# Information Market for TV White Space

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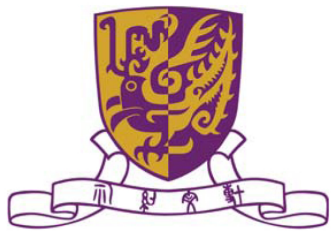

# What is TV white space?

- TV white space refers to radio frequencies (VHF and UHF) allocated to television broadcasting services but not used locally.

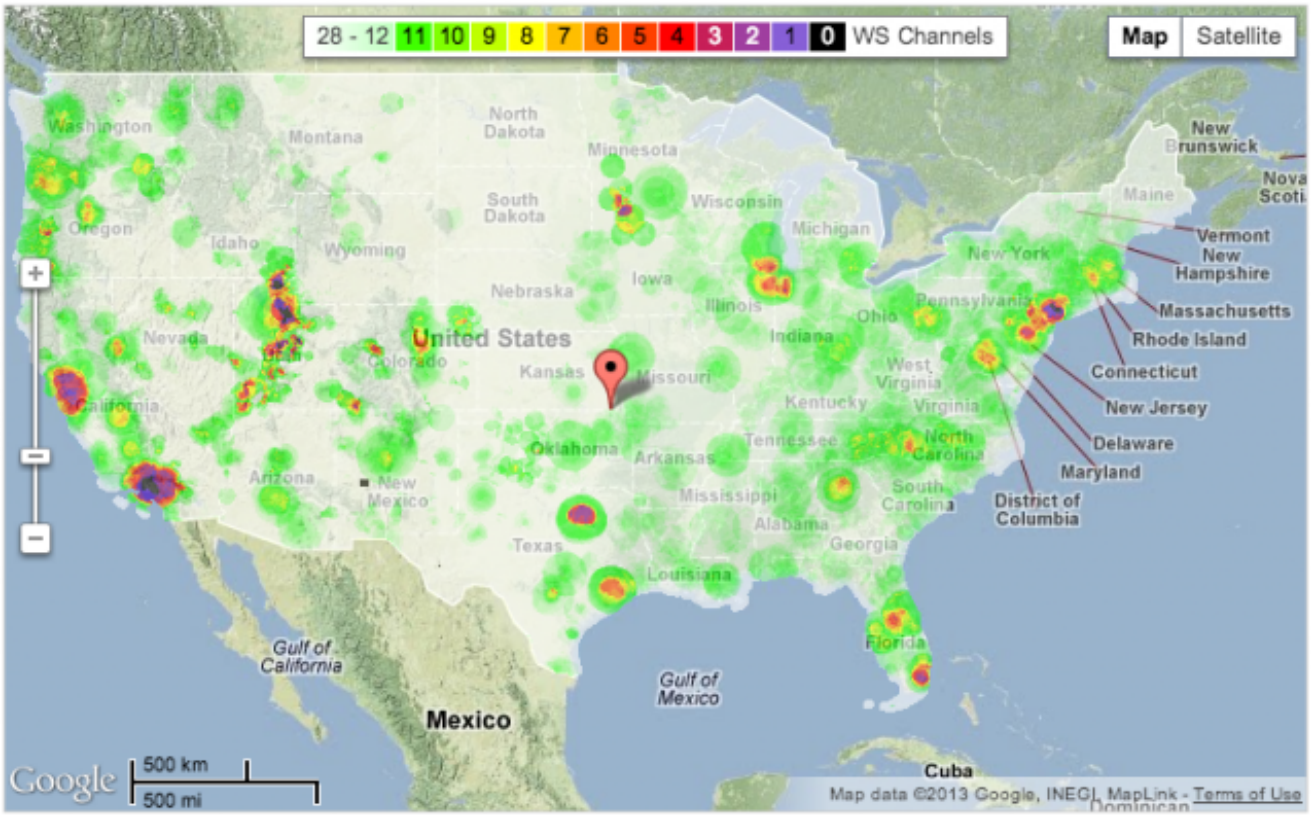


*Fig. Number of TV White Space Channels in the United States (from Google)*

# Focus of This Work

- We study the database-assisted TV white space network.

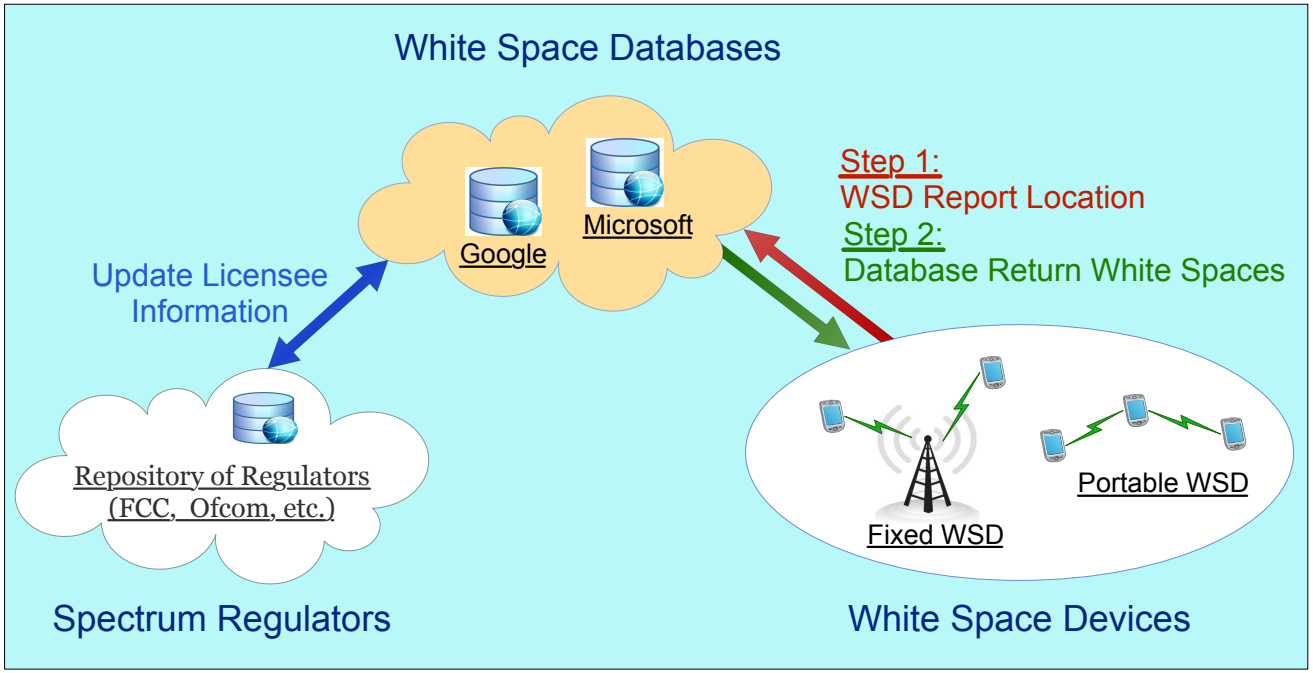


*Fig. Architecture of Database-Assisted TV White Space Network (by FCC)*

- Our focus: Propose a proper business model for TV white space networks.

# Outline

# Mobile Data Explosion

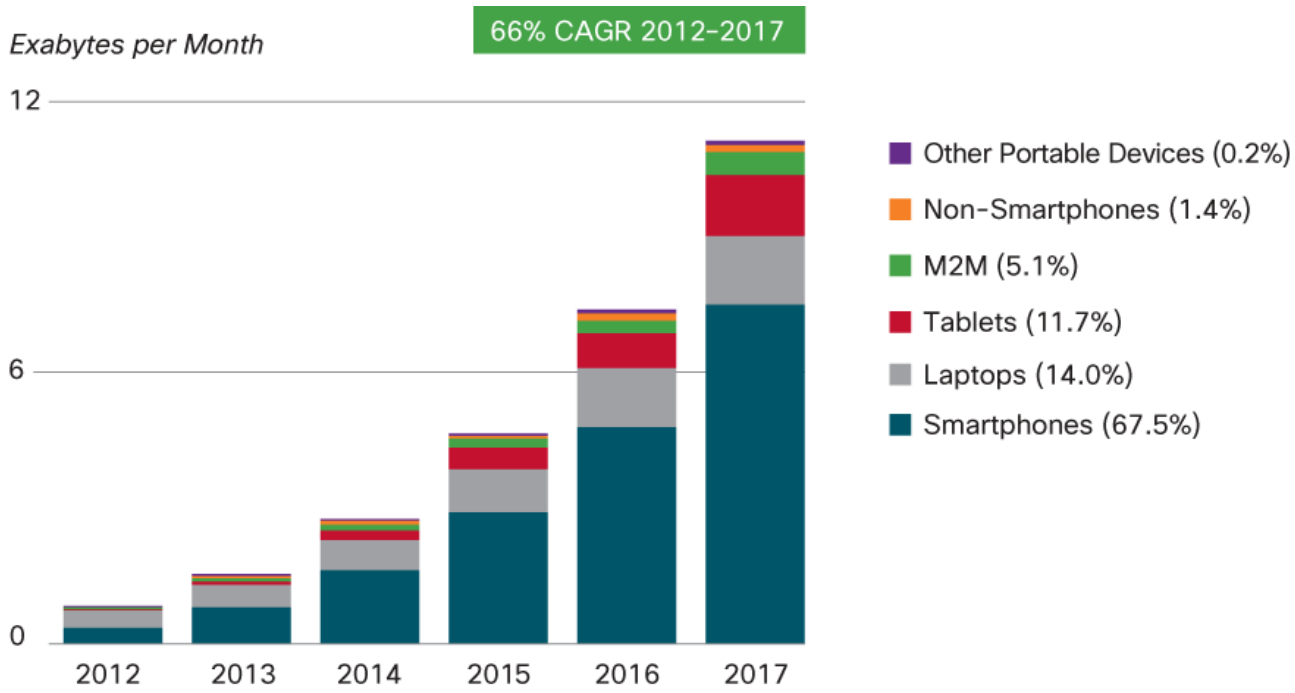


*Fig. Global Mobile Data Traffic, 2012 to 2017 (from Cisco VNI)*

- Mobile data traffic explosive growth: 66% annual grow rate
  - Reaching 11.2 exabytes per month by 2017, a 13-fold increase over 2012 or a 46-fold increase over 2010.

# How about radio spectrum resource?

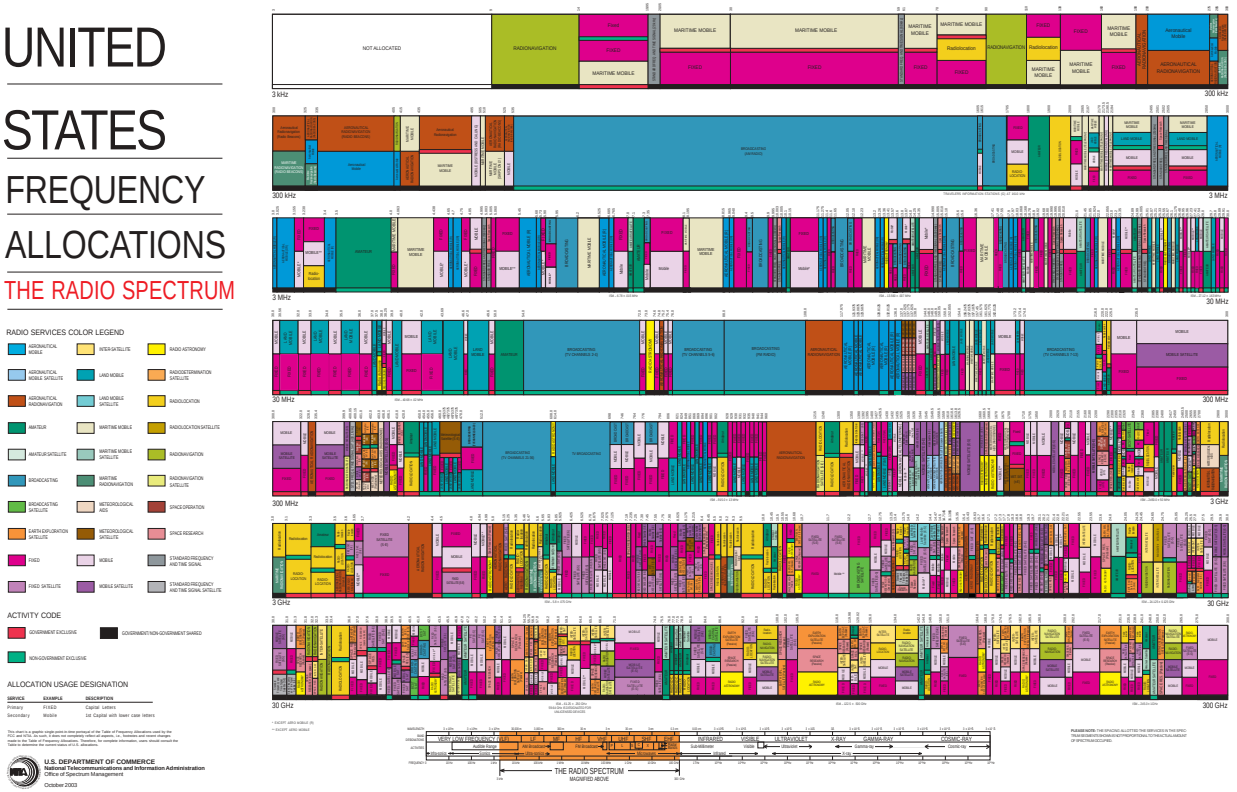


*Fig. Frequency Allocation Chart in USA*

- Radio spectrum is scarce: No new radio spectrum resource for telecommunication services.

# TV White Space

- Many frequencies are in inefficient usage, especially those in UHF/VHF for television broadcasting services.
  - TV services may not be provided continuously;
  - Some frequencies are free up from the digital switchover.

- TV White Space
  - Frequencies (VHF/UHF) allocated to television broadcasting services but not used locally.
    - ★ Time- and location-dependent.
  - In most places of USA, there are more than 10 TV white space channels (each with 6MHz).

# Utilization of TV White Space

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  - Nov 2008, FCC approved the unlicensed use of TV white space.
  - Sept 2010, FCC determined the final rules for the use of white space for unlicensed devices:
    - ★ Removed the mandatory sensing requirements for unlicensed devices;
    - ★ Unlicensed devices must consult an FCC-certified geo-location database to determine which channels are available at a given location;

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    - ★ Unlicensed devices must consult an FCC-certified geo-location database to determine which channels are available at a given location;
  - Jan 2011, FCC conditionally designated 9 companies to serve as geo-location white space database operators in USA,
    - ★ E.g., Google, Spectrum Bridge, Microsoft, LS Telecom, etc.

# TV White Space Network

- Database-Assisted TV White Space Network

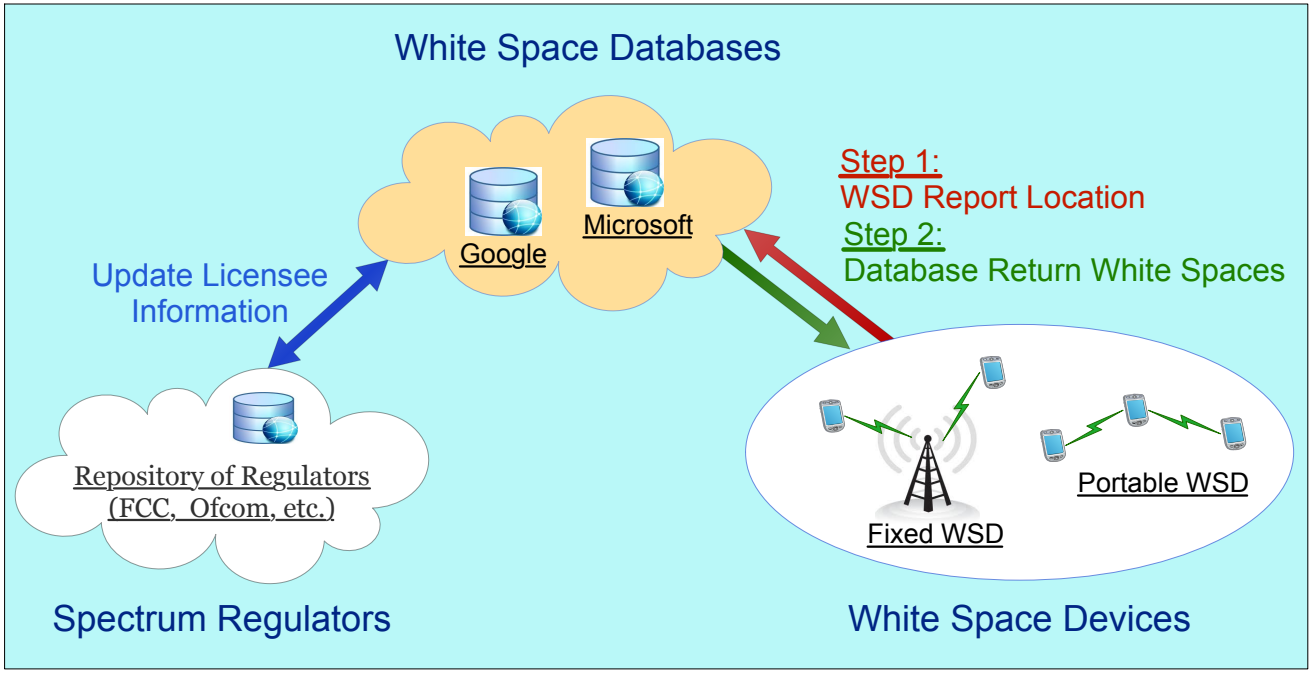
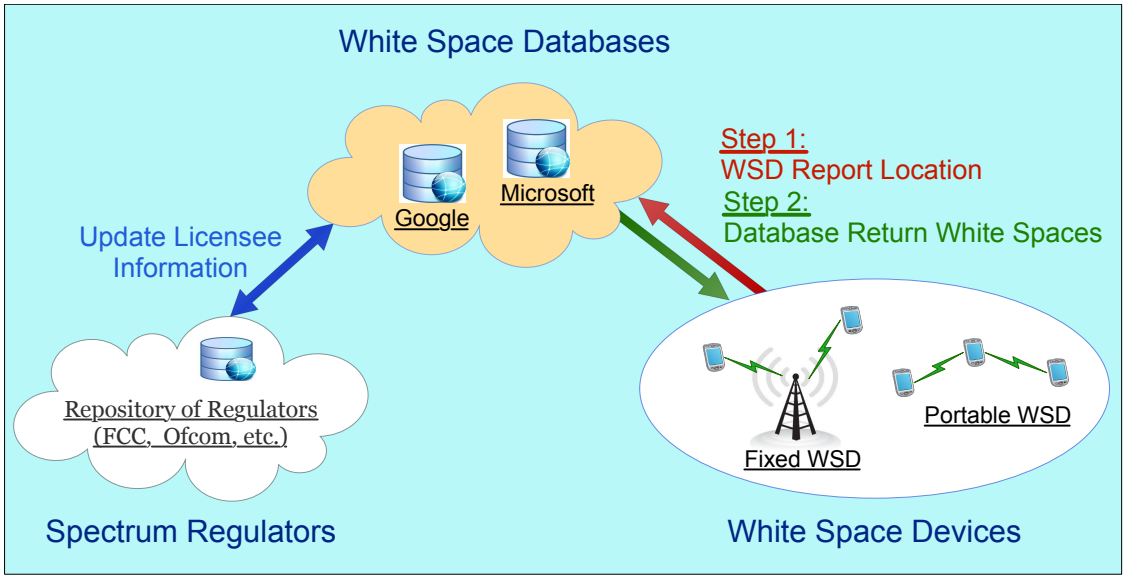



*Fig. Architecture of Database-Assisted TV White Space Network (by FCC)*

- Supporters: spectrum regulators, standards bodies, industrial organizations, and major IT companies.

# TV White Space Network

- Geo-location White Space Databases
  - Update TV licensees information periodically;
  - Identify the available white spaces at any location and time;
    - ★ Step 1: White space devices report their locations to a database;
    - ★ Step 2: Database returns the available white spaces at a given location;



# Business Model

- We study the business model for the TV white space network.
- Modeling Techniques
  - Traditional Approach — Secondary Spectrum Market
    - ★ (i) Formulate a secondary spectrum trading process among the unlicensed devices and spectrum licensees;
    - ★ (ii) Database acts as a broker or agent in this trading process.
    - ★ Limitation: Some TV white spaces cannot be traded!

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    - ⋆ Limitation: Some TV white spaces cannot be traded!
  - Our Approach — Information Market
    - ⋆ Key idea: Database sells the advanced information regarding the quality of white space channels to unlicensed devices.

# An Example

- Consider a particular white space device (WSD):
  - Available white space channels: $[ch1, ch2, ch3, ch4]$
  - Interference levels: $[1, 2, 3, 4]$ (equivalent data rates: $[5, 2, 1, 0]$)

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    - ⋆ Known by the database, but not known by the WSD.
- If not purchasing the advanced information,
  - Receive the available white space channels, and Choose an available channel randomly;
  - Average data rate: $\frac{5+2+1+0}{4} = 2$;

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    - ⋆ Known by the database, but not known by the WSD.
- If not purchasing the advanced information,
  - Receive the available white space channels only, and Choose an available channel randomly;
  - Average data rate: $\frac{5+2+1+0}{4} = 2$;
- If purchasing the advanced information,
  - Receive both the available white space channels and the interference levels (or equivalent data rates), and Choose the best channel;
  - Average data rate: $5$;

# Information Market Model

- Key Idea: Databases sell the advanced information regarding the qualities of white space channels to unlicensed devices.
  - Advanced information: Quality (e.g., interference level) of each white space channel (non-free and optional);
  - Basic information: Available TV white space channels at a given location (free and mandatory);

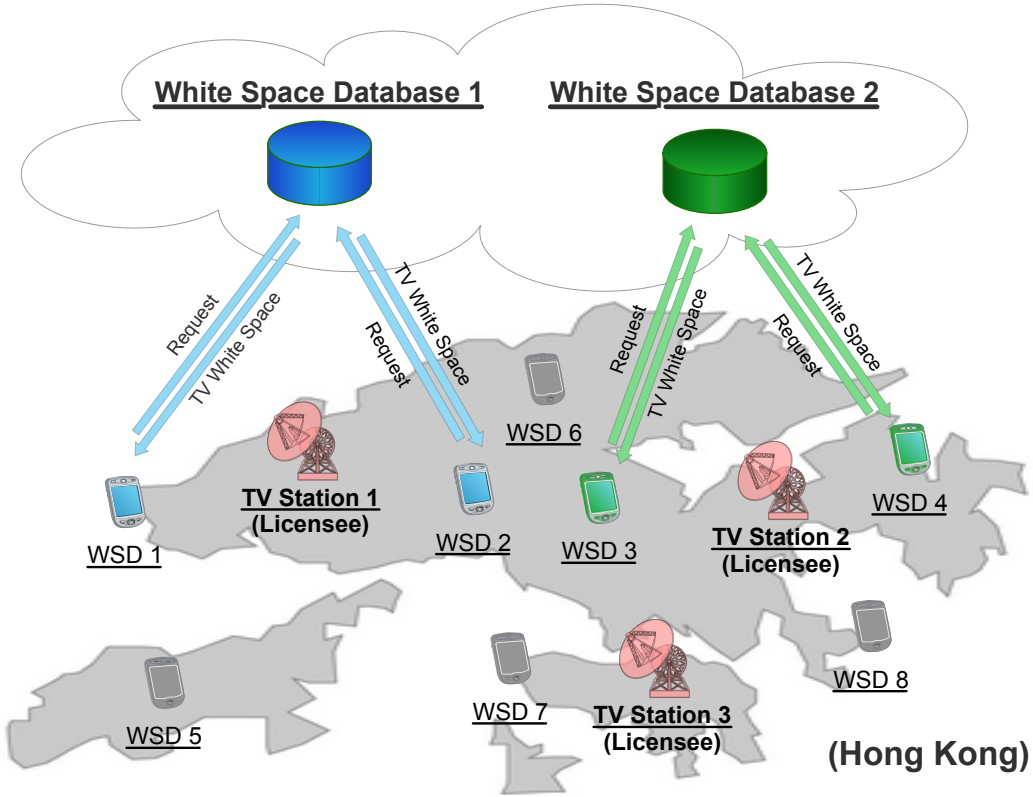
# Information Market Model

- Key Idea: Databases sell the advanced information regarding the qualities of white space channels to unlicensed devices.
  - Advanced information: Quality (e.g., interference level) of each white space channel (non-free and optional);
  - Basic information: Available TV white space channels at a given location (free and mandatory);
- Key Problems
  - How to explicitly define the advanced information?
  - How to accurately evaluate the advanced information?
  - How the information market dynamically evolves?
  - What is the market equilibrium point?

# Outline

# TV White Space Network Model

- Network Model
  - 2 Databases, $N$ white space devices (WSDs), $K$ white space channels



# Definition of Advanced Information

- Interference on each white space channel $k$
  - $L_k$: Interference from licensed devices;

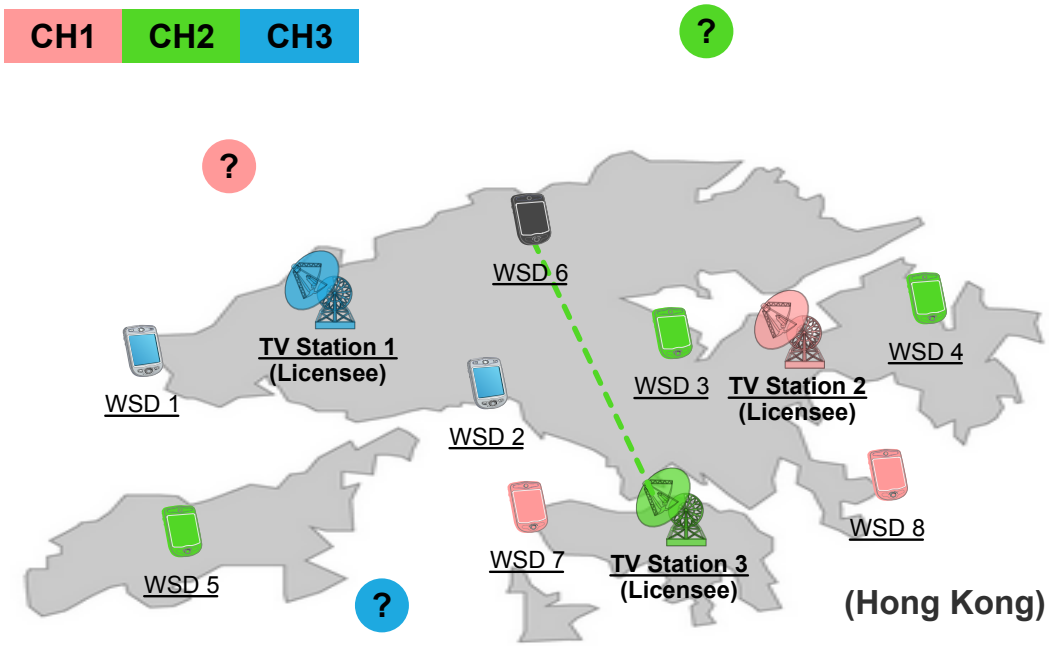



*Fig: Interference from licensed devices (on channel 2) for WSD 6.*

# Definition of Advanced Information

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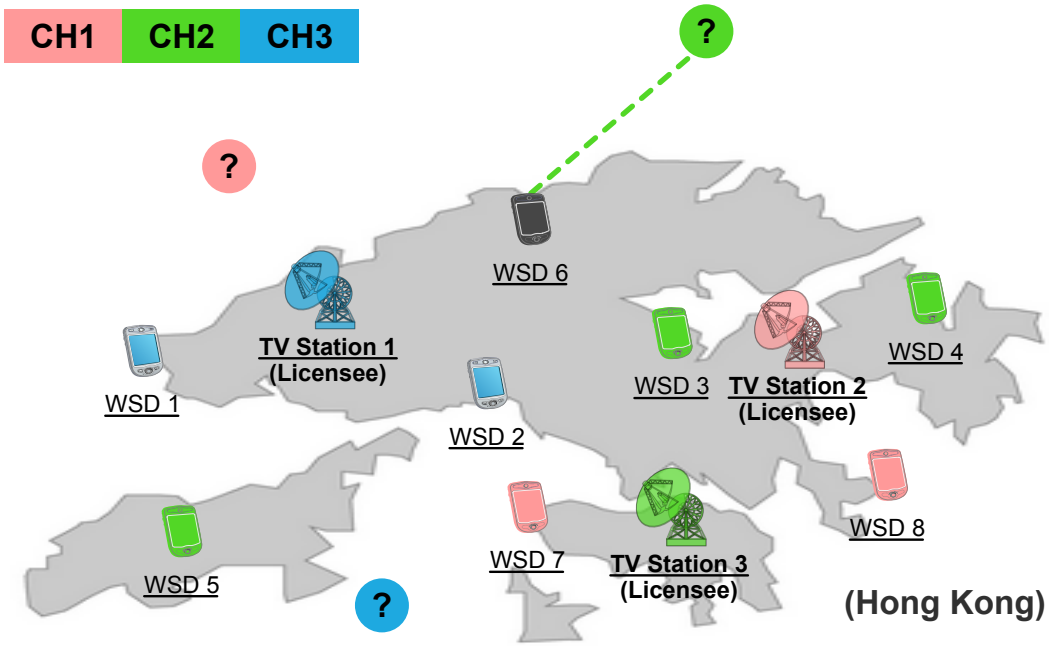


*Fig: Interference from outside systems (on channel 2) for WSD 6.*

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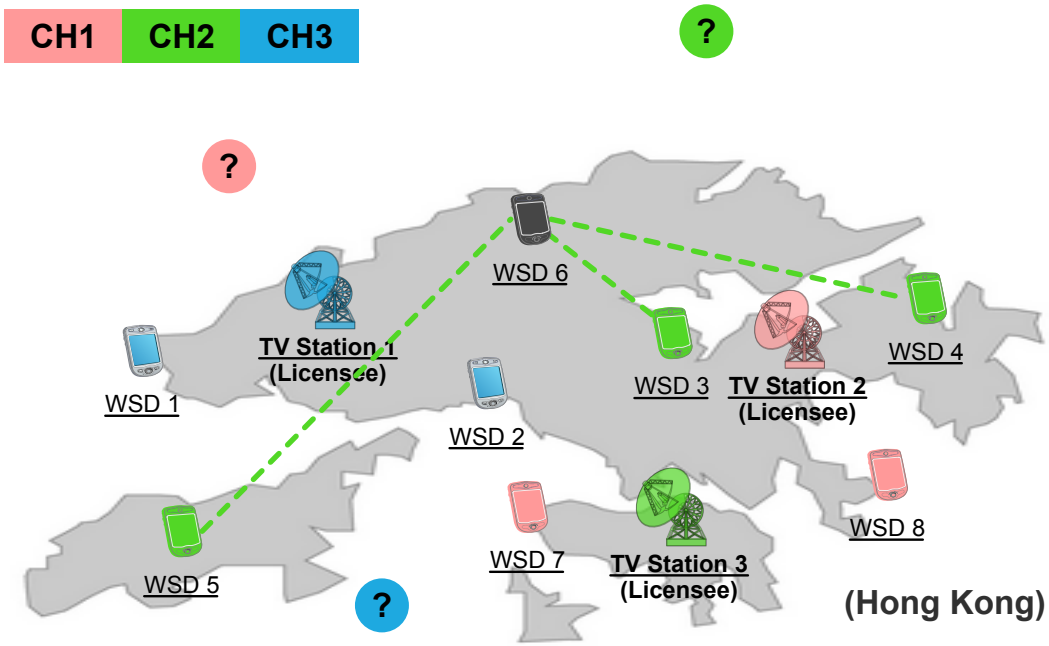


*Fig: Interference from WSDs (on channel 2) for WSD 6.*

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  - $L_k$: Interference from licensed devices;
  - $I_k$: Interference from unknown outside systems;
  - $W_{k,m}$: Interference from an other WSD $m$;
  - Total interference on channel $k$: $Z_k = L_k + I_k + \sum_{m \in \mathcal{N}_k} W_{k,m}$.

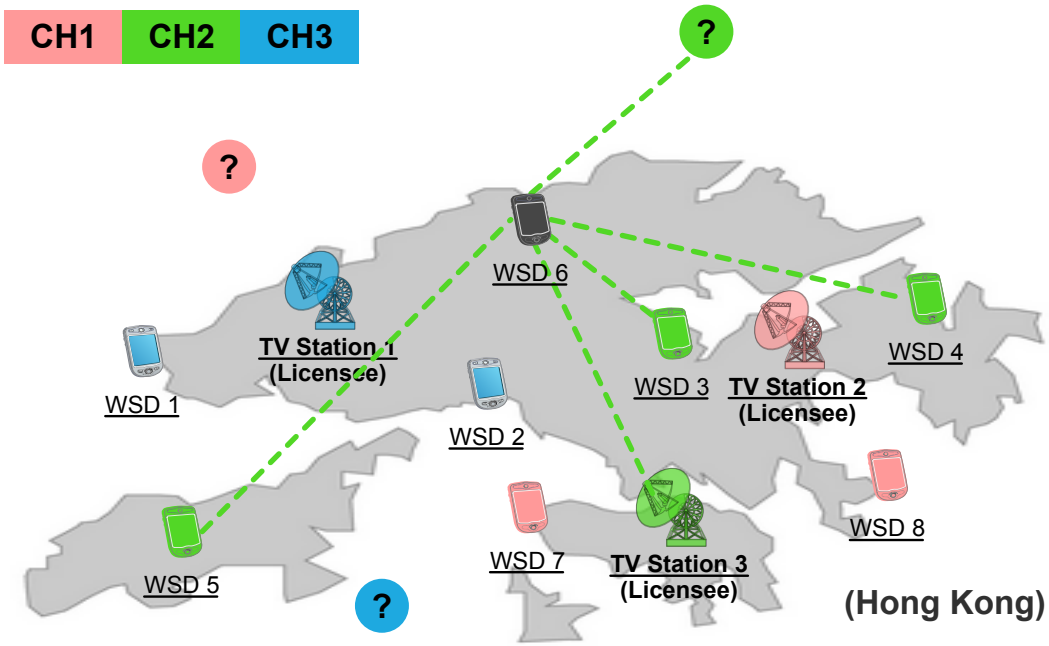


*Fig: Total interference on channel 2 for WSD 6.*

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- Advanced information is defined as the interference components on each channel $k$ known by the database.

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  - $L_k$: Interference from licensed devices $\rightarrow$ known;
  - $I_k$: Interference from unknown outside systems $\rightarrow$ unknown;
  - $W_{k,m}$: Interference from an other WSD $m \rightarrow$ known or unknown;
    - ★ If WSD $m$ purchases the advanced information from a database, $W_{k,m}$ is known by that database;
    - ★ If WSD $m$ does not purchase the advanced information from a database, $W_{k,m}$ is not known by that database;

# Definition of Advanced Information

- Advanced information is defined as the interference components on each channel $k$ known by the database.

$$Z_k = L_k + I_k + \sum_{m \in \mathcal{N}_k} W_{k,m}$$

  - Advanced information (of database $i$) on channel $k$ (sold to WSDs):

$$Z_k^{[i]} = L_k + \sum_{m \in \mathcal{N}_k^{[i]}} W_{k,m}$$

  - Uncertain inforamtion (of database $i$) on channel $k$:

$$\widetilde{Z}_k^{[i]} = I_k + \sum_{m \notin \mathcal{N}_k^{[i]}} W_{k,m}$$

    - ★ $\mathcal{N}_k^{[i]}$: Set of WSDs purchasing advanced information from database $i$.

# Evaluation of Advanced Information

- Without advanced information,
  - WSDs randomly choose a channel;
  - Expected data rate is:

$$R_0 = \mathrm{E}_Z[\mathcal{R}(Z)]$$

    - ⋆ where $Z$ is the random variable denoting the interference on an arbitrary channel, i.e., $Z_k^{[i]} + \widetilde{Z}_k^{[i]}$.
- With advanced information,
  - WSDs choose a channel with the minimal $Z_k^{[i]}$;
  - Expected data rate is:

$$R_i = \mathrm{E}_Y[\mathcal{R}(Y)]$$

    - ⋆ where $Y$ is the random variable denoting the interference on the channel with minimum $Z_k^{[i]}$, i.e., $\min\{Z_1^{[i]}, Z_2^{[i]}, ..., Z_K^{[i]}\} + \widetilde{Z}_k^{[i]}$.

# Positive Externality

- WSDs purchasing advanced information from a database always choose a channel with the minimal $Z_k^{[i]}$.
  - This implies that the database always knows the channel selection of these WSDs (purchasing advanced information from him)!

- Therefore, more WSDs purchasing advanced information from a database, more accurate the information of that database.

  — Positive Externality

# Oligopoly Competitive Databases

- Two competitive databases
- Parameters related to each database $i \in \{1, 2\}$:
  - $\pi_i$: the price of database $i$'s advanced information;
  - $\eta_i$: the percentage of WSDs purchasing database $i$' advanced information (market share of database $i$);
  - $R_i$: the expected data rate of WSDs when purchasing database $i$' advanced information;
    - ⋆ $R_i$ is an increasing function of $\eta_i$ (positive externality).

# WSD's Best Subscription Decision

- Given the prices $(\pi_1, \pi_2)$ and market shares $(\eta_1, \eta_2)$ of both databases' advanced informations, each WSD decides whether and from which database to purchase the advanced information.
  - When not purchasing, its utility is

$$\Pi_0 = \theta \cdot R_0$$

  - When purchasing from database 1, its utility is

$$\Pi_1 = \theta \cdot R_1 - \pi_1$$

  - When purchasing from database 2, its utility is

$$\Pi_2 = \theta \cdot R_2 - \pi_2$$

    - ⋆ $\theta \in [0, 1]$ denotes the WSD's evaluation for data rate.

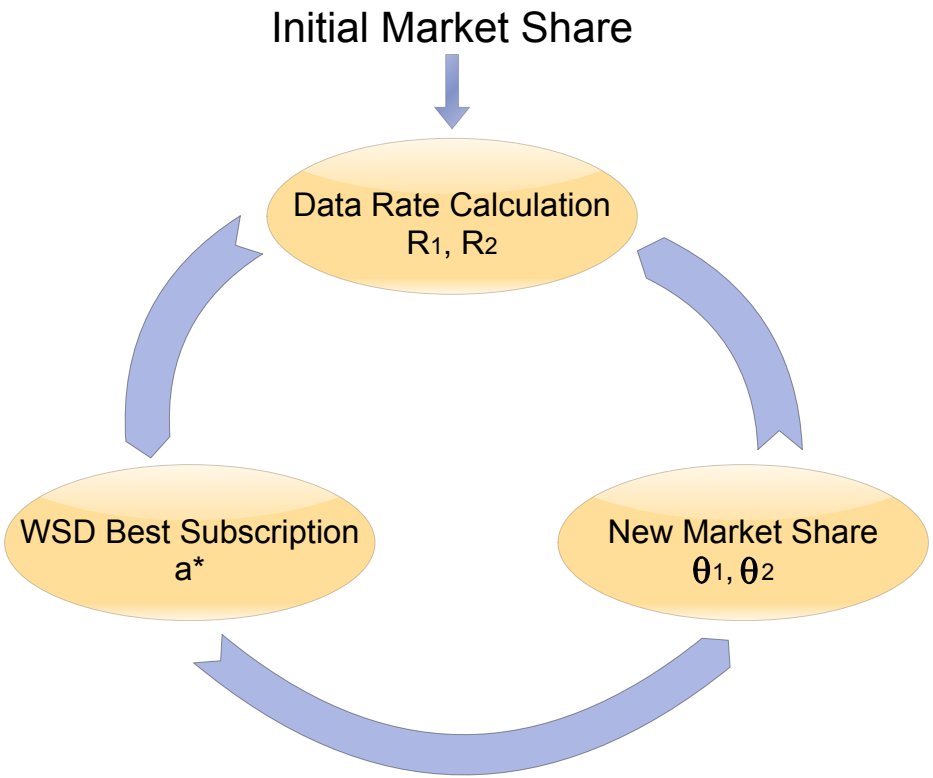
# WSD's Best Subscription Decision

**Best Subscription Decision**

$$a^* = \begin{cases} 0 \text{ (not purchasing)} & \text{if } R_0 = \max\{R_0, R_1, R_2\} \\ 1 \text{ (purchasing from DB1)} & \text{if } R_1 = \max\{R_0, R_1, R_2\} \\ 2 \text{ (purchasing from DB2)} & \text{if } R_2 = \max\{R_0, R_1, R_2\} \end{cases}$$

# WSD Subscription Dynamics

- Market Equilibrium: the market shares no longer change.



# WSD Subscription Dynamics Example

- Case 1: $\pi_2 << \pi_1$

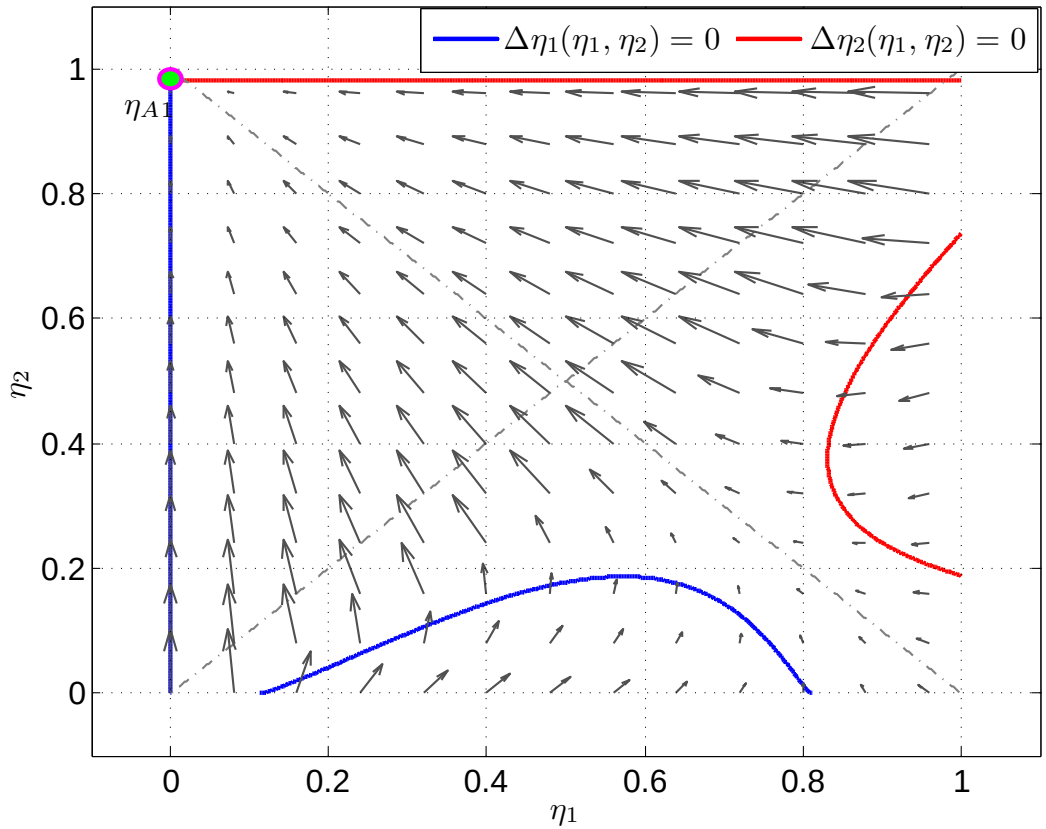
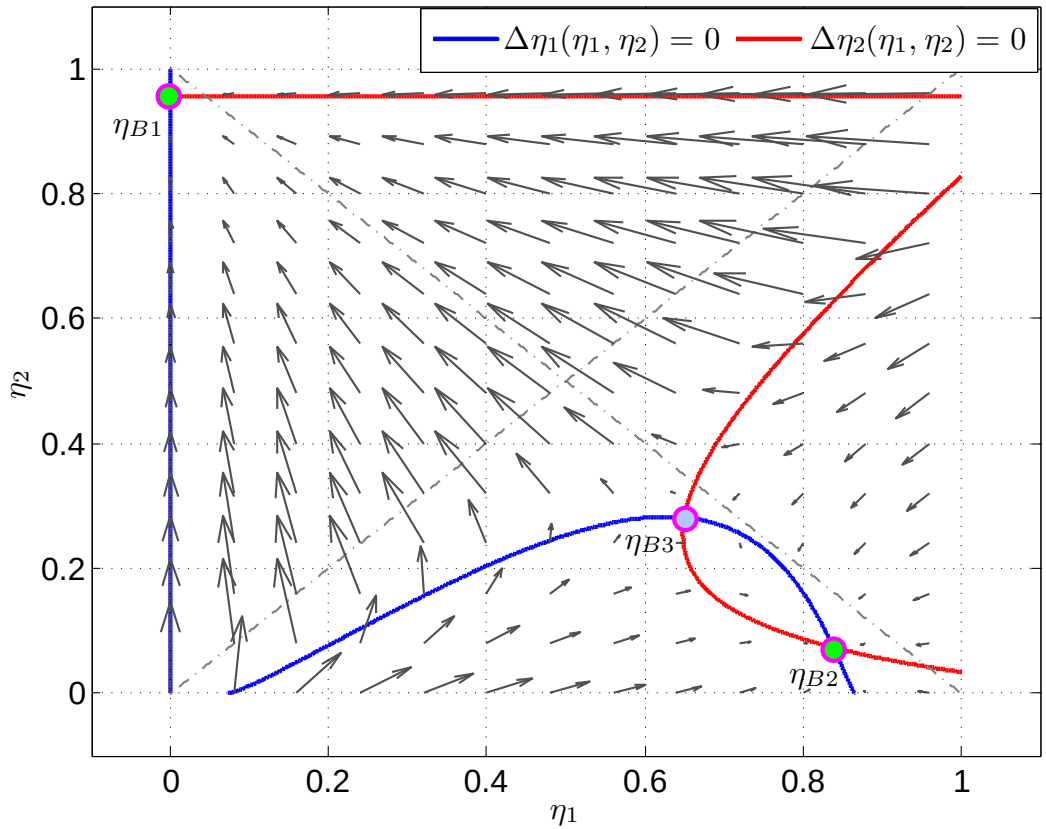



*Fig. Dynamics of two databases' market shares:* $(\eta_1, \eta_2)$

# WSD Subscription Dynamics Example

- Case 2: $\pi_2 < \pi_1$

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# Outline

# Conclusion and Future Work

- Conclusion
  - We propose a information market for TV white space networks;
  - We analyze the information market in a oligopoly competitive market scenario with two databases.

- Future Work
  - Study the databases' price competition game.
  - Analyze the information market in a general scenario with many databases.

# *Thank You*


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