Optimal Joint Partitioning and Licensing of Spectrum Bands in Tiered Spectrum Access under Stochastic Market Models

Alhussein Abouzeid

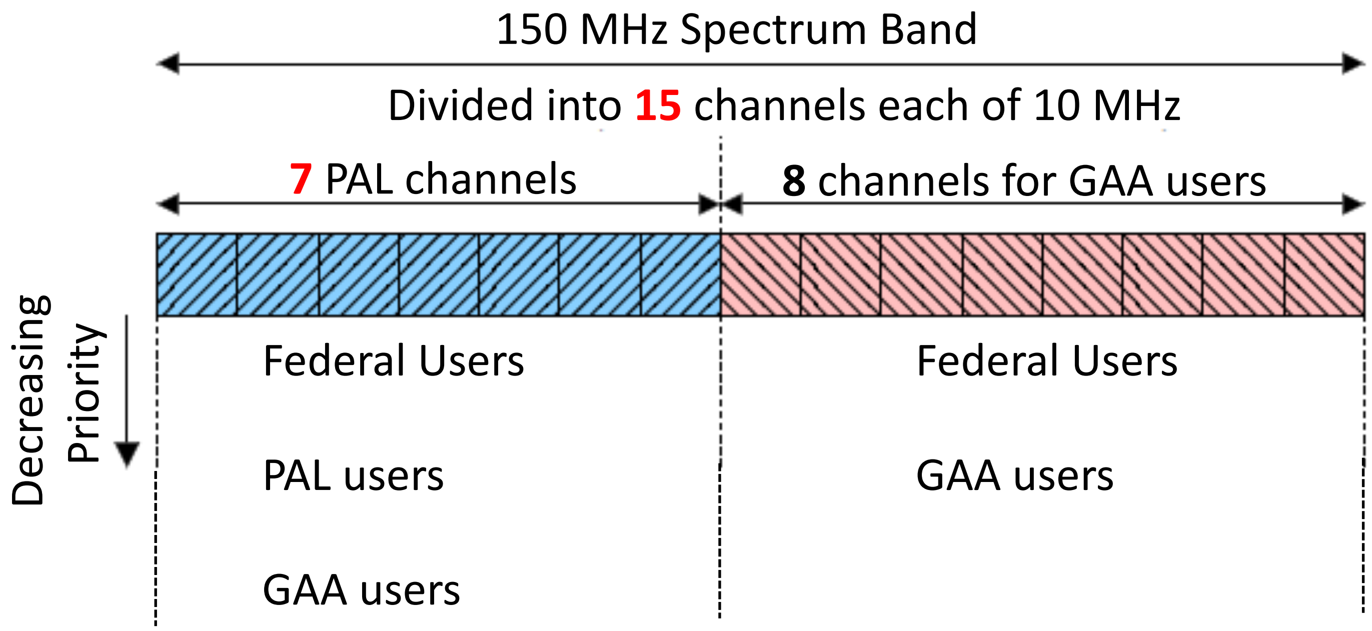
Professor, Electrical Computer and Systems Engineering
Rensselaer Polytechnic Institute

Joint work with Mr. Gourav Saha, PhD Candidate, RPI, NY, USA

Motivation

- CBRS band is 150 MHZ band
- Spectrum sharing with 3-Tiers of priority.
  - Tier-1: Federal users
  - Tier-2: PAL users (licensed channel access)
  - Tier-3: GAA users (opportunistic channel access)
- Partitioned into **15**, 10 MHz channel.
  - **7** PAL channels; primarily for PAL users.
  - **8** reserved channels only for GAA users.

CBRS Model



Does partitioning the CBRS Band in **15** channels and allocating **7** channels for PAL licenses maximize spectrum utilization?

Related work

Optimal Partitioning

- [4] : Maximizing spatial density of transmission subject to a fixed link transmission rate and packet error rate.
- [5] : Game theoretic approach towards partitioning of bandwidth in presence of guard bands.

Optimal Licensing

- [9] : Effect of the ratio between licensed and unlicensed channel for CBRS band on market competition in presence of Environmental Sensing Capability operators.
- Works similar to licensed and unlicensed band:

  - [10] : macro cells and small cells.

  - [12] : long-term leasing market and short-term rental

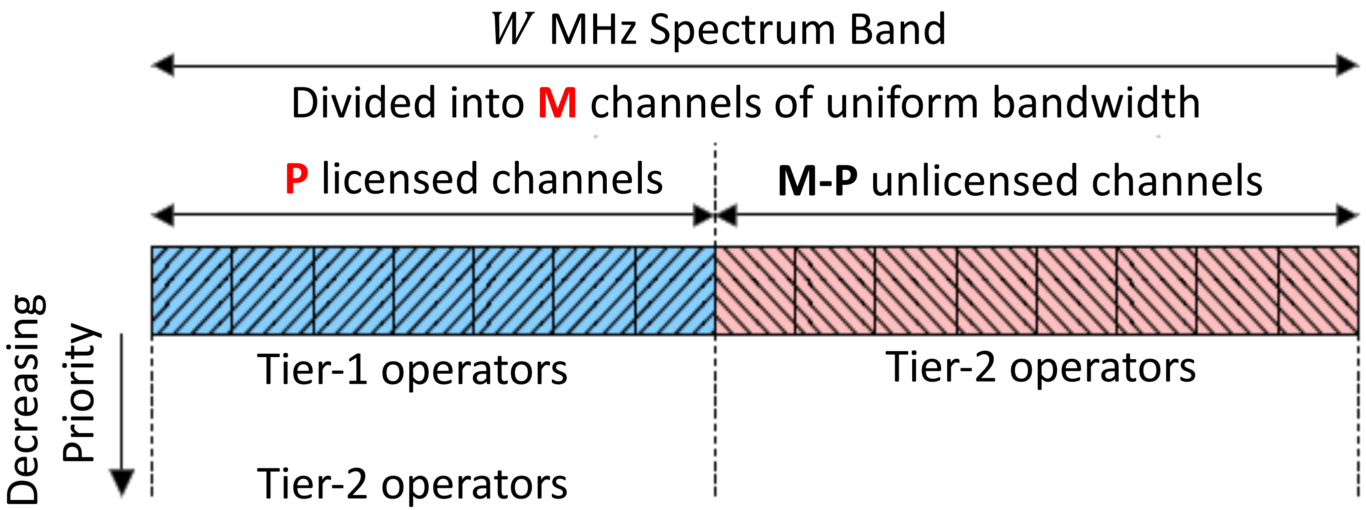
  - [13] : 4G cellular and Super Wifi services

Our work: *joint* partitioning and licensing problem in *tiered* spectrum sharing

Channel Model

- A spectrum band $W\ MHz$
- Partitioned into M, $\frac{W}{M}$ MHz channels.
  - P licensed channels → PAL channels
  - $M-P$ unlicensed channels → Channels reserved for GAA users
- Tier-1 operators → PAL users
  - Leases licensed channels.
  - Allocated through auctions.
- Tier-2 operators → GAA users
  - Uses unlicensed channels opportunistically.
  - Uses a licensed channel opportunistically if a Tier-1 operator is not using the channel.
  - Allocation algorithm should be fair.

Generalized Channel Model



Channel Model

- $W\ MHz$ bandwidth can serve a maximum of D units of customer demand.
- Tier-1 operators using licensed channels:

  Channel capacity = $\frac{D}{M}$

- Tier-2 operators using licensed channels:

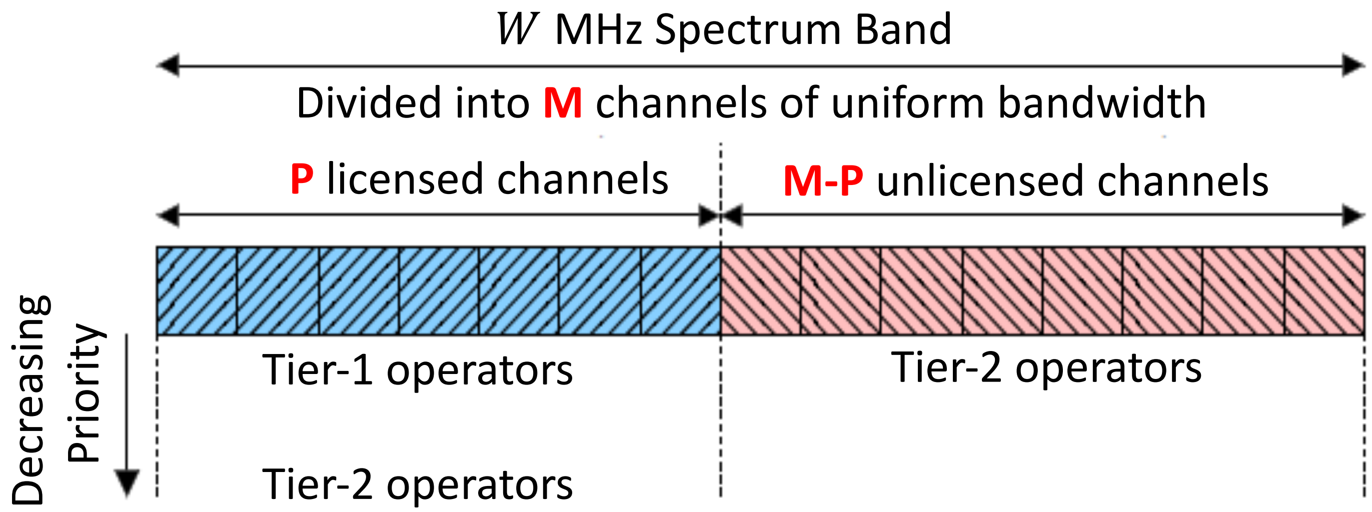
  Channel capacity = $\frac{\alpha_L D}{M}$

- Tier-2 operators using unlicensed channels:

  Channel capacity = $\frac{\alpha_U D}{M}$

α_L , α_U → Efficiency of licensed and unlicensed channels for opportunistic use. We have, $\alpha_L , \alpha_U \leq 1$. Typically, T2 operators don't get a lot of a licensed channel, compared to an unlicensed channel, hence typically $\alpha_L \leq \alpha_U$

Generalized Channel Model



Types of Wireless Operators

- Set of candidate licensed operators $\mathcal{S}_L^C$.
  - Primarily interested in licensed channel access.
  - If they are not allocated a licensed channel, then they access channels opportunistically.

- Set of candidate unlicensed operators $\mathcal{S}_U^C$.
  - Only interested in opportunistic channel access.

- Only a subset of candidate operators joins the market. Decision to join the market is based on an operator's preferences.
  - Set of interested licensed operators $\mathcal{S}_L$.
  - Set of interested unlicensed operators $\mathcal{S}_U$.

Example: Sequence of Events

s

Increasing time $t = 0$

$\mathcal{S}_L^C = \{1, 2, 3, 4, 5\}$

$\mathcal{S}_U^C = \{6, 7, 8\}$

Stage 1 game: Regulator decides the value of number of channels M and number of licensed channels P. Let's say, $M = 4, P = 2$.

Stage 2 game: Operators in sets $\mathcal{S}_L^C$ and $\mathcal{S}_U^C$ decides whether to enter the market or not based on their preferences. Let's say,
$\mathcal{S}_L = \{1, 2, 3, 4\}$
$\mathcal{S}_U = \{6, 7\}$

$t = 1$ $t = T + 1$ **Increasing time** $t = 2T + 1$

Epoch 1 **Epoch 2**

1^{st} auction

Operators 1 and 4 wins the auction.
Tier-1 Operators:
$\mathcal{T}_1 = \{1, 4\}$
Tier-2 Operators:
$\mathcal{T}_2 = \{2, 3\} \cup \{6, 7\} = \{2, 3, 6, 7\}$

2^{nd} auction

Operators 3 and 4 wins the auction.
Tier-1 Operators:
$\mathcal{T}_1 = \{3, 4\}$
Tier-2 Operators:
$\mathcal{T}_2 = \{1, 2\} \cup \{6, 7\} = \{1, 2, 6, 7\}$

3^{rd} auction

Demand and Revenue Model

- The k^{th} interested licensed operators is associated with five gaussian random variables.

Tier-1 operator

$$X_{k,1} \overset{\rho_k}{\longleftrightarrow} R_{k,1} \overset{\omega_k}{\longleftrightarrow} B_k$$

- $X_{k,1}$: Net demand served by k^{th} operator in an epoch if it is a Tier-1 operator.
- $R_{k,1}$: Net revenue earned by k^{th} operator in an epoch if it is a Tier-1 operator.
- B_k: Bid of a licensed channel for k^{th} operator.

Tier-2 operator

$$X_{k,2} \overset{\rho_k}{\longleftrightarrow} R_{k,2}$$

- $X_{k,2}$: Net demand served by k^{th} operator in an epoch if it is a Tier-2 operator.
- $R_{k,2}$: Net revenue earned by k^{th} operator in an epoch if it is a Tier-2 operator.

- The k^{th} interested unlicensed operators is associated with two gaussian random variables.

Revenue and Objective Function

- Revenue function $\mathcal{R}_k(M, P, \mathcal{S}_L, \mathcal{S}_U)$: Net expected revenue of the k^{th} operator in an epoch.
  - Decides which operators are interested in entering the market.
  - It is a function of the set of interested licensed and unlicensed operators.
  - Monotonic property: It decreases if the set of interested licensed and unlicensed operators increases.

- Objective function $\mathrm{U}(M, P, \mathcal{S}_L, \mathcal{S}_U)$: A measure of the net customer demand served by all the interested operators.

- We built a Monte-Carlo integrator to evaluate these two functions.

- $\mathcal{S}_L$ and $\mathcal{S}_U$ are themselves functions of M and P, and in general not independent

Stackelberg Game

Stage-1 game

- The regulator decides the value of M and P to maximize the objective function:

$$\mathrm{U}\left(M, P, \underbrace{\mathcal{S}_L(M,P), \mathcal{S}_U(M,P)}_{\text{Output of Stage-2 game}}\right)$$

- We do this by performing a grid-search over M and P.
  - This possible because for any practical setup, the possible values of M and P are not too large.

Stackelberg Game

Stage-2 game

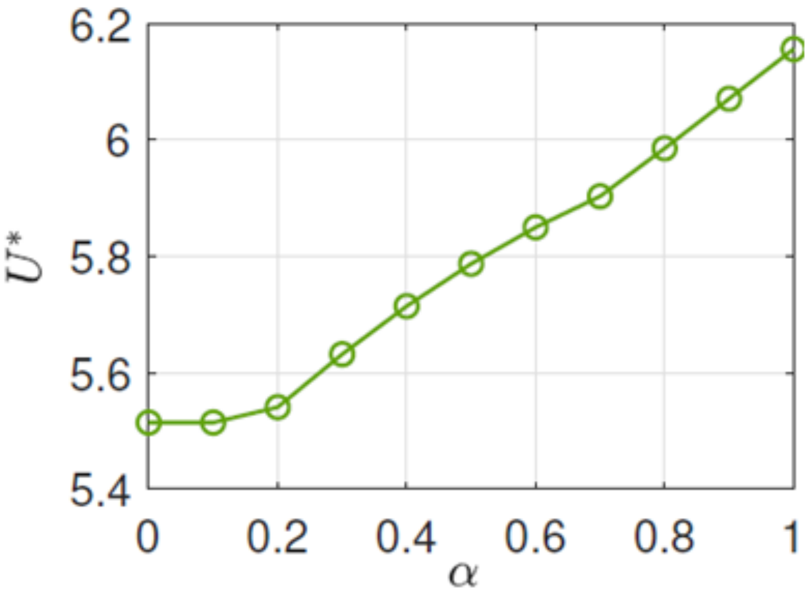
- Wireless operators decides whether to join the market or not based on the value of M and P set by the regulator in Stage-1 game.
  - Output of Stage-2 game: $\mathcal{S}_L(M,P)$ and $\mathcal{S}_U(M,P)$

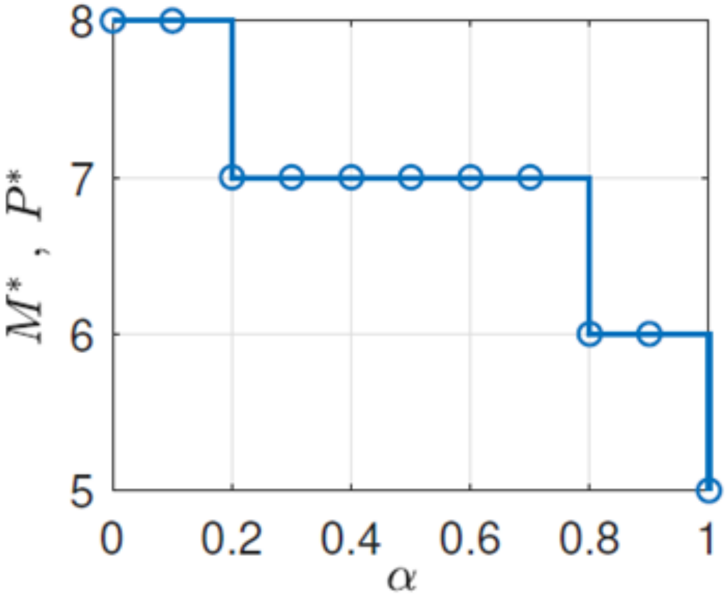
- The k^{th} operator enters the market only if the expected revenue it can earn in an epoch is greater than λ_k, i.e. $\mathcal{R}_k(M,P,\mathcal{S}_L,\mathcal{S}_U) \geq \lambda_k$. (minimum revenue requirement)

- Operators are pessimistic in nature, i.e. they will enter the market only if the minimum expected revenue in an epoch with respect to $\mathcal{S}_L$ and $\mathcal{S}_U$ is greater than λ_k.
  - An operator joins the market only if the dominant strategy is to join the market. Due to monotonic nature of revenue function, joining the market is dominant strategy if

$$\boldsymbol{\mathcal{R}_k\left(M,P,\mathcal{S}_L^C,\mathcal{S}_U^C\right) \geq \lambda_k}$$

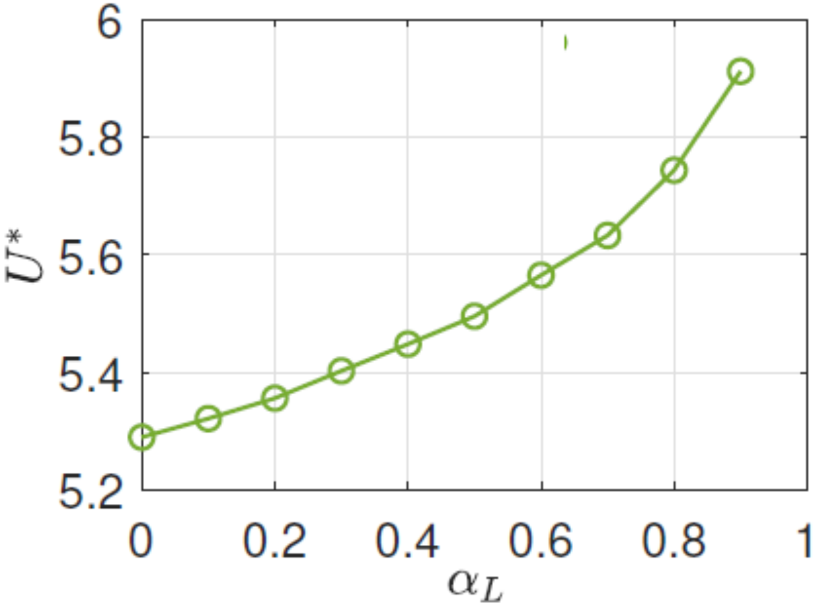
Numerical Result 1

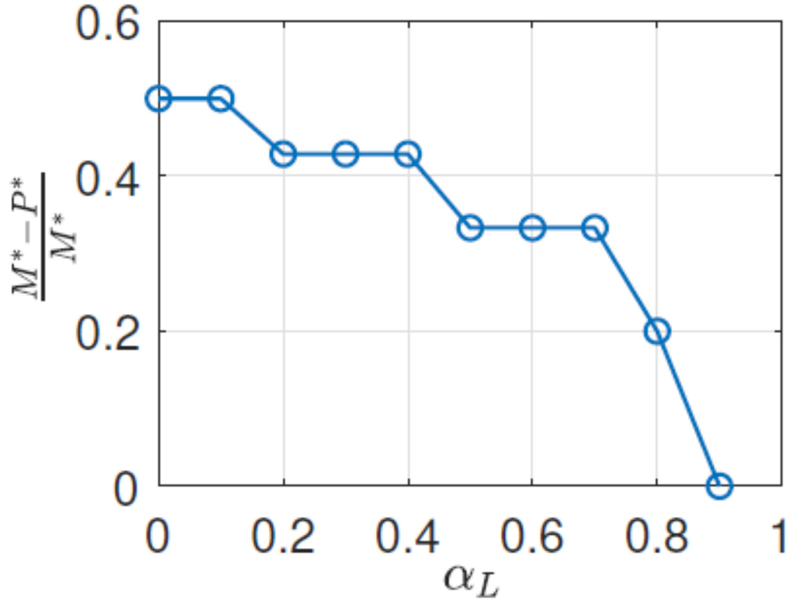




- We study the variation of optimal value of M, P and the objective function with change in interference parameter for opportunistic access α_L and α_U. We set $\alpha_L = \alpha_U = \alpha$.
- 8 licensed operators, NO unlicensed operators and $\lambda_k = 0\,;\ \forall k$.
  - No unlicensed operators implies no unlicensed channel, i.e. $M^* = P^*$.
- As α increases, U^* increases.
  - Opportunistic access becomes more efficient.
- As α increases, M^* decreases.
  - Lower M implies more Tier-2 operators who uses channels opportunistically.
  - Efficiency of opportunistic access increases with increase in α.
  - Therefore, lower M is preferred when α is high.

Numerical Result 2



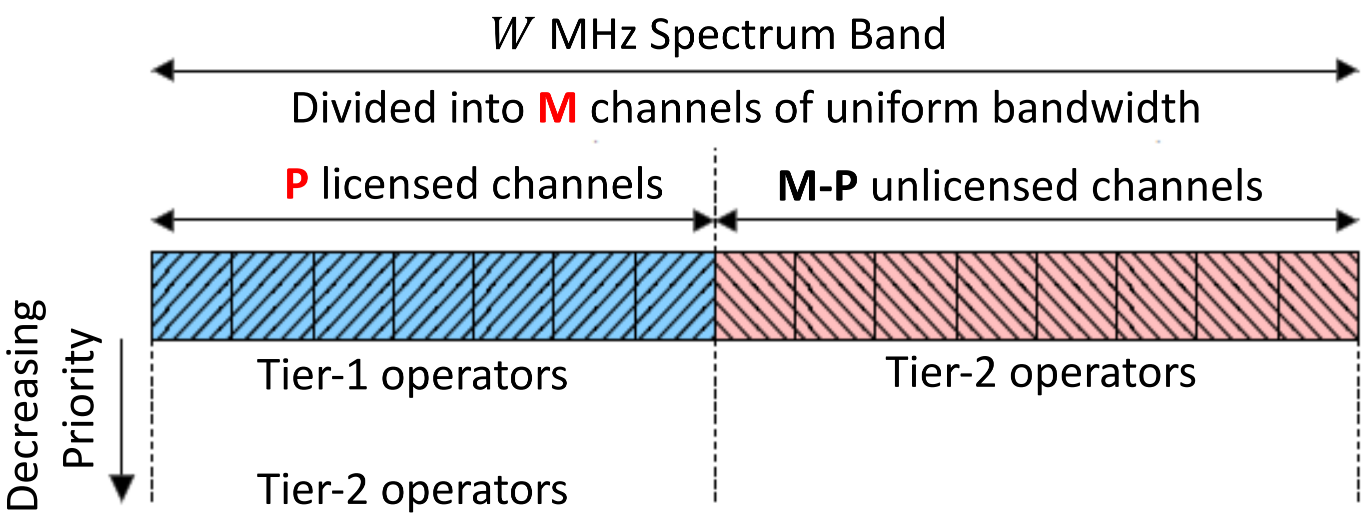


- We study the variation of optimal value of the objective function and optimal ratio of unlicensed band, $\frac{M^*-P^*}{M^*}$, with change in α_L. α_L and α_U are NOT equal; α_U is a constant.
- 4 licensed operators, 4 unlicensed operators and $\lambda_k = 0\ ;\ \forall k$.
- As α_L increases, U^* increases.
  - Opportunistic access becomes more efficient.
- As α_L increases, $\frac{M^*-P^*}{M^*}$ decreases.
  - As α_L increases, efficiency of opportunistic access for licensed channels increases.
  - Therefore, it is better to have more licensed channels than unlicensed channels.

Conclusion

- We consider the joint problem of partitioning a band into channels, and allocating channels to licensed tiered access or unlicensed access
- Modeled as a two-stage Stackelberg game
- Takes into account minimum revenue requirement of operators as well as the difference in channel capacity between opportunistic versus licensed access

Channel Model



Thank you for listening!

Please email abouzeid@ecse.rpi.edu or sahag@rpi.edu for questions/ comments