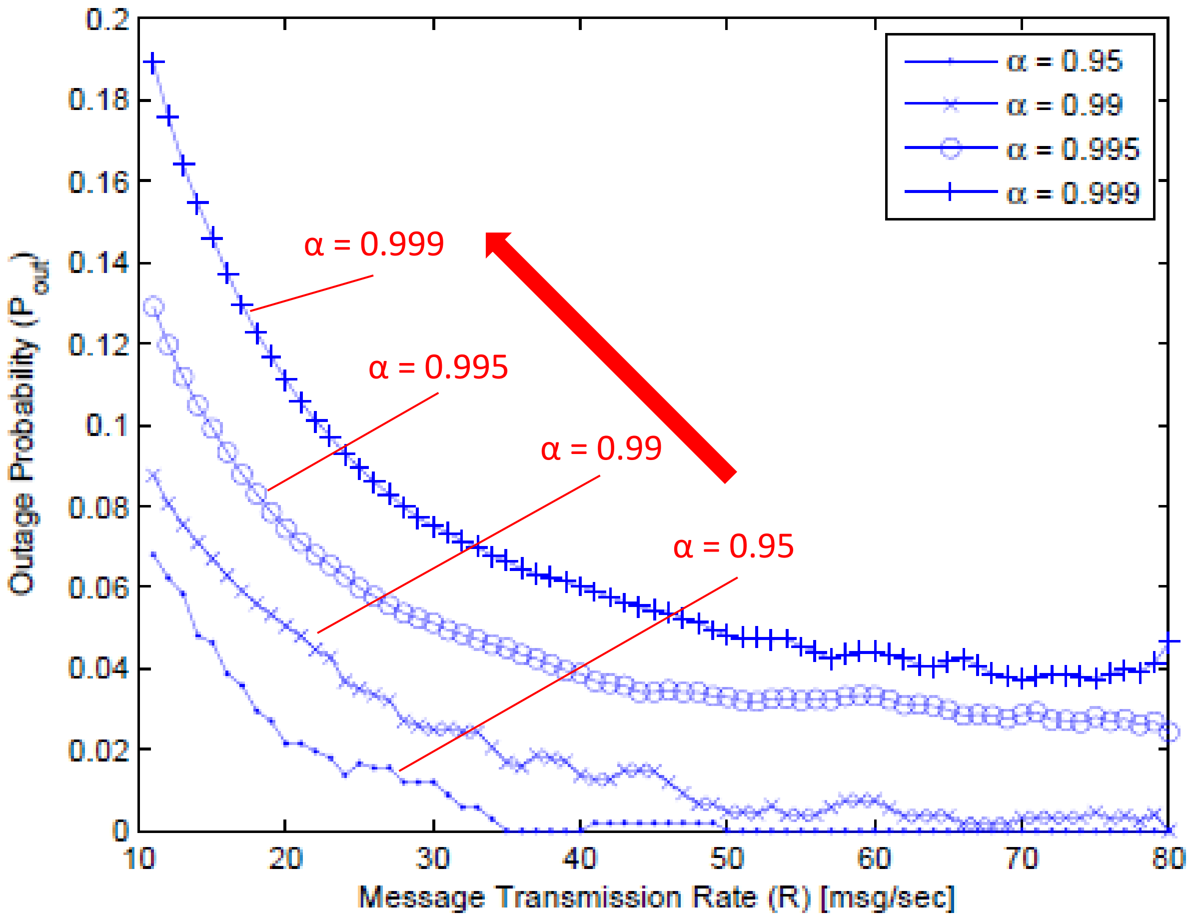

Increasing Transmission Rate (R)

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

** Proposed system modeled and simulated in MATLAB®*

# Simulation Results (Cont’d)

Increasing Outage Probability

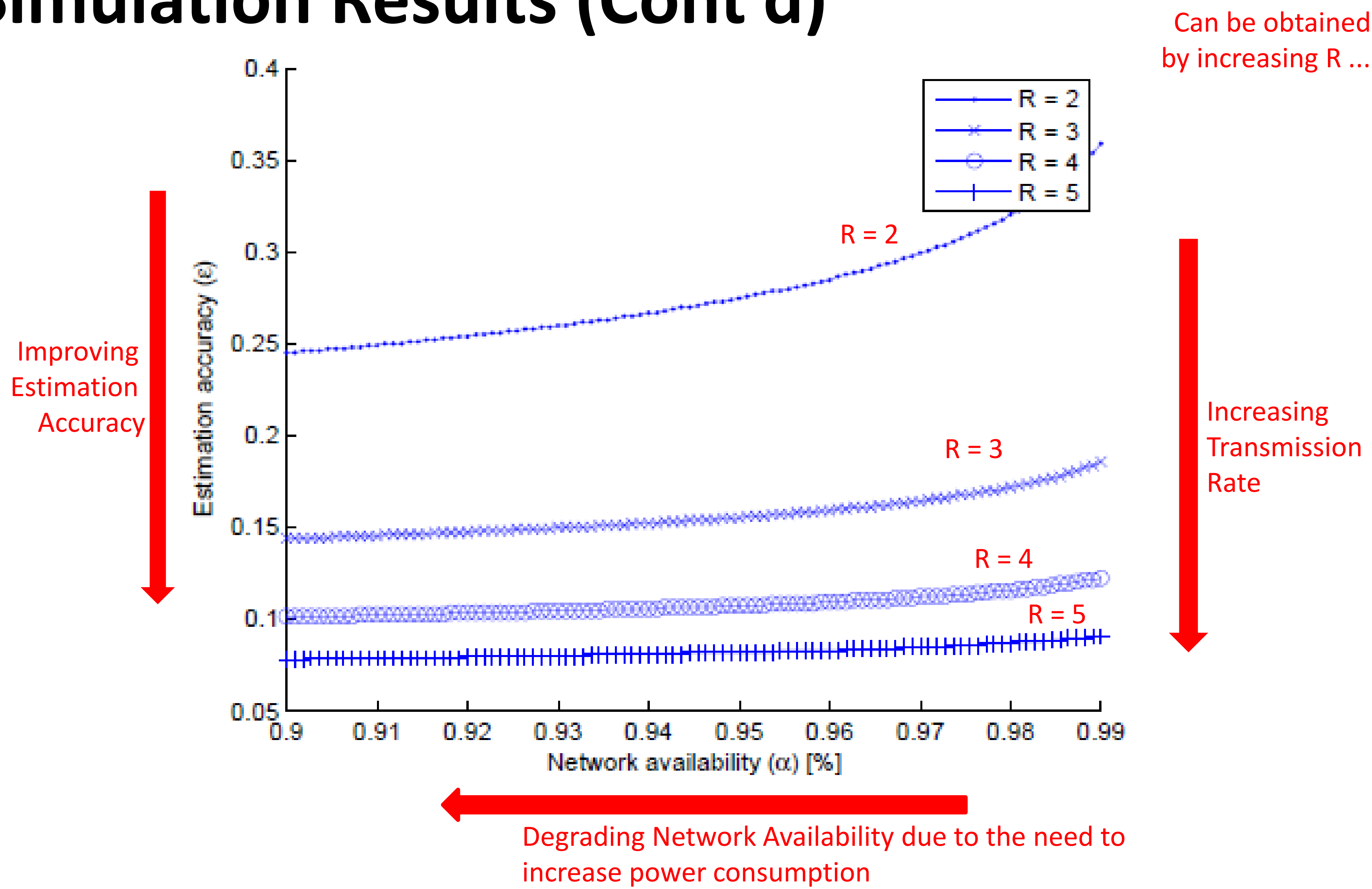



As high is the expected availability (network lifetime), higher is the Outage Probability if the transmit power (energy consumption) is maintained constant

Reduction of Message Transmission Rate (R) increases transmit power (energy consumption) to maintain the same target lifetime

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)




Better (i.e., smaller) **estimation accuracy** implies worse (i.e., smaller) **network availability** due to **increased power consumption, which reduces node lifetime**.

# Questions?

# Thanks for your kind attention!