Markov Modeling of Fault-Tolerant Wireless Sensor Networks

Arslan Munir and **Ann Gordon-Ross**[+]

Department of Electrical and Computer Engineering
University of Florida, Gainesville, Florida, USA

[+] Also affiliated with NSF Center for High-Performance Reconfigurable Computing

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC)

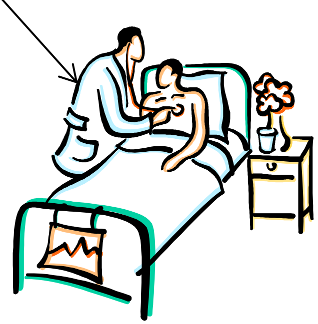
Wireless Sensor Networks (WSNs)

WSN Applications

Ever Increasing

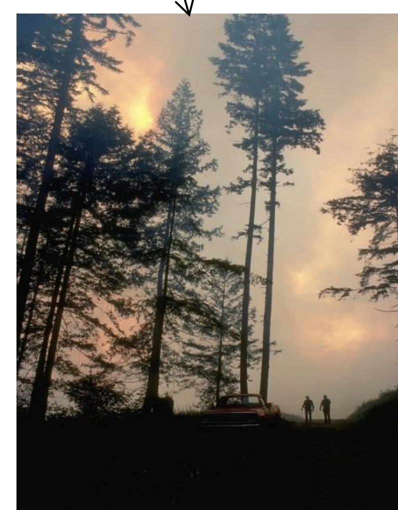
Security and Defense Systems

Health Care



Industrial Automation

Ambient conditions Monitoring, e.g. , forest fire detection



Logistics

WSN Design Challenges

WSN Design

↓

Challenges

Failure to meet

→ Catastrophic Consequences

Forest fire could spread uncontrollably in the case of a forest fire detection application

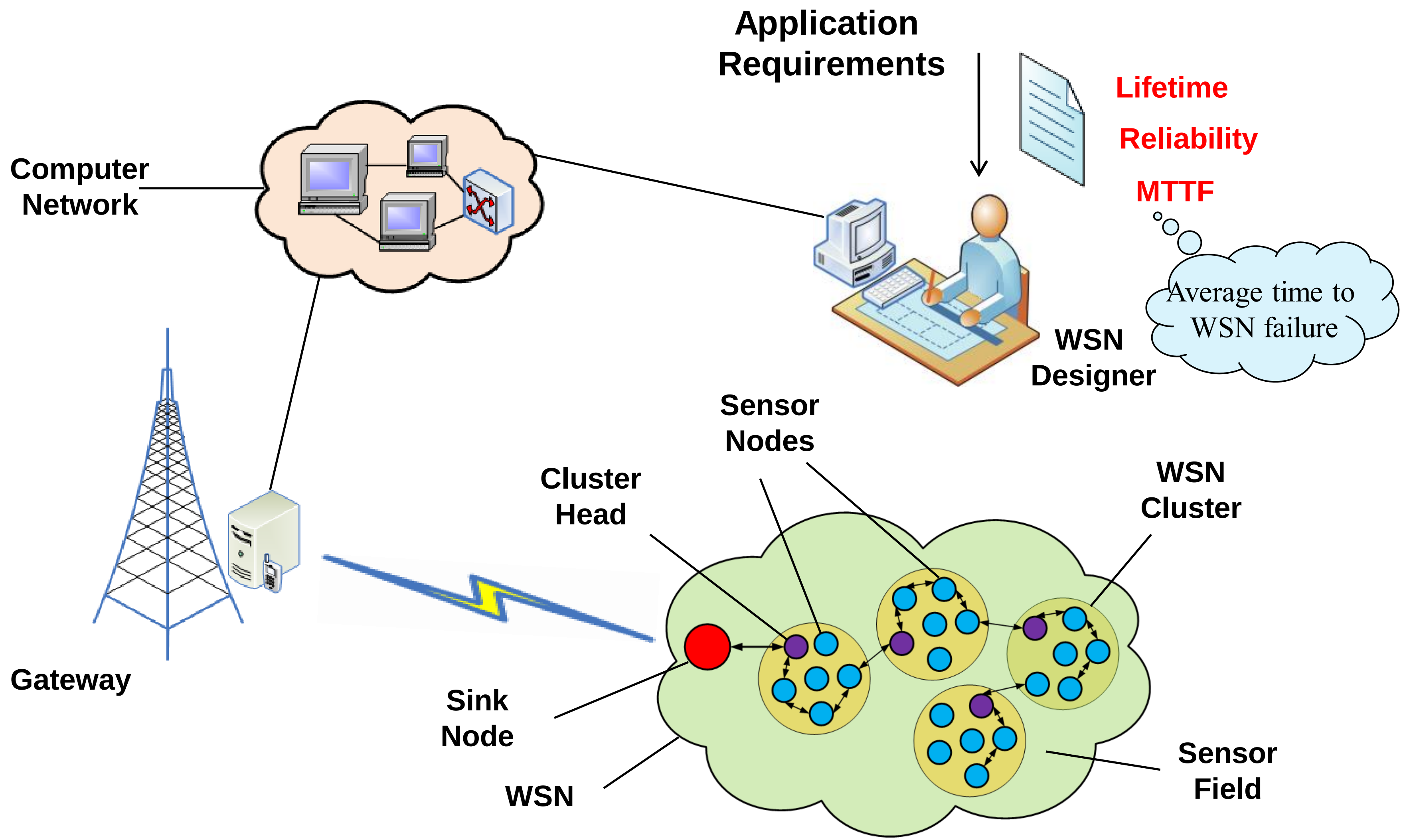
Loss of life in the case of health care application

Major disasters in the case of defense systems

Challenges:

- Meeting application requirements e.g., reliability, lifetime, throughput, delay (responsiveness), etc.
- Application requirements change over time
- Environmental conditions (stimuli) change over time

WSN Hierarchical View



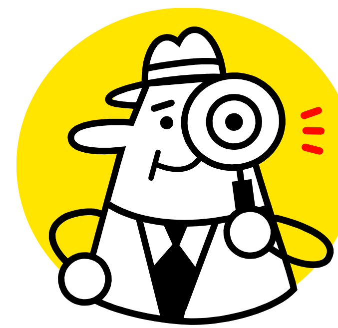
WSN Fault-Detection and Fault-Tolerance

WSN Fault-detection & Fault-tolerance

Fault-detection => Distributed fault-detection (DFD) algorithms that identify faulty sensor readings to indicate sensor faults

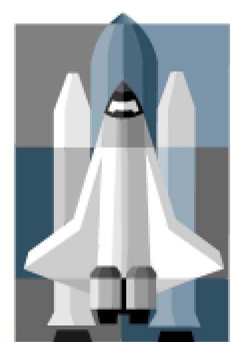
DFD algorithm's accuracy => Algorithm's ability to accurately identify faults

Fault-tolerance => Adding hardware/software redundancy to the system



Necessity

- Sensor nodes deployed in unattended and hostile environments => susceptible to failures
- Manual inspection of faulty sensor nodes after deployment is impractical
- Many WSN applications are mission critical and require continuous operation



WSN Fault-Tolerance

WSN Fault-tolerance

Fault-tolerance => Adding hardware/software redundancy to the system

Where to add redundancy?

Within a sensor node

Sensors (e.g., temperature and humidity sensors) have higher failure rates than other components (e.g., processors, transceivers, etc.)

Sensors are cheap => Adding spare sensors contribute little to a sensor node's cost

Within a cluster => redundant sensor nodes

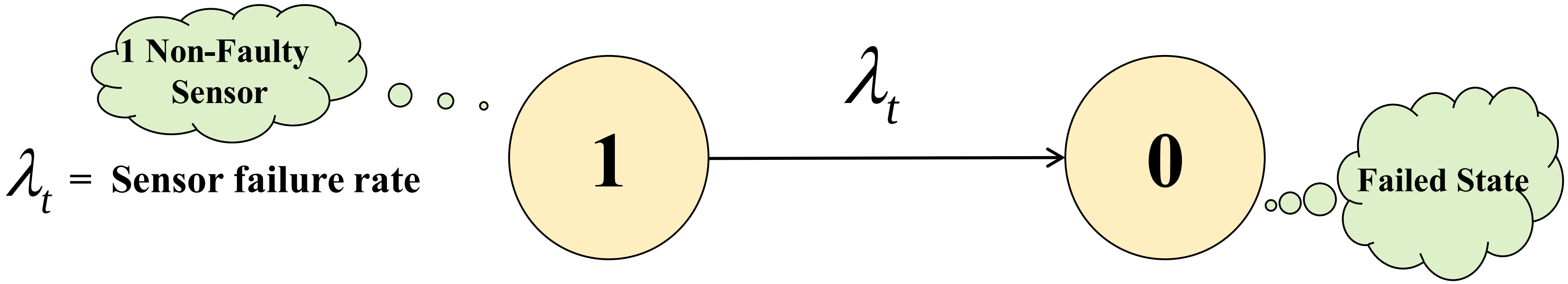
Within a WSN => redundant WSN clusters

Contributions

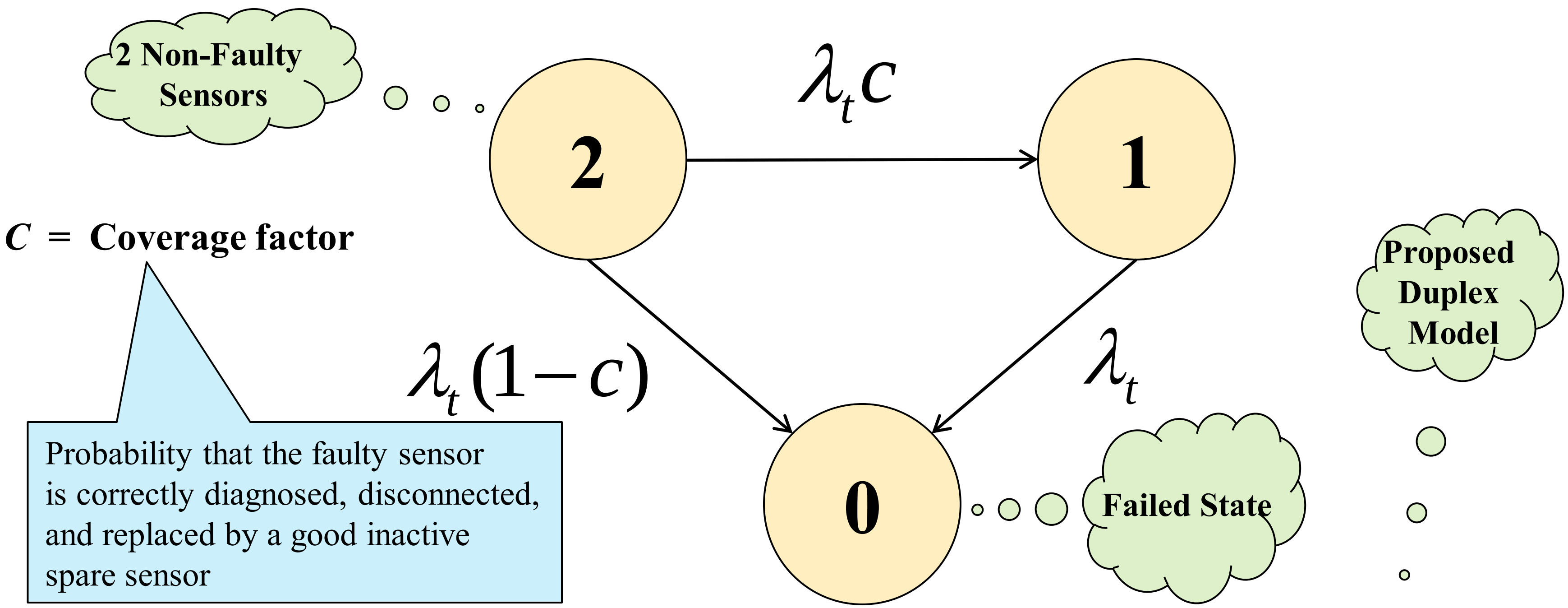
Fault-tolerance for WSNs

- Investigate synergy between fault-detection and fault-tolerance (FT) for WSNs
  - A good DFD algorithm is necessary for robust FT
- Develop a Markov model for characterizing WSN reliability and MTTF
  - Provides an insight into the type of sensor nodes (duplex or simplex) feasible for an application to meet the application's requirements
  - Used a hierarchical approach => **WSN Markov model** leverages **WSN cluster model** which in turn leverages **sensor node model**
  - Helps WSN designer in determining the exact number of sensor nodes required to meet the application's lifetime and reliability requirements
- Proposed a duplex sensor node model for fault-tolerance

NFT and FT Sensor Node Markov Model



Non-fault-tolerant (NFT) Sensor Node Markov Model



Fault-tolerant (FT) Sensor Node Markov Model

FT Sensor Node Markov Model – Differential Equation Solutions

- Reliability

$$R_{s_d}(t) = 1 - P_0(t)$$
$$= e^{-\lambda_t t} + c\lambda_t t e^{-\lambda_t t}$$

where

– $P_i(t)$ = Probability that sensor node will be in state *i* at time *t*

- MTTF

$$\text{MTTF}_{s_d} = \int_0^{\infty} R_{s_d}(t)\, dt = \frac{1}{\lambda_t} + \frac{c}{\lambda_t}$$

- Average Failure Rate (or Failures in Time (FIT))

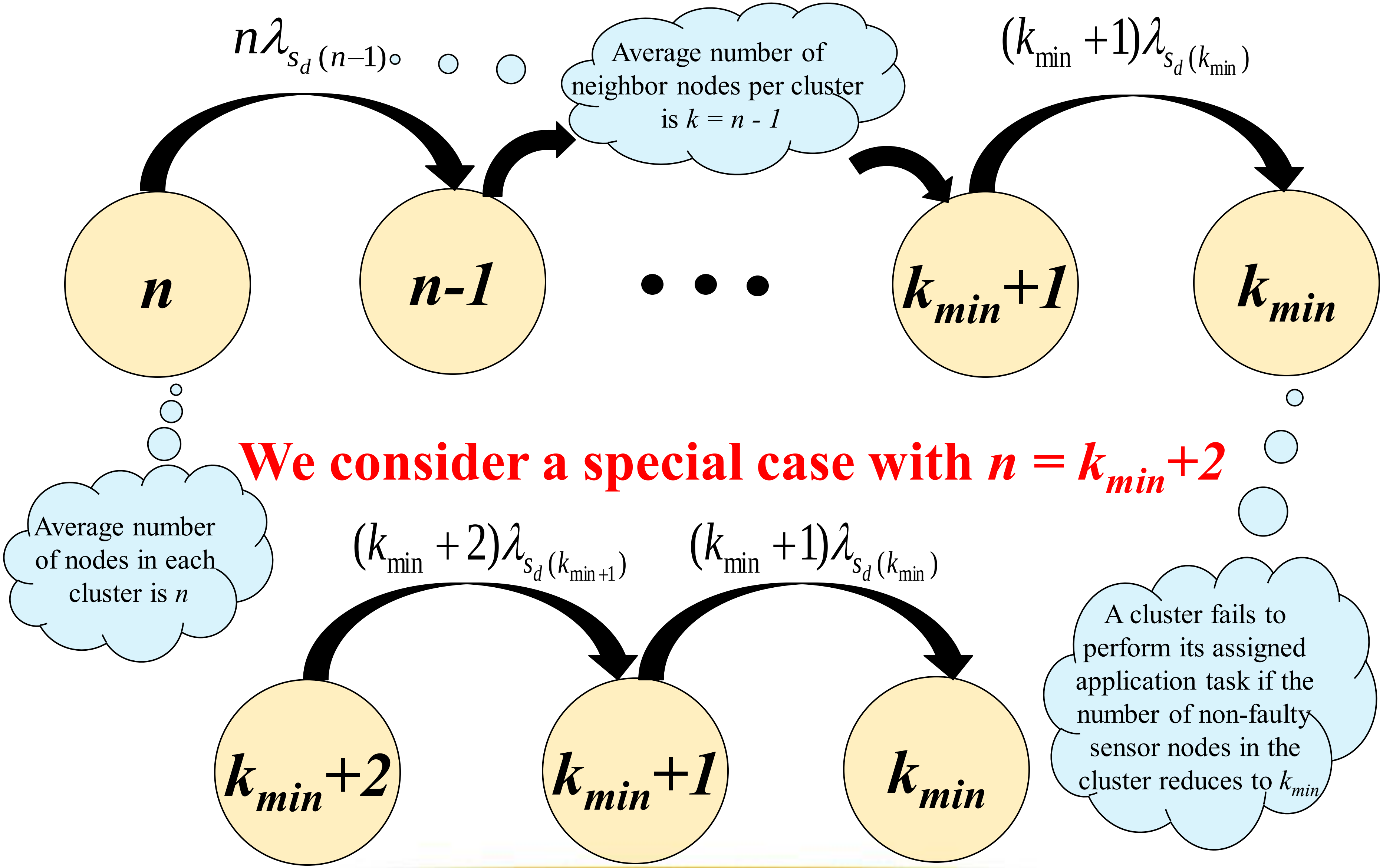
$$\lambda_{s_d(k)} = \frac{1}{\text{MTTF}_{s_d(k)}}$$

where

– *k* denotes the average number of sensor node neighbors

– *k* is important as DFD algorithm's accuracy depends upon *k*

FT WSN Cluster Model



FT WSN Cluster Markov Model – Differential Equation Solutions ($n = k_{min}+2$)

- Reliability

$$
\begin{aligned}
R_c(t) &= 1 - P_{k_{min}}(t) \\
&= e^{-(k_{min}+2)\lambda_{s_d(k_{min}+1)}t} + \\
&\frac{(k_{min}+2)\lambda_{s_d(k_{min}+1)}e^{-(k_{min}+2)\lambda_{s_d(k_{min}+1)}t}}{(k_{min}+1)\lambda_{s_d(k_{min})} - (k_{min}+2)\lambda_{s_d(k_{min}+1)}} + \\
&\frac{(k_{min}+2)\lambda_{s_d(k_{min}+1)}e^{-(k_{min}+1)\lambda_{s_d(k_{min})}t}}{(k_{min}+2)\lambda_{s_d(k_{min}+1)} - (k_{min}+1)\lambda_{s_d(k_{min})}}
\end{aligned}
$$

- MTTF

$$
\begin{aligned}
\mathrm{MTTF}_c &= \int_0^\infty R_c(t)\,dt = \frac{1}{(k_m+2)\lambda_{s_d(k_m+1)}} + \\
&\frac{1}{(k_m+1)\lambda_{s_d(k_m)} - (k_m+2)\lambda_{s_d(k_m+1)}} + \\
&\frac{(k_m+2)\lambda_{s_d(k_m+1)}}{(k_m+2)(k_m+2)\lambda_{s_d(k_m)}\lambda_{s_d(k_m+1)} - (k_m+1)^2\lambda^2_{s_d(k_m)}}
\end{aligned}
$$

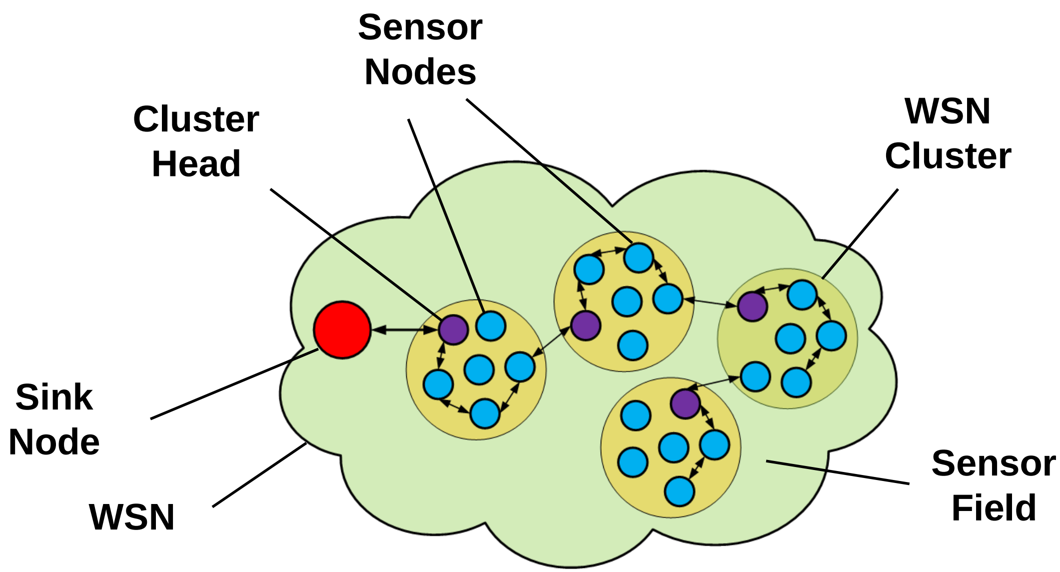
FT WSN Cluster Markov Model – Differential Equation Solutions ($n = k_{min}+2$)

- Average Failure Rate

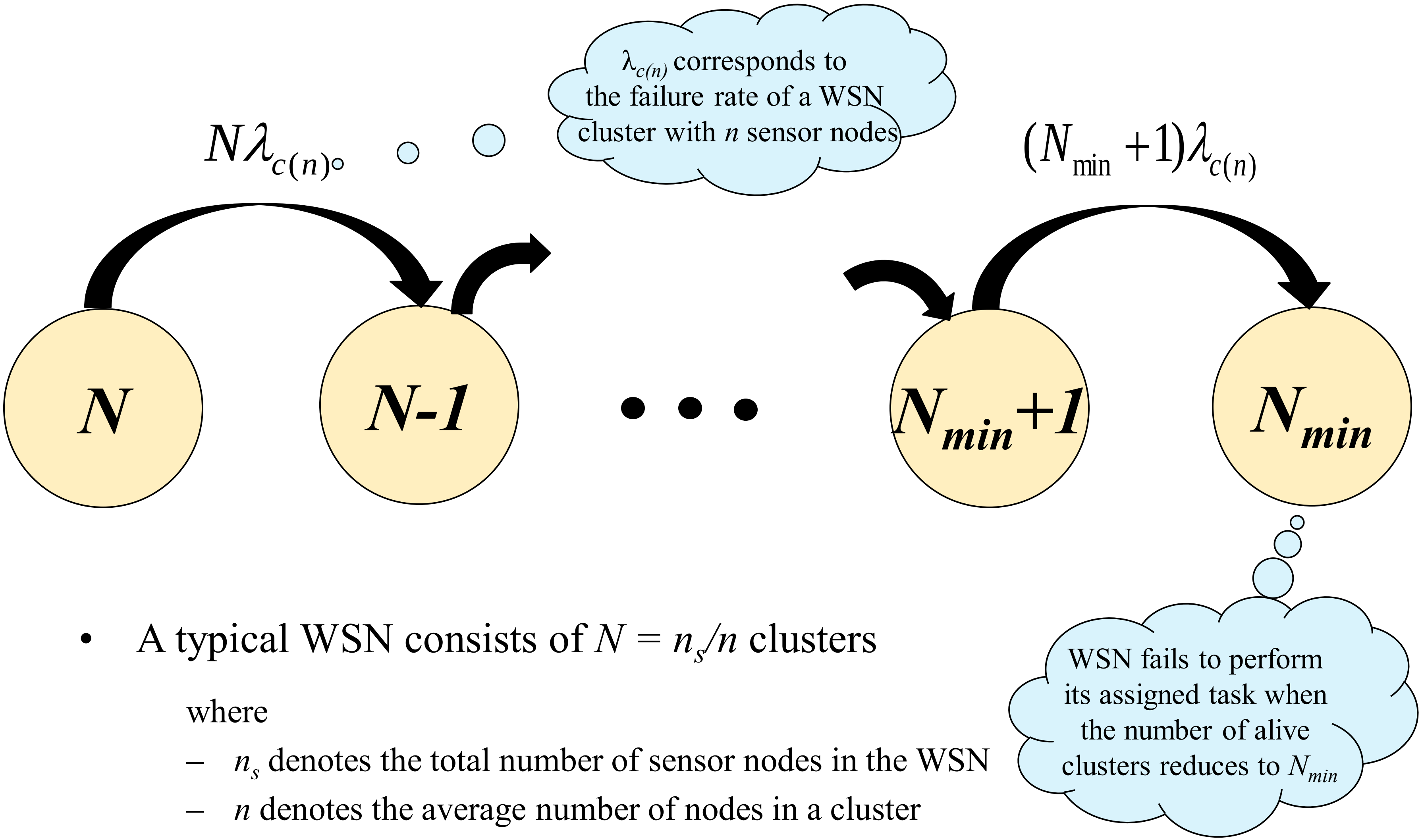
$$\lambda_{c(n)} = \frac{1}{\text{MTTF}_{c(n)}}$$

where

– $\text{MTTF}_{c(n)}$ denotes the MTTF of a WSN cluster of n sensor nodes



FT WSN Model



- A typical WSN consists of $N = n_s/n$ clusters

  where
  - n_s denotes the total number of sensor nodes in the WSN
  - n denotes the average number of nodes in a cluster

FT WSN Markov Model – Differential Equation Solutions ($N = N_{min}+2$)

- Reliability

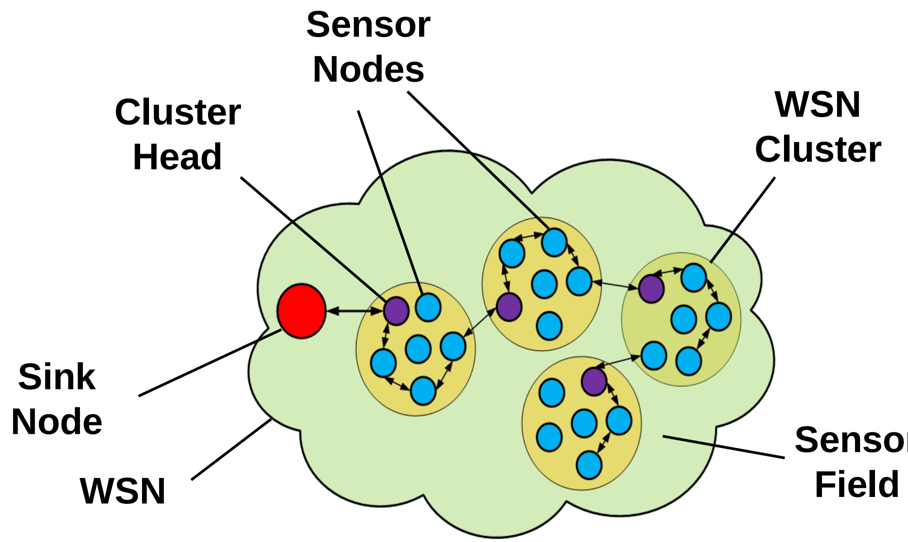
$$
\begin{aligned}
R_{wsn}(t) &= 1 - P_{N_{min}}(t) \\
&= e^{-(N_{min}+2)\lambda_{c(n)}t} + (N_{min}+2)\lambda_{c(n)} \times \\
&\quad \left[e^{-(N_{min}+1)\lambda_{c(n)}t} - e^{-(N_{min}+2)\lambda_{c(n)}t}\right]
\end{aligned}
$$

- MTTF

$$
\begin{aligned}
\mathrm{MTTF}_{wsn} &= \int_0^\infty R_{wsn}(t)\,dt \\
&= \frac{1}{(N_{min}+2)\lambda_{c(n)}} + \frac{N_{min}+2}{N_{min}+1} - 1
\end{aligned}
$$

Experimental Results

- SHARPE Software Package
  - Markov model implementations
    - NFT sensor node
    - FT sensor node
    - NFT WSN cluster
    - FT WSN cluster
    - NFT WSN
    - FT WSN



- Sensor Failure Probability
  - Exponential distribution

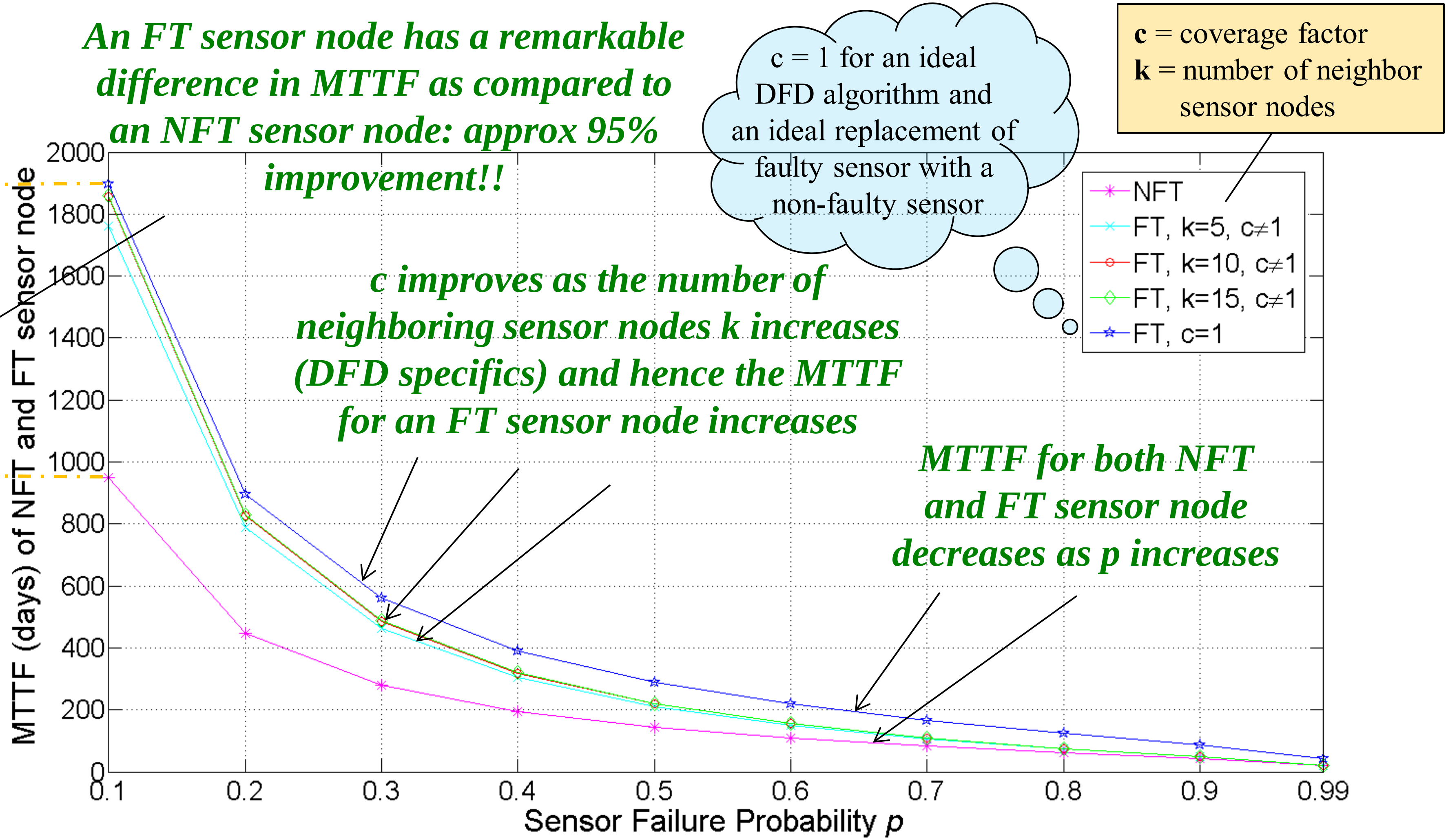
$$p = 1 - \exp(-\lambda_s t_s)$$

Our Markov models are valid for any other distribution as well

where

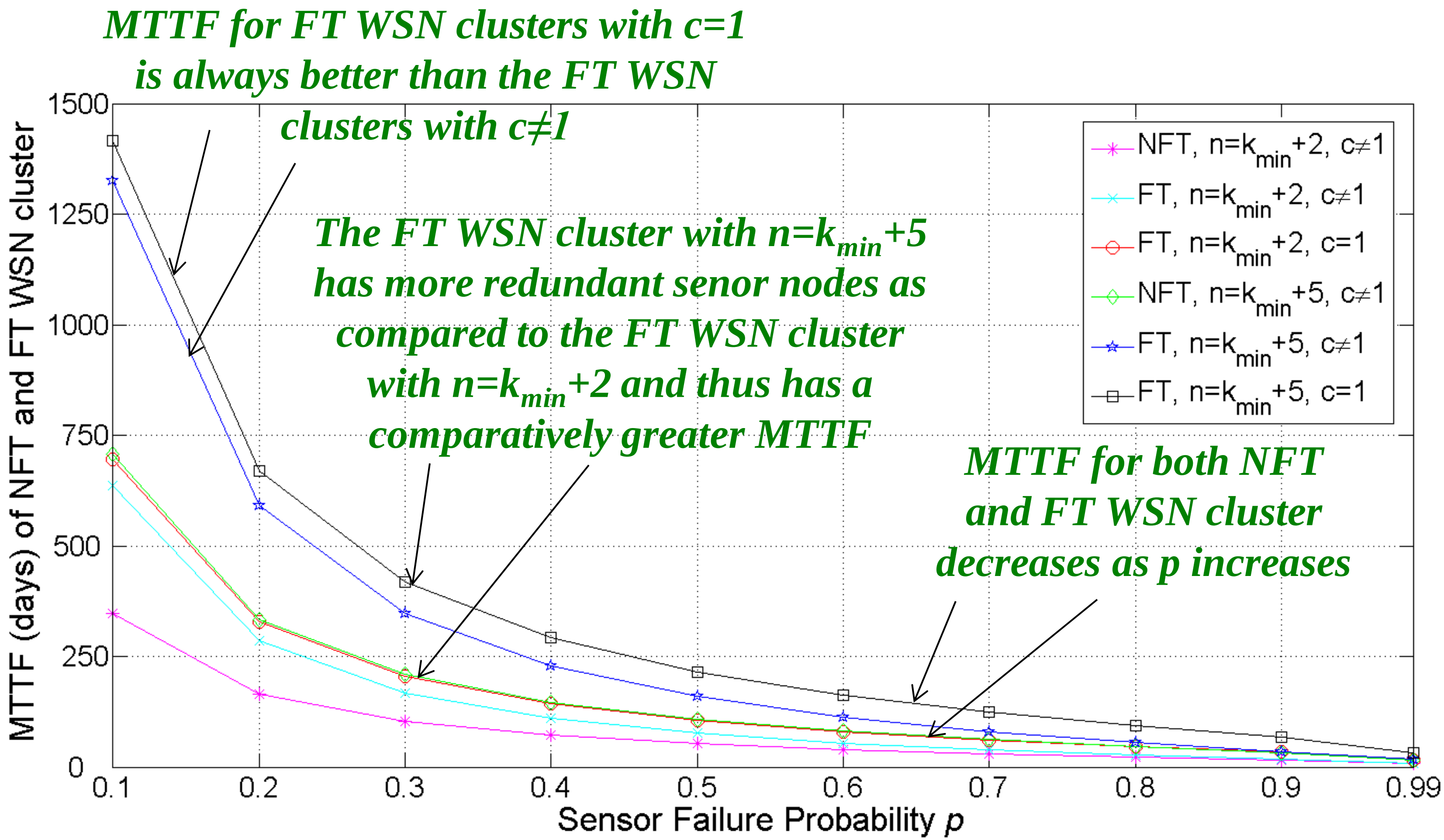
- p = sensor failure probability
- λ_s = sensor failure rate over period t_s
- t_s = time over which sensor failure probability/failure rate is specified
- We present results for t_s = 100 days

Results – MTTF FT & NFT Sensor Nodes



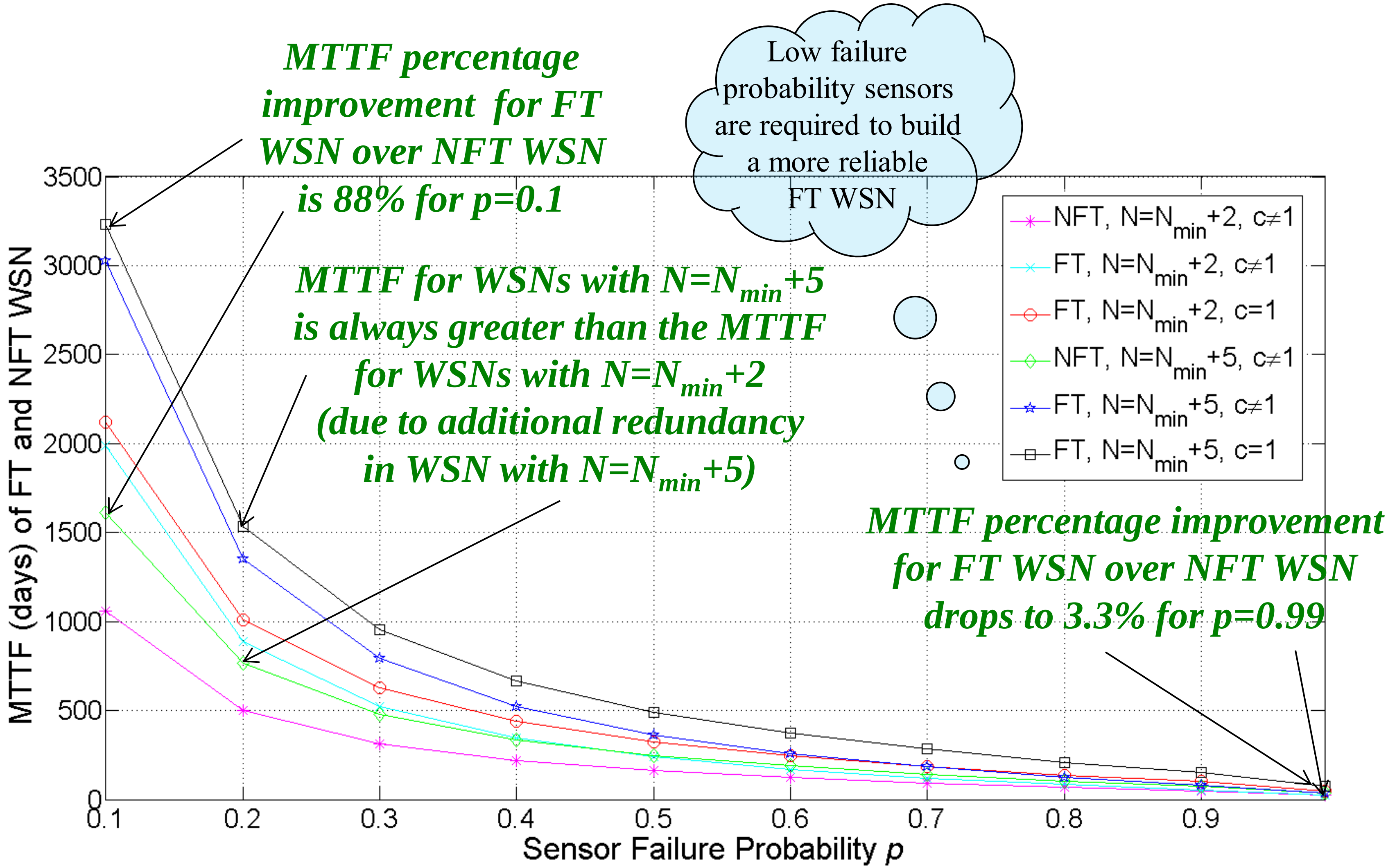
MTTF (days) for an FT and a non-FT (NFT) sensor node.

Results – MTTF FT & NFT WSN Cluster



MTTF (days) for the FT and non-FT (NFT) WSN clusters with $k_{min} = 4$.

Results – MTTF FT & NFT WSN



MTTF (days) for the FT and non-FT (NFT) WSNs with $N_{min} = 0$.

Conclusions

- We proposed an FT duplex sensor node model
  - A novel concept for determining the coverage factor using sensor fault detection algorithm accuracy
- We developed hierarchical Markov models for WSNs consisting of sensor node clusters to compare the MTTF and reliability for FT and NFT WSNs
  - Aids design of WSNs with different lifetime and reliability requirements
- Fault detection algorithm's accuracy plays a critical role in FT WSNs
- FT duplex sensor node provides improvement over an NFT sensor node
  - **100%** MTTF improvement with a perfect fault detection algorithm ($c = 1$)
  - MTTF improvement from **96%** for current fault detection algorithms with low p ($p < 0.3$) - MTTF improvement reduces to 1.3% as $p \rightarrow 1$
- Percentage reliability improvement for an FT WSN with $c = 1$ over an NFT WSN with $c \neq 1$ is **350%** and over an FT WSN with $c \neq 1$ is **236%** for $p=0.9$
- **Redundancy in WSN plays an important role in improving MTTF**
  - Our models allow designers to determine the fault detection algorithm's accuracy and required redundancy to meet application requirements