University of Duisburg-Essen
Networked Embedded Systems Group
Institute for Computer Science and
Business Information Systems (ICB)
Schützenbahn 70
D-45127 Essen, Germany

An Approach to Detect Anomalous Degradation in Signal Strength of IEEE 802.15.4 Links

Songwei Fu[1], Matteo Ceriotti[1], Yuming Jiang[2], Chia-Yen Shih[1], Xintao Huan[1], Pedro José Marrón[1]

[1]University of Duisburg-Essen, Germany

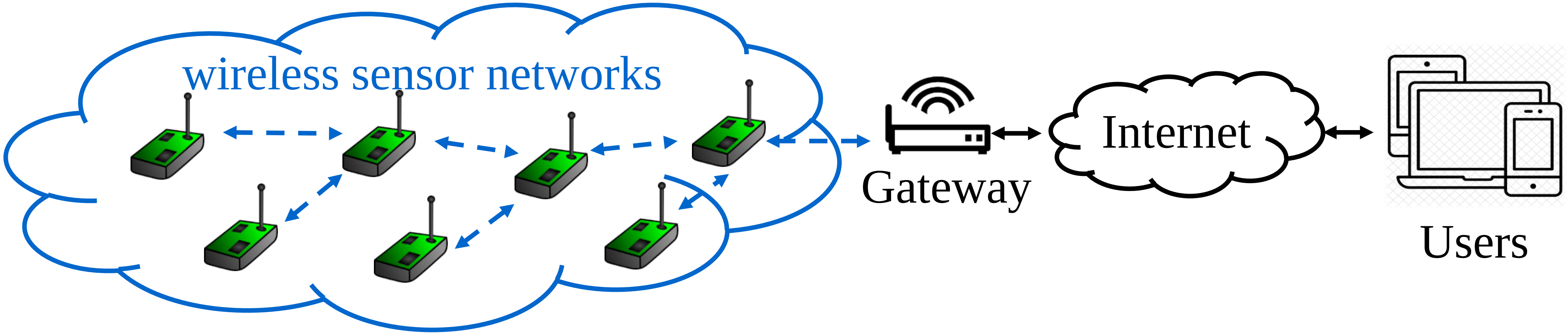
[2]Norwegian University of Science and Technology (NTNU), Norway

Outline

- Background & Motivation
- The Approach
    - Overview
    - Major system components
- Evaluation
- Conclusion

Background & Motivation

- IEEE 802.15.4 and Wireless Sensor Networks (WSNs)



- Demanding QoS requirements VS. Actual performance
- One major cause
  - The performance of 802.15.4 links can be easily affected by the surrounding environment (terrain, climate, human activities, etc.)
- Detection of Link Quality Degradation is crucial for taking remedial actions at different stack layers.

Goal

- We use Received Signal Strength (RSSI) – why not loss rate?
  - RSSI – direct measurement of the channel at the radio hardware
- Terminology
  - Good link vs. Bad link
  - Anomalous RSSI Degradation
  - Error rate
    - False Positive Rate (FPR):

      The ratio of detecting anomalous RSSI degradations while good link
    - False Negative rate (FNR):

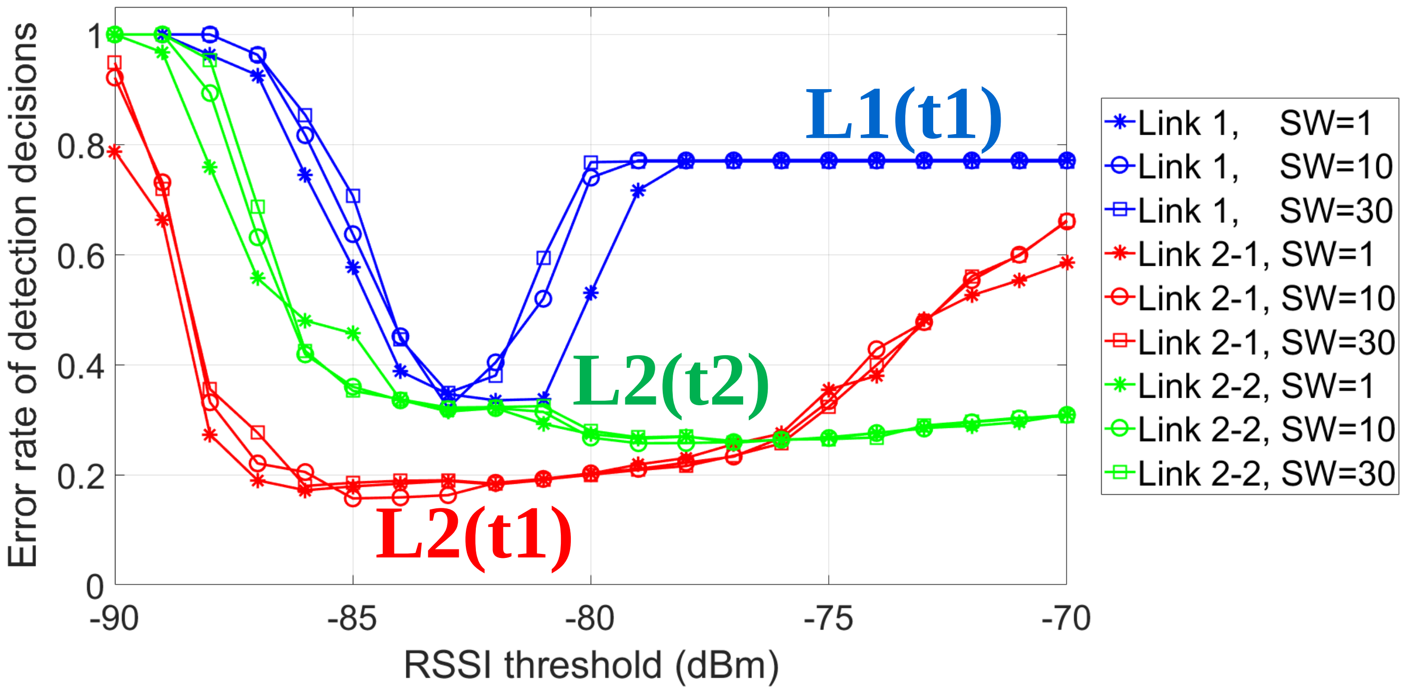
      The ratio of missing to detect the anomalous RSSI degradations
- Goal
  - design an approach to detect anomalous RSSI degradation of 15.4 links

Requirements

- Functional Requirements
  - Low error rate
    - Previous studies show that RSSI is not well correlated with Packet Reception Rate (PRR)
- Non-functional Requirements
  - The low error rate should be consistent for all links
    - i.e. No need of manually tuning for each link
  - The low error rate should be robust over time
    - i.e. Adapt to environmental changes
  - Lightweight due to resource-constrained sensor nodes
    - i.e. No ML techniques: Clustering, SVM, NN etc.

Intuitive Approach

- Initial try: Data Smoothing + Fixed RSSI Threshold
- Results based on data traces



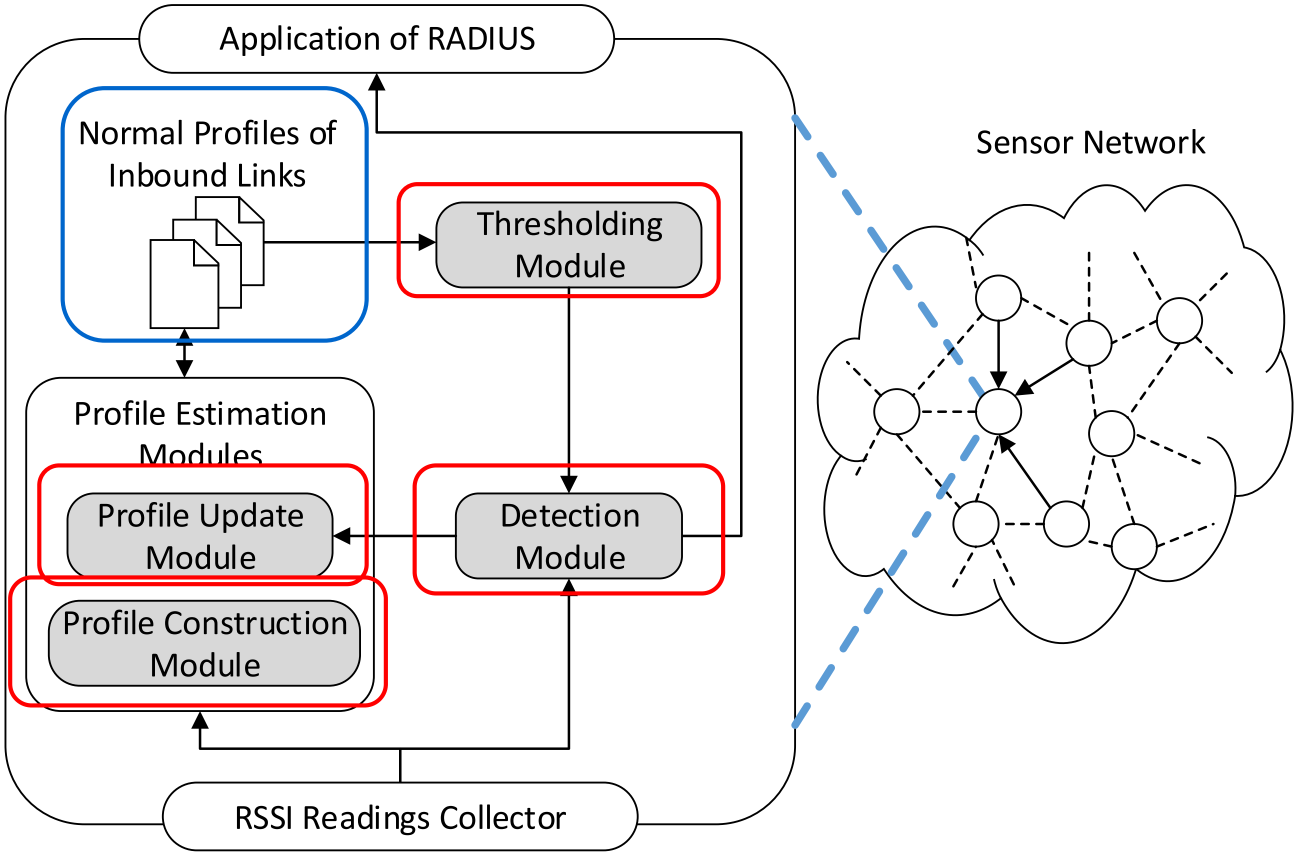
- Reasons and implications

Our Approach: RADIUS

- RADIUS
    - a lightweight yet accurate and robust approach to detect locally at sensor nodes the anomalous RSSI degradation of inbound radio links

- Core features
    - A thresholding method computing RSSI thresholds tailored to each link
    - The optimal thresholds are computed based on Bayesian decision theory
    - Threshold adapts to environmental changes
    - Low overhead (computation, memory, communication)

System Overview



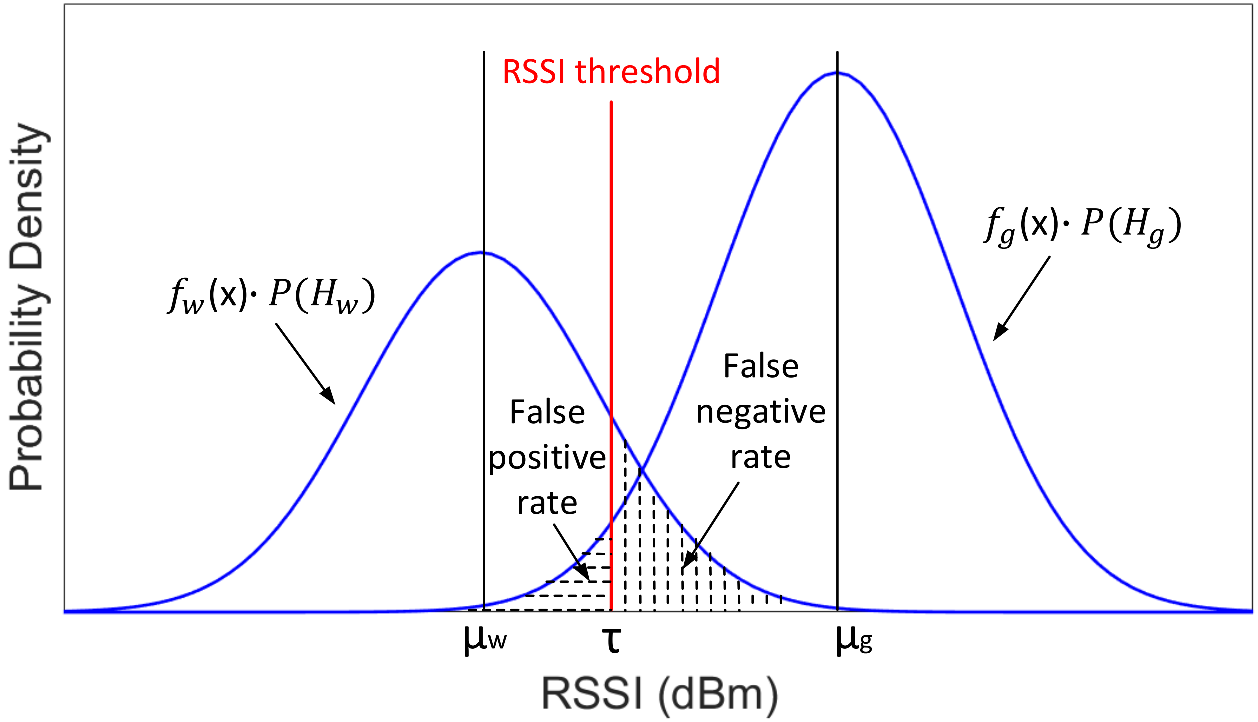
- 2-phase operations
  - (1) Offline, (2) Online

RSSI Thresholding: The Bayes Threshold (1)

- The goal the module is to compute RSSI thd. that minimizes error rate
- Problem formulation
  - Let H_g and H_w denote a link being a good link and a bad link
  - *a priori* probability of being a good link

    $$P(E) = \underbrace{P(E|H_g)P(H_g)}_{\text{False Positive Rate (FPR)}} + \underbrace{P(E|H_w)P(H_w)}_{\text{False Negative Rate (FNR)}}$$
  - Assumption
    - RSSI follows a normal distribution $N(\mu, \sigma)$
    - RSSI distribution of good and bad link have different μ but similar σ

RSSI Thresholding: The Bayes Threshold (2)



- $P_E(\tau) = \underbrace{\int_{-\infty}^{\tau} f_g(x)dx \cdot P(H_g)}_{\text{False Positive Rate}} + \underbrace{\int_{\tau}^{\infty} f_w(x)dx \cdot P(H_w)}_{\text{False Negative Rate}}$

RSSI Thresholding: The Bayes Threshold (3)

- Minimize $P_E(\tau)$ by letting $\frac{d\,(P_E(\tau))}{d\tau} = 0$

a priori probability of being a good link

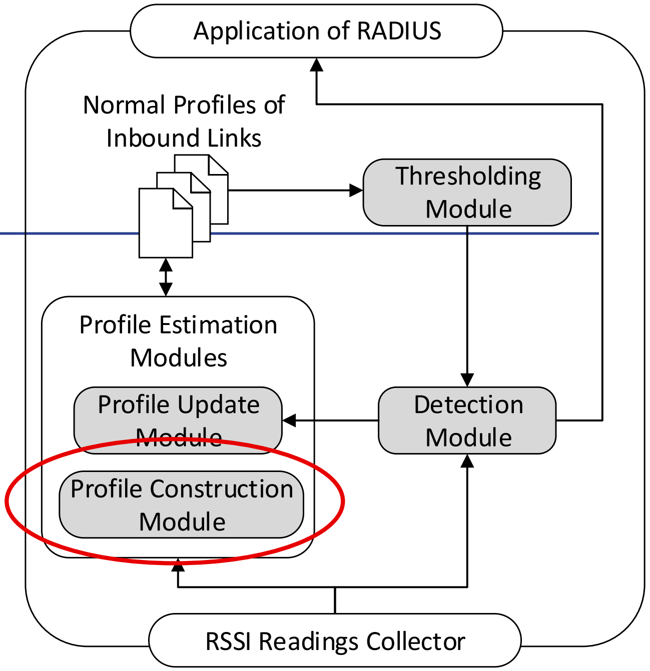
- $$T_{Bayes} = \frac{1}{2}(\mu_g + \mu_w) + \frac{\sigma^2 \ln(P(H_g)/P(H_w))}{\mu_g - \mu_w}$$

RSSI mean of good link and bad link

RSSI standard deviation of good link

  - $P(H_g)$ – User-defined thresholding parameter
  - μ_w – border value of the transitional zone (e.g., -89 dBm)
  - $(\mu_g,\ \sigma)$ – Normal Profile

Normal Profile Construction



- Profile Construction
  - Goal: estimate RSSI μ_g and σ when links are good links
  - Problem: How many RSSI samples are needed?
    - Trade-off between estimation accuracy and training time
    - The number may differ from link to link
  - Solution based on *Central Limit Theorem*:

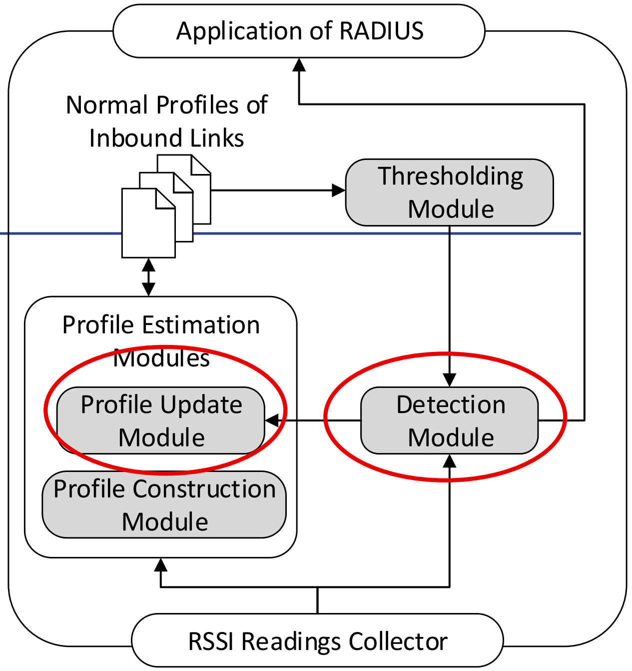
Z-score

RSSI std. of first n packets (e.g., n = 50)

- $N = (\frac{z \cdot \sigma_p}{E_\mu})^2$

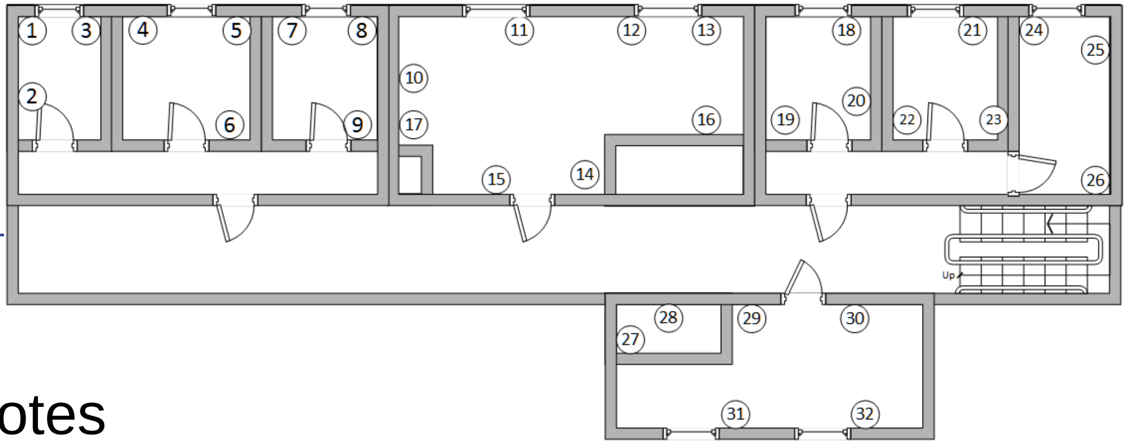
Estimated error of RSSI mean (system parameter)

Detection and Profile Update



- Detection Module
  - Goal:
    - Detect anomalous RSSI degradation
  - Problem:
    - Random RSSI fluctuation
  - Solution:
    - Data smoothing over a sliding window
- Profile Update Module
  - Problem:
    - When environmental changes, normal profile changes
  - Solution:
    - Update (μ_g, σ) of each link based on detection decision

Evaluation



- Testbed Setup
  - Indoor testbed of 32 TelosB motes
  - TinyOS 2.1.2

- Evaluation
  - Bayes threshold vs. 2 other thresholding methods
  - 72-hour experiment to evaluate the whole system
  - An application of RADIUS

Comparison of Thresholding Methods (1)

- Relevant statistical thresholding methods
  - Percentile-based threshold
    - User-defined parameter: *x-th percentile*
  - Chebyshev inequality-based threshold
    - $T_{cheby} = \mu_g + \sigma \cdot \sqrt{\frac{1-P_{target}}{P_{target}}}$
    - User-defined parameter: P_{target}

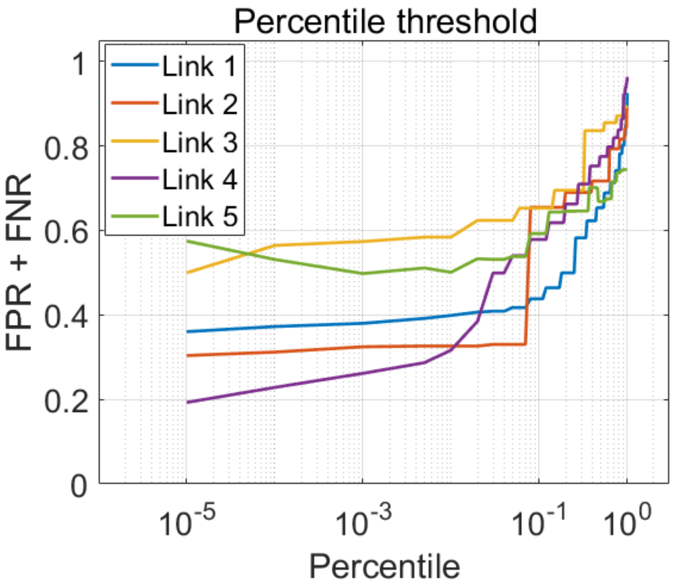
- Comparison perspective:

  (1) Impact of thresholding parameter

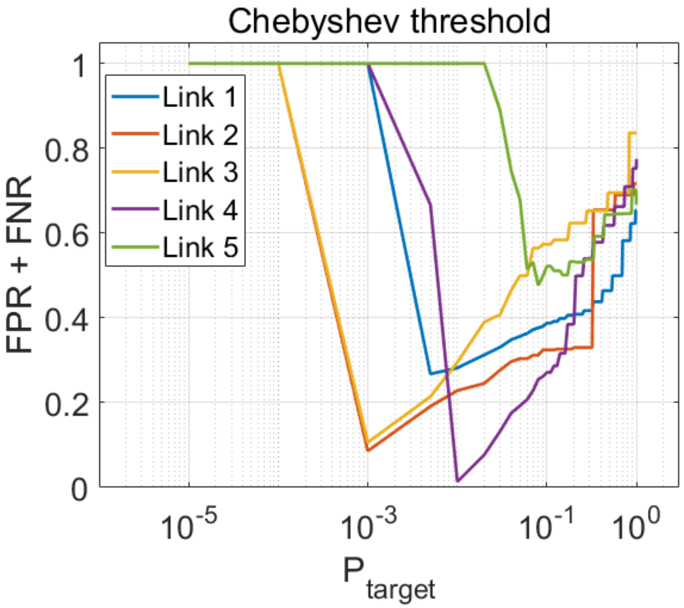
  (2) What if the RSSI distribution of a good link and a bad link overlaps

Comparison of Thresholding Methods (2)

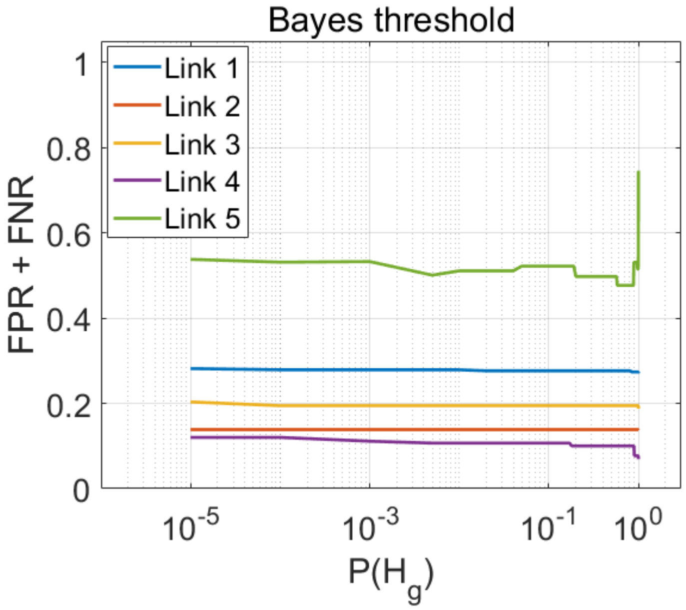
- Impact of thresholding parameters



Percentile threshold



Chebyshev threshold

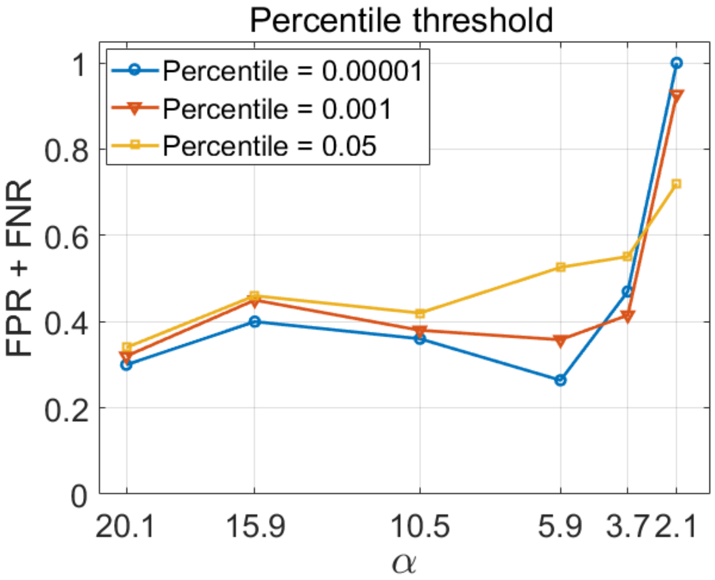


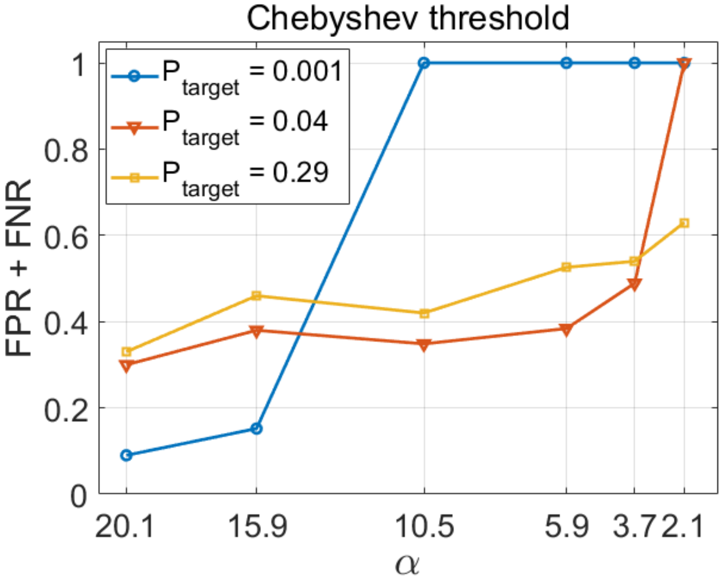
Bayes threshold

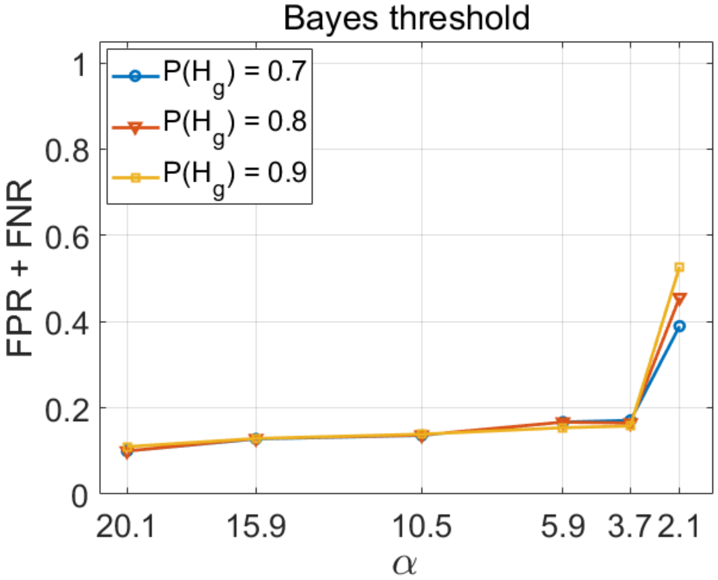
- Bayes threshold
  - Less sensitive to its thresholding parameter
  - Near-optimal accuracy with a coarse parameter setting

Comparison of Thresholding Methods (3)

- When RSSI distributions of good link and bad overlaps


Percentile threshold


Chebyshev threshold


Bayes threshold

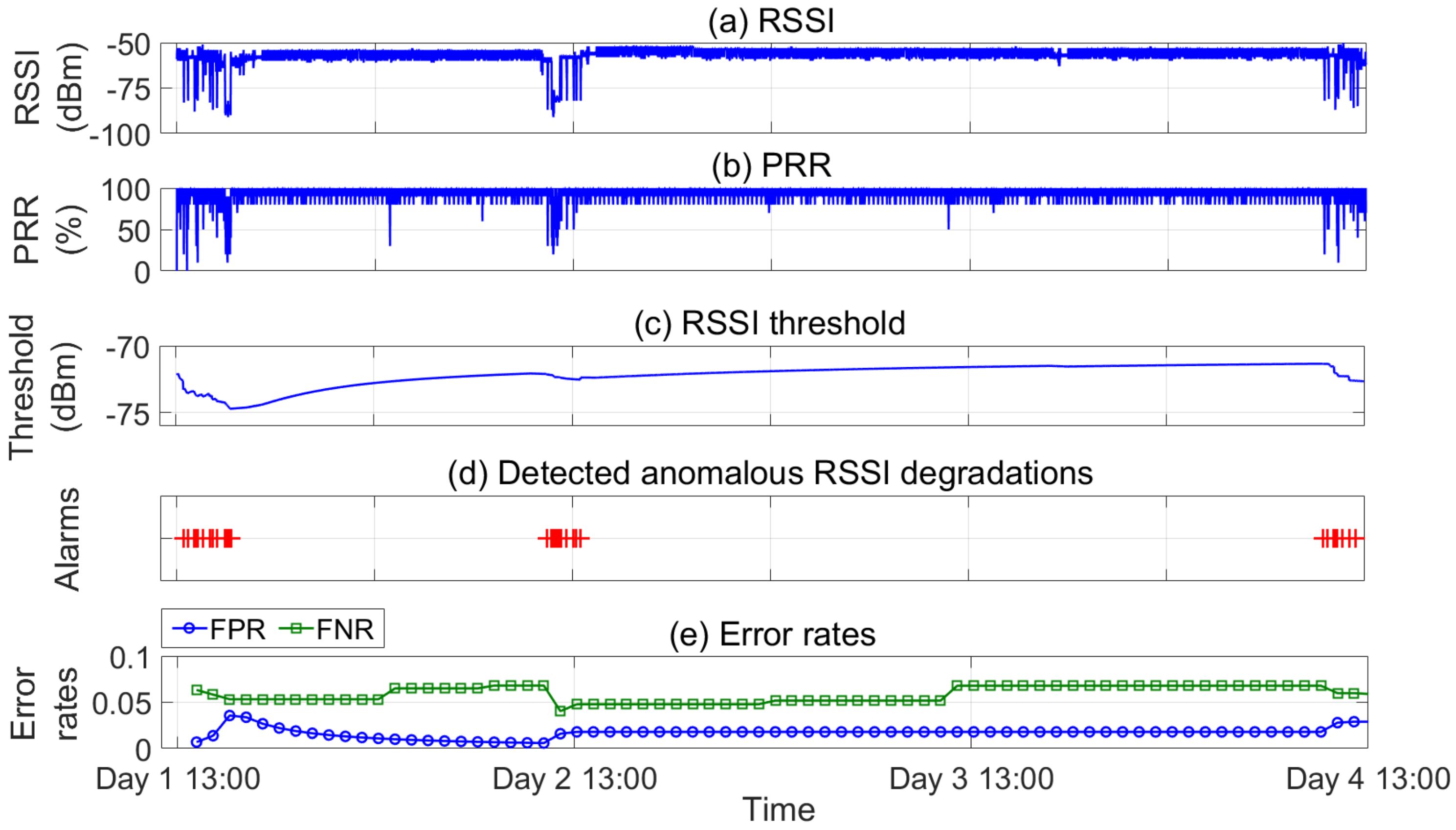
  - Overlapping level is indicated by $\alpha = \frac{\mu_g - \mu_w}{2\sigma}$

- Overhead

Techniques	RAM (bytes)	ROM (bytes)	Computation (ms)
Percentile	66	2850	8.3
Chebyshev	66	3052	8.9
Bayes	68	4688	10

Evaluation of the Overall System

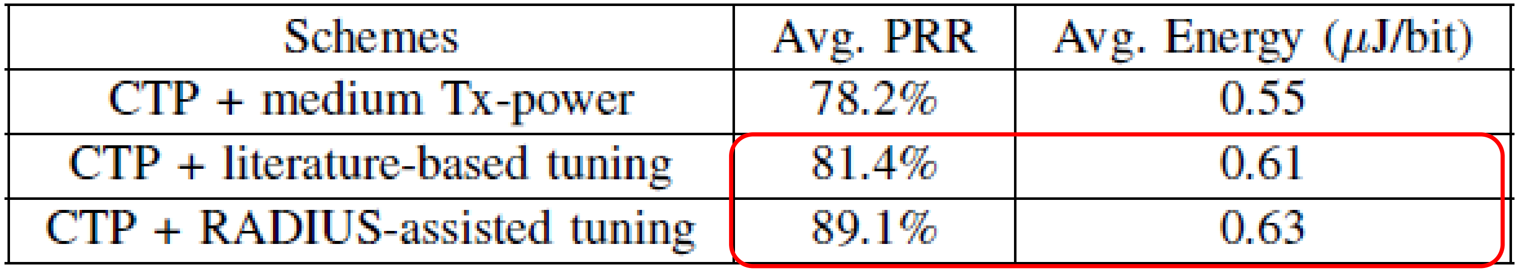
- 72-hour experiments with whole system (Bayes threshold + update)
  - Results of one link



  - Average error rate of all links: 5.78%

Application of RADIUS

- Applicability
  - Inbound links
  - Not limited to a specific communication topology (e.g. Tree, Mesh)
  - Not limited to a specific MAC protocol (e.g. TDMA, CSMA)
  - Performance degrades when excessive packet losses (disconnected link)
  - With modification, it can work with dynamic routing protocol
- An exemplary application
  - RADIUS-assisted Tx-Power tuning vs. Literature[1]-based approach



Schemes	Avg. PRR	Avg. Energy (μJ/bit)
CTP + medium Tx-power	78.2%	0.55
CTP + literature-based tuning	81.4%	0.61
CTP + RADIUS-assisted tuning	89.1%	0.63

Conclusions

- RADIUS:
  - a lightweight yet accurate and robust approach to detect anomalous RSSI degradation for 802.15.4 links
    - based on a Bayes thresholding scheme and threshold adaptation
    - no need of tuning for each link or over time
  - considered as a good trigger to perform remedial actions to deal with link packet losses due to degraded channel quality

- Ongoing work
  - Investigate how a multi-layer parameter tuning scheme **[2]** can benefit from RADIUS

References

- [1] Lin, S., Miao, F., Zhang, J., Zhou, G., Gu, L., He, T., ... Pappas, G. J. . ATPC: Adaptive transmission power control for wireless sensor networks. ACM Transactions on Sensor Networks, 2016
- [2] S. Fu, Y. Zhang, Y. Jiang, C. Hu, C. Y. Shih and P. J. Marrón, "Experimental Study for Multi-layer Parameter Configuration of WSN Links," in Proc. of ICDCS, 2015.

Thank you for your attention!