The Need for Dynamic Spectrum Distribution
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  - Unlicensed band → too crowded! 😞
  - Licensed band → long-term usage, pricy! 😞

GoogleWiFi Network
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- Dynamic spectrum distribution with spatial reuse

GoogleWiFi Network
“eBay in the Sky”
“eBay in the Sky”

Dynamically distribute spectrum via *auctions*
- Auctioneer auctions currently unused spectrum periodically
- Bidders bid for spectrum to match their needs
“eBay in the Sky”

Dynamically distribute spectrum via *auctions*

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• Key requirements:
  – Maximize spectrum distribution efficiency
    • Enabling spectrum reuse
  – Resist bidder cheating
A Closer Look at Bidder Cheating
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• Individual cheating
  – Change bid to gain unfair advantage
  – Solution: truthful spectrum auction designs
    • VERITAS [zhou08], TRUST[zhou09], [jia09]...
A Closer Look at Bidder Cheating

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• Collusion
  – Cheat in groups, improving the group’s utility
  – Popular in large-scale networks
    • Example: P2P networks
  – Few studies in dynamic spectrum auctions
Our Contributions

• Understand the impact of bidder collusion in dynamic spectrum auctions

• Propose a collusion-resistant design for large scale spectrum auctions
Outline

• Is bidder collusion a serious threat to spectrum auction?

• How to address bidder collusion?

• Evaluation

• Conclusion and future works
(Truthful) Spectrum Auctions 101
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- Must enable spatial reuse
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• VERITAS: A representative truthful spectrum auction
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(Truthful) Spectrum Auctions 101

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- Allocation
  - Bid-dependent greedy allocation
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• Must enable spatial reuse
• **VERITAS**: A representative truthful spectrum auction
• Allocation
  – Bid-dependent greedy allocation
• Pricing
  – **Critical neighbor**: for bidder $i$, if $i$ bids lower than its critical neighbor, then $i$ cannot win the auction; otherwise it wins.
An Illustrative Collusion Example

Channel

A

B

$5

C

$4

D

$3

$1

$5
An Illustrative Collusion Example

- Winner-Critical Neighbor (WCN) Collusion
  - B identifies critical neighbor C
  - B pays C to bid lower
  - B wins and pays ONLY $1
    → Improve (B, C)'s group utility
**An Illustrative Collusion Example**

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$\rightarrow$ *Improve (B, C)'s group utility*
An Illustrative Collusion Example

- **Winner-Critical Neighbor (WCN) Collusion**
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  \[
  \rightarrow \text{Improve (B, C)'s group utility}
  \]

\[
\text{Price(B)} = $1
\]
Impact of WCN Collusion

- Impact on auction revenue
  - 4000 bidders, 100 random rounds, WCN collusion
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Single Collusion group
Impact of WCN Collusion

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**Single Collusion group**

**Multiple Collusion groups**

![CDF Graph]

Normalized revenue loss (in log scale)

Up to 50% revenue loss!
• Is bidder collusion a serious threat to spectrum auction? – Yes, small-size bidder collusion is a huge threat

How to address bidder collusion?

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Our Methodology
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• **Prevention** rather than detection
  – ‘Needle in a hay’: hard to detect small size collusion group
  – Prevention $\equiv$ nullify collusion gain $\Rightarrow$ no gain, no collusion
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- **Soft prevention** rather than hard prevention
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  - Soft prevention $\equiv$ prob.(successful collusion) $< p$
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  - Hard prevention $\Rightarrow$ unbounded revenue loss
  - Soft prevention $\equiv$ prob.(successful collusion) $< p$

- **Soft prevention while enabling spectrum reuse**
  - Existing designs assume “all conflict” or “none conflicts”
  - Need new design
Athena Spectrum Auctions
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Enabling spectrum reuse
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Enabling spectrum reuse

- Form bidder segments
- Bidders in each segment do not conflict
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- **Diminishing collusion gain**
  - Tackle collusion within a segment
    - Use collusion-resistant design (tCP) to choose potential winners in each segment
Athena Spectrum Auctions

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- Tackle collusion within a segment
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- Tackle collusion across segments
  - Add *randomness* to winning segment selection
Enabling spectrum reuse

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Diminishing collusion gain

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- Tackle collusion across segments
  - Add randomness to winning segment selection
Divide

Conquer

Combine
Detailed Design

- Divide bidders into segments
- Bidders in each segment do not conflict
- Partition is bid-independent
Detailed Design

Divide

Conquer

Combine

Segment 1

Segment 2

Segment 1

Segment 2

...
Detailed Design

- For each segment $i$, select potential winners using a uniform price $p_i$
- tCP method$^1$: make $p_i$ insensitive to bid changes within segment $i$
  → no gain for intra-segment collusion

1: [goldberg03]
Detailed Design

- Estimate each segment’s revenue
- Choose winning segments based on estimated revenue
- Add randomness in revenue estimation to diminish the impact of inter-segment collusion
Detailed Design

- Divide
  - Estimate each segment’s revenue
  - Choose winning segments based on estimated revenue
  - Add randomness in revenue estimation to diminish the impact of inter-segment collusion

- Conquer
  - Combine

Segment 1

Segment 2

Segment 1

Segment 2

Final winners & prices

Estimated Revenue $

Estimated Revenue $
Summary

Divide
- Spatial reuse by bid-independent partition

Conquer
- Addressing collusion within segment

Combine
- Addressing collusion across segments
Athena’s collusion resistance

- \((t, p)\)-truthfulness: with probability \(\geq p\), no collusion group of \(\leq t\) bidders can improve group utility by collusion
  - Athena achieves \((t, p)\)-truthfulness, \(p\) depends on \(t\) and the #winners in the smallest segment
Fine-Tuning Athena

• **Segment sizes** affect the choice of the pricing scheme in ‘Conquer’ in order to maximize revenue given \((t, p)\)
  - Uniform segment sizes
  - Non-uniform segment sizes
    - Carefully select segments running tCP and their configurations

• Athena’s revenue bound
  - When all segments run tCP, the distance of Athena’s revenue to the optimal is a function of \(t, p, \text{and segment sizes}\)
• Is bidder collusion a serious threat to spectrum auction? – Yes, small-size bidder collusion is a huge threat

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• Conclusion and future works
Evaluating Athena
• **Challenge:** bidder behaviors are hard to model
Evaluating Athena

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- **Solution:** Combine theory and experiments
  - Theory proof for *any* bids;
  - Experiment with *typical* bid patterns;
Evaluating Athena

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- **Case study 1:** Effectiveness on resisting collusion
  - Can Athena diminish collusion group gain?
Evaluating Athena

- **Challenge**: bidder behaviors are hard to model
- **Solution**: Combine theory and experiments
  - Theory proof for *any* bids;
  - Experiment with *typical* bid patterns;

- **Case study 1**: Effectiveness on resisting collusion
  - Can Athena diminish collusion group gain?

- **Case study 2**: The cost of collusion resistance
  - How much revenue Athena needs to sacrifice for collusion-resistance?
  - Compare to VERITAS (truthful auctions)
Athena’s Collusion Resistance
Athena’s Collusion Resistance

• Experimental result \((t = 2, p = 0.9)\)
  – WCN collusion as an example

![Graph showing CDF of utility gain of each collusion group with two lines representing Athena and VERITAS.](image)
Athena’s Collusion Resistance

- Experimental result \( t = 2, \ p = 0.9 \)
  - WCN collusion as an example

![Graph showing CDF of utility gain of each collusion group with Athena and VERITAS comparing to no incentive, no collusion scenario.](image)
The Cost of Collusion-Resistance

Normalized revenue loss = \( 1 - \frac{\text{Revenue}}{\text{VERITAS revenue}} \)
The Cost of Collusion-Resistance

Normalized revenue loss = 1 - \( \frac{\text{Revenue}}{\text{VERITAS revenue}} \)

CDF

Normalized revenue loss

Athena(2, 0.8)  
Athena(2, 0.9)
The Cost of Collusion-Resistance

Normalized revenue loss  = 1 - \frac{Revenue}{VERITAS revenue}

10\% - 20\% revenue loss
The Cost of Collusion-Resistance

Normalized revenue loss = 1 - \( \frac{\text{Revenue}}{\text{VERITAS revenue}} \)
Conclusion and Future Works
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- **Small-size** collusion is harmful
  - Huge revenue degradation
  - Complex interference constraints amplify the impact
Conclusion and Future Works

- **Small-size** collusion is harmful
  - Huge revenue degradation
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- **Athena**: efficient collusion-resistant spectrum auction design
  - Utilizes *randomization* to diminish the collusion gain, enabling reuse
  - Customizable collusion-resistance
Conclusion and Future Works

• **Small-size** collusion is harmful
  – Huge revenue degradation
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• Athena: efficient collusion-resistant spectrum auction design
  – Utilizes **randomization** to diminish the collusion gain, enabling reuse
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• Future work
  – Extend to multi-channel request
  – Explore the optimal segment formation
• Thanks!

For more information, please visit:
http://link.cs.ucsb.edu/project/mercury.html
BACK-UP SLIDES
For all \((t, p)\)
Comparing to Posted Price

- Assuming no bidders collude due to the awareness of the design’s collusion resistance

\[
\text{Normalized revenue loss} = 1 - \frac{\text{Revenue}}{\text{VERITAS revenue}}
\]

10% ~ 100% revenue loss