Coopetition between LTE Unlicensed and Wi-Fi: A Reverse Auction with Allocative Externalities

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Background

- **Spectrum resources**
  - **Licensed spectrum**: network providers pay the government for licenses and use the spectrum *exclusively* (e.g., conventional LTE network)
  - **Unlicensed spectrum**: network providers *share* the spectrum without licenses (e.g., Wi-Fi network)

- **LTE unlicensed technology**
  - **Description**: operate the LTE network also in the *unlicensed spectrum*
  - **Reason**: limited *licensed spectrum* vs. explosive data growth
Key Challenge: Coexistence with Wi-Fi

Throughputs of LTE & Wi-Fi On Unlicensed Channel ©Nokia

- **Observations**
  1. LTE unlicensed has a **higher spectrum efficiency** than Wi-Fi;
  2. **Co-channel interference** decreases the throughputs of both networks, especially the throughput of Wi-Fi;
  3. Recent studies proposed **coexistence mechanisms** to achieve fair sharing between LTE and Wi-Fi, but cannot avoid inefficiency.

- **Problem:** How to avoid the throughput loss in LTE and Wi-Fi due to the co-channel interference between these two networks?
Why Not Avoid Interference Through Cooperation

Previous works studied LTE/Wi-Fi coexistence mechanisms (competition), and didn’t consider the cooperation between LTE and Wi-Fi.

**Competition**
LTE and AP share the same channel based on a coexistence mechanism (studied by previous works)

**Cooperation:**
LTE serves AP’s traffic in exchange for the exclusive use of the channel

Illustration for one AP case
Our LTE/Wi-Fi Coopetition Framework

- **Basic idea:** explore the potential benefits of cooperation before deciding whether to enter head-to-head competition.

- **Cooperation:** LTE exclusively uses the channel, and allocates some rate to AP’s traffic based on the agreement.

- **Competition:** LTE and AP share the channel based on a coexistence mechanism.

- **Challenge:** incomplete information complicates the coordination.
  - Each network’s (LTE or AP) throughput is its private information.

- **Mechanism:** Second-price reverse auction.
  - Will not reveal the private information of networks.
System Model

- We consider one LTE network and two APs (different channels)
  - Results can be generalized to the case with an arbitrary number of APs
- LTE network
  - $R_{LTE}$: throughput without interference
  - $\delta_{LTE} \in (0, 1)$: data rate discounting factor due to interference
  - $R_{LTE}$ and $\delta_{LTE}$ can be either known or unknown to the APs
- AP $k$ ($k = 1, 2$) occupies channel $k$
  - $r_k \in [r_{min}, r_{max}]$: throughput without interference, follows a general distribution with PDF $f(\cdot)$ and CDF $F(\cdot)$
  - $\eta^{AP} \in (0, 1)$: data rate discounting factor due to interference
  - $r_k$ is AP $k$’s private information;
    $r_{min}, r_{max}, f(\cdot), F(\cdot), \text{ and } \eta^{AP}$ are common knowledge
Second-Price Reverse Auction

- **Key idea**
  - LTE is the buyer (auctioneer), and APs are the sellers (bidders)
  - APs “sell” the exclusive access rights of their channels to LTE
  - LTE’s “payment” is the allocated data rate to the winning AP

- **Auction procedures**
  - **Stage I**: LTE announces the reserve rate $C$, i.e., the maximum rate that LTE is willing to allocate to the winner
  - **Stage II**: AP $k$’s submits its bid $b_k \in [0, C] \cup \{ "N" \}$:
    - if $b_k \in [0, C]$: AP $k$ sells its channel with an asking rate $b_k$
    - if $b_k = \{ "N" \}$: AP $k$ does not want to sell its channel

![Diagram showing the process of a second-price reverse auction with LTE as the buyer and APs as sellers.](image-url)
Second-Price Reverse Auction

Auction outcome:

- When \( b_1 = b_2 = \{ "N" \} \), LTE randomly picks channel \( i \) (\( i = 1, 2 \)) with an equal probability and coexists with AP \( i \) (competition).
- Otherwise, the AP with the lower bid becomes the winner, and sells its channel to the LTE with the second lowest rate from \( \{ b_1, b_2, C \} \) (cooperation).

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**Diagram:**
- LTE Provider (auctioneer & buyer)
- AP1 (seller)
- AP2 (seller)
- Bid \( b_1 \in [0, C] \cup \{ "N" \} \)
- Bid \( b_2 \in [0, C] \cup \{ "N" \} \)
- Reserve Rate: \( C \geq 0 \)

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Allocative Externalities in Our Auction

- Comparison with conventional auction
  - Conventional auction: if a bidder loses the auction, it does not care whether the other bidder wins the auction
  - Our auction: if an AP loses the auction, it is more willing to see the other AP winning rather than losing the auction

- Positive allocative externalities: the cooperation between LTE and an AP benefits the other AP

An Example Showing Allocative Externalities

Case A: AP2 wins the auction
Impact on AP1: AP1 **DOES NOT** interfere with LTE

If AP1 loses the auction

Case B: AP2 loses the auction
Impact on AP1: AP1 **MAY** interfere with LTE
Auction Analysis

- Two-Stage Structure
  Each network (LTE or AP) maximizes the data rate its users receive

<table>
<thead>
<tr>
<th>Stage I</th>
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<tbody>
<tr>
<td>LTE announces the reserve rate $C$</td>
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<table>
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<tr>
<th>Stage II</th>
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<tr>
<td>APs bid based on strategies $b(r_k, C)$</td>
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- Backward Induction
  - For Stage II, we characterize the APs’ unique symmetric equilibrium strategy $b^*(r_k, C)$ under the LTE’s reserve rate $C$ in Stage I
  - For Stage I, we characterize the LTE’s optimal reserve rate $C^*$ by anticipating APs’ equilibrium strategy $b^*(r_k, C)$ in Stage II
Stage II: APs’ Bidding $b^* (r_k, C)$ at Equilibrium

Results:

- $b^* (r_k, C)$ has **four different forms** based on the intervals of $C$
- As $C$ increases, more AP types are willing to cooperate with LTE

APs bid “N” with prob. 1

some AP types bid C

some AP types bid “N”

some AP types bid C

some AP types bid “N”

APs’ Equilibrium Bidding Based on Different Intervals of $C$
Stage II: APs’ Bidding $b^*(r_k, C)$ at Equilibrium

Unique feature due to allocative externalities

- **Description:** When $C \in \left(\frac{1+\eta_{AP}}{2} r_{min}, r_{max}\right)$, some AP types bid $C$
- **Reason**
  - Worst situation for these AP types: no AP wins the auction $\rightarrow$ bid from $[0, C]$ to guarantee the LTE can find someone to cooperate with
  - Best situation for these AP types: other AP wins the auction $\rightarrow$ bid the highest value, i.e., $C$, from $[0, C]$ to reduce the chance of winning
Stage I: LTE’s Optimal Reserve Rate $C^*$

- **Analytical results**
  - set $C^* \leq (1+\eta_{AP})r_{min}/2$ to compete with APs
  - search $C^*$ in $((1+\eta_{AP})r_{min}/2, R_{LTE})$ based on Golden Section method
  - search $C^*$ in $((1+\eta_{AP})r_{min}/2, r_{max})$ based on Golden Section method

- **Numerical results:** the LTE chooses a large $C^*$ when:
  1. the LTE has a large throughput ($R_{LTE}$);
  2. the LTE is heavily affected by the interference ($\delta_{LTE}$);
  3. the APs are not heavily affected by the interference ($\eta_{AP}$).

LTE’s Optimal Reserve Rate Based on Different Intervals of $R_{LTE}$

- LTE can’t satisfy any AP
- LTE can satisfy APs with small bids
- LTE can satisfy any AP
Conclusion and Future Work

**Conclusion**
- Proposal of the LTE/Wi-Fi coopetition framework
- APs’ equilibrium analysis in an auction with allocative externalities
- Characterization of the LTE’s optimal reserve rate

**Future work**
- APs use different channels → can use the same channel
  - Need to consider the interference among APs
- One LTE provider → multiple LTE providers
  - Need to consider the externalities among LTE providers