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

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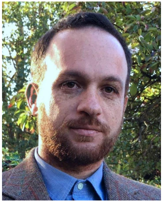
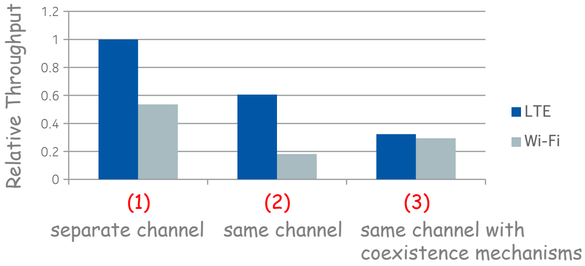


Background

- 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

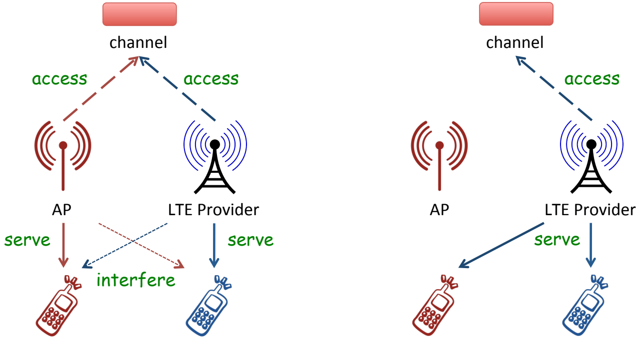


Throughputs of LTE & Wi-Fi On Unlicensed Channel ©Nokia

- 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.



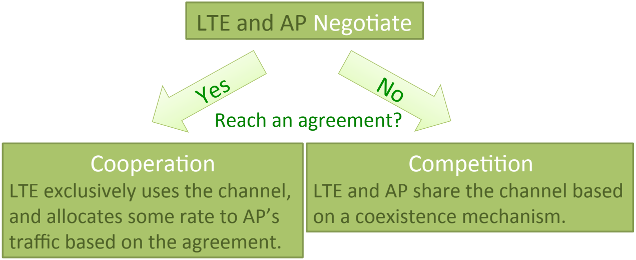
Competition
LTE and AP share the same channel based on a coexistence mechanism (studied by previous works)

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



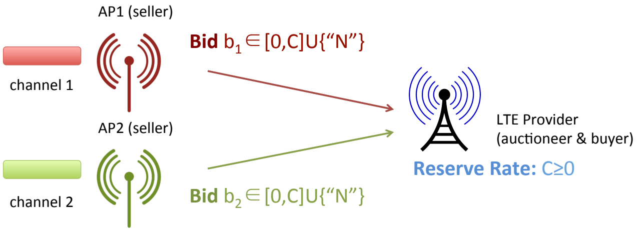
- Challenge: incomplete information complicates the coordination
  - Each network's (LTE or AP) throughput is its private information
- Mechanism: Second-price reverse auction
  - Will not reveal the private information of networks

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
  - $\delta^{\mathrm{LTE}} \in (0,1)$: data rate discounting factor due to interference
  - *R_{LTE} and δ^{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 $F(\cdot)$
  - $\eta^{\mathrm{AP}} \in (0,1)$: data rate discounting factor due to interference
  - *r_k is AP k's private information;*
    $r_{\min}, r_{\max}, f(\cdot), F(\cdot)$, and η^{AP} are common knowledge

Second-Price Reverse Auction

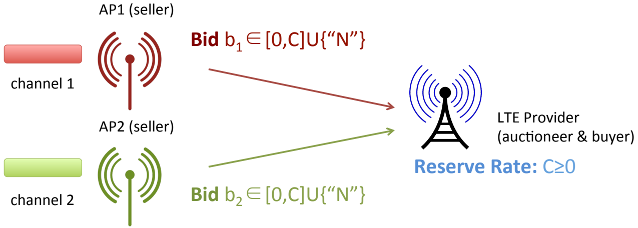
- Key idea
  - LTE is the buyer (auctioneer), and APs are the sellers (bidders)
  - APs "sell" the exclusive access rights of their channels to LTE
  - LTE's "payment" is the allocated data rate to the winning AP
- Auction procedures
  - Stage I: LTE announces the reserve rate C, *i.e.*, the maximum rate that LTE is willing to allocate to the winner
  - Stage II: AP k's submits its bid $b_k \in [0, C] \cup \{\text{“N”}\}$:
    - ★ if $b_k \in [0, C]$: AP k sells its channel with an asking rate b_k
    - ★ if $b_k = \{\text{“N”}\}$: AP k does not want to sell its channel



Second-Price Reverse Auction

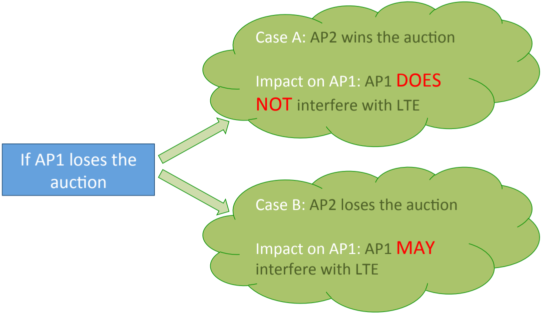
Auction outcome:

- When $b_1 = b_2 = \{\text{“N”}\}$, 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)



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

Auction Analysis

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

Stage I
LTE announces the reserve rate C

$$\Downarrow$$

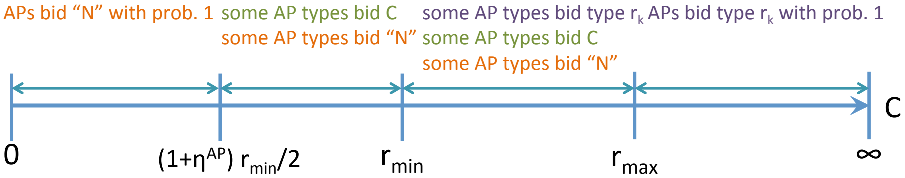
Stage II
APs bid based on strategies $b(r_k, C)$

- 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

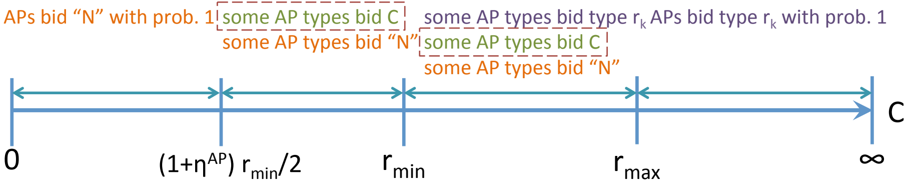


APs' Equilibrium Bidding Based on Different Intervals of C

Stage II: APs' Bidding $b^*(r_k, C)$ at Equilibrium

Unique feature due to allocative externalities

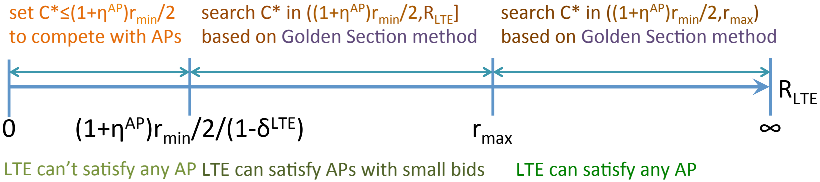
- Description: When $C \in \left(\frac{1+\eta^{\rm AP}}{2} r_{\min}, r_{\max}\right)$, some AP types bid C
- Reason
  - Worst situation for these AP types: no AP wins the auction $\rightarrow$ bid from $[0, C]$ to guarantee the LTE can find someone to cooperate with
  - Best situation for these AP types: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



APs' Equilibrium Bidding Based on Different Intervals of C

Stage I: LTE's Optimal Reserve Rate C^*

- Analytical results



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

- Numerical results: the LTE chooses a large C^* when:
  (1) the LTE has a large throughput (large R_{LTE});
  (2) the LTE is heavily affected by the interference (small δ^{LTE});
  (3) the APs are not heavily affected by the interference (large η^{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 $\rightarrow$ can use the same channel
    - Need to consider the interference among APs
  - One LTE provider $\rightarrow$ multiple LTE providers
    - Need to consider the externalities among LTE providers

THANK YOU

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