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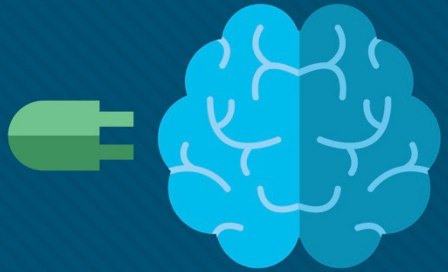

OSA and Spectrum Sensing Theories and Methods

Lector Materials

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Lessons content
Key Topics

Week	Topic description
7.	Cognitive Radio for Dynamic Spectrum Management
8.	OSA and Spectrum Sensing Theories and Methods
9.	Concurrent Spectrum Access
10.	Blockchain for Dynamic Spectrum Management
11.	Artificial Intelligence for Dynamic Spectrum Management
12.	ML for Spectrum Sharing, ML for Signal Classification, Deep Reinforcement Learning for Dynamic Spectrum Access
13.	

Week 8. Lector Content

This chapter covers the following content:

- Opportunistic Spectrum Access (OSA)
  - Key functions of the PHY and MAC layer in the OSA model
- Sensing-Throughput Tradeoff
  - Basic Formulation
  - Average throughput
  - The problem of sensing-throughput tradeoff
  - Optimal sensing time
- Applications: LTE-U

1.1 Opportunistic Spectrum Access (OSA)

- **Spectrum sensing** is the enabling function for OSA.
- The inability for a secondary user (SU) to perform **spectrum sensing** and **spectrum access** at the same time requires a joint design of sensing and access strategies to maximize SUs' own desire for transmission while ensuring sufficient protection to the primary users (PUs).
- This chapter starts with a brief introduction on the opportunistic spectrum access model and the functionality of sensing-access design at PHY and MAC layers.

OSA model

The opportunistic spectrum access

- Is the most **appealing model** for unlicensed/secondary users to access the radio spectrum.
- In this model, the secondary users (SUs) **opportunistically** access the spectrum bands of primary users (PUs) which are temporally unused.
- By definition, before transmission, the SUs need to know the **busy/idle** status of the spectrum bands which they are interested in.
- With such knowledge, the SUs can access the unused spectrum bands of the PUs, i.e., the spectrum holes, or the spectrum white space so that the PUs' QoS will not be degraded.
- such knowledge can be acquired using two approaches, including the use of a **geolocation database** and **spectrum sensing technique**.

OSA model

The opportunistic spectrum access design

- Batch of works have focused on improving the accuracy of spectrum sensing, while others have focused on the coordination of spectrum sensing and access, i.e., **the sensing-access design**.
- As essentially a signal detection technique, spectrum sensing might lead to incorrect results due to the noise uncertainty and the channel effects such as multipath fading and shadowing.
- The sensing-access structure of the OSA reveals that the spectrum access is largely dependent on the results of spectrum sensing.
- Moreover, the optimization of the performance on spectrum sensing and access might be conflicting with some practical concerns such as the limited computational capability of the SUs, which gives rise to the tradeoff design between the spectrum sensing and access.

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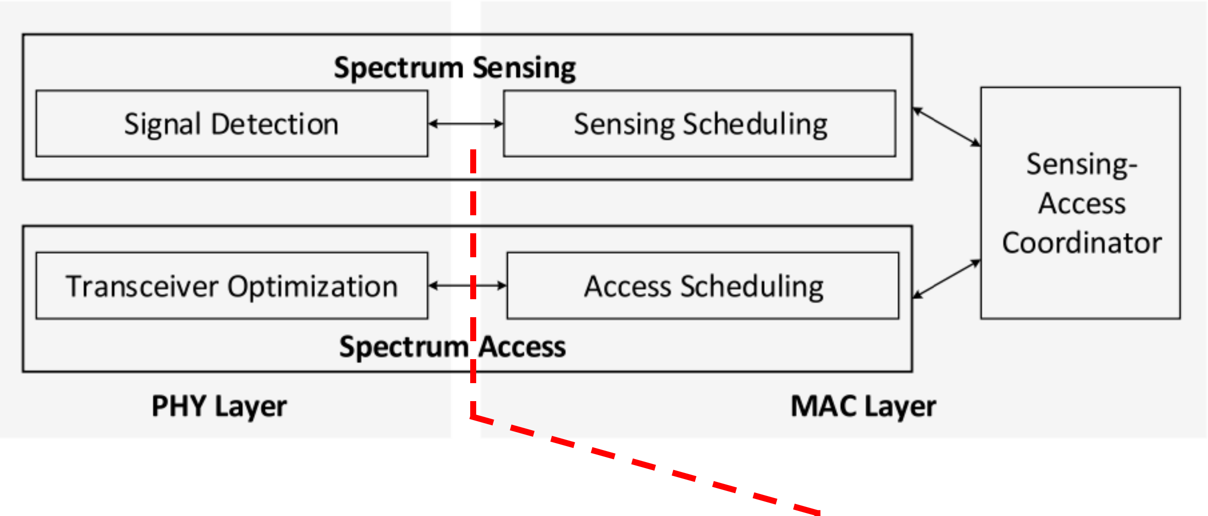
OSA model

Key functions of the PHY and MAC layer in the OSA model



- In the PHY layer, SS enables the SUs to detect the spectrum holes,
- while the access control optimizes the transceiver design with respect to the carrier frequency, the modulation and coding scheme, etc.

In the MAC layer, there are mainly two functions, including the sensing scheduling and access scheduling.

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Key functions of the PHY and MAC layer in the OSA model

- sensing scheduling – when and on which channel, how long and how frequently the spectrum sensing should be implemented
- access scheduling – governs the access of multiple users to the detected spectrum holes.
- A coordinator of the two functions, called as the **sensing-access coordinator**, is established.
- In the following sections, we will investigate classic problems in the sensing-access design by first presenting their basic ideas and concerns, and then reviewing the existing literatures on solving

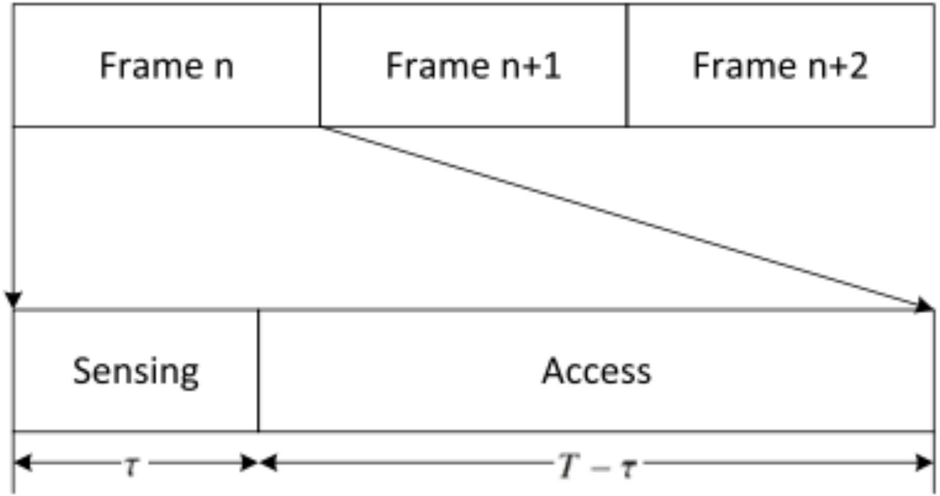
1.2 Sensing-Throughput Tradeoff

- Due to the half duplex operation of a transceiver, an SU cannot perform spectrum sensing and access at the same time.
- As a result, it must alternate between sensing operation and access operation within a data frame.

Sensing-Throughput Tradeoff

Basic Formulation

- Assuming that the spectrum sensing is performed **periodically** in each frame, the frame structure for the SU is illustrated in figure
- Denote τ as the spectrum sensing time and T as the frame length. Then the time duration left for potential spectrum access is thus T − τ:



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Sensing-Throughput Tradeoff

Basic Formulation

- Intuitively, with longer sensing time, the accuracy of spectrum sensing can be improved and it is higher chance that the status of the spectrum can be correctly detected.
- However, this reduces the time left for spectrum access and thus affects the throughput of the SU.
- Therefore, there is a tradeoff between spectrum sensing and throughput.
- This problem is known as **sensing-throughput tradeoff**

Sensing-Throughput Tradeoff

Basic Formulation

- The **performance of spectrum sensing** is characterized by two performance metrics, namely:
  - the probability of false alarm *Pf* (i.e., the probability of detecting the PU as being present when the PU is actually absent) and
  - the probability of detection *Pd* (i.e. the probability of detecting the PU as being present when the PU is present).
- The decision whether to access the spectrum depends on the result of spectrum sensing. There are two scenarios when the SU could access the spectrum:

sc_0: When the PU is not present and no false alarm is generated by spectrum sensing: (<<*Pf*)

sc_1: When the PU is present but it is not detected by spectrum sensing: (<<*Pd*).

Sensing-Throughput Tradeoff

Average throughput

- The **average throughput *R*** of the secondary network can be calculated by taking into consideration the achievable throughput for both scenarios:

$$R = R_0 + R_1$$

- *P*(*H*0) as the probability that the PU is absent. Denote the *C*0 and *C*1 as the throughout of the SU when it continuously transmits in the first scenario and second scenario, respectively. Then, *R*0 and *R*1 can be expressed as follows:

$$R_0(\epsilon, \tau) = P(\mathcal{H}_0)\frac{T-\tau}{T}C_0(1 - P_f(\epsilon, \tau))$$

$$R_1(\epsilon, \tau) = (1 - P(\mathcal{H}_0))\frac{T-\tau}{T}C_1(1 - P_d(\epsilon, \tau))$$

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The problem of sensing-throughput tradeoff (PSTT)

- **Note**: that different from the first scenario, in the second scenario, the SU transmits in the presence of the PU.
- Hence, in general, we have C0 >> C1. More beneficial is to explore the spectrum that is underutilized, for example, when *P*(*H*0) ≥ 0.5
- Therefore, it can safely assume that *R*0 dominates the overall throughput R. Hence, R(ε,τ) ≈ R0(ε,τ).
- PSTT is to optimize the spectrum sensing parameters to maximize the achievable throughput of the SU subject to that the PU is sufficiently protected. Mathematically, the problem can be expressed as:

$$\max_{\epsilon,\tau} \quad R(\epsilon,\tau) \approx P(\mathcal{H}_0)\frac{T-\tau}{T}C_0(1-P_f(\epsilon,\tau))$$

$$\text{s.t.} \quad P_d(\epsilon,\tau) \geq \bar{P}_d \qquad\qquad 0 < \tau < T,$$

Sensing-Throughput Tradeoff

The *P*d and *P*f conflicting

- Previous formulation highly depends on the two performance metrics of spectrum sensing, i.e., ***Pd*** and ***Pf***
- The former can be considered as an indication to the level of protection to the PU since a higher probability of detection reduces the chance that the SU accesses the spectrum over which the PU is operating;
- the lower the false alarm, the better that the SU can reuse the spectrum. These two metrics in the form of ***Pd*** and (**1 − *Pf***) are conflicting with each other.
- For example, an increase in the probability of detection can improve the protection to the PU; however, this is achieved at the expense of increasing probability of false alarm which leads to decreasing spectrum access opportunities to the SU.

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Sensing-Throughput Tradeoff

Optimization problem reduction

- By using energy detection and setting *P*d = *P*̄d , the probability of false alarm can be expressed as:

$$P_f(\tau) = Q\left(\sqrt{2\gamma+1}Q^{-1}(\bar{P}_d) + \sqrt{\tau f_s}\gamma\right)$$

- Then the above optimization problem reduces to an optimization problem with only a single variable τ with the objective function given as follows:

$$R(\tau) \approx C_0 P(\mathcal{H}_0)\left(1 - \frac{\tau}{T}\right)\left(1 - Q\left(\sqrt{2\gamma+1}Q^{-1}\left(\bar{P}_d\right) + \sqrt{\tau f_s}\gamma\right)\right)$$

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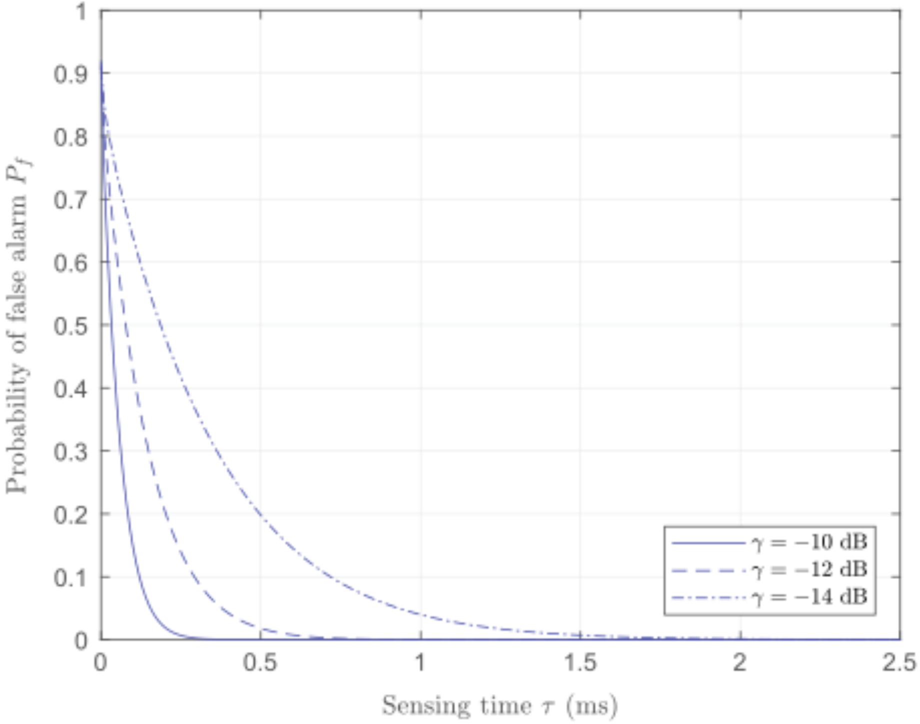
Sensing-Throughput Tradeoff

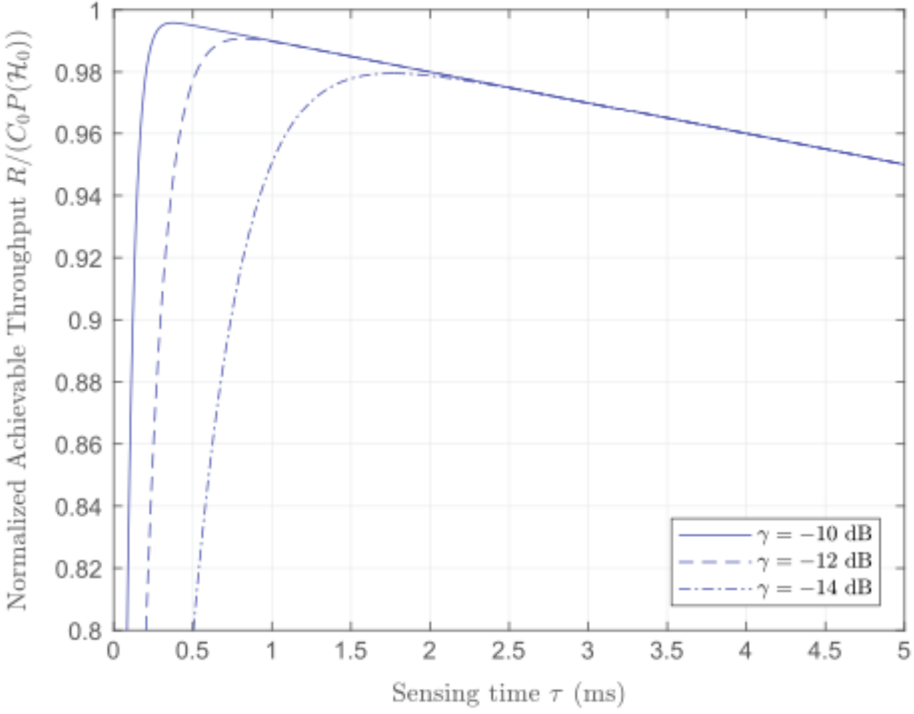
Optimal sensing time

- there exists an optimal sensing time that maximizes the achievable throughput of the secondary network
- Consider the scenario when P(H0) = 0.8, T = 100 ms and fs = 6 MHz.
- The probability of false alarm *P*f and the normalized achievable throughput **R/C0P(H0)** of the secondary network are plotted with respect to the spectrum sensing time τ in next Figures, respectively, under different received SNRs of the primary signal γ.

Sensing-Throughput Tradeoff

Optimal sensing time





Sensing-Throughput Tradeoff

Cooperative Spectrum Sensing

- When there are multiple nearby SUs, spectrum sensing can be improved by combining the sensing result of these users
- Thus, the quality of spectrum sensing does not only depend on the detection threshold ε and the sensing time τ but also the way how the individual sensing results are combined, i.e., the fusion rule (center)
- The overall probability of false alarm and the probability of detection are given by

$$\mathbf{P}_f(\epsilon, \tau, k) = \sum_{i=k}^{N} \binom{N}{i} P_f(\epsilon, \tau)^i \left(1 - P_f(\epsilon, \tau)\right)^{N-i}$$

$$\mathbf{P}_d(\epsilon, \tau, k) = \sum_{i=k}^{N} \binom{N}{i} P_d(\epsilon, \tau)^i \left(1 - P_d(\epsilon, \tau)\right)^{N-i},$$

k-out-of-N fusion rule

Sensing-Throughput Tradeoff

Cooperative Spectrum Sensing

- Then the basic formulation can be revised to the following problem:

$$\max_{\epsilon,\tau,k} \; R(\epsilon,\tau,k) \approx P(\mathcal{H}_0)\frac{T-\tau}{T}C_0\left(1-\mathbf{P}_f(\epsilon,\tau,k)\right)$$

$$\text{s.t. } \mathbf{P}_d(\epsilon,\tau,k) \geq \bar{P}_d \qquad 0 < \tau < T \qquad 0 \leq k \leq N$$

- Then the above optimization problem can be reduced to an optimization problem of only two variables (τ, k)

1.3 Applications: LTE-U

- An important application of OSA is the long-term evolution in unlicensed band (LTE- U), which is also known as licensed-assisted access (LAA)

- The motivation of introducing LTE service in unlicensed band comes from the crisis of licensed spectrum exhausting of LTE service and the under-utilization of unlicensed bands, such as 5 GHz band which contains 500 MHz radio resource and is mainly used by WiFi service.

Applications: LTE-U

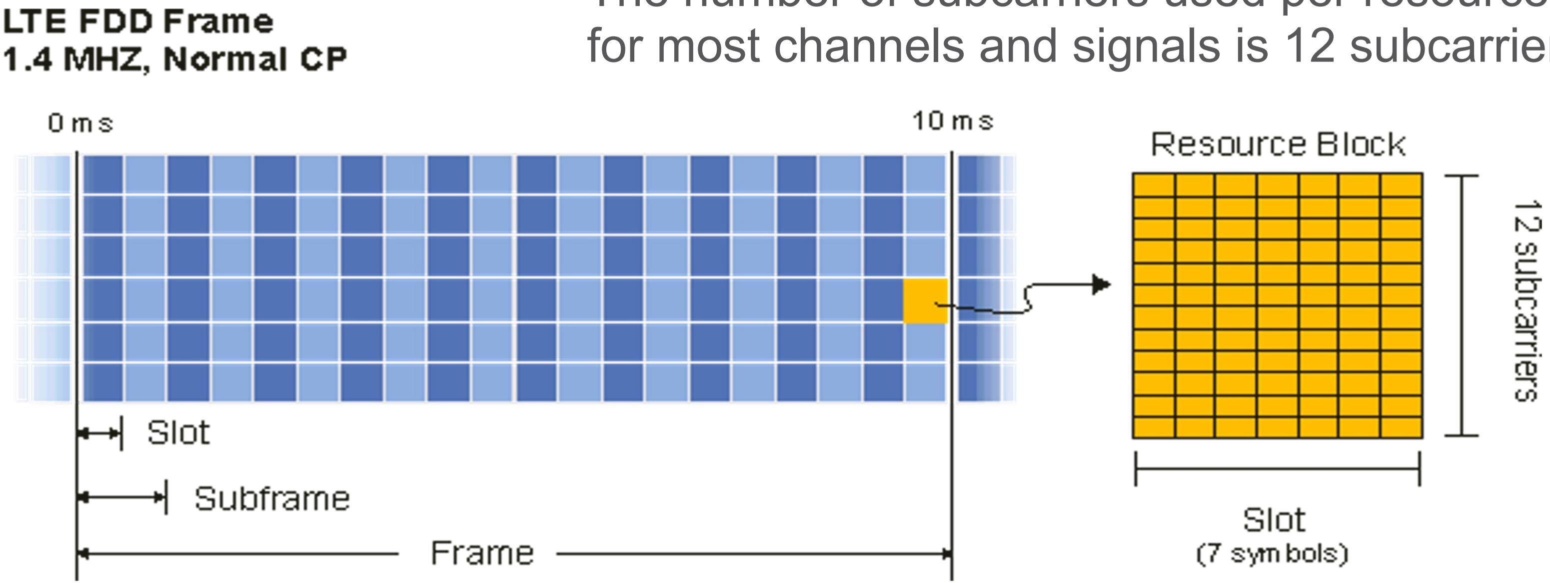
LTE Overview

- targets for the initial deployments of LTE included download rates of 100Mbps, and upload rates of 50Mbps for every 20MHz of spectrum.
- In addition to this LTE was required to support at least 200 active users in every 5MHz cell. (i.e. 200 active phone calls).
- **A resource block** (RB) is the smallest unit of resources that can be allocated to a user.
- The resource block is 180 kHz wide in frequency and 1 slot long in time.

Applications: LTE-U

LTE Overview

- The resource block is 180 kHz wide in frequency and 1 slot long in time.
  - The number of subcarriers used per resource block for most channels and signals is 12 subcarriers.



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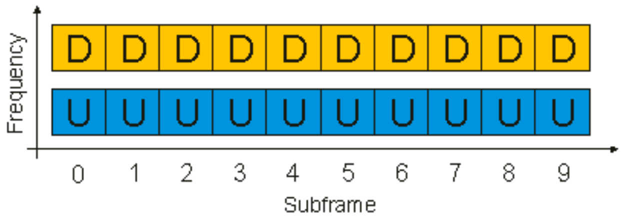
Applications: LTE-U

LTE Overview

- In frequency, resource blocks are either 12 x 15 kHz subcarriers or 24 x 7.5 kHz subcarriers wide = 180 kHz

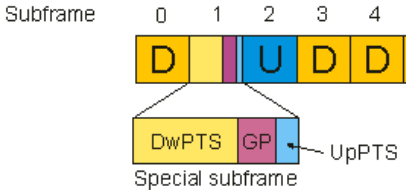
Bandwidth	Resource Blocks	Subcarriers (downlink)	Subcarriers (uplink)
1.4 MHz	6	73	72
3 MHz	15	181	180
5 MHz	25	301	300
10 MHz	50	601	600
15 MHz	75	901	900
20 MHz	100	1201	1200

LTE FDD Frame Type 1



LTE TDD Frame Type 2

UL/DL Config = 2, Special SF Config = 6



Applications: LTE-U

LTE Overview

- Frequency units can be expressed in number of subcarriers or resource blocks. For instance, a 5 MHz downlink signal could be described as 25 resource blocks wide or 301 subcarriers wide (DC subcarrier is not included in a resource block).

- The underlying data carrier for an LTE frame is the resource element (RE). The resource element, which is 1 subcarrier x 1 symbol, is the smallest discrete part of the frame and contains a single complex value representing data from a physical channel or signal.

Applications: LTE-U

Introduction to LTE-U

- These bands can be excellent complementary spectrum for enhancing the LTE performance.
- Through carrier aggregation, the data information can be conveyed via licensed and unlicensed spectrum simultaneously, while the control signal can be still transmitted via licensed spectrum for QoS guarantee.
- Introducing LTE in unlicensed bands requires the LTE to be a fair and friendly neighbor of the incumbent WiFi in unlicensed bands.
- To achieve this goal, critical problems, including the protection to WiFi system, efficient coexistence between LTE and WiFi system, and efficient user association need to be addressed.

Applications: LTE-U

LBT-Based Medium Access Control Protocol Design

- Since WiFi adopts contention-based media access, the access of LTE will introduce collision to the WiFi transmission.
- To mitigate this collision, listen-before-talk (LBT) scheme, which enables the LTE to monitor the channel status, can be adopted by LTE, which has been shown to be able to maintain the most advantages of LTE when coexisting with WiFi system.
- Moreover, when LTE transmits on the channel, the WiFi users will keep silent and wait for the channel becomes idle.
- To guarantee the normal service of WiFi, the LTE should vacate from the channel after a period of data transmission and leave the channel to WiFi operation.

Applications: LTE-U

LBT-Based Medium Access Control Protocol Design

- Thus, we can see that the LBT-based MAC protocol of LTE-U should contain the periodic channel sensing phase which is followed by data transmission phase and channel vacating phase:

1. In the channel sensing phase, the LTE monitors the channel idle/busy status.
2. If the channel is sensed idle, the LTE transmits data for a period of time.
3. After that, the LTE system vacates from the channel for WiFi transmission.

Applications: LTE-U

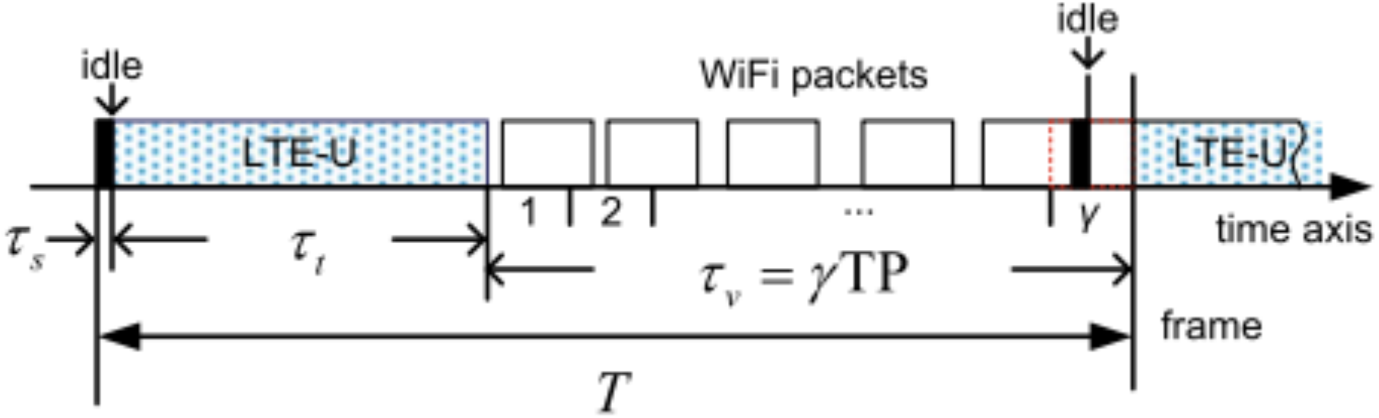
LBT-Based Medium Access Control Protocol Design

- It can be seen that the LBT-based MAC protocol is similar to the sensing-transmission protocol of the typical OSA system, except that the channel vacating phase is absent in the latter one.
- This is because that in the typical OSA system, the primary system has higher priority to the secondary system, and thus the secondary system can only passively adapt than the transmission of primary system.
- In the LTE-U system, however, although the legacy WiFi system is protected, the secondary LTE system can actively control the transmission of WiFi by carefully designing the sensing period and the transmission time.

Applications: LTE-U

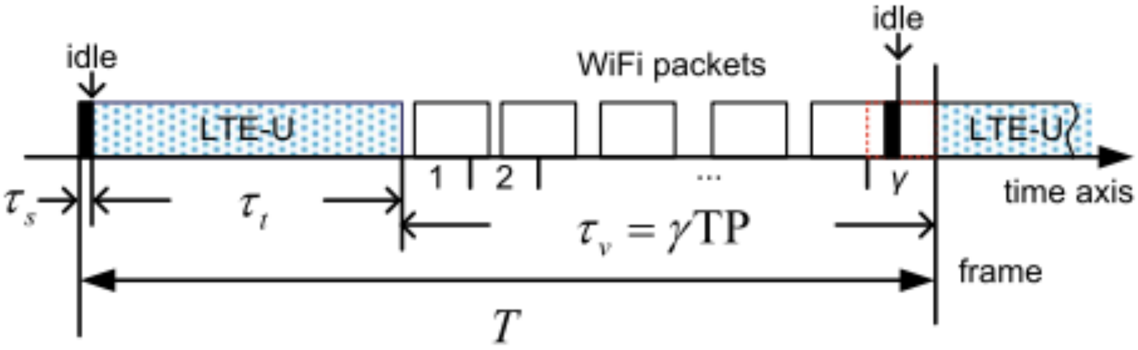
LBT-Based Medium Access Control Protocol Design

- To protect WiFi services, the performance of the multiple WiFi users should be quantified with the coexistence of LTE.
- To facilitate the theoretical analysis of LTE- U system, an LBT-based LTE-U MAC protocol is designed as shown in Figure:



Applications: LTE-U

LBT-Based Medium Access Control Protocol Design



- In this protocol, τs , τt and τv denote the spectrum sensing time, the LTE transmission time, and the LTE vacating time (WiFi transmission time), respectively.
- Moreover, the vacating time τv contains γ (γ ∈ Z+) transmission periods (TPs), each of which contains the WiFi packet transmission time and its propagation delay.

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Applications: LTE-U

LBT-Based Medium Access Control Protocol Design

- Assuming that the spectrum sensing result is perfect, the LBT-based MAC protocol can be specified as follows:
- Instead of sensing spectrum at the beginning of each frame, the LTE starts and keeps sensing from the beginning of the γ th TP in a frame.
- Once the channel is sensed to be idle and the TP is not completed, the LTE will send a dummy packet until the TP ends.
- By doing so, the WiFi packet arrived during the γ th TP will be deferred and the channel can be held by the LTE for the next frame.

Applications: LTE-U

LBT-Based Medium Access Control Protocol Design

- There is an **essential difference** between the proposed MAC protocol and the sensing-transmission protocol of the traditional OSA system, although they are both frame-based.
- In the traditional OSA system, SU can transmit only when the channel is sensed to be idle.
- In the proposed MAC protocol, however, the LTE not only senses the channel, but also grabs the channel for data transmission in the next frame.
- Therefore, there is always transmission opportunity for the LTE in each frame.

Applications: LTE-U

User Association: To be WiFi or LTE-U User?

- One important observation obtained in the performance analysis of the LBT-based LTE-U MAC protocol design is that when a batch of new users join in the networks, it is not always advantageous to be LTE-U users in terms of individual throughput of the new users or the overall channel utilization.
- Some simulation results have shown that whether the new users should join in the LTE-U system or the legacy WiFi system to get a better performance is highly determined by the traffic load of the existing WiFi system, including the packet arrival rate and the number of WiFi users.
- Therefore, the user association, which determines the provider of the service for the new users, should be optimized.

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Applications: LTE-U

User Association: To be WiFi or LTE-U User?

- In order to maximize the normalized throughput of the unlicensed band with guaranteeing the QoS of WiFi service, a joint resource allocation and user association problem is proposed for a heterogeneous network, where the LTE small cells opportunistically access the spectrum of WiFi system.
- For solving the problem, a two-level learning-based framework is proposed with which the original problem is decomposed into two subproblems.
- The master level problem, which aims to optimize the transmission time of LTE, has been solved by a Q-learning based method;
- while the slave one, which aims to optimize the user association, has been solved by a game-theory based learning method.

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Next lessons content

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