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
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Outline

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

- Chapter Summary

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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

Radio Frequency range →

3-30 Hz	**30-3000 MHz**	30-300 GHz
Extremely low frequency (ELF)	**Desirable: High bandwidth, reasonable propagation range**	Extremely high frequency (EHF)
Not desirable: low bandwidth, long propagation range		Not desirable: short propagation range, line-of-sight communication

Spectrum Allocation & Assignment

- 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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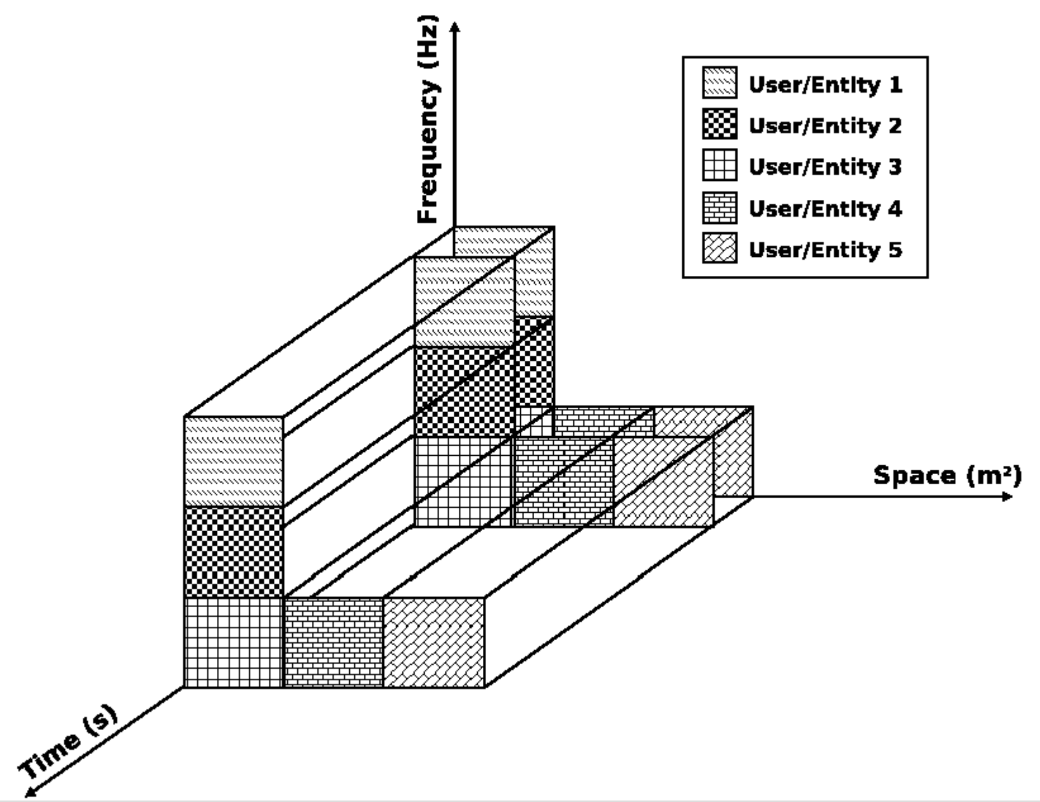
Spectrum Sharing: Definition

- There are 3 physical dimensions to share the spectrum

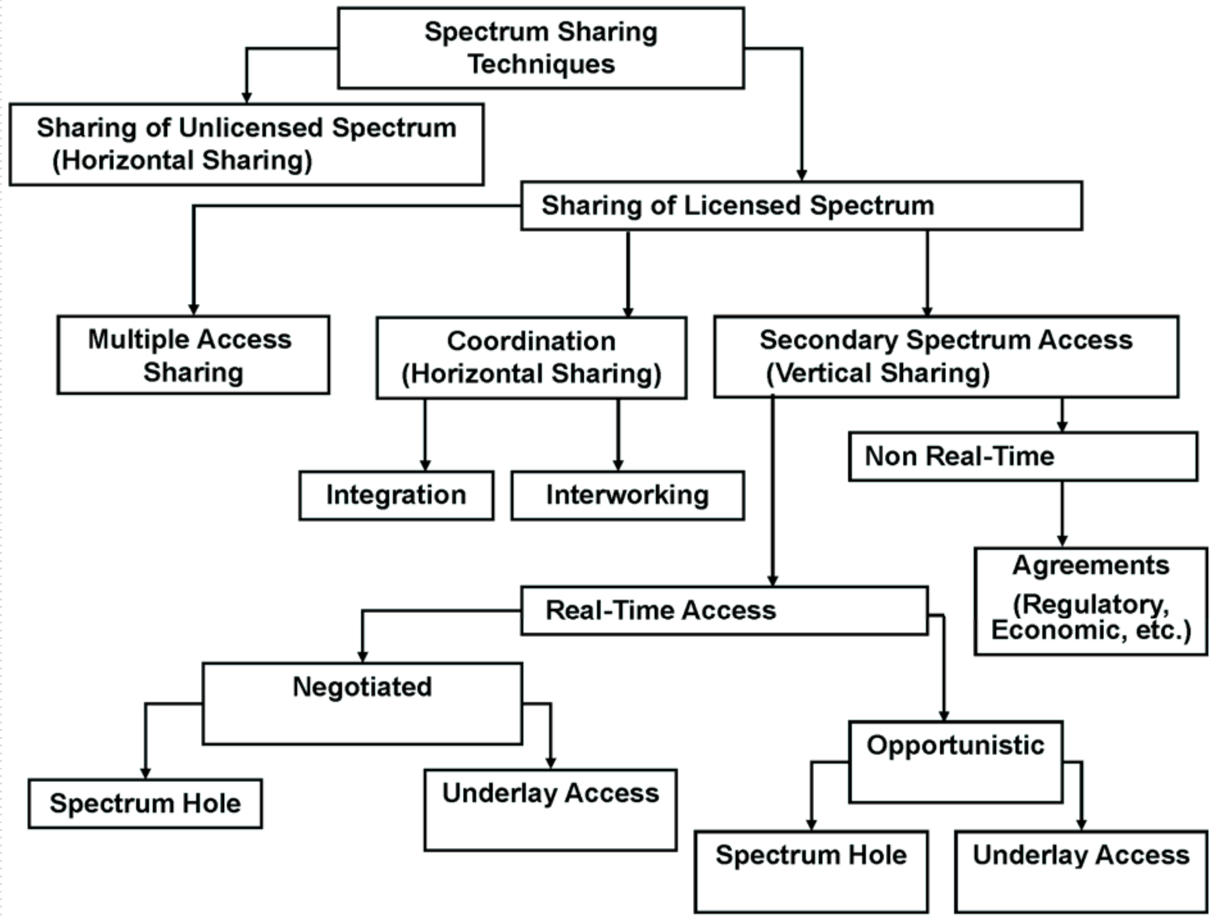


"*Cognitive Radio Communications and Networks: Principles and Practice*"
By A. M. Wyglinski, M. Nekovee, Y. T. Hou (Elsevier, December 2009)

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: 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

Unlicensed Spectrum Sharing

- 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:

$$P_{s,n}(t) = [\{1 - P_t(0)\} + D_n(t)](1 - p) + P_t(0)$$

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:

$$P_{collision}(t) = 1 - \prod^{N} P_{s,n}(t) - \binom{N}{1} \prod^{N-1} P_{s,n}(t)$$

  - Replacing all parameters, we get

$$P_{collision}(t) = 1 - [pe^{-G} + q(1 + D(t))]^{N-1}(N + pe^{-G} + q(1 + D(t)))$$

  - 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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Licensed Spectrum Sharing

- 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_mR_s
  - The accumulated revenue:

$$W_m(i) = W_m(0) + D_m R_s - \frac{\frac{D_m}{N_m} - 1}{\left| \frac{D_m}{N_m} - 1 \right|}(D_m - N_m)C_b$$

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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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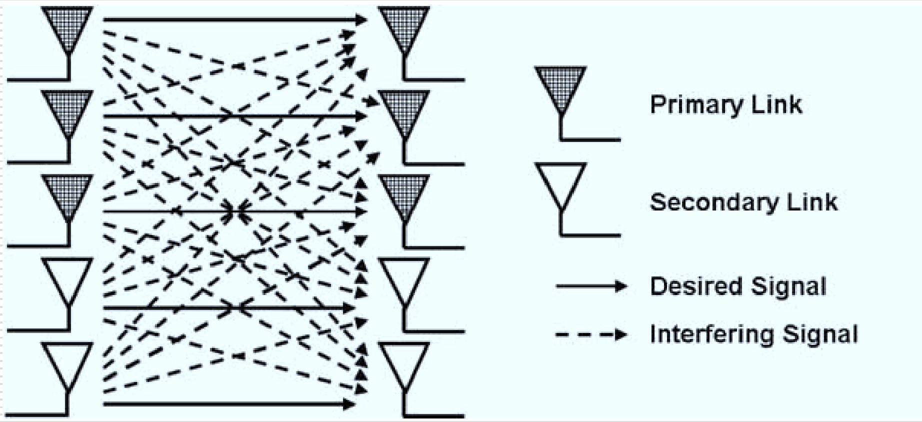
Real-Time SSA: Negotiated Access

- 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:

$$\underset{p_{i,n}}{Minimize} \sum_{n=1}^{N} E_{g_{i,n}} \{ p_{i,n}(g_{i,n}) \}$$

$$s.t.$$

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

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

$$where$$

$$R_{i,n} = \log(1 + \frac{p_{i,n} g_{i,n}}{\sigma_i^2 + p_{j,n} h_{j,n}})$$

Real-Time SSA: Negotiated Access

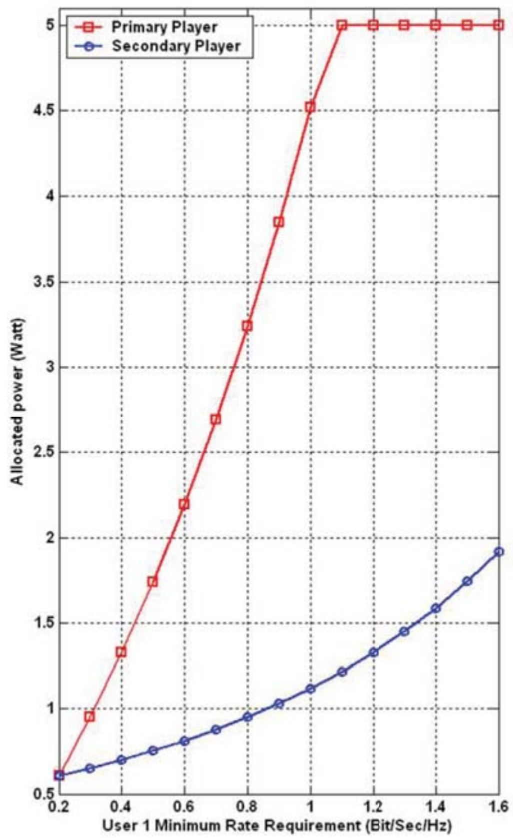
- It can be shown to satisfy this optimization problem, we should have (Details in Ch 05)

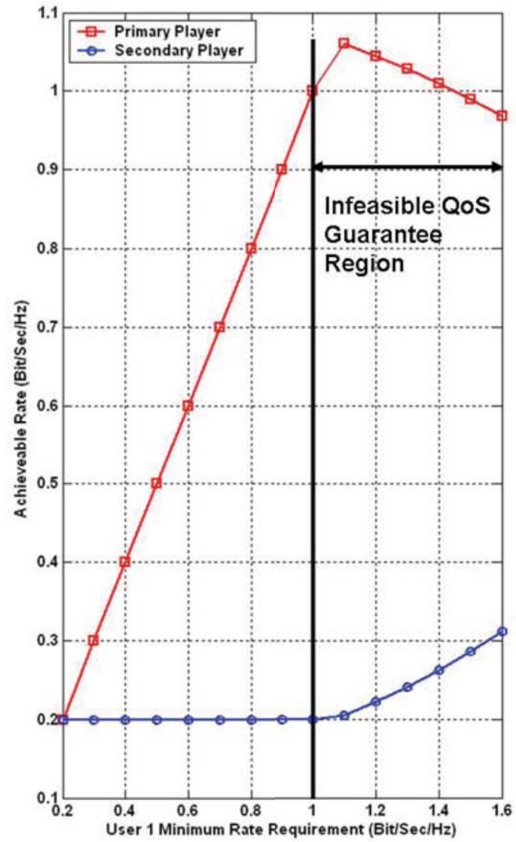
$$g_{1,n}g_{2,n} > h_{1,n}h_{2,n}(e^{\alpha_n R_{QoS,1}/w} - 1)(e^{\alpha_n R_{QoS,2}/w} - 1)$$

- 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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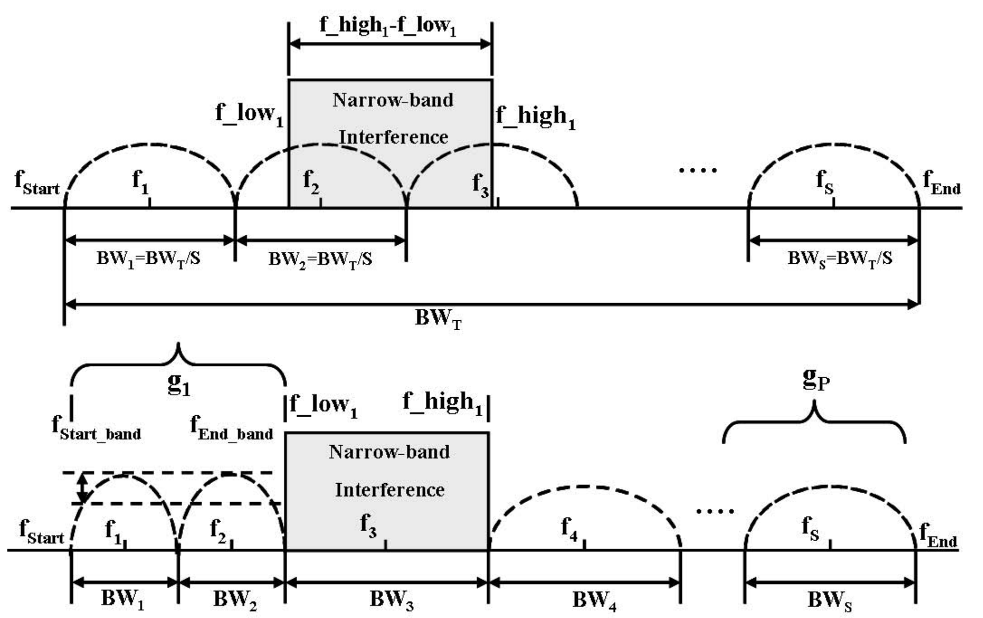
Opportunistic Access: Overlay Approach

- 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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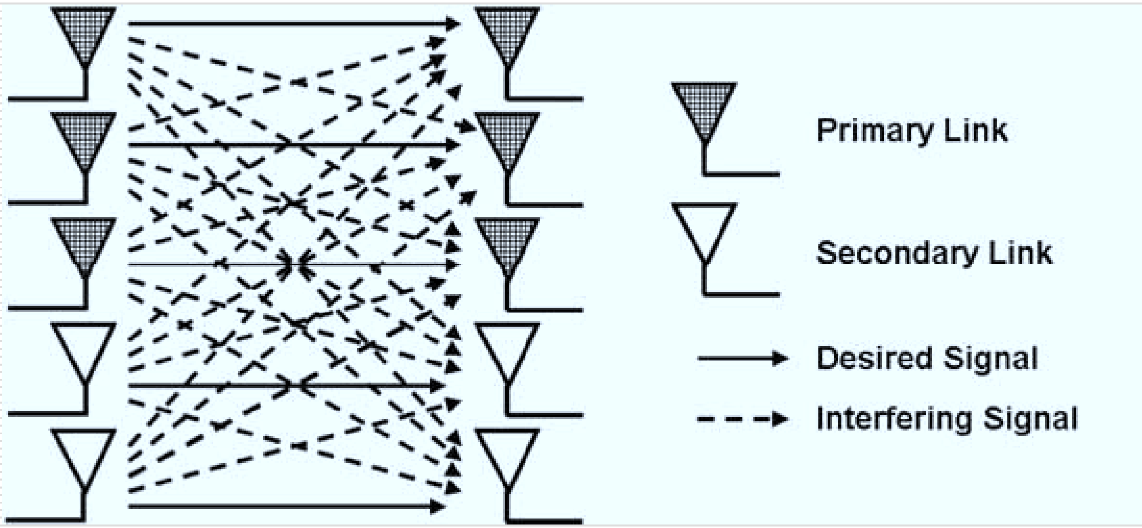
Opportunistic Access: Underlay Approach

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



Opportunistic Access: Underlay Approach

- Goal:

$$C_{ER,i} = \underset{g_{i,n},h_{i,n}}{Max}\ E_{g_{i,n},h_{i,n}}\left\{\sum_{n=1}^{N} R_{i,n}\right\},$$

$$s.t.$$

Average interference limit

or

Instantaneous interference limit

$$\begin{cases} E_{g_{i,n},h_{i,n}}\left[\sum_{n=1}^{N} p_{i,n}(g_{i,n},h_{i,n})h_{i,n}\right] \le \Gamma_{avg,i} \\ \sum_{n=1}^{N} p_{i,n}(g_{i,n},h_{i,n})h_{i,n} \le \Gamma_{inst,i} \end{cases}$$

$$and$$

$$E_{g_{i,n},h_{i,n}}\left\{\sum_{n=1}^{N} p_{i,n}(g_{i,n},h_{i,n})\right\} \le P_{\max,\ i}$$

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 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 exists

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