LTE in Unlicensed Spectrum

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Outline

Background

- The ever-increasing data rate requirement for 5G Networks.
- Some proposed techniques:
  - Massive MIMO,
  - Small cell,
  - Device-to-device communications.
- LTE in unlicensed spectrum (LTE-U)
  - Improve user experience for existing unlicensed devices.
  - Increase cellular operators' capacity.

Challenges

- Harmonious coexistence among different systems.
- Fair and efficient spectrum sharing unlicensed spectrum.
- Ensuring QoS for LTE traffic.

Outline

Introduction: Traffic offloading

- Using unlicensed bands to deliver cellular data traffic.
- How to guarantee QoS of cellular traffic?
  - No guarantee on QoS due to DCF protocol in WiFi (unlicensed) band.
  - Carefully selecting offloaded traffic to avoid saturation and excessive packet collisions.

Introduction: Resource sharing

- Transmitting cellular signals on the unlicensed spectrum.
- Advantages:
    - Higher spectrum efficiency
    - Better QoS
- Challenges: Effective resource sharing strategies for cellular and WiFi traffic.

Introduction: Existing works

Mobile data offloading

- Inter-network: Offloading cellular traffic to WiFi networks [K. Lee, IEEE Trans. Netw., 2013].
- Intra-network: Offloading macro base station traffic to femtocells [S. Yun, JSAC, 2012].

Resource sharing

- Joint radio resource management on licensed and unlicensed bands [A. R. Elsherif, JSAC, 2015].
- Resource management for energy efficiency LTE-U networks [Q. Chen, JSAC, 2016].

Introduction: Challenges

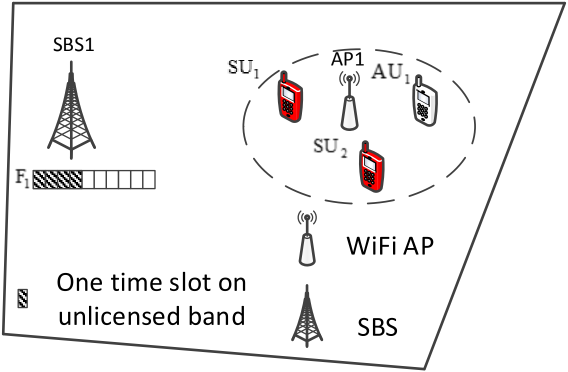
- Traffic offloading or resource sharing?
- Considering both?
- Strategy for LTE & WiFi networks.

Q. Chen, G. Yu, H. Shan, A. Maaref, G. Y. Li, and A. Huang, "Cellular meets WiFi: Traffic offloading or resource sharing," to appear in *IEEE Trans. Wireless Commun.*/also in *IEEE Globecom 2015*.

Three Different Methods

- Traffic offloading: SBS offloads some users to WiFi AP.
- Resource sharing: SBS occupies some time slots from WiFi AP.
- The hybrid method: SBS offloads some users to WiFi AP and occupies some time slots.

Single SBS & AP: System Model



N: WiFi user number in AP,

N^S: User number in SBS,

N^A: User number in AP.

WiFi Throughput

The saturation throughput of the WiFi network:

$$R(n) = \frac{P_{\mathrm{tr}} P_{\mathrm{s}} \mathbb{E}\left\{P\right\}}{\left(1 - P_{\mathrm{tr}}\right) \mathrm{T}_{\sigma} + P_{\mathrm{tr}} P_{\mathrm{s}} \mathrm{T}_{\mathrm{s}} + P_{\mathrm{tr}} \left(1 - P_{\mathrm{s}}\right) \mathrm{T}_{\mathrm{c}}},$$

- P_{tr}: probability that at least one transmission in a slot time.
- P_{s}: probability that a transmission is successful.
- T_{s}: average time that the channel is sensed busy because of a successful transmission.
- T_{c}: average time that the channel is sensed busy by each station during a collision.
- T_{σ}: duration of an empty slot time.
- $\mathbb{E}\left\{P\right\}$: average packet size.

G. Bianchi, "Performance analysis of IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535 - 547, Mar. 2000.

Single SBS & AP: Traffic Offloading

- Traffic offloading only: $L = 0$ (LTE occupies no WiFi time slots)

$$\max_{N} \frac{C^{\mathrm{S}}}{N^{\mathrm{S}} - N}$$

subject to

$$\frac{R\left(N^{\mathrm{A}} + N\right)}{\left(N^{\mathrm{A}} + N\right)} \geq R^{\mathrm{T}}$$

C^{S}: Average throughput of SBS on the licensed band.
R^{T}: The minimum per-user WiFi throughput.
L: Occupied time slots.

Results

- Average per-user throughput: $\frac{C^{\mathrm{S}}}{N^{\mathrm{S}} - \min\{N^*, N^{\max}\}}$[a].
- $N^{\mathrm{S}} - \min\left\{N^*, N^{\max}\right\}$: maximum offloaded user number.

[a] N^*: the largest integer satisfying $\frac{R\left(N^{\mathrm{A}}+N\right)}{N^{\mathrm{A}}+N} \geq R^{\mathrm{T}}$.

Single SBS & AP: Resource Sharing

- Resource sharing only: $N = 0$ (LTE offload no user to WiFi)

$$\max_{L} \frac{C^{\mathrm{S}} + C^{\mathrm{A}} L}{N^{\mathrm{S}}}$$

subject to

$$\frac{R\left(N^{\mathrm{A}}\right)(1-L)}{N^{\mathrm{A}}} \geq R^{\mathrm{T}}$$

C^{A}: Average throughput of SBS on the unlicensed band.

Results

- Average per-user throughput: $\frac{C^{\mathrm{S}}+C^{\mathrm{A}}L^*}{N^{\mathrm{S}}}$.
- $L^* = 1 - \frac{R^{\mathrm{T}}N^{\mathrm{A}}}{R(N^{\mathrm{A}})}$: maximum time slots to LTE.

Single SBS & AP: Hybrid method

- Consider both traffic offloading and resource sharing

$$\max_{N,L} \frac{C^{\mathrm{S}} + C^{\mathrm{A}} L}{N^{\mathrm{S}} - N}$$

subject to

$$\frac{R\left(N^{\mathrm{A}} + N\right)(1 - L)}{\left(N^{\mathrm{A}} + N\right)} \geq R^{\mathrm{T}}$$

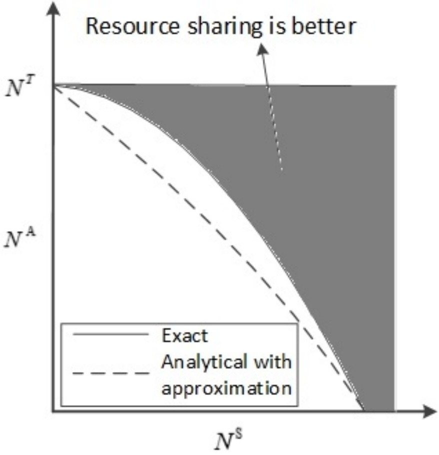
Results

- Maximum average per-user throughput

$$\max_{0 \leq N \leq N^{\max}} f(N) = \frac{C^{\mathrm{S}} + C^{\mathrm{A}} - \frac{C^{\mathrm{A}} R^{\mathrm{T}} \cdot \left(N^{\mathrm{A}} + N\right)}{R\left(N^{\mathrm{A}} + N\right)}}{N^{\mathrm{S}} - N}$$

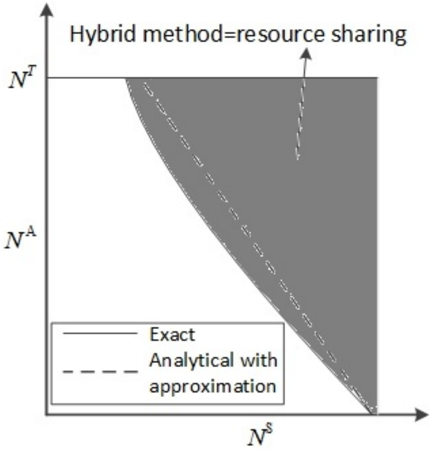
Traffic Offloading *vs* Resource Sharing

Traffic offloading performs better than resource sharing only if the number of existing users in WiFi is small enough.

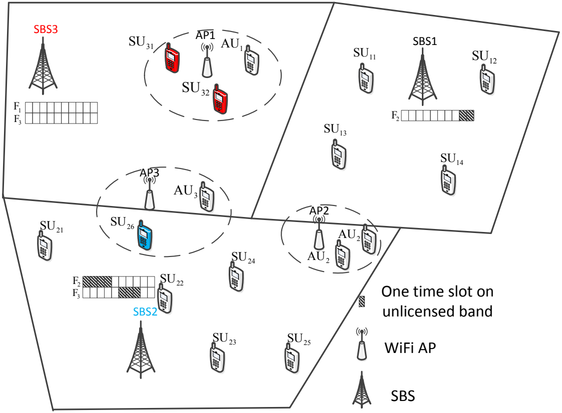


Hybrid Method *vs* Resource Sharing

When N^{A} is large enough, offloading users to WiFi is no longer necessary and the hybrid method is identical to the resource sharing.



Multiple SBSs & APs: System Model



M: number of SBSs,

K: number of WiFi APs,

N_k: WiFi user number in AP k.

N_m^S: LTE user number in SBS m,

N_k^A: LTE user number in AP k.

Multiple SBSs & APs: System Model

Assumptions

- SBSs and APs: located randomly according to the Poisson point process models.
- The WiFi network supporting the IEEE 802.11n protocol.

Goals

1. Maximizing the LTE throughput while guaranteeing the throughput of each WiFi user.
2. Maximizing the minimum average per-user throughput of LTE SBSs to ensure fairness.

Multiple SBSs & APs: Problem Formulation

Average per-user throughput among all SBSs:

$$\max_{\{N_{mk},L_{mk}\}} \min_{m} \left\{ \frac{C_m^{\mathrm{S}} + C_m^{\mathrm{A}} \sum_{k=1}^{K} L_{mk}}{N_m^{\mathrm{S}} - \sum_{k=1}^{K} N_{mk}} \right\}$$

subject to

$$\frac{R\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)\left(1 - \sum_{m=1}^{M} L_{mk}\right)}{\left(N_k^{\mathrm{A}} + \sum_{m=1}^{M} N_{mk}\right)} \geq R_k^{\mathrm{T}}, \ \forall k,$$

Minimum per-user WiFi throughput limitation.

$$N_{mk} \leq N_{mk}^{\max}, \ \forall m, k.$$

Maximum offloaded user number limitation.

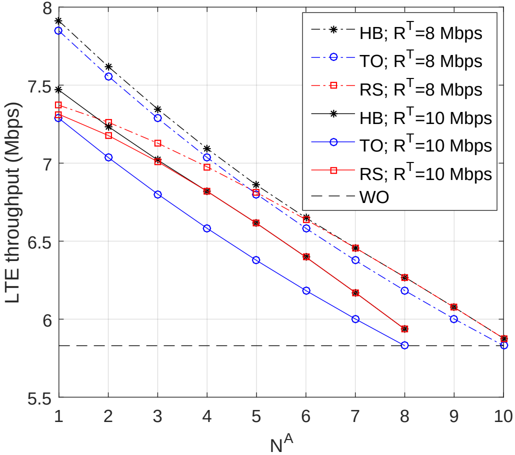
C_m^{S}: Average throughput of SBS m on the licensed band.

C_m^{A}: Average throughput of SBS m on the unlicensed band.

Simulation Parameters

Noise power	-95 dBm
Path loss model (Licensed, unlicensed)	$15.3 + \alpha \times 10\log_{10}(d)$ $\alpha = 3.75, 5$
Transmit power	20 dBm
$E[P]$	1500 byte
B^{S}, B	20 MHz, 20 MHz
$CW_{\min}$	16
$CW_{\max}$	1024
R_{limit}	6
WiFi channel bit rate	130 Mbps
PHY header	192 bits
MAC header	224 bits
T_δ	20 μs
SIFS	16 μs
DIFS	50 μs
Slot time	9 μs
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
L^{A}	100

Single SBS & AP: Performance



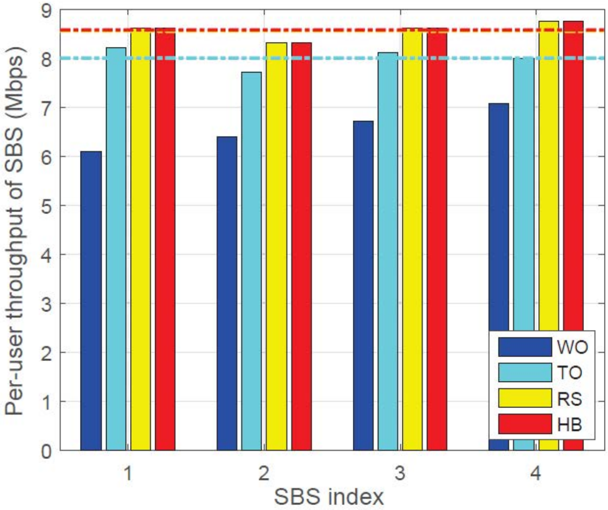
When WiFi user number is small:

- TO > RS.
- HB > {TO, RS}.

When WiFi user number is large:

- RS > TO.
- HB = RS.

Multiple SBSs & APs: Performance



- Dash line: Upper bound of each minimum SBS.
- Fairness: Almost the same performance for each SBS.

Conclusions

- Offloading LTE traffic to WiFi network.
- Sharing unlicensed spectrum with LTE.
- WiFi performance is degraded but a minimum threshold is guaranteed.

- Any win-win approach?

Outline

Traditional Data Offloading

- Traditional offloading: transferring cellular traffic to WiFi networks.
- The WiFi network: less spectral-efficiency due DCF & package collision.
- How about operating unlicensed spectrum by LTE?

Motivation: Novel Data Offloading

- Novel data offloading: Transferring WiFi users to LTE (opposite to traditional data offloading).
- Relinquishing more unlicensed spectrum to LTE.
- A win-win situation
  - Better QoS of the transferred WiFi users.
  - Better performance for the remaining WiFi users due to fewer packet collision.
  - More unlicensed spectrum with efficient management in LTE.

Q. Chen, G. Yu, A. Maaref, G. Y. Li, and A. Huang, "Rethinking mobile data offloading for LTE in unlicensed spectrum," to appear in *IEEE Trans. Wireless Commun.*/also in *IEEE WCNC 2016*.

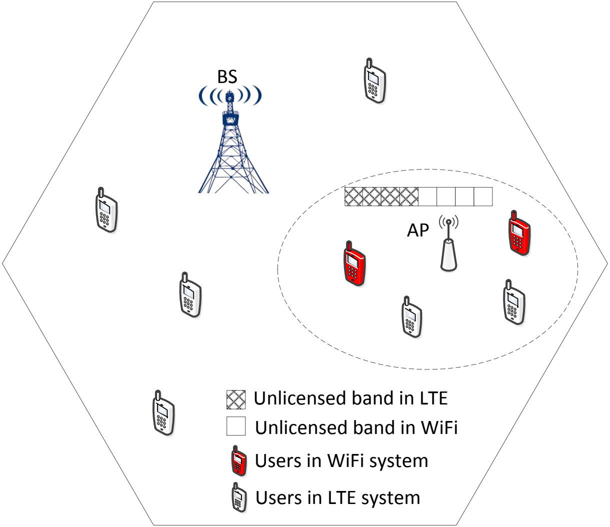
Challenging Issues

1. How many and which WiFi users to be transferred to the LTE network?
2. How much unlicensed resources to be relinquished to the LTE-U network?
3. What if there are many WiFi APs?

Three Different User Transfer Schemes

- Random transfer (RT): randomly selecting WiFi users to transfer.
- Distance-based transfer (DT): based on the distance between each WiFi user and SBS.
- CSI-based transfer (CT): based on CSI.

Single AP: System Model



Single AP: Problem Description

1. WiFi benefit (the improvement of per-user WiFi throughput): z^w.
2. LTE benefit for the leftover unlicensed time slots z^c.
3. Objective: balance the WiFi and LTE benefits.

The win-win problem

$$\max_{\{n,\rho\}} z^c z^w$$

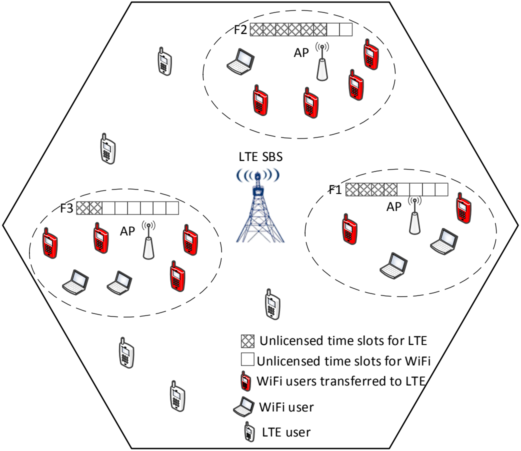
- n: Transferred user number,
- ρ: Relinquished unlicensed spectrum.

Single AP: Insights

Insights

- More WiFi benefit if more WiFi users are transferred.
- Less LTE benefit with more WiFi users transferred.
- The NBS strategy: balance between the two benefits.

Multi AP: System Model



K: number of WiFi AP.

L_k: distance between WiFi AP k and SBS.

N_k: WiFi user number in AP k.

Multi AP: Problem Description

1. WiFi benefit (the improvement of per-user WiFi throughput for AP k): z_k^w.
2. LTE benefit for the leftover unlicensed time slots z^c.
3. Objective: balance the WiFi and LTE benefits.

The win-win problem

$$\max_{\{n_k,\rho_k\}} z^c \prod_{k=1}^{K} z_k^w,$$

- n_k: Transferred user number from AP k.
- ρ_k: Relinquished unlicensed spectrum from AP k.

Multi AP: Insights

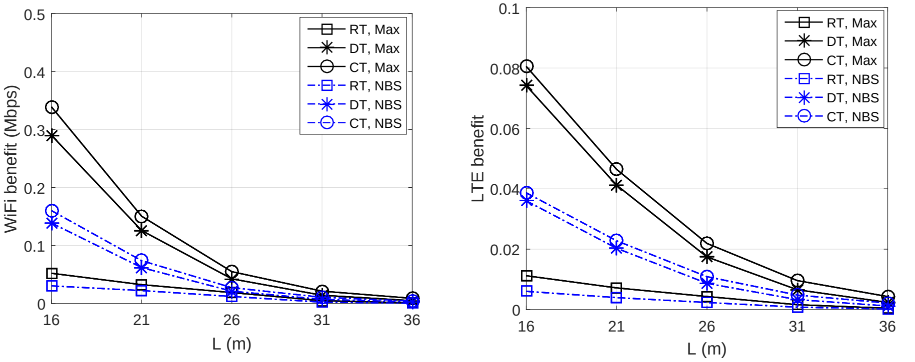
Fact 1

The WiFi APs near the SBS will transfer more users than those WiFi APs far away from the SBS.

Fact 2

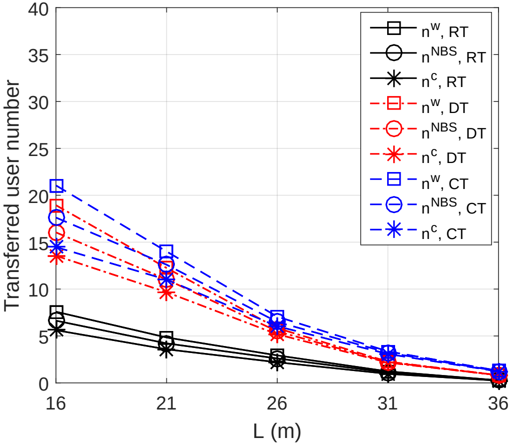
The optimal transferred users in the multi-AP case are in the range of $[n_k^c, n_k^w]$. (n_k^w and n_k^c are the user number that maximize the WiFi and LTE benefits, respectively.)

Single AP: Benefits for both WiFi and LTE



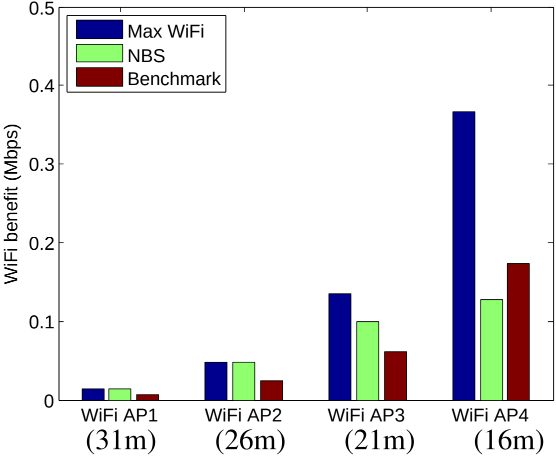
- The maximum WiFi (LTE) benefit is the upper bound for WiFi (LTE) benefit.
- The CT: the best performance.
- The RT: the worst performance.

Single AP: Transferred User Number



- The maximum WiFi benefit: the upper bound.
- The maximum LTE benefit: the lower bound.
- $n^c \leq n^{\text{NBS}} \leq n^w$: confirm Fact 2.

Multi AP: WiFi Benefit and Fairness



- Benchmark: Converting the K-dimensional searching into K 1-dimensional searching.
- WiFi AP closes to SBS achieves higher WiFi benefit.

Conclusions

- Transfer WiFi users and relinquish unlicensed resources to the LTE-U network (Subversively).
- Benefits both LTE and WiFi systems.
- The benefits: depend on the distance between APs and SBS, and the number of WiFi users in each AP.

Outline

Introduction

Licensed-assisted access (LAA):

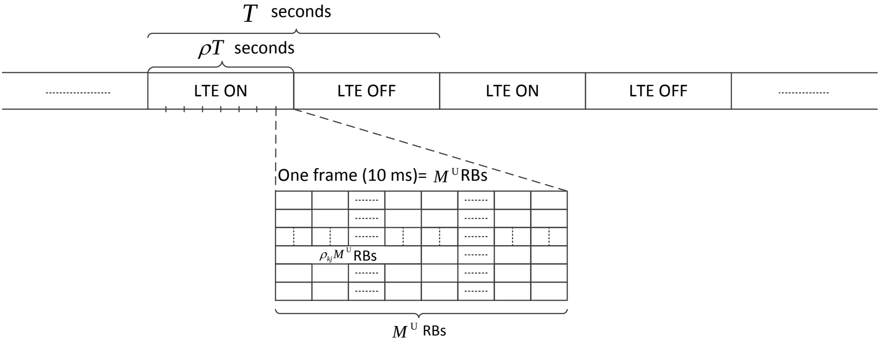
- Associating users with both licensed and unlicensed spectra under a unified LTE network infrastructure.

EE in LAA systems:

- May degrade EE of the LTE system.
- How to allocate resource blocks (RBs) to improve the EE?
- How to jointly allocate licensed and unlicensed RBs to achieve EE fairness among SBSs?

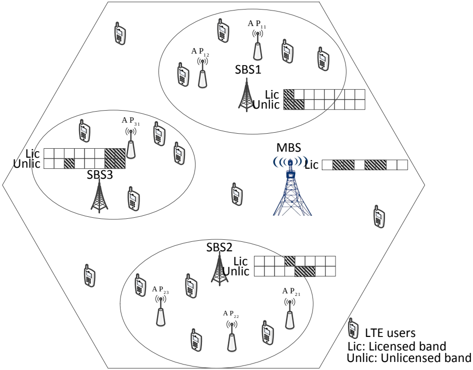
Q. Chen, G. Yu, R. Yin, A. Maaref, G. Y. Li, and A. Huang, "Energy efficiency optimization in licensed-assisted access," to appear in *IEEE J. Sel. Areas Commun.* also in *IEEE PIMRC 2015*.

The System Model for LAA



- LTE ON: for LTE.
- LTE OFF: for WiFi.

System Model



M^{L}: RB number in licensed band.

M^{U}: RB number in unlicensed band.

K: number of SBSs.

A_k: Number of WiFi access points in SBS k.

N_k: number of SBS users in SBS k.

ρ_{kj}: time slots on unlicensed band j occupied by SBS k.

EE Optimization

Energy efficiency of each SBS k:

$$\eta_k = \frac{\sum_{n=1}^{N_k} \alpha_{kn} R_{kn}^{\mathrm{L}} + \sum_{n=1}^{N_k}\sum_{j=1}^{A_k} \beta_{knj} R_{knj}^{\mathrm{U}}}{P_{\mathrm{s}}^{\mathrm{c}} + \varpi_{\mathrm{s}}^{\mathrm{L}} \sum_{n=1}^{N_k} \alpha_{kn} P_k^{\mathrm{L}} + \varpi_{\mathrm{s}}^{\mathrm{U}} \sum_{n=1}^{N_k}\sum_{j=1}^{A_k} \beta_{knj} P_{kj}^{\mathrm{U}}}$$

subject to

$$\sum_{k=1}^{K}\sum_{n=1}^{N_k} \alpha_{kn} \le M^{\mathrm{L}},$$ limitation of total RBs on licensed band

$$\sum_{n=1}^{N_k} \beta_{knj} \le \rho_{kj} M^{\mathrm{U}}, \forall k, j,$$ limitation of fair resource sharing on unlicensed band

$$\alpha_{kn} R_{kn}^{\mathrm{L}} + \sum_{j=1}^{A_k} \beta_{knj} R_{knj}^{\mathrm{U}} \ge R_n^{\min}, \ \forall n, k.$$ limitation of minimum data rate

P_k^{L}: transmit power on the licensed band. α_{kn}: RBs on licensed band.

P_{kj}^{U}: transmit power on the unlicensed band. β_{knj}: RBs on unlicensed band.

Properties of EE

- EE of each SBS increases with the licensed RBs.
- Don't use unlicensed bands if enough licensed ones.
- Improve EE by utilizing unlicensed bands only for small number of allocated licensed RBs.

Joint Licensed & Unlicensed Resource Allocation

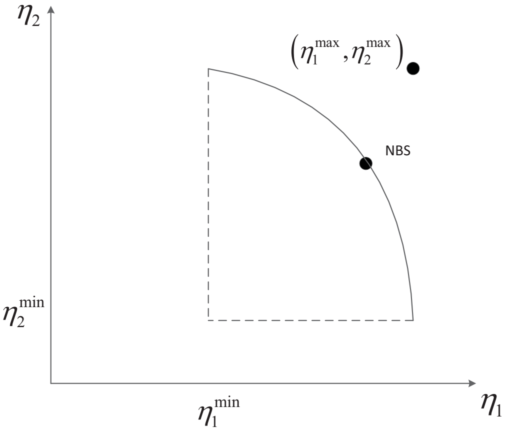
Maximize the EE for each SBS:

$$\boldsymbol{\eta}^{\max} = \max_{\{\boldsymbol{\alpha},\boldsymbol{\beta}\}} \left\{\eta_1, \eta_2, \cdots, \eta_K\right\},$$

Solutions

- Based on Weighted Tchebycheff method: Several Pareto optimal solutions.
- Based on Nash Bargaining Solution: Fair EE RB allocation algorithm.

Pareto optimal solution set *vs* NBS solution

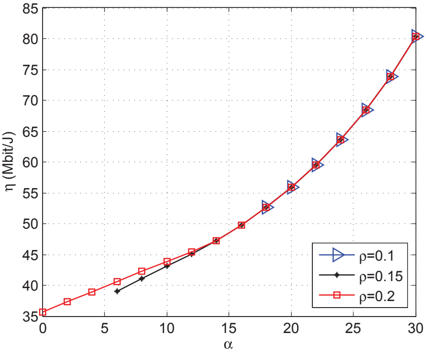


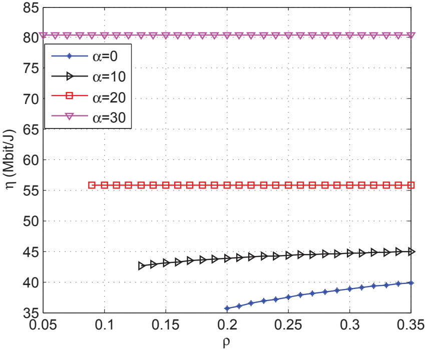
Results: The fair EE is also a Pareto optimal EE.

Simulation Results

Parameters	Settings
Noise power	-95 dBm (over 20MHz BW)
Path loss model Licensed Unlicensed	$15.3 + a \times 10\log_{10}(d)$ $a = 3.75$ $a = 5$
Transmit power P_{kj}^{U}, P_k^{L}	10 dBm, -3 dBm (per RB)
B^{L}, B^{U}	180 kHz, 180 kHz
ϖ_s^{L}, ϖ_s^{U}	$(35\%)^{-1}$, $(29\%)^{-1}$
M^{L}, M^{U}	100, 100
ϵ, Δ, ζ	0.05, 0.05, 0.05
$R_n^{\min}$	10 Mbps
P_s^c	27 dBm

Performance for Individual SBS

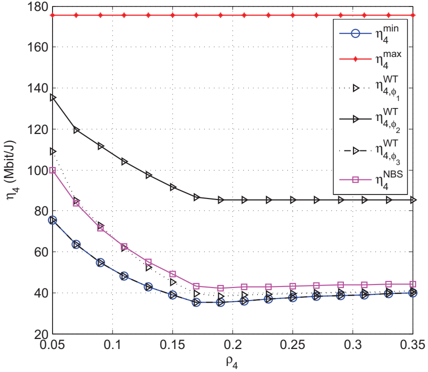




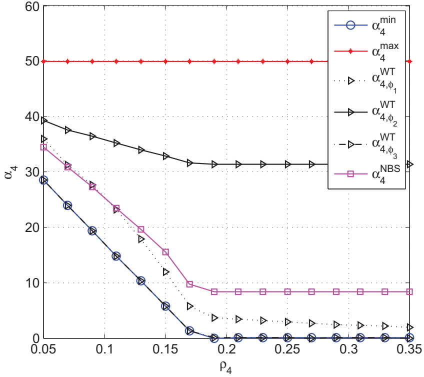
- EE increasing with licensed RBs (α).
- More unlicensed RBs, and higher EE for small α.
- EE saturated for large α.

Performance for Multiple SBSs

- EE *vs* time slots



- Licensed RB *vs* time slots



- More licensed RBs (α), and higher EE for each SBS (η).

Conclusions

- Improving the EE of a SBS when the licensed RBs are not enough.
- Achieving EE balance and fairness among different SBS.

Outline

Summary

1. Performance comparison for traditional traffic offloading and resource sharing.
   - Improve LTE performance, degrade WiFi performance.
2. Subversively, consider traffic offloading and resource sharing.
   - Win-win strategy.
3. Improve EE in LAA systems.