Economics of Database-Assisted Spectrum Sharing

Jianwei Huang, Lin Gao, and Yuan Luo

Network Communications and Economics Lab (NCEL)

The Chinese University of Hong Kong

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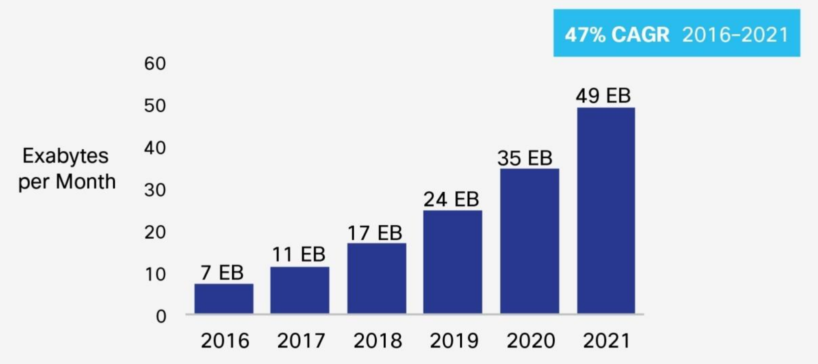
Outline

1. **Introduction**
2. **Technical Issues**
   - TVWS Availability Computation
   - WSD Development and Standardization
   - Resource Management and Optimization
   - Other Technical Issues
3. **Business Models**
   - Spectrum Trading Market
   - Information Trading Market
   - Hybrid Spectrum and Information Market

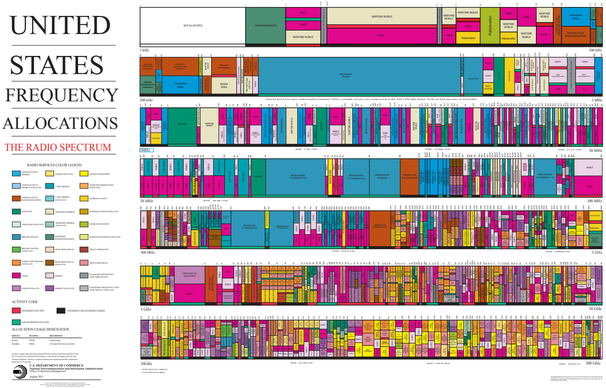
Mobile Data Explosion



Global Mobile Data Traffic, 2016 to 2021 (from Cisco VNI Mobile)

- Mobile data traffic explosive growth: 47% annual grow rate
- Need more spectrum resources to support wireless broadband services.

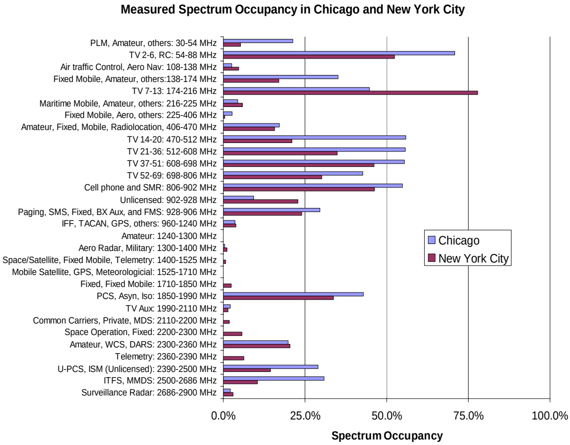
Radio Spectrum Scarcity



Frequency Allocation Chart in USA (from NITA)

- Spectrum resource is very limited.

Spectrum Usage Inefficiency

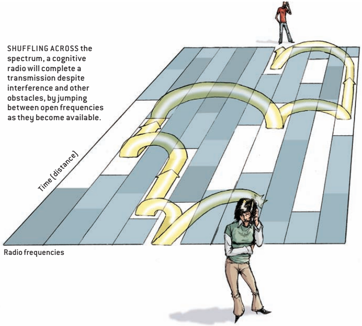


Spectrum Occupancy Measurement (from M. A. McHenry et al., ACM TAPAS'06)

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

Dynamic Spectrum Sharing (DSS)

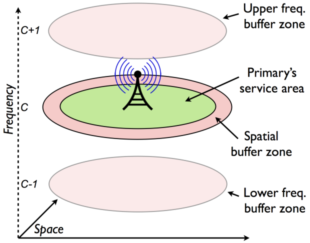
- A promising approach to provide more spectrum resources
- Enable unlicensed devices to share the spectrum bands in an opportunistic manner;
- Improve the spectrum utilization efficiency without affecting the licensed operations;



Dynamic Spectrum Sharing (from S. Ashley, Scientific American, 2006)

White Spaces

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



White Space Illustrative Example (from K. Harrison, Doctoral Dissertation, 2015)

TV White Spaces

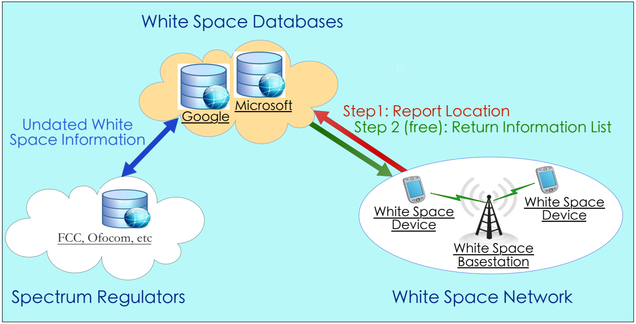
- One of the most promising white spaces for DSS
- What are TV White Spaces?
  - The idle frequencies in the VHF and UHF TV broadcast bands
    - 54-216 MHz and 470-698 MHz in the US
- Why TV White Spaces?
  - Wide Bandwidth
    - More than 280 MHz in USA
  - Excellent Propagation
    - Low frequency band
    - Strong penetration capability
    - Large transmission distance
- Potential Application — Super WiFi
  - Rural broadband/backhaul
  - Sensor networks
  - Indoor video distribution
  - M2M communications

Database-Assisted TV White Space Network

- Database-Assisted TV White Space Network
  - Unlicensed devices obtain the available 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 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 TV white spaces at a given location;



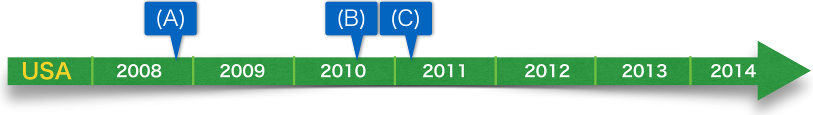
Architecture of Database-Assisted TV White Space Network (by FCC, Ofcom)

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)

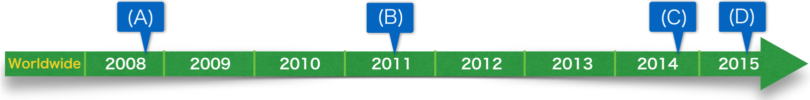
Regulatory Policy

- 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.



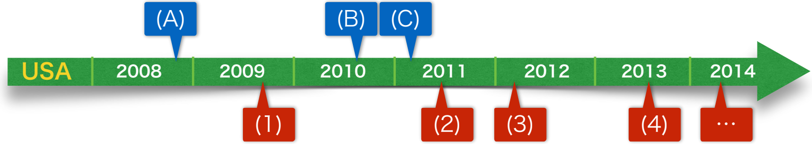
Regulatory Policy

- 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 and 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

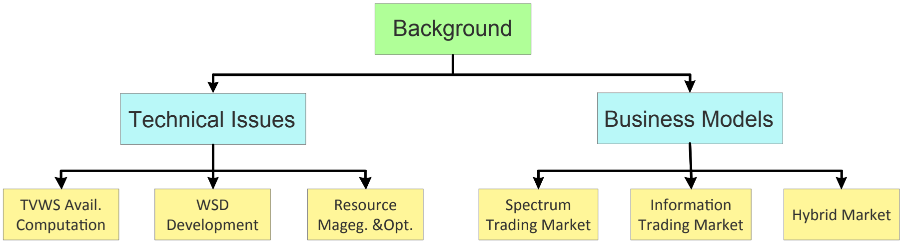


Trials and Demos

TV white spaces trials and demonstrations (from Microsoft)

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

Roadmap of This Tutorial



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][Mickenna 2016]
    - ★ Most important technical issue, Different in UK and USA

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  - WSD Development and Standardization
    - ★ How to design and standardize white space device (WSD)

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  - WSD Development and Standardization
    - ★ 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]

Outline

Challenge 1: 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 (100×100 m^2) geographic squares (pixels).
  - PMSE Location
    - A single point in the database

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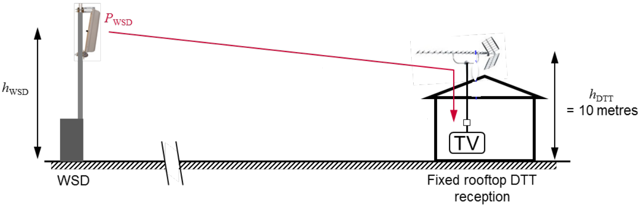
  - PMSE Location
    - ★ A single point in the database
  - DTT/PMSE Channel
    - ★ The operational channels of DTT/PMSE devices.

Challenge 1: 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



Calculation of WSD's Potential Interference to DTT (from Ofcom)

Challenge 1: TVWS Availability Computation in UK

- **PMSE Protection**
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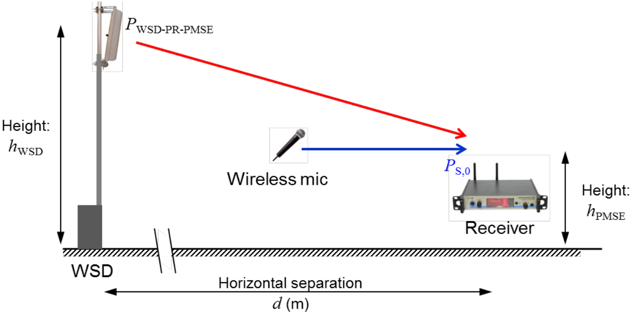
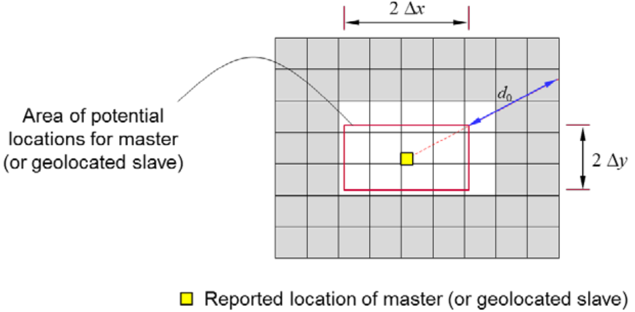
    - ★ Locations of PMSE
    - ★ Possible locations of WSDs
    - ★ Antenna Heights of WSDs
    - ★ Channel Usage of PMSE



Calculation of WSD's Potential Interference to PMSE (from Ofcom)

Challenge 1: TVWS Availability Computation in UK

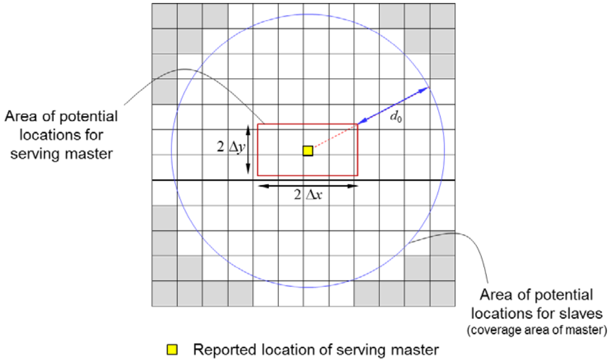
- **Uncertainty (Error)** of Master Location
  - Suppose a master reports location (x_0, y_0) with uncertainties $(\pm\Delta x, \pm\Delta y)$.
  - Then, possible locations of the master:
    - ★ Rectangle centred on (x_0, y_0) with sides of length $2\Delta x$ and $2\Delta y$
    - ★ Cover a set of M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



Location Uncertainty of A Master WSD (from Ofcom)

Challenge 1: TVWS Availability Computation in UK

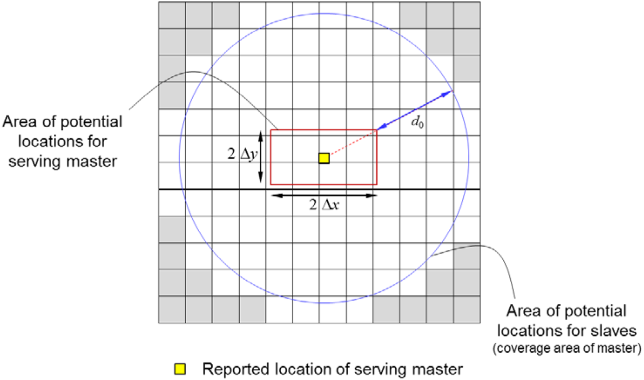
- **Uncertainty** of Slave Location
  - Slaves are not required to report their locations to the master;
  - Hence, possible locations of slaves are whole coverage area of master:
    - Circle centred on (x_0, y_0) with radii $d_0 + \sqrt{(\Delta x^2 + \Delta y^2)}$;
    - d_0 is the transmission range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



Location Uncertainty of A Slave WSD (from Ofcom)

Challenge 1: TVWS Availability Computation in UK

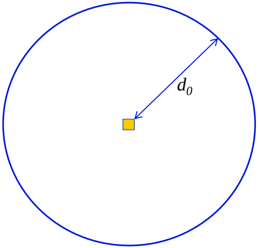
- **Available TV White Space**
  - The TV white spaces that are available in all N pixels;
- **Allowed Transmission Power** (on each channel)
  - The minimum allowed transmission power in all N pixels.



Location Uncertainty of A Slave WSD (from Ofcom)

Challenge 1: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;



Location Uncertainty of A WSD (from FCC)

Outline

Challenge 2: 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
    - ★ ....

Challenge 2: WSD Design and Standard

- **IEEE 802.22**: A standardized air interface for the use of TV bands on a non-interfering basis
  - The first world wide effort

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- Main features
  - Spectrum Sharing with licensees
  - Mobile device location identification
  - Frequency agility
  - Transmit power control
  - Adaptive modulation and coding
  - Mobility and connection management
  - Security management

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- Five active standards
  - 802.22: Policies and procedures for operation in the TV Bands
  - 802.22.1: Low-power licensed devices interference protection
  - 802.22.2: IEEE 802.22 systems's installation and development
  - 802.22a: Requirement for the management and control plane interfaces
  - 802.22b: Enhancement for broadband services

Challenge 2: WSD Design and Standard

- **IEEE 802.11af**: Applies the success of WiFi to implement wireless broadband networks in white spaces
  - Super Wifi or White-FI
- Covers the system operating at frequencies below 1 GHz
  - Traditional WiFi usage frequencies at 2.4 GHz and 5 GHz
- Three channel dependent stations (STAs)
  - Fixed STAs (Fixed WSDs in FCC) and enabling STAs (Mode II WSDs in FCC)
    - Registered stations
    - Broadcast their registered location
    - Correspond to master WSDs in Ofcom
  - Dependent STAs (Model I WSDs in FCC and slave WSDs in Ofcom)
    - Operating under the help of enabling STA

Challenge 2: WSD Design and Standard

- IEEE 802.22 vs. IEEE 802.11af
- Common
  - Have the same standards at the PHY layer
    - ⋆ OFDM modulation, convolutional coding, QPSK modulation, ...
  - Geolocation information accuracy: 50 m

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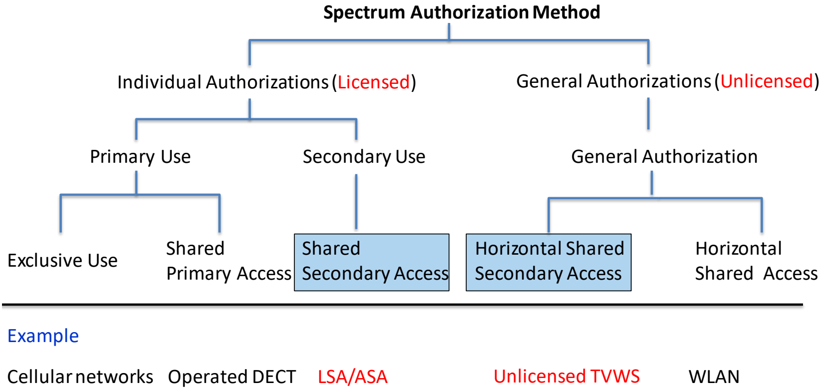
- Difference

Difference	**IEEE 802.22**	**IEEE 802.11af**
Operation Scenario	Outdoor ($<$ 5km)	Outdoor & Indoor ($<$ 100 m)
MAC Layer Access	TDM for downlink & OFDMA for uplink	CSMA/CA protocol
Geolocation Information	Satellite-based method & Terrestrial-based method	Satellite-based method

Outline

Challenge 3: Spectrum Manage. 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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- Authorized Shared Access (ASA)
  - Unlock access to additional frequency bands for mobile broadband
  - Alternative to spectrum sharing/refarming

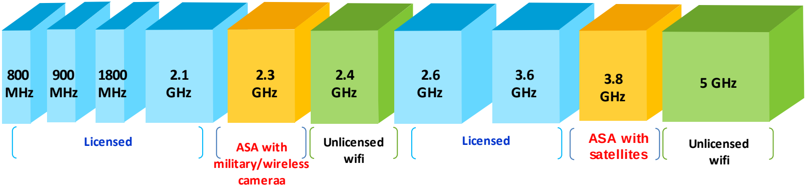

Fig. Frequency (from presentation at WG FM May 2011, doc. FM(11) 116)

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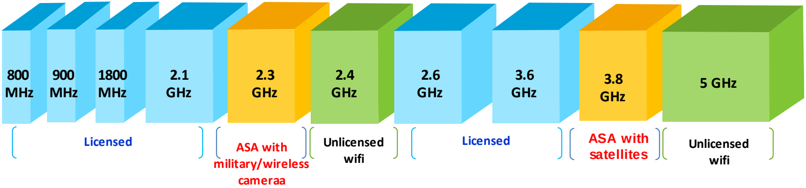

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- Licensed Shared Access (LSA)
  - Potential for other applications in addition to mobile broadband application

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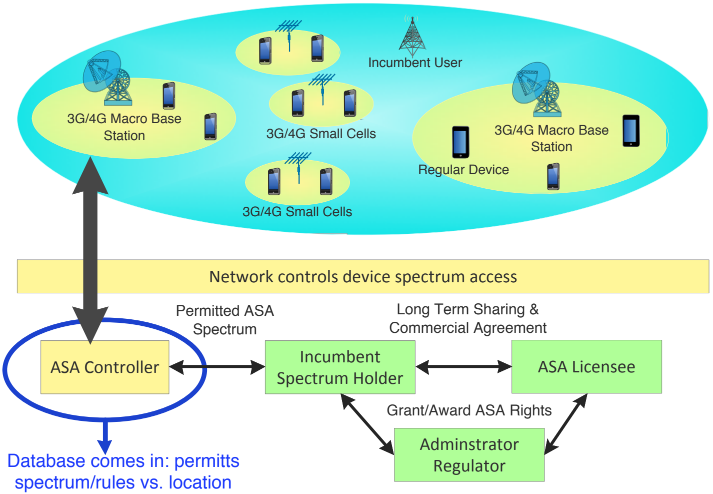

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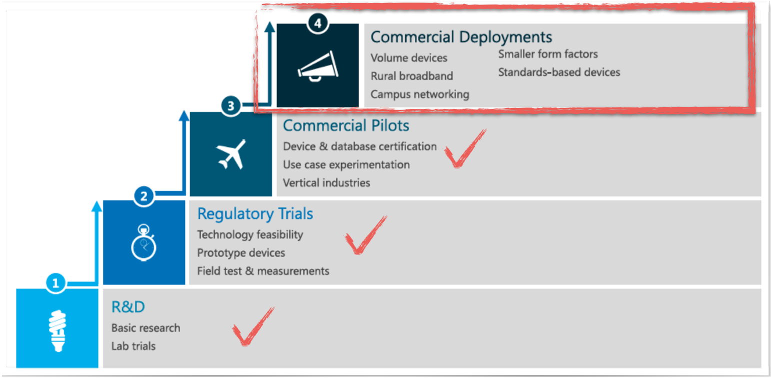
  - Coexistence
    - How do different WSDs deployed by different standardizations coexists in the same database-assisted network [Raykas eta al. 2012][IEEE 802.22, 2016]
  - Communication between WSD and Database
    - How does a **mobile** WSD identify the communication link [Z. Qin, Y. Gao, C. Parini, 2015]
  - Others

Outline

Current Status

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



TVWS Development (from Microsoft)

Economic Issues and Challenges

- **Economic issues**
  - Define an appropriate business model for this database-assisted network
  - Analyze the economics interactions among network entities
  - Design optimal trading mechanisms in an appropriate business model

Economic Issues and Challenges

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- **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 Database-Assisted Networks

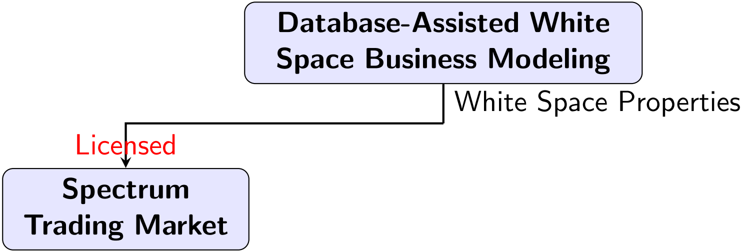
Database-Assisted White Space Business Modeling

Business Models of Database-Assisted Networks

Database-Assisted White Space Business Modeling

White Space Properties

Business Models of Database-Assisted Networks



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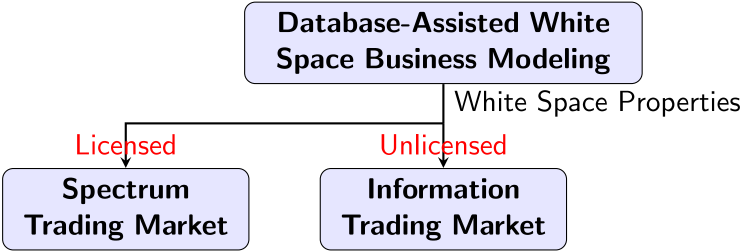

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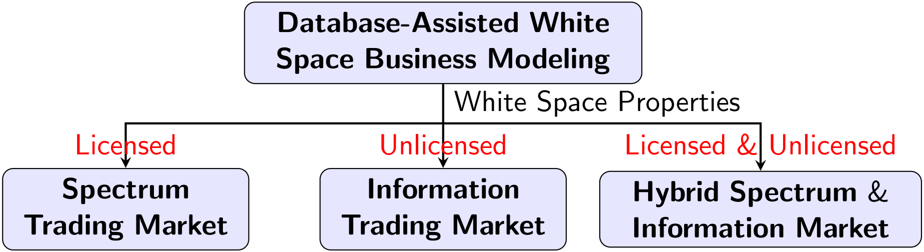

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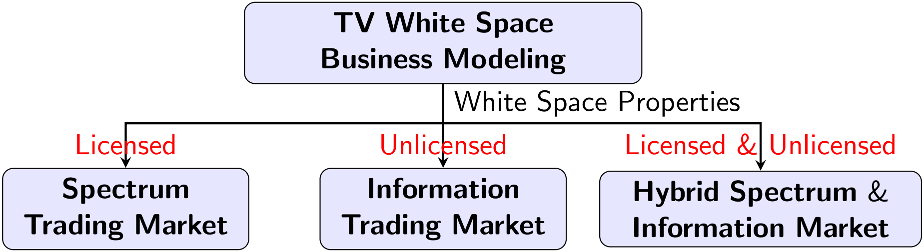
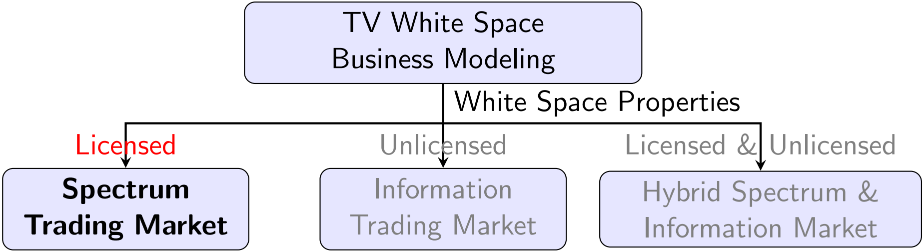
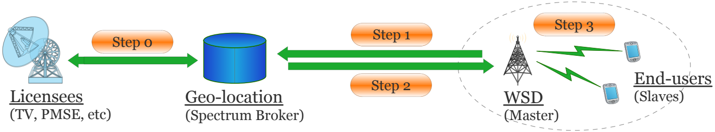


- **Key Focus**
  - Define the economics role for each involved network entity;
  - Analyze the economic behaviours of different players;
  - Design the efficient incentive mechanism for the whole network.

Business Models of TVWS Networks

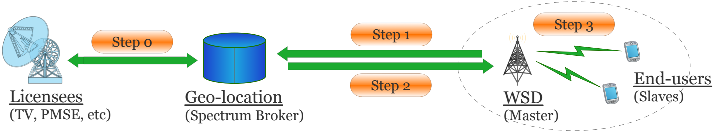


Spectrum Trading Market



- Database acts as the spectrum broker
  - Facilitate the interaction between the licensees and white space devices (WSDs)

Spectrum Trading Market



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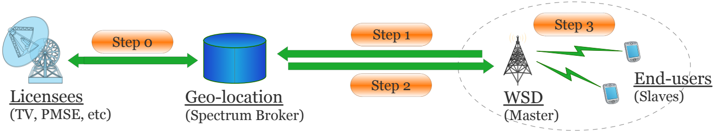

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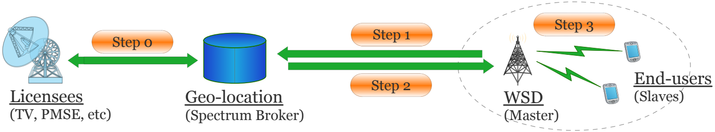

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  - Unlicensed TV white spaces (as backup resources)
    - ★ Shared by multiple white space devices (WSDs)
    - ★ Be requested in real-time

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 white spaces or the unlicensed TV white spaces

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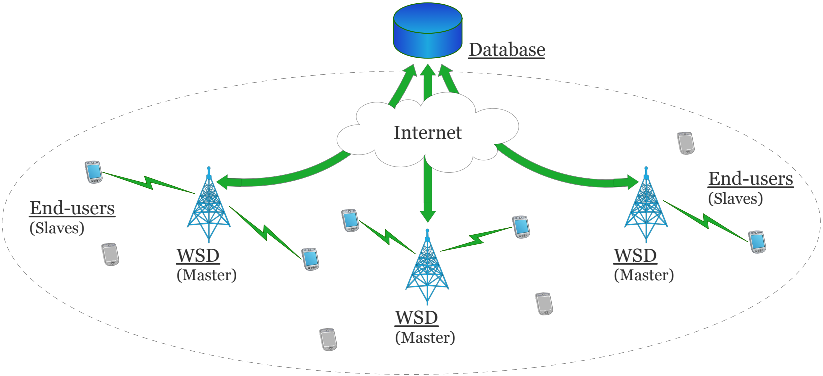
The Key Problems

- Quantity Competition: What is the optimal reserve quantity of licensed TV white spaces, considering the uncertainty of demand?
- Price Competition: What is the optimal prices of TV white spaces 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 white spaces wholesale prices (i.e., w for licensed TV white space and w^s for unlicensed TV white space).

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- Three-stage hierarchical model: analyzed by backward induction

Stage III: Demand of End-users

- An end-user will always choose the WSD that maximizes its payoff

$$U_m^{\mathrm{EU}} = \pi_m - p_m,$$

  - π_m is the benefit of an end-user when choosing WSD m

$$\pi_m = R_m + \epsilon_m,$$

    - ★ R_m is the average benefit (quality of WSD)
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- The average probability of an end-user choosing a WSD m

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

  - ε_m follows the Gumbel distribution

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- d: total demand of all active end-users
  - Random variable with cumulative distribution function (c.d.f.) $G(d)$
- d_m: demand directed to WSD m
  - $d_m(p_1, \ldots, p_M) = d \cdot \theta_m(p_1, \ldots, p_M)$
  - 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, $\forall m \in \mathcal{M}$
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Observation

- Payoff of WSD m

$$U_m(p_m, \boldsymbol{p}_{-m}, b_m) = p_m \cdot \mathrm{E}_{d_m}\left[\min\left\{d_m(p_m, \boldsymbol{p}_{-m}), b_m\right\}\right] - w_m \cdot b_m \\ + (p_m - \delta_m - w_m^s) \cdot \mathrm{E}_{d_m}\left[d_m(p_m, \boldsymbol{p}_{-m}) - b_m\right]^+,$$

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Reduce the game in two-dimensional space to one-dimensional

Reduce Two-Dimensional Strategy Space

- Payoff of WSD m

$$
\begin{aligned}
U_m(p_m, \boldsymbol{p}_{-m}, b_m) = & p_m \cdot \mathrm{E}_{d_m}\left[\min\left\{d_m(p_m, \boldsymbol{p}_{-m}), b_m\right\}\right] - w_m \cdot b_m \\
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\end{aligned}
$$

- WSD m's utility U_m is strictly concave in b_m
  - There exists an unique optimal order quantity b_m^* given any price $\boldsymbol{p}$

$$
b_m^*(p_m, \boldsymbol{p}_{-m}) = H_m^{-1}\left(1 - \frac{w_m}{\delta_m + w_m^s} | p_m, \boldsymbol{p}_{-m}\right)
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- New payoff of WSD m

$$\tilde{U}_m(p_m, \boldsymbol{p}_{-m}) = (p_m \cdot \mu - \tilde{w}_m) \cdot \theta_m(p_m, \boldsymbol{p}_{-m}),$$

Reduced Game $\widetilde{\Gamma}$

- Reduced price competition game $\widetilde{\Gamma} = (\mathcal{M}, \{p_m\}_{m\in\mathcal{M}}, \{\tilde{U}_m\}_{m\in\mathcal{M}})$

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Original PI-Game has a NE $(\boldsymbol{b}^*, \boldsymbol{p}^*)$

Existence and Uniqueness of Nash Equilibrium

Theorem (Existence and Uniqueness)

- The reduced game $\widetilde{\Gamma}$ has a unique Nash Euqilibrium $\boldsymbol{p}^*$
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  - The utility function has increasing difference property
    - $f(x^{'}, t^{'}) - f(x, t^{'}) \geq f(x^{'}, t) - f(x, t)\ \forall x^{'} \geq x, t^{'} \geq t$
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- The uniqueness is obtained by proving that the WSDs' utility function satisfies the dominant diagonal condition:

$$-\frac{\partial^2 \log \tilde{U}_m(p_m, \boldsymbol{p}_{-m})}{\partial {p_m}^2} \geq \sum_{j \neq m} \frac{\partial^2 \log \tilde{U}_m(p_m, \boldsymbol{p}_{-m})}{\partial p_m \partial p_j}, \forall m \in \mathcal{M}.$$

Best Response Update Based Algorithm

- Each WSD updates its price based on its best response to other WSDs' price in the previous round k

$$p_m(k+1) = \arg\max_{p_m} \tilde{U}_m(p_m, \boldsymbol{p}_{-m}(k))$$

Theorem (Convergence)

The best response update strategy globally converges to the unique NE.

Stage I: Wholesale Pricing Strategy

- Two kinds of wholesale pricing strategies
  - Database profit maximization (DPM)
    - ⋆ Profit-seeking database operator
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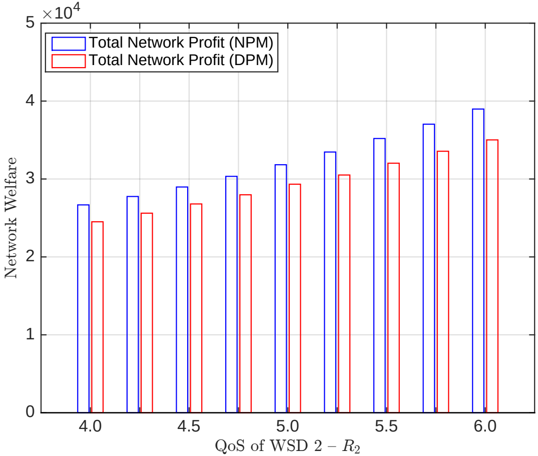
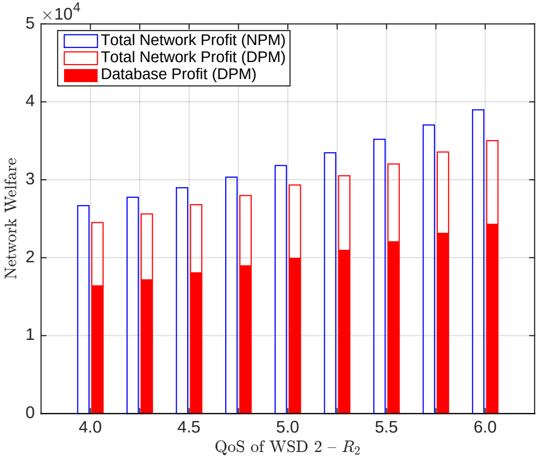
Simulation Results: Network Welfare



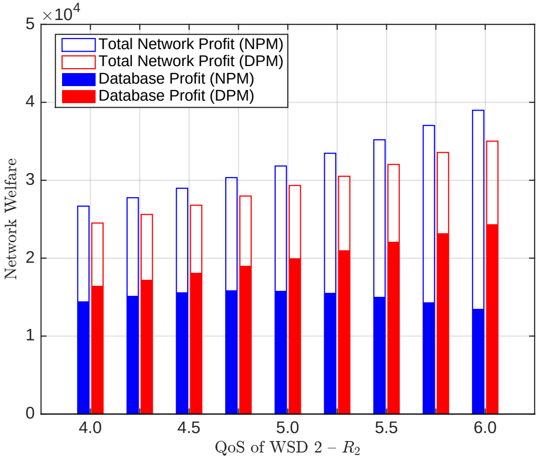
- Network welfare: Profit of database + Profit of two WSDs
- QoS of WSD 1 is fixed at $R_1 = 5$
- Network welfare increases with R_2

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

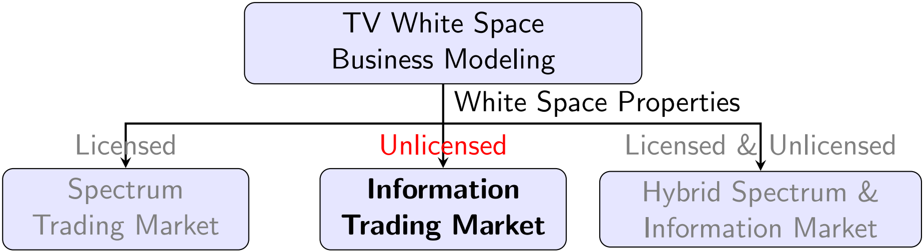


- Database's profit is not monotonic with R_2 under NPM scheme

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



Unlicensed TV White Spaces

- 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);
  - Similar as 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

Information Trading Market

- **Observation 1**: Different unlicensed white space channels may have different qualities for a particular WSD;
  - Due to different interferences from Licensed devices or other WSDs;

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- **Observation 2**: Databases know more information regarding such quality than WSDs;
  - 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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  - 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 (not free and optional)

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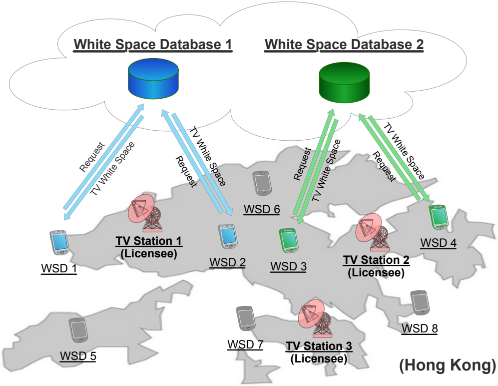
  - Basic information: Available TV white space channels at a given location (free and mandatory)
  - Advanced information: Quality (e.g., interference level) of each white space channel (not free and optional)
- **Key Problems**
  - How to define the advanced information
  - How to evaluate the advanced information
  - How to choose the best purchasing behaviors (WSDs)
  - How to optimally price the advanced information (databases)
  - What is the market equilibrium point

TV White Space Network Model

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



Interference Characterization

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

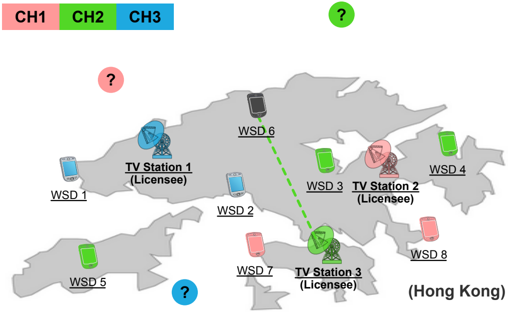


Fig: Interference from licensed devices (on channel 2) for WSD 6.

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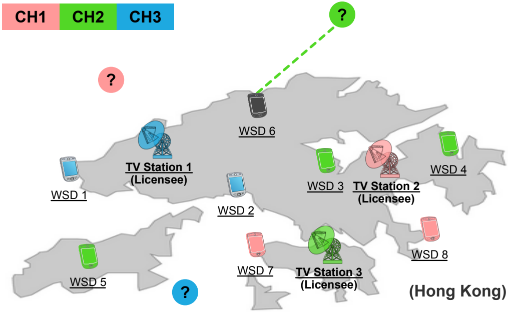
  - V_k: Interference from unknown outside systems



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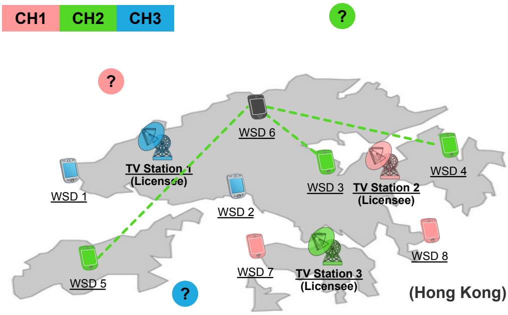

Fig: Interference from WSDs (on channel 2) for WSD 6.

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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:

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

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- Uncertain information of database m regarding channel k:

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

Evaluation of Advanced Information

- Total interference: $Z_k = X_{k,m} + Y_{k,m}$ (for each database m)
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    - ⋆ 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 $X_{k,m}$

Evaluation of Advanced Information

- 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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- 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

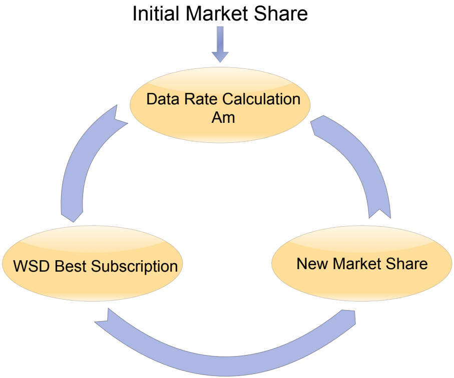
$$\Pi^{\mathrm{EU}} = \theta \cdot S - c$$

- 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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  - 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

$$\pi_m^* = \arg\max_{\pi_m^* \geq 0} \quad \Pi_m^{\mathrm{DB}}(\pi_m, \boldsymbol{\pi}_{-m}^*), \ \forall m \in \mathcal{M}$$

$$= \arg\max_{\pi_m^* \geq 0} \quad (\pi_m - c_m) \cdot \eta_m^*(\pi_m, \boldsymbol{\pi}_{-m}^*), \ \forall m \in \mathcal{M}$$

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

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

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:

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

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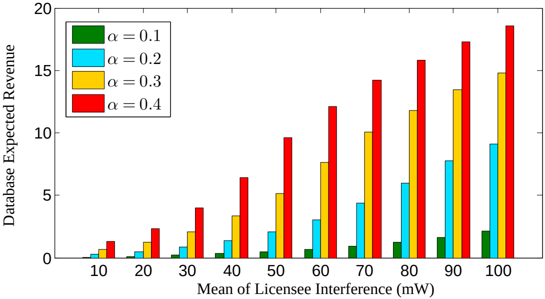
- Positive network externality function
  - α_m: the minimum benefit brought by the database's information
  - β_m: the maximum benefit brought by the database's information
  - γ_m: the elasticity of the positive network externality

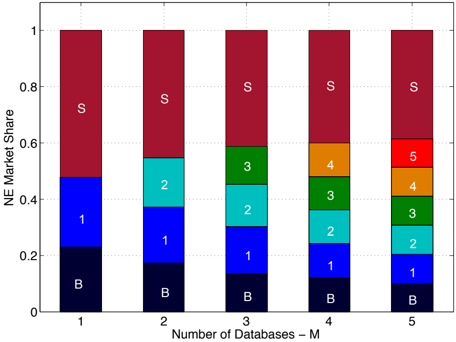
Monopoly Market

- **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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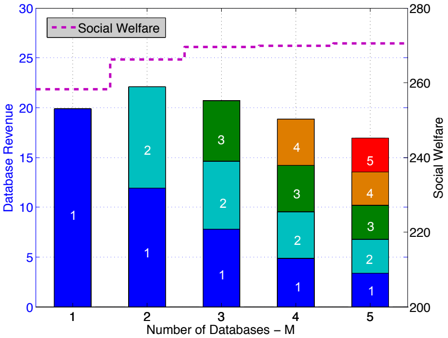

Summary

- **Conclusion**
  - We proposed an information market for unlicensed TV channels;
  - We characterized the positive externality of the information market;
  - We analyzed the market equilibrium of the information market;
  - We studied the price competition among databases.

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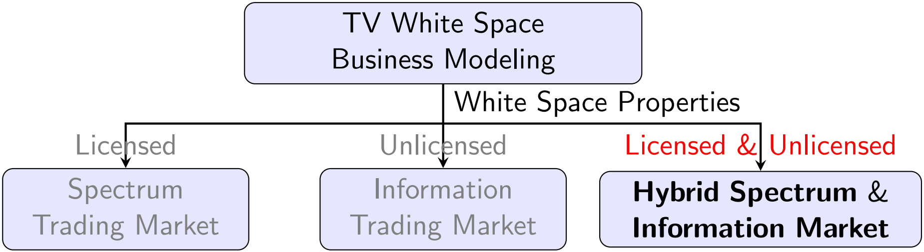
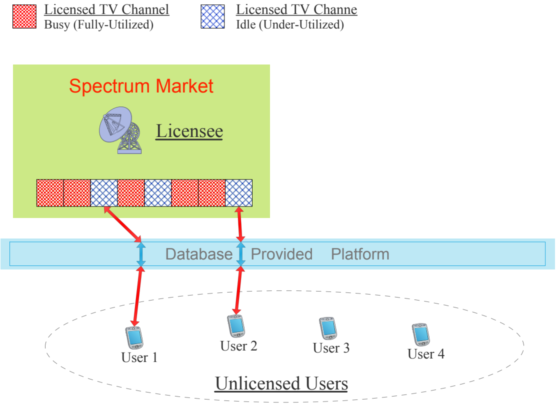
  - We studied the price competition among databases.
- **Next Step**
  - Joint consideration of licensed and unlicensed TV channels.

Business Models of TVWS Networks

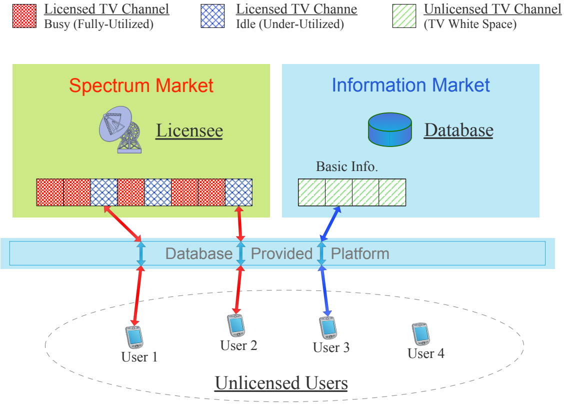


Hybrid Market Model: Spectrum Market



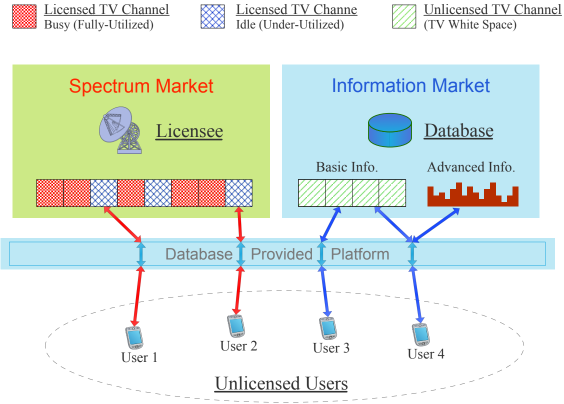
- The spectrum licensee *leases* his licensed TV channels via the platform of the database to unlicensed users
  - the database's *proximity* to both licensees and unlicensed users
  - Users can lease licensed channels for *exclusive usage*

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

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- **Positive externality**
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- **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

Three-Stage Stackelberg Model

Stage I: Commission Negotiation
The database and the the licensee negotiate the commission charge details (i.e., revenue sharing percentage under RSS or wholesale price under WPS);

$\Downarrow$

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Stage III: WSDs Behavior and Market Equilibrium

- When choosing basic service, its utility is

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

- When choosing advance service, its utility is

$$\Pi^{\mathrm{EU}} = \theta \cdot A - \pi_A$$

- When using leasing service, its utility is

$$\Pi^{\mathrm{EU}} = \theta \cdot L - \pi_L$$

  - θ: the WSD's evaluation for data rate
  - B and A decrease with the percentage of WSDs not choosing leasing service (negative externality)
  - A increases with the percentage of WSDs choosing advance service (positive externality)
  - L is independent of the WSDs choices

Stage III: WSDs Behavior and Market Equilibrium

- **Market Equilibrium**
  - Under market equilibrium, the market shares no longer change.
- **Our results**
  - There exists an unique market equilibrium

Stage III: WSDs Behavior and Market Equilibrium

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- **Our results**
  - There exists an unique market equilibrium
- **Observation**
  - The market share equilibrium of the licensee is less than half

Stage II: Price Competition Game Equilibrium

- Formulate the price competition games
  - Given unique market equilibrium in Stage III
  - Under two schemes
    - Revenue sharing scheme (RSS)
    - Wholesale price scheme (WPS)

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- Formulate the price competition games
  - Given unique market equilibrium in Stage III
  - Under two schemes
    - ★ Revenue sharing scheme (RSS)
    - ★ Wholesale price scheme (WPS)
- Transform the original price competition game (PCG) into an equivalent market share competition game (MSCG)
  - one-to-one correspondence between the market share & the prices
- Prove the existence of MSCG is a supermodular game
- Verify the uniqueness of MSCG satisfying the dominant diagonal condition
  - Holds for two schemes

Stage I: Commission Bargaining Solution

- Finding a feasible revenue sharing percentage (wholesale price) under RSS (WPS)
  - Both the database and the licensee achieve satisfactory payoffs
- Our solution: Nash Bargaining Solution
  - Key idea: The database and the licensee bargain for the revenue sharing percentage (wholesale price) under RSS (WPS) based on the Nash bargaining framework
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- Our results: There exists an optimal Nash Bargaining Solution
- **Our observations**
  - The database benefits from the positive network externality
  - The licensee benefits from the negative network externality

Summary

- Conclusion
  - We proposed a hybrid information and spectrum trading market
  - We characterized both the positive externality and negative externality of this hybrid market
  - We analyze the interaction and the optimal strategies of the database, the licensee, and WSDs

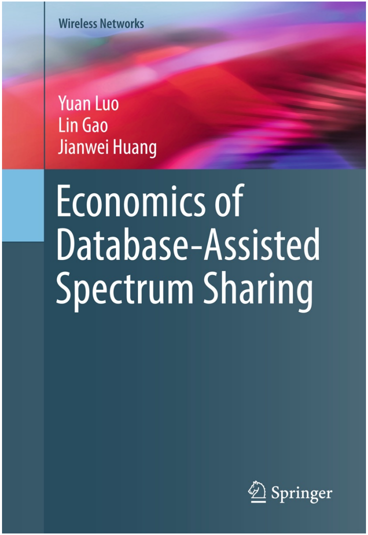
Conclusion

- **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**
  - Y. Luo, L. Gao, and J. Huang, "Business Modeling for TV White Space Networks", *IEEE Communications Magazine*, vol. 53, no. 5, pp. 82-88, May 2015.
- **Spectrum Trading Market**
  - Y. Luo, L. Gao, and J. Huang, "Spectrum Reservation Contract Design in TV White Space Networks", *IEEE Transactions on Cognitive Communications and Networking (Invited Paper)*, vol. 1, no. 2, pp. 147-160, June 2015.
  - Y. Luo, L. Gao, and J. Huang, "Price and Inventory Competition in Oligopoly TV White Space Markets", *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 5, pp. 1002-1013, October 2014
- **Information Trading Market**
  - Y. Luo, L. Gao, and J. Huang, "MINE GOLD to Deliver Green Cognitive Communications", *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 12, pp. 2749-2740, December 2015
- **Hybrid Spectrum and Information Trading Market**
  - Y. Luo, L. Gao, and J. Huang, "An Integrated Spectrum and Information Market for Green Cognitive Communications", *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 12, pp. 3326-3338, August 2016

Book



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