Trade Information, Not Spectrum

– A Novel Information Market for TV White Space Networks

Yuan Luo, Lin Gao, and Jianwei Huang

Network Communications and Economics Lab (NCEL)
The Chinese University of Hong Kong (CUHK), Hong Kong

Presented by Prof. **Fen Hou**

Faculty of Science and Technology
University of Macau, Macau

Outline

Mobile Data Explosion

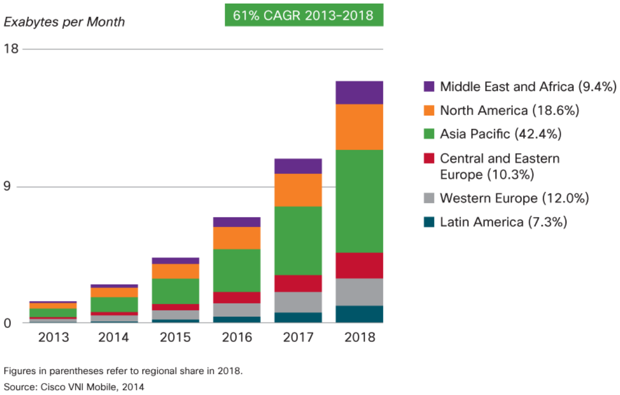


Fig. Global Mobile Data Traffic, 2013 to 2018 (from Cisco VNI)

- Mobile data traffic explosive growth: 61% annual grow rate
  - Reaching 15.9 exabytes per month by 2018, a 11-fold increase over 2013.

Radio Spectrum Scarcity

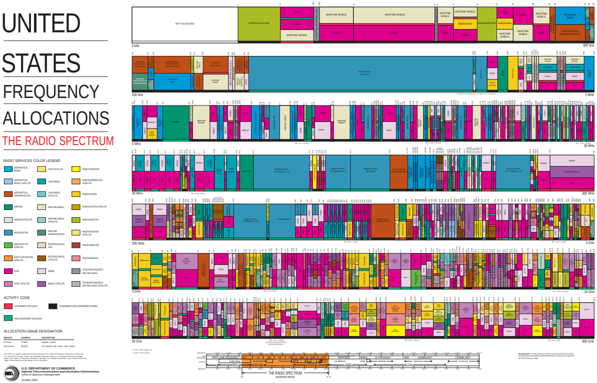


Fig. Frequency Allocation Chart in USA

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

TV White Space

- Spectrum Inefficient Usage
  - 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.

TV White Space in USA

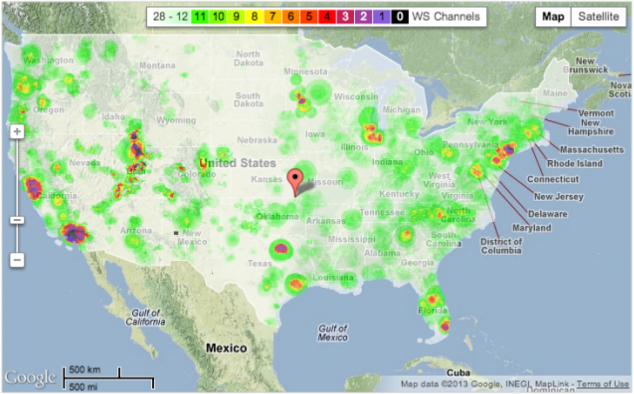


Fig. Number of TV White Space Channels in the United States (from Google)

- In most of the places, there are more than 10 TV white space channels (each with 6MHz).

TV White Space Network

- Database-Assisted TV White Space Network
  - This architecture has been supported by many spectrum regulators, standards bodies, industrial organizations, and major IT companies.

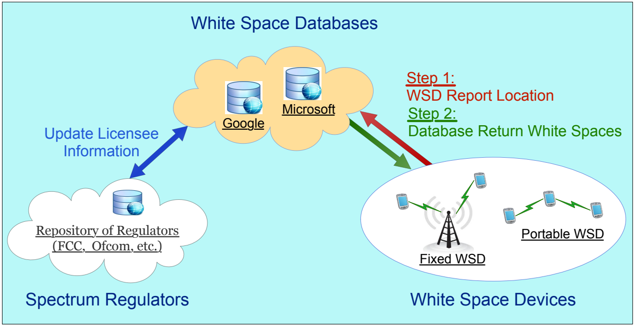


Fig. Architecture of Database-Assisted TV White Space Network (by FCC)

TV White Space Network

- Geo-location White Space Database
  - 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;

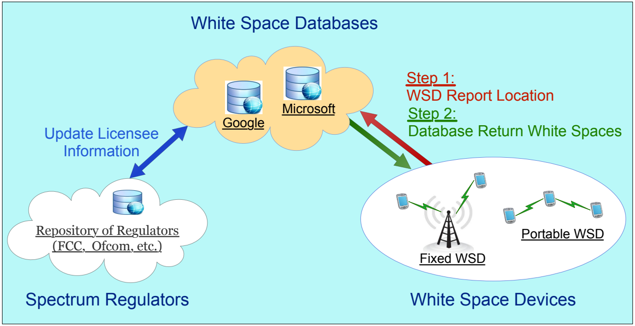


Fig. Architecture of Database-Assisted TV White Space Network (by FCC)

TV White Space Network

- **We study the business model for TV white space networks.**

- Business Modeling Techniques
  - Secondary Spectrum Market (Traditional Approach)
    - ⋆ Trade the spectrum among unlicensed devices and spectrum owners;
    - ⋆ Database acts as a broker or agent in the spectrum trading process.
    - ⋆ Limitation: Some TV white spaces cannot be traded!

TV White Space Network

- **We study the business model for TV white space networks.**
- Business Modeling Techniques
  - Secondary Spectrum Market (Traditional Approach)
    - Trade the spectrum among unlicensed devices and spectrum owners;
    - Database acts as a broker or agent in the spectrum trading process.
    - Limitation: Some TV white spaces cannot be traded!
  - Information Market (Our Approach)
    - Key idea: Trading the advanced information among the database and 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: $[5, 2, 1, 0]$)
    - ⋆ Known by the database, but not known by the WSD.

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: $[5, 2, 1, 0]$)
    - ⋆ 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: $\frac{5+2+1+0}{4} = 2$;

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: $[5, 2, 1, 0]$)
    - ⋆ 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: $\frac{5+2+1+0}{4} = 2$;
- 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;

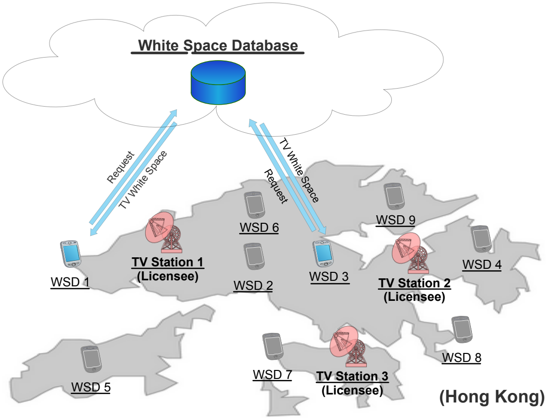
Information Market Modeling

- **Key Idea:** Databases sell the advanced information regarding the qualities of white space channels to unlicensed WSDs.
- Key Problems
  - How to explicitly define the advanced information?
  - How to accurately evaluate the advanced information (for WSDs)?
  - How the information market dynamically evolves?
  - What is the market equilibrium point?
  - How to optimally pricing the advanced information (for databases)?

Outline

TV White Space Network Model

- Network Model
  - One Database, N white space devices (WSDs), K white space channels



Definition of Advanced Information

- Interference on each channel k for a particular WSD
  - U_k: Interference from licensed devices;

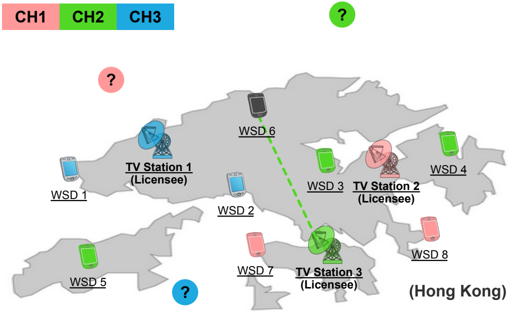


Fig: Interference (on channel 2) from licensed devices to WSD 6.

Definition of Advanced Information

- Interference on each channel k for a particular WSD
  - U_k: Interference from licensed devices;
  - V_k: Interference from unknown outside systems;

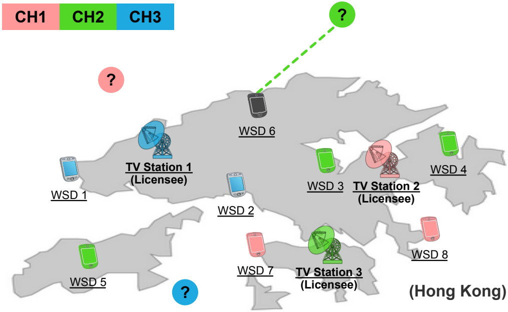


Fig: Interference (on channel 2) from outside systems to WSD 6.

Definition of Advanced Information

- Interference on each channel k for a particular WSD
  - U_k: Interference from licensed devices;
  - V_k: Interference from unknown outside systems;
  - $W_{k,m}$: Interference from an other WSD m;

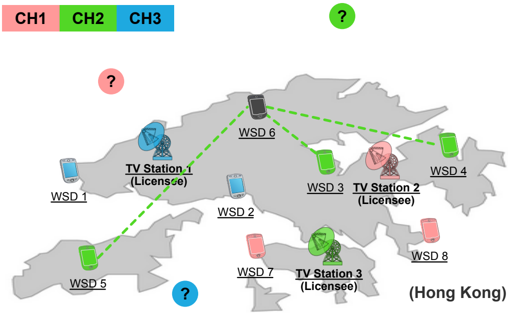


Fig: Interference (on channel 2) from other WSDs to WSD 6.

Definition of Advanced Information

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

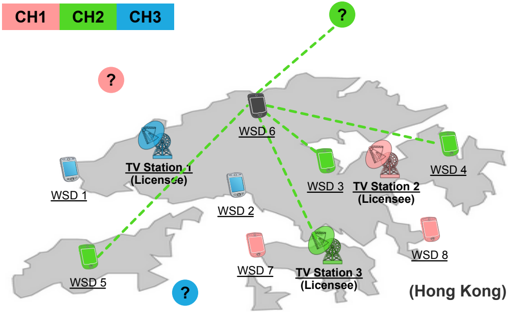


Fig: Total interference on channel 2 for WSD 6.

Definition of Advanced Information

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

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

Definition of Advanced Information

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

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

  - U_k: Interference from licensed devices $\rightarrow$ known;

Definition of Advanced Information

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

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

  - U_k: Interference from licensed devices $\rightarrow$ known;
  - V_k: Interference from unknown outside systems $\rightarrow$ unknown;

Definition of Advanced Information

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

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

  - U_k: Interference from licensed devices $\rightarrow$ known;
  - V_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:
- Advanced information of database on channel k:

$$X_k = \underbrace{U_k}_{\text{Licensed Devices}} + \underbrace{\sum_{m \in \mathcal{N}_k} W_{k,m}}_{\text{WSDs Purchasing Information}}$$

- Uncertain information of database on channel k:

$$Y_k = \underbrace{V_k}_{\text{Unknown Outside System}} + \underbrace{\sum_{m \notin \mathcal{N}_k} W_{k,m}}_{\text{WSDs Not Purchasing Information}}$$

Evaluation of Advanced Information

- Each WSD has 3 channel selection strategies:
  - (a) Choose a channel randomly
    - ★ Expected data rate is: $R_{[b]} = \mathrm{E}_Z[\mathcal{R}(Z)]$,
      where Z is the random variable denoting the interference on an arbitrary channel;
  - (b) Choose the best channel based on perfectly sensing
    - ★ Expected data rate is: $R_{[s]} = \mathrm{E}_{Z_{(1)}}[\mathcal{R}(Z_{(1)})]$,
      where $Z_{(1)} \triangleq \min\{Z_1, \ldots, Z_K\}$ is the random variable denoting the minimal interference on all channels;
  - (c) Choose the channel based on advanced information (purchased from the database)
    - ★ WSD will choose a channel with the minimal X_k;
    - ★ Expected data rate is: $R_{[a]} = \mathrm{E}_{Z_{[a]}}[\mathcal{R}(Z_{[a]})]$,
      where $Z_{[a]} \triangleq \min\{X_1, X_2, ..., X_K\} + Y$ is the random variable denoting the interference on the channel with minimum X_k.

Evaluation of Advanced Information

- Each WSD has 3 channel selection strategies:
  - (a) Choose a channel randomly
    - ★ Expected data rate is: $R_{[b]} = \mathrm{E}_Z[\mathcal{R}(Z)]$,
      where Z is the random variable denoting the interference on an arbitrary channel;
  - (b) Choose the best channel based on perfectly sensing
    - ★ Expected data rate is: $R_{[s]} = \mathrm{E}_{Z_{(1)}}[\mathcal{R}(Z_{(1)})]$,
      where $Z_{(1)} \triangleq \min\{Z_1, \ldots, Z_K\}$ is the random variable denoting the minimal interference on all channels;
  - (c) Choose the channel based on advanced information (purchased from the database)
    - ★ WSD will choose a channel with the minimal X_k;
    - ★ Expected data rate is: $R_{[a]} = \mathrm{E}_{Z_{[a]}}[\mathcal{R}(Z_{[a]})]$,
      where $Z_{[a]} \triangleq \min\{X_1, X_2, ..., X_K\} + Y$ is the random variable denoting the interference on the channel with minimum X_k.

Evaluation of Advanced Information

- Each WSD has 3 channel selection strategies:
  - (a) Choose a channel randomly
    - Expected data rate is: $R_{[b]} = \mathrm{E}_Z[\mathcal{R}(Z)]$,
      where Z is the random variable denoting the interference on an arbitrary channel;
  - (b) Choose the best channel based on perfectly sensing
    - Expected data rate is: $R_{[s]} = \mathrm{E}_{Z_{(1)}}[\mathcal{R}(Z_{(1)})]$,
      where $Z_{(1)} \triangleq \min\{Z_1, \ldots, Z_K\}$ is the random variable denoting the minimal interference on all channels;
  - (c) Choose the channel based on advanced information (purchased from the database)
    - WSD will choose a channel with the minimal X_k;
    - Expected data rate is: $R_{[a]} = \mathrm{E}_{Z_{[a]}}[\mathcal{R}(Z_{[a]})]$,
      where $Z_{[a]} \triangleq \min\{X_1, X_2, ..., X_K\} + Y$ is the random variable denoting the interference on the channel with minimum X_k.

Evaluation of Advanced Information

- When purchasing the advanced information (not sensing or randomly choosing), WSDs always choose the channel with the minimal X_k;
  - This implies that the database always knows the channel selection of the WSDs purchasing the advanced information.
- **Positive externality**
  - More WSDs purchasing the advanced information from a database, more accurate the advanced information of that database.

WSD's Utility

- When choosing channel randomly, its utility is

$$\Pi = \theta \cdot R_{[b]}$$

- When choosing channel based on sensing, its utility is

$$\Pi = \theta \cdot R_{[s]} - c$$

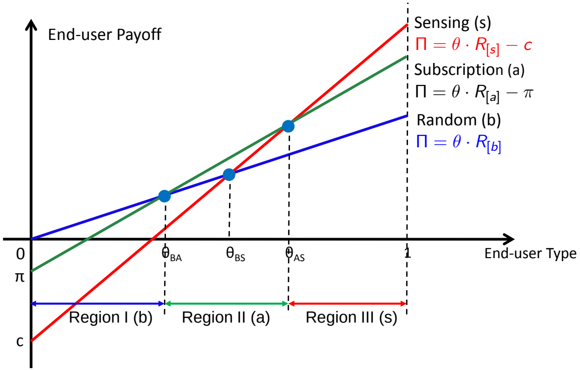
- When using the advanced information, its utility is

$$\Pi = \theta \cdot R_{[a]} - \pi$$

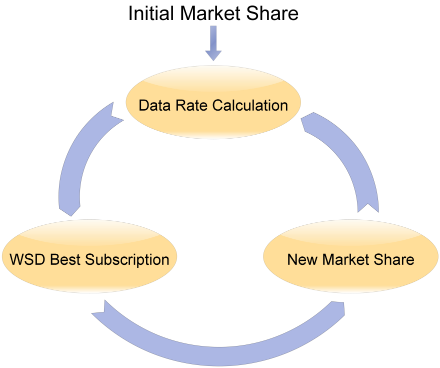
  - θ: the WSD's evaluation for data rate.
  - c: the cost of sensing;
  - π: the price of advanced information;
  - η: the percentage of WSDs purchasing the advanced information; (market share of the database)
    - $R_{[b]}$, $R_{[s]}$ independent of η
    - $R_{[a]}$ increases with η (positive externality)

WSD's Best Subscription Decision

- Illustration of WSD's Best Subscription Decision
  - Region I: choosing channel randomly;
  - Region II: purchasing the advanced information;
    - ★ The database's achieved market share is $\theta_{AS} - \theta_{BA}$;
  - Region III: choosing channel based on sensing;



WSD Subscription Dynamics

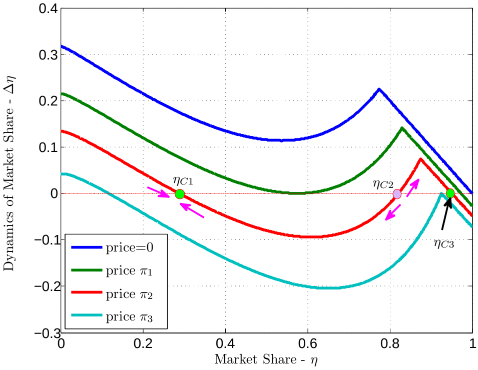


- **Market Equilibrium**

$$\triangle\eta = \eta^{t} - \eta^{t-1} = 0$$

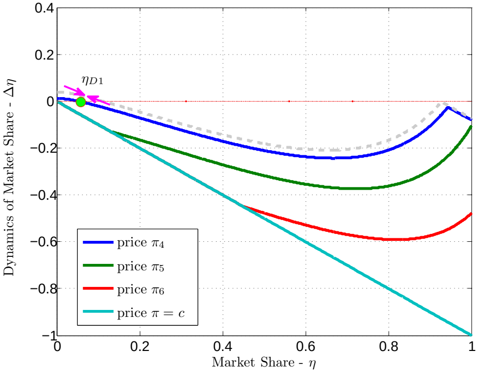
  - η^{t}: the database's market share at stage t;
  - Under market equilibrium, the market share no longer changes.

$\Delta\eta$ under Low Information Price



- Low Information price: $0 < \pi_1 < \pi_2 < \pi_3$
- Under the price π_2, there are 3 market equilibria η_{C1}, η_{C2}, and η_{C3}.
  - η_{C1} and η_{C3} are stable market equilibrium point;
  - η_{C2} is unstable market equilibrium point;

$\Delta\eta$ under High Information Price



- High Information price: $\pi_4 < \pi_5 < \pi_6 < c$
- Under the price π_4, there is a unique stable market equilibrium η_{D1}.

Outline

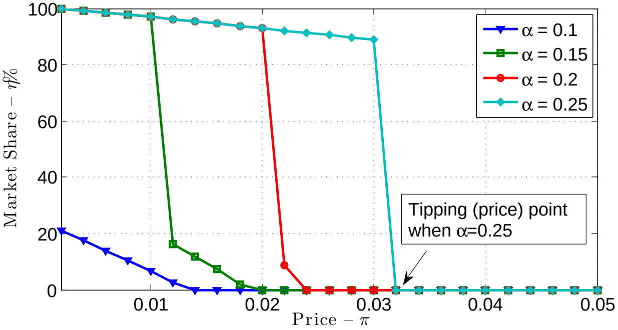
Database's Optimal Pricing Decision

- **Database's Revenue**

$$\Pi^{\mathrm{DB}}(\pi) = \pi \cdot \eta^*(\pi)$$

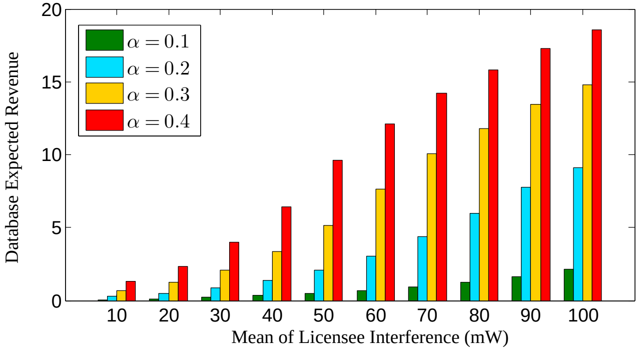
  - $\eta^*(\pi)$: the market equilibrium under price π;

$\eta^*(\pi)$ under Different Information Prices



- $\eta^*(\pi)$ increases with sensing cost α;
- $\eta^*(\pi)$ decreases with price π;
  - Tipping price: A slight increase on the price will lead to a significant decrease on the market equilibrium.
    - ★ E.g., $\pi = 0.03$ when $\alpha = 0.25$; $\pi = 0.02$ when $\alpha = 0.2$.

Database's Revenue



- Database's revenue increases with the degree of licensee interference;
  - A larger licensee interference makes the information more valuable.
- Database's revenue increases with the sensing cost α;
  - A larger sensing cost makes the information more valuable.

Outline

Conclusion

- **Main Contribution**
  - We propose a novel information market for TV white space networks;
  - We analyze the market equilibrium under the monopoly scenario with one database, and derive the database's optimal information pricing systematically.
- **Related Work**
  - Information market under duopoly competitive scenario (SDP 2014)
- **Future Work**
  - Information market under more general scenarios

Thank You !

jwhuang@ie.cuhk.edu.hk