Optimizing Inter-operator Network Slicing over Licensed and Unlicensed Bands

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June 12, 2018
IEEE SECON 2018 Conference
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5G Challenge 1: Wireless Resource Crisis

- The mobile data traffic has grown 18-fold over the past 5 years, will exceed half a zettabyte by 2020
- The spectrum allocated for cellular services has only increased 2.8 times over the past 30 years
- We are now facing Wireless Resource Crisis!!!
**5G Challenge 2: Operational Cost**

- Mobile broadband cost per bit decreases exponentially with each generation of technological advancement.
- Reduction in transport cost-per-bit must be matched by lower cost of operation.
- The cost of 5G is set to exceed $8 billion in capital investments for a single operator. This does not include the price to be paid for auctioning new 5G bands including 600MHz low-band, 3.5 GHz mid-band, and mmWave bands.
- Operators will have to pay more to deploy 5G network than they paid for 4G network to achieve the same footprint.
5G Challenge 3: Diverse Services, Use Cases, Applications

- **Massive MTC (IoT)**
  - $/Yr/Device; Low power;

- **Network Operations**
  - Low cost operations;

- **UR-LLC (Mission Critical Services)**
  - $$$$$$/Yr/Device
  - Low latency; Reliability

- **eMBB**
  - $$$/Yr/Device
  - High bandwidth

- **Vehicular**
  - (telemetry, driver assist, autonomous, etc.)
  - $$$$/Yr/Device; High mobility

Source: 3GPP SMARTER
Solution: Evolution of Network Architecture

- Wireless network architecture has been evolved from silos over monoliths towards slices
- **Slice-as-a-service** is a key enabling technology for 5G

Source: CONFIG Consortium
Network Slicing

**Definition:** Logical resource partitions (e.g., infrastructure, spectrum, etc.), orchestrated according to different service requirements

Slicing offers:
- QoS guarantees (by isolating and reservation resources for each slice)
- Simplicity: Only required functionality provided for each use case
- Flexibility: Supports location-dependent diversity in configurations and RATs

CP: Central processor
UP: Unit processor
RAT: Random access technology

Source: NGMN 5G white paper
Key Contributions

Network Slicing in Licensed Band:
• Propose an inter-operator spectrum aggregation approaches for MNOs to orchestrate the shared licensed spectrum

Network Slicing in Unlicensed Band:
• Introduce the concept of Value-of-Right (VoR) to quantify the benefit of MNOs in the unlicensed band
• Propose a modified back-of-the-envelop (mBoE) method for each MNO to estimate VoR

Network Slicing over Licensed and Unlicensed Band:
• Develop a network slicing game to investigate the complex interaction when MNOs can slice both licensed and unlicensed bands
• Prove the core of network slicing game is non-empty and any outcome in the core maximizes the social welfare

Performance Evaluation
• Develop a C++-based event simulator to simulate the contention between LTE-LAA and Wi-Fi
• Simulate the potential implementation using real BS location data in the city of Dublin deployed by two major operators in Ireland
• Each MNO has $B_i$ exclusive bandwidth of licensed band and can support a set $\mathcal{Y}$ of $Y$ types of services for each UE.
• Each MNO divides its licensed band into a set of subcarriers each of which can be allocated to support a single type of service, i.e., $w_i^{(l)}$ is the set of subcarriers allocated by MNO $i$ to support $l$ type of service.
• Multiple MNOs can share their portions of licensed band allocated to the commonly supported services, e.g., combined spectrum shared by a group of MNOs for type $l$ service is $w^{(l)} = \sum_{i \in \mathcal{G}(l)} w_i^{(l)}$. 

Group of spectrum sharing MNOs supporting the same type $l$ service.
Optimizing Network Slicing in Licensed Band

- Each type of service has a min QoS (e.g., throughput $\eta_{i}^{(l)}$) that must be guaranteed to each UE
- Total spectrum shared by a group of MNOs for serving type $l$ service
- Each MNO $i$ tries to optimize the utility sum of all types of service provided to its UEs

Utility obtained from serving type $l$ service for the $k$th UE of MNO $i$

$$\max_{w_{i}} \sum_{k \in \mathcal{L}_{i}} \sum_{l \in \mathcal{Y}} \pi_{k,i}^{(l)}$$

s.t.  
$$\sum_{l \in \mathcal{Y}} w_{i}^{(l)} \leq B_{i} \quad \text{and} \quad d_{k,i}^{(l)} R_{k,i} \sum_{i \in \mathcal{C}(l)} w_{i}^{(l)} \geq \eta_{i}^{(l)}$$

where  
$$\pi_{k,i}^{(l)} = \rho_{i}^{(l)} d_{k,i}^{(l)} w^{(l)} R_{k,i}$$

Price per data rate charged by MNO $i$

Group of spectrum sharing MNOs supporting the same type $l$ service

Transmission rate per Hz of the $k$th UE of MNO $i$
Unlicensed band is open to all wireless access technologies, e.g., LAA and Wi-Fi.

Both LAA and Wi-Fi follow listen-before-talk (LBT)-based channel access mechanism.

Even the probability of channel access is high, there is still a small chance that an LTE UE or BS cannot send any data packet on the unlicensed band.
Right Sharing in Unlicensed Band

- MNOs have equal rights to access the unlicensed band
- Each MNO can share its spectrum access right with other MNOs
- **Definition (Value-of-Right (VoR))**: 
  - Benefit that can be obtained by each MNO for accessing the unlicensed band
  - Different MNOs can observe different VoRs. The MNOs that can obtain higher benefits in the unlicensed band will less likely to give up their rights in the unlicensed band compared to others
  - Compensation to MNO $i$ for another MNO $j$ to give up the right to access unlicensed band is closely related to the benefit that can be obtained by MNO $i$ when the UEs and BSs associated with MNO $j$ stop accessing the unlicensed band
  - When an individual MNO stop accessing the unlicensed band, all the other co-located MNOs can benefit from the reduction of channel contending UEs and BSs

- In this paper, we consider the case that an MNO's VoR corresponds to the channel access probabilities of its associated UEs
VoR Estimation: mBoE

- Propose the mBoE, a simple method for each MNO to pre-evaluate the probability of access for each of its links

- **Contention graph** is a graphical model characterizing the possible contention among all the intra- and inter-operator links as well as channel contentions from other coexisting wireless technologies such as Wi-Fi

- **Definition:** A *contention graph* $G = \langle V, E \rangle$ comprises
  - Set $V$ of vertices corresponding to the set of all the coexisting links connecting UEs and BSs associated with all the MNOs as well as the coexisting Wi-Fi links
  - Set $E$ of edges each of which connects two vertices that can sense the existence of each other.

- **Definition:** *Contention subgraph* associated with MNO $i$ as the subgraph $G_i$ of $G$ comprising subsets of vertices and edges corresponding to communication links that are only associated with MNO $i$ as well as their sensed entities of other MNOs and Wi-Fi systems.
VoR Estimation: mBoE method

- **Definition**: An *independent set* associated with MNO $i$ is a set of vertices in $G_i$ in which no two of which are adjacent. A *maximum independent set* for MNO $i$ is an independent set with the largest possible size for graph $G_i$.

- **Proposition**: A CSMA-based system spends most of its time in the maximum independent sets and very little time in other states.

VoR Estimation Procedures for each MNO

1. Generate a contention subgraph $G_i$ in unlicensed band using the sensing results from the UEs and BSs of MNO $i$.
2. Each MNO $i$ identifies the possible maximum independent sets of $G_i$.
3. Each MNO $i$ generates a modified subgraph $G_i'$ by removing all the vertices that are not associated with any maximum independent set from $G_i$.
4. Each MNO $i$ searches for the probability of channel access $\xi_{k,i}$ for each link $k$ from a pre-stored contention subgraph table.

![Empirical Contention Subgraph Table obtained from our CSIM Simulator](image)

<table>
<thead>
<tr>
<th>Contention Graph</th>
<th>Probability of Access</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.659, 0.341)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.914, 0.067, 0.914)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.979, 0.010, 0.979)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.977, 0.005, 0.968)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.978, 0.003, 0.976)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.418, 0.162, 0.418)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.229, 0.540, 0.229)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.181, 0.181, 0.181, 0.456)</td>
</tr>
<tr>
<td><img src="image" alt="contention graph" /></td>
<td>(0.141, 0.141, 0.358, 0.358)</td>
</tr>
</tbody>
</table>

[Image of urban region and BSs]

- City of Dublin consisting of BSs deployed by two major MNOs in Ireland as well as Wi-Fi APs.
- Each MNO can detect the contention from other MNOs, it can also estimate the possible improvement of the channel access probability if one or more other MNOs stop accessing the unlicensed band.
- We define the estimated contention subgraph replacing graph $G_i$ with $h_i$. We write the vector for the probability of access for all links associated with MNO $i$ as $\xi_i = (\xi_{1,i}, \xi_{2,i}, \ldots, \xi_{m,i})$.

![Empirical Contention Subgraph Table obtained from our CSIM Simulator](image)

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[Table of contention subgraphs and the corresponding probabilities]
Example and Performance Validation

Fig. 2. Table of contention subgraphs and the corresponding probability of access measured by our CSIM simulator.

Fig. 3. List of notations.

Fig. 4. Use mBoE to calculate the probability of access in an urban environment: (a) real locations of the BSs, (b) abstracted contention graph, and (c) channel access probability estimated from our proposed mBoE method compared with the real probabilities generated by our CSIM simulator.

<table>
<thead>
<tr>
<th></th>
<th>CSIM Verif.</th>
<th>mBoE Estim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNO1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>0.3228</td>
<td>0.333</td>
</tr>
<tr>
<td>O2</td>
<td>0.3192</td>
<td>0.333</td>
</tr>
<tr>
<td>O3</td>
<td>0.4902</td>
<td>0.5</td>
</tr>
<tr>
<td>O4</td>
<td>0.4959</td>
<td>0.5</td>
</tr>
<tr>
<td>O5</td>
<td>0.4923</td>
<td>0.5</td>
</tr>
<tr>
<td>O6</td>
<td>0.4938</td>
<td>0.5</td>
</tr>
<tr>
<td>MNO2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1</td>
<td>0.3450</td>
<td>0.333</td>
</tr>
<tr>
<td>V2</td>
<td>0.9828</td>
<td>1</td>
</tr>
<tr>
<td>V3</td>
<td>0.9828</td>
<td>1</td>
</tr>
<tr>
<td>V4</td>
<td>0.659</td>
<td>0.659</td>
</tr>
<tr>
<td>V5</td>
<td>0.9825</td>
<td>1</td>
</tr>
<tr>
<td>Wi-Fi</td>
<td>W1</td>
<td>0.341</td>
</tr>
</tbody>
</table>
Optimizing Network Slicing in Unlicensed Band

- Channel access probability for link $k$ of MNO $i$ is $\xi_{k,i}$
- Each MNO can distribute the channel access of each link according to the QoS of the supported types of services
- Each MNO $i$ allocates $\alpha_{k,i}^{(l)}$ portion of the channel access probability that is allocated to support type $l$ service at link $k$ of MNO
- Each MNO tries to maximize its benefit in the unlicensed band

Utility obtained from serving type $l$ service for the $k$th UE of MNO $i$ in unlicensed band

$$\max_{\alpha_i} \sum_{k \in \mathcal{L}_i} \sum_{l \in \mathcal{Y}} \nu_{k,i}^{(l)}$$

s.t. $\sum_{l \in \mathcal{Y}} \alpha_{k,i}^{(l)} = \xi_{k,i}$ and $\alpha_{k,i}^{(l)} B^{(u)} R_{k,i} \geq \eta_{i}^{(l)}$, $\forall k \in \mathcal{L}_i$

Channel access probability when a set $D$ of MNOs stops accessing unlicensed band
Optimizing Network Slicing over Licensed and Unlicensed Bands

Utility obtained from serving type \( l \) service for the \( k \)th UE of MNO \( i \) in unlicensed band

\[
\max_{w_i, \alpha_i} \sum_{k \in \mathcal{L}_i} \sum_{l \in \mathcal{Y}} w_{k,i}^{(l)}
\]

s.t.
\[
\sum_{l \in \mathcal{Y}} \alpha_{k,i}^{(l)} = \xi_{k,i} \quad \text{and} \quad \sum_{l \in \mathcal{Y}} w_{i}^{(l)} \leq B_i,
\]

\[
(d_{k,i}^{(l)} \sum_{i \in \mathcal{C}^{(l)}} w_{i}^{(l)} + \alpha_{k,i}^{(l)} B(u)) R_{k,i} \geq \eta_{i}^{(l)}.
\]

where \( \omega_{k,i}^{(l)} = \pi_{k,i}^{(l)} + \nu_{k,i}^{(l)} \)

**Challenge:** If each MNO is given the choice to slice both licensed or unlicensed bands, the interaction between MNOs becomes very complex

- if an MNO cannot (or can) secure enough licensed spectrum, it becomes more (or less) aggressive and willing to pay more (or sell its right) to other MNOs
Network Slicing Game

Game setup
Players: MNOs
Resources: Licensed & unlicensed spectrum available to MNOs
Service types: QoS guarantees provided to various slices (\# of types = \# of slices)
Reward: Profit obtained by serving users of various types

Interactions among MNOs
- Each MNO evaluates required accessible resources based on received service demands
- MNOs negotiate to distribute their accessible spectrum
- Once an agreement has been reached, MNOs coordinate network slicing through a software-defined mobile network controller
Core and Main Result

Definition (Core):
Given a network slicing game $A = \langle M, B, Y, \pi \rangle$ and a subset of MNOs $N \subseteq M$. Suppose $\langle c, x \rangle$ and $\langle c', x' \rangle$ are two network slicing agreements such that for any slice $c(l) \in c$ either $\text{supp}(c(l)) \subseteq N$ or $\text{supp}(c(l)) \subseteq M \setminus N$. We say that network slicing agreement $\langle c', x' \rangle$ is a profitable deviation of $N$ from $\langle c, x \rangle$ if for all $j \in N$, we have $\pi_j (c', x') > \pi_j (c, x)$. We say that a network slicing agreement $\langle c, x \rangle$ is in the core of $A$ if no subset of $N$ has a profitable deviation from it.

Core is the set of stable network slicing structure in which no MNO can benefit from unilateral deviation

Main Result:
• Network slicing game is convex
• The core of the game is non-empty and any outcome in the core maximizes the social welfare
Simulation

Fig. 5. Distribution of BSs deployed by two major MNOs as well as Wi-Fi hotspots deployed at Starbucks in the city of Dublin.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi traffic class</td>
<td>Voice (AC = VO)</td>
</tr>
<tr>
<td>LAA traffic class</td>
<td>Voice (PC = 1)</td>
</tr>
<tr>
<td>PHY rate</td>
<td>52 Mbps</td>
</tr>
<tr>
<td>Unlicensed bandwidth</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Transmission power</td>
<td>23 dBms</td>
</tr>
<tr>
<td>LAA noise floor</td>
<td>−100 dBm</td>
</tr>
<tr>
<td>Wi-Fi noise floor</td>
<td>−90 dBm</td>
</tr>
<tr>
<td>Path Loss Model</td>
<td>$43.3 \log(d) + 11.5 + 20 \log(f_c)$</td>
</tr>
<tr>
<td>Wi-Fi CCA threshold</td>
<td>−62 dBm</td>
</tr>
<tr>
<td>LAA CCA threshold</td>
<td>−62 dBm</td>
</tr>
</tbody>
</table>
Simulation

Setup:

Two MNOs
Two types:
- Rate demand for Type 1 = 1 Mbps
- Rate demand for Type 2 = 25 Mbps

Unlicensed band = 20 MHz
Licensed band for each MNO = 10 MHz
Access technology: LTE LAA
Admitted traffic ~ Shannon’s capacity

Calculated from the average deployment densities of BSs in 9 areas from city center to rural area
Simulation
Conclusion and Future Work

• Propose an *inter-operator spectrum aggregation* approaches for MNOs to orchestrate the shared licensed spectrum

• Introduce the concept of *VoR* for MNOs to share their access rights in the unlicensed band

• Propose an *mBoE* method for each MNO to estimate the VoR

• Develop a *network slicing game* to investigate the complex interaction when MNOs can slice both licensed and unlicensed bands

• Develop a C++-based event simulator to simulate the contention between LTE-LAA and Wi-Fi

• Simulate the potential implementation using real BS location data in the city of Dublin deployed by two major operators in Ireland

• Develop simple distributed algorithm that can implemented in existing 3GPP architecture

• Develop dynamic network slicing protocols for time-varying (mobile UEs, time-varying traffic models, etc.) environment
Thank You