Chapter 5

Spectrum Access and Sharing
Outline

- Spectrum Allocation & Assignment
- Spectrum Sharing: Definition
- Unlicensed Spectrum Sharing
- Licensed Spectrum Sharing
- Secondary Spectrum Access (SSA)
- Real Time SSA
  - Negotiated Access
  - Cont’d next page
Outline

- QoS Provisioning
- Opportunistic Access
- Overlay Approach
- Underlay Approach

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Spectrum Allocation & Assignment

- Radio Spectrum is the medium upon which wireless communications is realized.
- Only portions of spectrum are suitable for mobile communications

<table>
<thead>
<tr>
<th>Radio Frequency range</th>
<th>3-30 Hz</th>
<th>30-3000 MHz</th>
<th>30-300 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely low frequency (ELF)</td>
<td>Extremely high frequency (EHF)</td>
<td>Desirable: High bandwidth, reasonable propagation range</td>
<td>Not desirable: short propagation range, line-of-sight communication</td>
</tr>
</tbody>
</table>

“Cognitive Radio Communications and Networks: Principles and Practice”
International Regulatory bodies, such as ITU, harmonize usage of spectrum through *spectrum allocation* (dedicating bands to specific applications: mobile & personal communication, Radar & military bands, Satellite comm. Band etc)

Regional or national regulatory bodies, such as FCC, *assign* the bands to service providers (such as AT&T, Verizon etc)

Each service provider acquires a *license* for its assigned band

A limited portion of spectrum is *unlicensed*, such as 2.4 GHz ISM band over which WiFi operates
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Spectrum Sharing: Definition

☐ There are 3 physical dimensions to share the spectrum
Spectrum Sharing: Definition

- Several ways of classifying spectrum sharing:
  - Licensed spectrum sharing
    - Horizontal (several systems with similar access right)
    - Vertical (several systems with a hierarchical access right)
    - MAC (single system, TDMA/FDMA/SDMA etc)
  - Unlicensed spectrum sharing
    - Horizontal
    - Single system (Random access, CSMA)
    - Next page a general classification
Spectrum Sharing: Definition

- Spectrum Sharing Techniques
  - Sharing of Unlicensed Spectrum (Horizontal Sharing)
  - Sharing of Licensed Spectrum
    - Multiple Access Sharing
    - Coordination (Horizontal Sharing)
    - Secondary Spectrum Access (Vertical Sharing)
      - Non Real-Time
        - Negotiated
          - Spectrum Hole
          - Underlay Access
        - Opportunistic
          - Spectrum Hole
          - Underlay Access
      - Real-Time Access
        - Integration
        - Interworking
        - Agreements (Regulatory, Economic, etc.)
Spectrum Sharing: Definition

Definition of spectrum sharing:

- Spectrum sharing is the **simultaneous** usage of a specific radio frequency band in a specific geographical area by a number of *independent* entities, leveraged through mechanisms other than traditional multiple- and random-access techniques.
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Unlicensed Spectrum Sharing

- No license is required for a system transmitting on dedicated unlicensed band
  - Obviously still transmit power limits and transmission masks are defined to prevent interfering to adjacent bands
  - Examples:
    - 2.4 GHz ISM band: IEEE 802.11 b/g/n and Bluetooth
    - 5 GHz UNII band: IEEE 802.11a and HyperLAN
  - Advantage:
    - Less regulatory hurdles, shorter time to market, more innovative solutions (Ex: success of WiFi)
  - Drawback:
    - No interference mitigation mechanism (Ex: Microwave Oven operates on the same 2.4 GHz band!)
    - Even among the similar systems: WiFi example next page
Example 1: Consider a WLAN hotspot with $N$ stations (STA)

- STAs use $p$-persistence CSMA (if channel idle, transmit with probability $p$, or wait with probability $q=1-p$)
- Packets at each STA: Poisson process with mean $G$ packet/time slot
- The probability of generating $k$ packets at slot $t$:
  \[ P_t(k) = \frac{G^k e^{-G}}{k!} \]

Assume $D_n(t)$ packets remained from previous time slots

- Probability of STA $n$ remain silent in next time slot:
  \[ P_{s,n}(t) = \left[ \{1 - P_t(0)\} + D_n(t) \right](1-p) + P_t(0) \]
Unlicensed Spectrum Sharing

Example: Consider a WLAN hotspot with \( N \) stations (STA) (Cont’d)

- For simplicity of analysis assume \( D_n(t) = D(t) \)
- The probability of collision:

\[
P_{\text{collision}}(t) = 1 - \prod_{n=1}^{N} P_{s,n}(t) - \binom{N}{1} \prod_{n=1}^{N-1} P_{s,n}(t)
\]

- Replacing all parameters, we get

\[
P_{\text{collision}}(t) = 1 - \left[ p e^{-G} + q(1 + D(t)) \right]^{N-1} (N + p e^{-G} + q(1 + D(t)))
\]

- An increasing function of load \( G \) and number of nodes \( N \)
- Have you tried checking your e-mail in a conference meeting?
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Consider a horizontal licensed spectrum sharing:
- A pool of spectrum that can be accessed by several RANs
- If the peak traffic load of the majority of RANs occur simultaneously, shortage of spectrum will happen at those times
- Conversely, during low traffic load times, most of resources will remain unutilized
- Hence, **correlation** of traffic pattern of RANs (in time) is an important factor in efficiency of spectrum sharing
- Traffic prediction models can help
  - Ex: Auto Regressive (AR), Moving Average (MA), ARMA etc
  - Refer to Ex. 2, Ch 05
- Another perspective, is from cost-revenue trade-off:
  - Cont’d Next slide
Licensed Spectrum Sharing

- Cost-Revenue Trade-off in licensed spectrum sharing:
  - Assume revenue from a “unit” of shared spectrum is $R_s$
  - Cost of borrowing a unit of shared spectrum is $C_b$
  - Initial stock of spectrum at RAN $m$ is $N_m$ unit
  - Accumulated revenue at this time is $W_m(0)$
  - For period $i$:
    - Cost = $(D_m - N_m)C_b$
    - Revenue = $D_m R_s$
  - The accumulated revenue:
    \[
    W_m(i) = W_m(0) + D_m R_s - \frac{D_m - N_m}{N_m} (D_m - N_m)C_b
    \]
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Secondary Spectrum Access (SSA)

- SSA is a vertical (licensed) spectrum sharing
  - License holder of the band operates as the “primary” system
  - “Secondary” users are allowed to access the licensed band of primary, complying with certain requirements
  - Cognitive Radio (CR) is an enabling technology to implement SSA
  - A recent example is FCC’s decision to allow secondary access to TV white spaces
  - Two approaches:
    - Overlay SSA
      - Only access the band IF the primary is absent
    - Underlay SSA
      - Secondary users can access the band when the primary is transmitting, BUT the received interference by primary receivers should be below a threshold
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Real-Time SSA: Negotiated Access

- When there exists an interaction mechanism between primary and secondary networks
  - Interaction can include information on available or idle primary spectral ranges (for overlay scheme) or received interference (for underlay scheme)
  - To facilitate such negotiations, dedicated signaling channel should be developed
    - Cognitive Pilot Channel (CPC) is one such channel
    - Refer to Ex. 4 Ch 05
Real-Time SSA: Negotiated Access

- Can QoS be guaranteed in this scheme?
  - Recall the collision problem of unlicensed spectrum sharing (Ex. 1, Ch. 05)
  - Consider the below channel set up
Real-Time SSA: Negotiated Access

Goal:

\[ \text{Minimize} \sum_{n=1}^{N} E_{g_{i,n}} \left\{ p_{i,n}(g_{i,n}) \right\} \]

s.t.

\[ R_{QoS,i} - \sum_{n=1}^{N} R_{i,n} \leq 0, \]

\[ E_{g_{i,n}} \left\{ \sum_{n=1}^{N} p_{i,n}(g_{i,n}) \right\} \leq 0, \]

where

\[ R_{i,n} = \log(1 + \frac{p_{i,n}g_{i,n}}{\sigma_i^2 + p_{j,n}h_{j,n}}) \]
Real-Time SSA: Negotiated Access

- It can be shown to satisfy this optimization problem, we should have (Details in Ch 05)

\[ g_{1,n} g_{2,n} > h_{1,n} h_{2,n} \left( e^{\frac{\alpha_n R_{QoS,1}}{w}} - 1 \right) \left( e^{\frac{\alpha_n R_{QoS,2}}{w}} - 1 \right) \]

- Intuition: If your transmission is making more interference than your direct communication, do not transmit (or in this case, do not allow secondary to transmit)

- This inequality, also depends on the level of QoS to be guaranteed \( (R_{QoS,i}) \) (see next slide)

- There is a need for negotiation: primary and secondary should exchange channel information as well as QoS requests
Real-Time SSA: Negotiated Access

- If $R_{QoS}$ is too high, depending on the direct and cross channel gains, QoS guarantee might be infeasible.
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Chapter Summary
Opportunistic Access: Overlay Approach

- In some scenarios, primary-secondary negotiation is not feasible
  - Recall the case secondary access to TV bands, authorized by FCC
  - Another example: if primary system is a RADAR
  - In that case, secondary should *opportunistically* access the licensed band
    - Recall Overlay is one possibility: only transmit when primary signal is not detected in a band
    - Secondary should “shape” its transmitting signal to avoid collision with primary’s signal
Opportunistic Access: Overaly Approach

- Multi-carrier modulation is a powerful tool to this end
  - OFDM, Multi-carrier CDMA (see below, details in Ch 05)
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- Chapter Summary
Opportunistic Access: Underlay Approach

- Another opportunistic SSA method is underlay
  - Recall underlay ensures the received interference of primary remain below a threshold
  - Consider:
Opportunistic Access: Underlay Approach

- **Goal:**

\[ C_{ER,i} = \max \mathbb{E}_{g_{i,n},h_{i,n}} \left\{ \sum_{n=1}^{N} R_{i,n} \right\}, \]

s.t.

- **Average interference limit**

\[ \mathbb{E}_{g_{i,n},h_{i,n}} \left[ \sum_{n=1}^{N} p_{i,n} (g_{i,n}, h_{i,n}) h_{i,n} \right] \leq \Gamma_{avg,i} \]

or

- **Instantaneous interference limit**

\[ \sum_{n=1}^{N} p_{i,n} (g_{i,n}, h_{i,n}) h_{i,n} \leq \Gamma_{inst,i} \]

and

\[ \mathbb{E}_{g_{i,n},h_{i,n}} \left\{ \sum_{n=1}^{N} p_{i,n} (g_{i,n}, h_{i,n}) \right\} \leq P_{max,i} \]

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Opportunistic Access: Underlay Approach

- It can be shown that average interference limit is superior than instantaneous interference limit
  - From primary point of view, one might think instantaneous interference limit will better protect the primary receivers
    - Instantaneous = at any instant of time!
  - However, it turns out that using an average interference limit, the secondary transmits with a higher power when channel quality permits (though not exactly the same concept, recall channel condition from negotiated access)
  - Also when channel is not desirable (low attenuation from secondary transmitter to primary receiver) secondary transmits with less power
  - On average, we achieve a better performance
  - Also, check out Ch05, for details of optimal transmission power in each case
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☐ Chapter Summary
Chapter 5 Summary

- Due to increasing demand for radio spectrum, we need to adopt spectrum sharing mechanisms.
- Cognitive Radio is the enabling technology for Secondary Spectrum Access.
- Spectrum sharing can be achieved in time, frequency and/or space dimensions.
- Several classifications of spectrum sharing solutions exist.
Chapter 5 Summary

- Spectrum sharing can be performed over licensed or unlicensed bands
- Unlicensed bands allow systems/devices to utilize those bands without requiring a spectrum license
- Unlicensed spectrum encourages innovative solutions but offers no interference mitigation mechanism
Chapter 5 Summary

☐ If an interaction mechanism between primary and secondary users exists, negotiated SSA can be deployed
  ■ In negotiated SSA, QoS guarantee is potentially feasible (depends on factors such as channel gains and requested QoS level)

☐ If negotiated SSA is not an option, opportunistic secondary access can be exploited.

☐ In opportunistic SSA, spectrum sharing can be overlay (no primary in the band) or underlay (simultaneous with primary but limiting the interference)
Chapter 5 Summary

- For overlay scheme, spectrum aggregation techniques, such as multi-carrier modulation, is required.
- In underlay scheme, average or instantaneous interference limits can be satisfied.
- It turns out that average interference limit outperforms instantaneous interference limit.