Topology and Power Control

Octav Chipara

Motivation

- **Energy and capacity are limited resources in wireless sensor networks**
- **Answer: Topology and Power Control**
  - maintain a topology with certain properties (e.g., connectivity) while ***reducing*** energy consumption and/or ***increasing*** network capacity
- **Terminology:**
  - **power control:** a wireless channel perspective - optimize the transmission power to for a wireless transmission
  - **topology control:** a system level perspective - optimize the choice of transmission power to achieve a global property

Energy optimization

Energy optimization

- **How do nodes waste energy?**
  - idle listening
  - overhearing
  - transmitting at higher power than necessary
  - receiving corrupted packets

How do topology and power control work?

- **Decide if a node should be ON or OFF**
  - motivation: it is sufficient for only a subset of nodes to be active at a time to ensure connectivity
  - consequence:
    - reduces the energy consumption
    - increases channel capacity [why?]

- **Determine the optimal transmission power**
  - motivation:
    - a higher than necessary transmission power ⇒ interference + contention
    - a lower than necessary transmission power ⇒ packet loss
  - consequences:
    - increases channel capacity
    - reduces energy consumption [is it effective?]

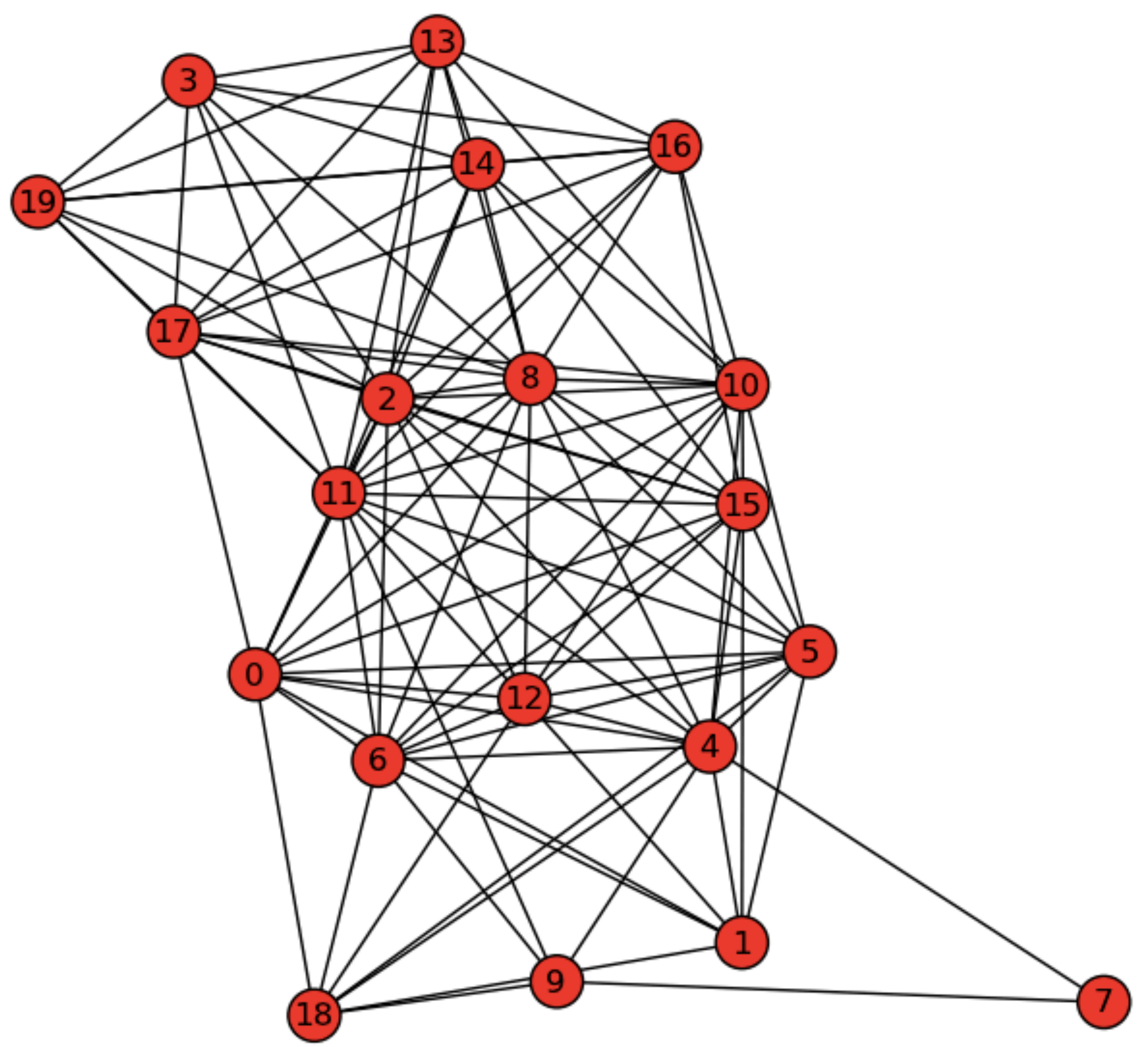
Today's lecture

- **SPAN: energy-efficient coordination algorithm**
  - Benjie Chen, Kyle Jamieson, ***Hari Balakrishnan***, and Robert Morris
  - MIT
  - ***MOBICOM***

- **Robust Topology Control for Indoor Wireless Sensor Networks,**
  - G. Hackmann, O. Chipara and C. Lu
  - WUSTL
  - ***SenSys***

Problem formulation

- **Goals:**
  - minimize the energy consumed by a node
  - while having a minimal impact on message delay and channel capacity
- **Approach: we will determine what nodes to turn off while maintaining connectivity**



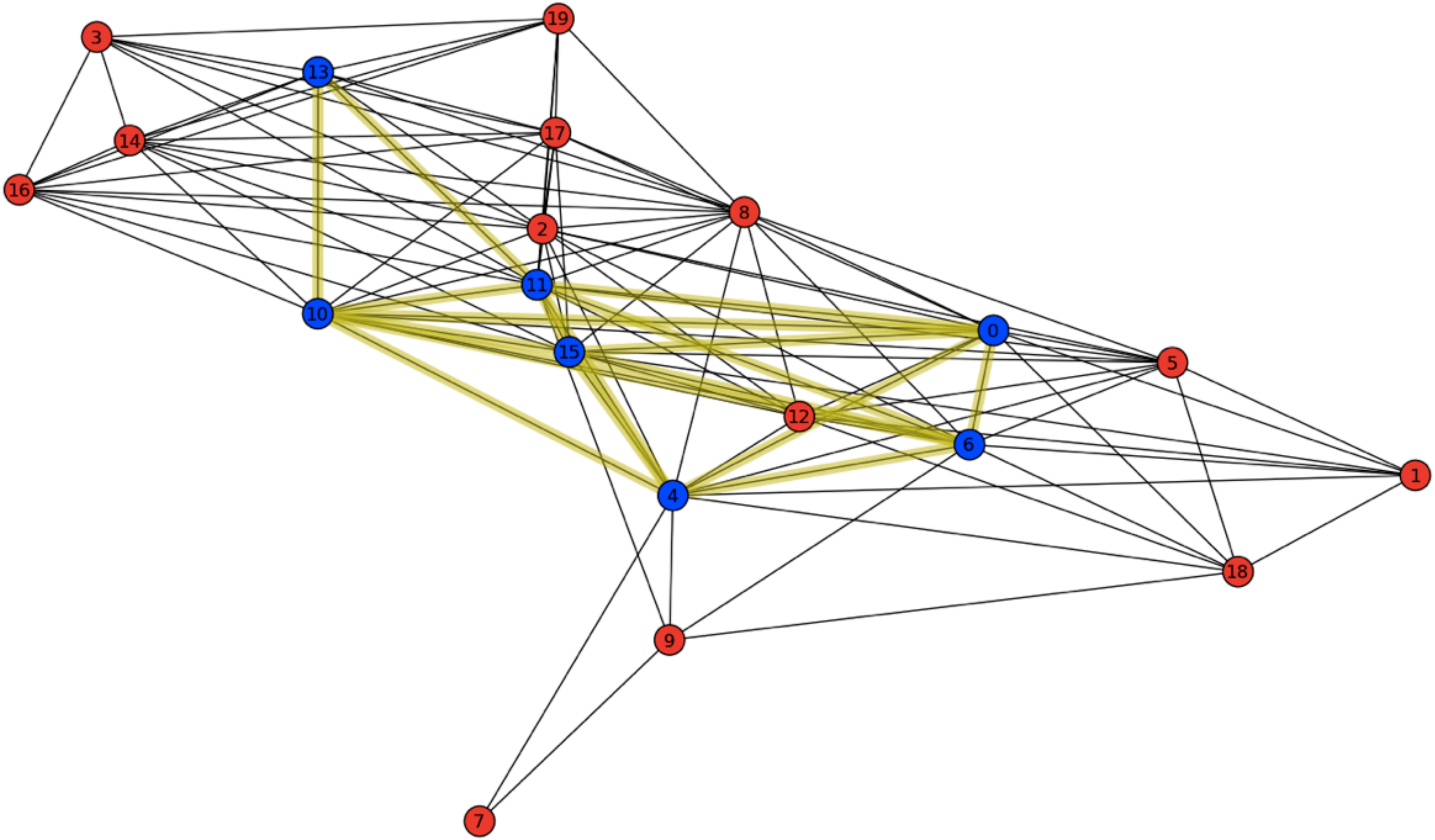
Protocol design

- **SPAN assigns nodes with two roles**
  - coordinators: remain awake to maintain connectivity
  - non-coordinator: enter power saving mode
- **Role assignments are rotated to maximized network life-time**

- **State maintenance:**
  - each node maintains
    - a list of its coordinators
    - a list of the coordinators of its neighbors
  - information exchanged in periodic beacons

Selecting coordinators

- **A node n is eligible to become coordinator if**
  - two neighbors of n cannot reach each other either directly or via one (or two) coordinators
- **Properties:**
  - enforces that the connected topology will be connected
  - no optimality guarantee
- **Unresolved issue:**
  - multiple nodes deciding to be coordinators at the same time



19
3
13
17
14
16
8
2
11
10
0
15
5
12
6
1
4
18
9
7

Coordinating announcements

- **Selecting the back-off for announcements based on topology considerations**
  - i - number nodes
  - Ci - number of additional connected pairs if i becomes a coordinator

$$u = \frac{C_i}{\mathbb{C}(N_i, 2)}$$

  - nodes with higher utility u should volunteer sooner

$$delay = ((1 - u) + R) * N_i$$

  - where R is a random number in [0, 1]

Coordinating announcements (2)

- **Incorporating energy availability considerations**
  - Er the amount of energy remaining out of Em the total amount of energy

$$delay = ((1 - \frac{E_r}{E_m}) + (1 - u) + R) * N_i$$

  - nodes will less energy will volunteer less frequently

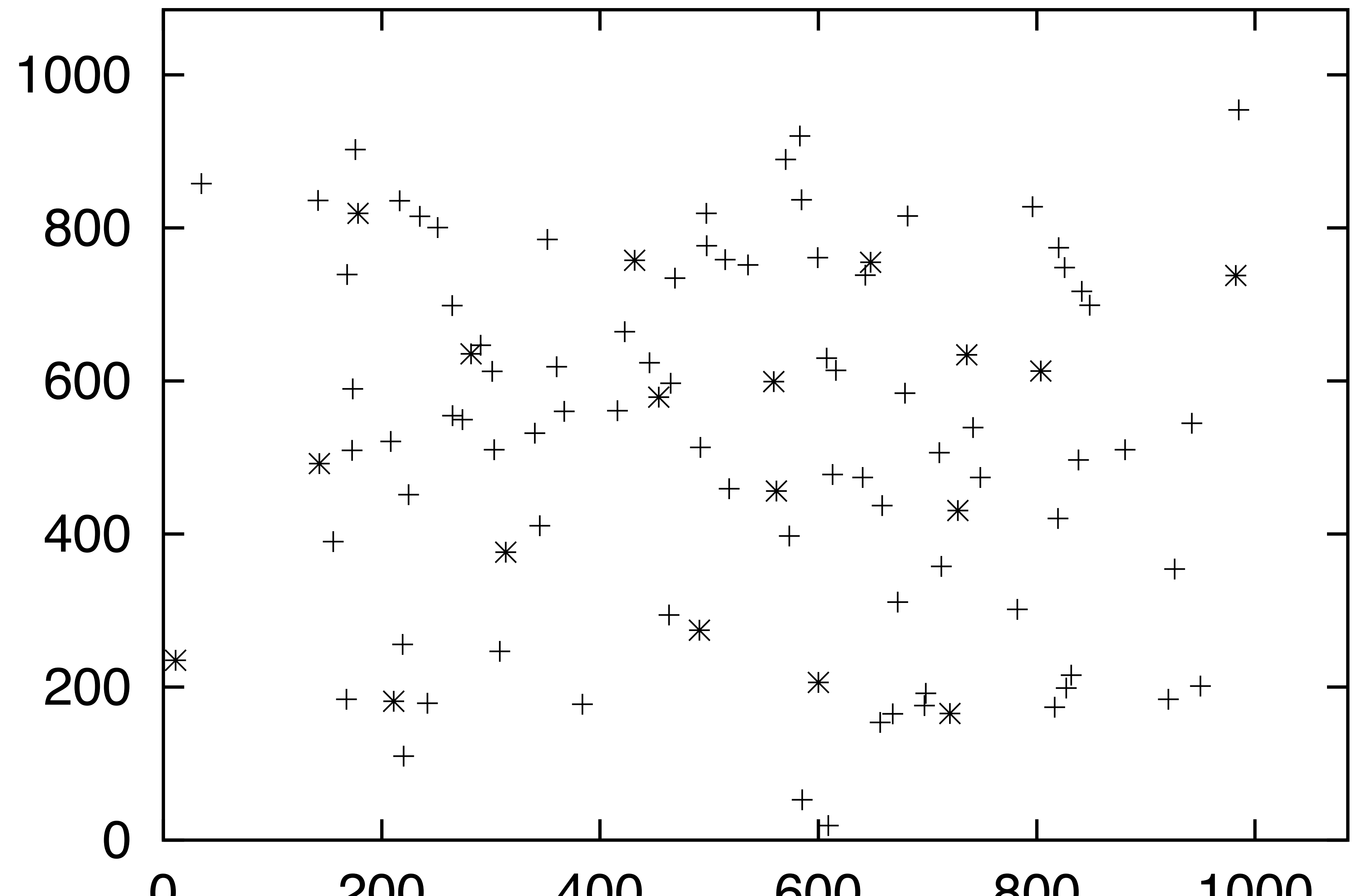


Figure 3: A scenario with 100 nodes, 18 coordinators, and a radio range of 250 meters. The nodes marked "∗" are coordinators; the nodes marked "+" are non-coordinator nodes.

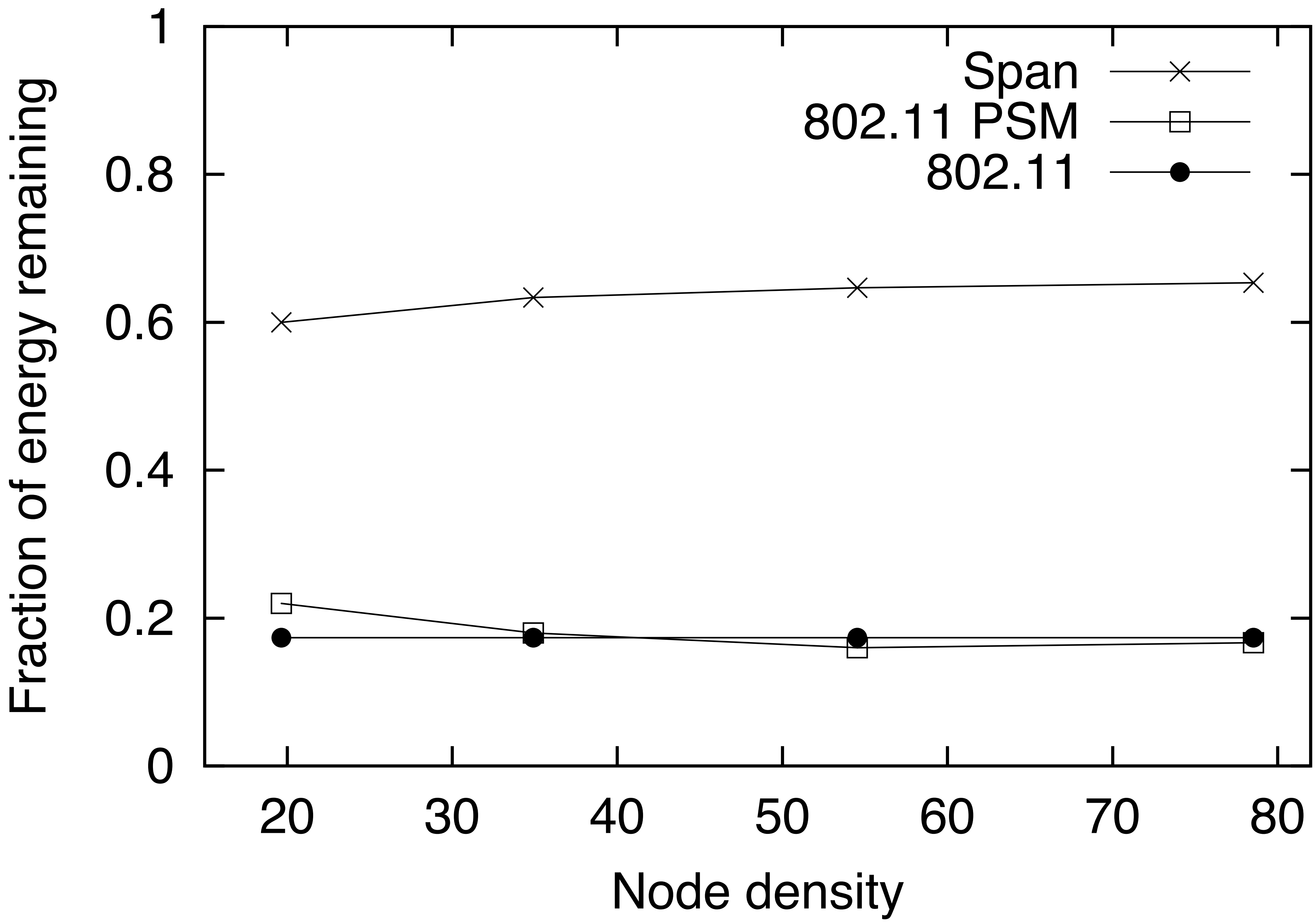


Figure 8: Fraction of energy remaining after 300 seconds of simulation. Span provides significant amount of savings over 802.11 PSM and 802.11.

Today's lecture

- **SPAN: energy-efficient coordination algorithm**
  - Benjie Chen, Kyle Jamieson, ***Hari Balakrishnan***, and Robert Morris
  - MIT
  - ***MOBICOM***
- **Robust Topology Control for Indoor Wireless Sensor Networks,**
  - G. Hackmann, O. Chipara and C. Lu
  - WUSTL
  - ***SenSys***

Motivation

Motivation

- **Goal: reducing transmission power while maintaining satisfactory link quality**

Motivation

- **Goal: reducing transmission power while maintaining satisfactory link quality**

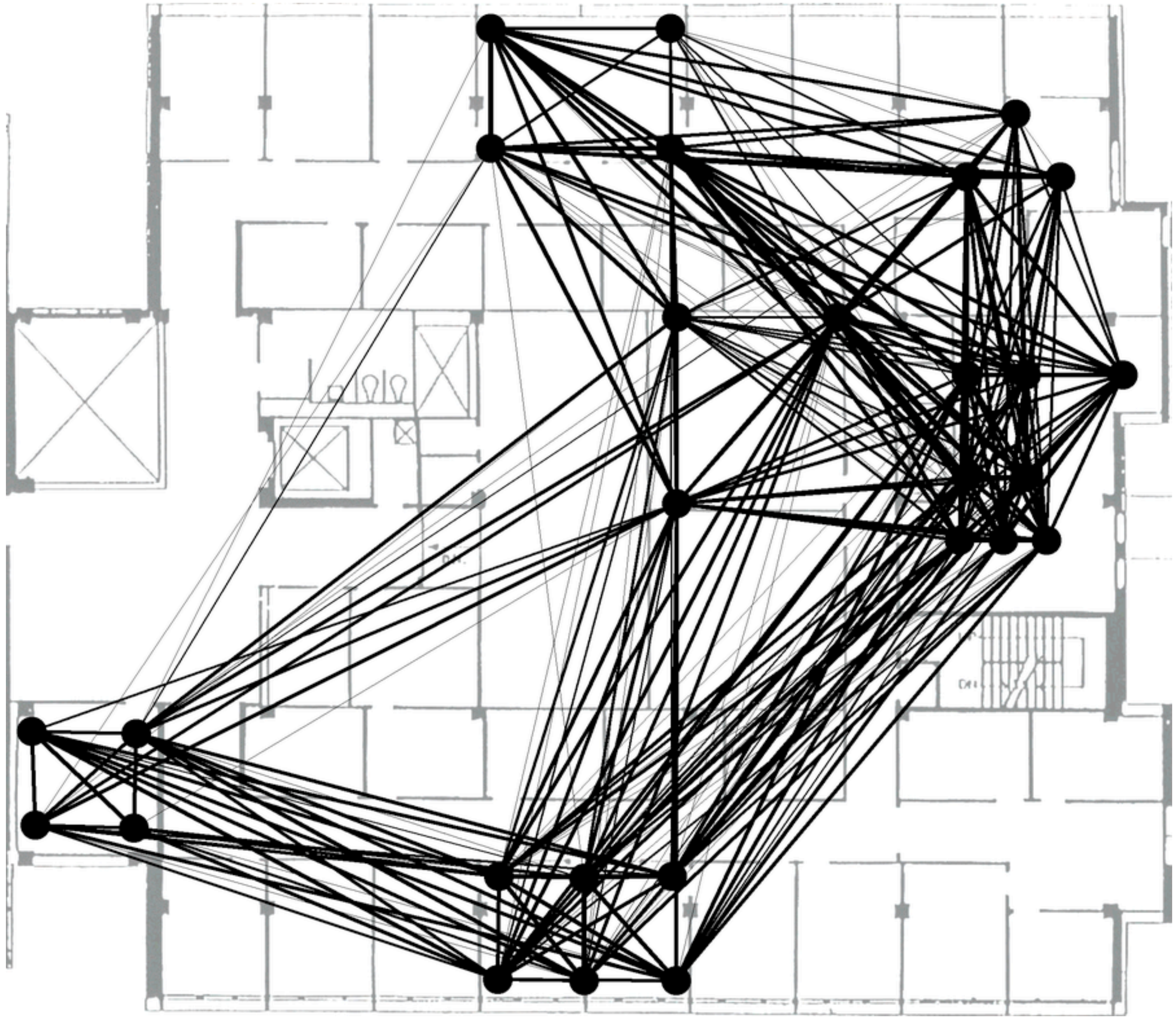
Motivation

- **Goal: reducing transmission power while maintaining satisfactory link quality**

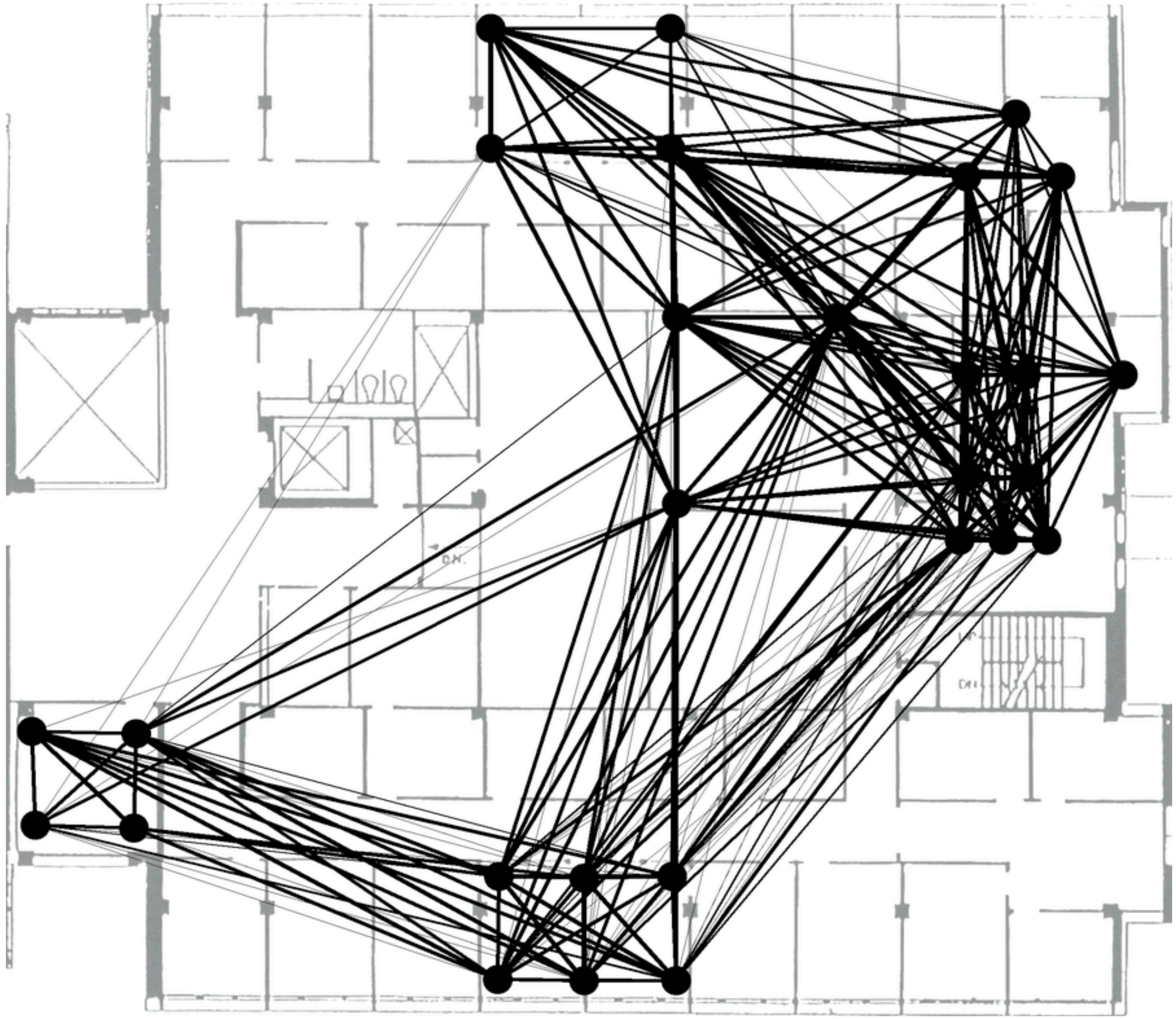
- **But it's challenging:**
  - Links have irregular and probabilistic properties
  - Link quality can vary significantly over time
  - Human activity and multi-path effects in indoor networks

Outline

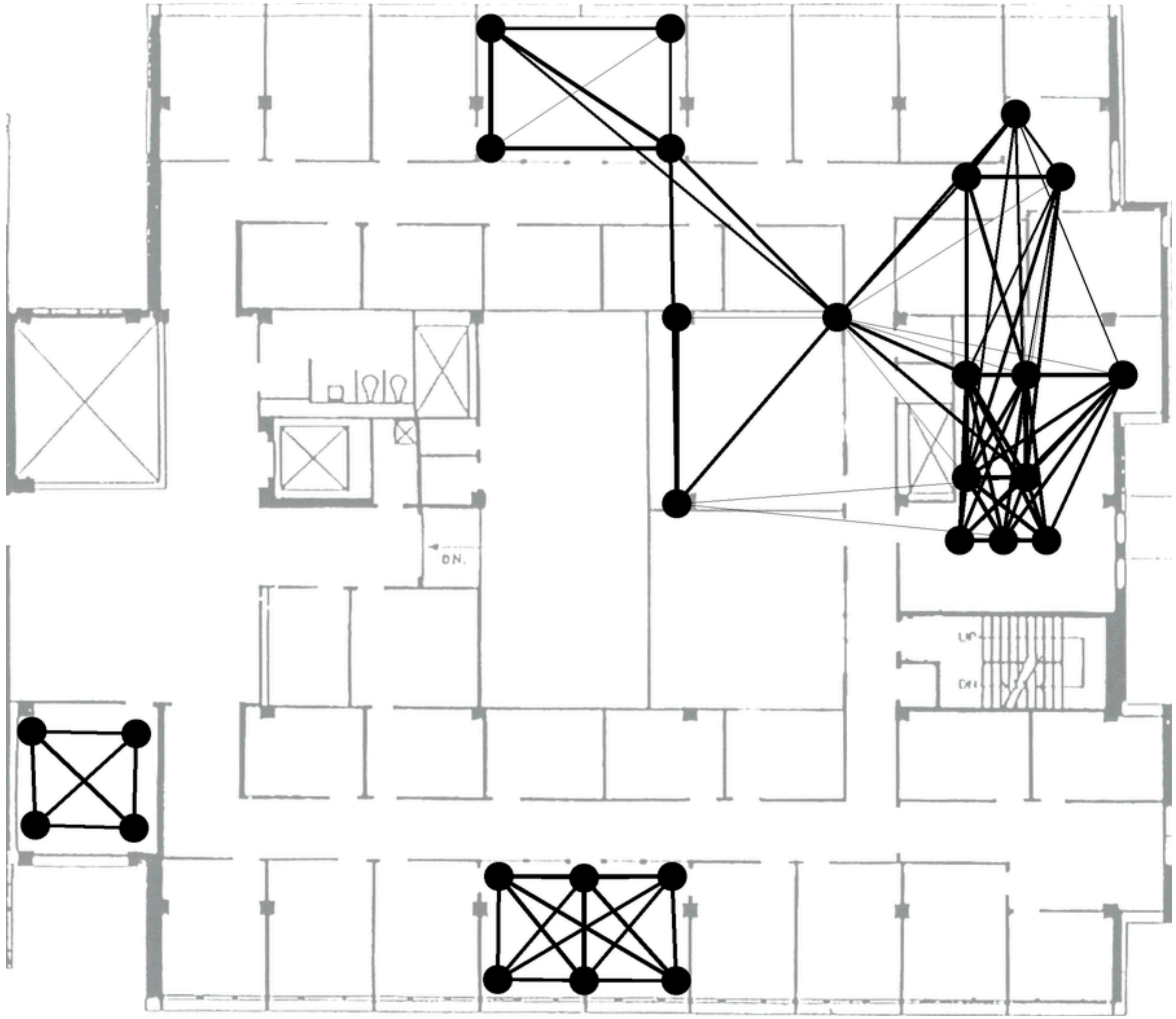
- Empirical study
- Algorithm
- Implementation and evaluation
- Conclusion



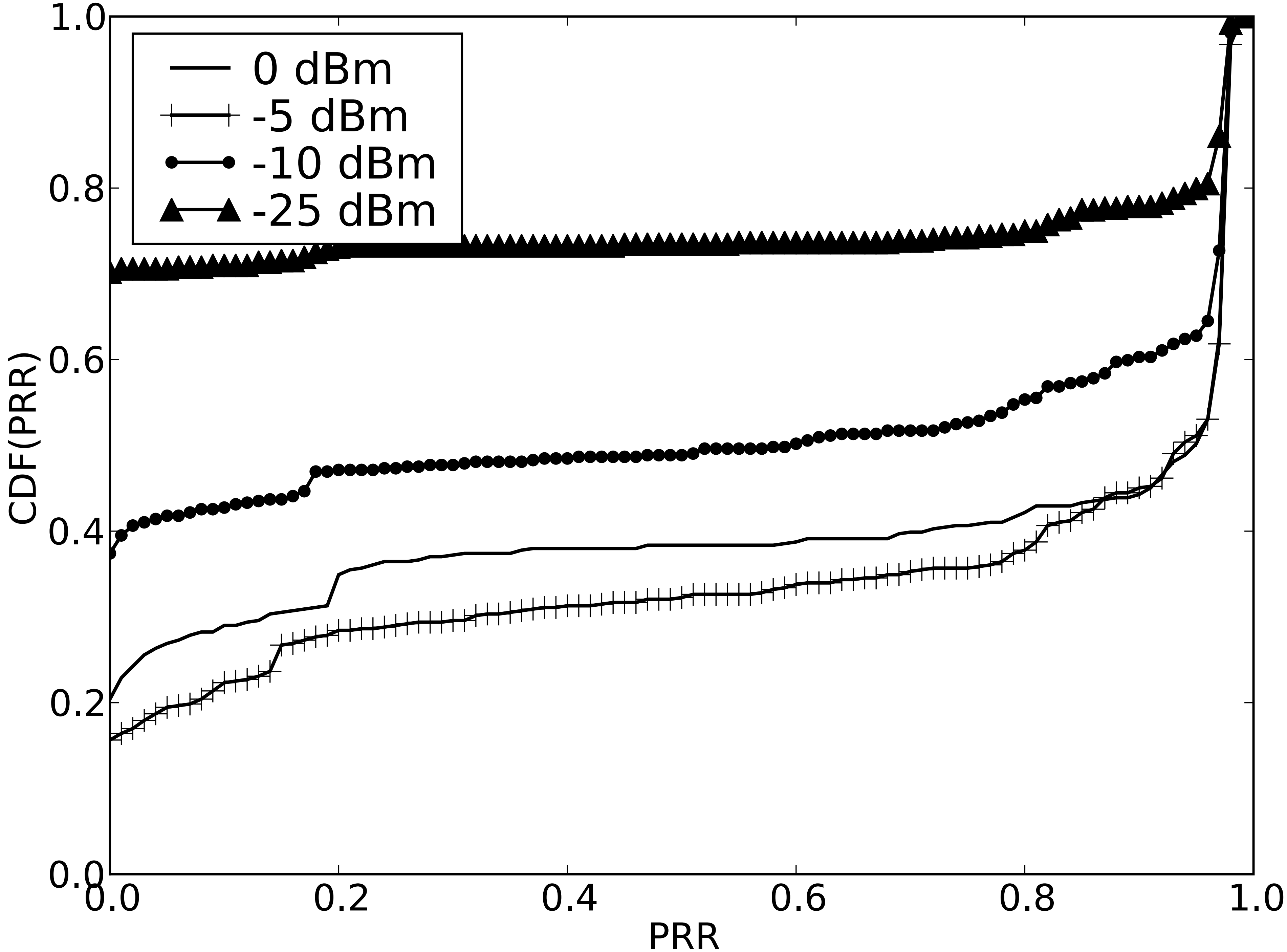
0 dBm

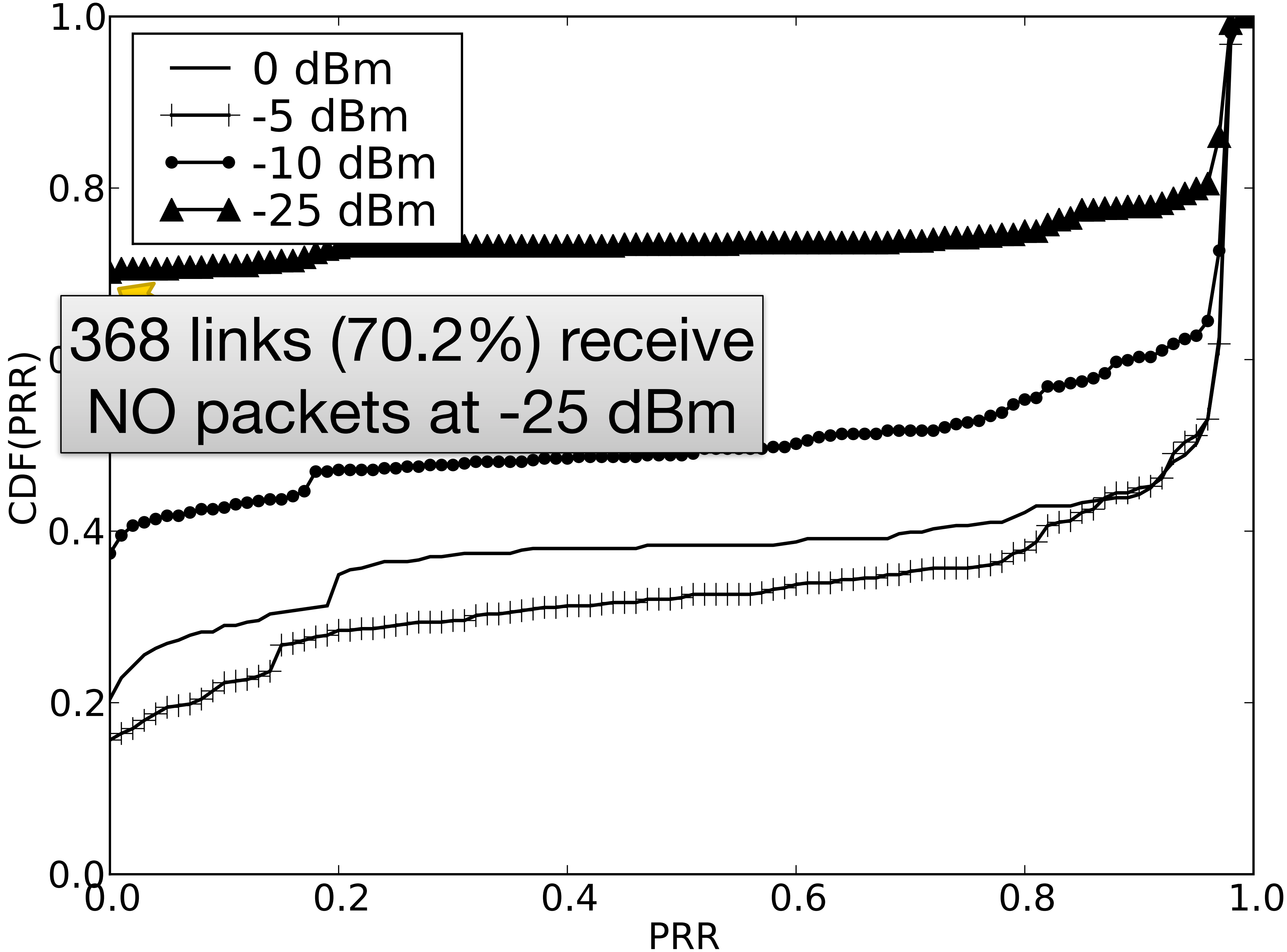


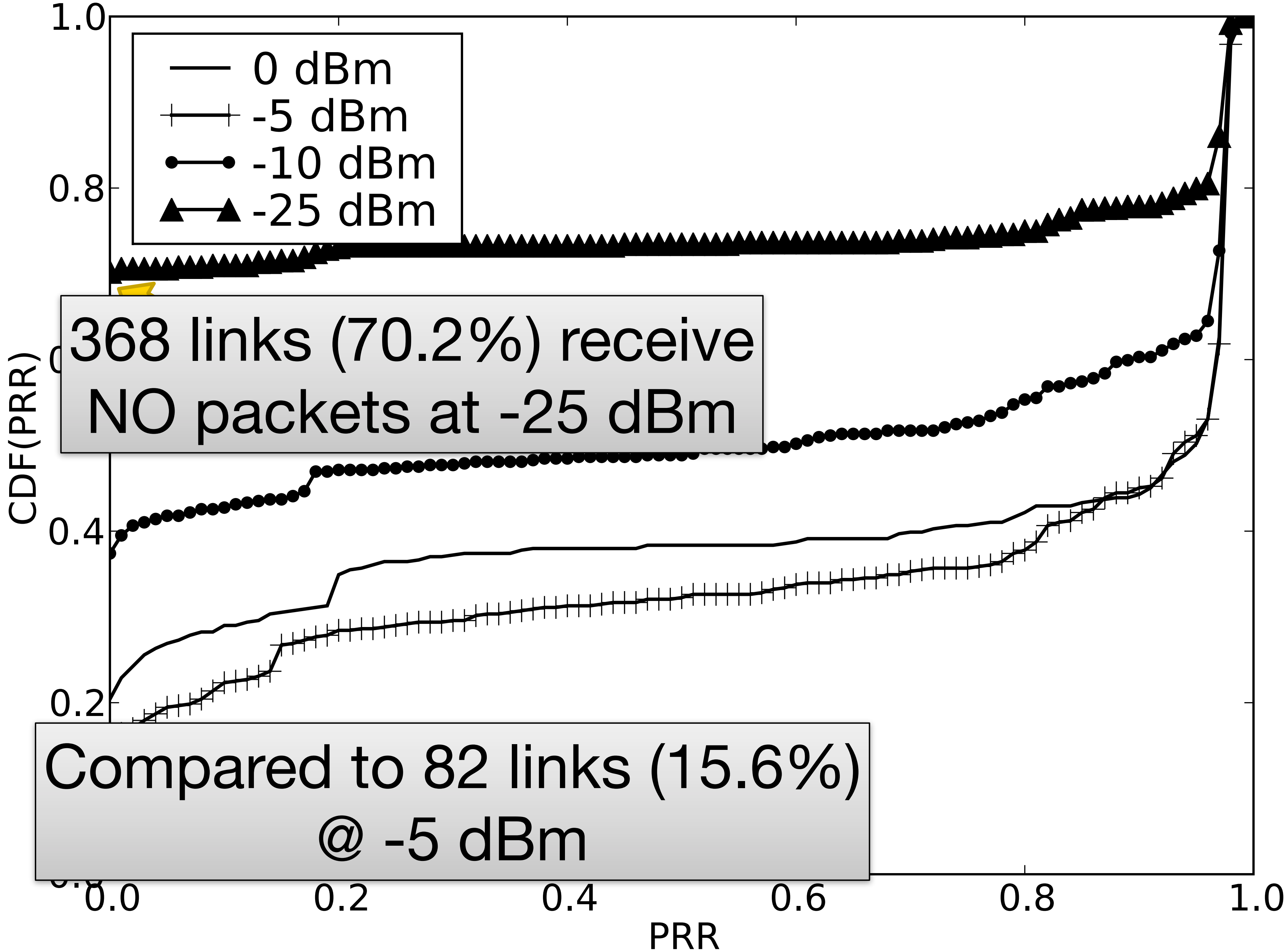
-15 dBm



-25 dBm

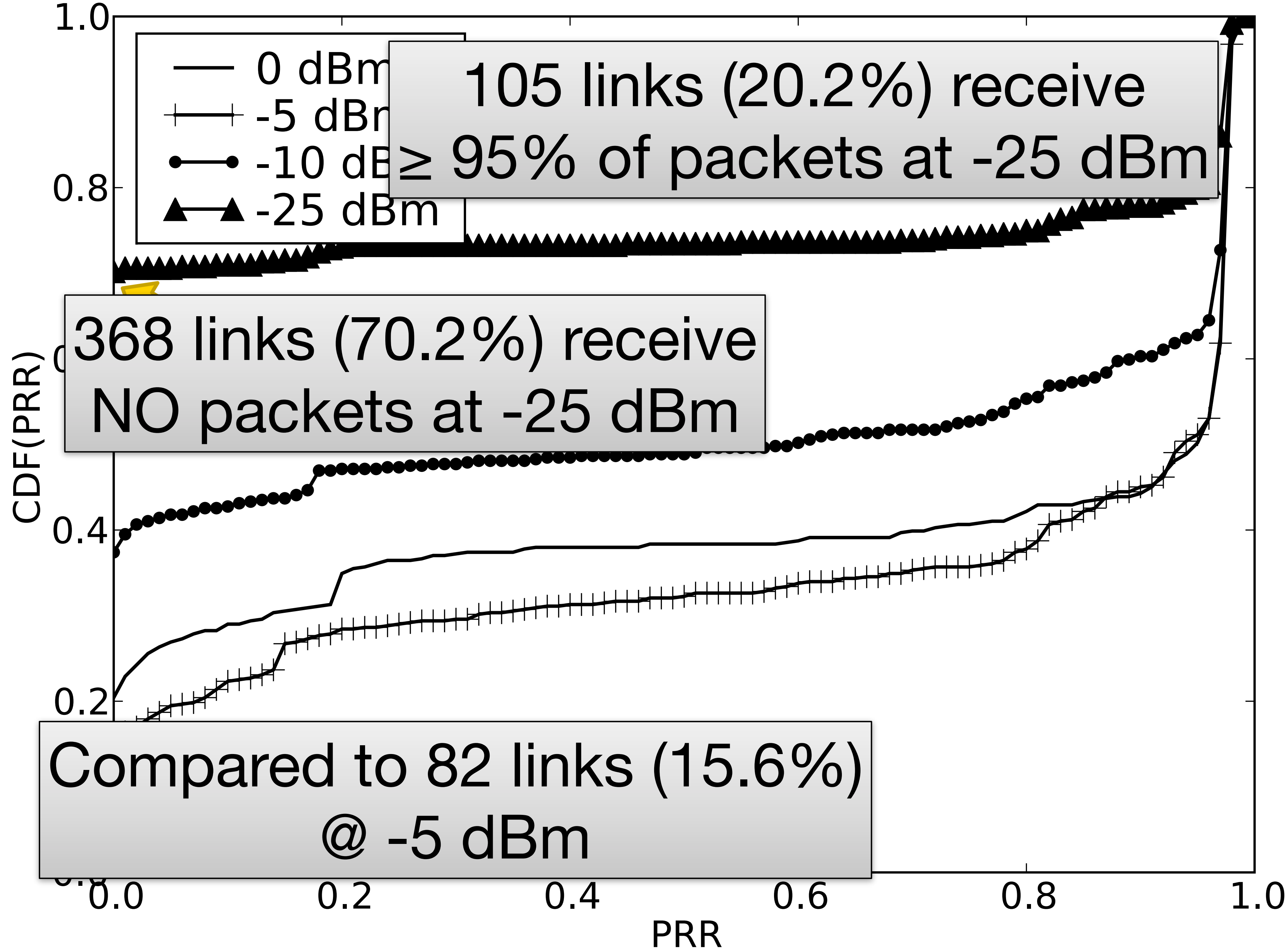

0 dBm
-5 dBm
-10 dBm
-25 dBm
CDF(PRR)
PRR
0.0
0.2
0.4
0.6
0.8
1.0


0 dBm
-5 dBm
-10 dBm
-25 dBm
CDF(PRR)
PRR
0.0
0.2
0.4
0.8
1.0
0.6
368 links (70.2%) receive
NO packets at -25 dBm

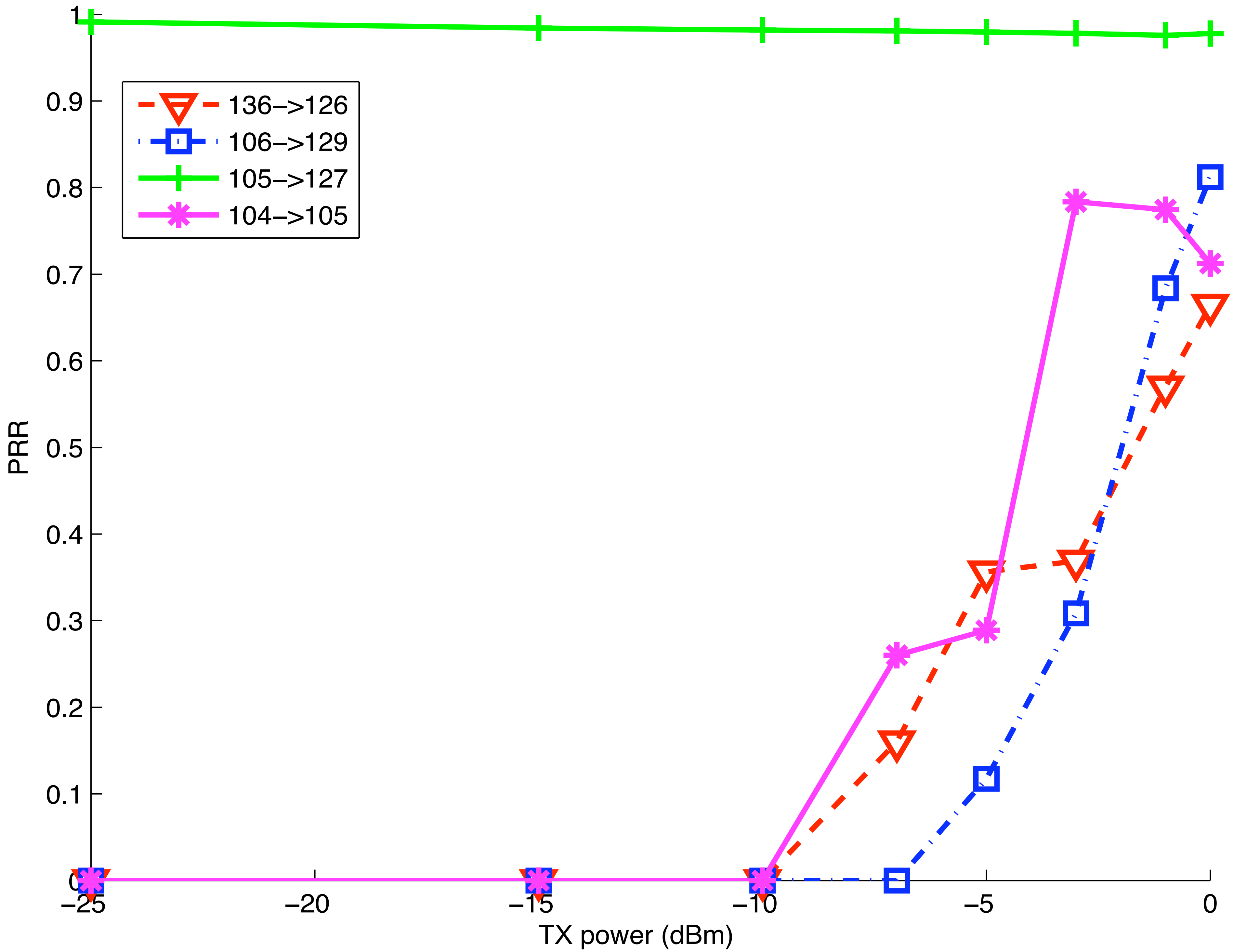


368 links (70.2%) receive NO packets at -25 dBm

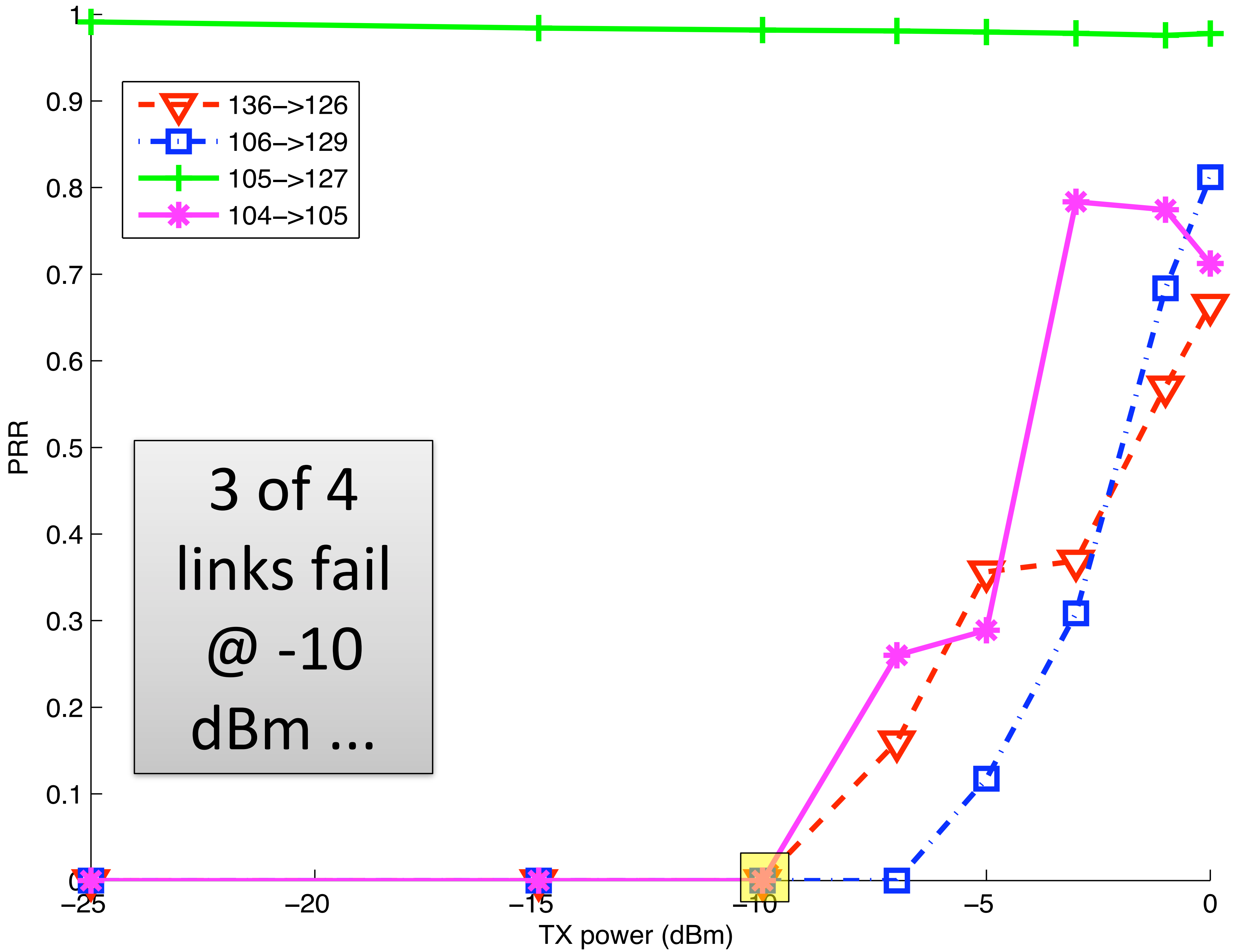
Compared to 82 links (15.6%) @ -5 dBm


0 dBm
-5 dBm
-10 dBm
-25 dBm
105 links (20.2%) receive
≥ 95% of packets at -25 dBm
368 links (70.2%) receive
NO packets at -25 dBm
Compared to 82 links (15.6%)
@ -5 dBm
CDF(PRR)
PRR
1.0
0.8
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0

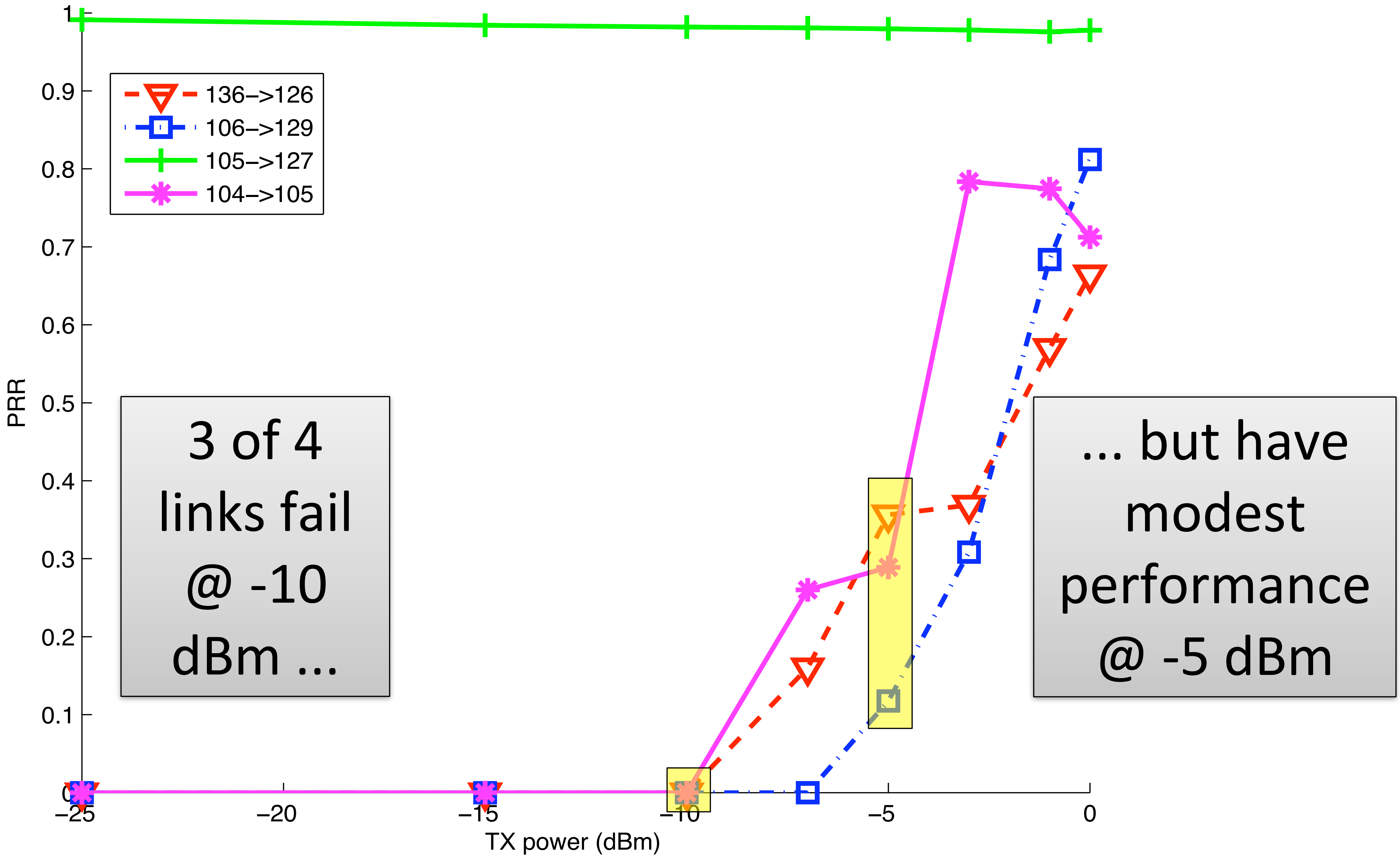
Is Per-Link Topology Control Beneficial?



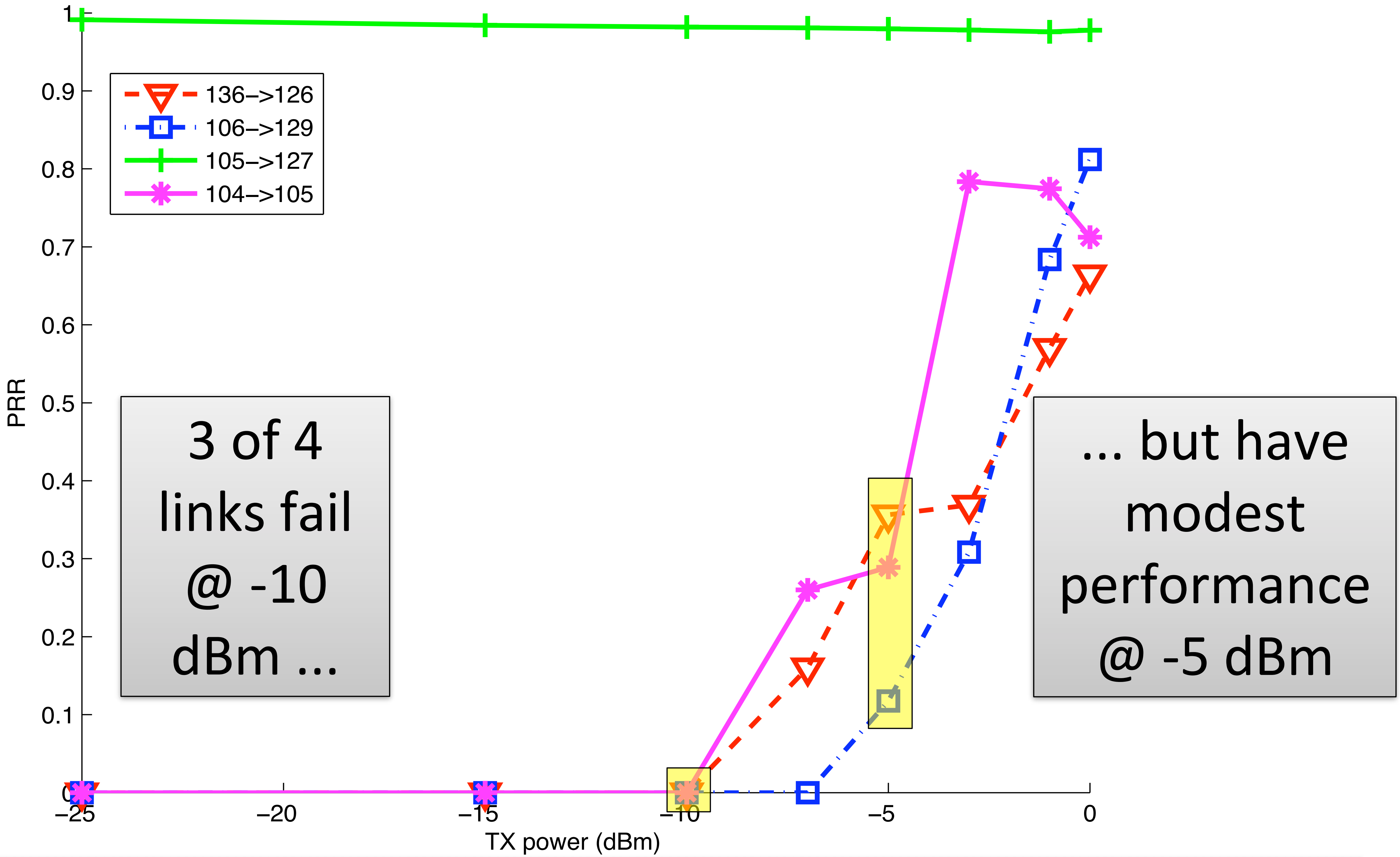
Is Per-Link Topology Control Beneficial?



Is Per-Link Topology Control Beneficial?

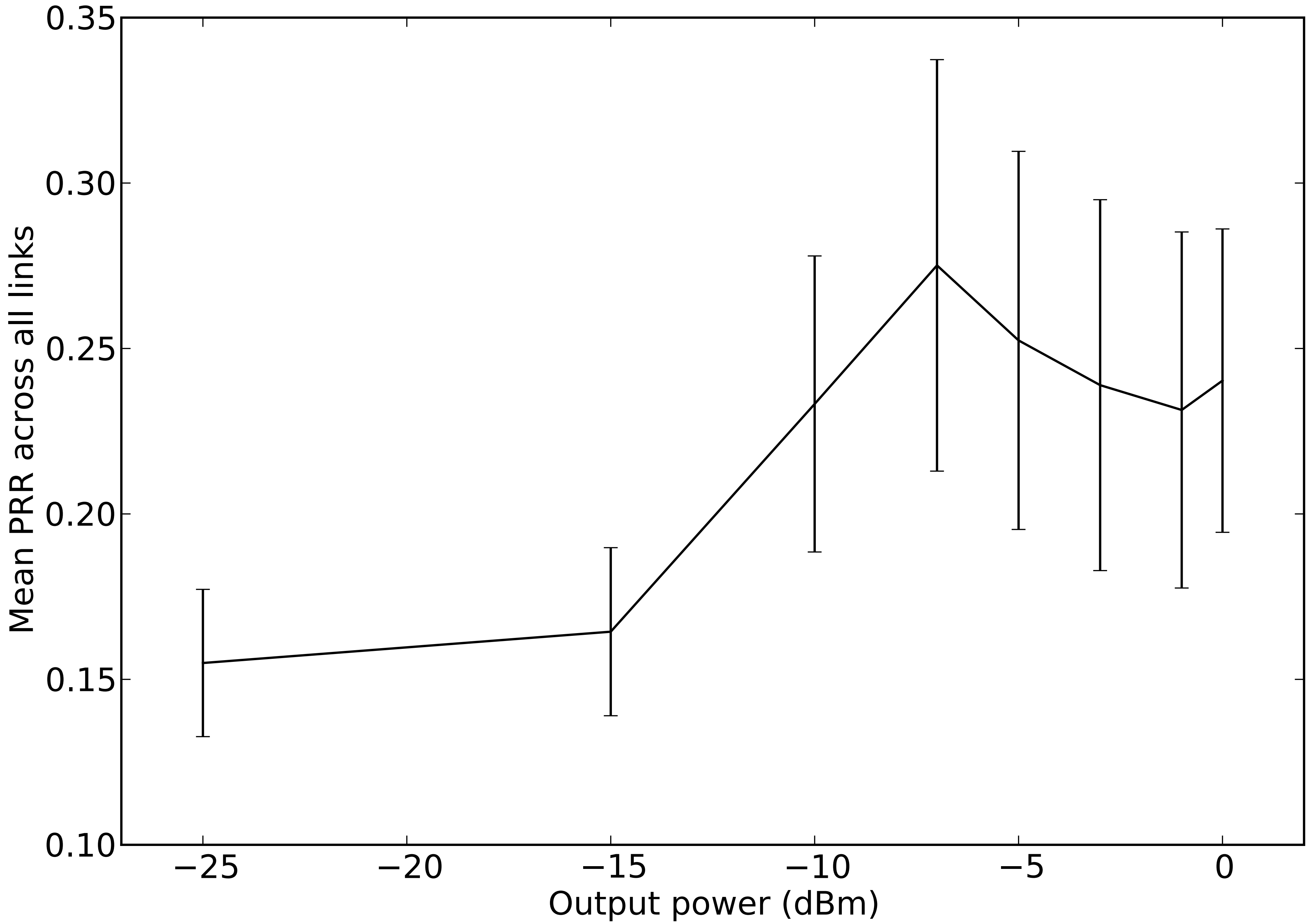


Is Per-Link Topology Control Beneficial?

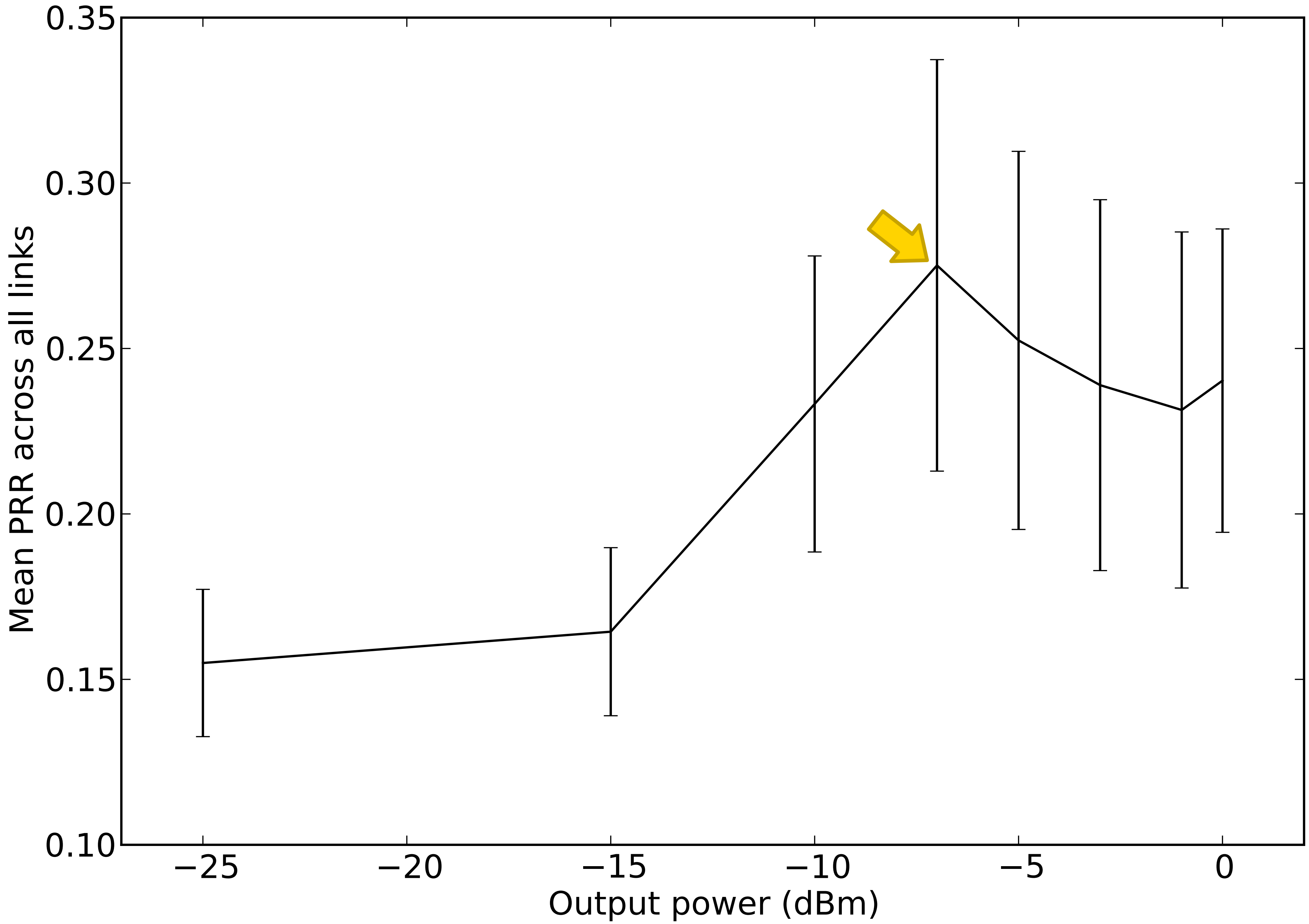


Insight 1: Transmission power should be set on a per-link basis to improve link quality and save energy.

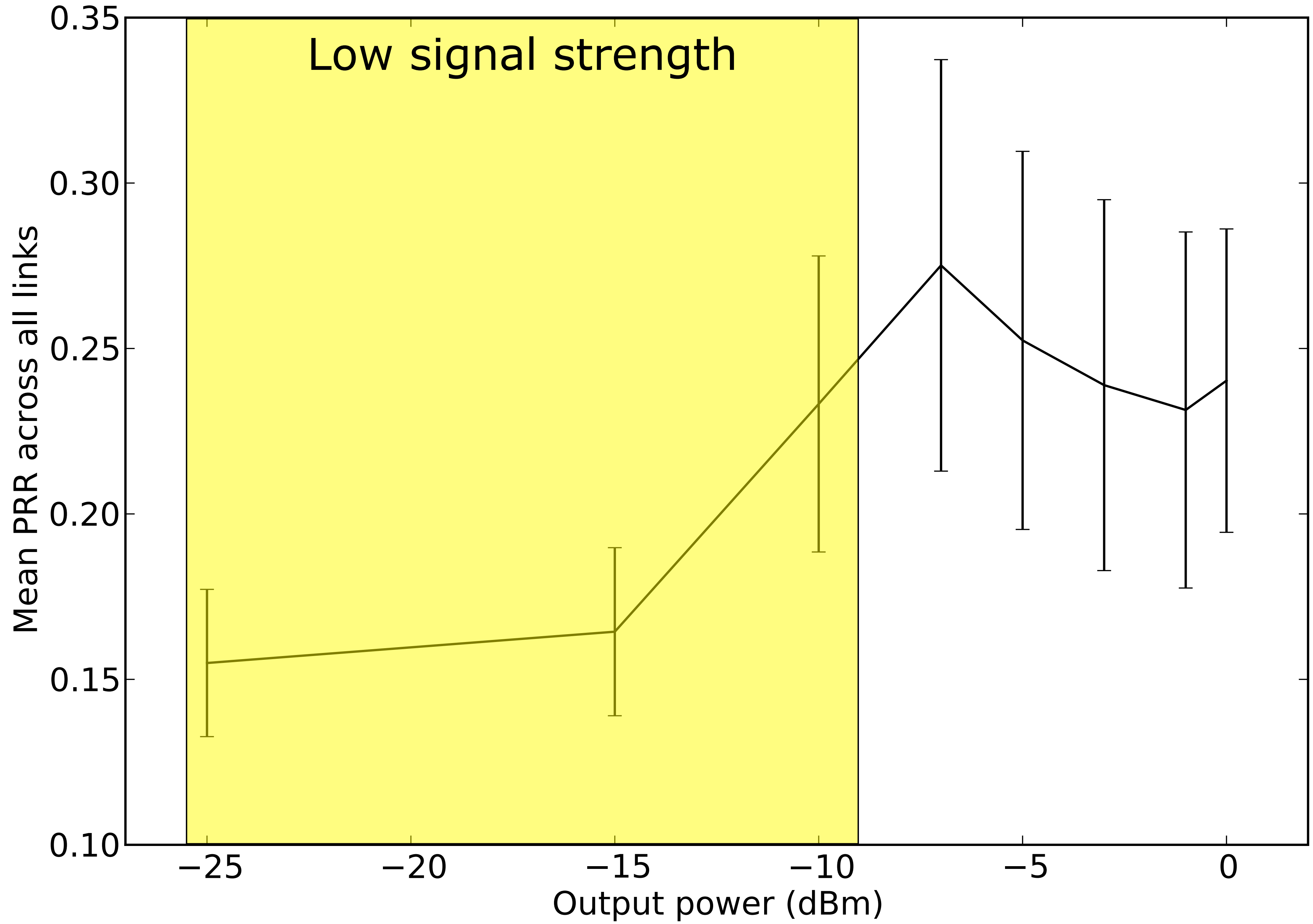
Impact of Transmission Power on Contention?



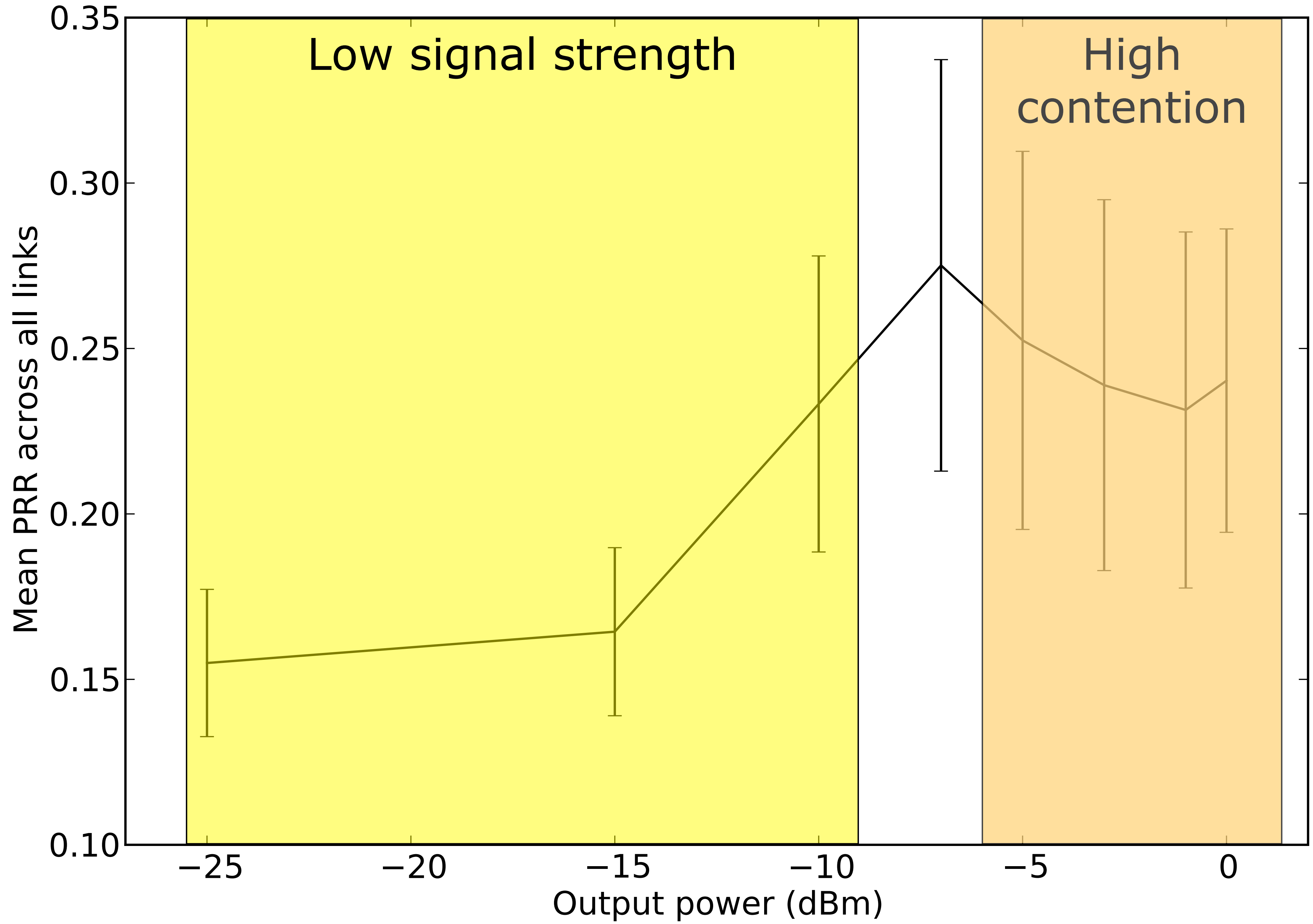
Impact of Transmission Power on Contention?



Impact of Transmission Power on Contention?

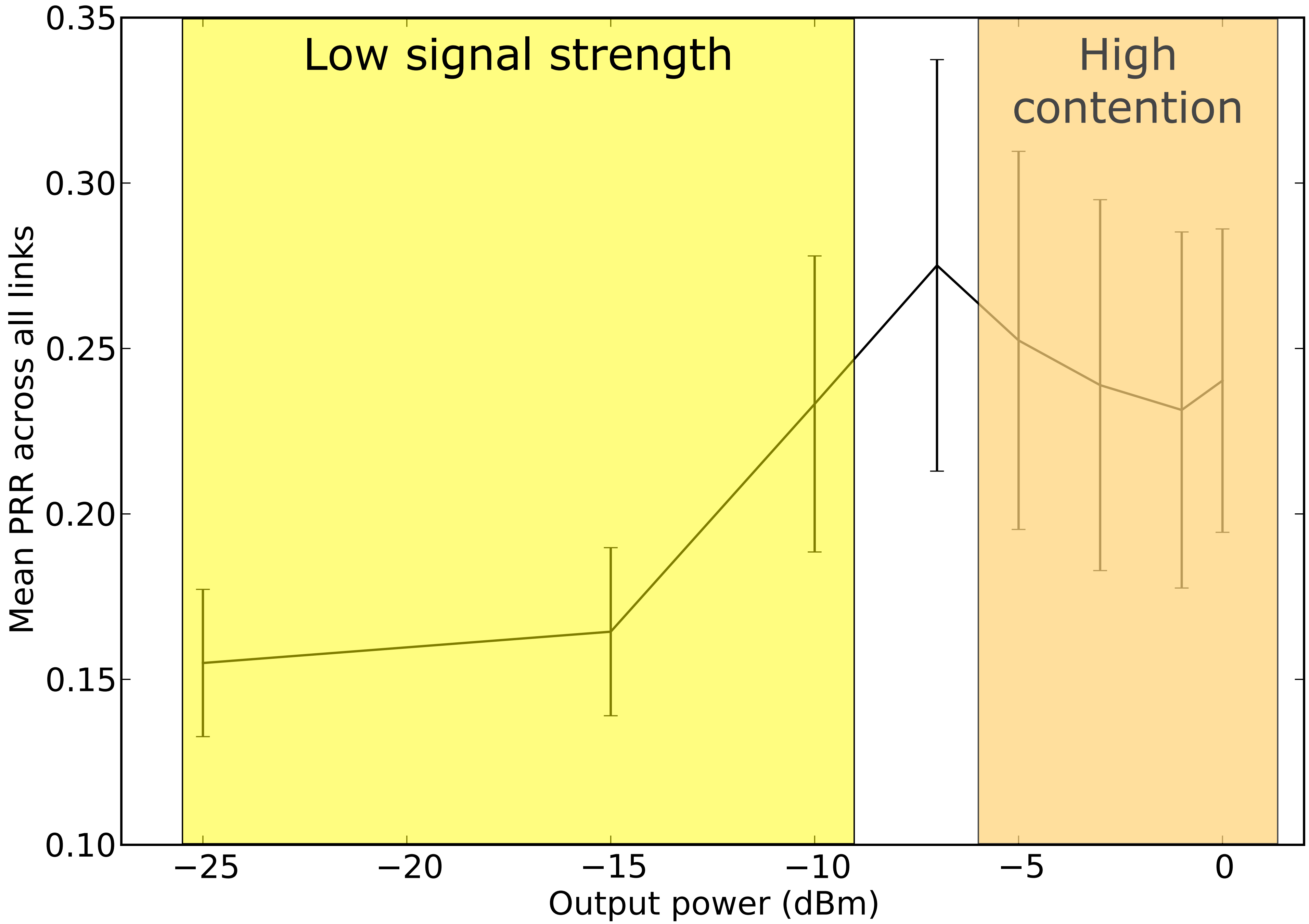


Impact of Transmission Power on Contention?

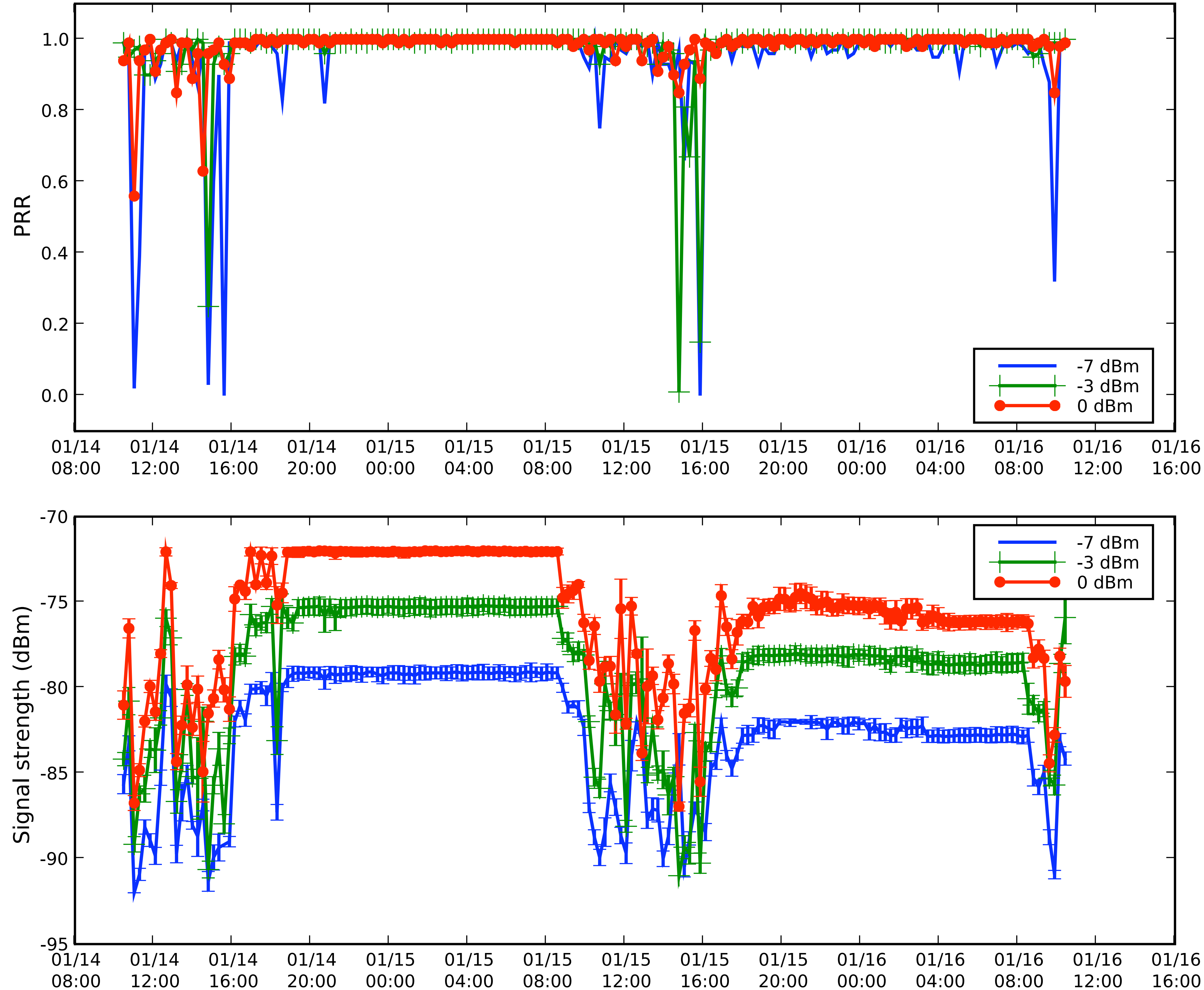


Impact of Transmission Power on Contention?

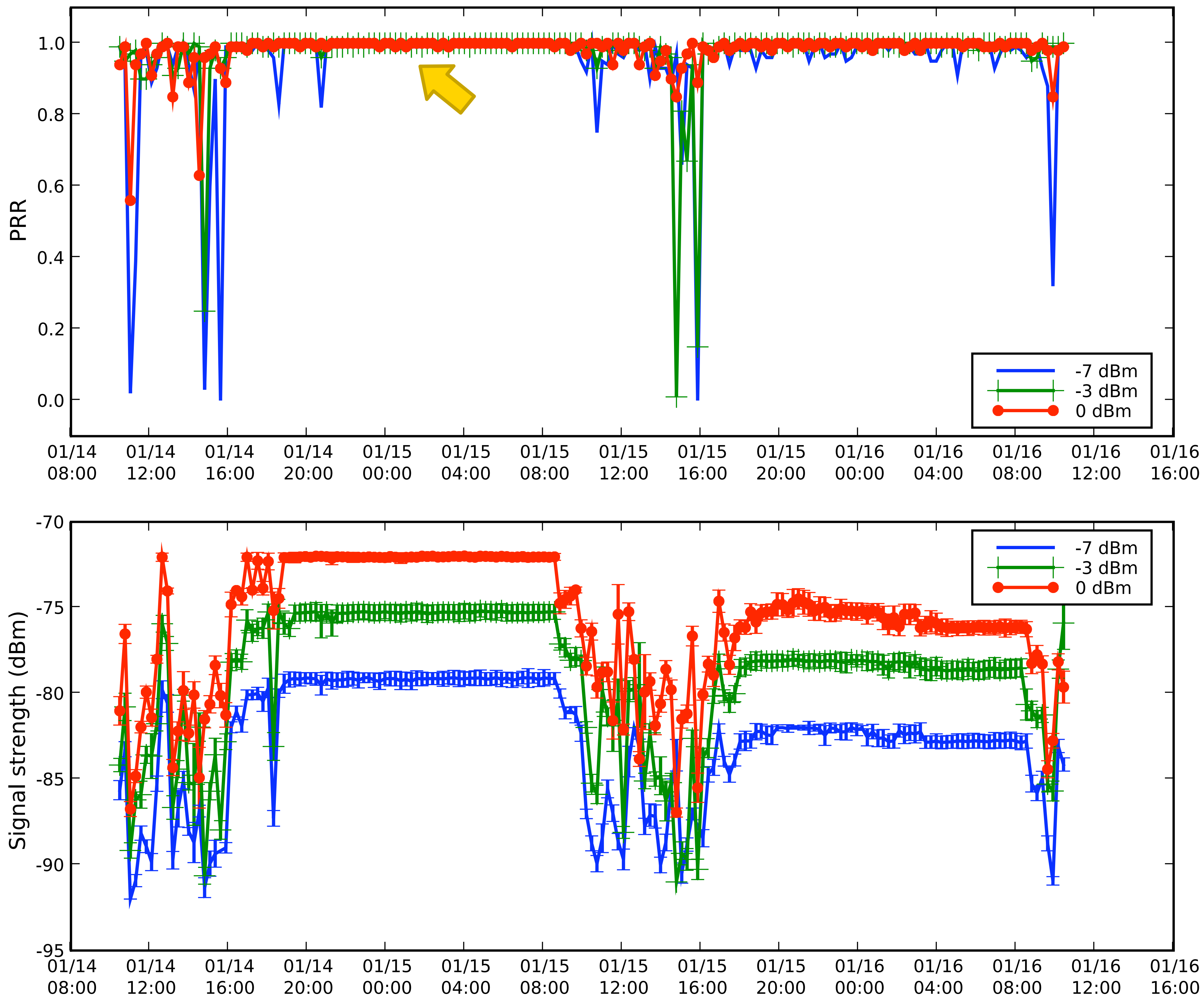
Insight 2: Robust topology control algorithms must avoid increasing contention under heavy network load.



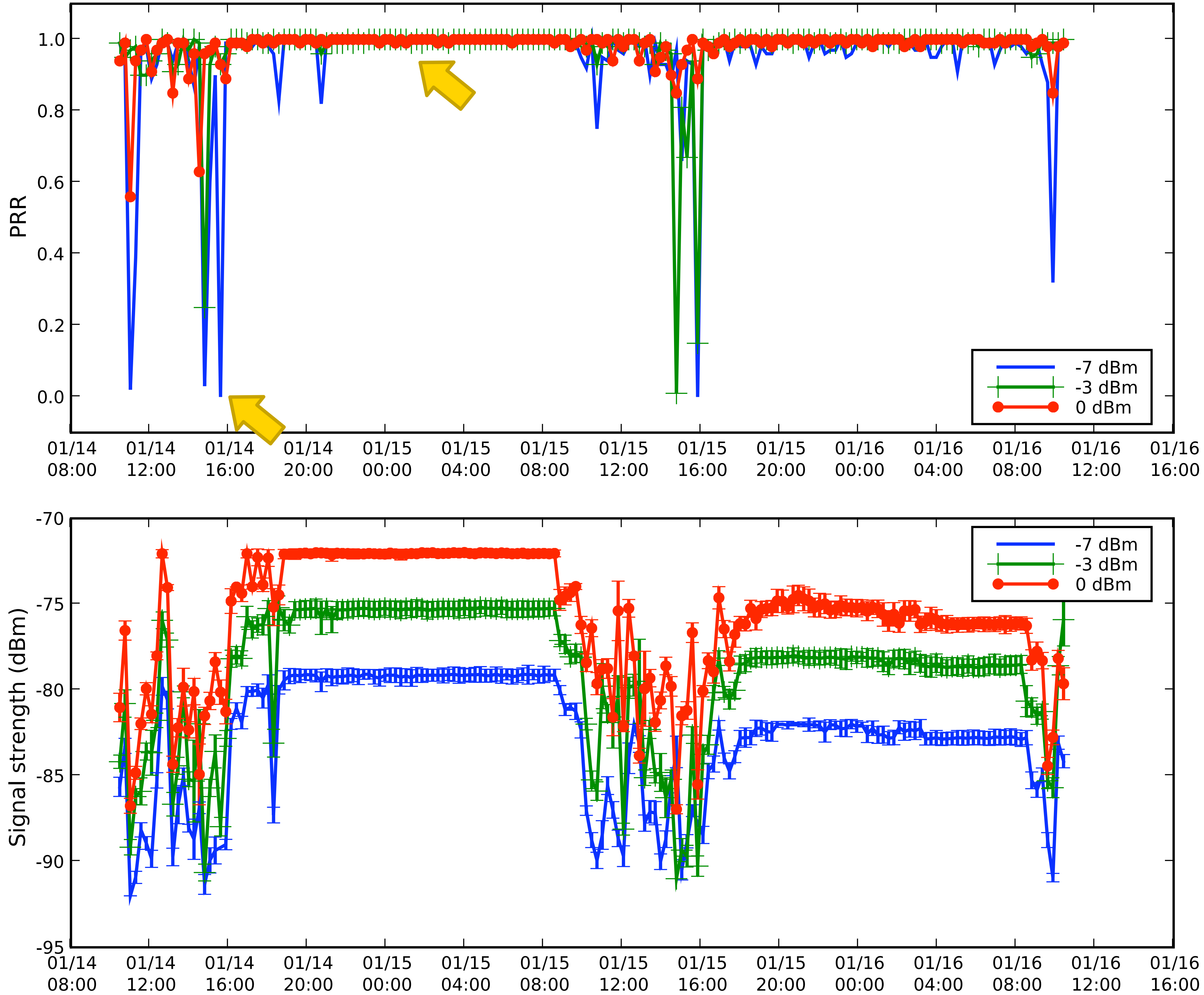
Is Dynamic Power Adaptation Necessary?



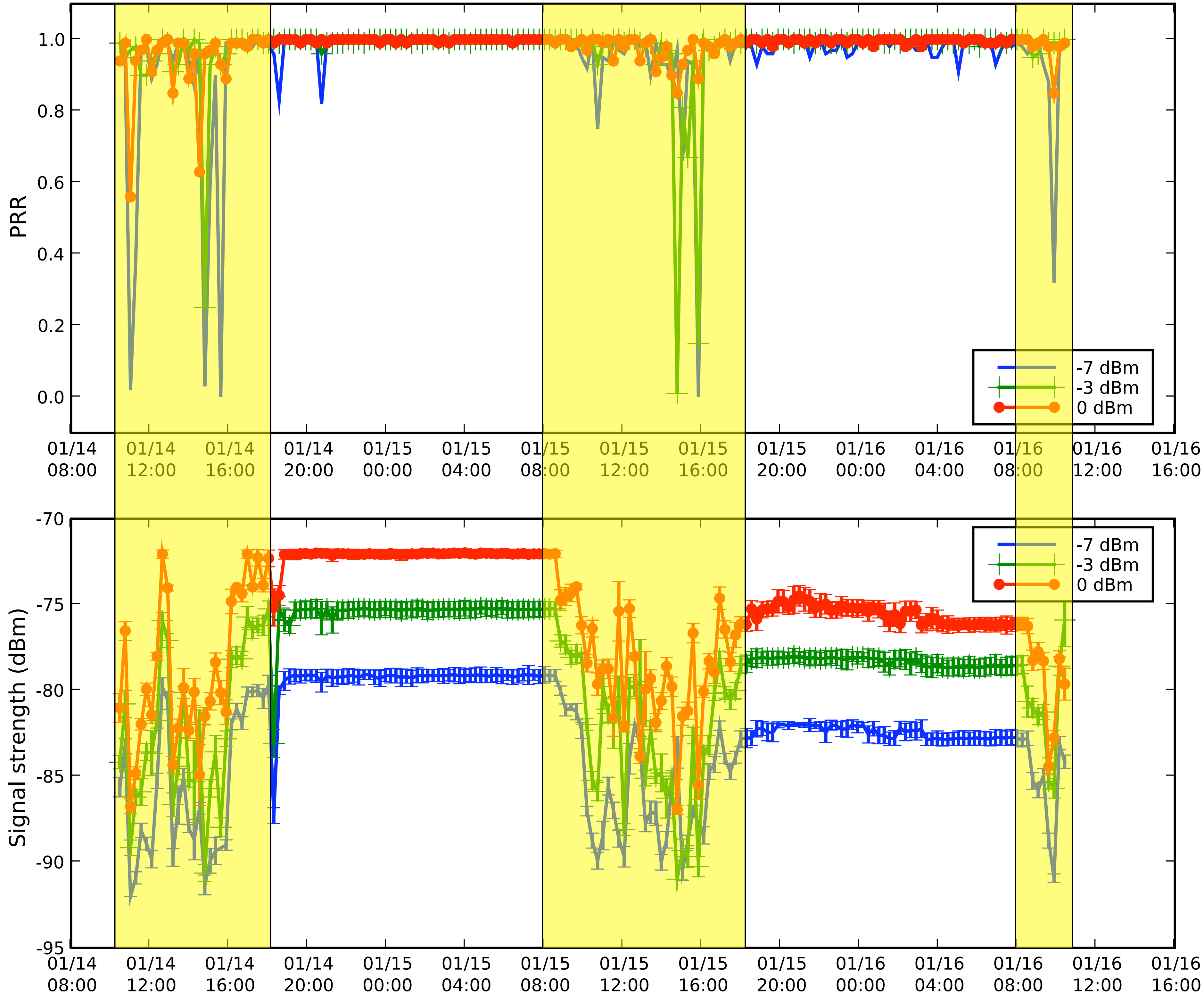
Is Dynamic Power Adaptation Necessary?



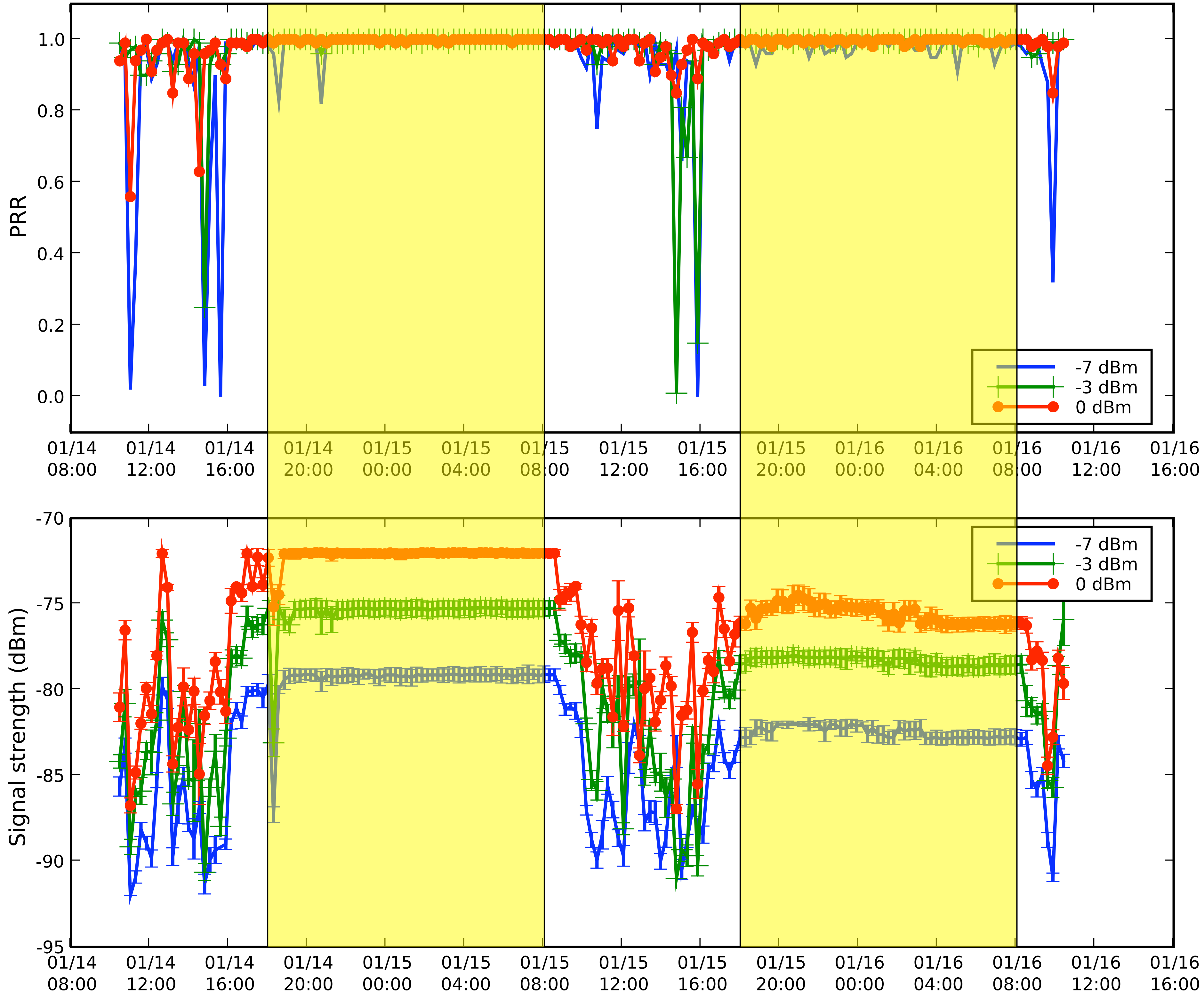
Is Dynamic Power Adaptation Necessary?



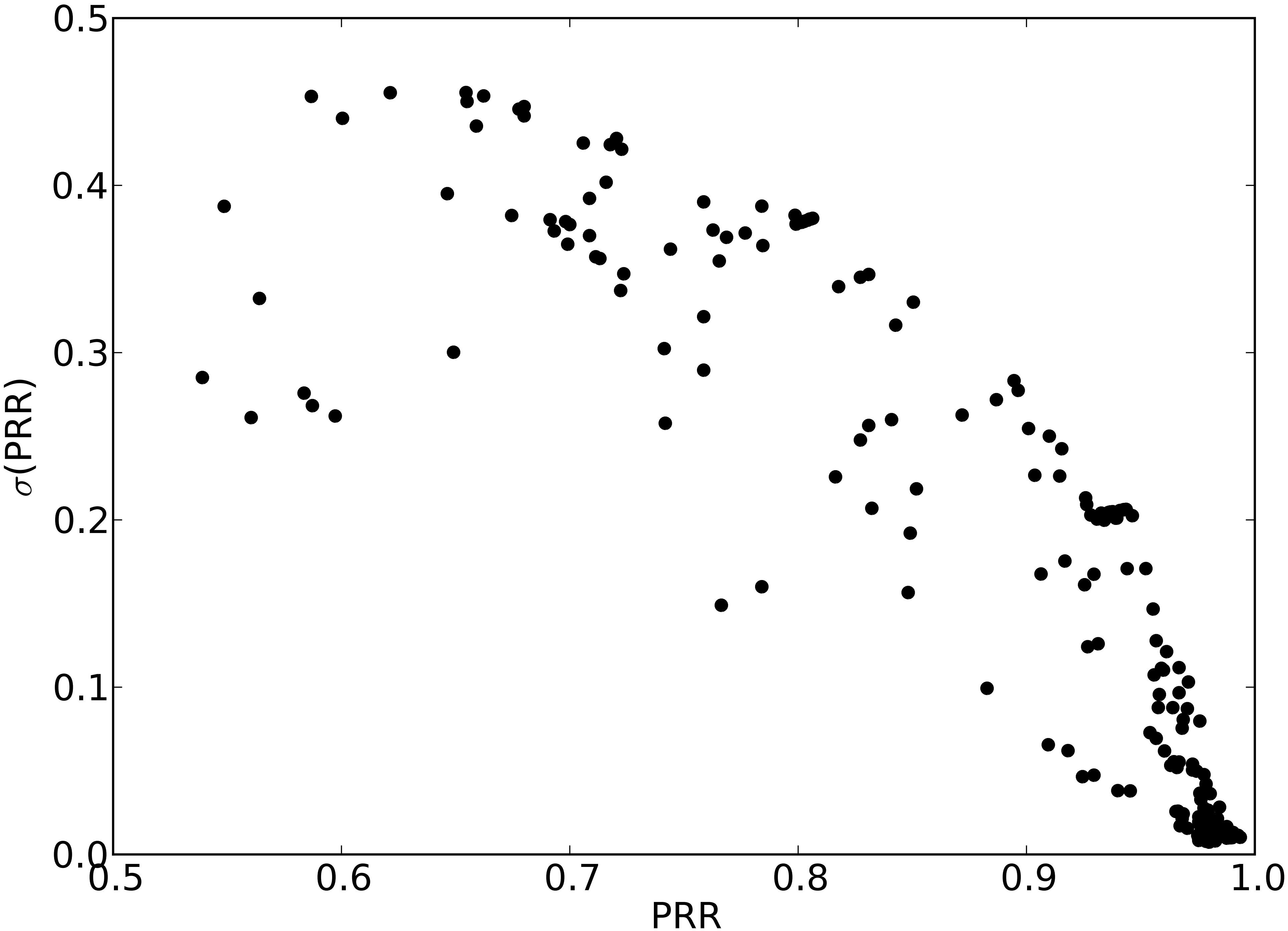
Is Dynamic Power Adaptation Necessary?



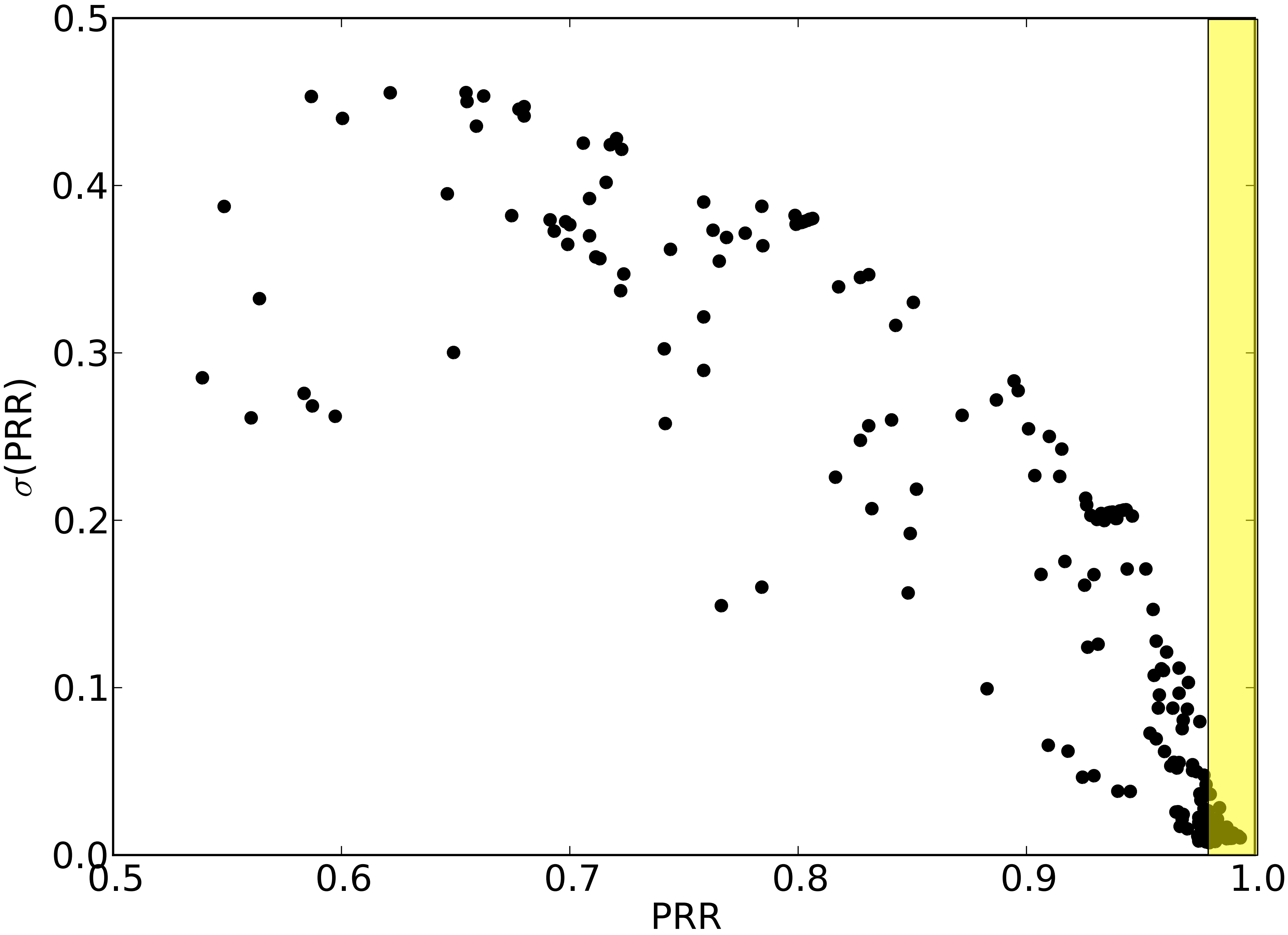
Is Dynamic Power Adaptation Necessary?



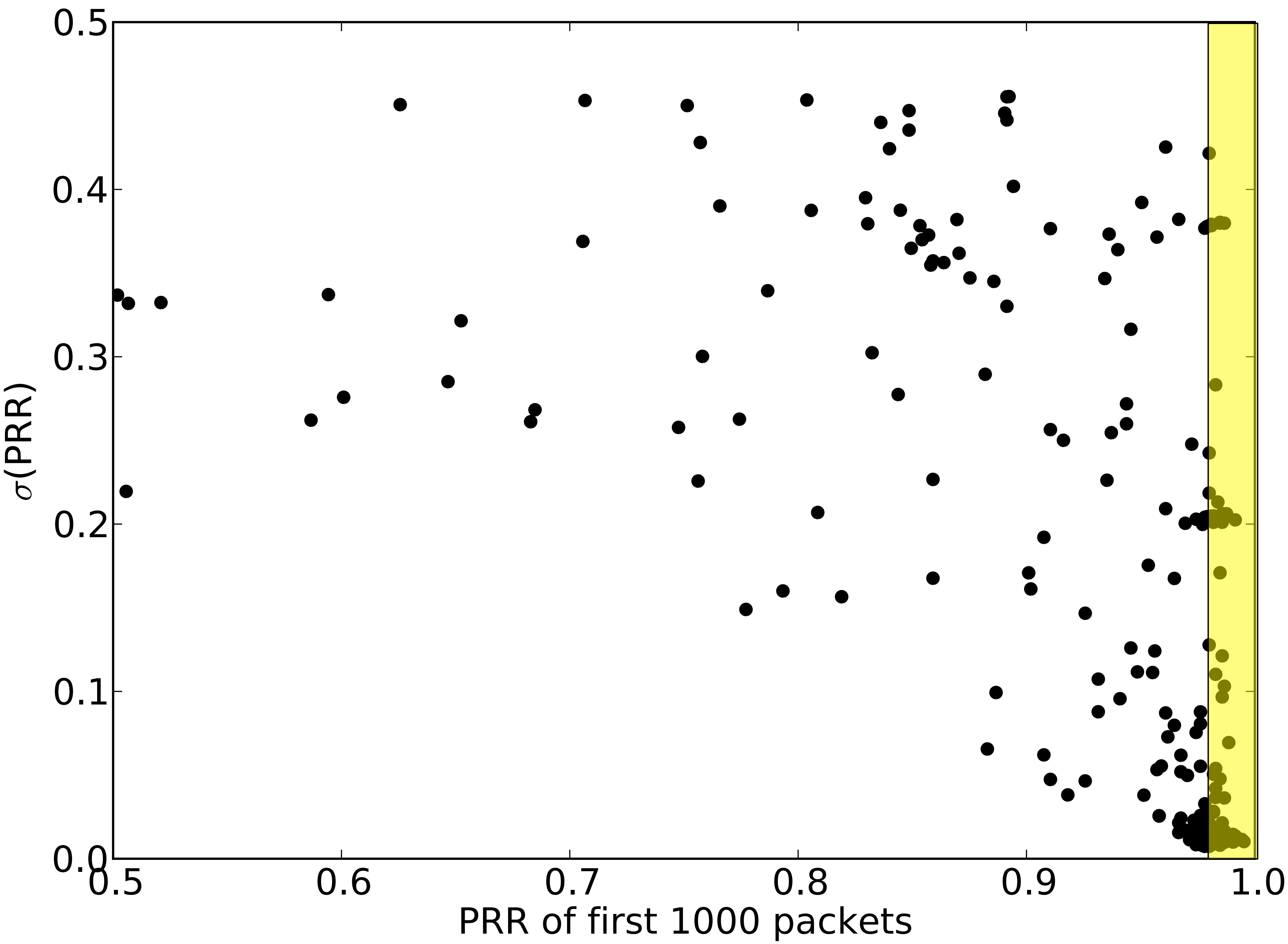
Can Link Stability Be Predicted?



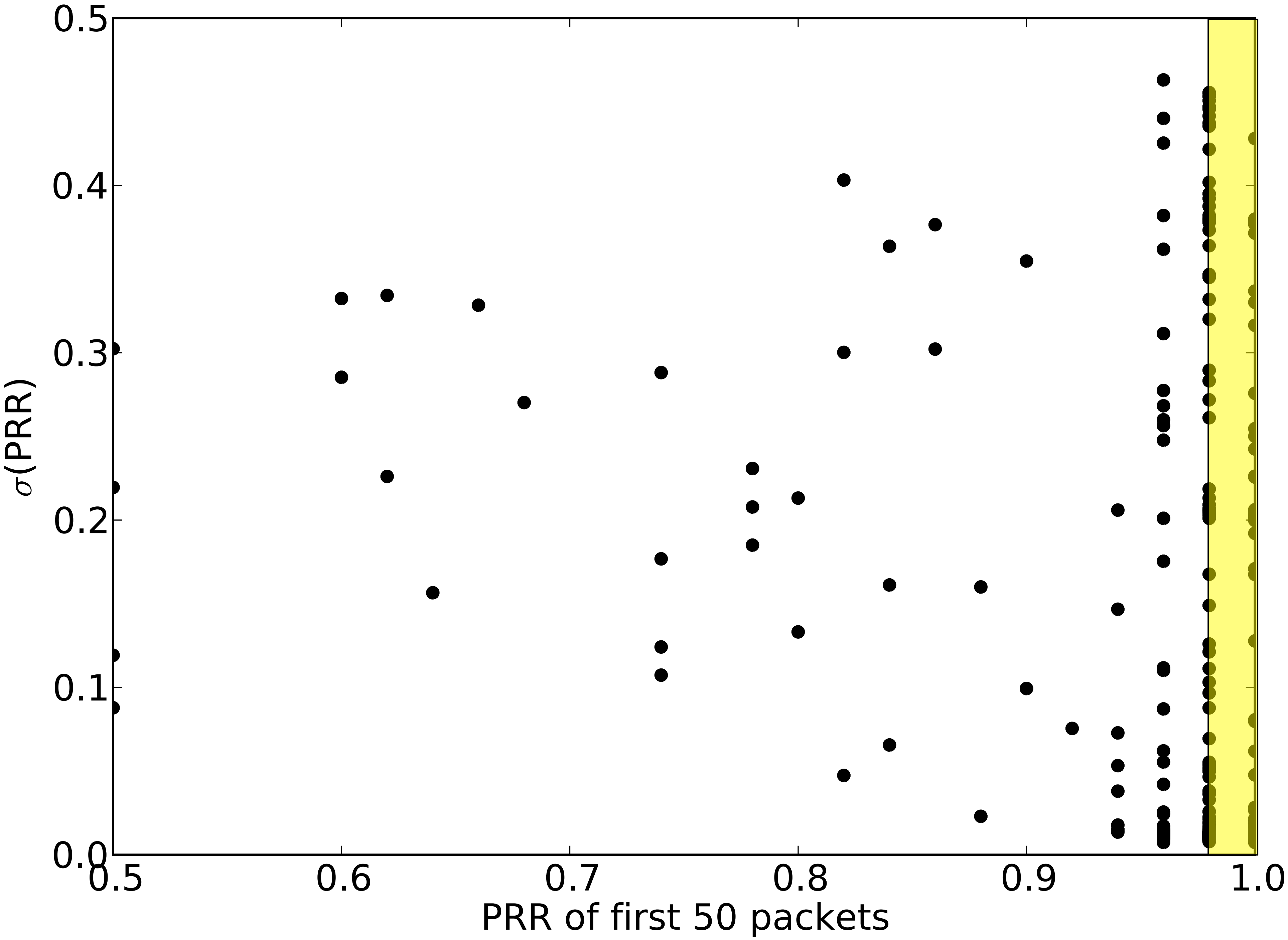
Can Link Stability Be Predicted?



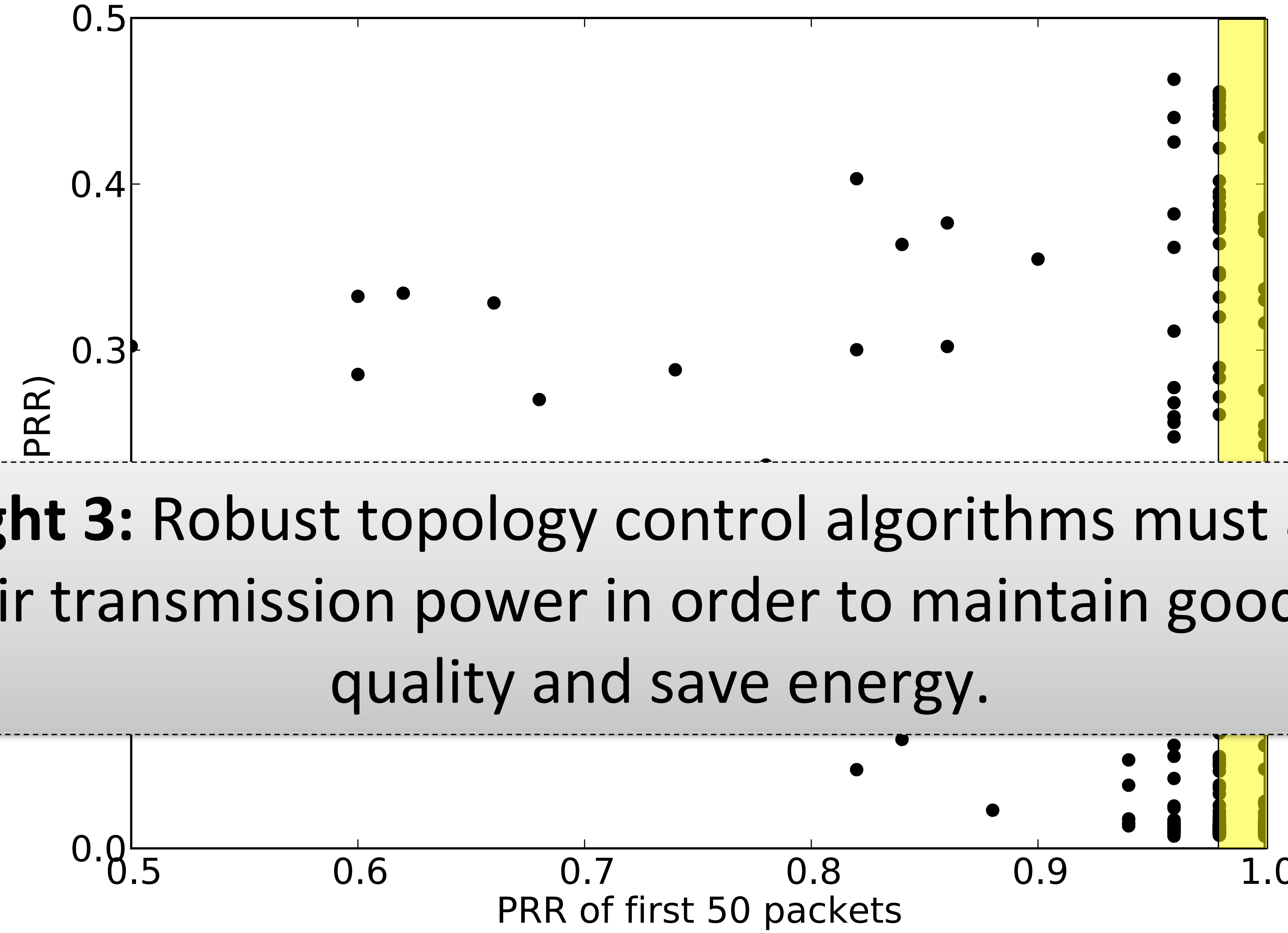
Can Link Stability Be Predicted?



Can Link Stability Be Predicted?



Can Link Stability Be Predicted?



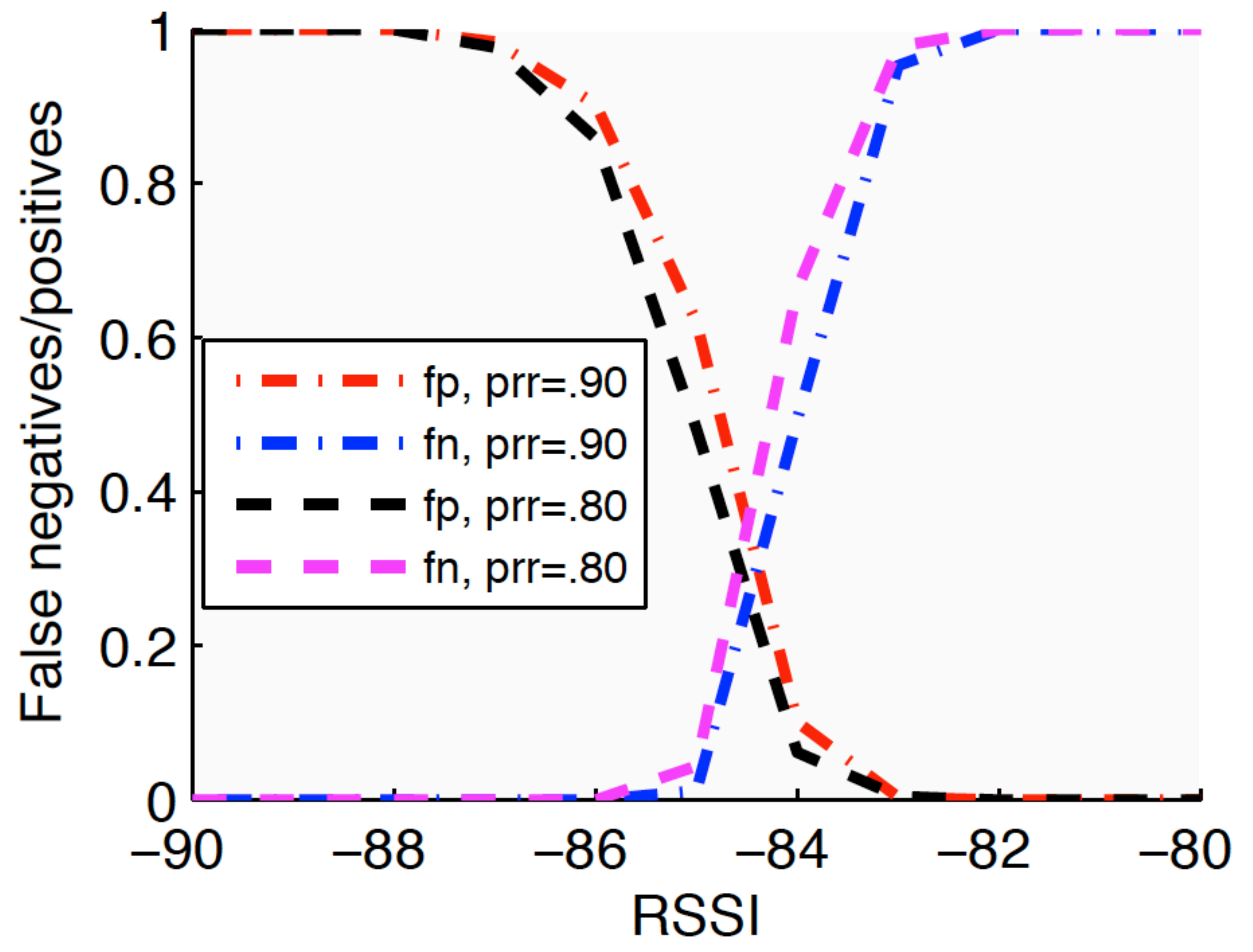
Insight 3: Robust topology control algorithms must adapt their transmission power in order to maintain good link quality and save energy.

Are Link Indicators Robust Indoors?

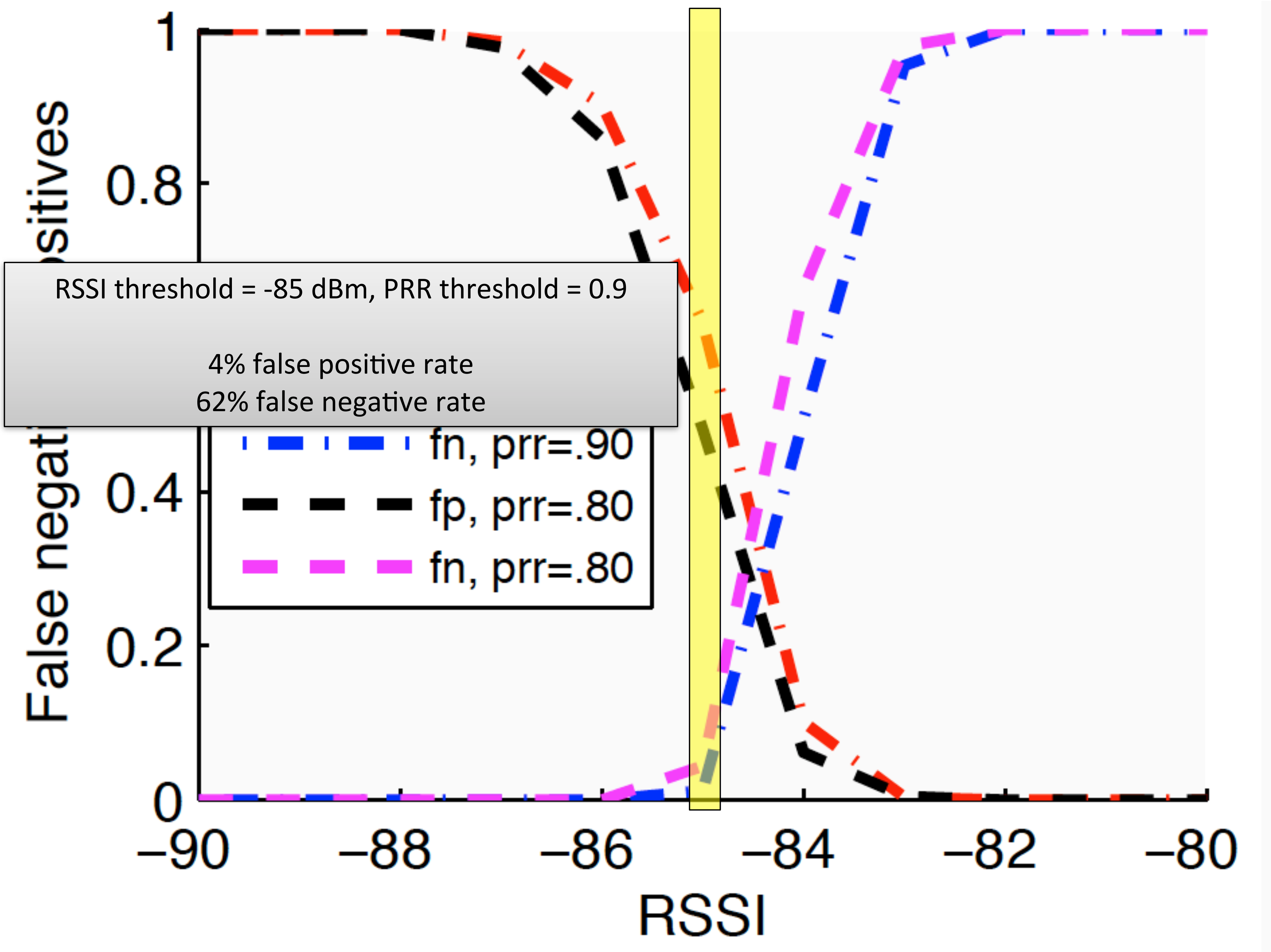
- **Two instantaneous metrics are often proposed as indicators of link reliability:**
  - Received Signal Strength Indicator (RSSI)
  - Link Quality Indicator (LQI)

- **Can you pick an RSSI *or* LQI threshold that predicts whether a link has high PRR or not?**

Are Link Indicators Robust Indoors?



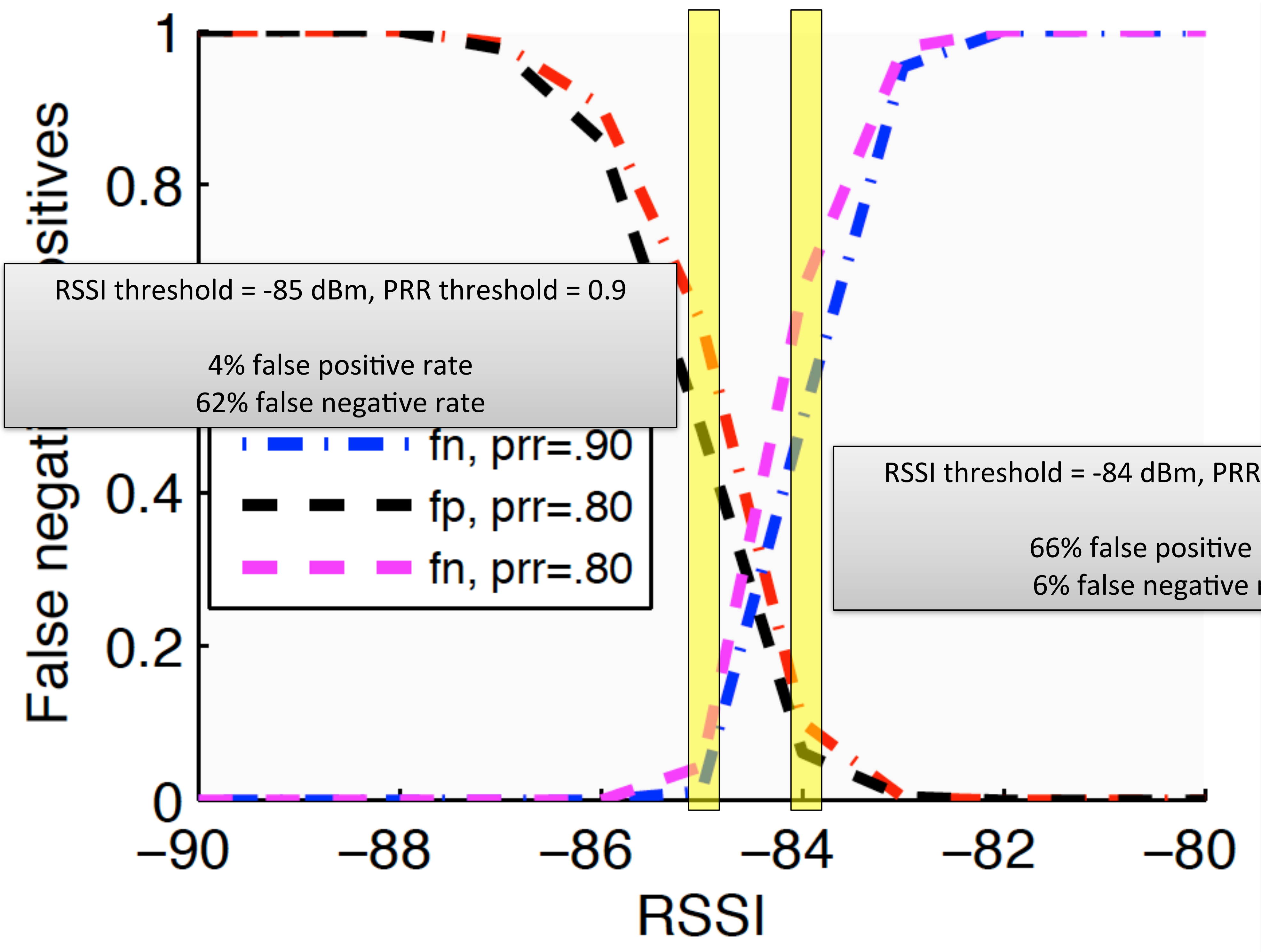
Are Link Indicators Robust Indoors?



RSSI threshold = -85 dBm, PRR threshold = 0.9

4% false positive rate
62% false negative rate

Are Link Indicators Robust Indoors?



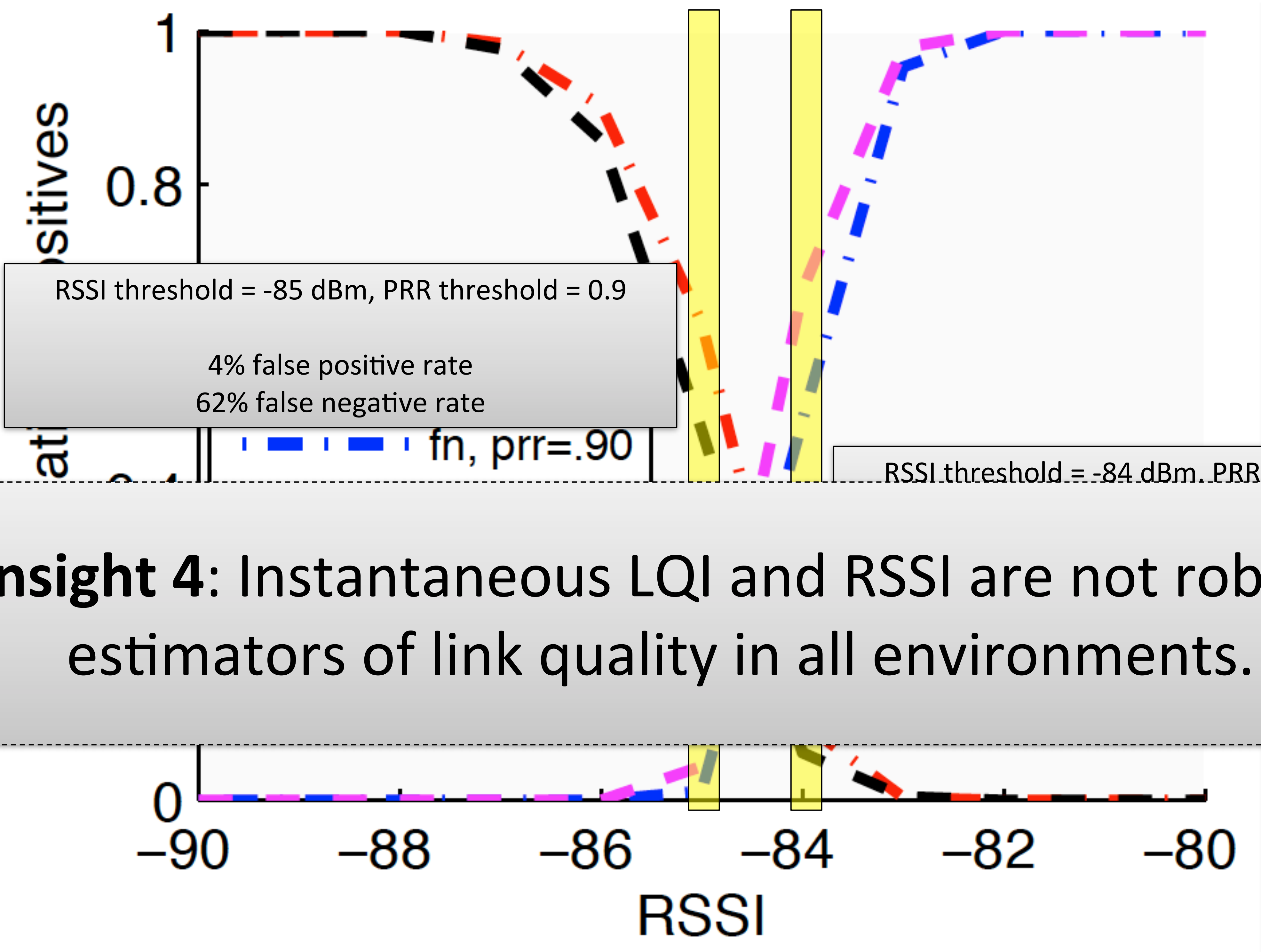
RSSI threshold = -85 dBm, PRR threshold = 0.9

4% false positive rate
62% false negative rate

RSSI threshold = -84 dBm, PRR threshold = 0.9

66% false positive rate
6% false negative rate

Are Link Indicators Robust Indoors?



RSSI threshold = -85 dBm, PRR threshold = 0.9

4% false positive rate
62% false negative rate

RSSI threshold = -84 dBm, PRR threshold = 0.9

Insight 4: Instantaneous LQI and RSSI are not robust estimators of link quality in all environments.

Summary of Insights

- Set transmission power on a per-link basis
- Avoid increasing contention under heavy network load
- Adapt transmission power online

- LQI and RSSI are not robust estimators of link quality in all environments

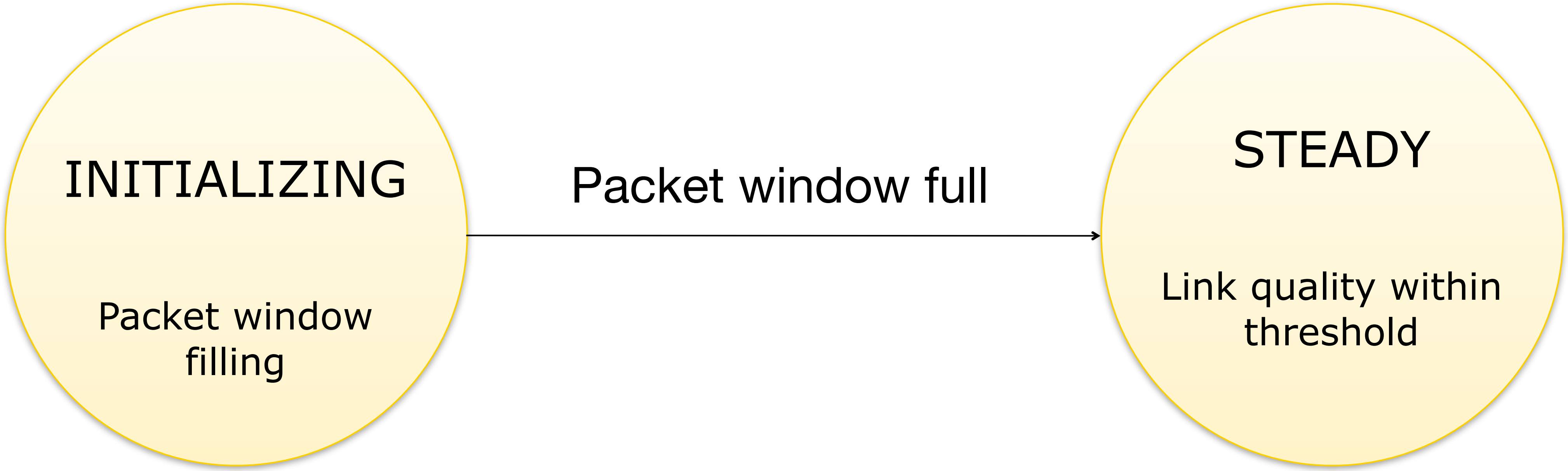
Adaptive and Robust Topology control (ART)

- **ART:**
  - Adjusts each link's power individually
  - Detects and avoids contention at the sender
  - Tracks link qualities in a sliding window, adjusting transmission power at a per-packet granularity
  - Does not rely on LQI or RSSI as link quality estimators

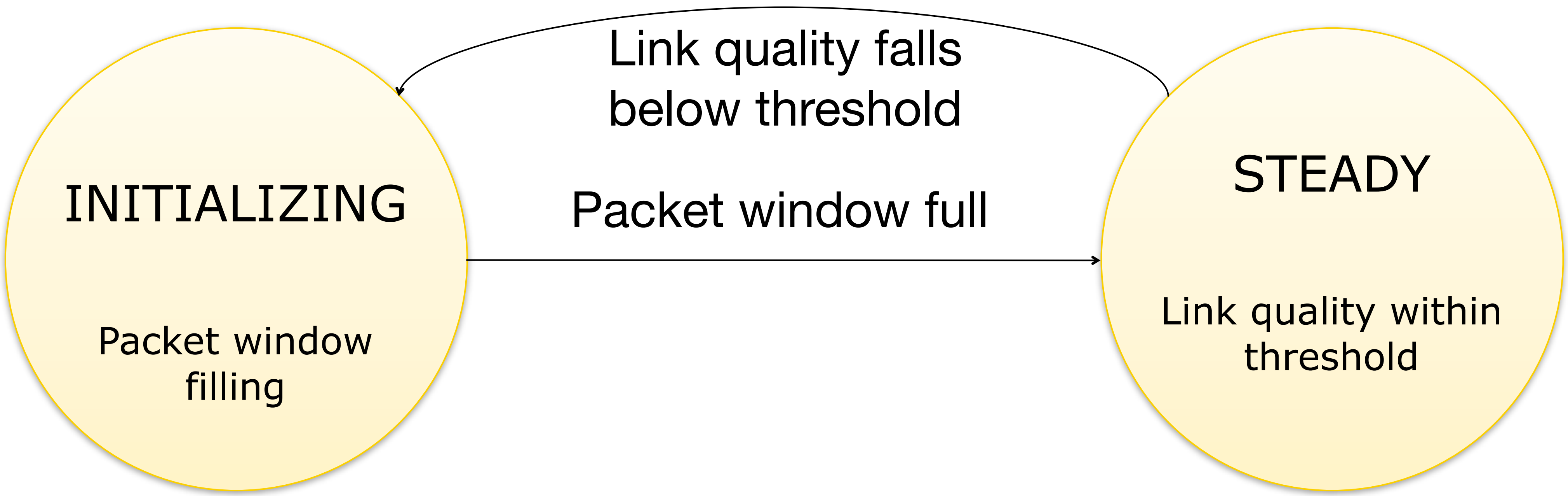
- **Is simple and lightweight by design**
  - 392 bytes of RAM, 1582 bytes of ROM, often zero network overhead

ART Algorithm Outline

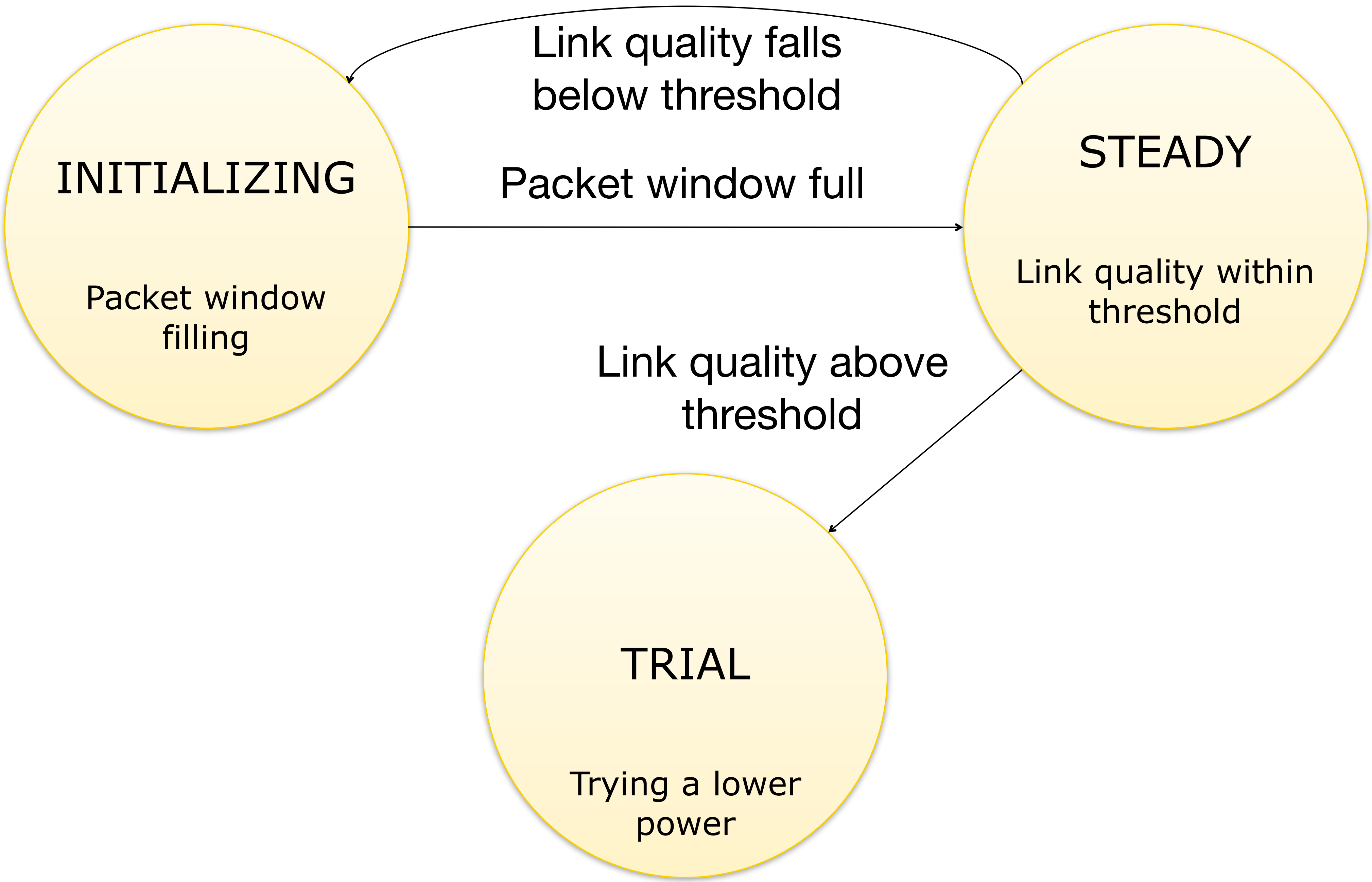
ART Algorithm Outline



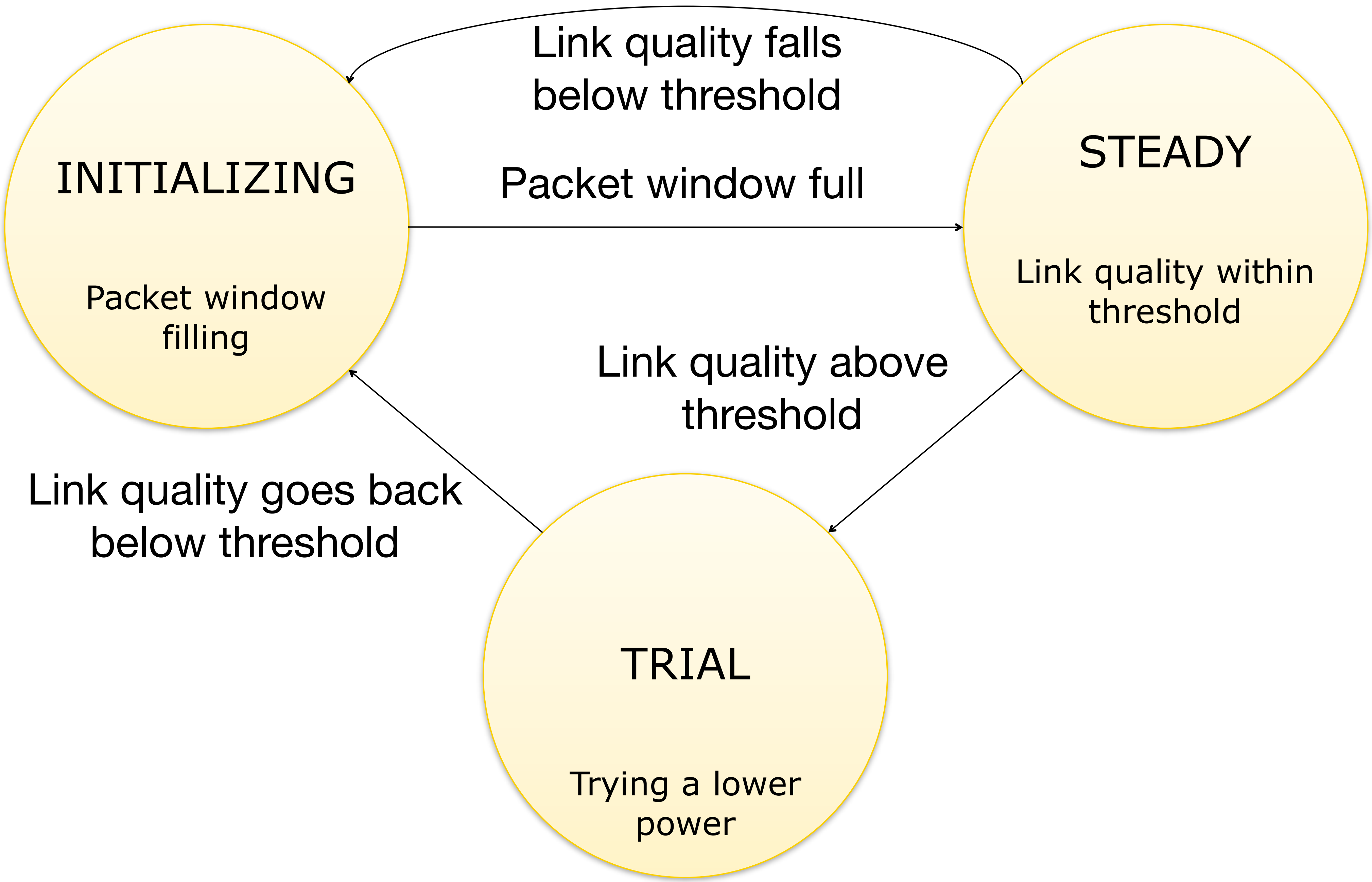
ART Algorithm Outline



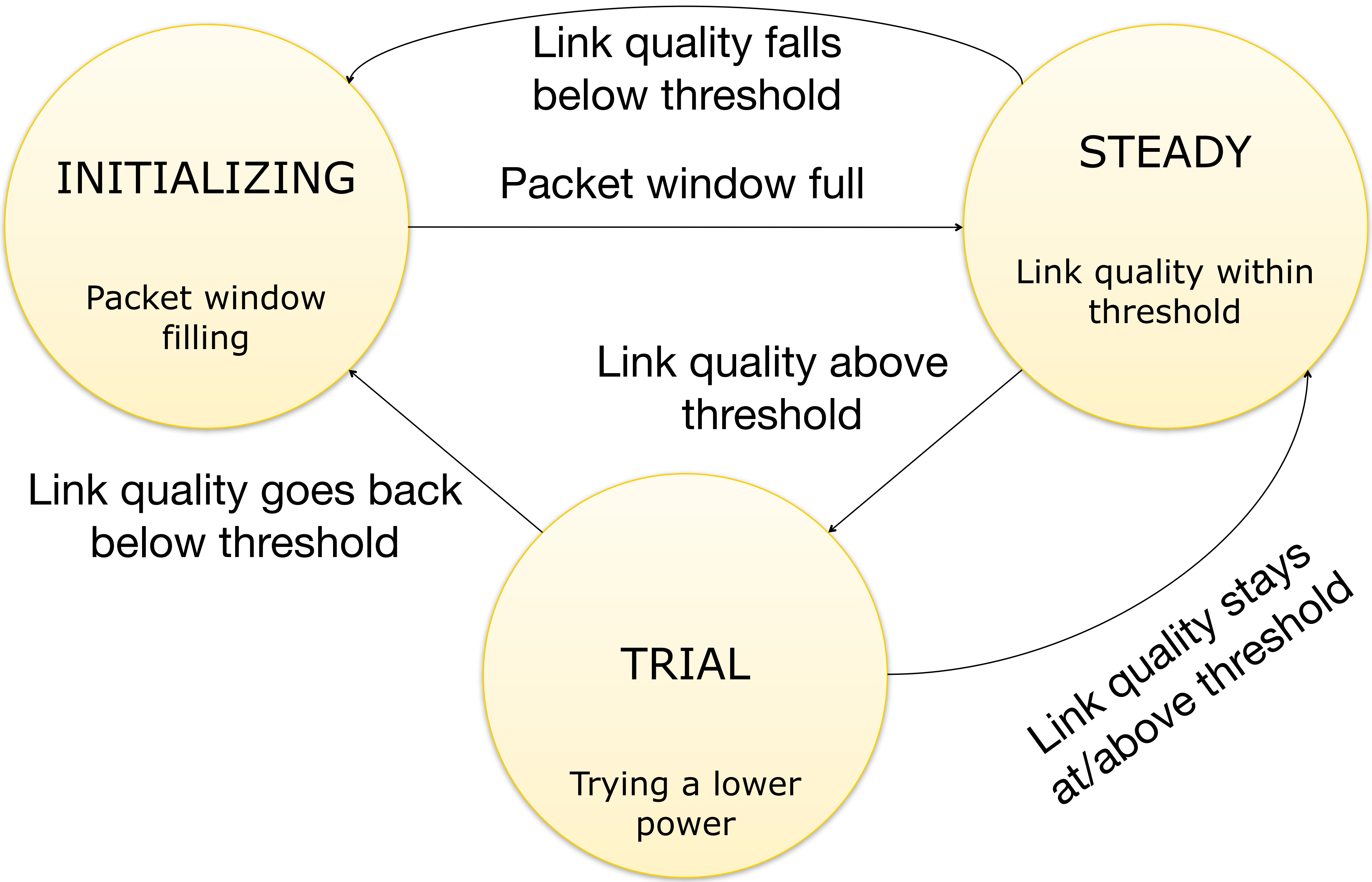
ART Algorithm Outline



ART Algorithm Outline



ART Algorithm Outline



Adaptive and Robust Topology control (ART)

Initializing

Power Level = 7

w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

Initializing

Power Level = 7

w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

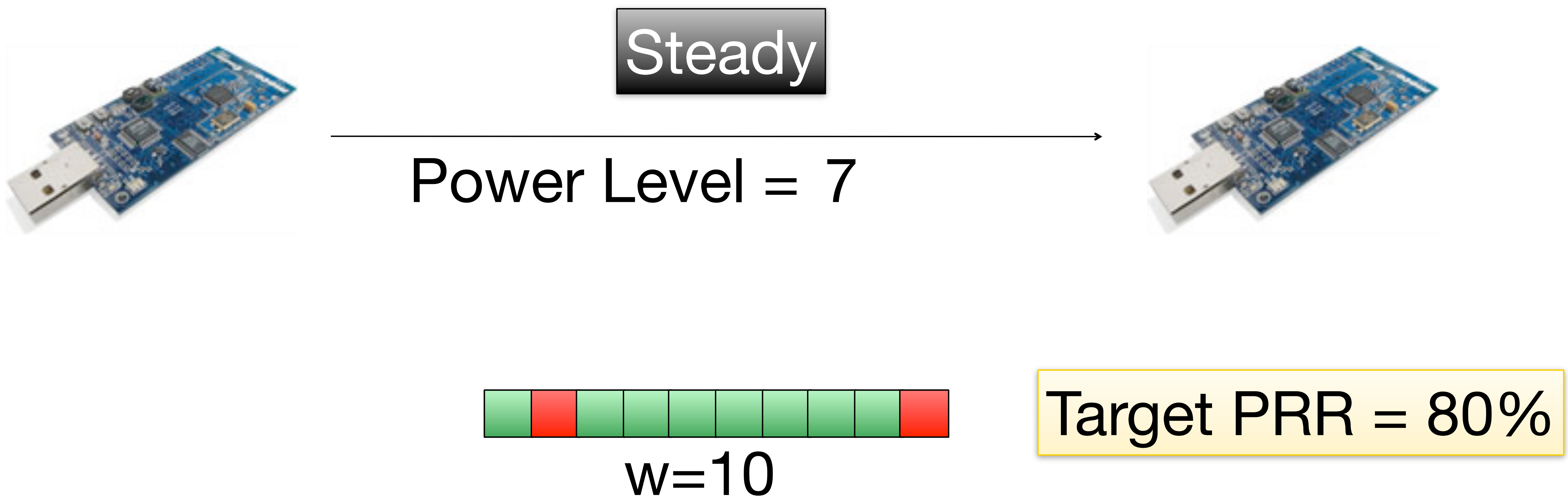
Initializing

Power Level = 7

w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)



Adaptive and Robust Topology control (ART)

Steady

Power Level = 7

w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

Trial

Power Level = 7

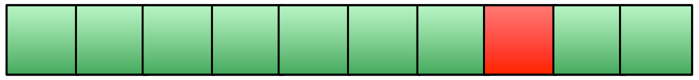
w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

Trial

Power Level = ~~7~~6?



w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

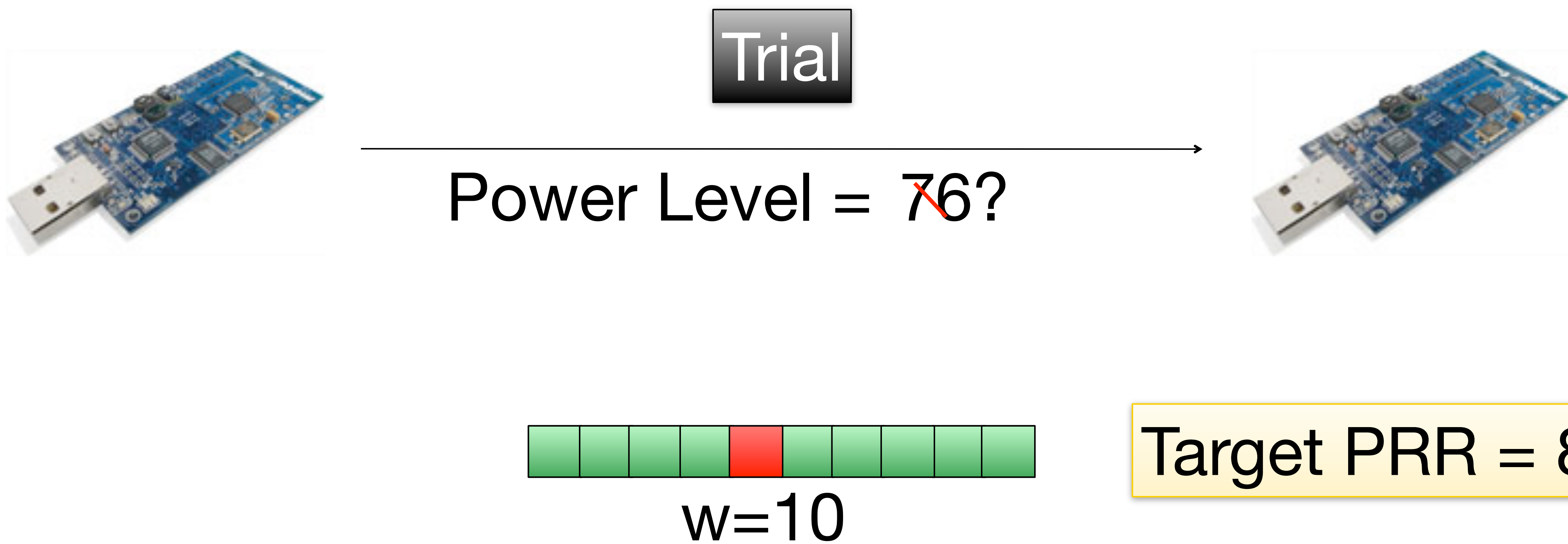
Trial

Power Level = ~~7~~6?

w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)



Adaptive and Robust Topology control (ART)

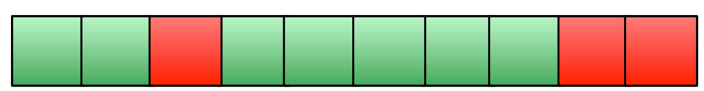
Power Level = ~~7~~6~~?~~6

w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

Power Level = ~~7~~6~~?~~6

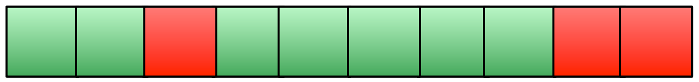


w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

Power Level = ~~7~~ ~~6~~ ~~?~~ ~~6~~ 7



w=10

Target PRR = 80%

Adaptive and Robust Topology control (ART)

Initializing

Power Level = ~~7~~6~~?~~~~6~~7

w=10

Target PRR = 80%

Selecting Bounds

- **PRR threshold *p* is converted into bound on TX failures**

$$d = (1 - p) \cdot w$$

- **What if we want to try out a lower power setting? One bound *d* not sufficient**
  - Link quality is often bimodal when switching power settings
  - If *d - 1* failures happen in steady state, and all transmissions fail in trial state, then PRR would be lower than *p*

- **Pick a tighter bound** $d' = \frac{2p}{p+1} \cdot w$ **for moving in and out of trial state**

Avoiding Contention

- **Naïve policy: When link quality falls below threshold, then increase power level**
- **But what if this makes things worse?**
  - Remember, higher power → more contention

- **Initially increase power when link quality is too low, but remember how many failures were recorded in window**
- **If # of failures is worse than last time, then flip direction and decrease power instead**

Implementation Details

- **Implemented using TinyOS 2.1 CVS on top of the MAC Layer Architecture [Klues 07]**
- **Sits below routing layer -> has been tested with CTP**
- **Deployed on Jolley Hall testbed for three experiments:**
  - Link-level
  - High contention
  - Data collection (not presented here)

Link-Level Performance

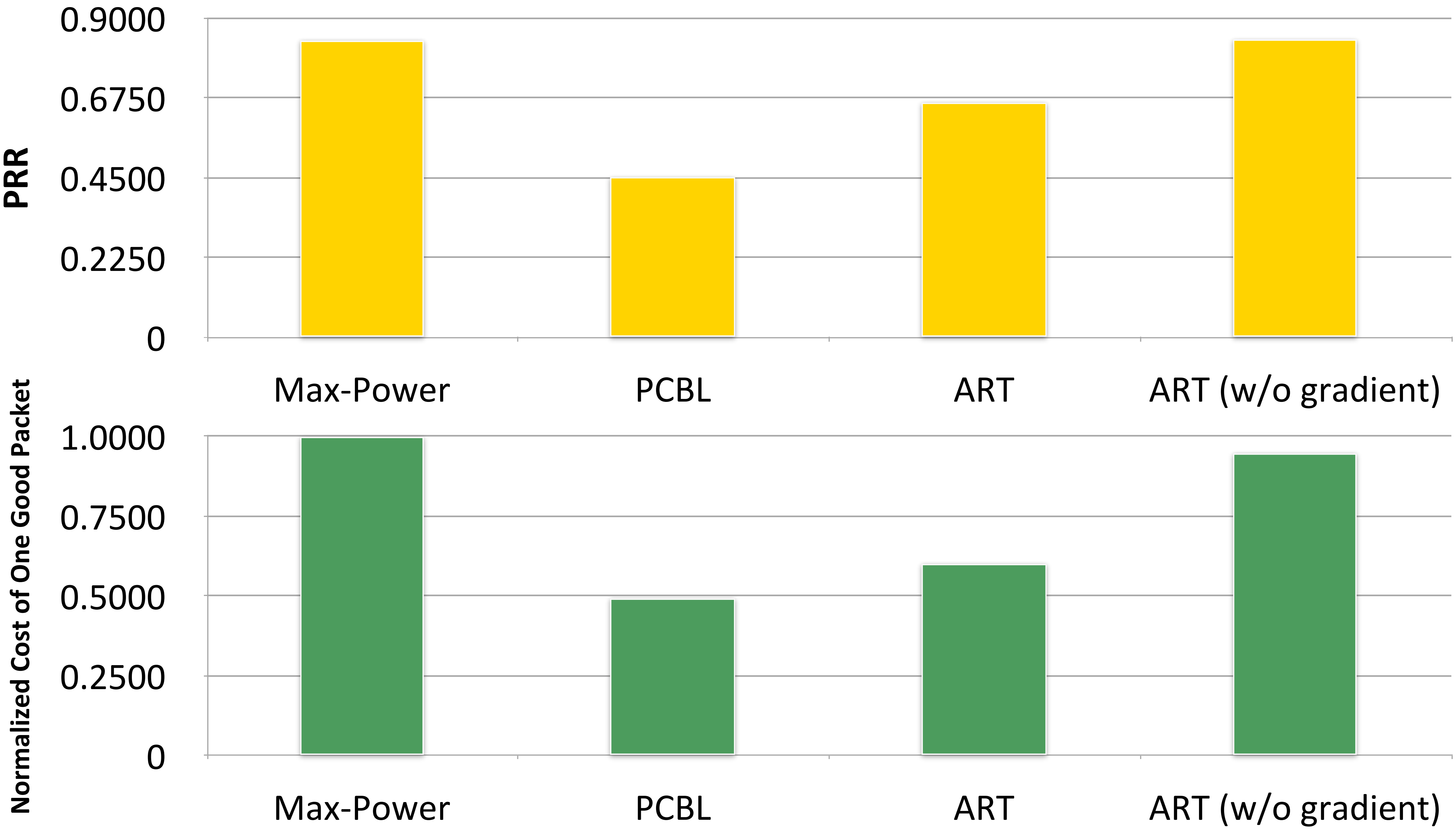
- Selected 29 links at random from 524 detected in empirical study
- Transmitted packets round-robin over each link in batches of 100, cycled for 24 hours (15000 packets/link)

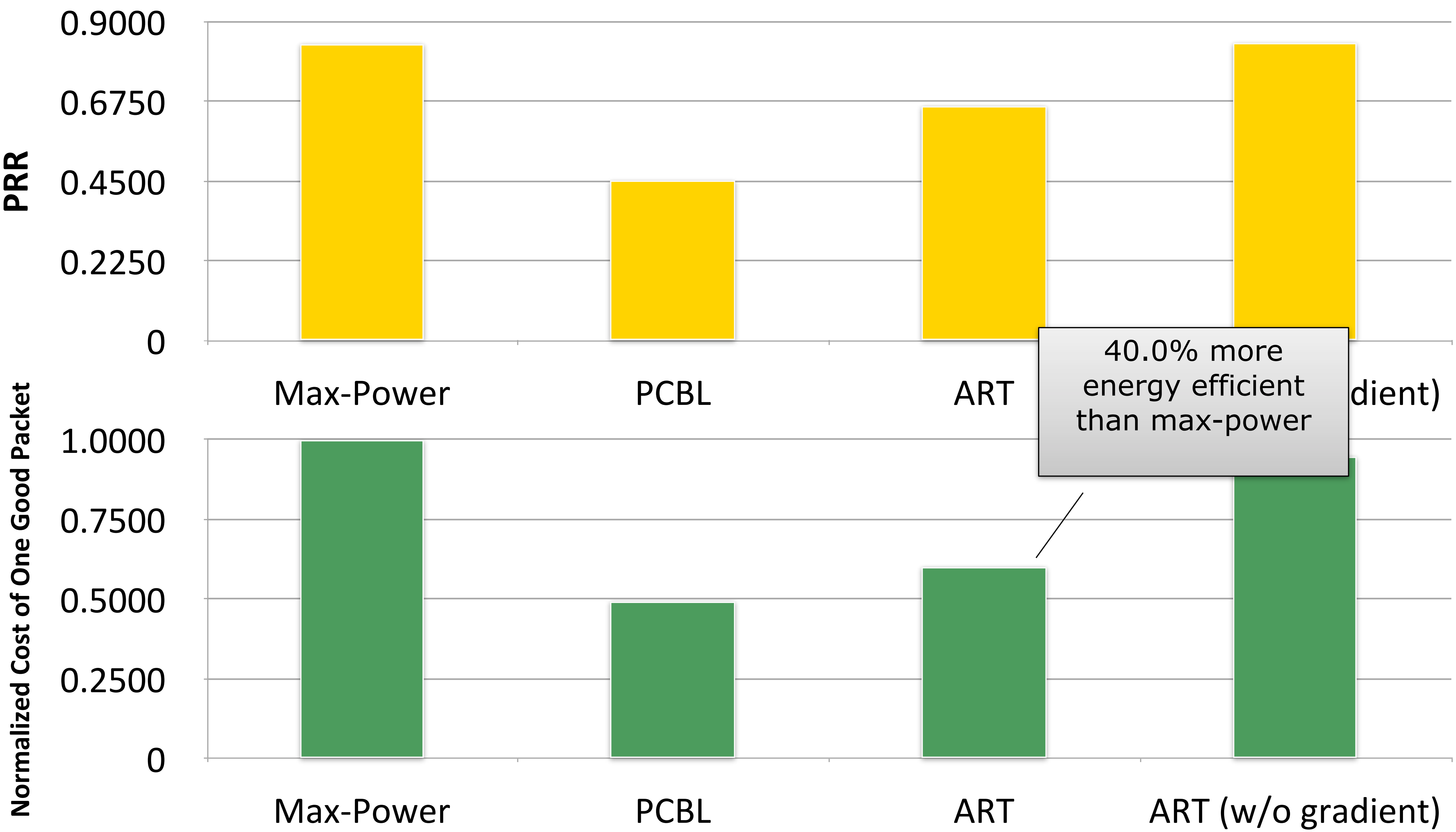
	PRR	Avg. Current
Max Power	56.7% (σ = 2.5%)	17.4 mA (σ = 0)
ART	58.3% (σ = 2.1%)	14.9 mA (σ = 0.32)

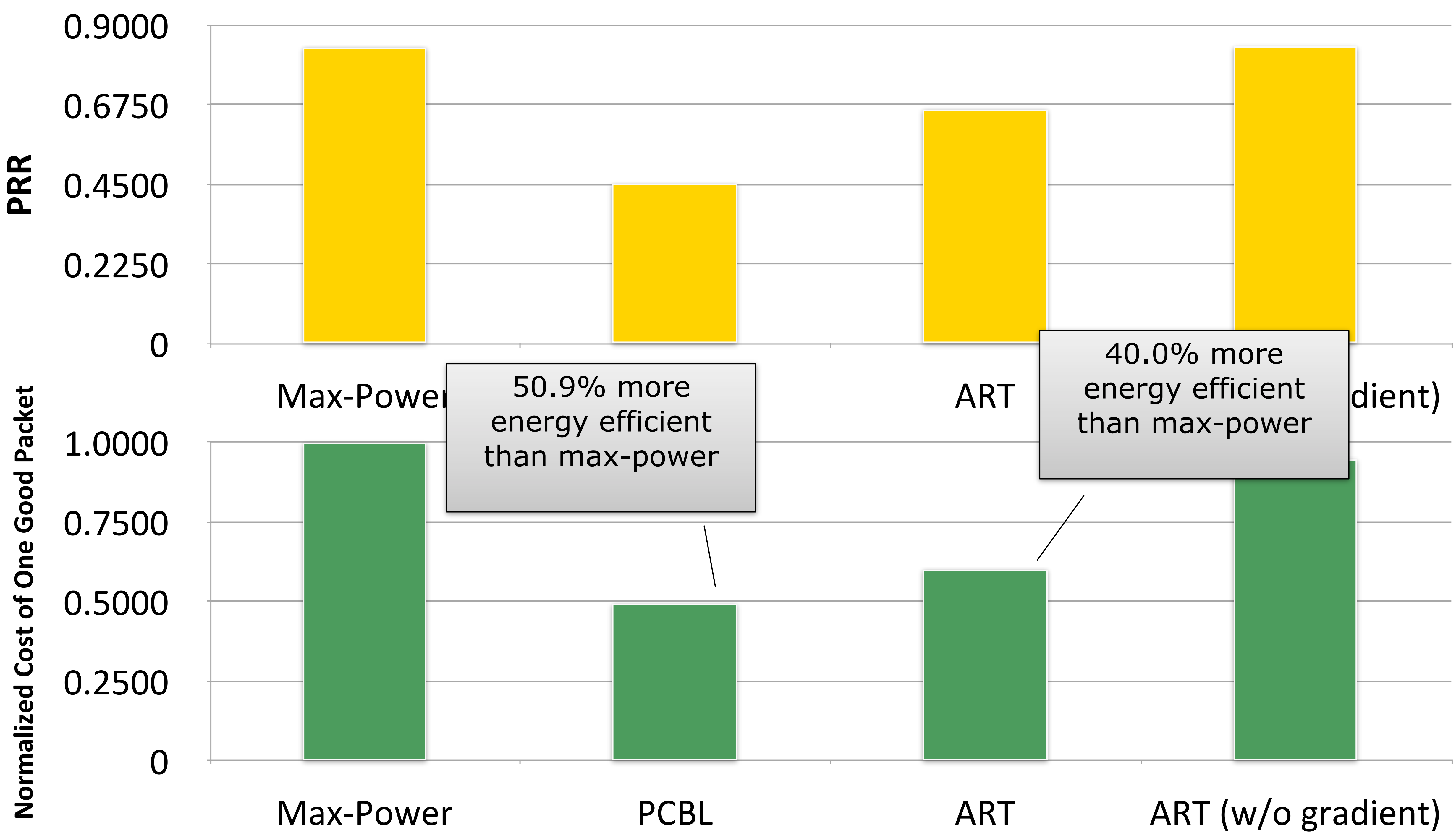
Handling High Contention

- Select 10 links at random from testbed
- Send packets over all 10 links simultaneously as possible (batches of 200 packets for 30 min.)

- Compare again against PCBL and max-power
- Also run ART without “gradient” optimization to isolate its effect on PRR

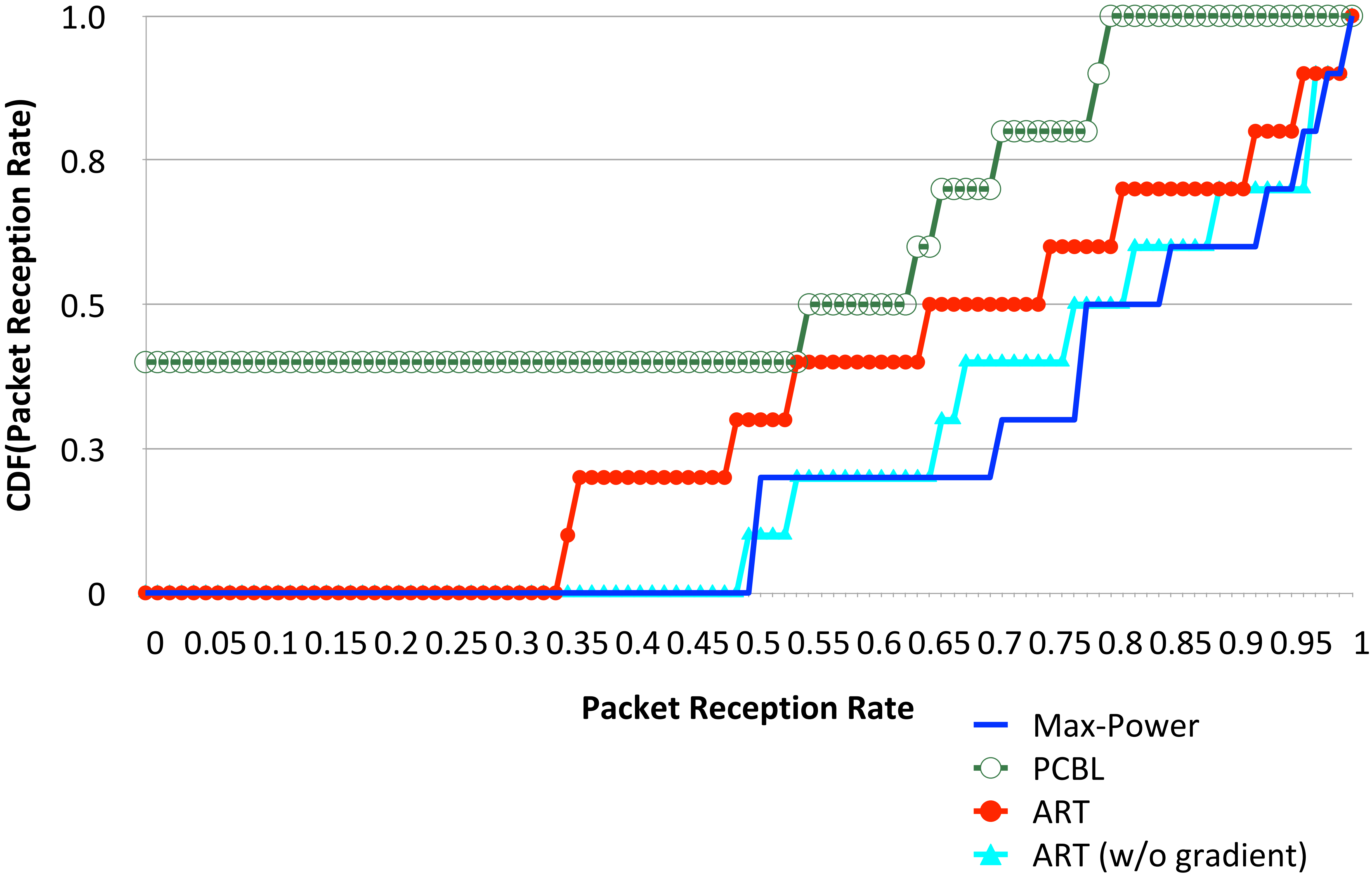

PRR
0.9000
0.6750
0.4500
0.2250
0
Max-Power
PCBL
ART
ART (w/o gradient)
Normalized Cost of One Good Packet
1.0000
0.7500
0.5000
0.2500
0
Max-Power
PCBL
ART
ART (w/o gradient)


PRR
0.9000
0.6750
0.4500
0.2250
0
Max-Power
PCBL
ART
dient)
40.0% more energy efficient than max-power
Normalized Cost of One Good Packet
1.0000
0.7500
0.5000
0.2500
0
Max-Power
PCBL
ART
ART (w/o gradient)

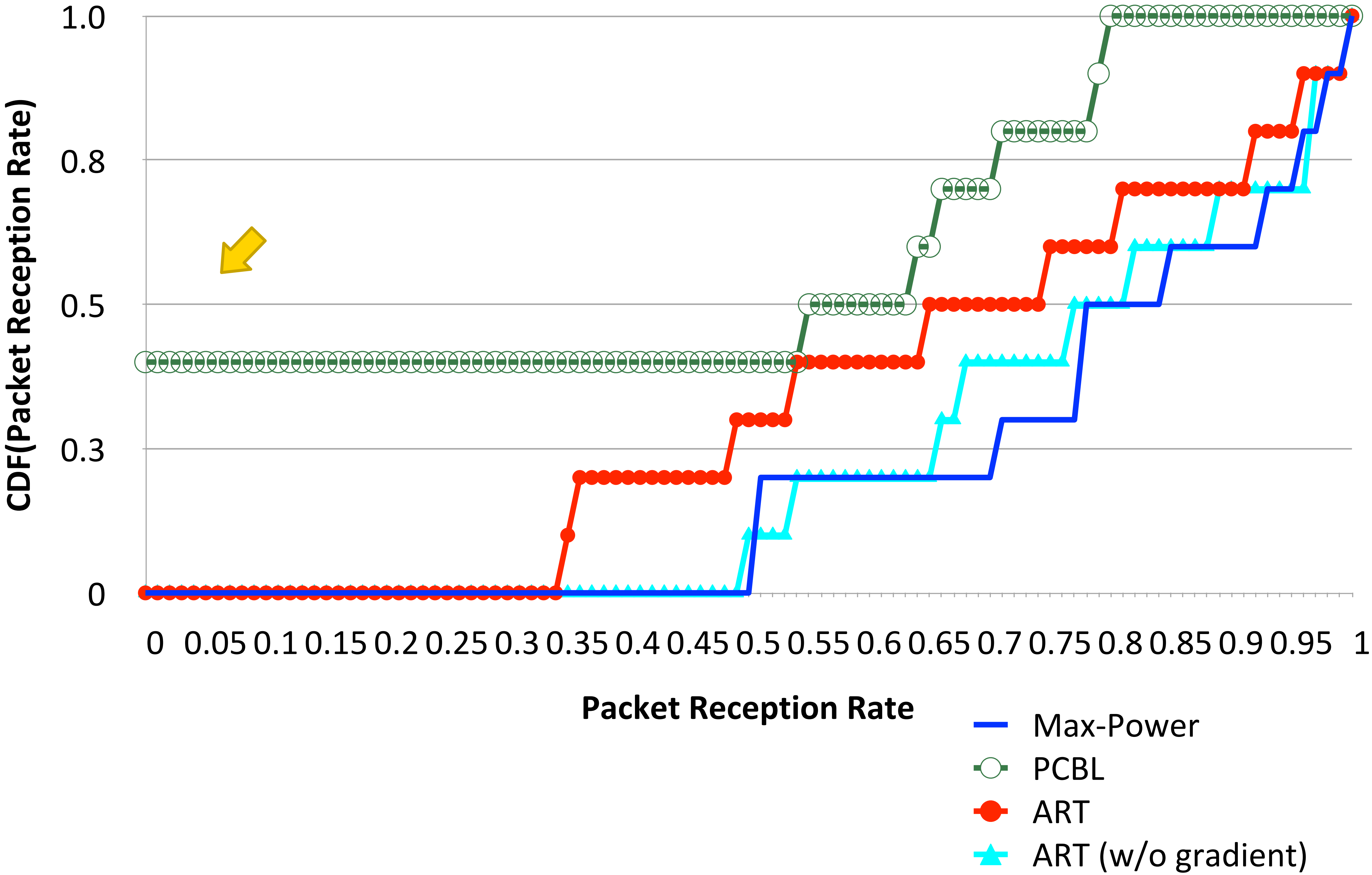


PRR
0.9000
0.6750
0.4500
0.2250
0
Max-Power
ART
dient)
50.9% more energy efficient than max-power
40.0% more energy efficient than max-power
Normalized Cost of One Good Packet
1.0000
0.7500
0.5000
0.2500
0
Max-Power
PCBL
ART
ART (w/o gradient)

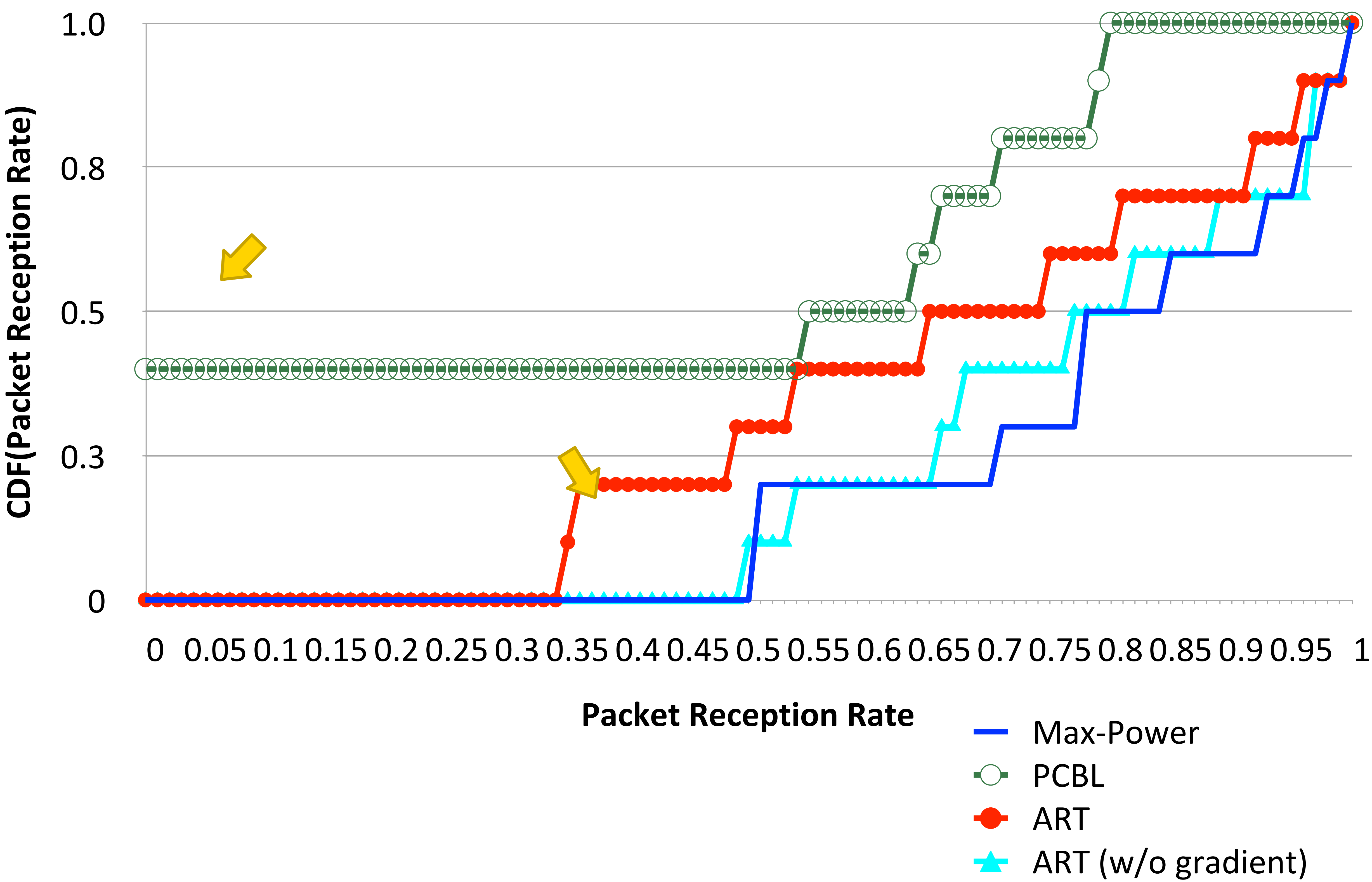
Handling High Contention



Handling High Contention



Handling High Contention



Conclusions

- **Our empirical study shows important new negative results:**
  - RSSI and LQI are not always robust indicators of link quality indoors
  - Profiling links even for several hours is insufficient for identifying good links
  - Inherent assumptions of existing protocols!
- **ART is a new topology control algorithm which is robust in complex indoor environments**
- **ART achieves better energy efficiency than max-power without bootstrapping or link starvation**