Economics of TV White Space Networks

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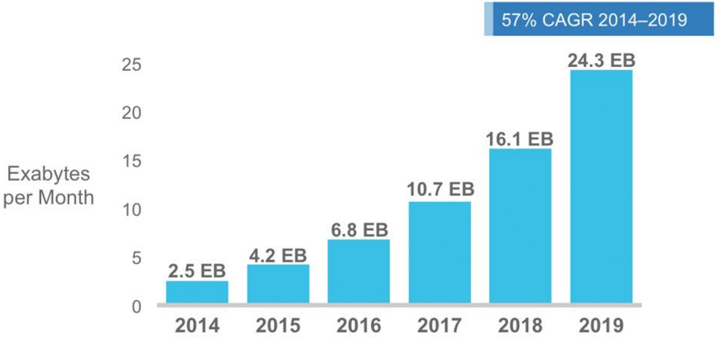
Outline

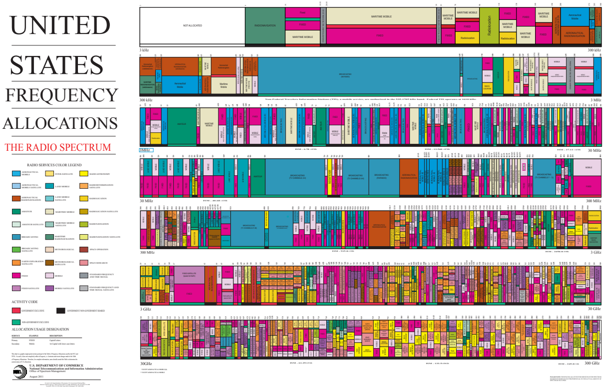
Mobile Data Explosion



Global Mobile Data Traffic, 2014 to 2019 (from Cisco VNI)

- Mobile data traffic explosive growth: 57% annual grow rate
- Need more spectrum resource to support wireless broadband services.

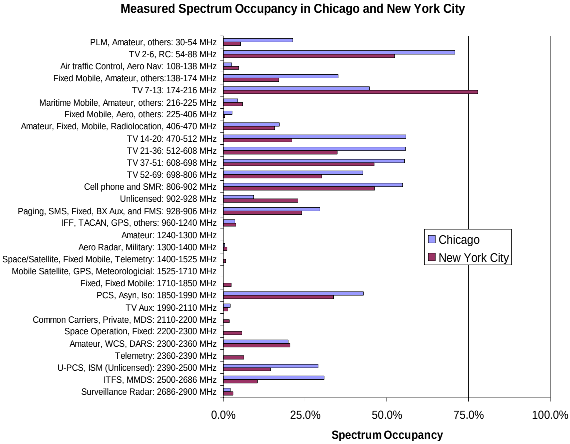
Radio Spectrum Scarcity



Frequency Allocation Chart in USA (from NITA)

- Spectrum resource is very limited.

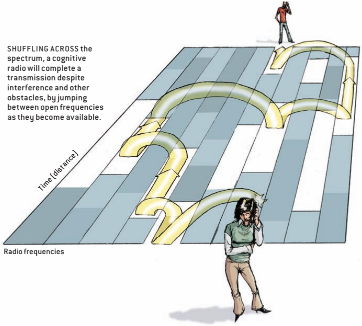
Spectrum Usage Inefficiency



- Licensed radio spectrums are under-utilized (on average $< 25\%$)

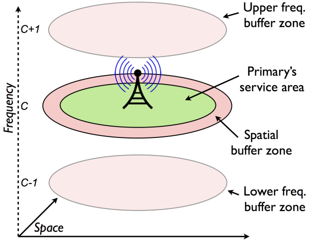
Dynamic Spectrum Sharing (DSS)

- A promising approach to provide more spectrum resources
- Enable unlicensed devices to share the licensed spectrum bands in an opportunistic manner;
- Improve the spectrum utilization efficiency without affecting the licensed operations;



An Example of DSS: Sharing TV White Space

- Under-utilized TV bands
  - Licensed to certain TV licensee but not fully utilized;
  - Example: The band "C" is licensed within the disk area (granted and exclusive usage).
- Unassigned TV bands
  - Not licensed to any TV licensee at a certain location;
  - Example: The band "C" is not licensed out of the disk area (license-exempt and shared usage).



Advantages of Using TV White Space

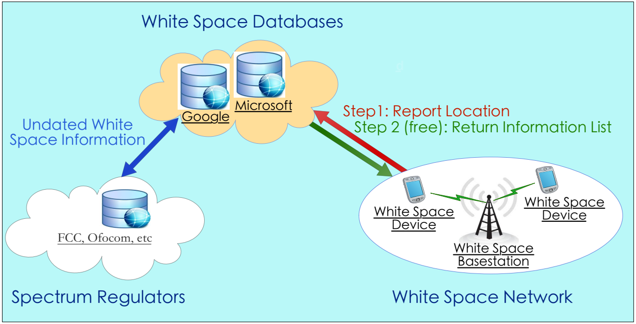
- Why TV White Space?
  - Wide Bandwidth
    - More than 280 MHz in USA
  - Excellent Propagation
    - Low frequency band
    - Strong penetration capability
    - Large transmission distance
- Potential Application — Super WiFi
  - Rural broadband/backhaul
  - Sensor networks
  - Indoor video distribution
  - M2M communications

Realization of TV White Space Network

- Database-Assisted TV White Space Network
  - Unlicensed devices obtain the available TV white space information through querying a certified database (instead of only replying on sensing);
- Supported by many regulators, standards bodies, industrial organizations, and major IT companies;
  - Regulators: FCC in USA, Ofcom in UK, IDA in Singapore, IC in Canada, etc.;
  - Standards: IEEE 802.22, IEEE 802.11af;
  - Companies: Google, Microsoft, SpectrumBridge, etc.

Database-Assisted TV White Space Network

- Database updates TV licensees information periodically;
- Database helps unlicensed users identify available TV white spaces;
  - Step 1: White space devices report their locations to a database;
  - Step 2: Database returns the available white spaces at a given location;



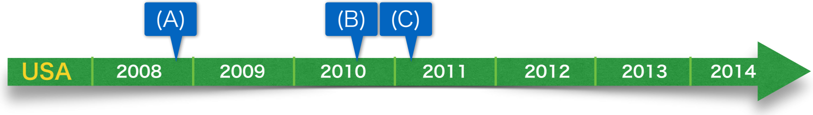
Architecture of Database-Assisted TV White Space Network (by FCC, Ofcom)

Unlicensed Users: White Space Device (WSD)

- Ofcom Framework (UK): Master and Slave WSDs
  - Master WSD: Geo-localization capability
    (Communicate directly with a database for available TV white space)
  - Slave WSD: No requirement of geo-localization capability
    (Served and under the control of a master WSD)
- FCC Framework (USA): Fixed and Portable WSDs
  - Fixed WSD: 30 meter height limit, fixed location
    (Communicate directly with a database for available TV white space)
  - Portable WSD: No height limit, mobility
    (Mode 2: Communicate directly with a database; Mode 1: Served and under the control of a mode 2 device)

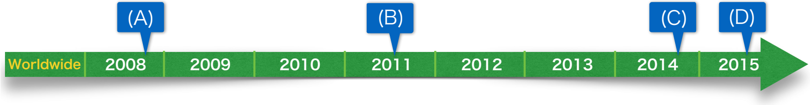
Regulatory Policy

- Policy of FCC in USA
  - (A) Nov 2008, FCC approved the unlicensed use of TV white spaces;
  - (B) Sep 2010, FCC determined the final rules for the use of TV white space (advocating database and removing sensing);
  - (C) Jan 2011, FCC conditionally designated 9 companies (including Google, Spectrum Bridge, Microsoft) to serve as geo-location white space databases in USA.



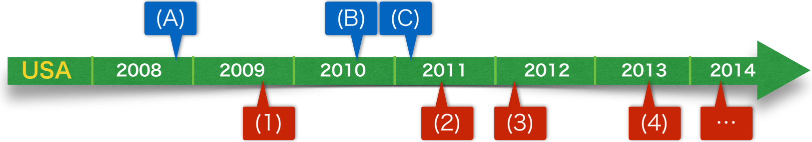
Regulatory Policy

- Policy of Other Countries
  - (A) 2008, USA approved the unlicensed use of TV white spaces
  - (B) 2011, Europe published a draft rule for using TV white spaces
  - (C) 2014, Singapore approved the unlicensed use of TV white spaces
  - (D) 2015, UK and Canada approved the unlicensed use of TV white spaces



Trials & Demos

- Trial Systems in North America
  - (1) Oct 2009, the WhiteFi network developed by Microsoft Research;
  - (2) May 2011, a commercial Super Wi-Fi network was developed in Calgary based WestNet City;
  - (3) Jan 2012, the United States first public Super Wi-Fi network was developed in Wilmington based SpectrumBridge;
  - (4) July 2013, West Virginia University launches the first campus Super WiFi network



Trials & Demos Summary

TV white spaces trials and demonstrations (from Microsoft)

- TV white space network is being actively explored in many countries.
  - Leading Countries: USA and UK

Outline

Technical Issues

- **Major Technical Challenges**
  - TVWS Availability Computation (for Database)
    - ⋆ How to accurately computes the available TV channels in a particular location [Dawei Chen et al. 2009] [Tan Zhang et al. 2014][Xuhang Ying et al. 2013]
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    - ★ How to design and standardize white space device (WSD)
  - Resource Management and Optimization (for Database and WSD)
    - ★ How to deploy and optimize a database-assisted TV white space network [Xiaojun Feng et al. 2011]

TVWS Availability Computation in UK

- **First Consideration — Interference**
  - Ensure low probability of harmful interference to licensees
    - ⋆ Digital Terrestrial Television (DTT) Services
    - ⋆ Programme Making and Special Events (PMSE) Usage

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  - WSD Location
    - ★ Master devices are required to report their locations (with error);
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    - ⋆ Represent by spatial pixels;
    - ⋆ Spatial resolution ($100 \times 100\ m^2$) geographic squares (pixels).

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  - DTT/PMSE Location
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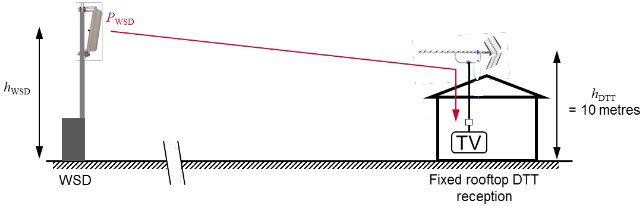
  - DTT/PMSE Channel
    - ⋆ The operational channels of DTT/PMSE devices.

TVWS Availability Computation in UK

- **DTT Protection**
  - Estimate the WSD's potential interference to DTT;
  - Compute the available TV white space and maximum transmission power for WSDs (with location uncertainty);
    - ⋆ Locations of DTT
    - ⋆ Possible locations of WSDs
    - ⋆ Antenna Heights of DTT and WSDs
    - ⋆ Channel Usage of DTT



TVWS Availability Computation in UK

- **PMSE Protection**
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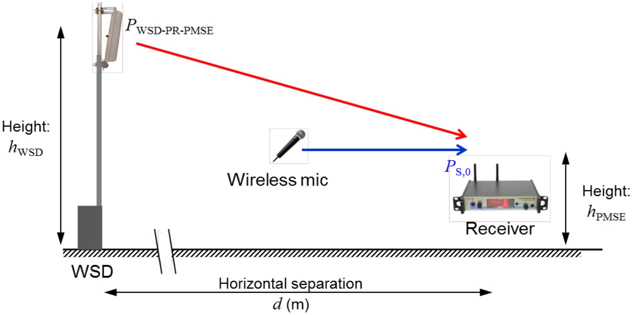
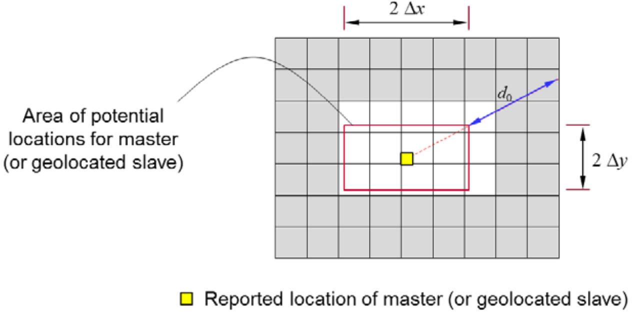


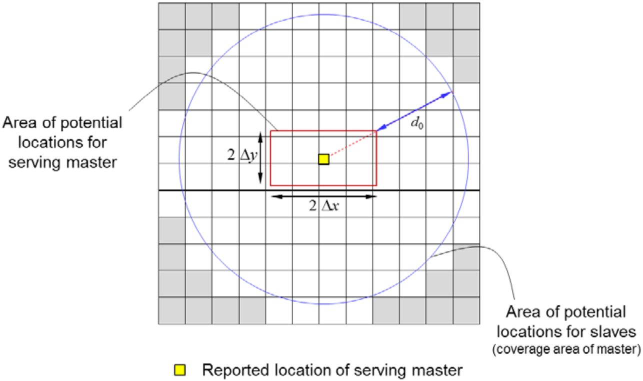
TVWS Availability Computation in UK

- **Uncertainty (Error)** of Master Location
  - Suppose a master reports location (x_0, y_0) with uncertainties $(\pm\Delta x, \pm\Delta y)$.
  - Then, possible locations of the master:
    - ★ Rectangle centred on (x_0, y_0) with sides of length $2\Delta x$ and $2\Delta y$
    - ★ Cover a set of M pixels (see the Figure below $M = 15$)



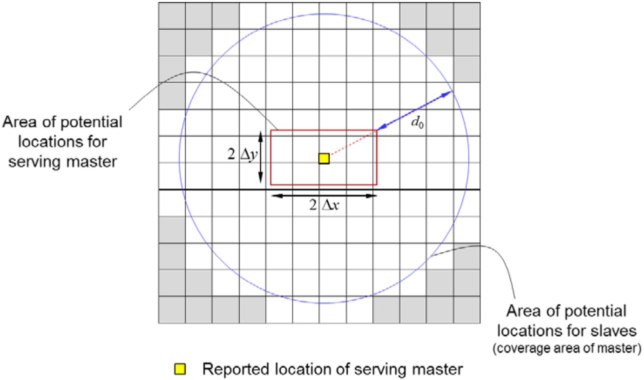
TVWS Availability Computation in UK

- **Uncertainty** of Slave Location
  - Slaves are not required to report their locations to the master;
  - Hence, possible locations of slaves are whole coverage area of master:
    - ★ Circle centred on (x_0, y_0) with radii $d_0 + \sqrt{(\Delta x^2 + \Delta y^2)}$;
    - ★ d_0 is the transmission range of the master;
    - ★ Cover a set of N pixels (see the Figure below).



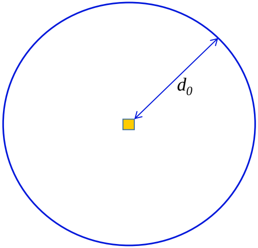
TVWS Availability Computation in UK

- **Available TV White Space**
  - The TV white spaces that are available in all N pixels;
- **Allowed Transmission Power** (on each channel)
  - The minimum allowed transmission power in all N pixels.



TVWS Availability Computation in USA

- The key idea in USA is **similar** as that in UK;
- **Differences**
  - Coverage range is measured by smooth circle, instead of pixels;
  - The available TV white space set for a WSD is only base on its own location, without considering the possible locations of its served WSDs (slaves):
    - ⋆ More available TV white spaces;
    - ⋆ Less transmission power constraints;
    - ⋆ Higher potential interference to licensees;

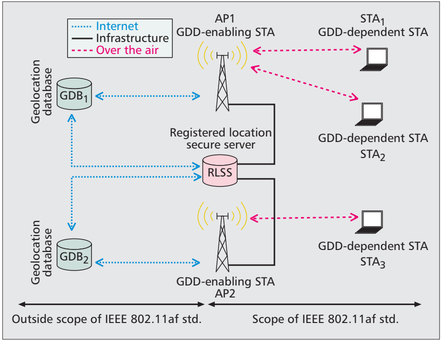


WSD Design and Standard

- European Telecom Standards Institute (**ETSI EN 203-598**)
  - Specify the standards that WSDs must comply with and test against;
  - Intend to be harmonised across Europe;
  - Specify the technical requirements for WSDs;
    - ★ Radio system
    - ★ Baseband system
    - ★ Mobility
    - ★ ....

Communication Standard

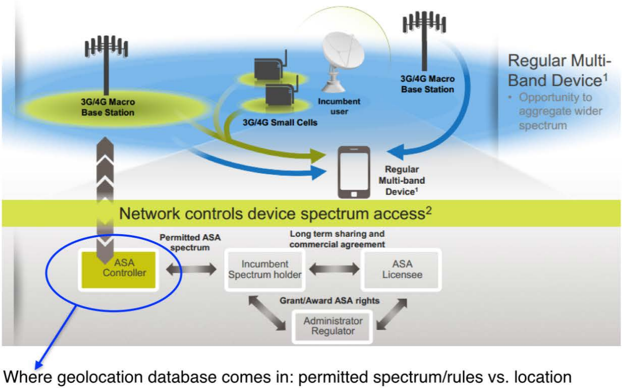
- **IEEE 802.11af**
  - Define modifications to both the 802.11 PHY and MAC layers to meet the legal requirements for channel access and coexistence in the TVWS



- **IEEE 802.22**

Spectrum Management and Optimization

- The database assists unlicensed TV white space access;
  - Unlicensed Shared Access (USA)
- The database assists licensed spectrum access;
  - Licensed/Authorized Shared Access (LSA/ASA)



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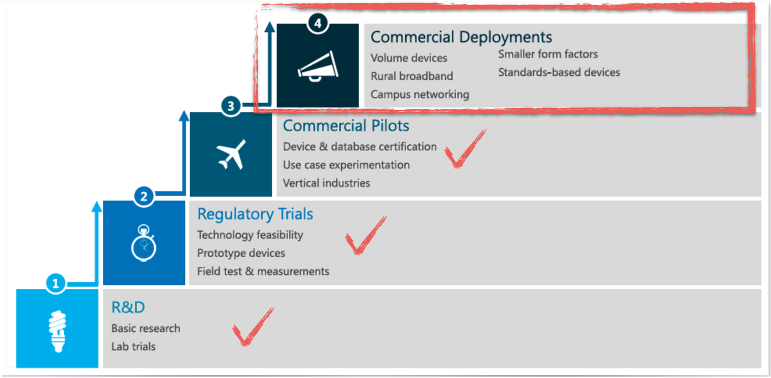
  - Database Development
    - ★ How to design and manage a database [Vania Goncalves 2011] [Hanna Bogucka et al 2012]
  - Communication between WSD and Database
    - ★ How does a **mobile** WSD identify the communication link [Z. Qin, Y. Gao, C. Parini, 2015]
  - Others

Outline

Current Status

- Fast technology development and policy change worldwide
- Lacking of a systematic economics analysis



Economic Issues and Challenges

- **Economic issues**
  - Who will be involved in a TV white space business model?
  - What kind of services will be supported in such a network?
  - How to design efficient mechanism to guarantee the economics performance with low implementation complexity?

Economic Issues and Challenges

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  - Who will be involved in a TV white space business model?
  - What kind of services will be supported in such a network?
  - How to design efficient mechanism to guarantee the economics performance with low implementation complexity?
- **Challenges**
  - Heterogeneous TV white spaces
    - licensed TV channels (Under-utilize): consider the licensee behavior
    - Unlicensed TV channels: public resource and cannot be traded freely
  - Heterogeneous database operators
    - Different interests and advantages

Business Models of TVWS Networks

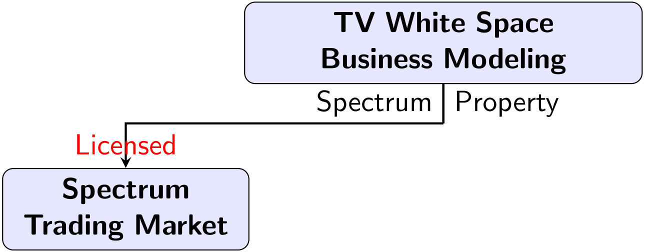
TV White Space
Business Modeling

Business Models of TVWS Networks

TV White Space Business Modeling

Spectrum | Property

Business Models of TVWS Networks



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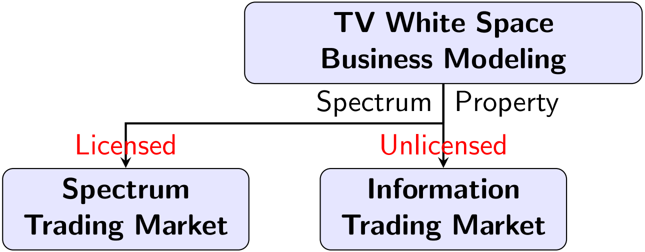

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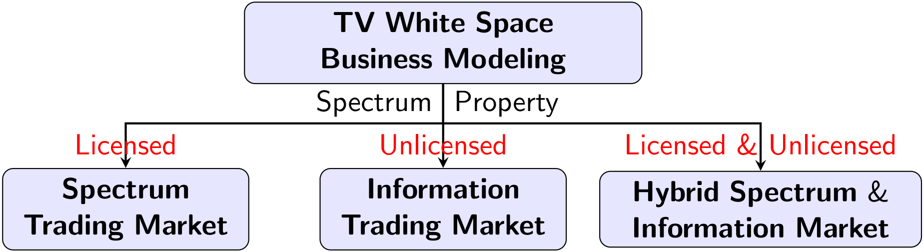

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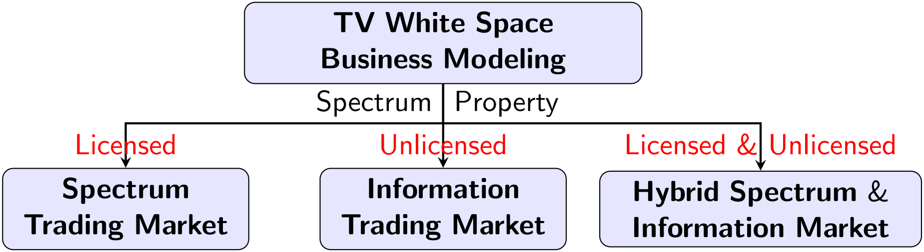

- **Key Focus**
  - Define the economics role for each involved network entity;
  - Analyze the economic behaviours of different players;
  - Design the efficient incentive mechanism for the whole network.

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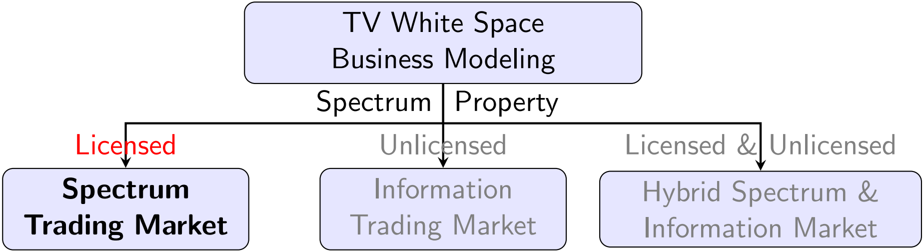
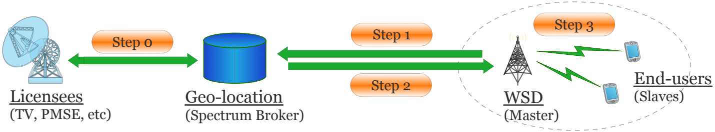


Spectrum Trading Market



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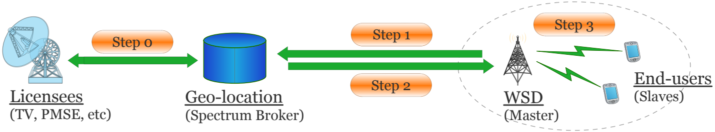

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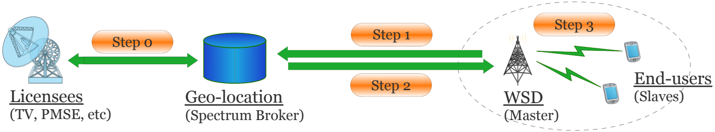

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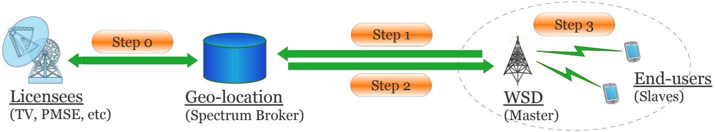

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    - ★ Exclusive used by one WSD
    - ★ Be reserved by database in advanced
  - Unlicensed TV spectrum
    - ★ Shared by multiple white space devices (WSDs)
    - ★ Be requested in real-time

Motivation

- **WSDs Competition Market**
  - Multiple WSDs compete for the same pool of end-users
  - WSDs serve the attracted end-users by using either the licensed TV spectrum or the unlicensed TV spectrum

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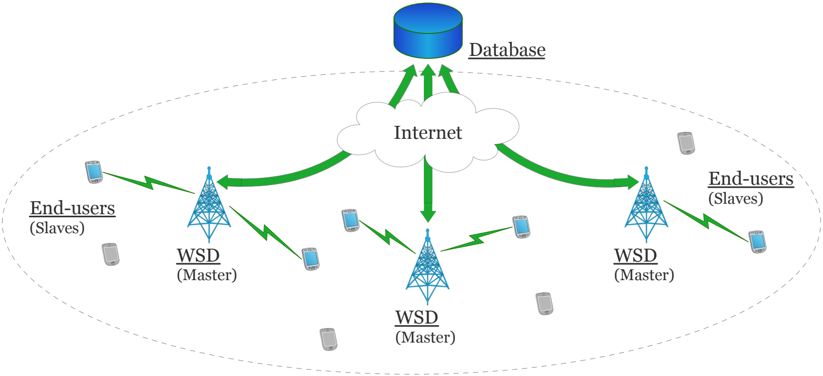
The Key Problems

- Quantity Competition: What is the optimal reserve quantity of licensed TV spectrum, considering the uncertainty of demand?
- Price Competition: What is the optimal prices of TV spectrum to the end-users?

System Model

- Multiple WSDs compete for the same pool of end-users
- $\mathcal{M} = \{1, 2, ..., M\}$: the set of WSDs



Three-Stage Interaction Model

Stage I: Wholesale Price Determination
The database determines TV channels wholesale prices (i.e., w for licensed TV spectrum and w^s for unlicensed TV spectrum).

$\Downarrow$

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End-users choose a WSD, and demands service from that WS-D;
WSDs replenish inventory by the unlicensed TV spectrum (if needed) and serve end-users;

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- Three-stage hierarchical model: analyzed by backward induction

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- d: total demand of all active end-users
  - Random variable with cumulative distribution function (c.d.f.) $G(d)$

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- d: total demand of all active end-users
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- d_m: demand directed to WSD m
  - $d_m(p_1, \ldots, p_M) = d \cdot \theta_m(p_1, \ldots, p_M)$
    - ★ $\theta_m(p_1, \ldots, p_M)$: an average probability of an end- user choosing an WSD m

$$\theta_m = \mathrm{Pr}\left\{ U_m^{\mathrm{EU}} \geq 0 \ \& \ U_m^{\mathrm{EU}} \geq \max_{i \in \mathcal{M}} U_i^{\mathrm{EU}} \right\} = \frac{e^{R_m - p_m}}{1 + \sum_{i \in \mathcal{M}} e^{R_i - p_i}}.$$

    - ★ R_m is the average benefit (quality of WSD)
  - Random variable related to all WSD' prices

Stage II: Price and Inventory Competition Game

- Price and Inventory competition game (PI-game)
  - Players: WSDs with set $\mathcal{M} = \{1, 2, \ldots, M\}$
  - Strategies: Inventory b_m and price p_m, $\forall m \in \mathcal{M}$
  - Payoff of WSD m: revenue - cost

Stage II: Price and Inventory Competition Game

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  - Players: WSDs with set $\mathcal{M} = \{1, 2, \ldots, M\}$
  - Strategies: Inventory b_m and price p_m, $\forall m \in \mathcal{M}$
  - Payoff of WSD m: revenue - cost
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  - This is an integrated investment and price competition game
  - Difficult to prove the uniqueness of Nash equilibrium directly

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Theorem (Existence and Uniqueness)

- The reduced price game has a unique Nash Euqilibrium $\mathbf{p}^*$
- The original PI-game has unique NE $(\mathbf{b}^*, \mathbf{p}^*)$

Stage I: Wholesale Pricing Strategy

- Two kinds of wholesale pricing strategies
  - Database profit maximization (DPM)
    - ⋆ Profit-seeking database operator
    - ⋆ Operated by third-party business companies
    - ⋆ Maximizing his own profit

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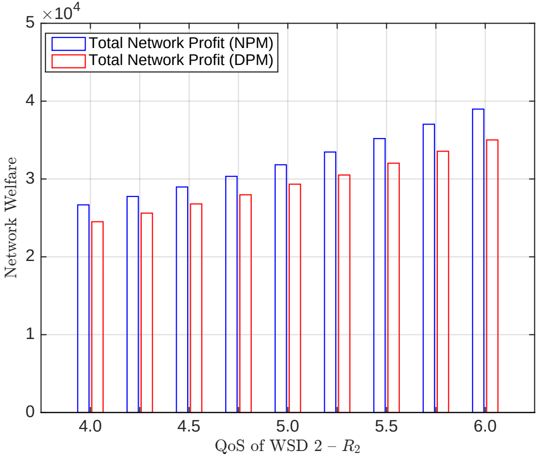
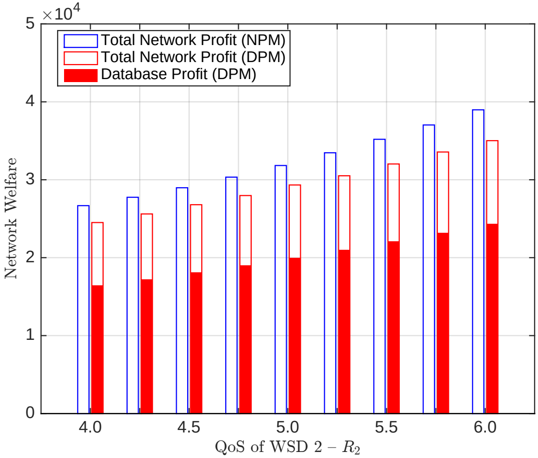
- There exist a wholesale price pair that maximize the network profit/database's profit

Simulation Results: Network Welfare



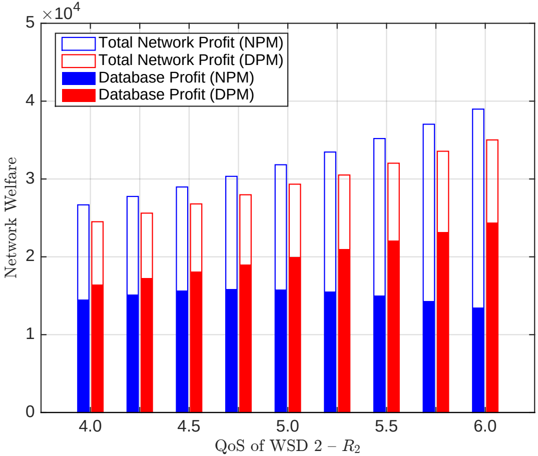
- Network welfare: Profit of database + Profit of two WSDs
- QoS of WSD 1 is fixed: 5
- Network welfare increases with QoS provided by WSD 2

Simulation Results: Database Profit



- Database's profit increases with R_2 under DPM scheme
  - A higher QoS attracts more end-users

Simulation Results: Database Profit

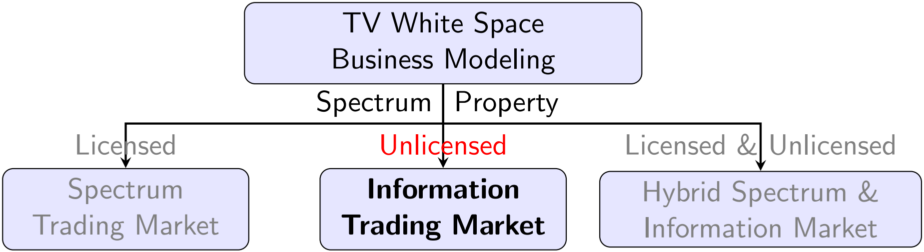


- Database's profit first increases and then decreases with R_2 under NPM scheme
  - QoS of WSD 1: 5

Summary

- We consider the competition of WSDs in the spectrum trading market
- We study the strategies of WSDs from a game-theoretic perspective
- We also study the database's wholesale pricing strategy

Business Models of TVWS Networks



TV White Spaces

- **Licensed TV bands**
  - Assigned to TV licensees but not fully utilized;
    - *E.g., some TV program channels shutdown between 12:00am to 6:00am;*
  - TV licensees have ownerships, and can fully decide whether, when, where, and how to share these spectrum with unlicensed WSDs;
    - *E.g., ask for financial compensation from unlicensed WSDs;*
  - Business model: **Spectrum Trading Market**
    - *TV licensees: Sellers of Spectrum*
    - *WSDs: Buyers of Spectrum*
    - *Database: Agent/Broker*

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- **Unlicensed TV bands**
  - Not licensed to any TV licensee at a certain location;
    - *Upgrade from analogue to digital TV: release a large amount of TV channels;*
  - Attitude of regulator: open and shared usage (FCC and Ofcom);
    - *E.g., like public resource, such as air and sunlight;*
    - *Spectrum market model is usually not suitable, due to the lack of ownership;*
  - Business model: **Information Trading Market**
    - *Databases: Sellers of Information*
    - *WSDs: Buyers of Information*

Business Modeling Technics

- **Spectrum Trading Market**
  - Target at Licensed TV bands
  - TV licensees: Sellers of Spectrum
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  - Databases: Agents/Brokers
- **Information Trading Market**
  - Target at Unlicensed TV bands
  - Databases: Sellers of Information
  - WSDs: Buyers of Information

Information Trading Market

- **Observations**
  - Different unlicensed white space channels may have different qualities for a particular WSD;
    - *E.g., due to different interferences from Licensed devices or other WSDs;*
  - Databases know more information regarding such quality than WSDs;
    - *E.g., Licensed devices' locations, channel occupancies, transmission powers, and other WSDs' locations and channel occupancies, etc.*
- **Thoughts**
  - Can WSDs benefit from such advanced information regarding the quality of white space channels?
  - If so, how to motivate databases to share such advanced information with WSDs?

An Example

- Consider a WSD at a particular location
  - Available white space channels $[ch1, ch2, ch3, ch4]$ (basic information)
  - Interference levels $[1, 2, 3, 4]$ or equivalent data rates $[5, 2, 1, 0]$ (advanced information)
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- If not purchasing the advanced information
  - Receive the available white space channels only, and Choose an available channel randomly
  - Average data rate: $\frac{5+2+1+0}{4} = 2$

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- 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
  - Basic information: Available TV white space channels at a given location (free and mandatory)
  - Advanced information: Quality (e.g., interference level) of each white space channel (non-free and optional)

Information Market Model

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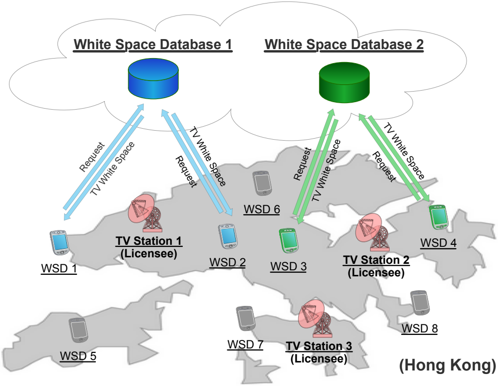
  - Basic information: Available TV white space channels at a given location (free and mandatory)
  - Advanced information: Quality (e.g., interference level) of each white space channel (non-free and optional)
- **Key Problems**
  - How to explicitly define the advanced information
  - How to accurately evaluate the advanced information
  - How to choose the best purchasing behaviors for WSDs
  - What is the market equilibrium point
  - How to optimally pricing the advanced information for databases

TV White Space Network Model

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



Definition of Advanced Information

- Interference on each white space channel k
  - U_k: Interference from licensed devices

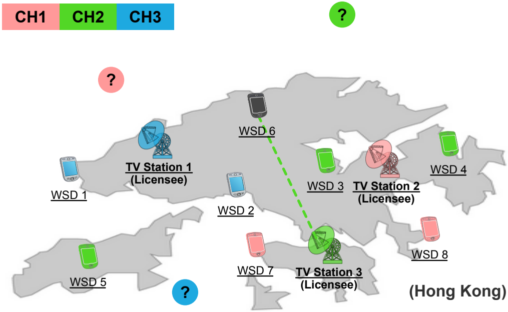


Fig: Interference from licensed devices (on channel 2) for WSD 6.

Definition of Advanced Information

- Interference on each white space channel k
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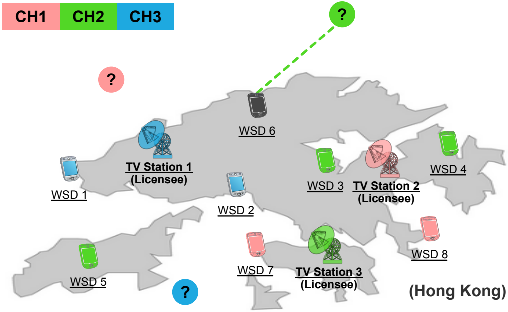

Fig: Interference from outside systems (on channel 2) for WSD 6.

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  - $W_{k,n}$: Interference from an other WSD n

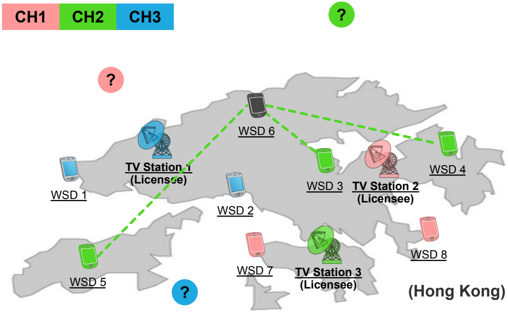

Fig: Interference from WSDs (on channel 2) for WSD 6.

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- Total interference on channel k (for a particular WSD)

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  - V_k: Interference from unknown outside systems $\rightarrow$ unknown
  - $W_{k,n}$: Interference from another WSD n $\rightarrow$ known or unknown
    - If WSD n purchases the advanced information from the database, $W_{k,n}$ is known by that database
    - If WSD n does not purchase the advanced information from the database, $W_{k,n}$ is not known by that database

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

Definition of Advanced Information

- Advanced information of database m regarding channel k:

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

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- Uncertain information of database m regarding channel k:

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

Evaluation of Advanced Information

- Total interference: $Z_k = X_{k,m} + Y_{k,m}$ (for each database m)
- Each WSD has $M + 2$ channel selection strategies:
  - (a) Choose a channel randomly
    - ★ Expected data rate is: $B = \mathrm{E}_Z[Rate(Z)]$
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  - (c) Choose the channel based on advanced information of database m
    - WSD will choose a channel k with the minimal $X_{k,m}$
    - Expected data rate is: $A_m = \mathrm{E}_{Z_{[m]}}[Rate(Z_{[m]})]$
      where $Z_{[m]} \triangleq \min\{X_{1,m}, X_{2,m}, ..., X_{K,m}\} + Y_m$ is the random variable denoting the interference on the channel with minimum $X_{k,m}$

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- When purchasing the advanced information from a database, 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

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- **Positive externality**
  - More WSDs purchasing the advanced information from a database,
  - $\rightarrow$ More information the database knows,
  - $\rightarrow$ More accurate the channel estimation for WSDs

Two-Stage Stackelberg Model

Stage I: Price Competition Game
Databases determine the information price;

$\Downarrow$

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Databases determine the information price;

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Stage II: WSD Behaving and Market Dynamics
WSDs determine and update their best choices; The market dynamically evolves to the equilibrium point.

Two-Stage Stackelberg Model

Stage I: Price Competition Game
Databases determine the information price;

⇓

Stage II: WSD Behaving and Market Dynamics
WSDs determine and update their best choices; The market dynamically evolves to the equilibrium point.

- We analyze the two-stage hierarchical model by backward induction.

Stage II - WSDs Behavior and Market Equilibrium

- When choosing channel randomly, its utility is

$$\Pi^{\mathrm{EU}} = \theta \cdot B$$

- When choosing channel based on sensing, its utility is

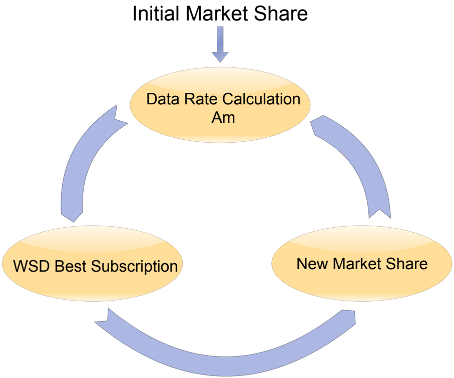
$$\Pi^{\mathrm{EU}} = \theta \cdot S - c$$

- When using the database *m*'s advanced information, its utility is

$$\Pi^{\mathrm{EU}} = \theta \cdot A_m(\eta_m) - \pi_m$$

  - θ: the WSD's evaluation for data rate
  - c: the cost of sensing
  - π_m: the price of database *m*'s advanced information
  - η_m: the market share of database *m*

Stage II - WSDs Behavior and Market Equilibrium



- **Market Equilibrium**
  - Under market equilibrium, the market shares no longer change.

Stage II - WSDs Behavior and Market Equilibrium

Market Equilibrium

The market converges to an equilibrium, if the following condition holds:

$$\triangle_m^t = \eta_m^t - \eta_m^{t-1} = 0, \ \forall m \in M$$

where η_m^t is the database m's market share at stage t.

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Existence and Uniqueness

Given a particular initial market share set $\{\eta_m\}_{m \in \mathcal{M}}$ and information price set $\{\pi_m\}_{m \in \mathcal{M}}$, the market always converges to a unique market share equilibrium.

Stage I: Price Competition Game Equilibrium

- **Price Competition Game**
  - Players: M databases

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  - Players: M databases
  - Strategies: Information price π_m offered by each database $m \in \mathcal{M}$

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  - Players: M databases
  - Strategies: Information price π_m offered by each database $m \in \mathcal{M}$
  - Payoffs: Profit of each database $m \in \mathcal{M}$

$$\Pi_m^{\mathrm{DB}}(\pi_m, \boldsymbol{\pi}_{-m}) = (\pi_m - c_m) \cdot \eta_m^*(\pi_m, \boldsymbol{\pi}_{-m})$$

  - ★ c_m: operational cost of database m
  - ★ η_m^*: equilibrium market share of database m in Stage II.

Stage I: Price Competition Game Equilibrium

Nash Equilibrium

A price profile $\{\pi_m^*\}_{m\in\mathcal{M}}$ is called a price equilibrium, if

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- Challenges
  - Characterizing market equilibrium η_m^* as a function of prices $\{\pi_m\}_{m\in\mathcal{M}}$.

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Stage I: Price Competition Game Equilibrium

- **Observations**
  - One-to-one correspondence between $\{\eta_m^*\}_{m\in\mathcal{M}}$ and $\{\pi_m\}_{m\in\mathcal{M}}$;
- **Our Solution**
  - Transform the price competition game into an equivalent market share competition game (MSCG).
    - ⋆ Players: M databases
    - ⋆ Strategies: Market share η_m of each database $m \in \mathcal{M}$
    - ⋆ Payoffs: Profit of each database $m \in \mathcal{M}$,

$$\Pi_m^{\mathrm{DB}}(\eta_m, \boldsymbol{\eta}_{-m}) = \left(\pi_m^*(\eta_m, \boldsymbol{\eta}_{-m}) - c_m\right) \cdot \eta_m$$

where price π_m^* is a function of market shares $\{\eta_m\}_{m\in\mathcal{M}}$.

Stage I: Price Competition Game Equilibrium

Existence of MSCG NE (Duopoly Market)

In the duopoly market with two databases, the market share competition game (MSCG) is a supermodular game with respect to η_1 and $-\eta_2$. Hence, there exists at least one equilibrium.

Stage I: Price Competition Game Equilibrium

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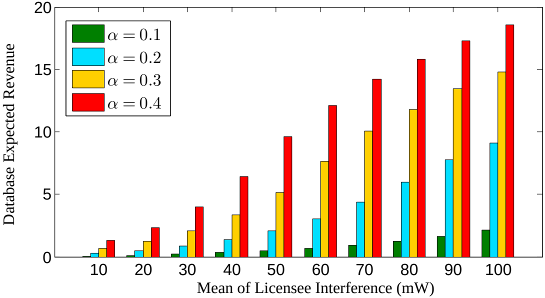
Existence of MSCG NE (Oligopoly Market)

In the oligopoly market with more than two databases, there exists a pure-strategy Nash equilibrium, under the following positive network externality function:

$$g(\eta_m) = \alpha_m + (\beta_m - \alpha_m) \cdot {\eta_m}^{\gamma_m}, \ \gamma_m \in (0, 1].$$

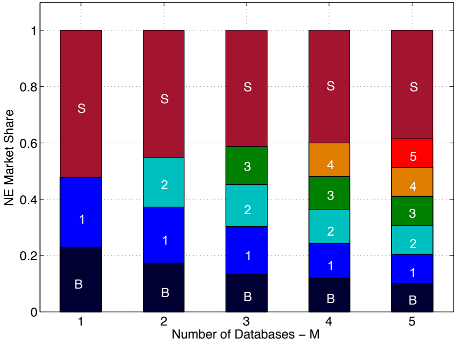
Monopoly Market

- **Monopoly Market**: Single Database
  - Database's revenue increases with the degree of licensee interference and the sensing cost α;
    - ★ A larger licensee interference or sensing cost makes the information more valuable.



Competitive Market

- **Competitive Market**: Multiple Database
  - Each database market share decreases with the number of databases due to competition;
  - Total database market share increases with the number of databases;
    - ★ Competition drives the information price down
    - ★ Low price attract more WSDs



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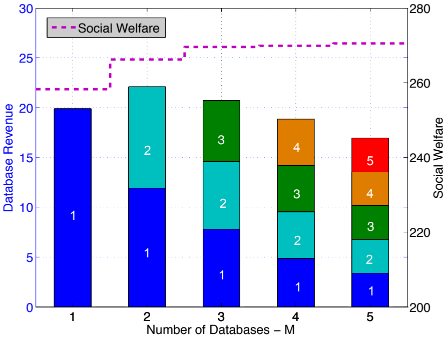

Summary

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  - We characterized the positive externality of the information market;
  - We analyzed the market equilibrium of the information market;
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  - We characterized the positive externality of the information market;
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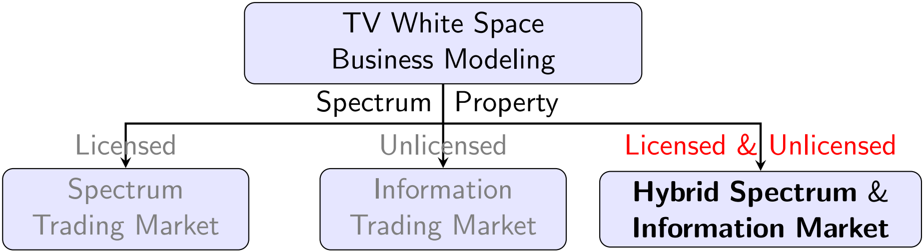
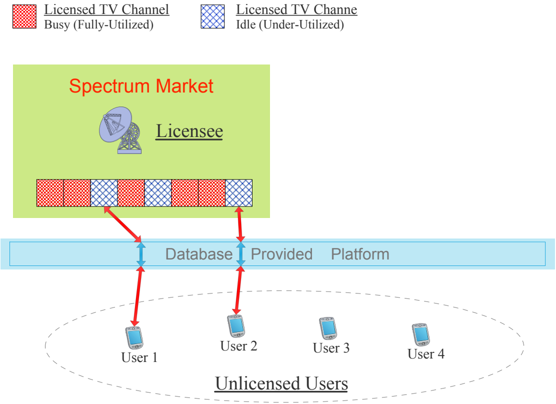
- **Next Step**
  - Joint consideration of licensed and unlicensed TV channels.

Business Models of TVWS Networks

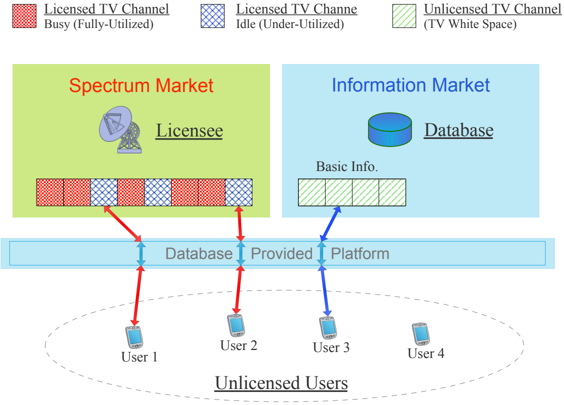


Hybrid Market Model: Spectrum Market



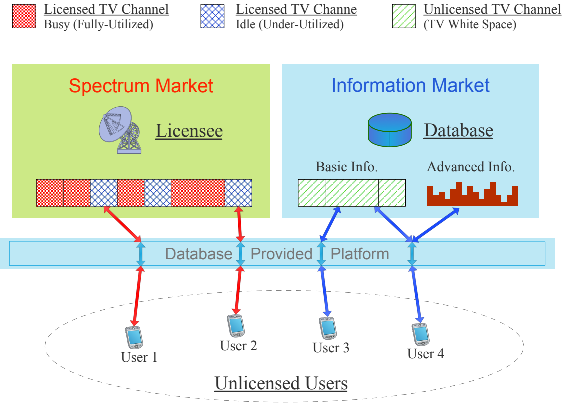
- The spectrum licensee *leases* his licensed TV channels via the platform of the database to unlicensed users
  - the database's *proximity* to both licensees and unlicensed users
  - Users can lease licensed channels for *exclusive usage*

Hybrid Market Model: Information Market



- *Basic Service (free)*: The database returns available unlicensed TV channels list to users without quality information

Hybrid Market Model: Information Market



- *Basic Service (free)*: The database returns available unlicensed TV channels list to users without quality information
- *Advance Service (paid)*: The database returns available unlicensed TV channels list to users with quality information

Property of Hybrid Market

- **Positive externality**
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Property of Hybrid Market

- **Positive externality**
  - More WSDs purchasing the advanced information from a database, more information the database knows, more accurate channel estimation information
- **Negative externality**
  - Less WSDs leasing licensed TV channels increases the level of congestion (interference) of unlicensed TV channels

Property of Hybrid Market

- **Positive externality**
  - More WSDs purchasing the advanced information from a database, more information the database knows, more accurate channel estimation information
- **Negative externality**
  - Less WSDs leasing licensed TV channels increases the level of congestion (interference) of unlicensed TV channels
- **Competition and Cooperation**
  - Database and licensee compete for providing different services
  - Database assists the licensee to display leasing information

Observations and Insights

- The market share equilibrium of the licensee is less than half

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Conclusion

- **Background**
  - Historical Background
  - Standardization Efforts
  - Policy Considerations
- **Technique Issues**
  - Database and WSD Development
  - TVWS Availability Computation
  - Resource Management and Optimization
- **Business Models**
  - Spectrum Market Model
  - Information Market Model
  - Hybrid Market Model

Publications

- **Overview**
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