# Efficient Relaying for Cognitive Radios

Dr. Wei Chen
Dept. EE, Tsinghua University
State Key Lab on Microwave & Digital Communications
Tsinghua National Lab for Information Science & Technology

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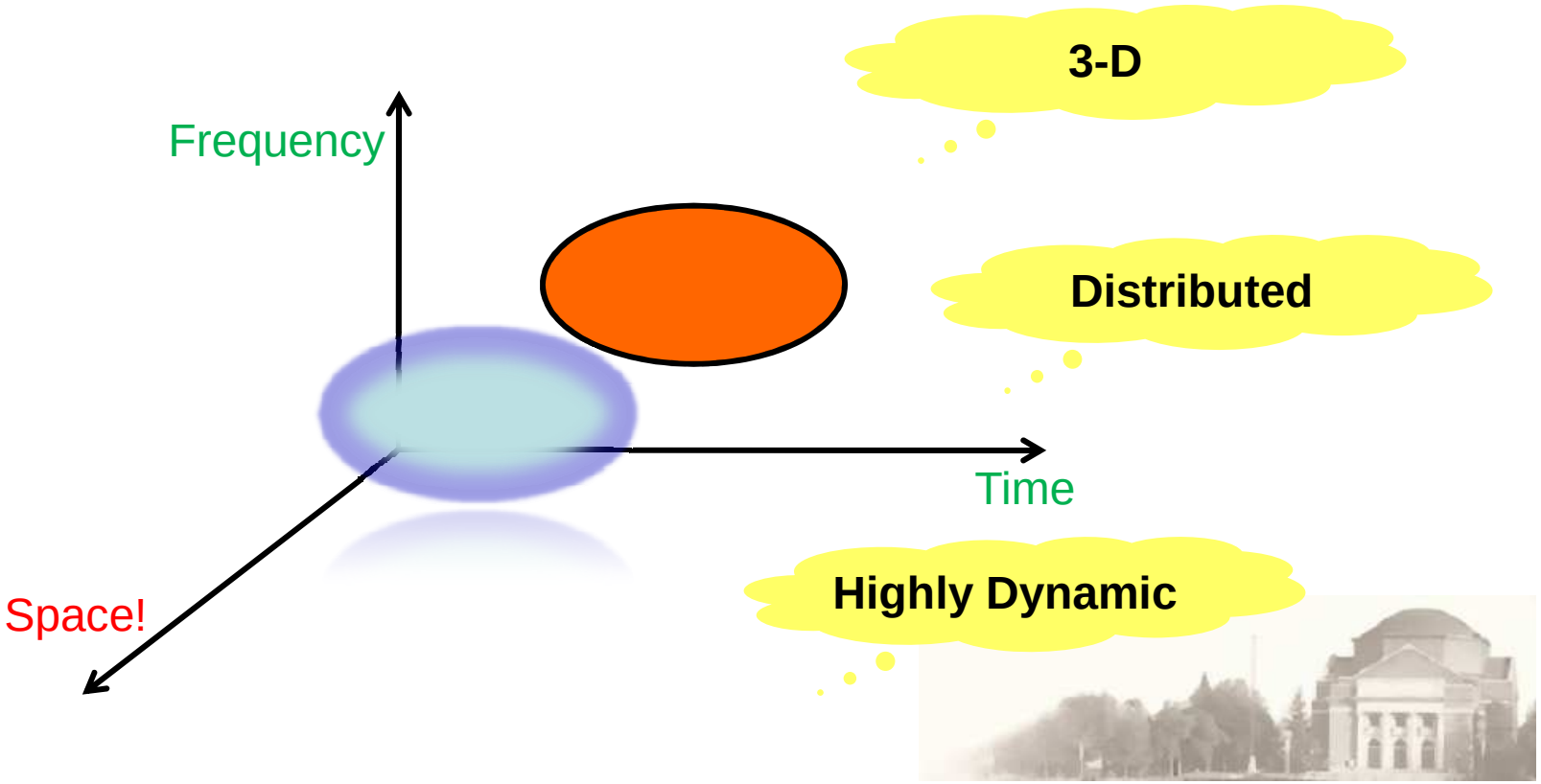
# CR @ Tsinghua University

- Understanding and Utilization of 3-D (Time, Frequency, Space) Spectrum Holes
  - NSFC Key Project Group (10 Million)
  - NSFC Young Investigator Project
  - Ministry of Education Project
  - Beijing NSF Key Project (REM Measurement)
  - Industrial Projects
  - …

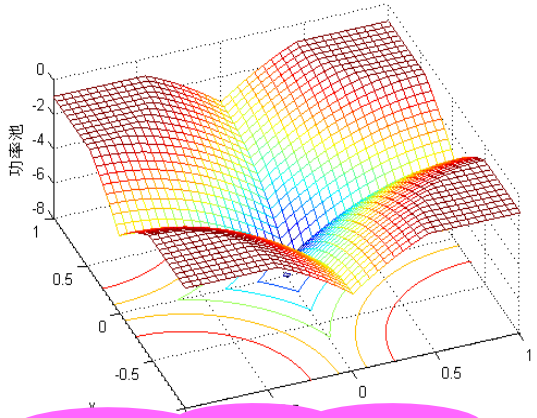
# Understanding Spectrum Holes

- Cognitive Radio is designed to make use of spectrum holes!
- But what is a spectrum hole?



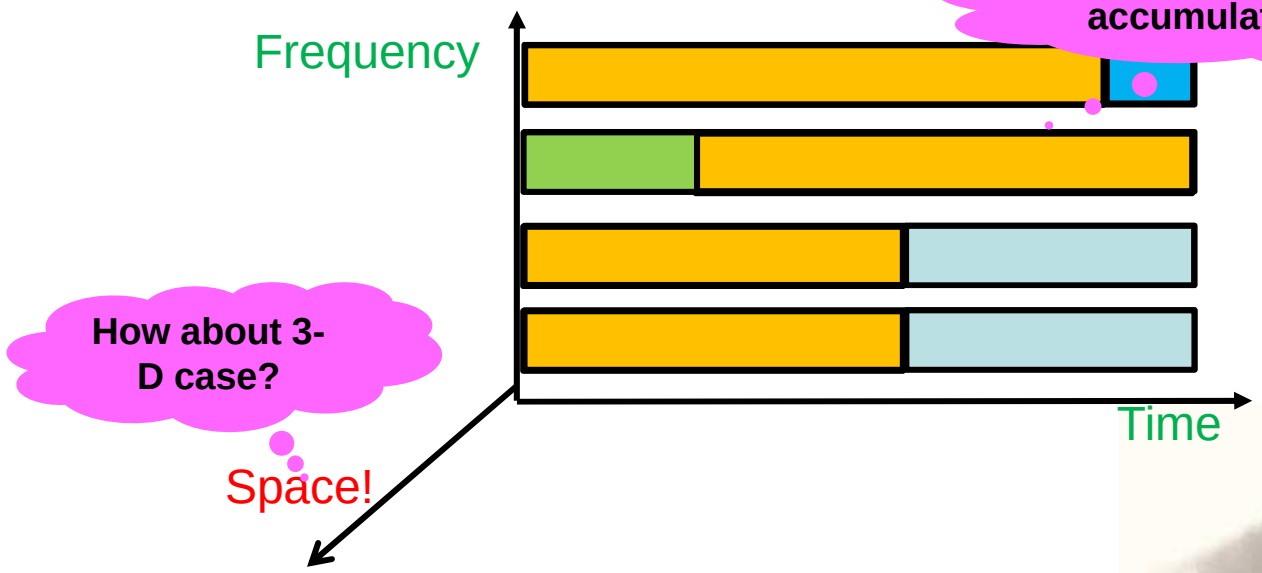
# 3-D Spectrum Holes

- Techniques for Detecting 3-D Holes
  - Radio Environment Map (REM)
  - Primary User Localization
  - …



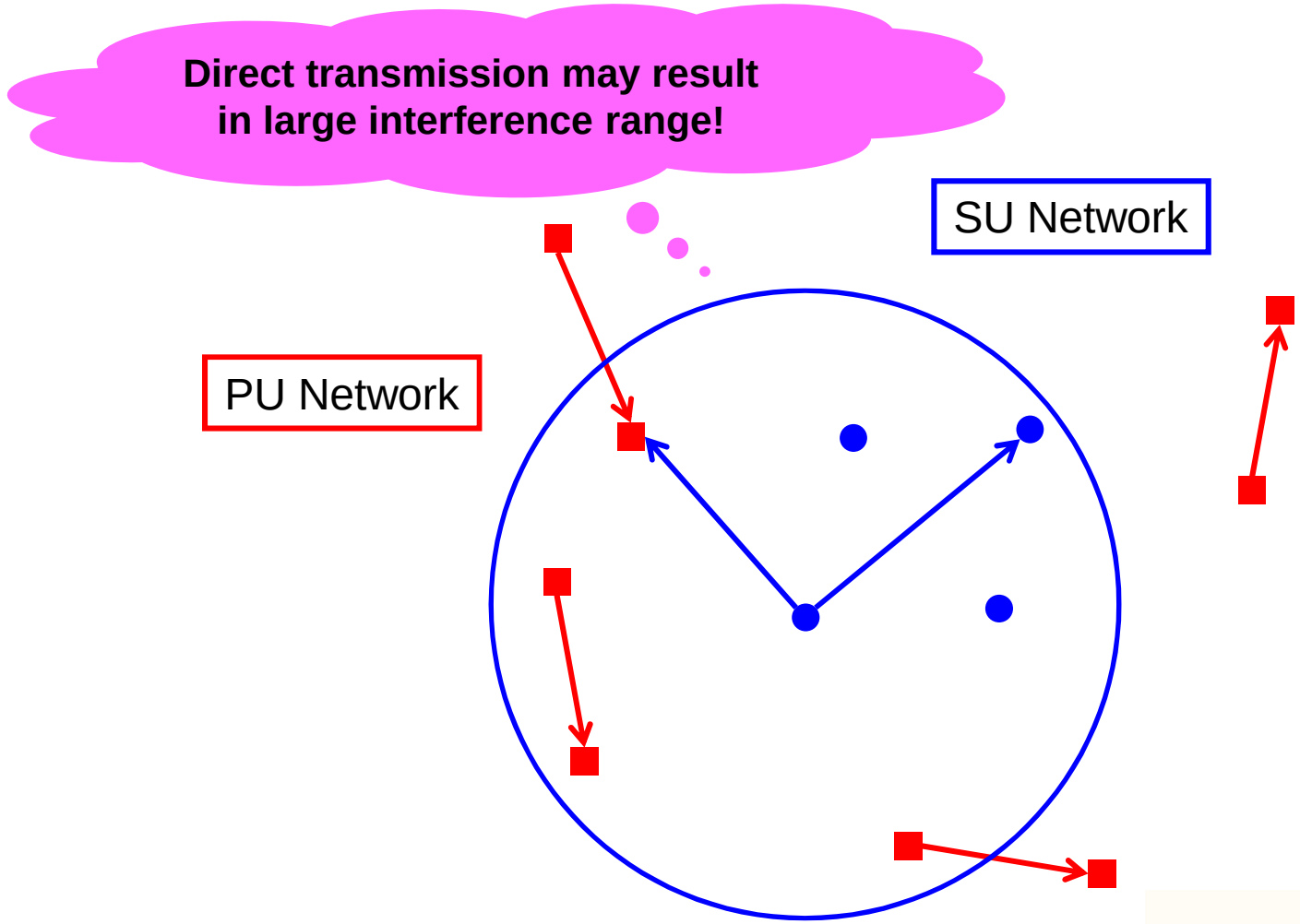

**In this talk, let us focus on how to make use of these 3-D spectrum holes!**

**In 2-D case, it is efficient to accumulate multiple holes**



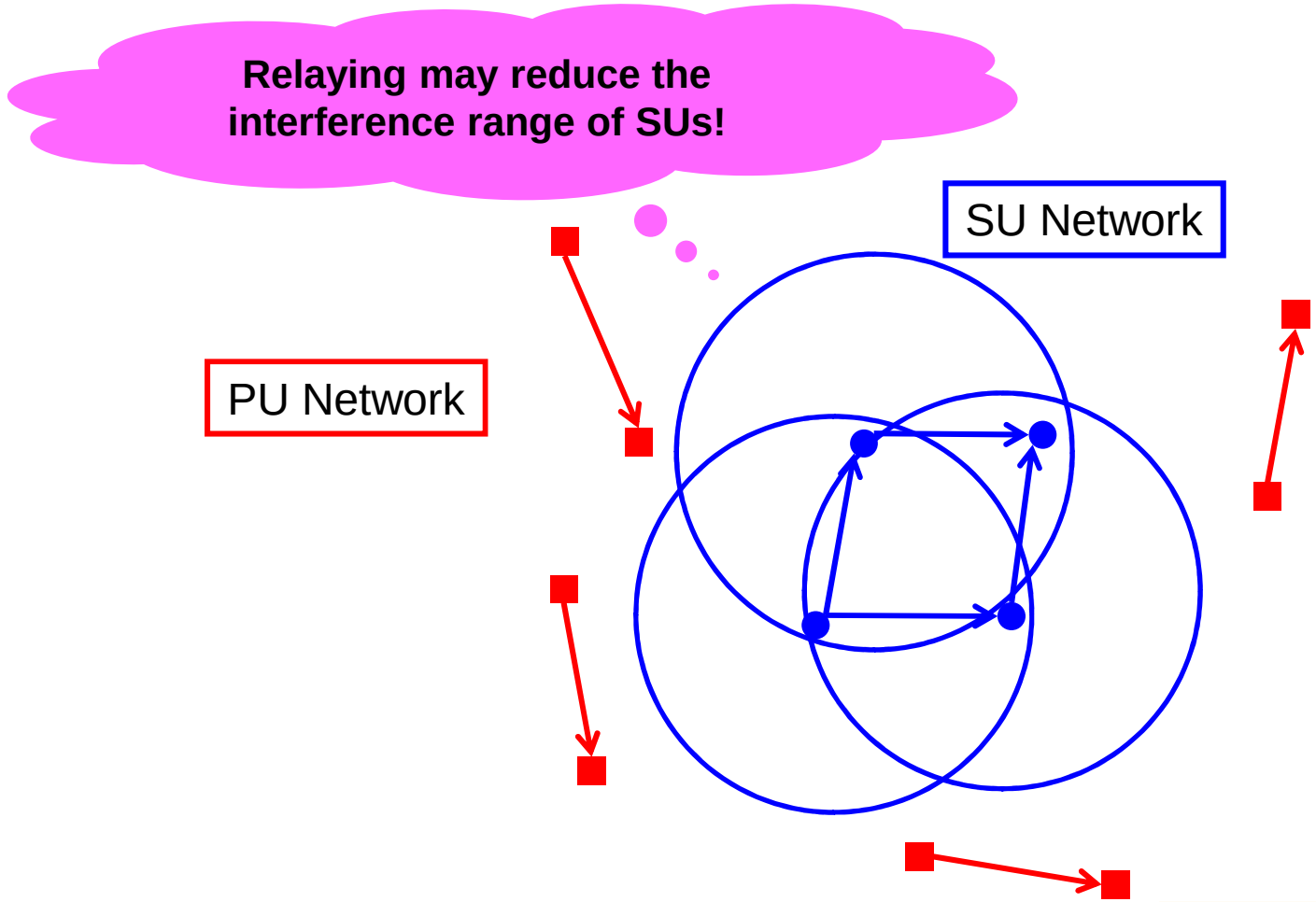

**How about 3-D case?**

# Efficient Utilization of 3-D Holes




**More 3-D holes can be utilized by transmitting in low power!**

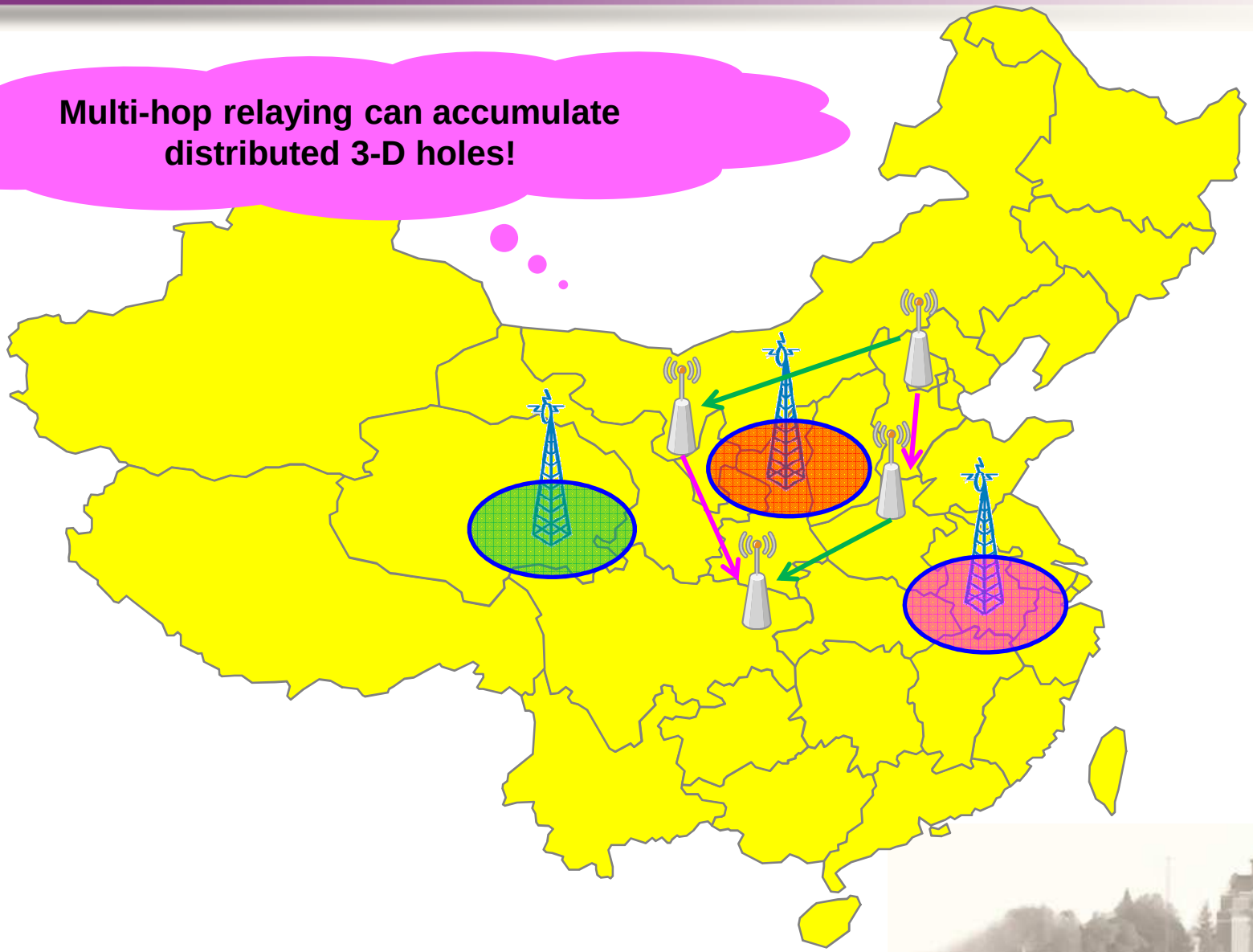
# Multi-hop Relay with Low Power




**Multi-hop relaying may make full use of geographical holes!**

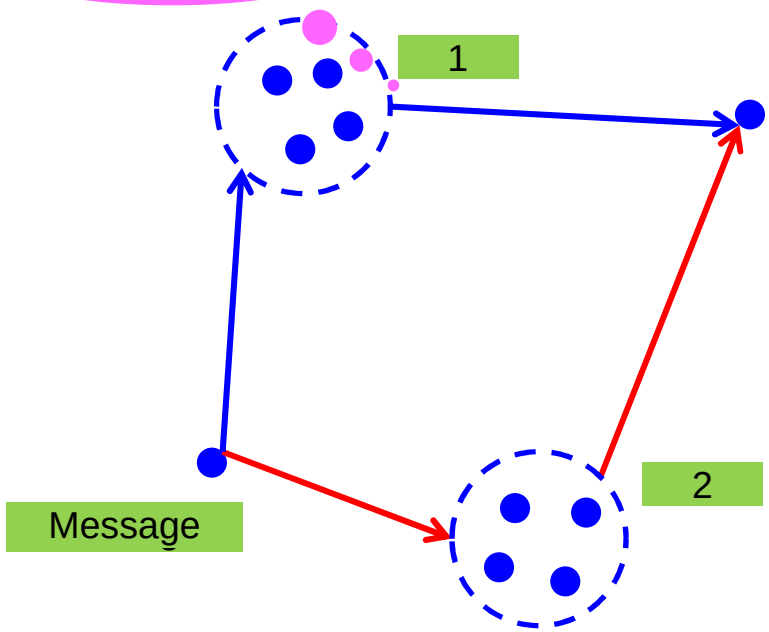
# Accumulating 3-D Holes

**Multi-hop relaying can accumulate distributed 3-D holes!**



# Relaying w/o PU

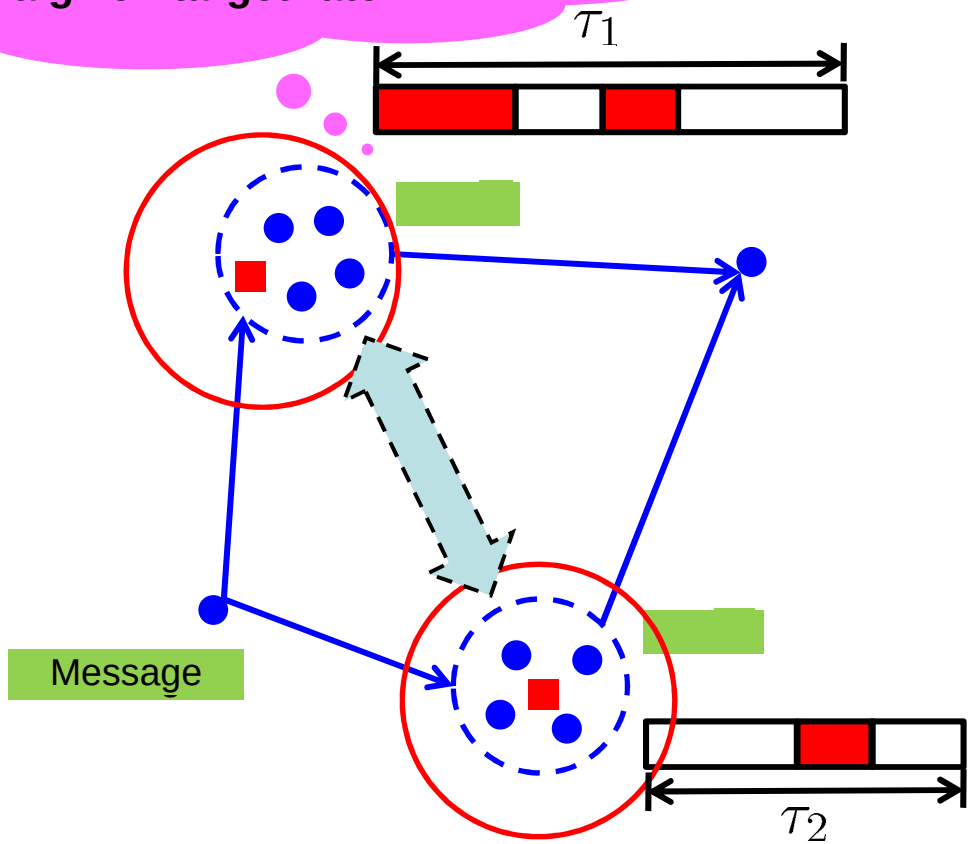
**Each link is assigned a fixed rate!**




**Regular packet can reduce protocol complexity**

# Relaying Issues in CR

Spectrum holes can never guarantee a given target rate

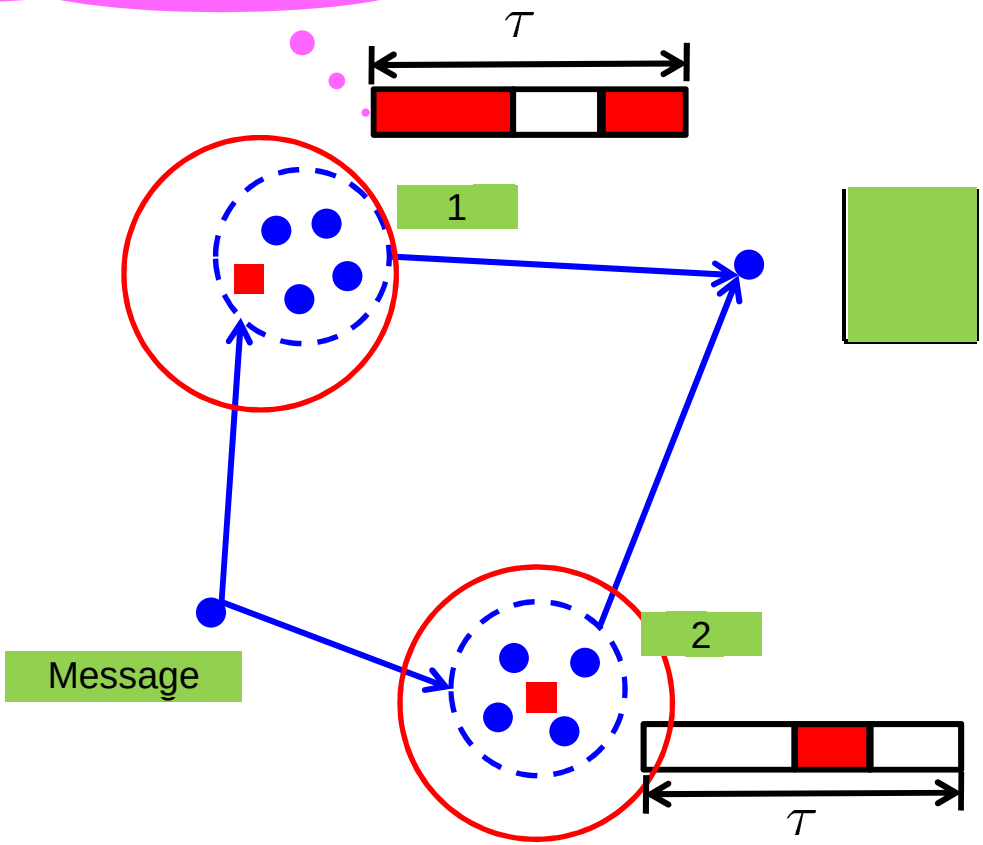



**Regular packet can induce very low efficiency and poor QoS**

**Adaptation to holes may result in high protocol overhead**

# Rateless Coded Relaying

**Rateless coding can adapt to spectrum holes without much signaling**

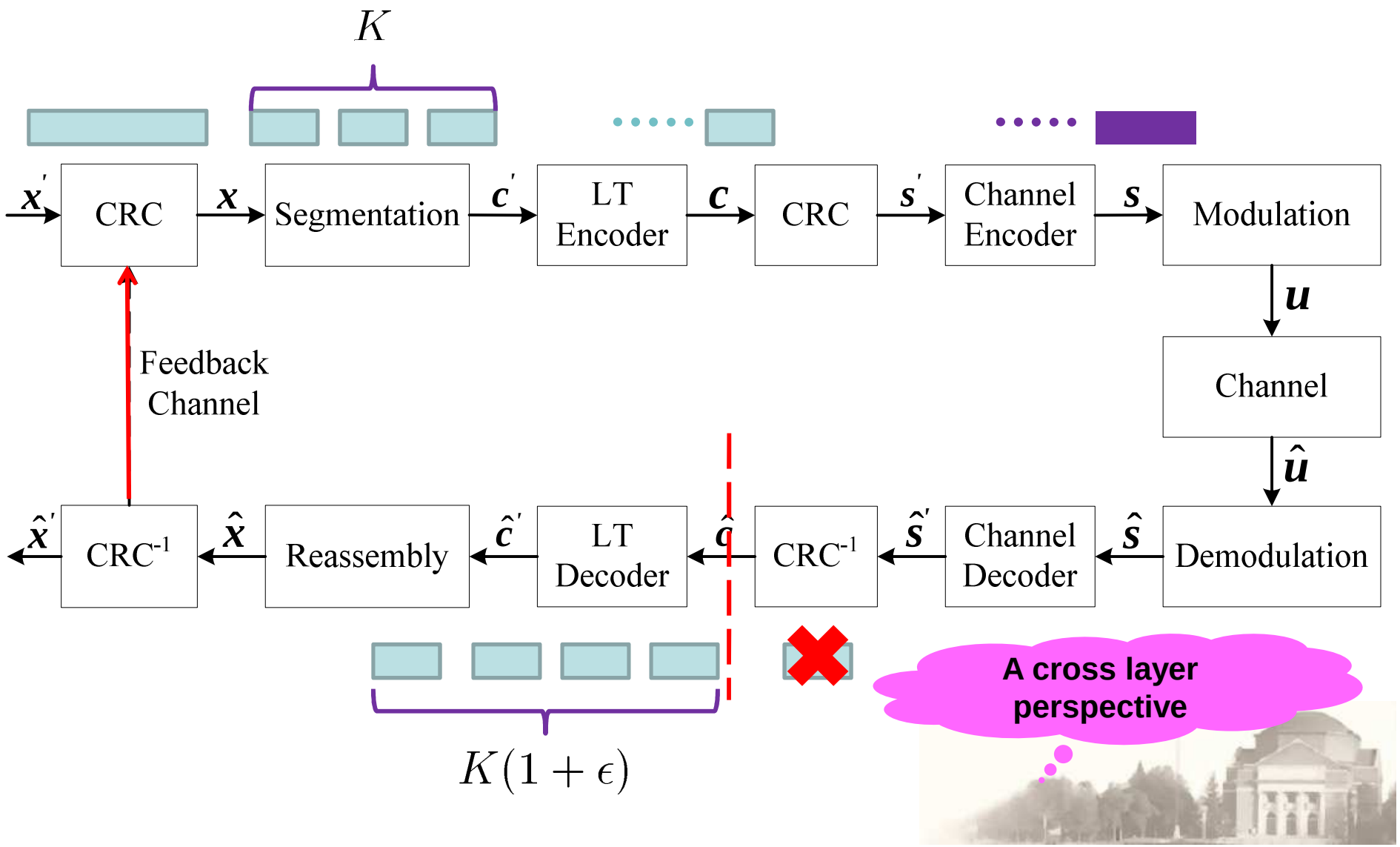



**Distributed!**

**Adaptive to access opportunity!**

**Efficiently accumulate multiple 3-D holes!**

# Physical Layer Designs



# System Performance

## Throughput efficiency

$$\max_{l} \quad \frac{1-P_e(l)}{1+\bar{\epsilon}(K)} R(1-h(l))$$

$$s.t. \quad K = \lceil m/l \rceil$$

Message size constraint

$$1 \le l \le m, l \in \mathbb{Z}$$

## Packet error probability for convolutional codes over fading channels

$$P_e \le 1 - \int_0^\infty \left(1 - \min\left[1, \sum_{d=d_f}^{\infty} a(d) P_2(d \mid \gamma)\right]\right)^l f(\gamma) d\gamma$$

$$P_e \le 1 - \left(1 - \sum_{d=d_f}^{\infty} a(d) P_2(d)\right)^l$$

## Average decoding overhead

$$\bar{\epsilon} = \frac{E[K'] - K}{K}$$

Estimation: Gaussian Mixture Model (GMM)

$$\hat{\epsilon} = \int_x x f(x) dx = \sum_{j=1}^{J} \pi_j \int_x x \mathcal{N}(x; \mu_j, \sigma_j^2) dx$$

Asymptotic analysis

$$\bar{\epsilon} = \sum_{i \ge 1} \Pr(\epsilon \ge \frac{i}{K})$$

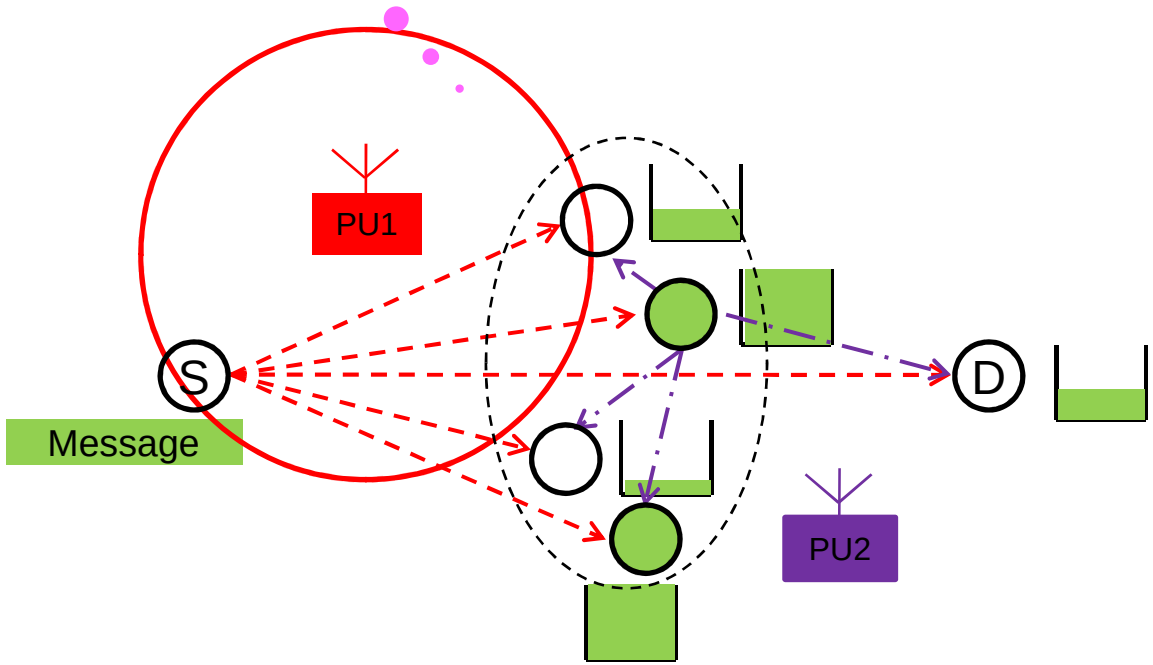
$$= \sum_{i \ge 1} 1 - (1 - \lambda(1 - \omega(1 - y_{l-1}(i/K))))^K$$

## CRC overhead

$$h(l) = l_{crc}/l$$

# Efficient Scheduling of Multiple Relays

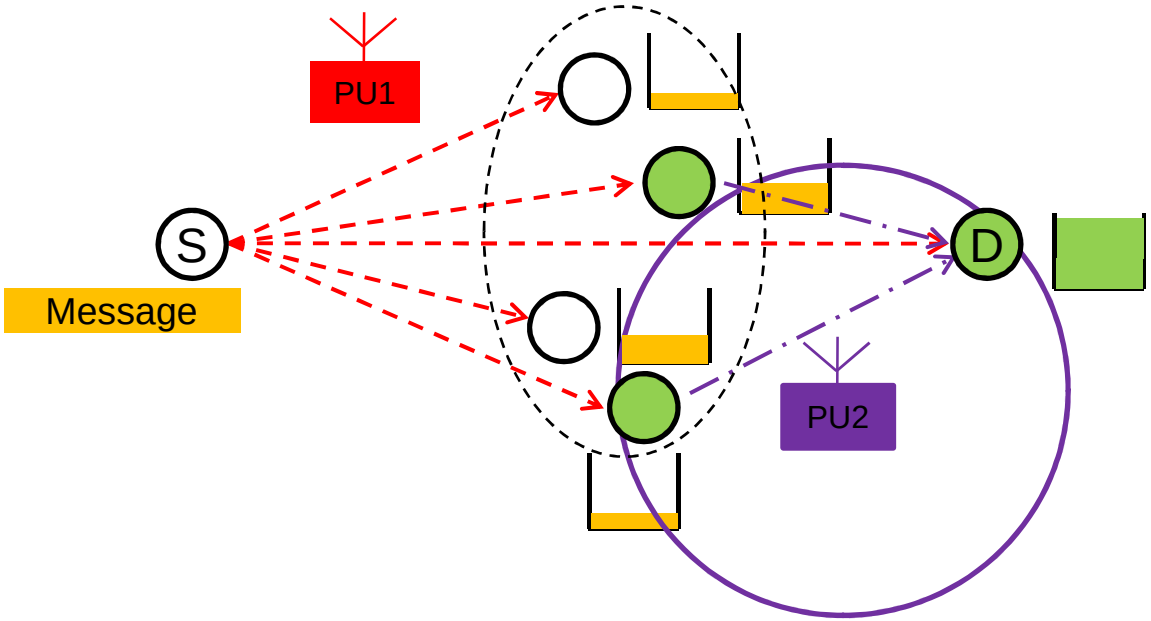
**Transmission in the 1st hop**




**Transmission delay will be increased with the number of relays that are required to decode a message!**

# Efficient Scheduling of Multiple Relays

**Transmission in the 2nd hop**

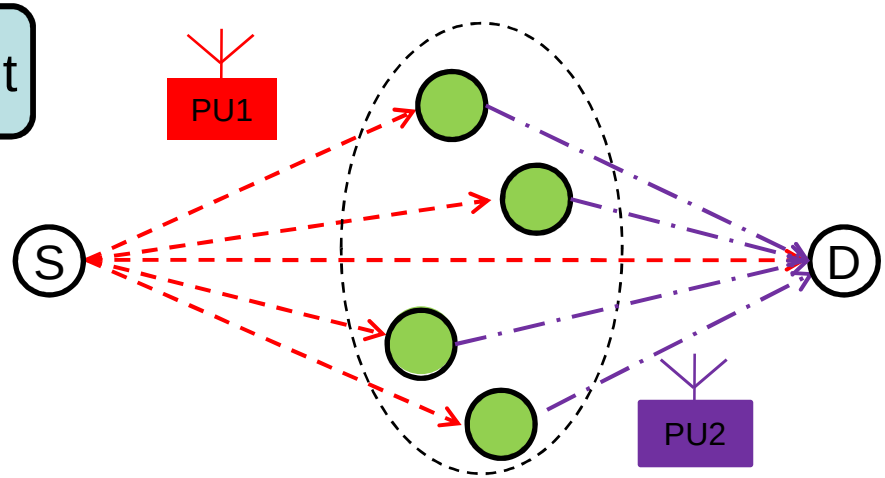



**With more relays decoding a message in the 1st hop, transmission delay will be decreased!**

# Cooperative Relaying

Maximize average end-to-end throughput

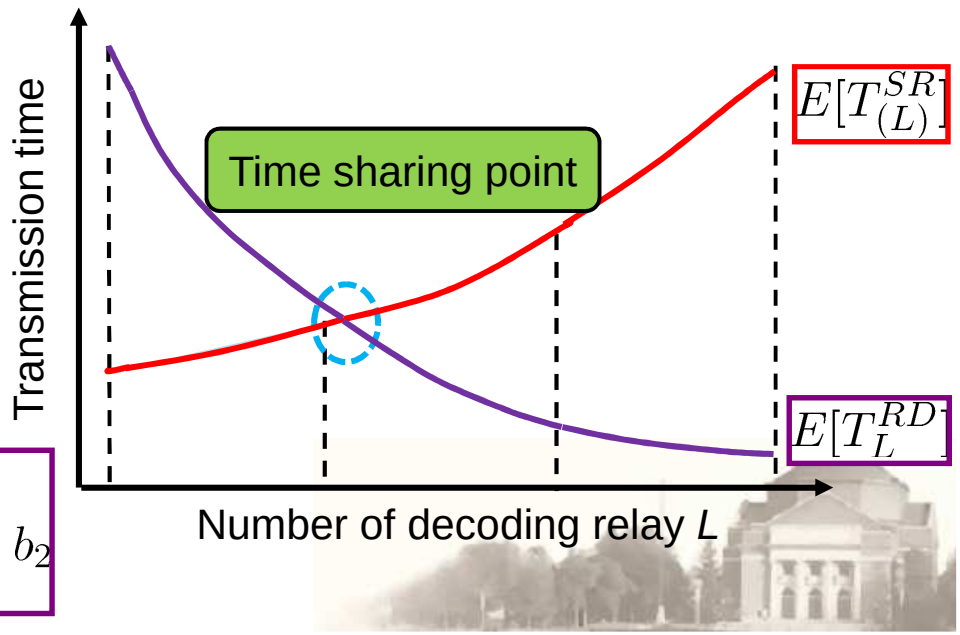
$$\max_{L} \frac{N}{\max\left(E[T_{(L)}^{SR}], E[T_{L}^{RD}]\right)}$$




$$E[T_{(L)}^{SR}] = a_1 E[T_{d(L)}^{SR}] + b_1$$

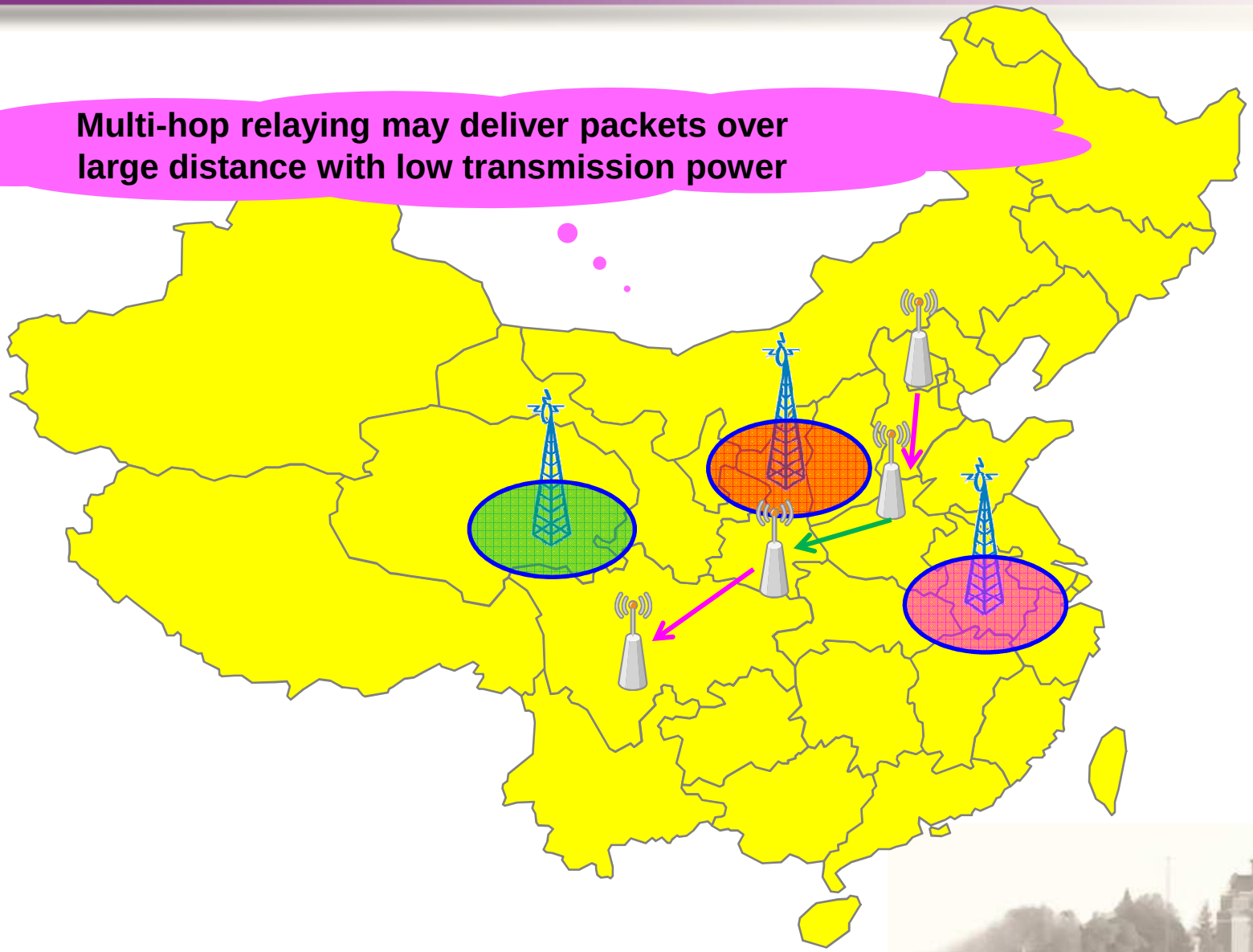
$$E\left[T_{d(L)}^{SR}\right] = E\left[T_{d(L-1)}^{SR}\right] + \sum_{y}\left(1 - \sum_{x} G_{1:M-L+1,L}(y \mid x) g_{T_{d(L-1)}^{SR}}(x)\right)$$

$$E[T_{L}^{RD}] = a_2 \frac{\widetilde{N} - E\left[\hat{N}_{d,L}\right]}{1 - \epsilon_{id,L}} \Pr\left(\hat{N}_{d,L} < \widetilde{N}\right) + b_2$$

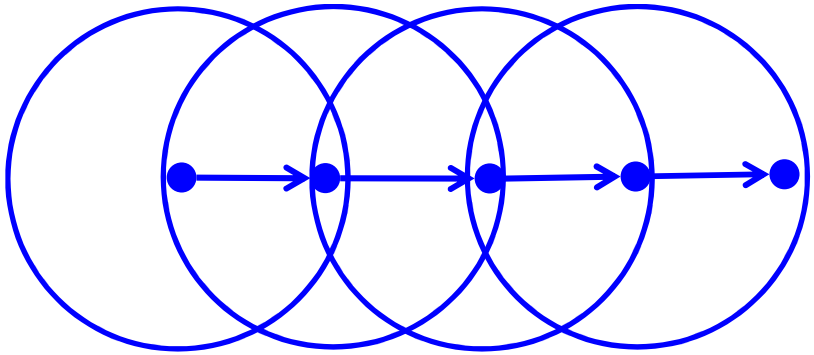


# Multi-hop Relaying

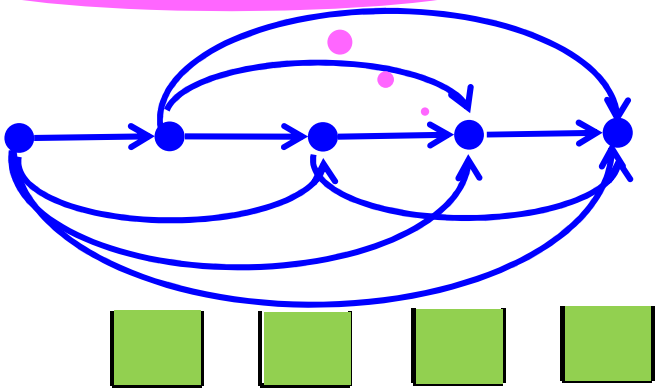
**Multi-hop relaying may deliver packets over large distance with low transmission power**



# From Dist Model to Fluid Model



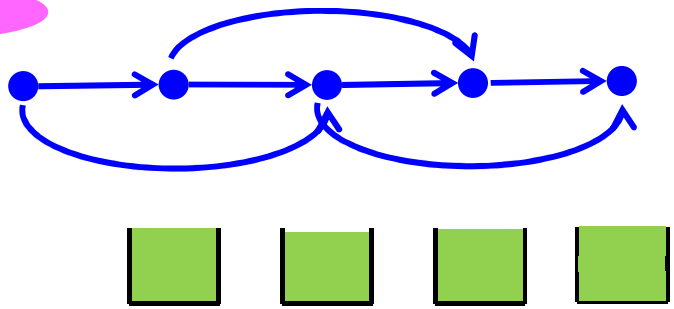
**To maximize the utilization of 3-D holes, transmission power of SUs may adapt to these holes**



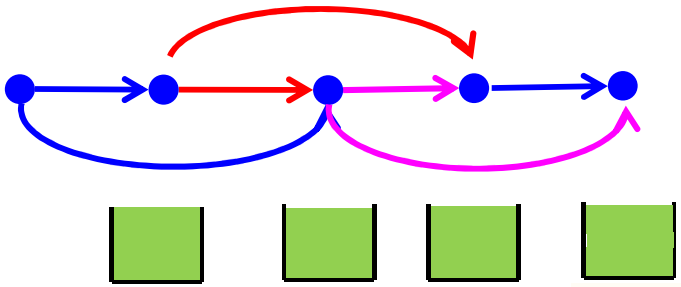
**Rateless coded multi-hop relaying can achieve high spectral efficiency in a distributed manner!**

# Efficient Multi-hop Relaying

Spatial Reuse
within one Band



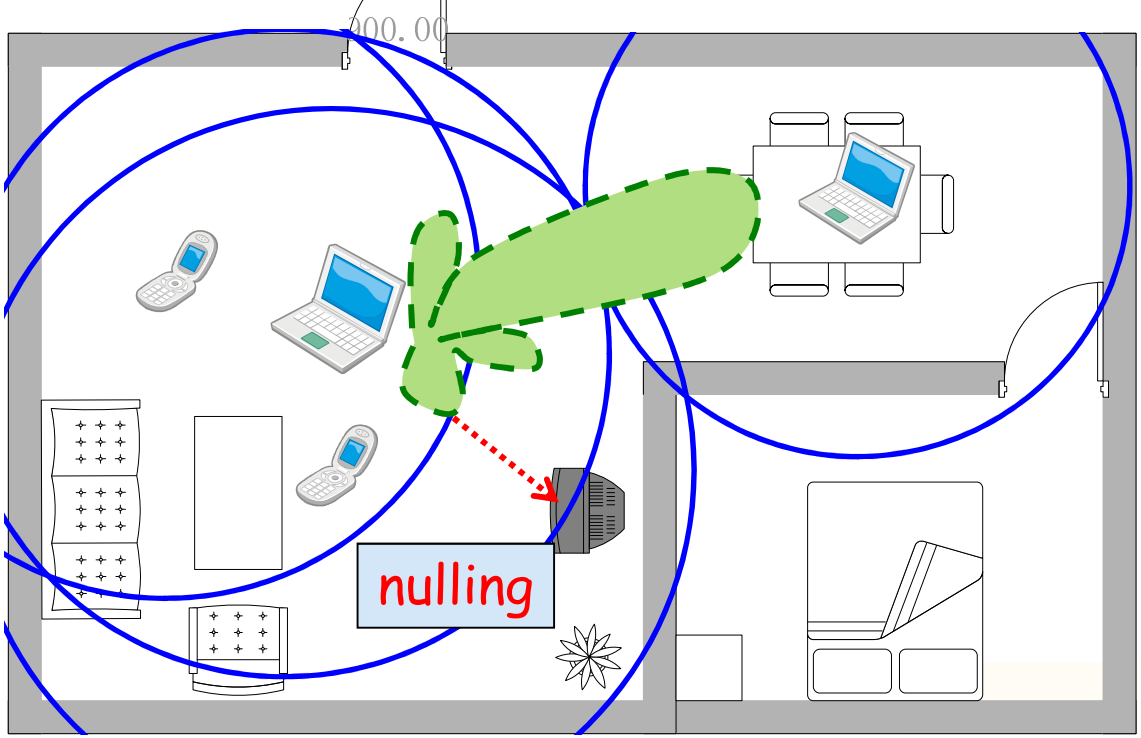
Spatial reuse &
chain cooperation
within multiple Bands



**Chain cooperation accumulates holes in multiple dimensions**

# From Geographical to Spatial

- For indoor applications, geographical spectrum holes hardly exist!
- Intuitively, directional antenna helps!

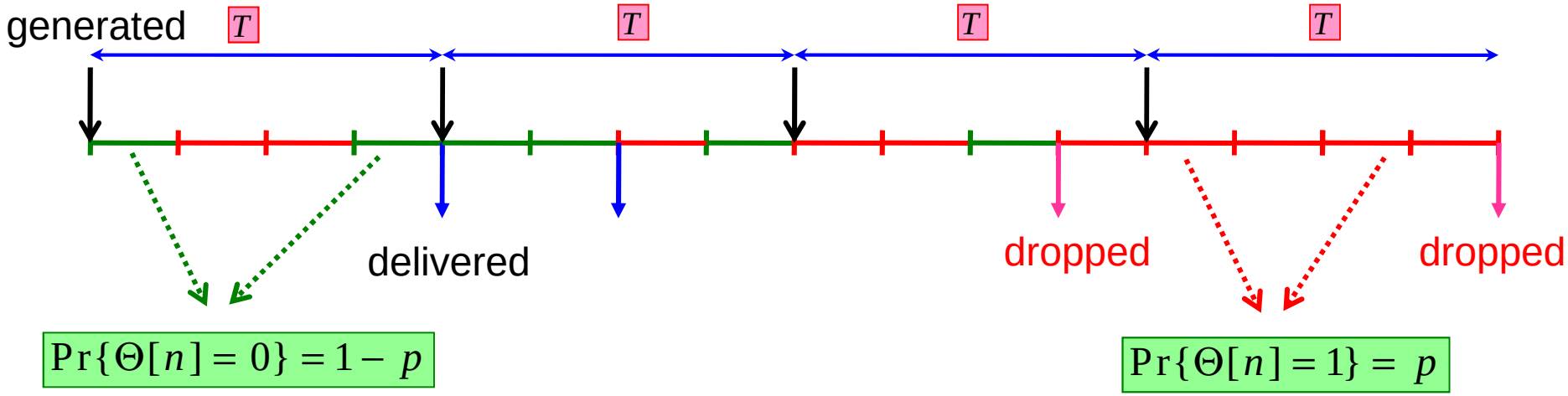



**Spatial Spectrum Holes!**

# A QoS Model for CRNs

## Objective

- messages are generated at a constant rate
- they are expected to be delivered within a given period T seconds

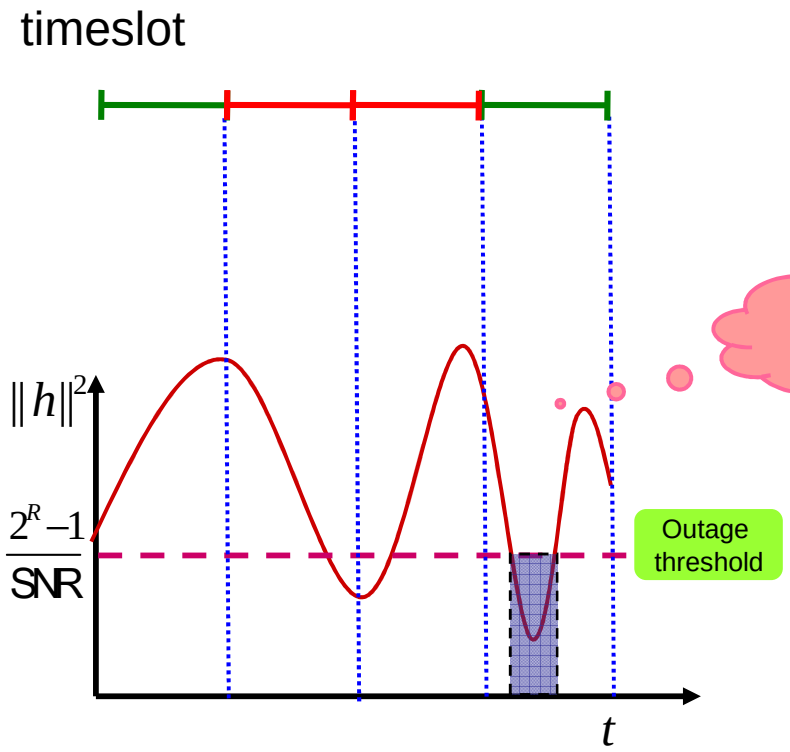


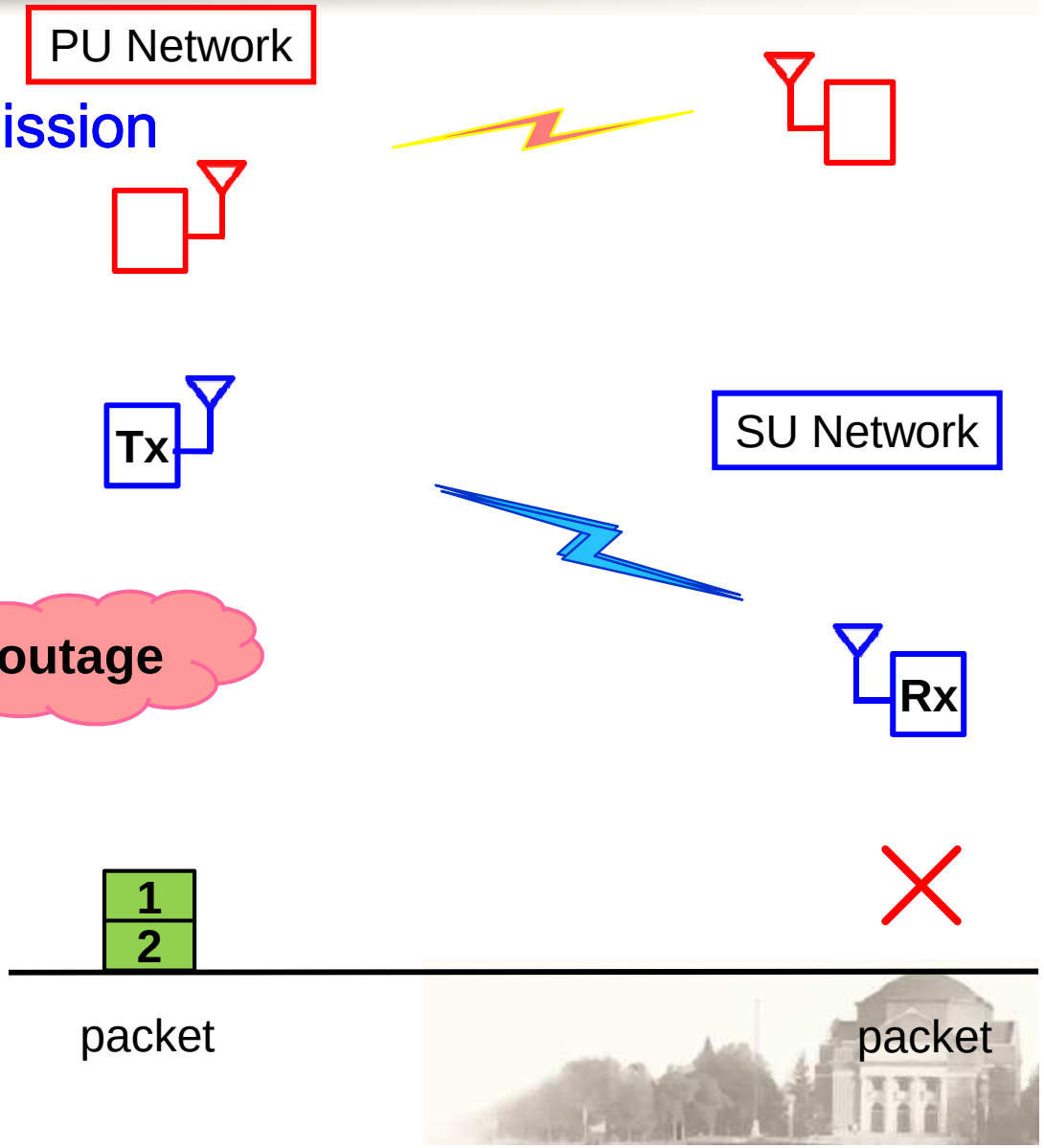

## Assumptions

- slow fading: wireless channel remains constant during T seconds
- channel gains are assumed to be known to each relay
- PUs' presence or absence is assumed to be i.i.d. across timeslots

# Direct Transmission

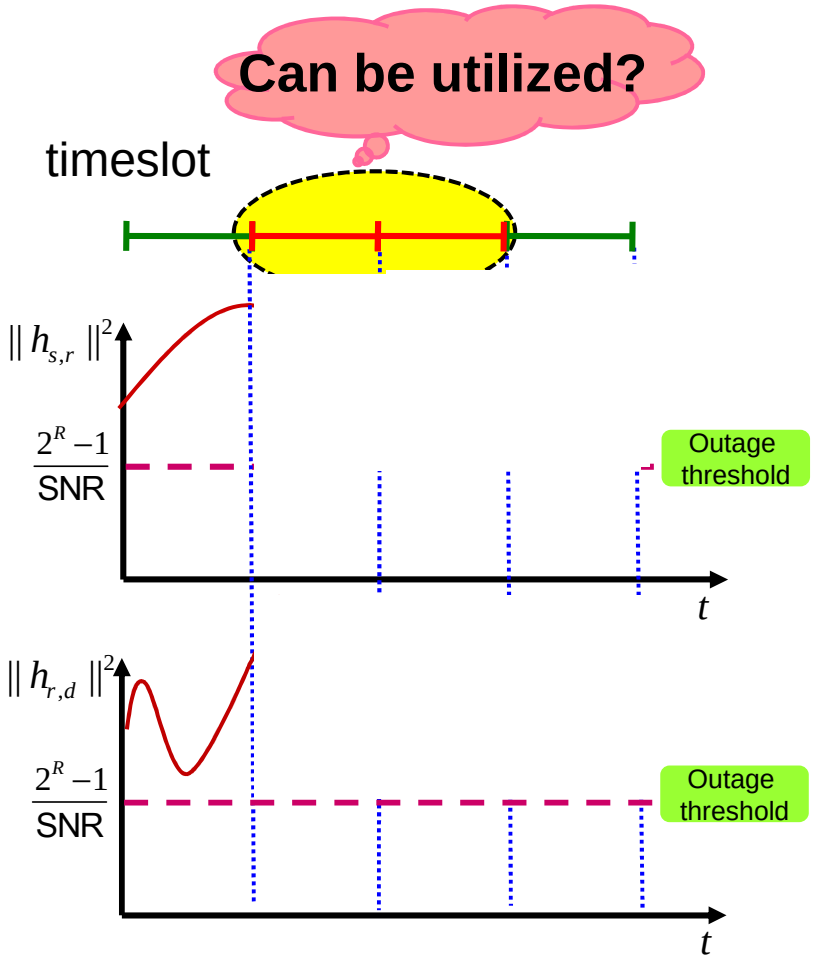
- 1 idle timeslot per transmission
- No diversity

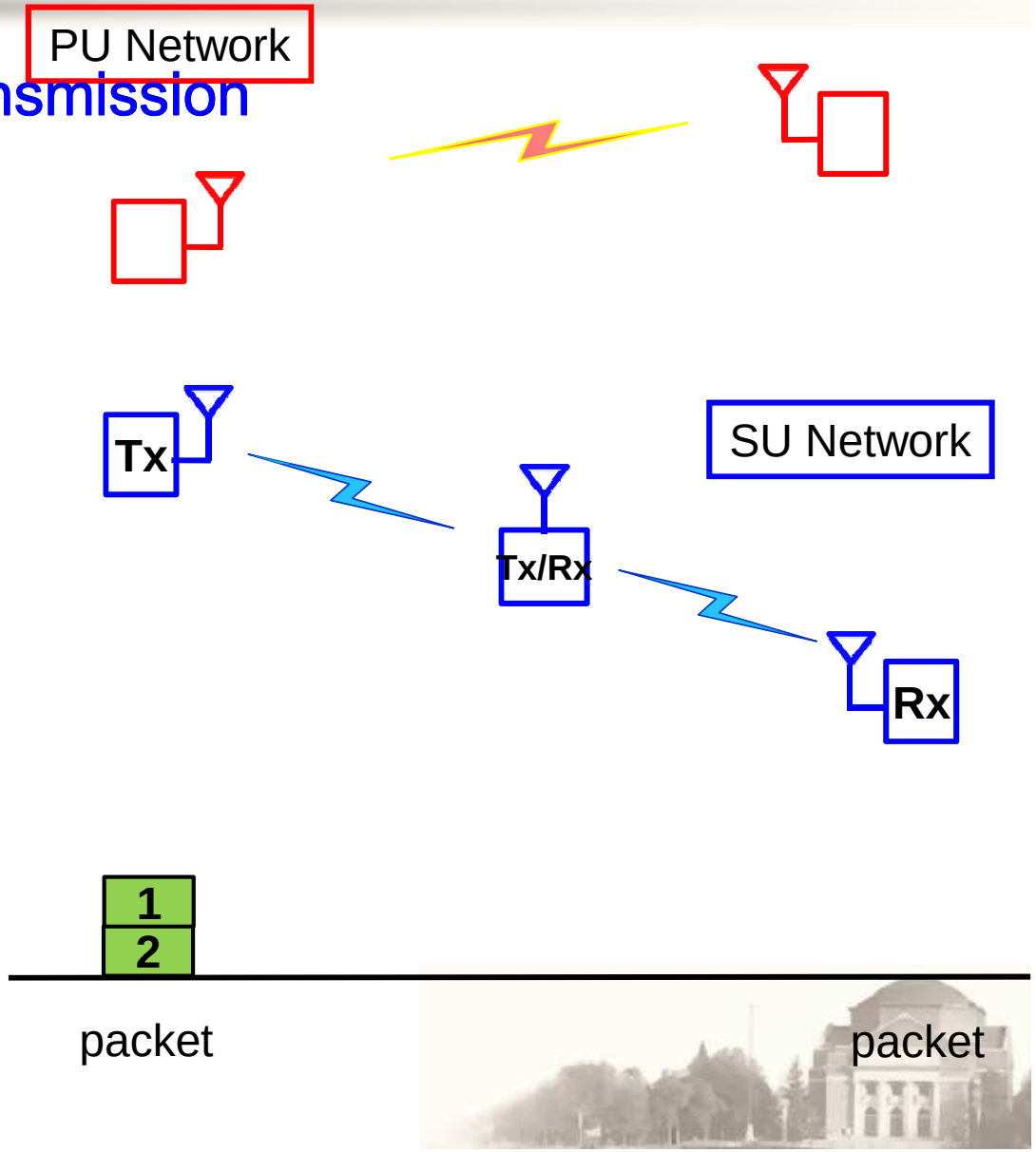


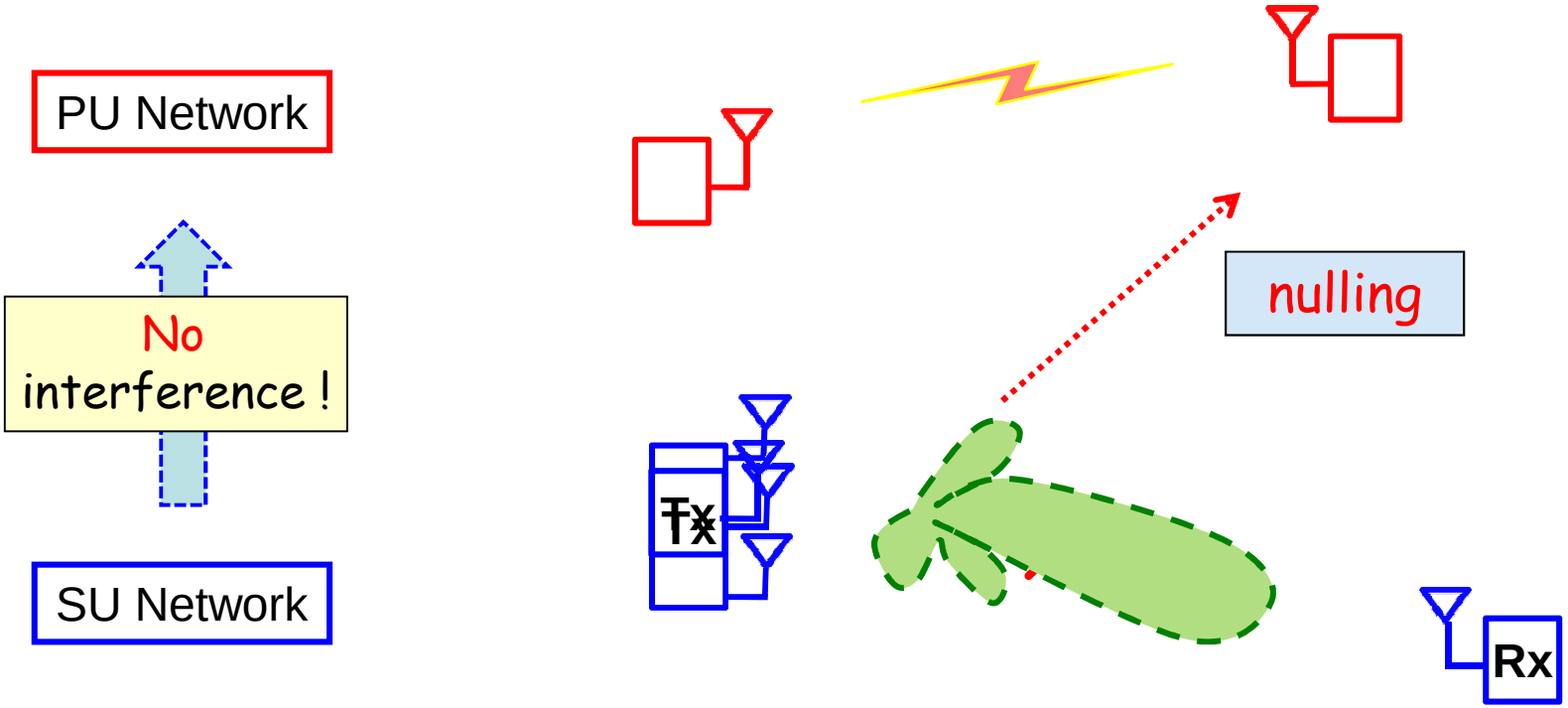
# Cooperative Diversity

- 2 idle timeslots per transmission
- Achieve diversity gain



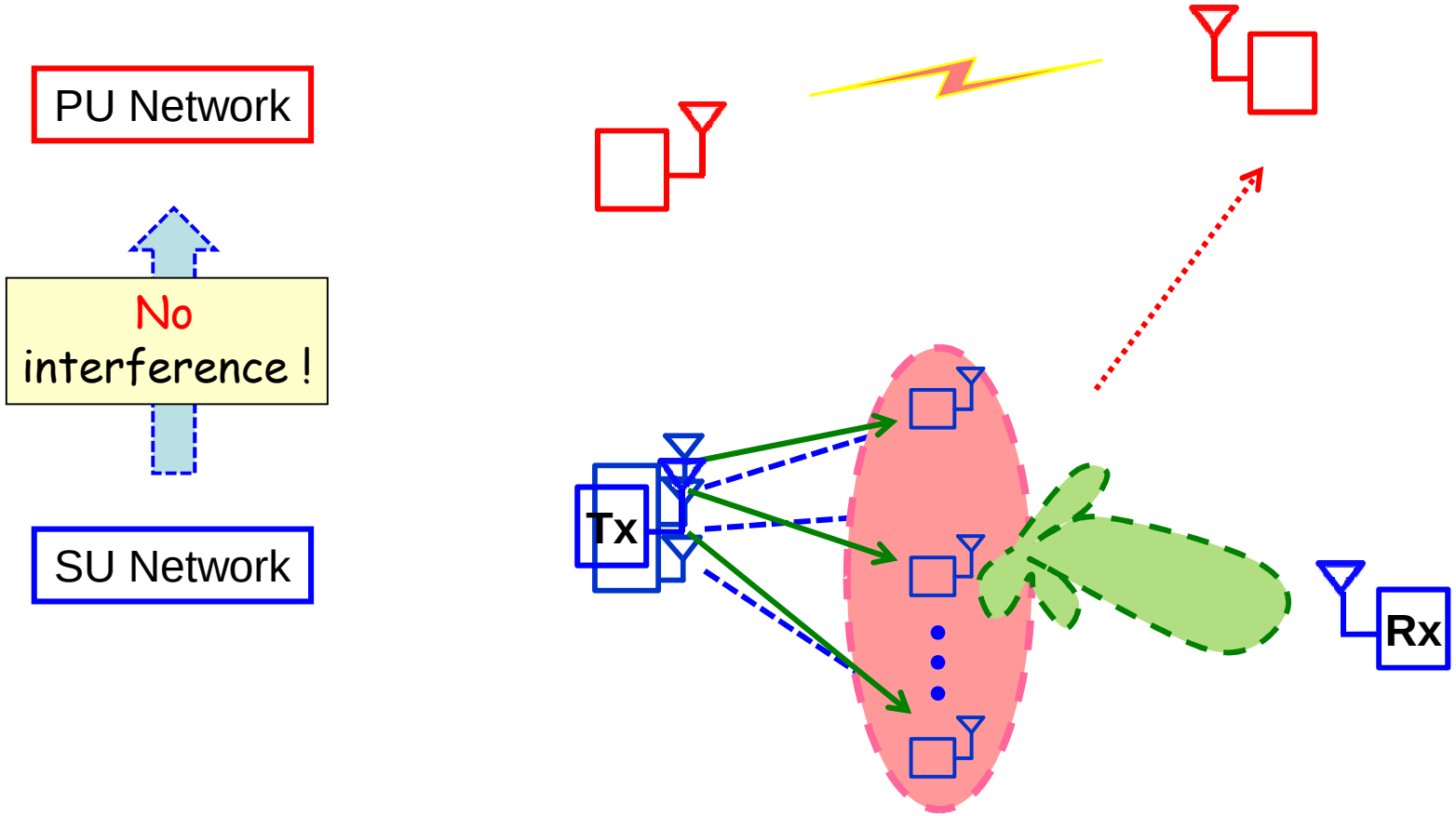



# Beamforming for Cognitive Radios




- Beamforming - Directional Transmission
  - Making use of spatial spectrum holes
  - Achieve diversity gain

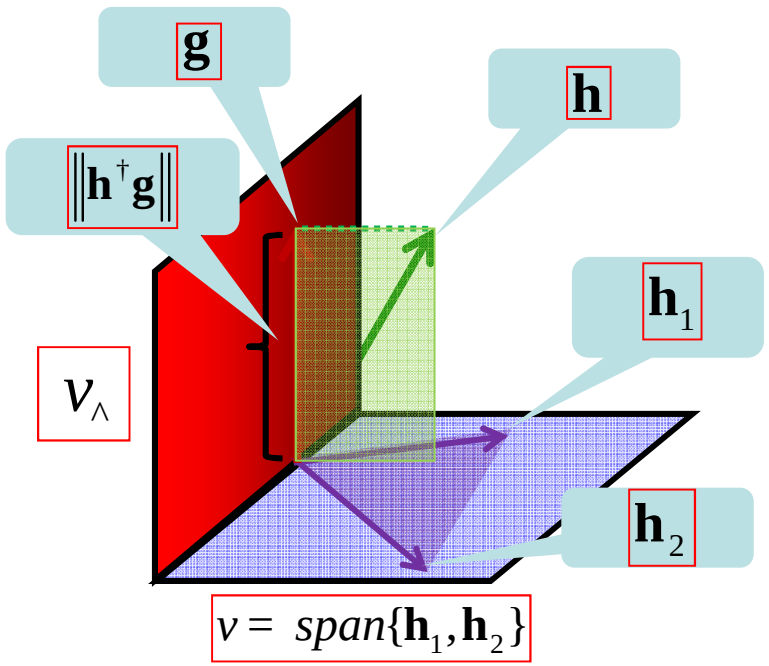
# Cooperative Beamforming

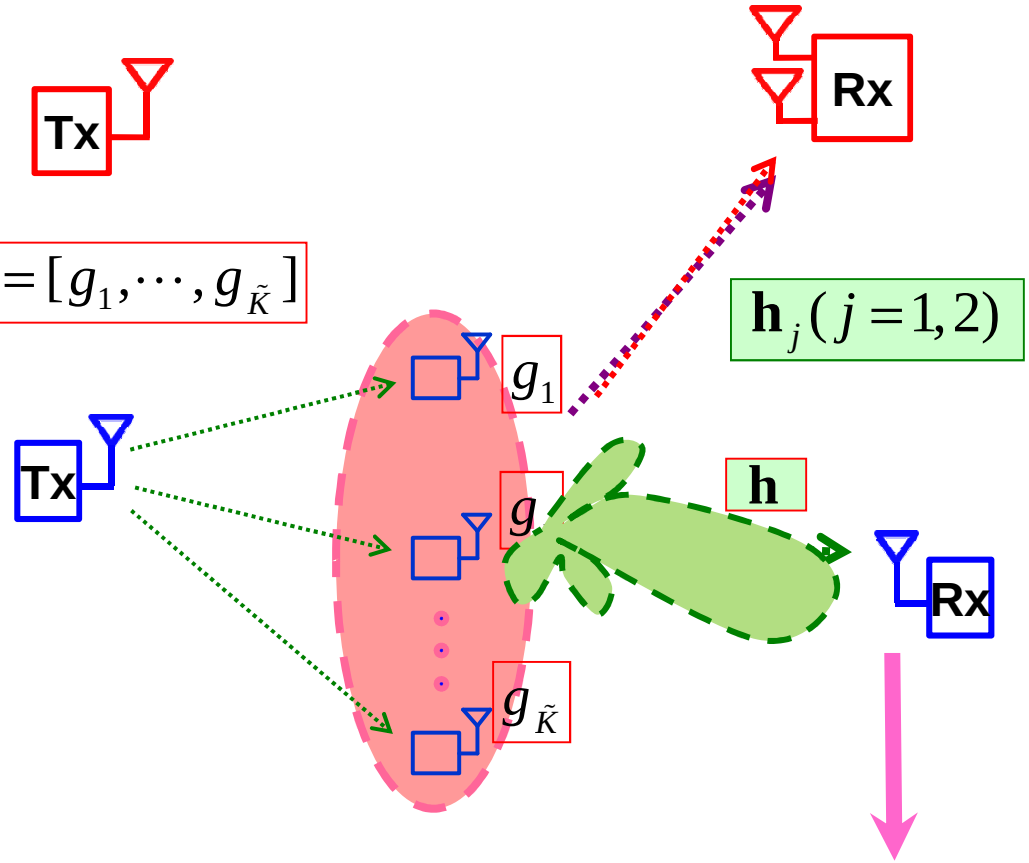



- Cooperative beamforming a set of relays
  - With only one atenna in each SU

# A Geometric Approach

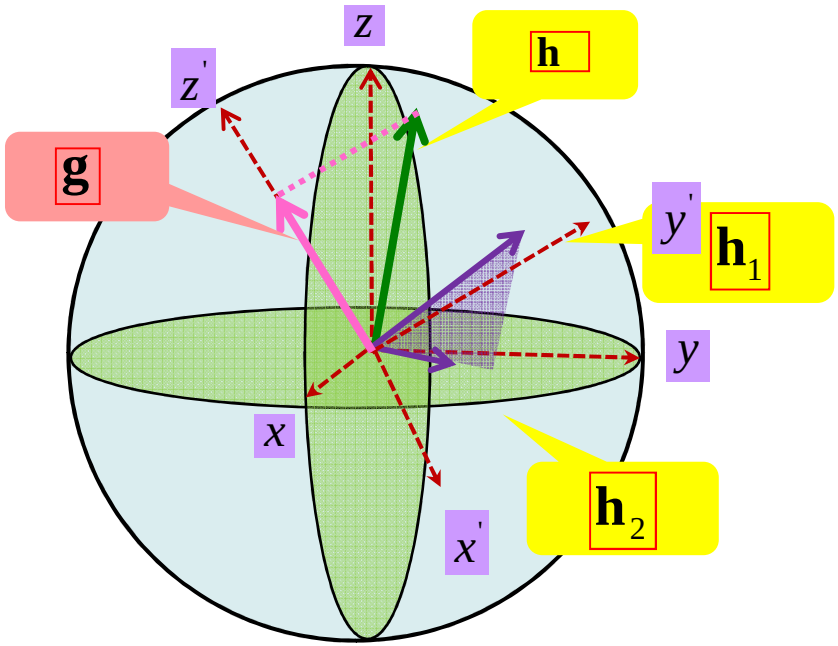
- Objective
  - zero-forcing to PU
  - maximizing SNR of SU
- ZFBF weight vector
  - orthogonal projection

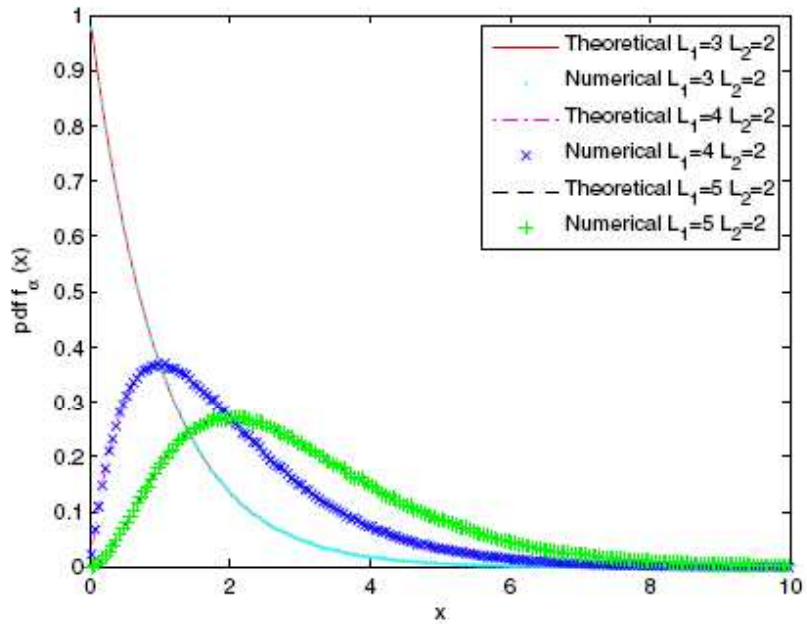



Received signal → $y_{d(s)} = \mathbf{h}^{\dagger}\mathbf{g}\tilde{x} + z_{d(s)}$

# Diversity Gain of ZFBF for CR




- The distribution of $\alpha = |\mathbf{h}^{\dagger}\mathbf{g}|^2$

$$f_{\alpha}(x) = \frac{1}{(L-1)!} x^{L-1} e^{-x}, \; x \geq 0,$$

$$L = \tilde{K} - N_r \; (L > 0)$$

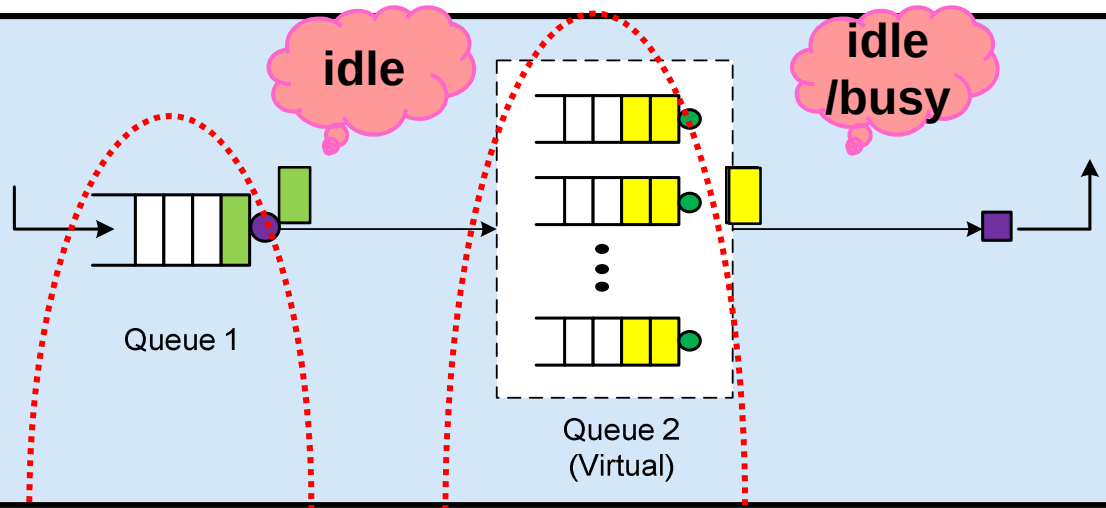
the number of decoding relays

the number of primary receivers

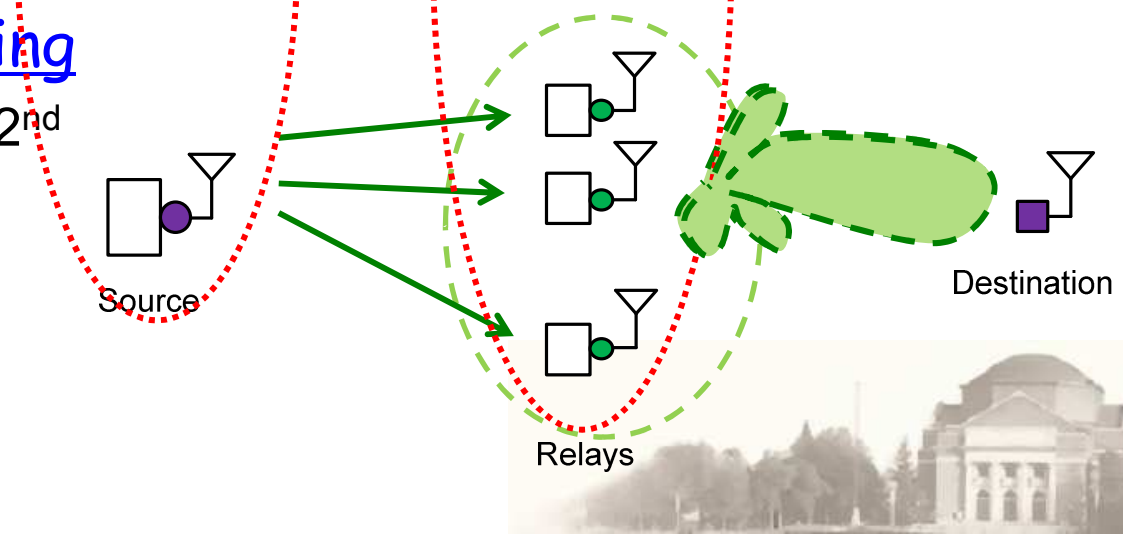
# Scheduling: A Cross-layer Perspective

1 2 3

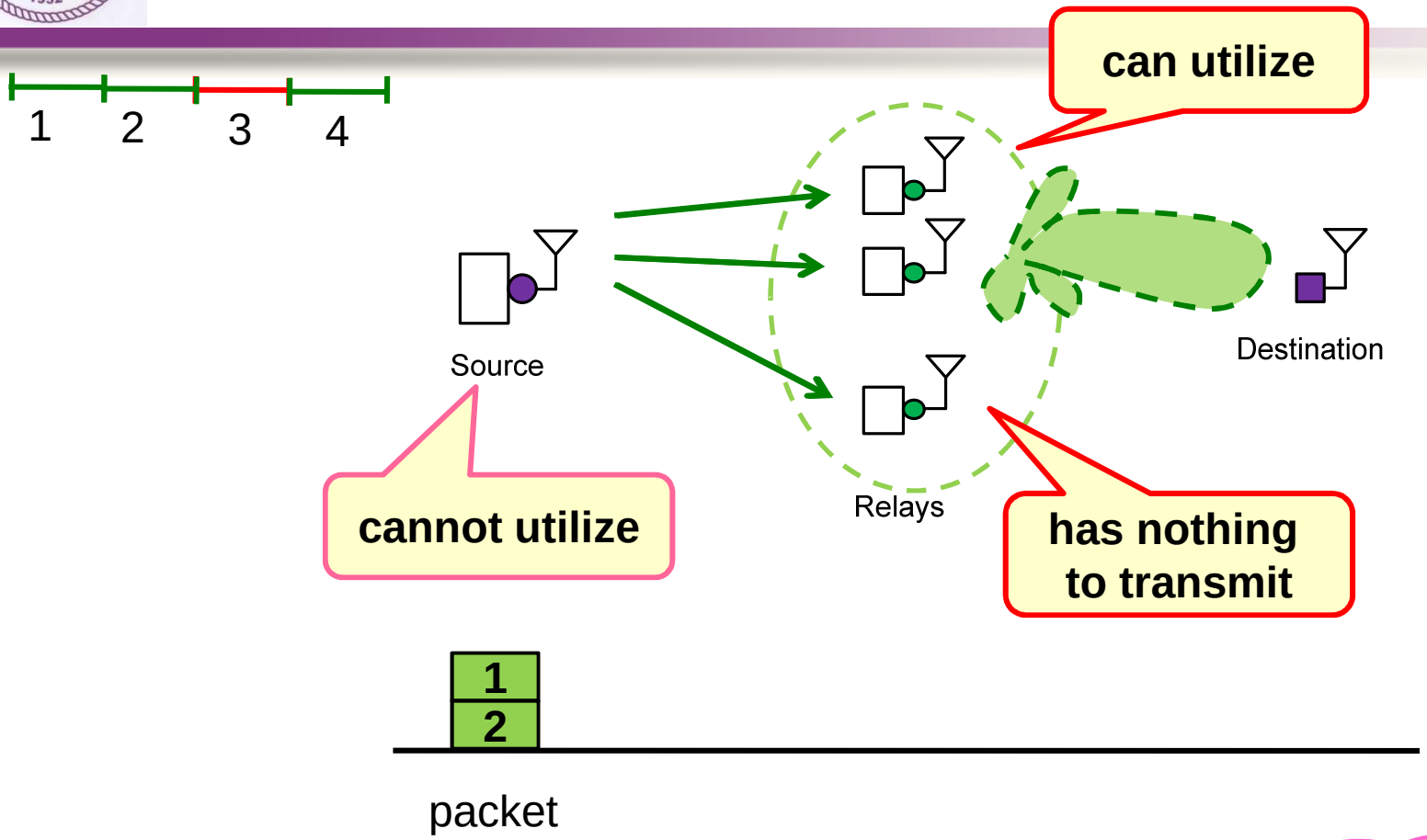
- Queueing model – tandem queueing
  - More service to queue 2




- PHY Layer model – cooperative beamforming
  - More spatial hole for the 2nd hop



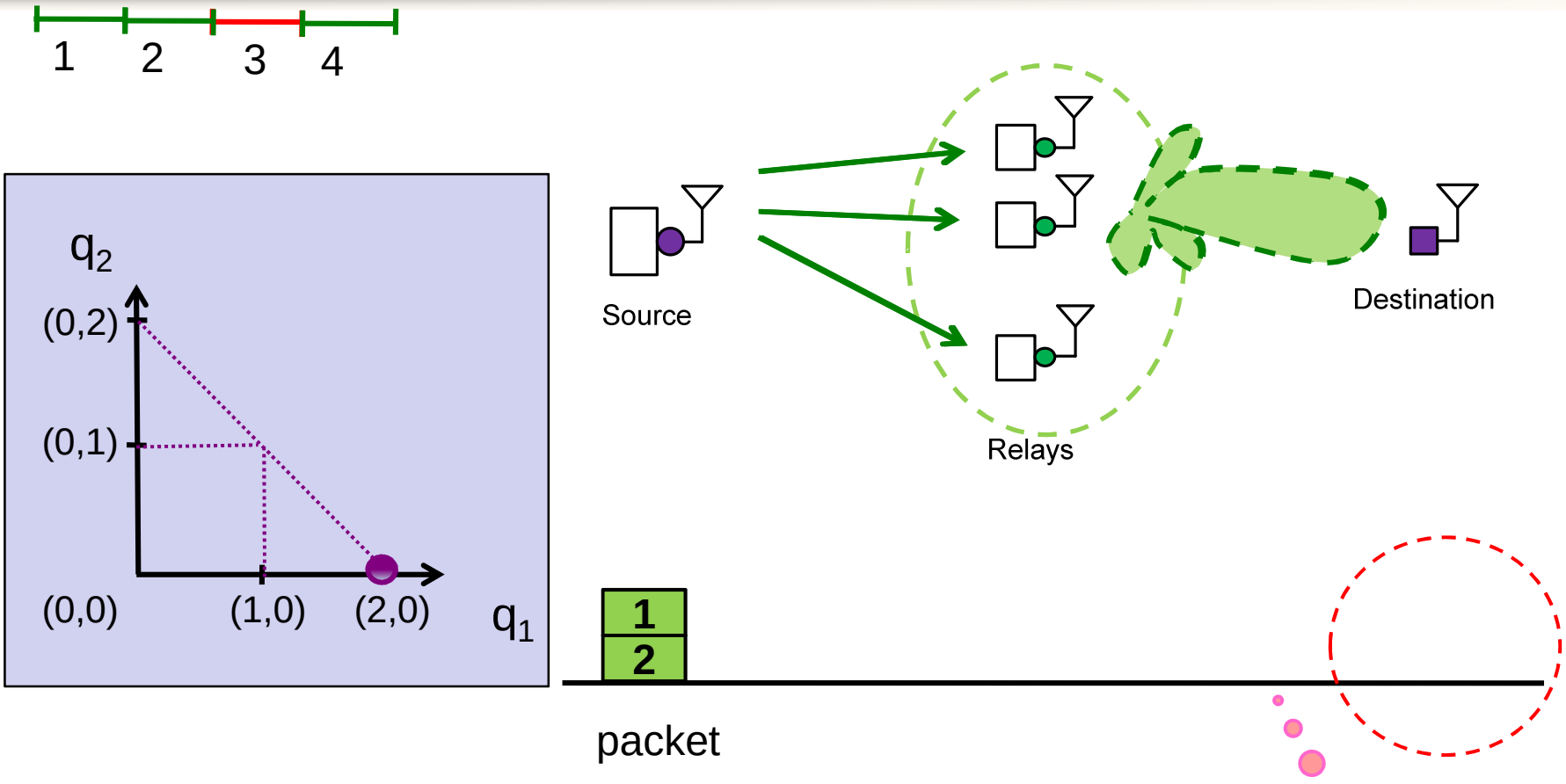
# How to Efficiently Schedule Two Hops?




- A simple scheduling protocol
  - source and relays take turns transmitting packets by accessing available timeslots

NOT optimal !

# Opportunistic Scheduling

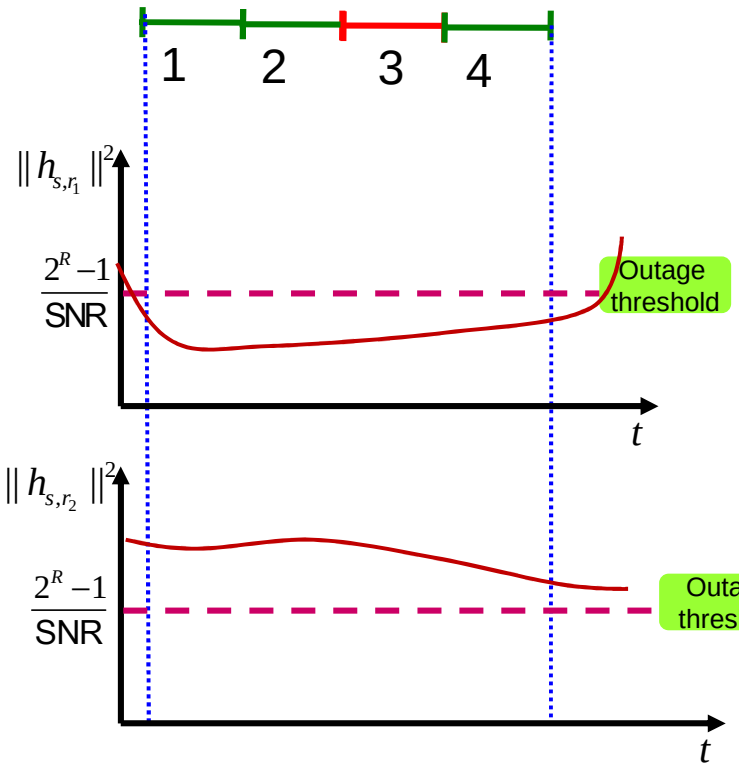


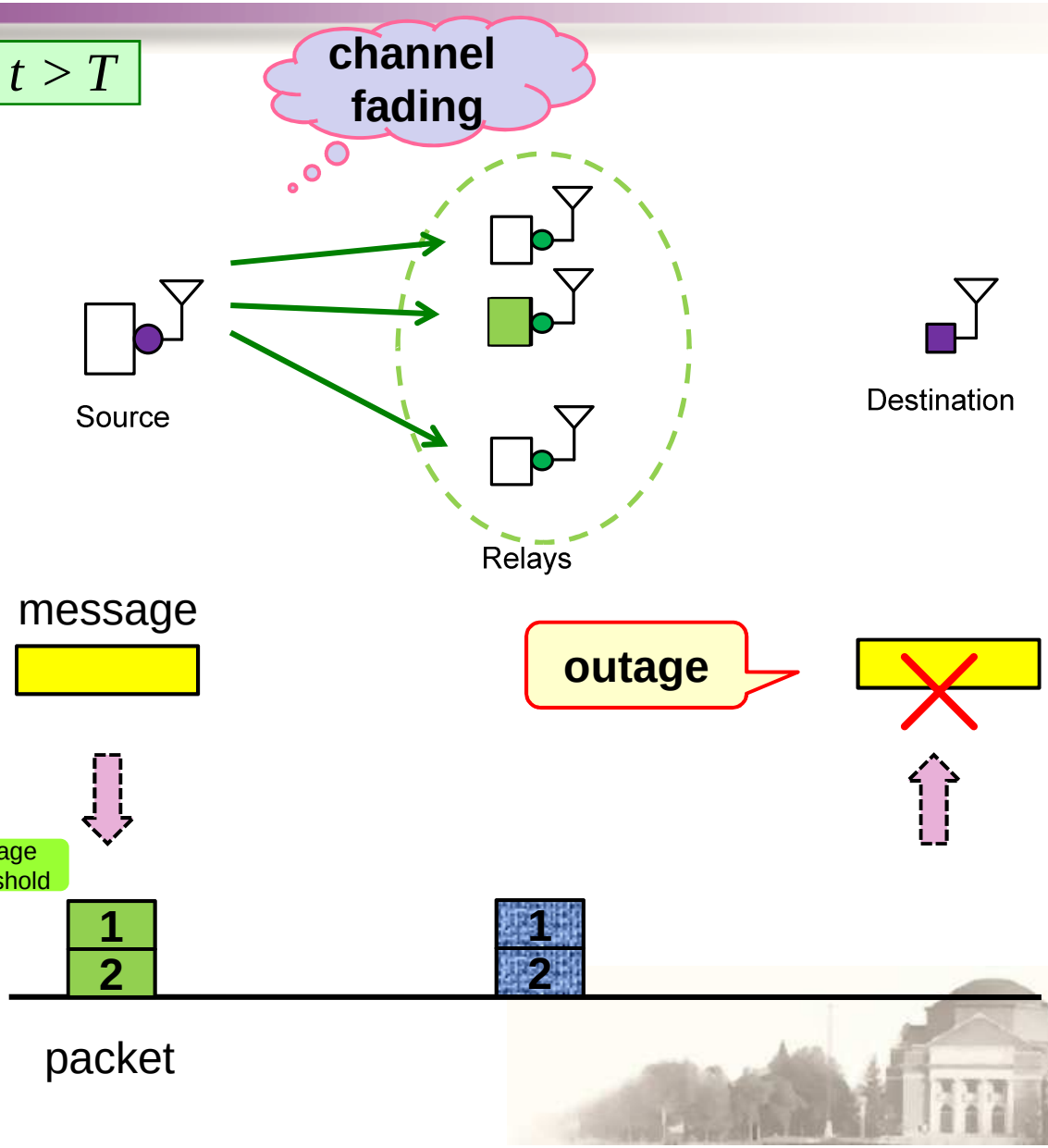

- Opportunistic scheduling protocol
  - Give higher priority to the 1st hop
  - It is optimal to serve constant rate delay-sensitive traffics

# Analysis of PHY

- PHY Outage
  - Fading in the 1st hop
  - Fading in the 2nd hop

$t > T$



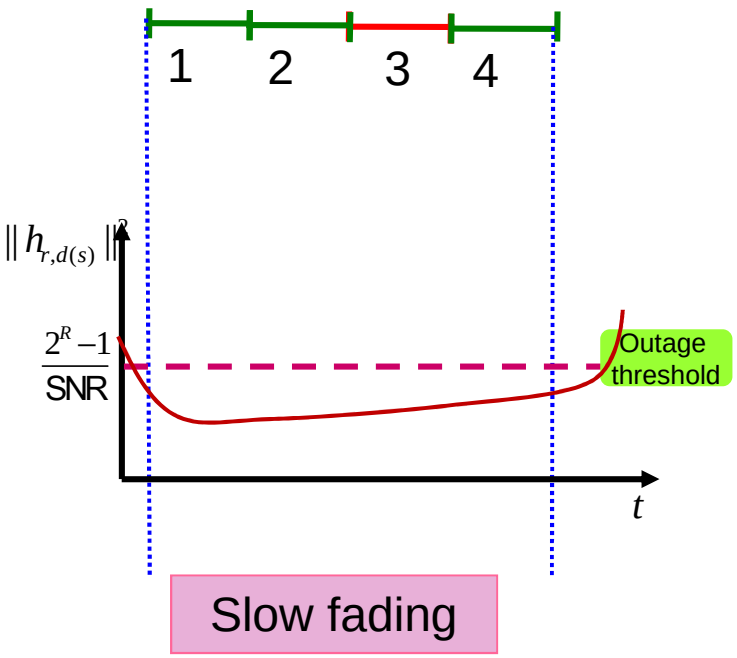



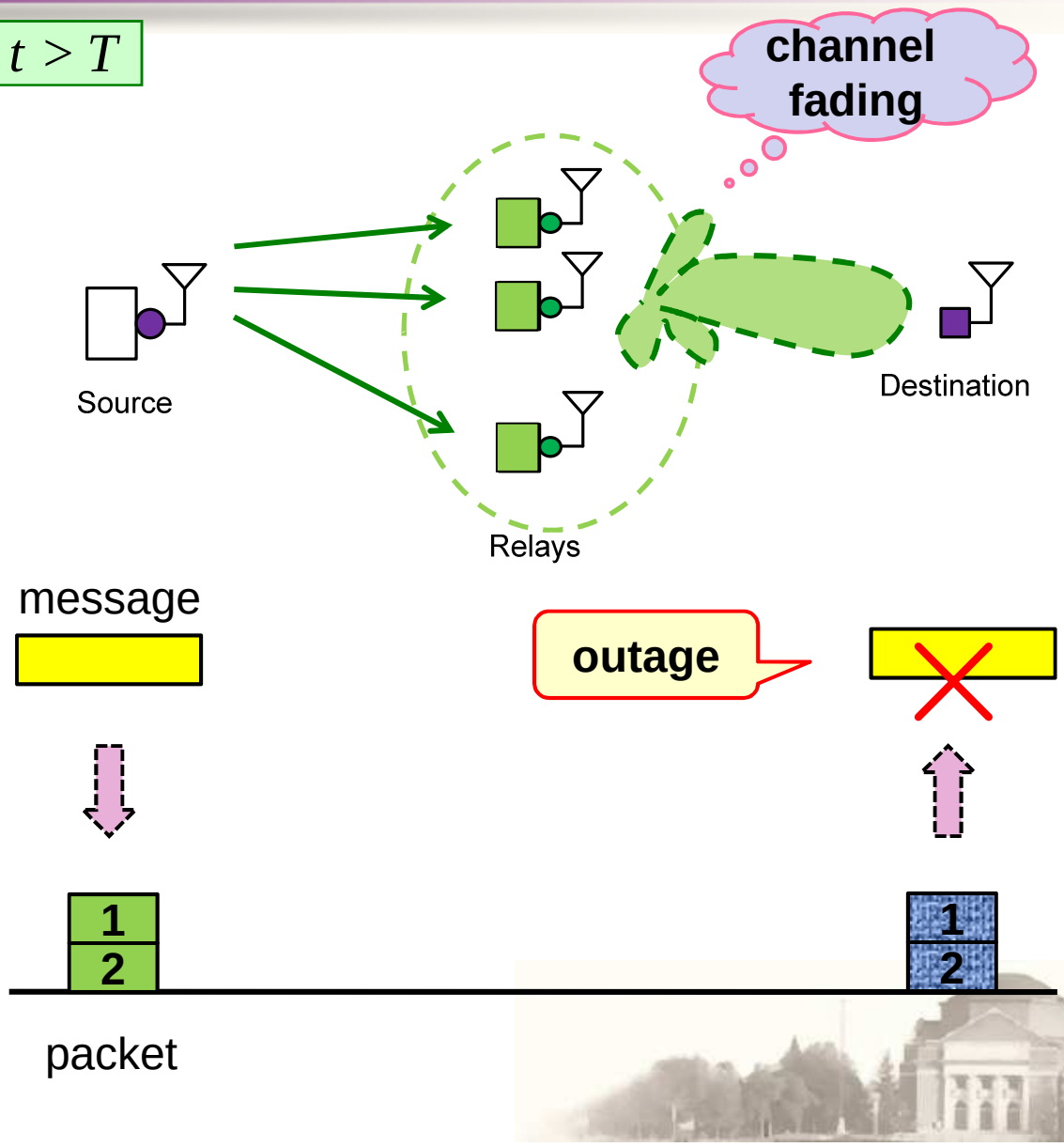

Slow fading

# Analysis of PHY

- PHY Outage
  - Fading in the 1st hop
  - Fading in the 2nd hop

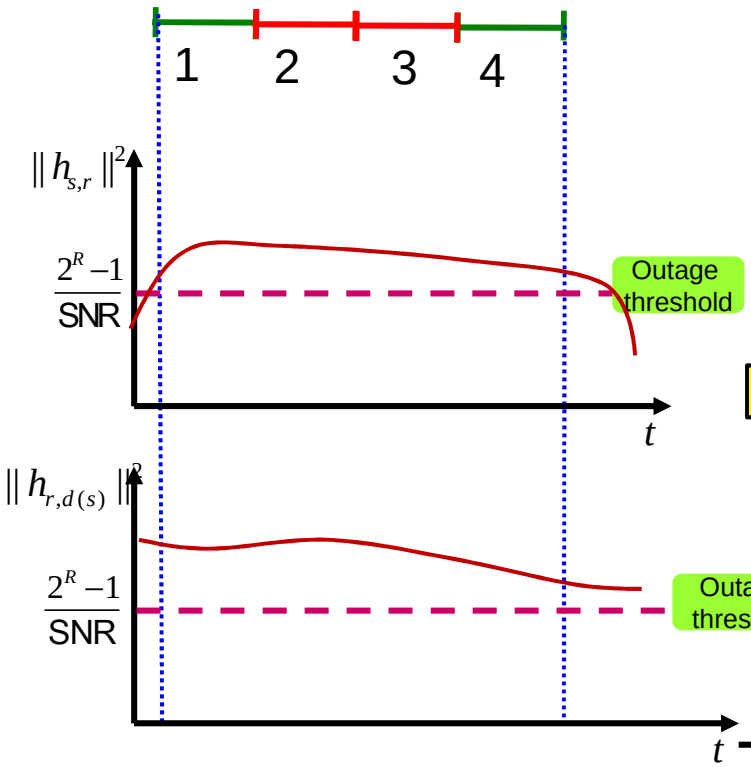
$t > T$

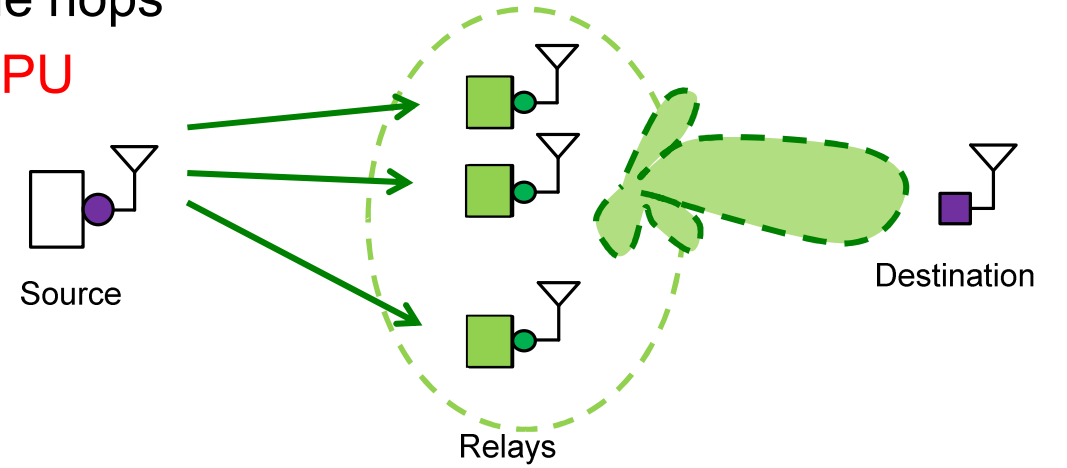


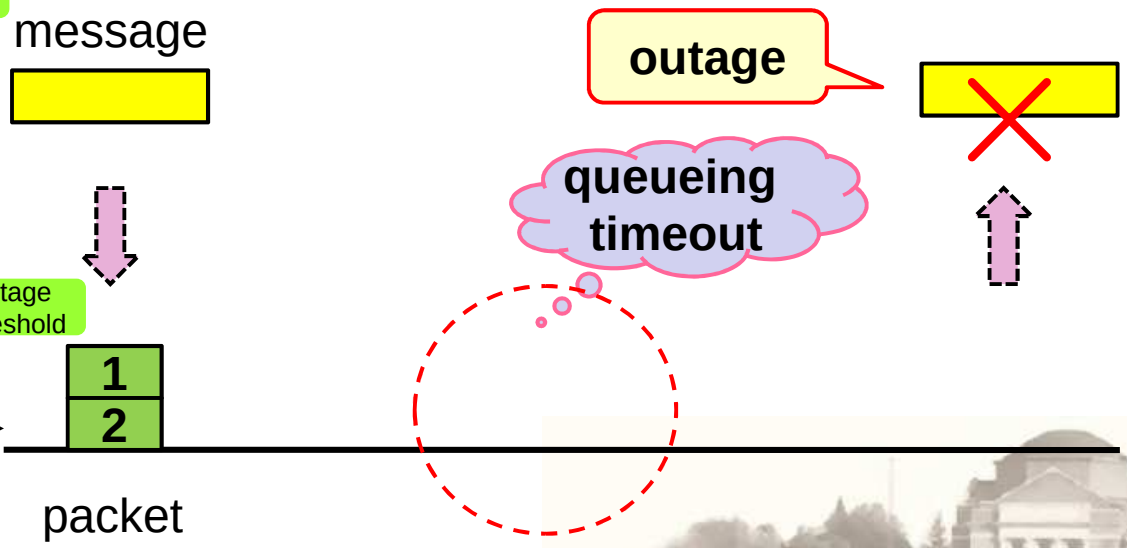



# Beyond PHY

- Outage event $t > T$
  - Fading in either one of the hops
  - queueing timeout due to PU




Slow fading

# Overall Outage

- The overall average outage probability

$$f_{sys} = \Pr\{t > T\} = 1 - s_{phy} \times s_{mac}$$
$$= f_{phy} + (1 - f_{phy}) \times f_{mac}$$

cooperative diversity

$$f_{phy} = f_1 + f_2 = 1 - \sum_{\tilde{K}=K_t}^{K} f(\tilde{K}) \sum_{l=0}^{\tilde{K}-N_r-1} \frac{1}{l!} g_2^l e^{-g_2} \sim g_c \cdot \left(\frac{2^R - 1}{\gamma}\right)^{K+1-K_{th}}$$

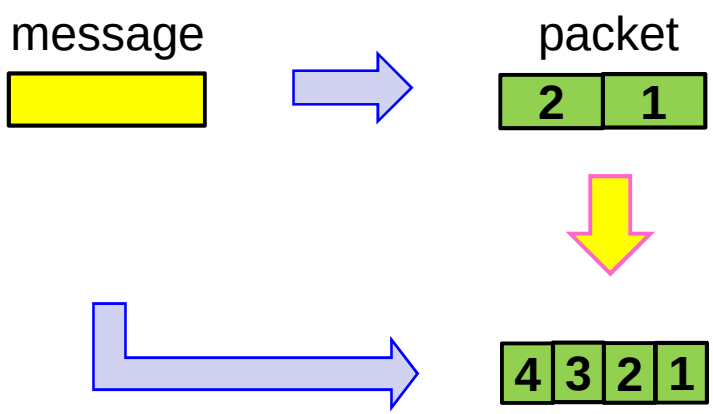
$$f_{mac} = 1 - s_{mac} = 1 - (1-p)^{n_p} \left[\sum_{m=0}^{n_p-1} p^m \left(\sum_{l=0}^{m} c_l \left(\sum_{i=0}^{n_t-2n_p} \binom{m-l+i}{i} p^i\right)\right)\right]$$

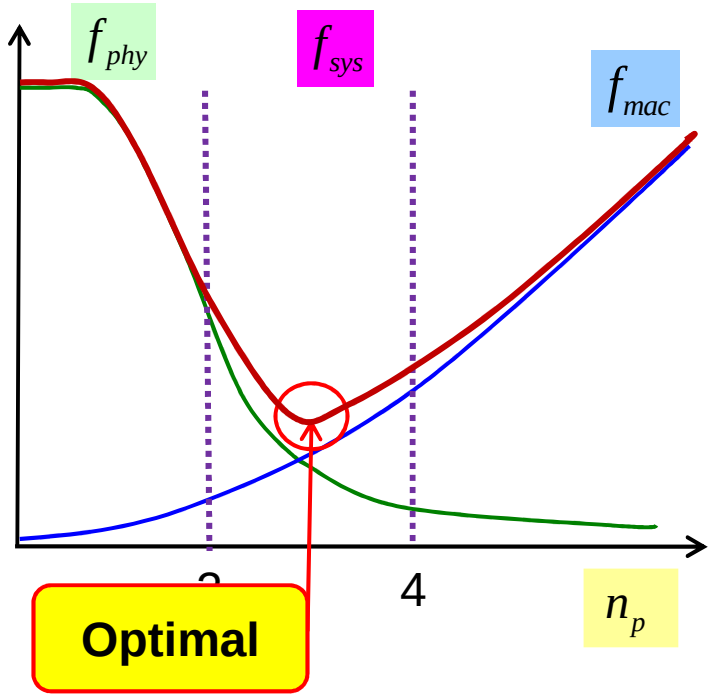
- Scheduling parameter
  - R : physical layer
  - $n_p$: MAC layer

$$R = \frac{L_p}{L_t} = \frac{L n_t}{T n_p} \text{ bit/s,}$$

Can be optimized !

# A Cross Layer Optimization



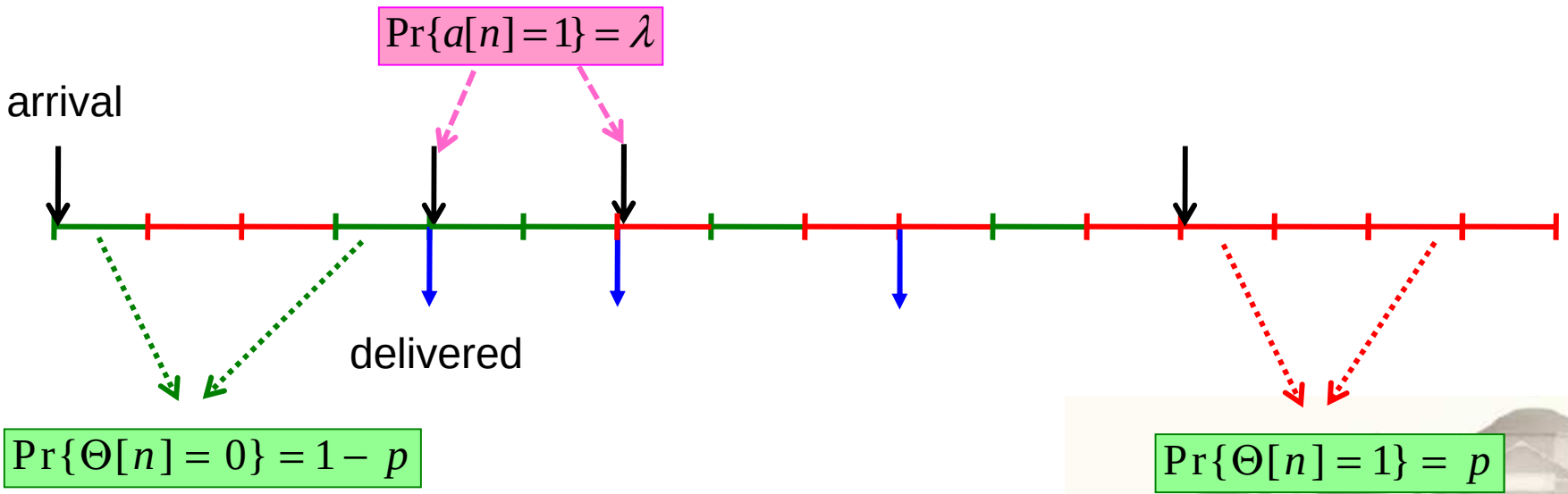




## Optimization problem

$$\min_{n_p \in \{1, \cdots, n_p^m\}} \quad 1 - (1 - f_{phy}(n_p))(1 - f_{mac}(n_p))$$

# Random Packet Arrival

- **Model**
  - Packet arrival follows Bernoulli processes
  - PUs' presence or absence is assumed to be i.i.d. across timeslots
  - Wireless channel follows i.i.d. Rayleigh fading across timeslots
- **Objective**
  - Optimize the end-to-end throughput

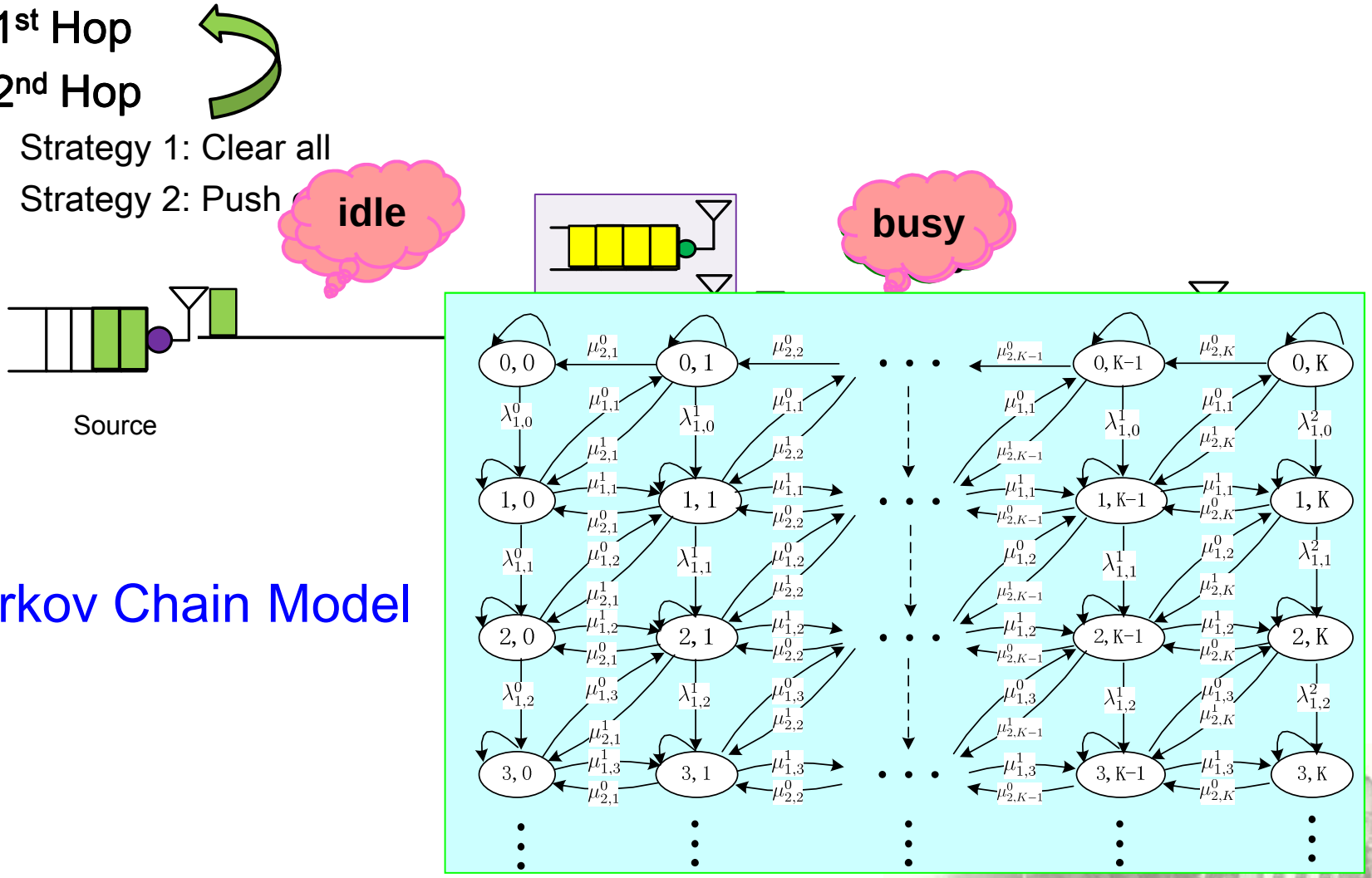


# Opportunistic Scheduling with Token

- Scheduling
  - 1st Hop
  - 2nd Hop

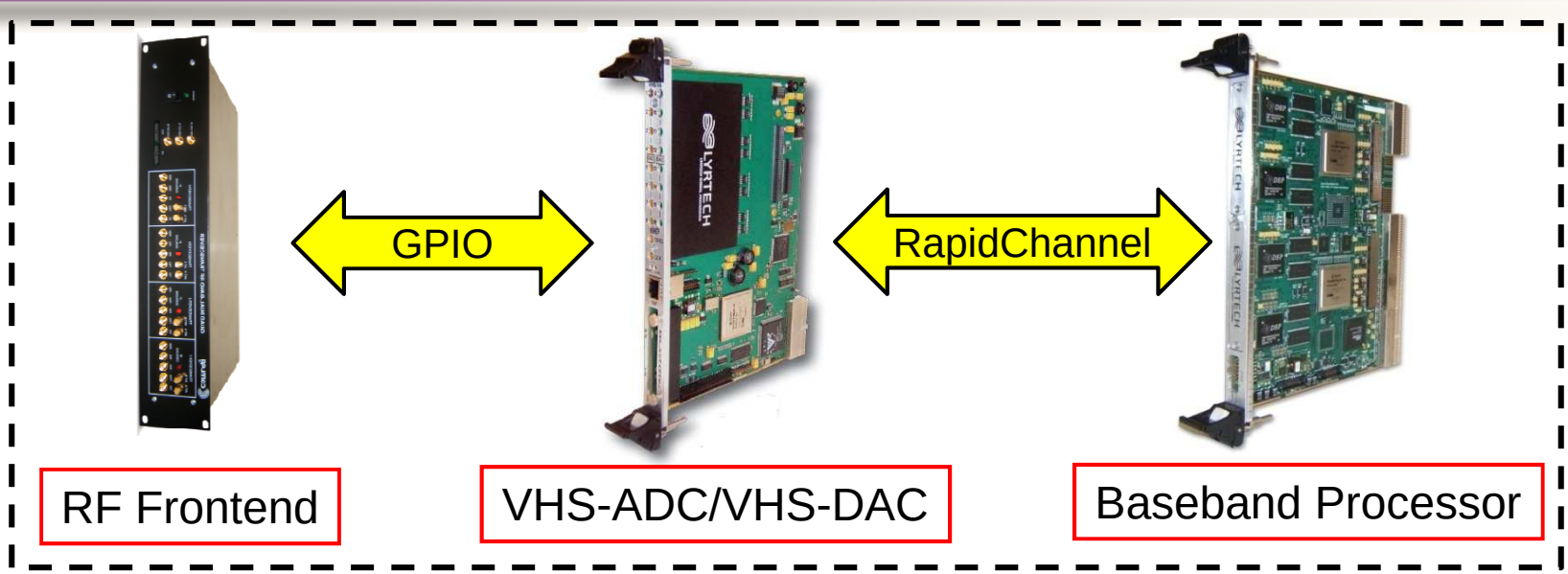
    Strategy 1: Clear all

    Strategy 2: Push




- Markov Chain Model

# Lyrtech Based Prototype Design




# Thanks You!

Q & A