CHAPTER 5.3.
OPTIMAL SENSING TIME

W. Y. Lee and I. F. Akyildiz,
"Optimal Spectrum Sensing Framework for Cognitive Radio Networks",
IEEE Transactions on Wireless Communications, Oct. 2008.

Optimal Sensing Framework: Overview

Solve

- * Interference Avoidance and
- * Spectrum Efficiency Problems

CONTRIBUTIONS

1. Derivation of Optimal Sensing Parameters
   → maximize the sensing efficiency subject to interference constraints.

2. Development of Spectrum Selection and Scheduling methods
   → to select the best spectrum bands for sensing
   in order to maximize the sensing capacity.

3. Development of an Adaptive and Cooperative Spectrum Sensing Method
   → sensing parameters are optimized adaptively based on the
   number of cooperating users.

Motivation

- Spectrum Sensing
  - To provide more spectrum access opportunities to CR users (Sensing Efficiency)

    without interference to the primary network (Interference Avoidance)
  - Sensing accuracy is very important !!

Motivation

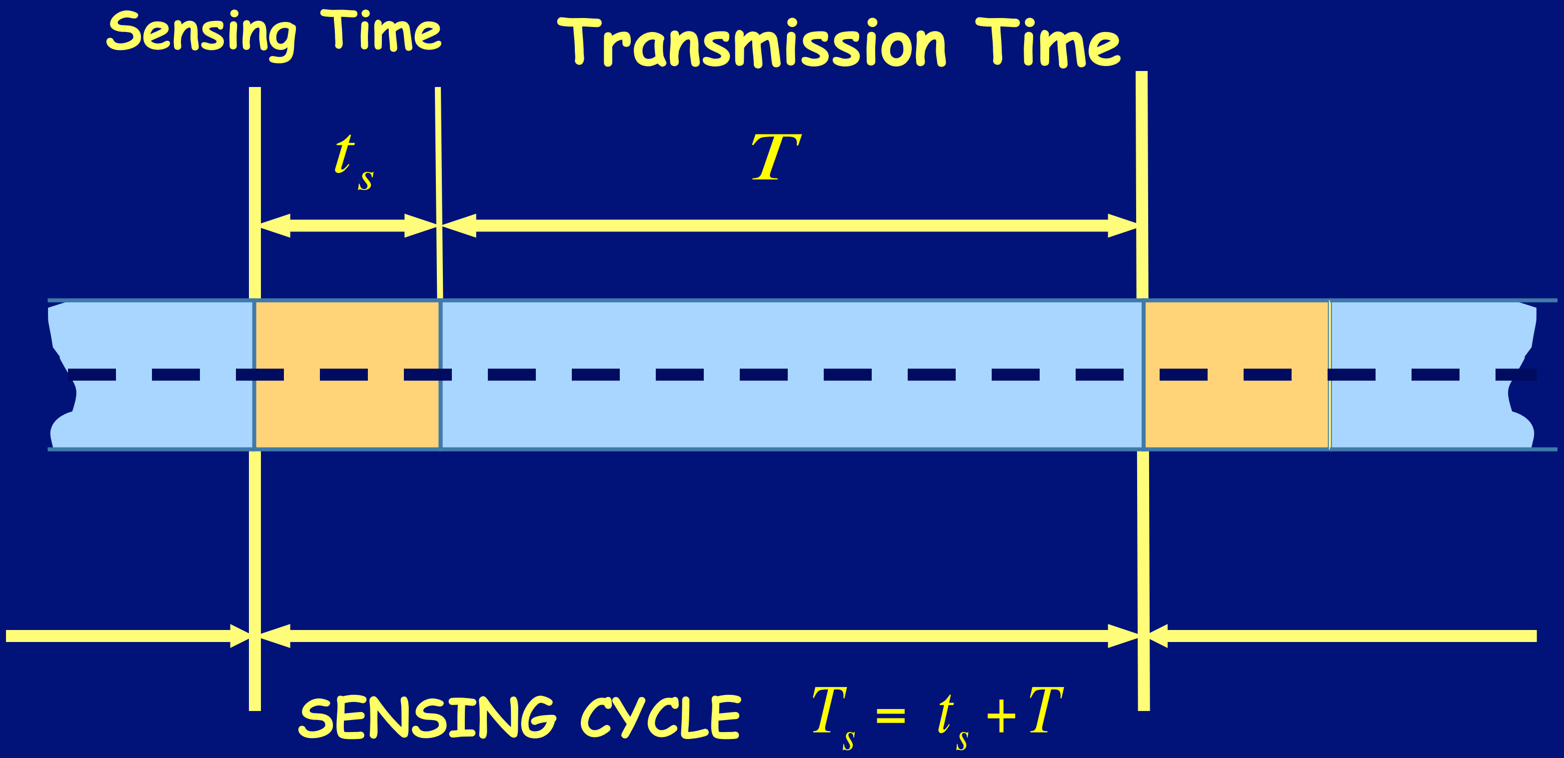
- Hardware Limitations
  - RF front-end cannot differentiate between the PU & CR user signals
  - CR users are not able to perform the transmission and sensing tasks at the same time

Periodic Spectrum Sensing

- Sensing and transmission operations are performed in a periodic manner with separate observation (SENSING) and transmission periods.

- CR users should stop their transmissions during the sensing time to prevent false alarms from unintended CR signals.

Periodic Sensing Structure



Objective

Trade-off between interference and sensing efficiency:

- Longer observation (SENSING) time → higher sensing accuracy → less interference → shorter transmission times !

- Longer transmission time → lower sensing performance → higher interference due to the lack of sensing information.

Objective

- Observation (SENSING) time and transmission time influence both the spectrum efficiency and interference avoidance.

- Proper selection of these sensing parameters is the most critical factor influencing the performance of CR networks.

ASSUMPTIONS

CR users are assumed to be aware of the following a priori spectrum information about primary networks:

- Centralized (INFRASTRUCTURE BASED/CELLULAR TYPE) Network
- Energy Detection Sensing scheme
- Bandwidth and Operating Frequency Range of Primary Networks
- Minimum SNR

  The worst signal level needed to decode the received signal

ASSUMPTIONS

- Acceptable Interference Ratio
  - CR networks cannot guarantee interference-free transmission
  - Instead exploit → INTERFERENCE CONSTRAINT:

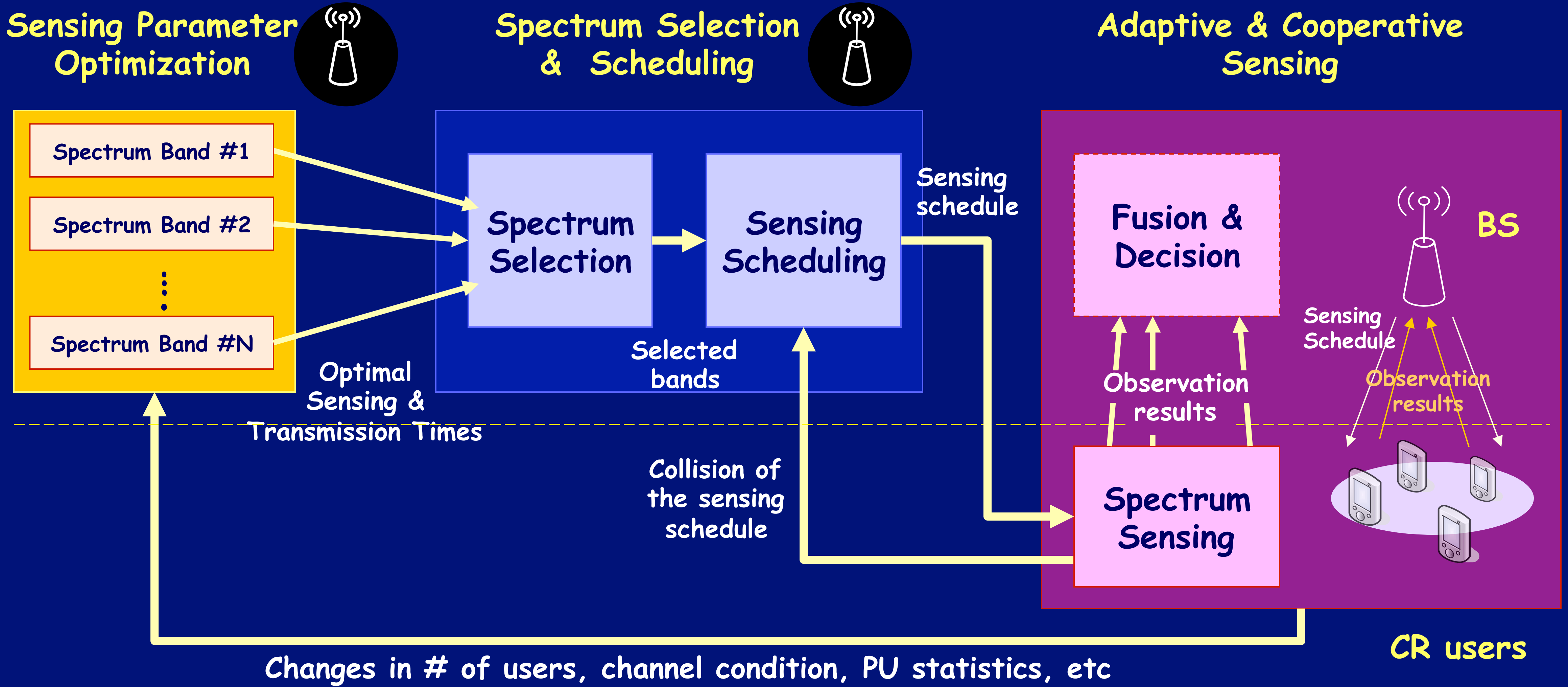
    Defined as the Maximum Interference Level (more suitable) or
    Maximum Interference Probability (more practical)
    that primary networks can tolerate

- Primary User Activity
  - Traffic statistics of the primary networks

Primary User Activity Model

- Two state birth-death process with death rate α and birth rate β
  - ON (Busy) state: period used by PUs
  - OFF (Idle) state: unused period.
- Since each user arrival is independent, each transition follows the Poisson arrival process.
- The length of ON and OFF periods are exponentially distributed (Exponentially Distributed Interarrivals)♪

Optimal Spectrum Sensing Framework



PART 1:
Sensing Parameter Optimization: Overview

The BS initially optimizes the sensing parameters (sensing time and transmission time) of all available spectrum bands according to interference constraints, PU statistics, channel conditions, etc

PART 1:
Sensing Parameter Optimization: Overview

Determine the optimal sensing time and optimal transmission time for each single spectrum band

- However, CR networks may have multiple available licensed bands
- Our proposed optimization scheme can be applied to each licensed band independently.

→ Thus, each spectrum has its own optimal sensing parameters

→ (optimal sensing times and transmission times are different for each spectrum).

EXAMPLE:
Sensing Parameter Optimization

Bands 1,2,3 have different optimal sensing parameters according to their spectrum characteristics as follows:

	Optimal Sensing Time	Optimal Transmission Time	Sensing Cycle
Band 1	10msec♪	40msec	10 + 40 = 50msec
Band 2	20msec♪	10msec	20 + 10 = 30msec
Band 3	15msec	30msec	15 + 30 = 45msec
…			

All these optimizations are calculated by BS, and once BS determines optimal sensing parameters for each band, CR users should use these parameters (optimal sensing parameters for each band) for their sensing operations.

EXAMPLE:
Sensing Parameter Optimization: Overview

- If the CR user wants to detect the PU signal on a certain band, it should use its RF front-end periodically according to the optimal sensing parameters of that band.

In the example:

- In case of sensing Band 1, the CR user should use the RF front-end for 10msec (optimal sensing time) per a sensing cycle (50msec).

PART 2:
Spectrum Selection: Overview

- In sequential sensing, the RF front-end can sense only a single spectrum band at a time.

- For spectrum sensing over multiple bands, the RF front-end should sense one spectrum band after another.

- Furthermore, each band requires a certain level of RF-front-end utilization ratio according to its optimal sensing parameters

EXAMPLE:
Spectrum Selection

Bands 1, 2, 3 require 0.2 (10msec/50msec), 0.67 (20msec/30msec), and 0.33 (15msec/45msec) RF Front-end utilization ratios, respectively.

* RF Front-end utilization ratio of a certain band

- Ratio of optimal sensing time to the optimal sensing cycle.
- Represents how much RF front-end should serve sensing that band.

REMARK:
If the CR user has a single RF frond-end, and the sum of RF front-end utilization ratios of all spectrum bands is greater than 1, it cannot sense all of them.

EXAMPLE: Single RF Front End senses up to two bands

(Bands 1 & 2, Bands 1 & 3, or Bands 2 & 3)

PART 2:
Spectrum Selection: Overview

- BS selects spectrum bands → to maximize the total capacity subject to the sensing capability of CR users (# of sensing RF front-ends that a CR user has).

* Conditions to achieve higher spectrum capacity

- Wider bandwidth and better channel condition
- Lower PU activity and higher sensing efficiency (Uniqueness in CR networks)

PART 2:
Sensing Scheduling: Overview

Sensing operation of the selected bands may also experience:

* Each spectrum band may have different operational parameters, and hence different sensing cycles.

→ Each band may collide its sensing cycle with the sensing cycles of other bands, i.e., more than one band may want to use the sensing front-end at the same time

Example:
Sensing Scheduling

Assume that a CR user senses Bands 1 and 2 with the single RF front-end:

Band 1: 10msec sensing time and 50msec sensing cycle:

- CR user should sense Band 1 periodically according to the sensing cycle (0-10msec, and 50-60msec, 100-110msec, ---).

Band 2: 20msec sensing time and 30msec sensing cycle:

- CR user must sense Band 2 during (10msec-30msec, 40msec-60msec, 70-90msec, ….

- We can see there is a conflict between sensing schedules of Bands 1 and 2 (50-60msec) → RF front-end cannot sense both bands at the same time.

(Need Coordination !!!)
(This is just a simple example to show how sensing schedules collide)

Part 2:
Sensing Scheduling: Overview

Thus, BS determines the sensing schedule of the selected bands,

i.e., determines when and which spectrum can use the sensing RF front-end,

called Sensing Scheduling

Part 3:
Adaptive & Cooperative Sensing: Overview

- After sensing parameter optimization, BS informs its CR users of optimal sensing parameters of selected bands and sensing schedules (considering when and which band the CR user senses)

- Accordingly CR users sense the selected spectrum bands, feed the results back to BS.

- BS determines the availability of each band according to its fusion rule.

- If there is any change in network conditions to affect the optimal sensing parameters such as # of users, PU activities, etc, the BS re-optimizes the sensing parameters and repeats the above processes.

Optimal Spectrum Sensing Framework: Summary

- **PART 1: Sensing Parameter Optimization**

  Finding optimal sensing time and transmission time

  - Based on radio characteristics, the BS initially determines the optimal sensing parameters for each spectrum band

- **PART 2: Spectrum Selection and Scheduling**

  Determining best spectrum bands and their sensing schedule

  - BS selects the best spectrum bands for sensing subject to the sensing RF front-end constraint and accordingly configures the sensing schedules of selected bands.

Optimal Spectrum Sensing Framework: Summary

- PART 3: Adaptive and Cooperative Sensing

  Sense the spectrum bands and determine their availability in a cooperative manner

  - CR users monitor spectrum bands based on the optimized sensing schedule and report sensing results to the BS.
  - Using these results, BS determines the spectrum availability.
  - If BS detects any changes which affect the sensing performance, sensing parameters need to be re-optimized and announced to CR users

PART 1:

SENSING PARAMETER OPTIMIZATION:

SOME DEFINITIONS

- **Interference Ratio:** T_I is the expected fraction of the ON state (transmission time of PUs) interrupted by the tx of CR user

- **Maximum Outage Ratio:** T_p is the maximum fraction of interference that primary networks can tolerate.

- **Sensing Efficiency**

  η is the ratio of the transmission time over the entire sensing cycle:

$$\eta = T / (T + t_s)$$

PART 1: Sensing Parameter Optimization

- **Goal of Spectrum Sensing:**
  - Achieve accurate detection probability as well as high sensing efficiency which are related to T and t_s

  Formulate the optimization problem to maximize the spectrum efficiency satisfying interference constraint T_P

$$\text{Find} : \quad T^*, \quad t_s^*$$

$$\text{Maximize} : \quad \eta = \frac{T}{T + t_s}$$

$$\text{Subject to} : \quad T_I < T_P$$

η: Spectrum efficiency

T_I: Interference ratio

T_P: Maximum interference limit

Part 1: Sensing Parameter Optimization

- Find Optimal Sensing Parameters

  (Observation (sensing) Time t_s and Transmission Time T)

STEPS:

- MAP (Maximum a posteriori)-based Energy Detection Model
- Analytical Interference Model
- Optimization Procedure for sensing parameters based on the MAP and the interference model

Maximum A Posteriori (MAP) Energy Detection for Spectrum Sensing

A maximum likelihood (ML) detection is widely used for energy detection without considering the ON and OFF state probabilities in the literature so far.

Since the MAP energy detector is optimal, we use MAP based energy detection and its decision criterion based on the PU activities.

Maximum A Posteriori (MAP) Energy Detection for Spectrum Sensing

- Hypothesis Test for CR users

$$r(t) = \begin{cases} n(t) & H_0 \quad (No\ PU\ Signal) \\ s(t) + n(t) & H_1 \quad (PU\ Signal) \end{cases}$$

- *A posteriori* Probabilities from the PU Activity Model

$$P_{on} = \frac{\beta}{\alpha + \beta} \qquad P_{off} = \frac{\alpha}{\alpha + \beta}$$

α: death rate (on -> off)
β: birth rate (off -> on)
P_{on}: prob for the period used by PUs
P_{off}: prob. of idle period

Maximum A Posteriori (MAP) Energy Detection for Spectrum Sensing

- From the definition of MAP detection → the Detection and False Alarm Probabilities

$$P_d = \Pr[Y > \lambda \mid H_1] \cdot P_{on} = \overline{P_d} \cdot P_{on}$$

$$P_f = \Pr[Y > \lambda \mid H_0] \cdot P_{off} = \overline{P_f} \cdot P_{off}$$

$\overline{P_d}$: Detection Prob. (ML detection)

$\overline{P_f}$: False Alarm Prob. (ML detection)

λ is the decision threshold of the MAP detection.

How do we determine λ ??

CONVENTIONAL APPROACH

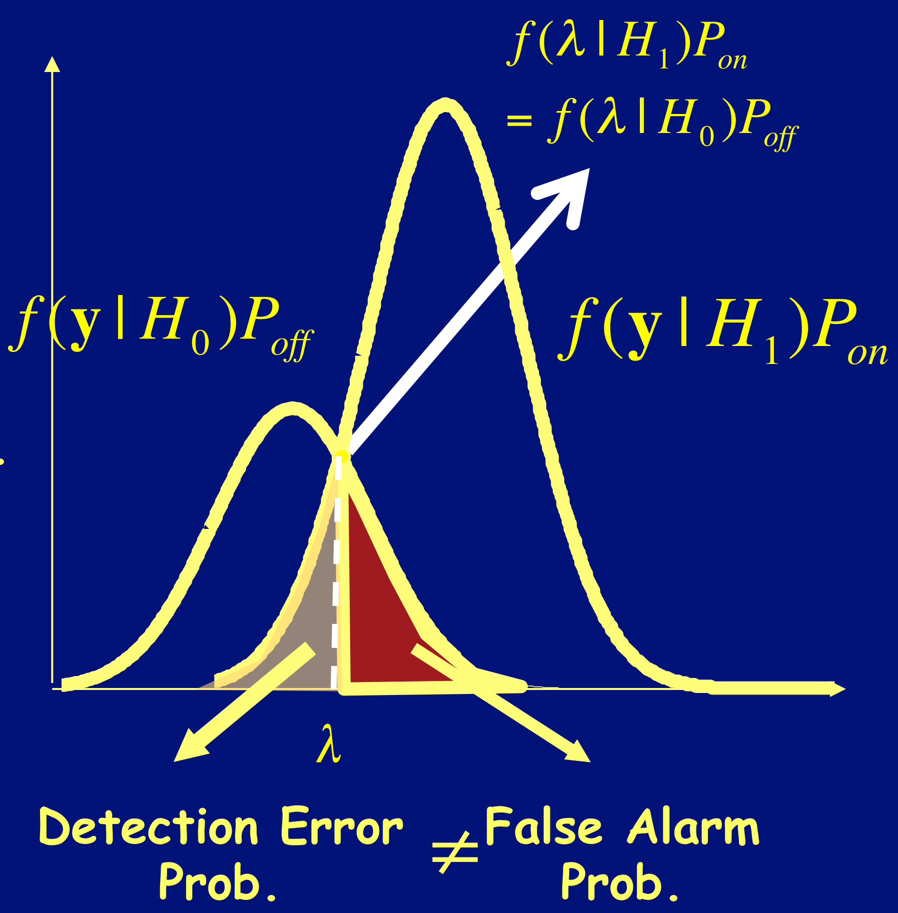
λ is determined to minimize total error probability, i.e, the sum of false alarm and miss detection probabilities:

$$f(\lambda \mid H_1)P_{on} = f(\lambda / H_o)P_{off}$$

where $f(y/H_1)$ and $f(y/H_0)$ are pdfs of the received signal through the occupied spectrum and the idle spectrum.

PROBLEM:

One of the error probabilities may be greater than the other → e.g. if False Alarm Prob. > Detection Error Prob., detects less spectrum opportunities.



In this point, the sum of miss-detection & false alarm probabilities is minimized

EXPLANATION: Conventional Approach

- λ is determined to minimize total error probability, i.e., the sum of false alarm and miss detection probabilities
  - Obtained as the intersection of $f(y/H_1)$ and $f(y/H_0)$.
- In the detection theory →

a) Miss-detection probability is related to interference avoidance.

- Higher miss-detection probability leads to higher interference to PUs.

b) False alarm probability is related to the discovery of spectrum opportunity

- Under higher false alarm probability, CR user misses more idle spectrum.

EXPLANATION: Conventional Approach

- However,

  One of the error probabilities may be greater than the other!!

  (critical issue in spectrum sensing!).

e.g., if false alarm prob. > miss-detection prob

CR user can detect less spectrum opportunities !

-Not desirable since both

* Interference avoidance to PUs and

* Discovery of spectrum opportunity

are important in spectrum sensing.

How do we determine λ ?? Proposed Method

Instead of minimizing total error probability, λ is determined to balance detection error and false alarm probabilities, i.e., to make both probabilities equal.

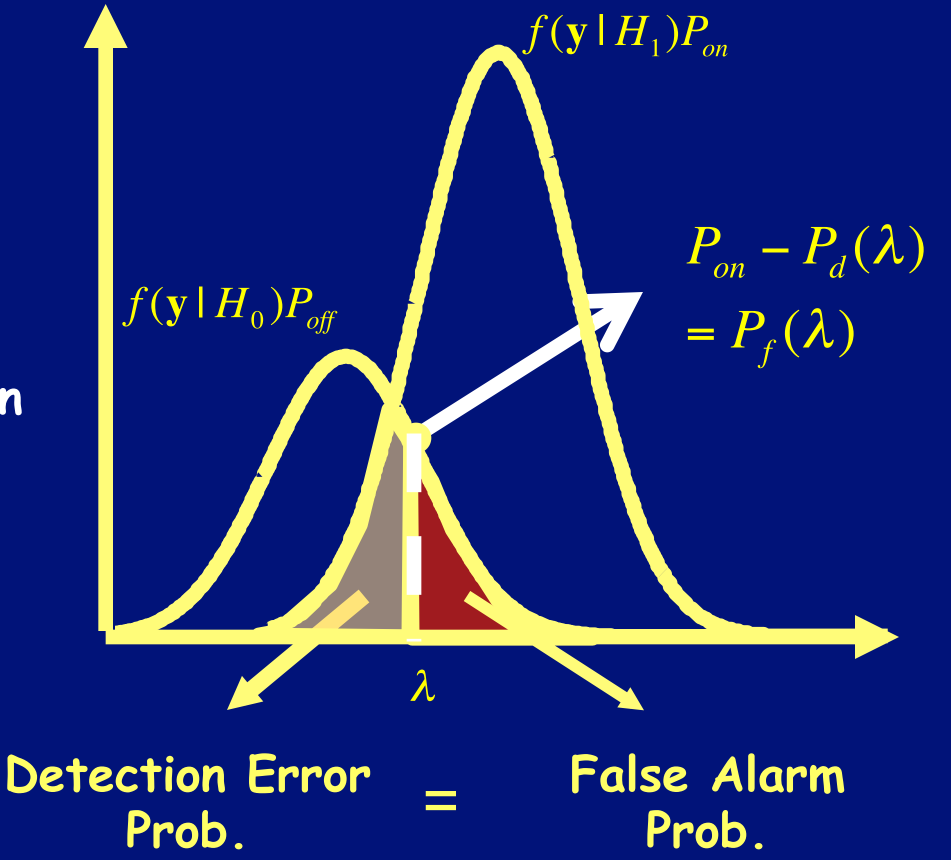
$$\underbrace{P_{on} - P_d(\lambda)}_{\text{Mis-detection Prob.}} = \underbrace{P_f(\lambda)}_{\text{False Alarm Prob.}}$$

Mis-detection Prob.

→ Affecting the detection accuracy on PU signals

False Alarm Prob.

→ Affecting the detection accuracy on spectrum opportunities



ADVANTAGE:

Emphasize detection accuracies of both PU signals and unused spectrums equally

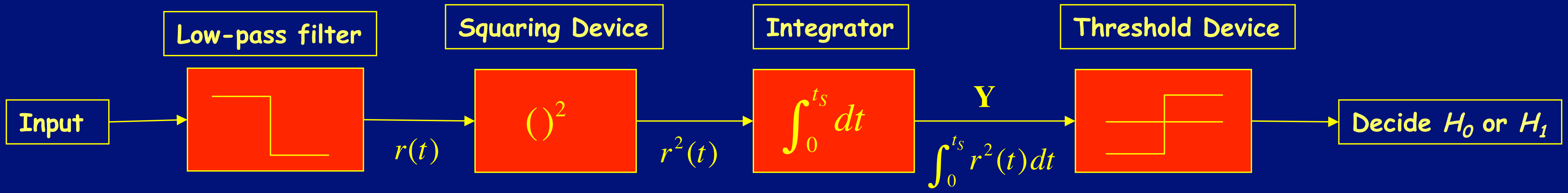
EXPLANATION: Proposed Approach

The detection threshold, λ is determined to make both error probs

(miss-detection probability and false alarm probability) equal.

→ λ is determined not in the intersection of $f(y/H_1)$ and $f(y/H_0)$.

Energy Detection



Input

Low-pass filter

$r(t)$

Squaring Device

$()^2$

$r^2(t)$

Integrator

$\int_0^{t_s} dt$

Y

$\int_0^{t_s} r^2(t)\,dt$

Threshold Device

Decide H_0 or H_1

- In order to measure the energy of the received signal, the output signal of bandpass filter with bandwidth W is squared and integrated over the observation interval t_s.
- Finally, the output of the integrator, Y , is compared with a threshold, λ, to decide whether a licensed user is present or not.

Energy Detection

- Output Y of the Integrator in the Energy Detector is known as
  → Originally: Chi-Square Distribution

HOWEVER,

If the number of samples is large, we can use the central limit theorem to approximate Chi Square distribution by Gaussian distribution:

$$Y \sim \begin{cases} N(n\sigma_n^2, 2n\sigma_n^4) & H_0 \\ N(n(\sigma_n^2+\sigma_s^2), 2n(\sigma_n^2+\sigma_s^2)^2 & H_1 \end{cases}$$

n : number of samples

σ_n^2 : variance of noise

σ_s^2 : variance of received signal $s(t)$

MAP-based Energy Detection

According to Nyquist sampling theorem, the minimum sampling rate should be 2*W

Hence, n can be represented as $(2*t_s)*W$

where t_s is the observation time.

MAP-based Energy Detection

- **Detection and False Alarm Probabilities**
  (from previous equations for P_d and P_f and Y)

$$P_d = P_{on} Q\left(\frac{\lambda - 2t_s W(\sigma_s^2 + \sigma_n^2)}{\sqrt{4t_s W(\sigma_s^2 + \sigma_n^2)^2}}\right) = P_{on} - P_f$$

$$P_f = P_{off} Q\left(\frac{\lambda - 2t_s W \sigma_n^2}{\sqrt{4t_s W \sigma_n^4}}\right)$$

Each spectrum band has different detection and false alarm probabilities and dependent on α, β, W (BW of the spectrum band) and observation time t_s.

λ can be obtained using numerical methods.

Analytical Interference Model

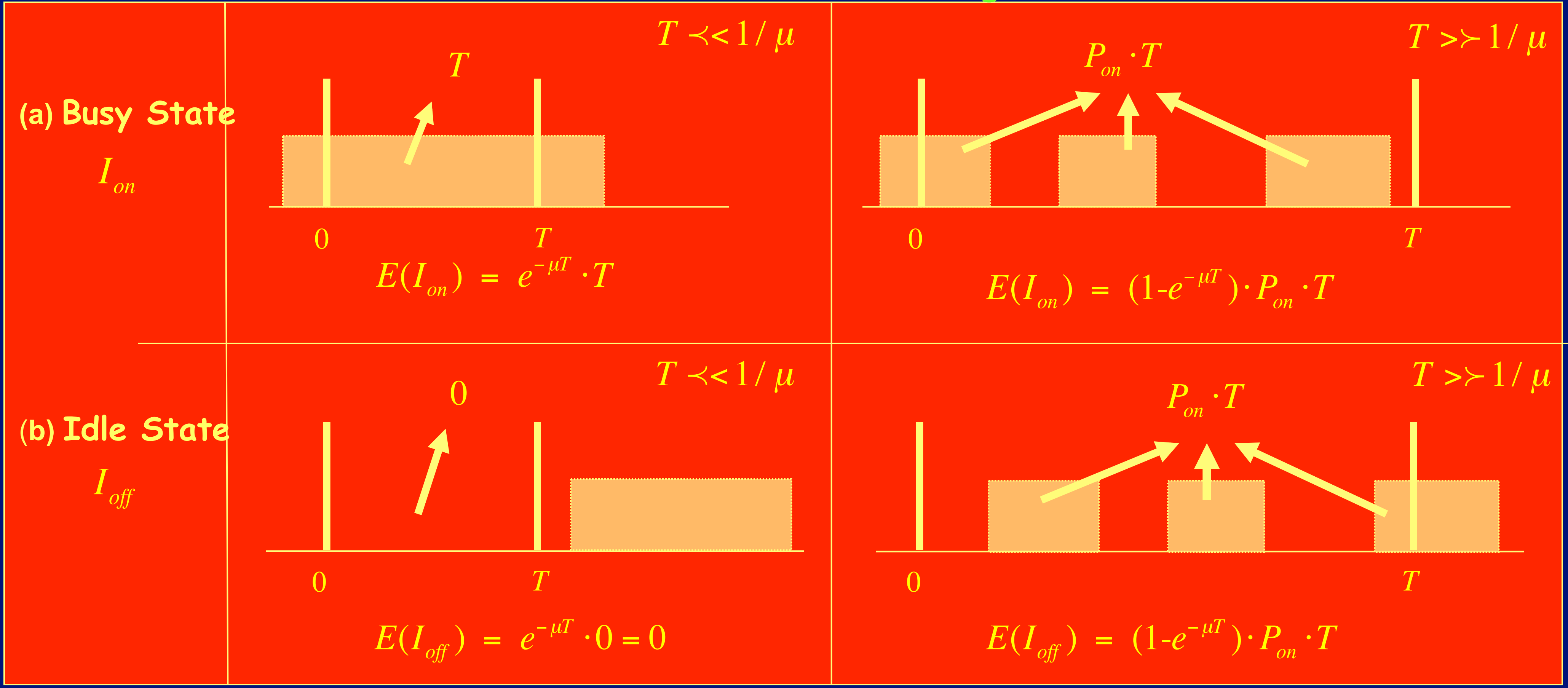
- According to the sensing timing, there are two types of interferences
- Interference on "Busy State I_{on}"
  - Spectrum band is busy but not detected by CR users
  - CR users begin to transmit
  - Interference can occur during the transmission period T
- Interference on "Idle State I_{off}"
  - Spectrum band is idle
  - CR users detect it correctly and starts to transmit
  - But PU activity appears during the transmission period T and interference may occur

Interference Types

$\mu = \max(\alpha, \beta)$ 🟧 PU Transmitting

No change in PU activity during T

One or More Changes in PU activity during T



(a) Busy State I_{on}

$E(I_{on}) = e^{-\mu T} \cdot T$

$E(I_{on}) = (1\text{-}e^{-\mu T}) \cdot P_{on} \cdot T$

(b) Idle State I_{off}

$E(I_{off}) = e^{-\mu T} \cdot 0 = 0$

$E(I_{off}) = (1\text{-}e^{-\mu T}) \cdot P_{on} \cdot T$

Expected Interference Ratio

- **Expected Interference on Busy State**

$$E[I_{on}] = (\underbrace{P_{on} - P_d}_{\text{Prob. of the detection err.}})(\underset{\substack{\downarrow \\ \text{Prob. with no PU activity during T}}}{e^{-\mu T}} T + (\underbrace{1 - e^{-\mu T}}_{\text{Prob. with one or more PU activities during T}}) P_{on} T)$$

- **Expected Interference on Idle State**

$$E[I_{off}] = (\underbrace{P_{off} - P_f}_{\text{Prob. of the detection of idle state.}})(e^{-\mu T} \cdot 0 + (1 - e^{-\mu T}) P_{on} T)$$

Expected Interference Ratio

$$T_I = \frac{E[I_{on}] + E[I_{off}]}{T \cdot P_{on}}$$

$$= \frac{\alpha}{\beta}\left(e^{-\mu T}\,\overline{P}_f + (1 - e^{-\mu T})\frac{\beta}{\alpha + \beta}\right)$$

The range of T_I can be determined as

$$\frac{P_{off}}{P_{on}}\,\overline{P}_f < T_I \le P_{off}$$

EXPECTED INTERFERENCE RATIO

IMPLICATIONS:

* If $T_I > P_{off}$,

this spectrum band always satisfies interference limit T_I and can be used for CR transmission without any coordination of sensing parameters.

* If $T_I < [(P_{off}/P_{on})\, P_f]$,

this spectrum band cannot be used since the interference constraint is always violated.

Expected Loss Spectrum Opportunity

$$T_L = \frac{\beta}{\alpha}(e^{-\mu T}\overline{P}_f + (1 - e^{-\mu T})\frac{\alpha}{\alpha+\beta})$$

Since T_I and T_L have duality characteristics of α and β the interference and loss spectrum opportunity can be balanced.

The range of T_L can be determined as

$$\frac{P_{on}}{P_{off}}\overline{P}_f < T_L \le P_{on}$$

Observation Time in terms of (False Alarm Prob)

$$t_s = \frac{1}{W \cdot \gamma^2}[Q^{-1}(\bar{P}_f) + (\gamma + 1)Q^{-1}(\frac{P_{off}\bar{P}_f}{P_{on}})]^2$$

$\gamma = \frac{\sigma_s^2}{\sigma_n^2}$ is the SNR of the received signal

W is the BW

→ a monotonically decreasing function since it is the sum of two different inverse Q functions!

Derivation of Observation Time

Since we determine threshold λ as the value to equalize both error probabilities, the detection error probability P_m becomes:

$$\begin{aligned} P_m &= P_{on}\left(1 - Q\left(\frac{\lambda - 2t_s W({\sigma_s}^2 + {\sigma_n}^2)}{\sqrt{4t_s W({\sigma_s}^2 + {\sigma_n}^2)^2}}\right)\right) \\ &= P_{on} Q\left(\frac{2t_s W({\sigma_s}^2 + {\sigma_n}^2) - \lambda}{\sqrt{4t_s W({\sigma_s}^2 + {\sigma_n}^2)^2}}\right) \end{aligned}$$

From the false alarm prob P_f, threshold λ can be obtained

$$\begin{aligned} \lambda &= \sqrt{4t_s W {\sigma_n}^4}\, Q^{-1}\left(\frac{P_f}{P_{off}}\right) + 2t_s W \\ &= \sqrt{4t_s W {\sigma_n}^4}\, Q^{-1}(\bar{P}_f) + 2t_s W \end{aligned}$$

Derivation of Observation Time

Assume SNR ratio

$$\gamma = \frac{\sigma_s^2}{\sigma_n^2}$$

We can get another equation for threshold λ from detection error probability P_m

$$\lambda = 2t_s W(\gamma+1){\sigma_n}^2 - \sqrt{4t_s W}(\gamma+1){\sigma_n}^2 Q^{-1}\left(\frac{P_{off} P_f}{P_{on}}\right)$$

Since both equaions should be the same, t_s can can be obtained as

$$t_s = \frac{1}{W \cdot \gamma^2}\left[Q^{-1}(\bar{P}_f) + (\gamma+1)Q^{-1}\left(\frac{P_{off}\bar{P}_f}{P_{on}}\right)\right]^2$$

Operating Region for Transmission Time
(Transmission Time vs False Alarm Prob.)

From eqs. T_I and optimzation framework; the transmission time T has the foll. Operating Region

$$\bar{P}_f < P_{on} - P_{on}(1 - \frac{T_P}{P_{off}})e^{\mu T} = \bar{P}_f(T)$$

where $\bar{P}_f(T)$ is the boundary function of the operating region & is monotically decreasing (bec. $T_P < P_{off}$).

Also $\bar{P}_f$ is bounded by min(0.5,0.5 * (T_{on}/T_{off})) since false alarm and detection error probabilities are assumed to be the same.

Operating Region for Transmission Time

Also from eq. $\bar{P}_f$ and $\bar{P}_f > 0$

the maximum transmission time T is bounded by:

$$0 < T < -\frac{1}{\mu}\log(1-\frac{T_P}{P_{off}})$$

i.e., if T is greater than this value, this spectrum band cannot satisfy the interference constraint T_P regardless of $\bar{P}_f$ (false alarm probability)

OPTIMIZATION PROCEDURE

The optimization problem is not easy to solve numerically since the objective function and the constraints are combined with the false alarm probability $\bar{P}_f$

$$
\begin{aligned}
&\mathit{Find} &&: \quad T^*, t_s^* \\
&\mathit{Maximize} &&: \quad \eta = \frac{T}{T + t_s} \\
&\mathit{Subject\ to} &&: \quad T_I < T_P
\end{aligned}
$$

Instead, we introduce an iterative method to exploit $\bar{P}_f(t_s)$, the inverse function of

$$t_s = \frac{1}{W \cdot \gamma^2}\left[Q^{-1}(\bar{P}_f) + (\gamma + 1)Q^{-1}\left(\frac{P_{off}\bar{P}_f}{P_{on}}\right)\right]^2$$

and

$$\bar{P}_f < P_{on} - P_{on}\left(1 - \frac{T_P}{P_{off}}\right)e^{\mu T} = \bar{P}_f(T)$$

How to find optimal Sensing Parameters ?

- **Observation Time**
  ← MAP detection

$$t_s = \frac{1}{W\cdot\gamma^2}[Q^{-1}(\bar{P}_f)+(\gamma+1)Q^{-1}(\frac{P_{off}\bar{P}_f}{P_{on}})]^2$$

γ : SNR of the PU signal

- **Operating Region**
  ← Interference model + Constraint

$$\bar{P}_f < P_{on} - P_{on}(1-\frac{T_P}{P_{off}})e^{\mu T} = \bar{P}_f(T)$$

- **Optimization Problem**
  - To find $\bar{P}_f$ to maximize $T/(T+t_s)$ inside the operating region

Problem Formulation

Find : T^*, t^*_s

Maximize : $\eta = \frac{T}{T+t_s}$

Subject to : $T_I < T_P$

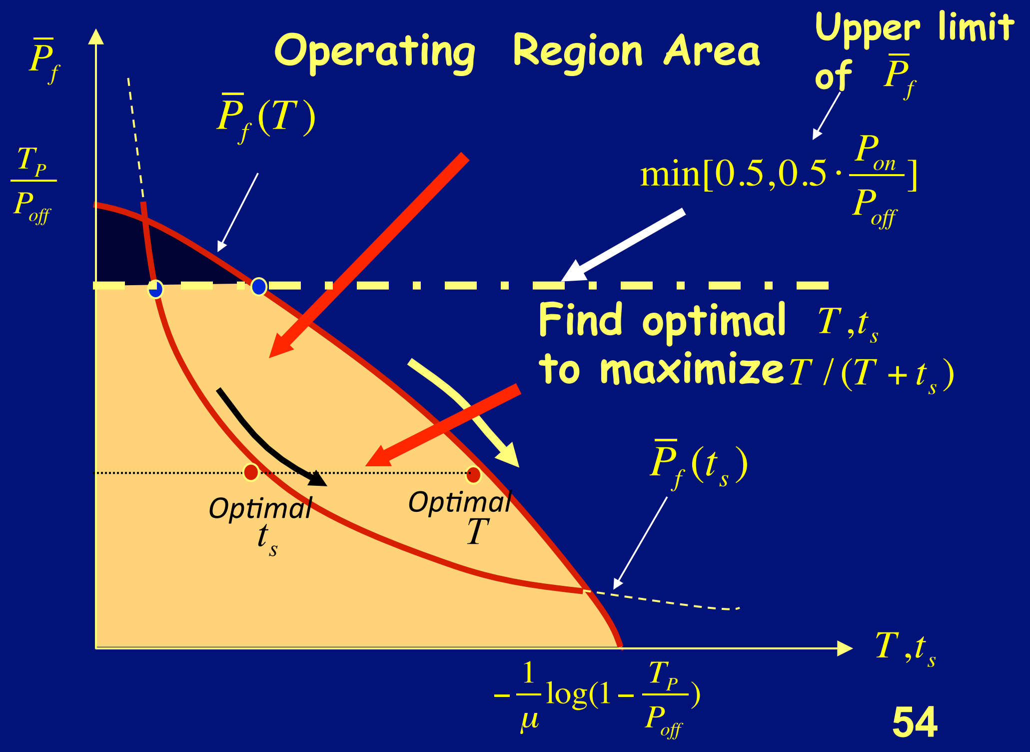


FIGURE EXPLANATION

- Operating region given in formulas of t_s and the inverse function of $\bar{P}_f(t_s)$
- T and t_s have same false alarm probability $\bar{P}_f$
- The OPERATING REGION is the area of $\bar{P}_f$ and T where the interference constraint T_p is always satisfied.
- I.o.w., T, t_s and $\bar{P}_f$ should be placed inside the operating region to satisfy the interference constraints.

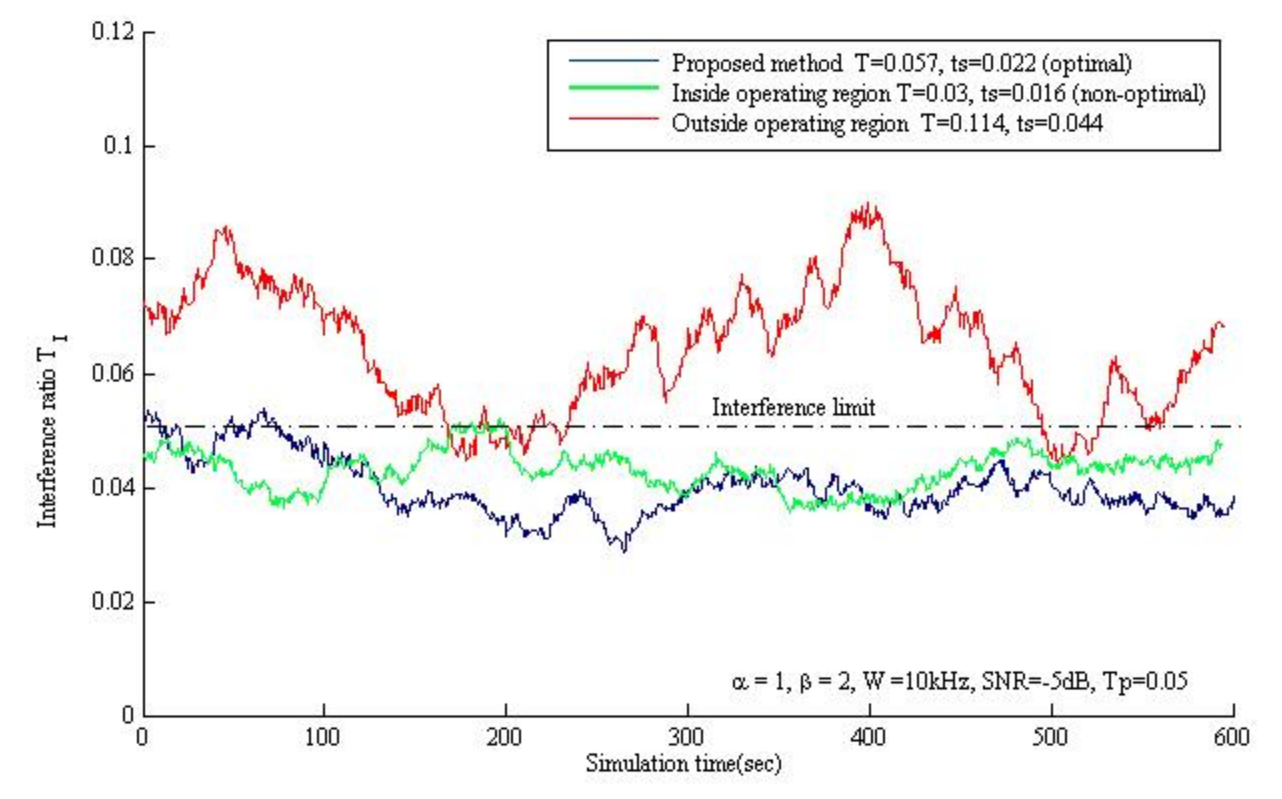
Optimization Problem (simplified):

Find an optimal false alarm prob $\bar{P}_f$ to maximize the sensing efficiency ! (obtained through iterative numerical method!)

FIGURE EXPLANATION

- Calculate first $\bar{P}_f$ to according to T using the boundary function $\bar{P}_f(T)$
- According to $\bar{P}_f$ → t_s is obtained from eq. t_s formula
- Then calculate spectrum efficiency η using T and t_s
- By searching all possible transmission times T within the operating region we can obtain an optimal $\bar{P}_f$ which provides the max sensing efficiency.

Results: Interference Simulation



- **Optimal sensing parameter:**
  - satisfy interference constraint with highest sensing efficiency
- **Both optimal and non-optimal sensing parameters inside operating region**
  - satisfy interference limit but optimal sensing parameters show a better sensing efficiency
- **Sensing parameters outside operating region**
  - Same sensing efficiency as of optimal parameters but exceed the interference limit

Part 2:
Spectrum Selection and Scheduling

- So far SINGLE BAND/SINGLE USER sensing
- However, CR users need to exploit multiple available spectrum bands.
- To handle multiple spectrum bands, 2 types of sensing strategies:
  - WIDEBAND SENSING
  - SEQUENTIAL SENSING

WIDEBAND SENSING

A sensing RF front-end can sense multiple spectrum bands over a wide frequency range at a time.

- Although it requires only one single sensing radio, it uses identical observation (sensing) and transmission times over multiple spectrum bands without considering their different characteristics → violation of interference limit.

- Also it requires a high speed A/D converter

SEQUENTIAL SENSING

A sensing RF front-end monitors only a single spectrum band at a time

→ CR user senses multiple spectrum bands one by one

- Enables the CR user to use sensing parameters adaptively to the characteristics of each spectrum band

- Widely used for CR networks

SEQUENTIAL SENSING

PROBLEMS:

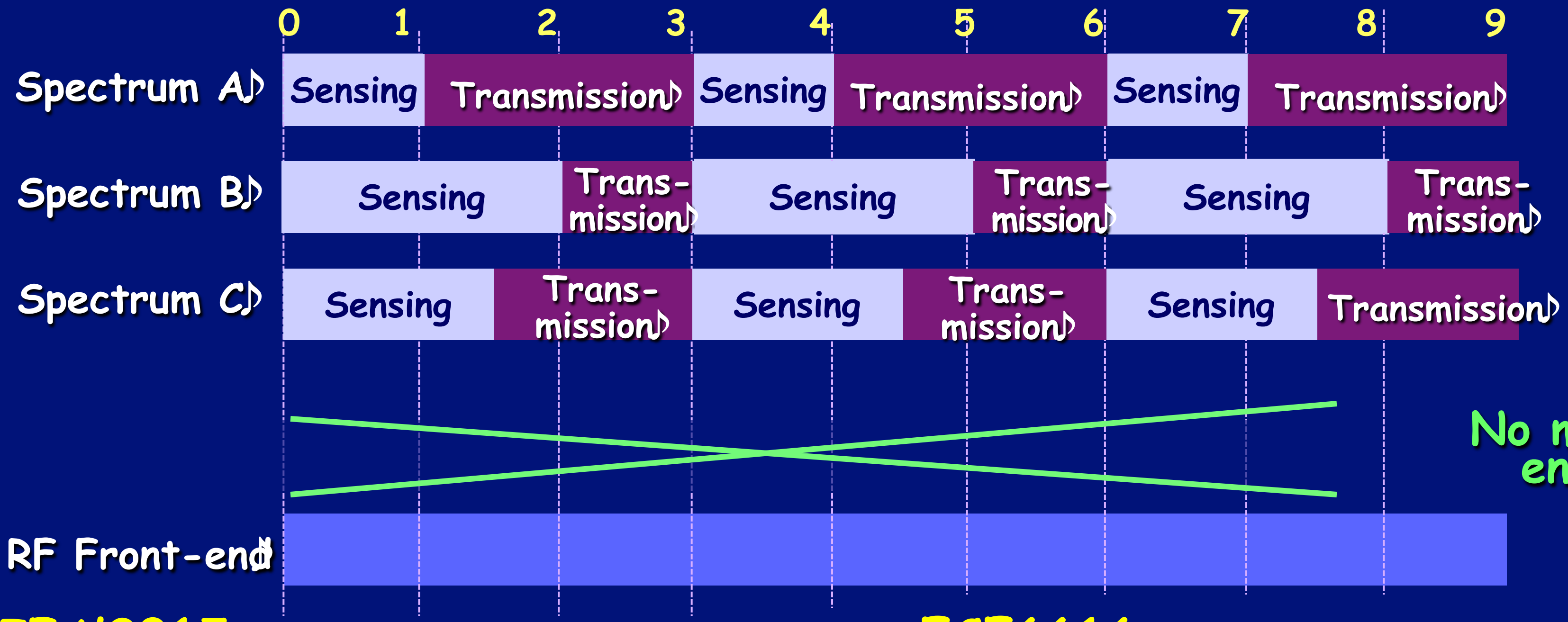
- To detect the PU signals in sequential sensing, the RF front-end senses each band in every sensing cycle.
- When sensing one band, RF front-end cannot sense other bands,
- Hence the # of bands that a RF front-end can sense is limited !!

→ Need for a sensing scheduling solution !!!

Spectrum Selection: Motivation

* Each RF front-end should sense each band in every sensing cycle
* In sequential sensing, CR user may not sense all spectrum bands at the same time

Example: Assume a single RF front-end & three bands



Requires 1/(1+2) RF front-end resource

Requires 2/(1+2) RF front-end resource

Requires 1.5/(1.5+1.5) RF front-end resource

No more resource in RF front-end → C cannot be sensed

Current utilization ratio
1/3 + 2/3 + 1/2 > 1

Spectrum Selection

CR users monitoring all spectrum bands using sequential sensing, require N_{req} sensing RF front-ends:

$$N_{req} = \sum_{i \in A} \boxed{\frac{t^{*}_{s,i}}{T^{*}_{i} + t^{*}_{s,i}}}$$

A : A set of all available spectrum bands

$t^{*}_{s,i}$: Optimal observation time of spectrum i

T^{*}_{i} : Optimal transmission time of spectrum i

$\downarrow$

RF Front-end utilization ratio for sensing spectrum band i

*** If a CR user has less than N_{req} RF front-ends, it cannot sense all available spectrum bands.**

→ Need to select the best spectrum bands for sequential sensing, given the # of sensing RF front-ends of a CR user (N_{sen})

Spectrum Selection:
Opportunistic Sensing Capacity (OSC)

Definition:

OSC represents the expected transmission capacity of spectrum band i that CR users can achieve

$$C_{o,i} = \rho_i \cdot \eta_i \cdot W_i \cdot P_{off,i}$$

ρ_i : Spectral efficiency of spectrum band i (bit/sec/Hz) (depends on modulation & channel coding)

η_i : sensing efficiency of spectrum band i, i.e., $\eta_i = T^*_i / (T^*_i + t^*_{s,i})$

W_i: Bandwidth of spectrum band i;

(ρ_i * W_i) → represents how much transmission rate this spectrum band can support

$P_{off,i}$: idle probability of spectrum band i

Spectrum Selection:
Opportunistic Sensing Capacity

Goal: CR user selects and utilizes spectrum bands having higher opportunistic sensing capacity.

For this we need to compute

- IDLE PROBABILITY of a spectrum band
  (since CR users can transmit only in the idle period) and,

- SENSING EFFICIENCY
  (since CR users cannot transmit during the sensing period).

→ Spectrum capacity in CR networks → Opportunistic Sensing Capacity.

Spectrum Selection for Selective Sensing

Objective

To select spectrum bands to maximize the sum of their opportunistic sensing capacities subject to the constraint of sensing resources (# of sensing RF front-ends of the CR user, N_{sen}), i.e., total RF front-end utilization ratio required for sensing all selected bands should be less than N_{sen}

$$\mathit{Maximize}: \sum_{i\in A} \underbrace{\rho_i \cdot \eta_i \cdot W_i \cdot P_{off,i} \cdot x_i}_{\xrightarrow{\hspace{2em}} \text{Total opportunistic capacity of selected bands}}$$

$$\mathit{Subject\ to}: \underbrace{\sum_{i\in A} \frac{t^*_{s,i}}{T^*_i + t^*_{s,i}}}_{\xrightarrow{\hspace{2em}} \text{Total RF front-end utilization ratio of selected bands}} \cdot x_i \le N_{sen}$$

- A: Set of all available spectrum bands
- $x_i \varepsilon \{0,1\}$: Spectrum selection parameter
- N_{sen}: # of sensing RF front-ends of a CR user
- W_i : Bandwidth efficiency of band i
- ρ_i : Spectral efficiency
- η_i : sensing efficiency

- Solved by "Binary Integer Programming". (Once spectrum bands are selected, transceiver is required to be scheduled for spectrum sensing).

Sensing Scheduling for Multiple Spectrum Bands:

Motivation

- Selected spectrum bands may have different optimal sensing and transmission times, and hence different sensing cycles
- Thus, the sensing period of each band is highly likely to collide !

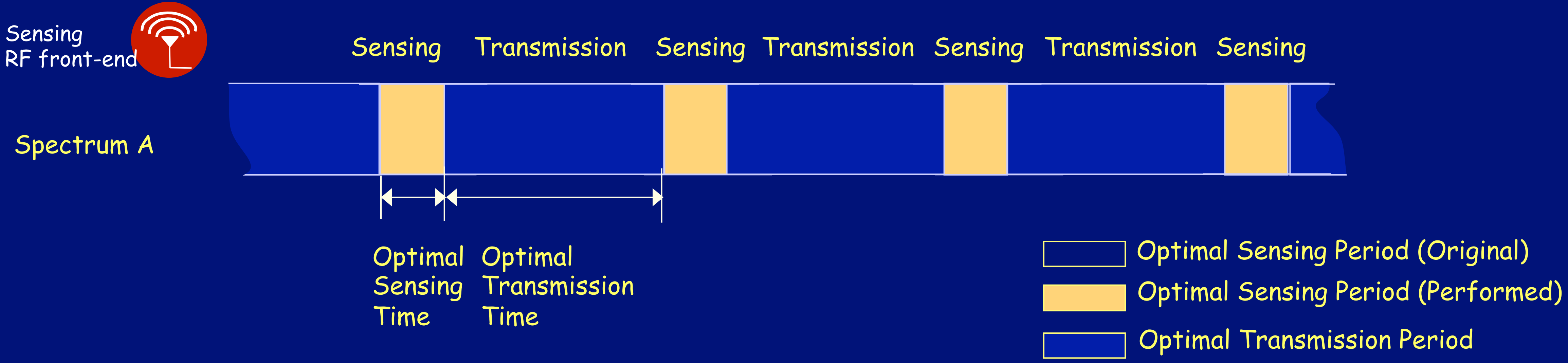
SOLUTION OF THE COLLISIONS:

CR user needs to coordinate the sensings when multiple bands compete for the RF front-end

(i.e., CR user needs to determine which band is picked by the RF front-end for sensing, while minimizing capacity loss due to the RF front-end competition between spectrum bands).

Sensing Scheduling: Concept

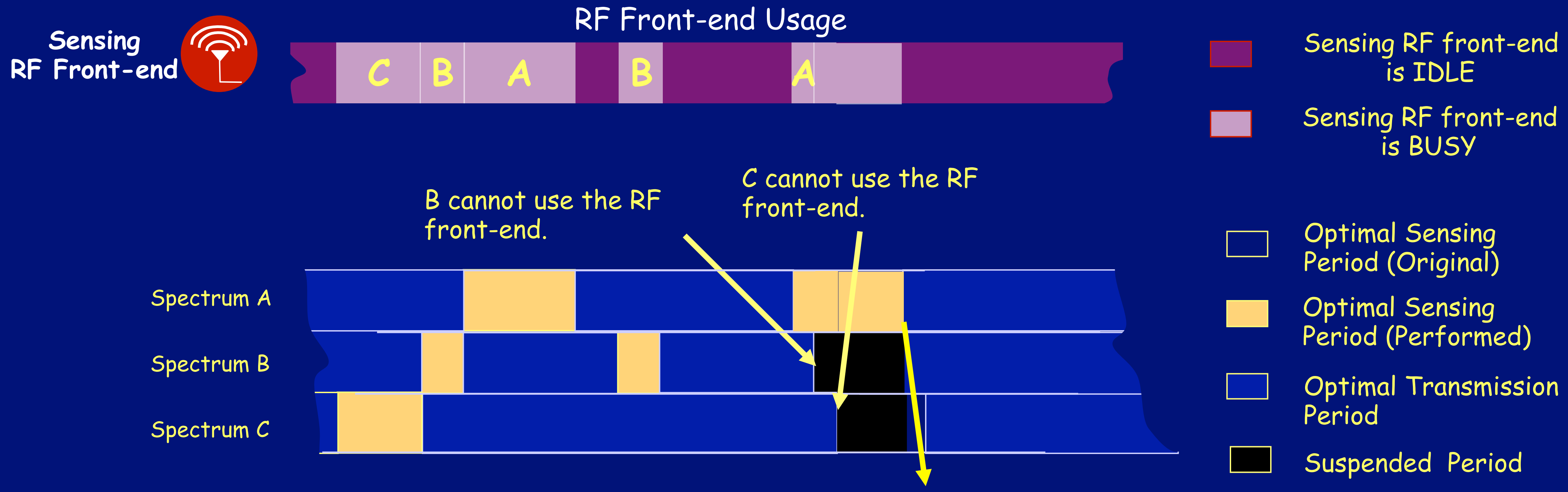
EXAMPLE: Single RF front-end & Single Band (Ideal Case)



- No competition in using the sensing RF front-end
- Periodically sensing and transmitting while keeping the sensing cycle.

Sensing Scheduling: Concept

EXAMPLE: Single RF Front-end & Multiple Bands with Different Sensing Cycles



A finishes sensing
B & C compete for the sensing RF front-end
Need to determine who will use the RF front-end for its sensing

Sensing Scheduling

How is the sensing RF front-end scheduled to sense multiple spectrum bands to satisfy optimal sensing cycles of each spectrum?

Assumption:

A time-slotted sensing scheduling is used where a time-slot is used as the minimum time unit for observation and transmission time

IDEA:

If multiple spectrum bands compete for the sensing slot at the same time, CR users determine one of the spectrum bands through the proposed sensing scheduling algorithm based on the OPPORTUNITY COST !!

Opportunity Cost & Scheduling Algorithm

DEFINITION: **Opportunity Cost of Spectrum Band j:**

Sum of the expected opportunistic sensing capacities of the spectrum bands to be blocked if one of the competing spectrum bands is selected.

Proposed Method:

The current time slot is assigned to the one of the competing spectrum bands to minimize the opportunity cost, referred as

LEAST COST FIRST SERVE (LCFS) scheduling algorithm !

Sensing Scheduling Algorithm

LCSF (Least Cost First Serve): How to assign the sensing slot to the best spectrum band j* due to LCFS scheduling

$$j^* = \arg\min_{j\in B}(\overbrace{t^*_{s,j}\sum_{i\in B,i\neq j}\rho_i W_i P_{off,i}}^{\text{Opportunity cost of spectrum band j}} + \overbrace{\sum_{i\varepsilon B,i\neq j} t_i^b\cdot\rho_i\cdot W_i\cdot P_{off,i}}^{\text{Sum of the opportunistic capacities of the blocked spectrum bands during the past blocked time } t_i^b})$$

LCFS algorithm assigns the current time slot to the spectrum band such a way as to minimize the sum of the opportunity cost and the blocked opportunistic capacity of other spectrum bands.

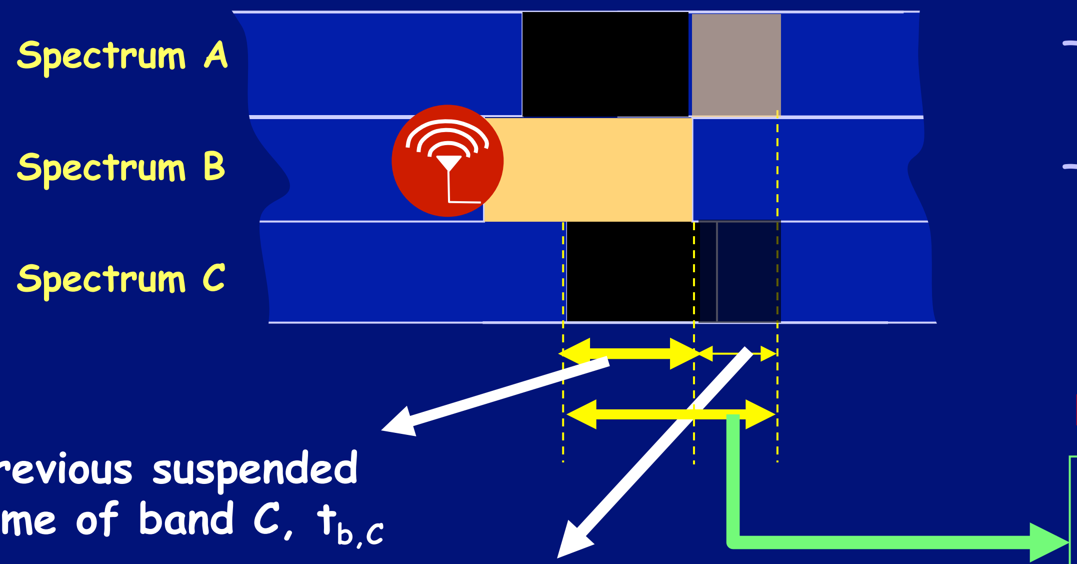
Procedure for Sensing Scheduling

- When a sensing cycle starts, CR users check the state of the current time slot
- If the current time slot is already occupied by another spectrum band, all competing bands go to the blocked period
- When the time slot is available, CR users assign the current time slot to one of the competing spectrum bands
- The rest of the spectrum bands should block their sensing operations to the next available time slot.
- When the observation period ends after the observation time t_s, the spectrum band goes to the transmission period and the current time slot is available to other spectrum bands.

Example: Opportunity Cost of Band A

* RF front-end just finishes the sensing task of band A

* Bands B and C compete for the RF front-end



Previous suspended time of band C, $t_{b,C}$

Future suspended time of band C, $t^*_{s,B}$ if band B is selected for sensing (= Sensing time of band B)

- If spectrum A is selected for sensing,
  - it can use the RF front-end for its sensing time.
  - On the other hand, the other spectrum bands (spectrum C) will suspend its sensing task during the sensing time of spectrum A

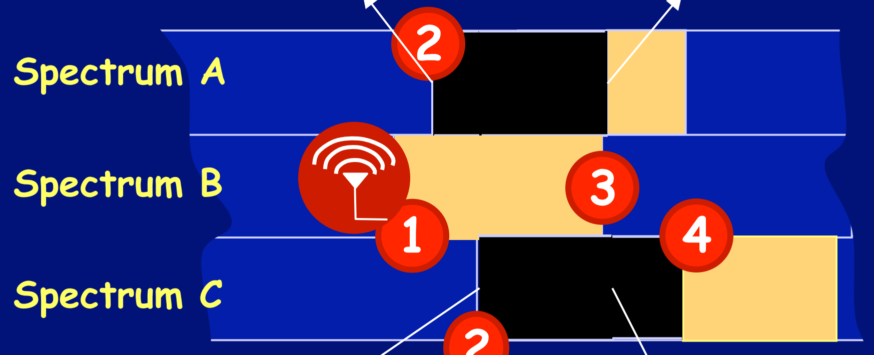
- The opportunity cost of band A

Amount of data capacity that other band (spectrum C) cannot transmit during the previous & future suspended times, $t_{b,C} + t^*_{s,B}$

Example: LCSF Procedure

① Sense spectrum band B

② Suspend the sensing tasks of other bands A & C during the sensing time of band B



Suspend the sensing task of A

Calculate the opportunity cost of band A

Suspend the sensing task of C

Calculate the opportunity cost of band C

③ When finishing the sensing of band B, start LCSF.

a) Each band suspending the sensing (A and C) calculates its opportunity cost.

b) The band that has the lowest opportunity cost gets the access to the RF front-end (Assume the opportunity cost of A is lower than that of B)

c) Select band A for sensing, and keep suspending the sensing task of C

④ After sensing band A, the RF front-end starts to sense band C

Part 3:
Adaptive and Cooperative Sensing

High Spatial Correlation:

* Neighboring CR users are highly likely to be located in the same transmission range of the primary network

* Exploit spatial correlation by allowing CR users to exchange their sensing information → Cooperative Sensing

Cooperative Sensing:

- Enhance the sensing accuracy
- Mitigate the receiver uncertainty problem

Part 3:
Adaptive and Cooperative Sensing

Problems

- **Cooperative Gain:** Time-varying characteristic according to the number of CR users involved in the cooperation.
- Cooperative sensing can enhance the detection probability which affects the optimal sensing parameters

→ Optimal sensing parameters must be adaptive to the time-varying cooperative gain

Availability Decision using Cooperative Gain

* In traditional cooperative sensing the spectrum band is decided to be available only if no PU activity is detected out of all sensing data.

* Even if only one PU activity is detected, CR users cannot use this spectrum band.

From this detection criteria, the cooperative detection probability is obtained by cooperative gain of N sensing data (CR users)

$$\bar{P}_d^c = 1 - (1 - \bar{P}_d)^N$$

This decision strategy increases the detection probability but also increases the lost spectrum opportunities due to the increase in cooperative false alarm probabilities:

$$\bar{P}_f^c = 1 - (1 - \bar{P}_f)^N$$

A New Cooperative Gain for the Decision of Spectrum Availability

* The number of detections follows the BINOMIAL DISTRIBUTION $B(N,\bar{P}_d)$

* Similarly, the number of False Alarms also follows $B(N,\bar{P}_f)$

* In order to determine the detection threshold N_{th} to balance between detection error prob. and false alarm prob. we exploit

$$P_{on}(1-P_{bd}(N_{th})) = P_{off} \cdot P_{bf}(N_{th})$$

Binomial CDF of the # of detections

Binomial CDF of the # of false alarms

Cooperative Detection and False Alarm Probabilities

Detection and false alarm probabilities can then be calculated:

$$P_d^c = P_{on}\bar{P}_d^c = P_{on}\sum_{i=N_{th}}^{N}\begin{pmatrix} N \\ i \end{pmatrix}\bar{P}_d^i(1-\bar{P}_d)^{N-i}$$

$$P_f^c = P_{off}\bar{P}_f^c = P_{off}\sum_{i=N_{th}}^{N}\begin{pmatrix} N \\ i \end{pmatrix}\bar{P}_f^i(1-\bar{P}_f)^{N-i}$$

Adaptive Re-optimization of Sensing Parameters

- Since detection and false alarm probabilities change → optimal sensing parameters need to be re-optimized

- Optimal observation time $t*_s$ is already considered for the false alarm probability in the calculation of the cooperation gain

- Cooperation gain only affects the transmission time T*
  → re-optimize according to the changes of cooperative gain (the number of sensing data)

- BS re-optimizes the transmission time which improves the RF front-end utilization