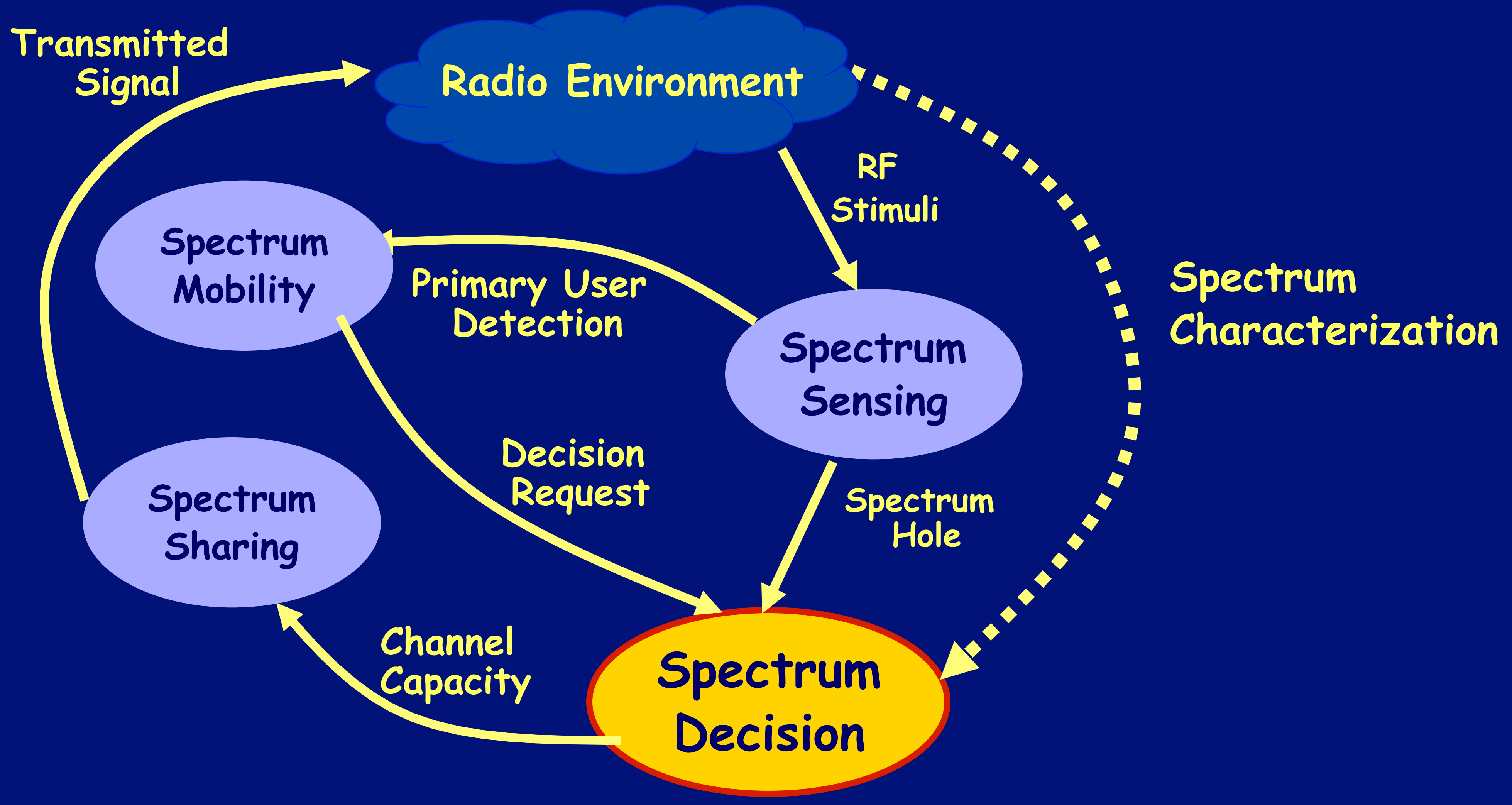
CHAPTER 6.
SPECTRUM DECISION

Spectrum Decision



Spectrum Decision

- Unused spectrum bands will be spread over wide frequency range including both unlicensed and licensed bands.

- Decide for best spectrum band among the available bands

- This notion is called "spectrum decision" and constitutes a rather important but yet unexplored topic in CR networks.

- Spectrum decision is closely related to the channel characteristics and the operations of PUs.

Why Spectrum Decision?

Heterogeneous Spectrum Environment

- Different characteristics of available spectrum bands in terms of capacity, PER, delay, etc.
- Different QoS requirements for applications

→ How to find the best spectrum is an important issue in CR networks

Why Spectrum Decision?

- Dynamic Nature of Underlying Spectrum
  - Due to the PU activity, available spectrum bands vary with time significantly

→ Need a dynamic admission control method to maintain QoS in CR networks (collaborating with spectrum decision)

Spectrum Decision

Usually consists of two steps:

1. Each spectrum band is characterized based on not only local observations of CR users but also statistical information of primary networks.

2. Then, based on this characterization, the most appropriate spectrum band can be chosen.

Spectrum Characterization

- To describe the dynamic nature of CR networks, each spectrum hole should be characterized by considering

  * time-varying radio environment

  * PU activity and

  * the spectrum band information
    (e.g., operating frequency and bandwidth).

Spectrum Decision Framework

W. Y. Lee and I. F. Akyildiz,
"A Spectrum Decision Framework for Cognitive Radio Networks,"
IEEE Trans. on Mobile Computing, Vol. 10, No. 2, pp. 161-174, February 2011

- Provide a spectrum decision framework to support efficient transmissions over dynamic spectrum environment

  - Determine the best spectrum bands according to the QoS requirements of real-time and best effort applications
  - Develop dynamic admission control scheme to maintain QoS of CR network according to the variation of available spectrum bands

Motivations

Switching delay caused by PU activity

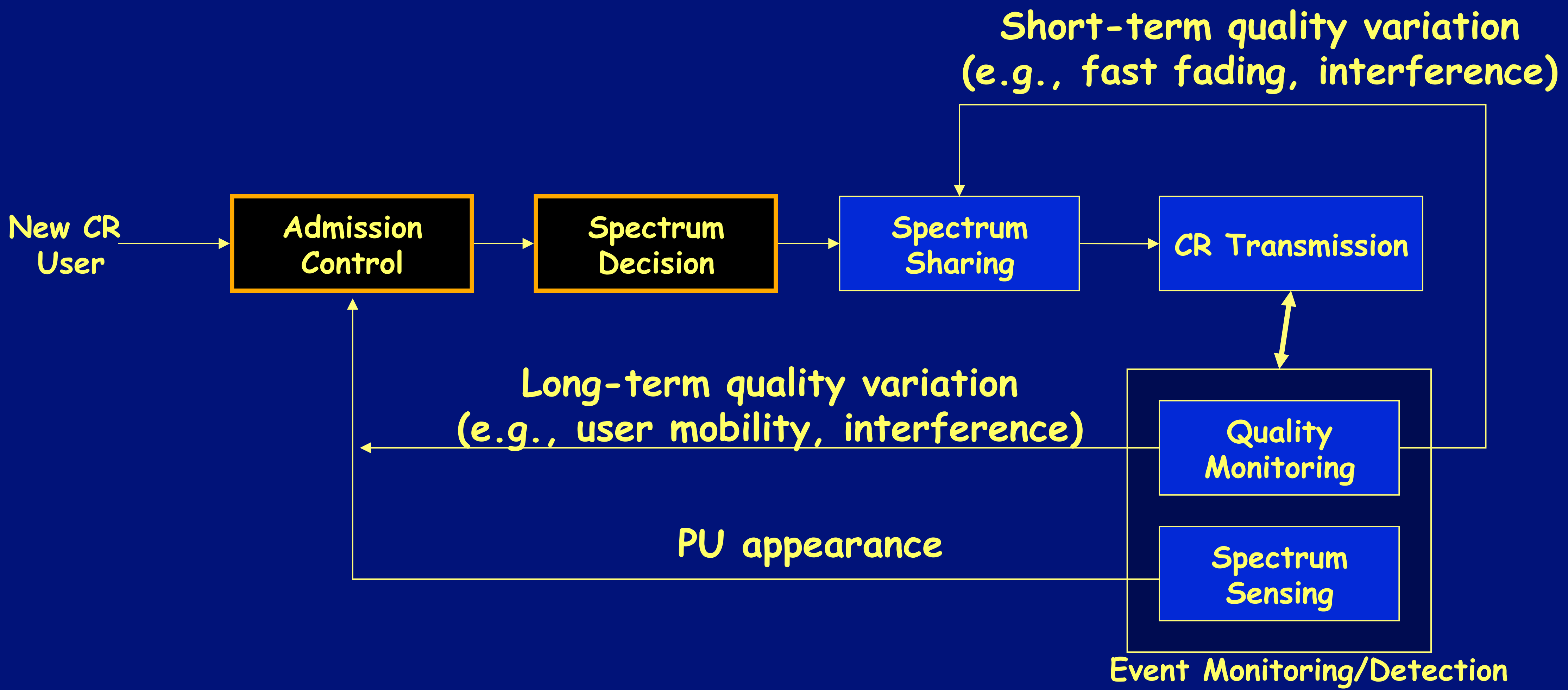
- When PUs are detected, CR users need to switch the spectrum.
- Since available spectrum are spread over a wide frequency range, an additional delay is introduced in switching spectrum

Motivations

PU activity influences the QoS significantly

- The higher PU activity, the higher capacity variation over time due to the switching delay
- Real-time applications should maintain the sustainable rate over time to satisfy their delay constraint.

Spectrum Decision Framework



All is done in BS except CR users do event detection

System Model

- Infrastructure-based Networks
  - BS performs all decision functionalities
- Multi-Spectrum Transmission
- Primary User Activity: ON and OFF Birth-Death Model
  - Arrival Rate (off → on) β, Departure Rate (on → off) α
- Available spectrum bands over a wide frequency range
- Media Access: OFDMA
  - Enable flexible bandwidth utilization

Spectrum "CR Capacity" Characterization

* PU activity
* Sensing efficiency
* Switching delay, and
* Channel condition

Spectrum Characterization – New Features

- **Periodic Spectrum Sensing**
  - Cannot transmit when CR users perform spectrum sensing
- **Spectrum Switching Delay**
  - Exploiting discontiguous spectrum bands over a wide frequency range
  - IEEE 802.22 requirement: channel switching time < 2 sec
  - Conventional wireless system (Qualcomm MediaFLO): physical layer channel switching time = 1.5sec

Spectrum Characterization – CR Capacity

- **CR Capacity**
  - Expected Capacity of Spectrum i
  - Consider the periodic sensing and switching delay

$$C_i^{CR}(k) = E[\mathbf{C'_i(k)}] = \frac{1/\beta_i}{1/\beta_i + \tau} \cdot \eta_i \cdot C'_i(k)$$

Transmission efficiency based on switching delay

Transmission efficiency in periodic sensing

$1/\beta_i$: Average idle time of spectrum i

η_i : Transmission efficiency of spectrum i (comes from the periodic sensing)

$C'_i(k)$: Normalized capacity (C_i/B) of spectrum i at user k (bps/Hz)

τ : Spectrum switching delay

Spectrum Decision Events

- CR User Appearance
  - Newly assign the spectrum band
- Primary User Appearance
  - Vacate the current spectrum band and move to the new one
- Long-Term Channel Quality Variation
  - Select the new spectrum band to satisfy QoS requirements

Spectrum Decision Framework Overview: Spectrum Decision

- Decision Principles
  - MVSD (Minimum Variation based Spectrum Decision) for real-time applications: Select spectrum bands by minimizing capacity variation
  - MCSD (Maximum Capacity based Spectrum Decision) for best-effort applications: Select spectrum bands by maximizing total network capacity

Spectrum Decision Framework Overview: Admission Control

- **Admission Control** (Closely cooperating with spectrum decision)

  * To decide the admission of a new user,
  * Maintain the QoS of current users, and
  * Balance the spectrum resources between real-time and best-effort applications

  - According to the available spectrum and its utilization, use different spectrum decision schemes
    (Conservative / Aggressive MVSDs, MCSD, MCSD with selective / full rate controls)

Decision Methods

Spectrum Decision

Traffic Type:

- Real-Time Traffic: **MVSD** (Minimum Capacity Variance-based Spectrum Decision)
  - **Event Type:** MVSD-SS, MVSD-MS
- Best Effort Traffic: **MCSD** (Maximum Total Capacity-based Spectrum Decision)
  - **Event Type:** MCSD-SS♪, MCSD-MS♪

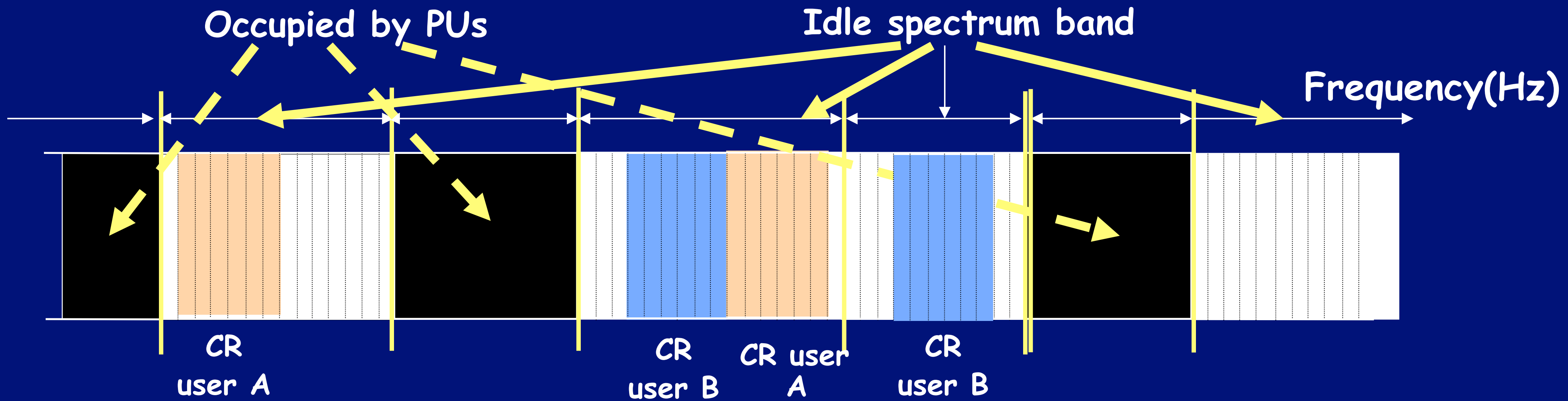
	MVSD-SS	MVSD-MS	MCSD-SS♪	MCSD-MS♪
User Activity	New CR User Appearance	Primary User Appearance	New CR User Appearance	Primary User Appearance
Quality Activity	e.g., User Mobility (User-Based Degradation)	e.g., Increasing Interference (Band-Based degradaton)	User Mobility (User-Based)	Increasing Interference (Band-Based)

SS (Single Selection): BS assigns multiple spectrum bands to a CR user.

MS (Multiple Selection): PU appears; BS needs to handoff multiple CR users occupying that spectrum to another spectrum. We need to determine the decision order of each CR user.

SS: SINGLE SELECTION

- SS (Single Selection): Spectrum Decision for a Single CR User

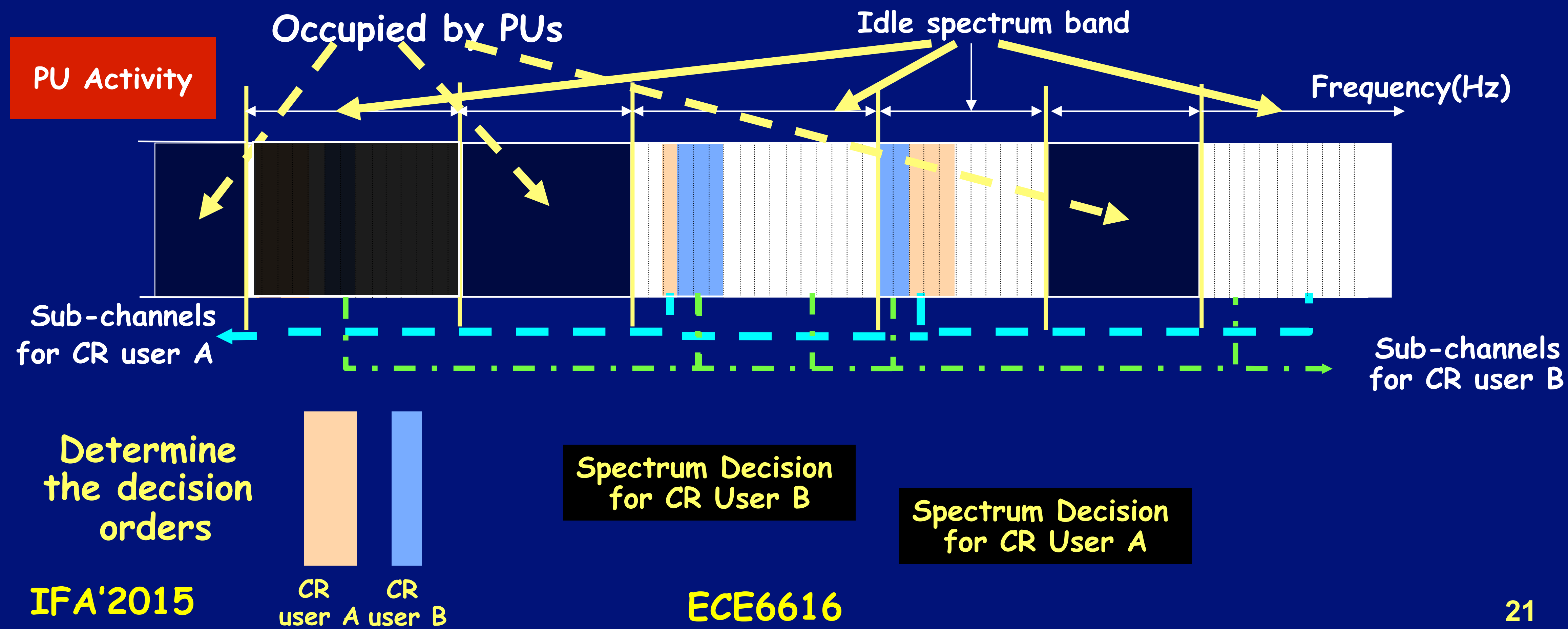


A new incoming CR user C

Spectrum Decision for a CR User C

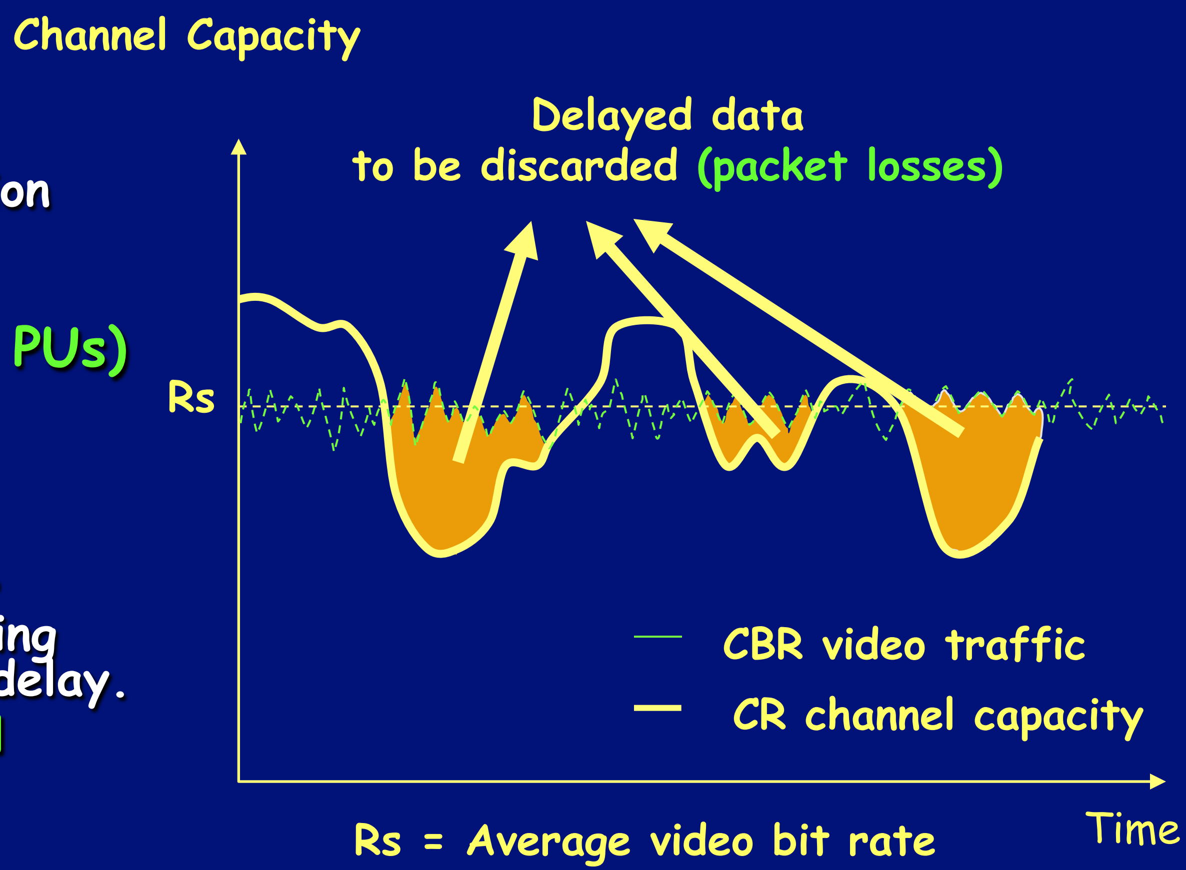
MS: MULTIPLE SELECTIONS

- MS (Multiple Selections): Spectrum Decision for Multiple CR Users



MVSD for Real-Time Applications

- Real-time applications
  - Delay and Jitter Sensitive
  - Require a reliable channel to maintain a sustainable rate over its session time
  - → DELAY BOUND and SUSTAINABLE RATE
- High Variation in Channel Capacity (e.g. PUs)
  - Causes delay and jitter
  - Delayed data will be discarded
- Assumption:
  - Delay bound is already used up for other delay factors such as application processing delay, link-layer delay, and propagation delay.
  - Additional delay from the PU activity will directly affect the loss rate.
- QoS requirement in this paper: Acceptable Loss Rate



Rs = Average video bit rate (Sustainable rate) = Average channel capacity

MVSD: Objective

- Find the spectrum bands
  - To meet the loss rate and sustainable rate constraints (CR User's perspective)
  - To minimize bandwidth utilization (minimum resource utilization) (Network's perspective)

- Minimize BW utilization subject to the constraints on sustainable rate and data loss rate and number of transceivers
  - Mixed with discrete optimization for spectrum selection and cont. optimization for resource (BW) allocation
  - Not easy to solve
- Proposed a three-step spectrum decision

MVSD-SS: Step 1. Spectrum Selection

- Select the spectrum bands
  - To consider channel quality and PU activity simultaneously

    (real-time applications prefer the spectrum with higher CR capacity C_i^{CR} and lower PU activity β_i)

  - To exploit multiple transceivers

    (# of selected bands x_i is restricted to the # of transceivers N)

  - To maintain a sustainable rate over its session time, i.e.,

    selected spectrum bands have enough BW for resource allocation

A CR user k selects the spectrum bands according to linear integer optimization

$$Maximize: \sum_{i=1}^{M} \frac{C_i^{CR}(k)}{\beta_i} x_i$$

$$Subject\ to: \sum_{i=1}^{M} x_i = N$$

$$C_i^{CR}(k) \cdot W_i \cdot x_i \geq \frac{R_S(k)}{N} \quad (i = 1, \ldots, M)$$

$R_S(k)$: Sustainable rate of user k

x_i : Selection vector {0,1}

W_i : Available bandwidth of spectrum i

N : # of transceivers

M : # of currently available spectrum bands

MVSD-SS: Step 2. Resource Allocation

- CR network determines the BW to meet the constraints on both sustainable rate $R_s(k)$ and the target data loss rate P_{loss}^{th}.

- To allocate the bandwidth properly, we derive

  * the total capacity $R_T(k)$ and

  * data loss rate $P_{loss}(k)$ of a user k.

MVSD-SS: Step 2. Resource Allocation

- When the BW $w_i(k)$ is allocated to the selected spectrum i for a user k, the expected total capacity is

$$E[R_T(k)] = \sum_{i=1}^{M} C_i^{CR}(k) \cdot w_i(k) = R_S(k)$$

To satisfy the QoS requirement
→ must be equal to $R_s(k)$

MVSD-SS: Step 2. Resource Allocation

* Data loss rate $P_{loss}(k)$ formula is complex and is not easy to optimize. (In the paper/Appendix)
* Since the variance of the total capacity is proportional to the data loss rate (see Appdx), we use the variance of the total capacity for resource allocation instead of data loss rate

$$var[R_T(k)] = \sum_{i \varepsilon S} \frac{\frac{1}{\beta_i}\eta_i\left(\frac{1}{\beta_i} + \tau - \frac{1}{\beta_i}\eta_i\right)}{\left(\frac{1}{\beta_i} + \tau\right)^2} \cdot c_i(k)^2 w_i(k)^2$$

where S is the set of selected spectrum bands

$c_i(k)$ is normalized capacity of spectrum band i for user k

$w_i(k)$ is the BW of spectrum band i for user k

β_i is PU arrival rate to spectrum band i

η_i is transmission efficiency of spectrum band i

τ is the spectrum switching delay

MVSD-SS: Step 2. Resource Allocation

CR network determines the optimal BW $w_i(k)$ of the selected spectrum bands by minimizing the variance of the total capacity to satisfy the sustainable rate and available BW

$$Minimize: \quad \mathrm{var}[R_{\mathrm{T}}(k)]$$

$$Subject\ to: \quad \sum_{i=1}^{M} C_i^{CR}(k) \cdot w_i = R_S(k)$$

$$w_i < W_i \quad (\forall i \in A)$$

$\mathrm{R_T(k)}$: the user capacity at user k

w_i : BW allocated to spectrum i

A : a set of selected spectrum bands

MVSD-SS: QoS Guarantees

- By the Lagrange Multiplier Method, the optimal BW is obtained

$$w_i(k) = \frac{R_s(k)(\frac{1}{\beta_i} + \tau)}{c_i(k)\eta_i \frac{1}{\beta_i}\eta_i(\frac{1}{\beta_i} + \tau - \frac{1}{\beta_i}\eta_i)\sum_{i \varepsilon S} \frac{\frac{1}{\beta_i}}{(\frac{1}{\beta_i} + \tau - \frac{1}{\beta_i}\eta_i)}}$$

MVSD-SS: Step 3: QoS Checkups

- Optimization based on minimum variance can guarantee the minimum data loss rate but may not always satisfy the target loss rate
- If $P_{loss}(k) > P_{loss}^{th}$ after optimization, then we need to do
- Aggressive Approach
  - By sacrificing BW utilization (i.e., increasing bandwidth), find the spectrum band to meet the acceptable loss rate.
- Conservative Approach
  - By reducing sustainable rate through negotiations, find the spectrum band to meet the acceptable loss rate.

Minimum Variance Spectrum Decision-MS ♪

- Multiple users may need new spectrum bands
  - Need to decide the order of spectrum decision for CR users which need the new spectrum band

Minimum Variance Spectrum Decision-MS ♪

Procedure

- Let $R_{lost}(k)$ be the lost capacity of user k resulting from spectrum switching.
- Loss rate of user k is obtained as $R_{lost}(k)/R_s(k)$

- Select CR users in the order from highest to the lowest loss rates.

- After that they select a single spectrum band with the highest $C_i^{CR}(k)/Beta_i$ to meet the $R_s(k)$ and accordingly allocate the BW of all assigned spectrum bands.

MCSD for Best Effort Applications

- Best Effort Application
  - No strict QoS requirement
- Objective
  - Maximize total network capacity, i.e., throughput
- Optimal Decision
  - Spectrum decision over all current active CR users

  → High computational complexity

- Assume current assignment is optimal, propose sub-optimal method

MCSD-SS

- Maximize the decision gain (defined as the sum of the difference)
  - Between Expected capacity gain: when a new user k joins a spectrum band
  - And Expected capacity loss (when other users in that spectrum)

$$Maximize: \quad \sum_{i}^{M} (G(i, C_i^{CR}(k), W_i) - L(i, C_i^{CR}(k), W_i)) x_i$$

$$Subject\ to: \quad \sum_{i=1}^{M} x_i = N$$

$G(.)$: Expected capacity gain
$L(.)$: Expected capacity loss
x_i : Selection vector {0,1}

W_i : Available bandwidth of spectrum i
N : # of transceivers
M : # of currently available bands

MCSD for Best Effort Applications

- Assume the spectrum sharing algorithm assigns the BW to the users fairly.
- Then the capacity of each user competing for the same spectrum can be approximated as

$$[C_i^{CR}(k) * W_i / n_i]$$

where n_i represents the number of best effort users currently residing in spectrum *i*.

MCSD for Best Effort Applications

- Based on this capacity, the decision gain can be derived as follows:

$$G_i(\cdot) - L_i(\cdot) = \frac{C_i^{CR}(k)\cdot W_i}{n_i+1} - \sum_{j\in\varepsilon_i}\left(\frac{1}{n_i} - \frac{1}{n_i+1}\right)\cdot C_i^{CR}(j)\cdot W_i$$

Where ε_i is the set of the best-effort CR users currently residing in spectrum band *i*.

The first term represents the capacity gain of a new CR user *k*

The second term describes the total capacity loss of n_i CR users in the spectrum *i* due to the addition of a new CR user.

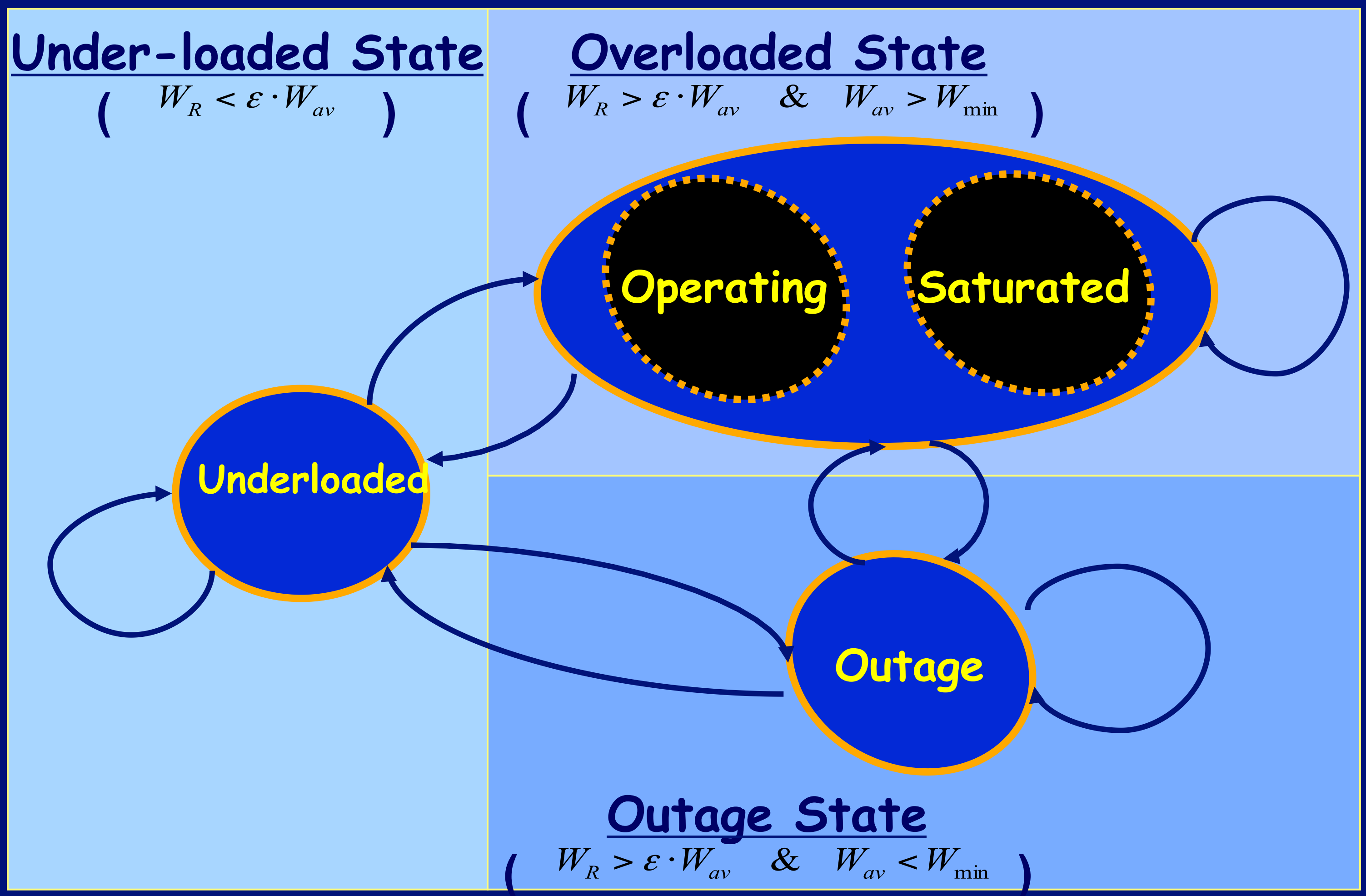
MCSD-MS

- Multiple users need their new spectrum bands
  - Need to decide the order of spectrum decision
- Procedure
  - Select a CR user with highest decision gain
  - Assign this CR user to the spectrum using opt. eq.
  - Based on the current allocation, repeat the procedure for the rest of users

Admission Control

- Available spectrum resource varies over time
  - Need additional functionality to perform spectrum decision adaptively dependent on the network/spectrum condition
- Admission Control
  - Decide the acceptance of a new incoming CR user without influencing the QoS of currently transmitting users
  - Maintain the QoS of currently transmitting users by considering the fluctuation of available BW
  - Balance bandwidth between real-time and best effort applications

Spectrum States for Resource Management



In PU appearance, the overloaded state can be classified as follows:

- If available BW is enough for spectrum decision → Operating
- Otherwise → Saturated

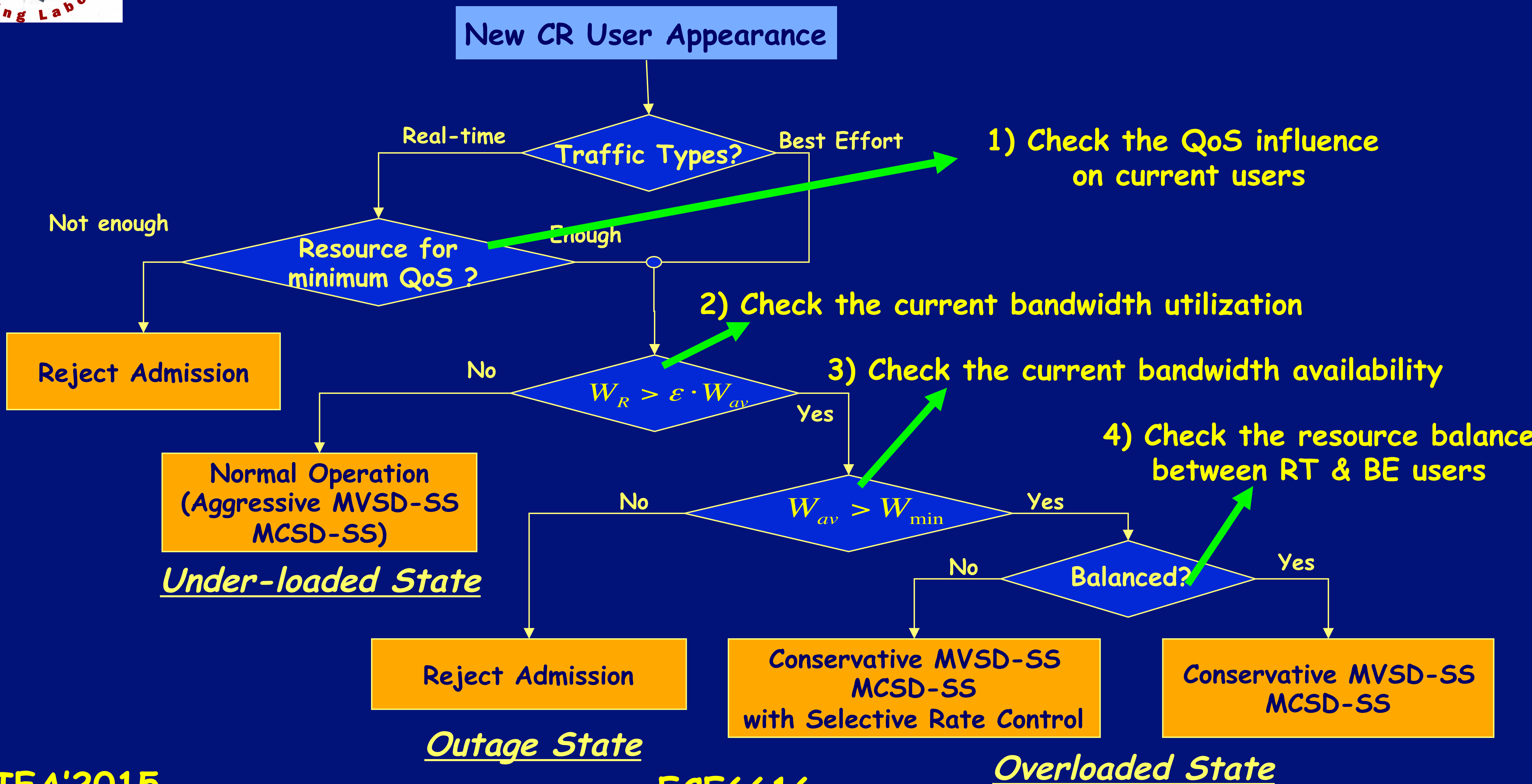
W_{av} Available BW

W_R BW occupied by RT users

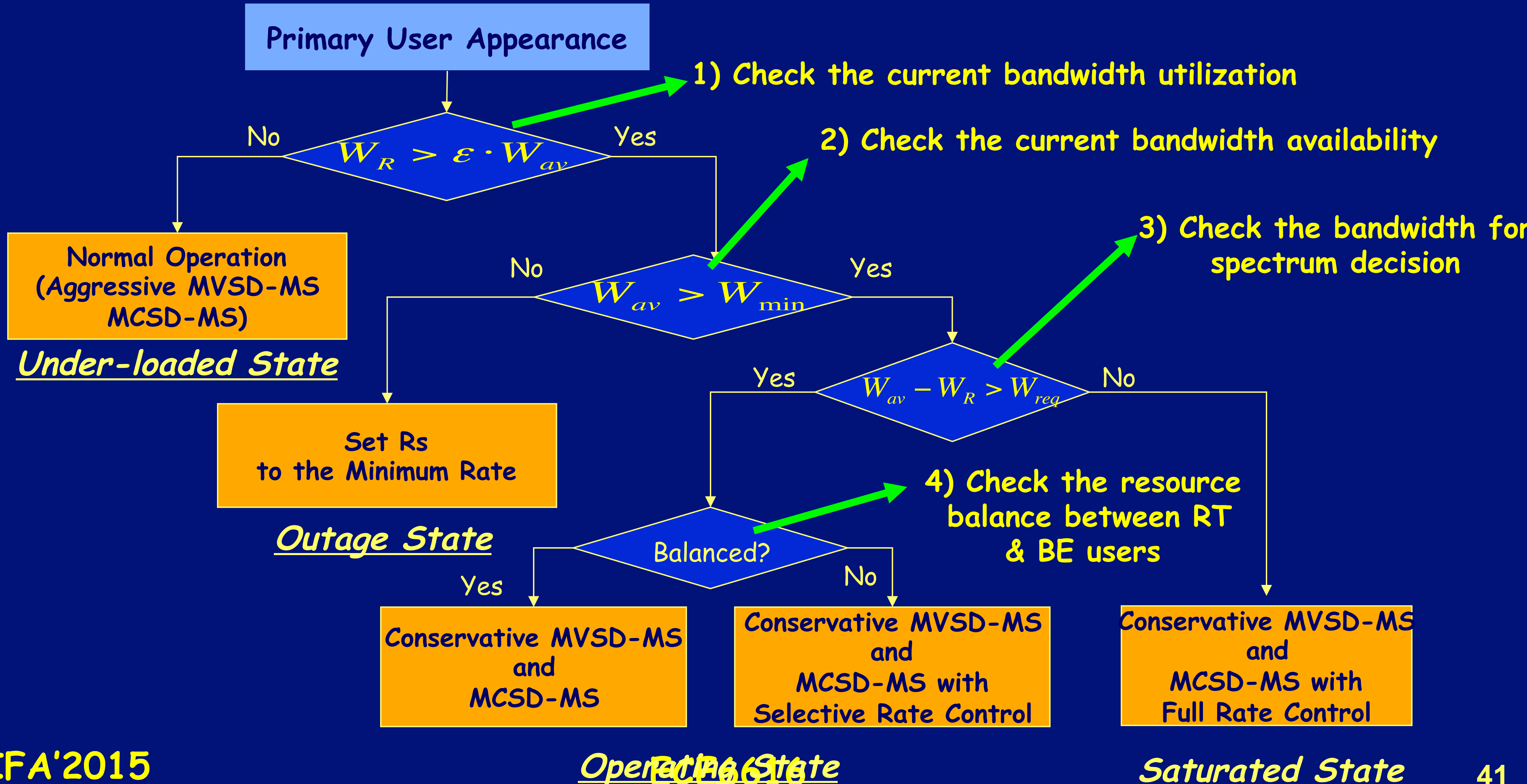
W_{min} Minimum BW for QoS guarantee

ε Overload coefficient (0.5)

Admission Control for CR User Appearance



Admission Control for PU Appearance



Conclusions

- Spectrum decision provides capability
  - To decide the best spectrum band
  - By considering both different QoS requirements and different spectrum characteristics
- Propose a QoS aware spectrum decision framework
  - MVSD for real-time application
  - MCSD for best-effort application
  - Dynamic admission control
- The proposed framework shows good performance both in terms of QoS guarantees and balancing spectrum resources

Open Research for Spectrum Decision

→ Determine not only spectrum bands (operating frequency, bandwidth) but also transmission parameters (transmission power, modulation, channel coding, upper layer protocols, etc)

i.e., cooperation and reconfiguration needed..

Open Research for Spectrum Decision

- Primary Network Modeling and Analysis
- Primary User Behavior Predictivity Models