COLLEGE OF ENGINEERING
Electrical & Computer Engineering

Optimizing Inter-operator Network Slicing over Licensed and Unlicensed Bands

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Outline

- Introduction
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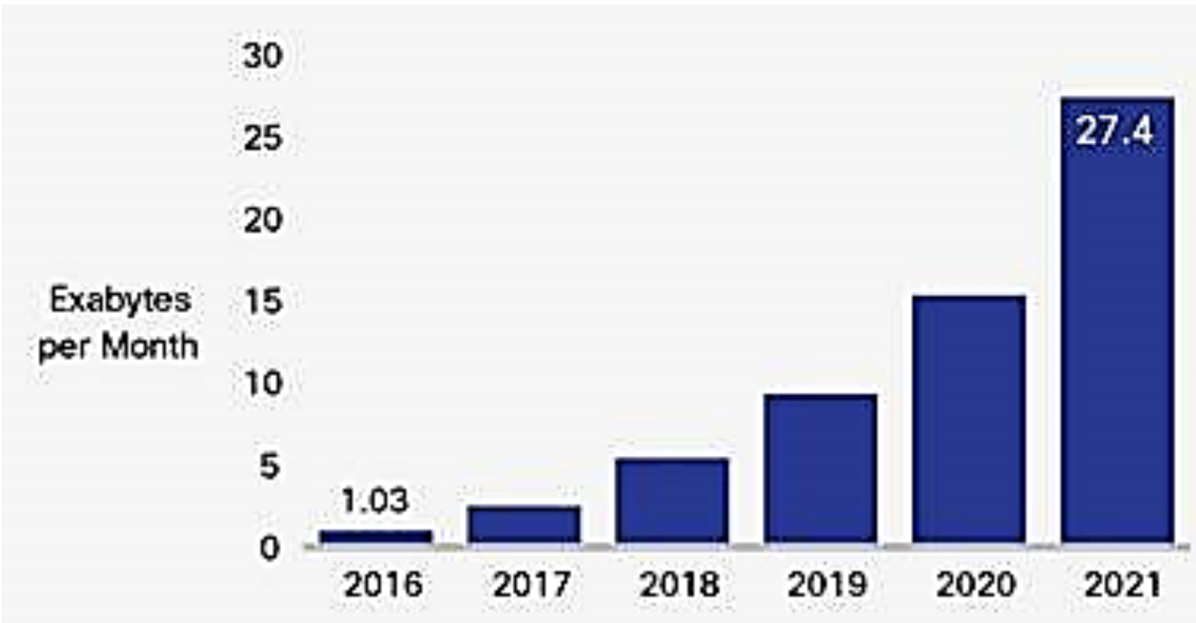
  - Network Slicing over Licensed & Unlicensed Bands
- Network Slicing Game
- Simulation Results
- Conclusion and Future Work

5G Challenge 1: Wireless Resource Crisis



Sources: Cisco Network Index

Sources: Go-Globe.com

- 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!!!**

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18 Dec 2014 12:35 PM

Wireless industry calls on Governments to release more spectrum for mobile broadband

By James

Speakers ahead un

The New York Times

TECHNOLOGY

Carriers Warn of Crisis in Mobile Spectrum

By BRIAN X. CHEN

AT&T, Verizon, T-M they need more rad government-ration

The New York Times

TECHNOLOGY

European Mobile Stocks Fall After Costly Spectrum Auction

By KEVIN J. O'BRIEN DEC. 17, 2012

BERLIN — Shares of four big European cellphone operators fell Monday after they paid more than twice what investors had been expecting in a spectrum auction in the Netherlands, raising concern that a damaging bidding war could sap the industry.

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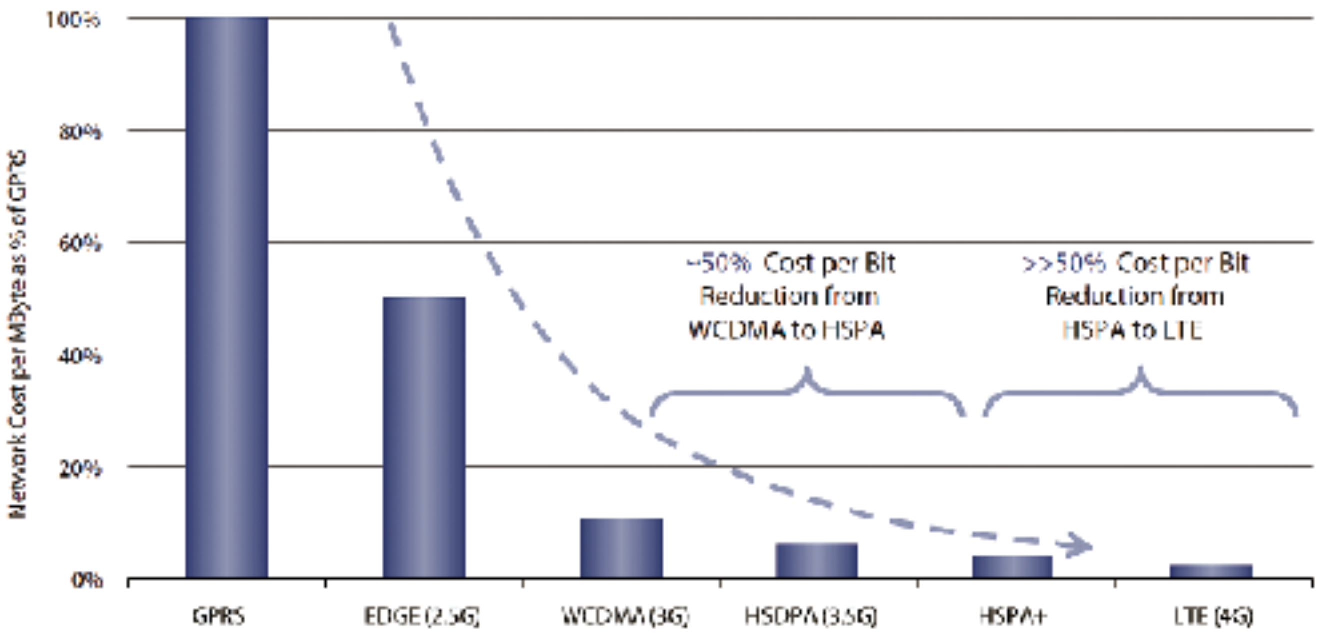
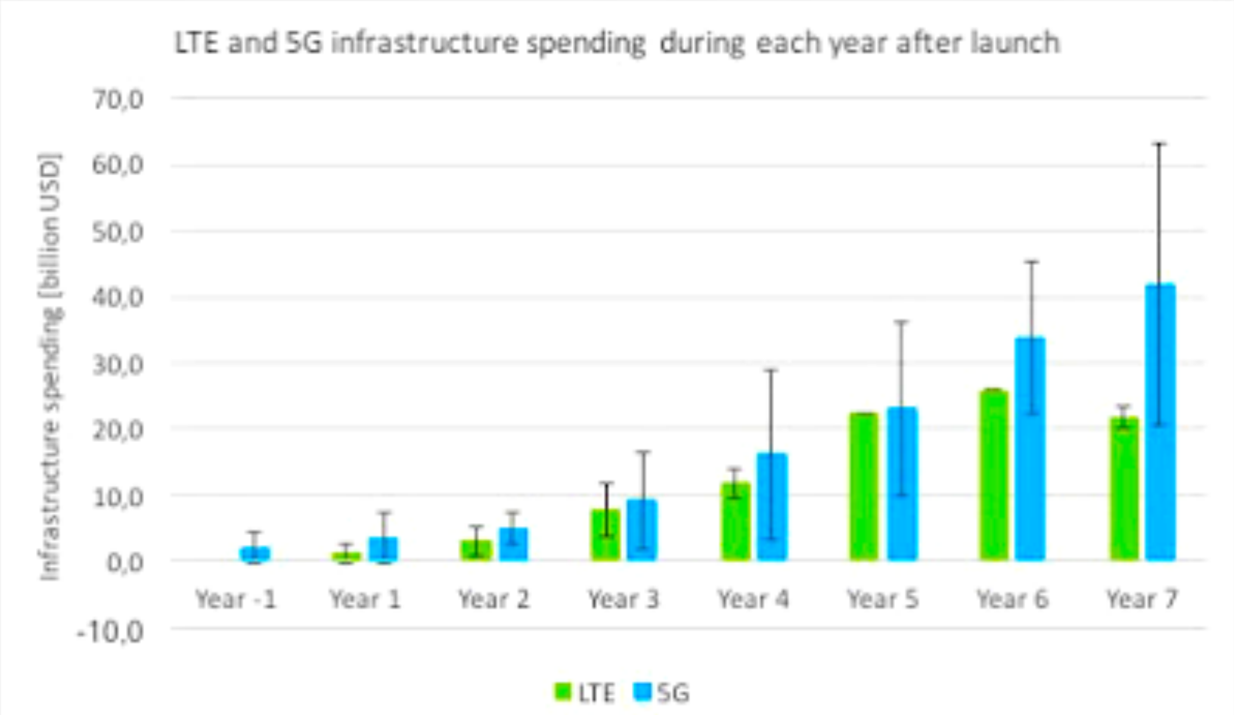
5G Challenge 2: Operational Cost



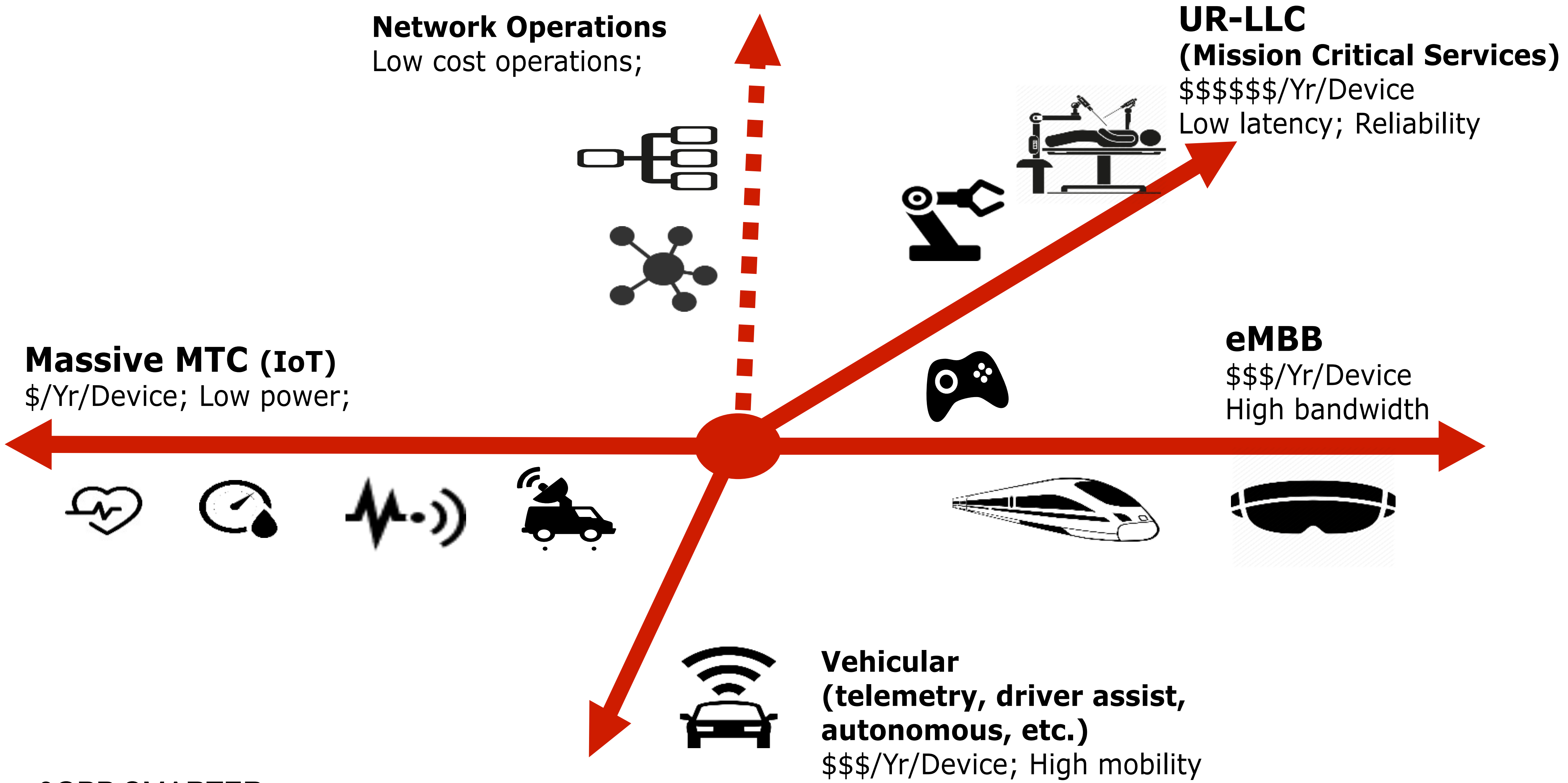
Source: Wavelengths Magazine



Sources: spectrumfutures.org

- 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

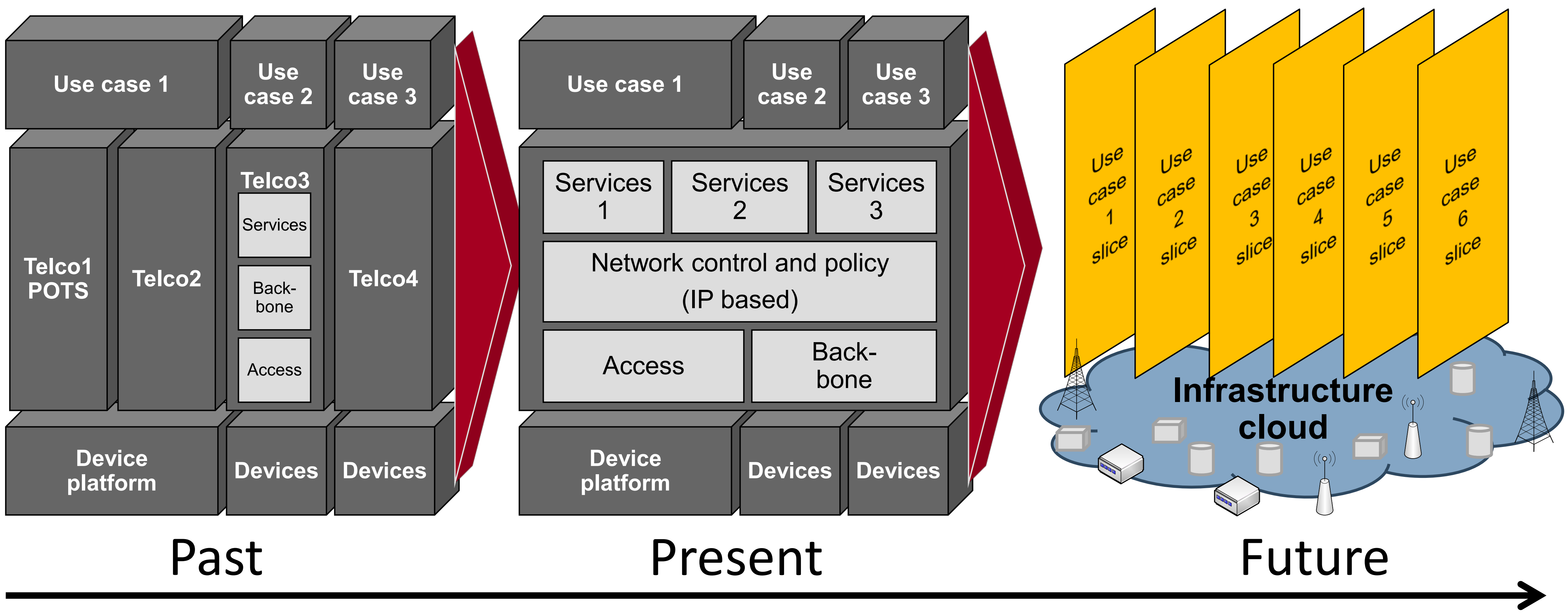
5G Challenge 3: Diverse Services, Use Cases, Applications



Source: 3GPP SMARTER

Solution: Evolution of Network Architecture

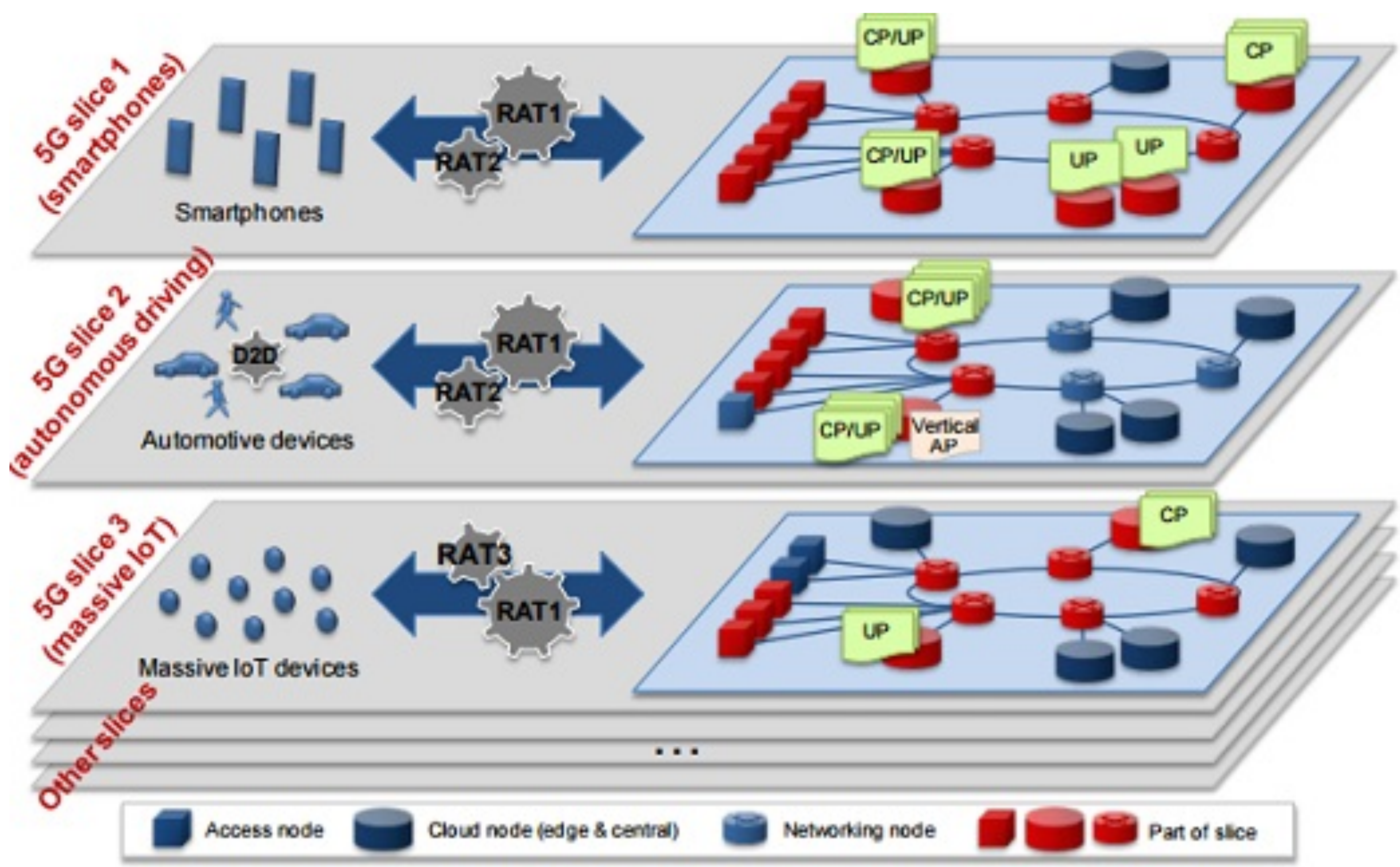
- Wireless network architecture has been evolved from silos over monoliths towards slices
- Slice-as-a-service is a key enabling technology for 5G



Source: CONFIG Consortium

Network Slicing

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



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

Source: NGMN 5G white paper

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

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

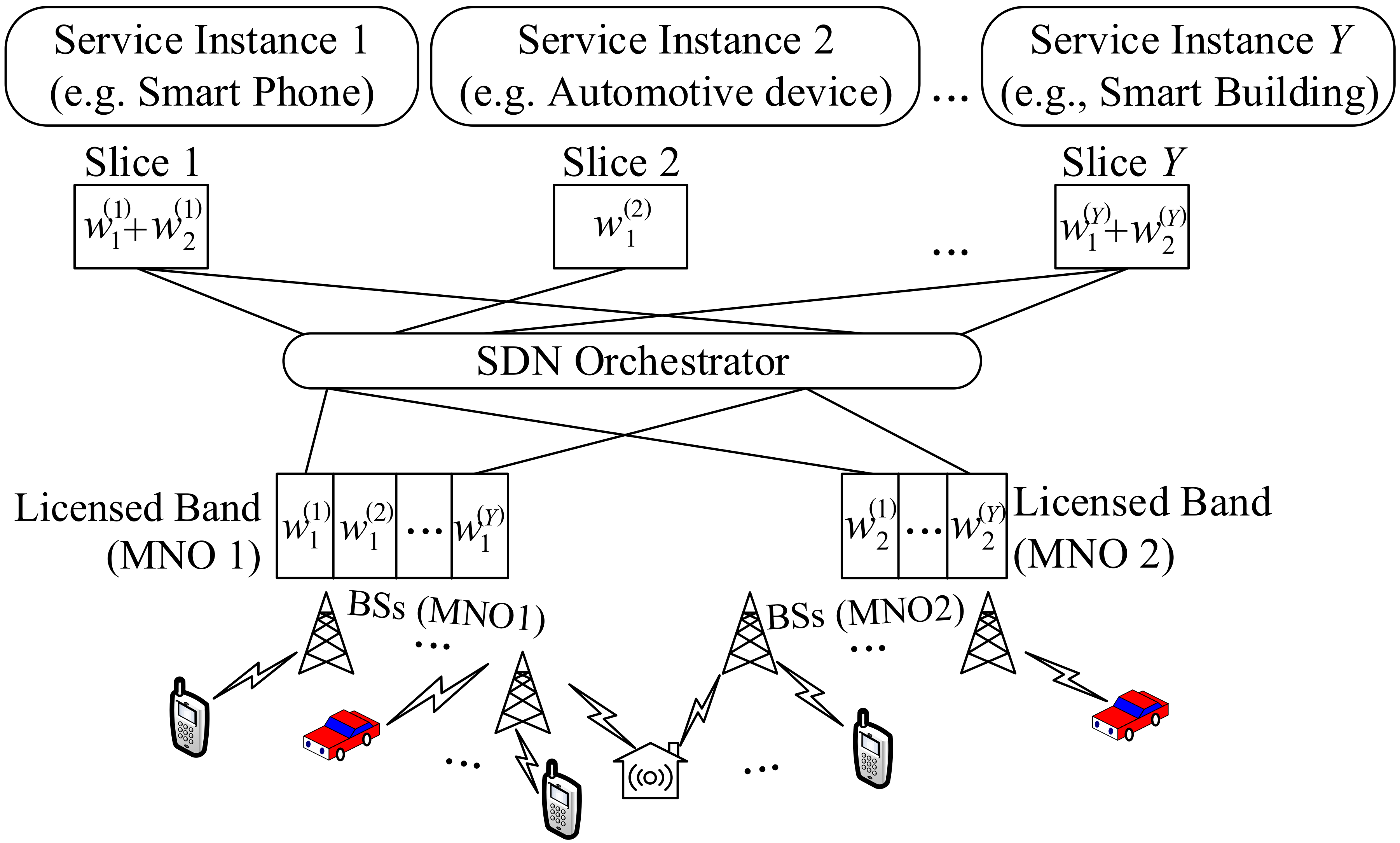
Network Slicing over Licensed and Unlicensed Band:

- 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

Network Slicing in Licensed Band



- 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 $w^{(l)} = \sum_{i \in \mathcal{C}^{(l)}} w_i^{(l)}$.

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 kth UE of MNO i

$$\max_{\boldsymbol{w}_i} \sum_{k \in \mathcal{L}_i} \sum_{l \in \mathcal{Y}} \pi_{k,i}^{(l)}$$

Portion of combined spectrum allocated to the kth UE

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

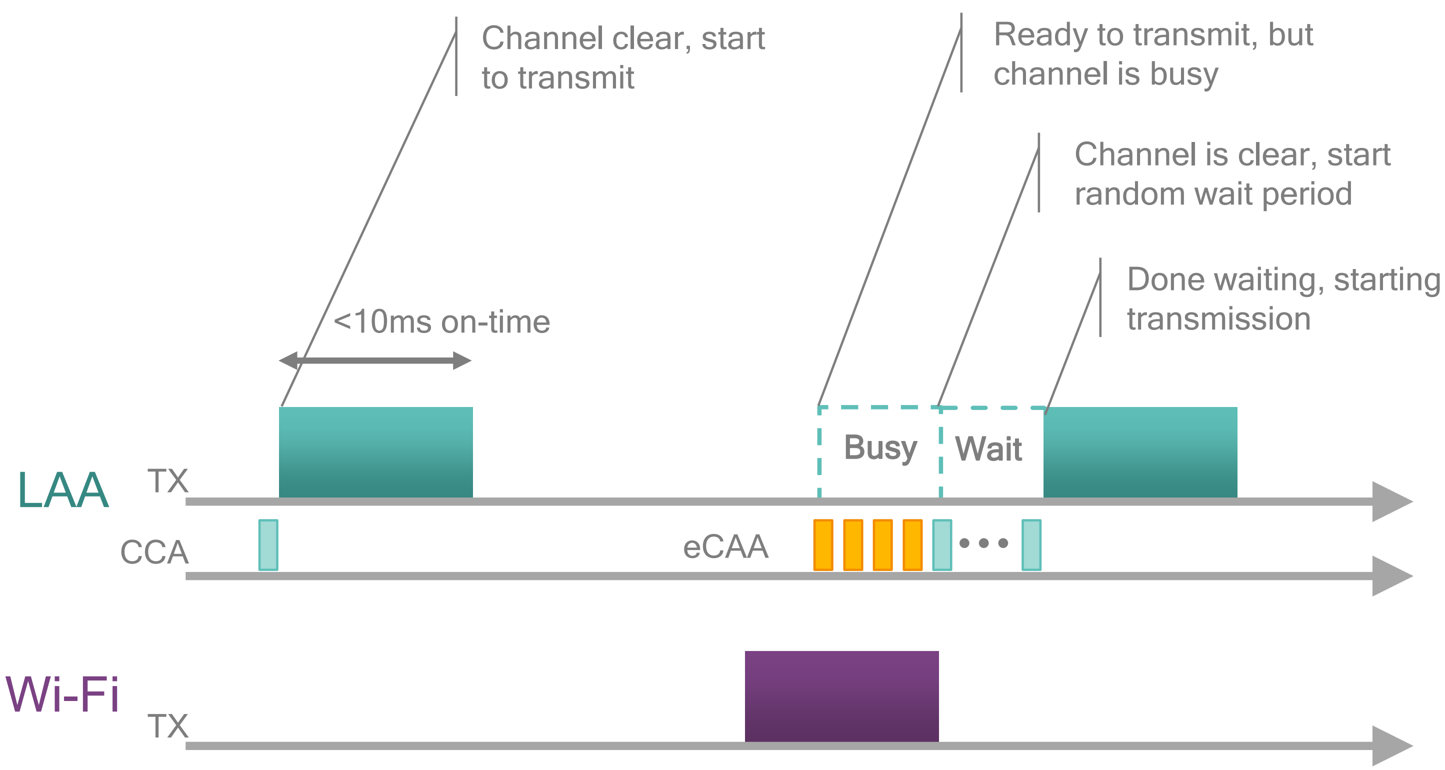
Group of spectrum sharing MNOs supporting the same type l service

Price per data rate charged by MNO i

Transmission rate per Hz of the kth UE of MNO i

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

LTE-LAA/Wi-Fi Coexistence in Unlicensed Band



ED - Energy Detect Threshold

Introducing[1] a more sensitive threshold that is common for all technologies when sensing each other.

CCA - Clear channel assessment

If no signal is sensed based on ED threshold, then go ahead with transmission right away.

eCCA - Extended CCA

If channel is busy (CCA), then wait for it to become clear. Once it is clear, wait for a random number of additional CCAs indicating that the channel has remained clear before starting transmission.

- 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

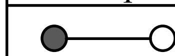
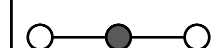
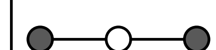
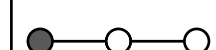
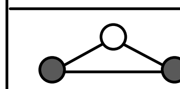
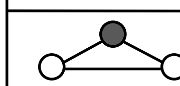
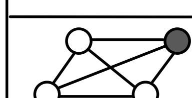
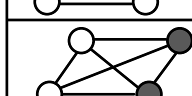
(1) Generate a contention subgraph G_i in unlicensed band using the sensing results from the UEs and BSs of MNO i

(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

Contention Graph	Probability of Access
	(0.659, 0.341)
	(0.914, 0.067, 0.914)
	(0.979, 0.010, 0.979)
	(0.977, 0.005, 0.968)
	(0.978, 0.003, 0.976)
	(0.418, 0.162, 0.418)
	(0.229, 0.540, 0.229)
	(0.181, 0.181, 0.181, 0.456)
	(0.141, 0.141, 0.358, 0.358)

● LAA BS ○ Wi-Fi AP

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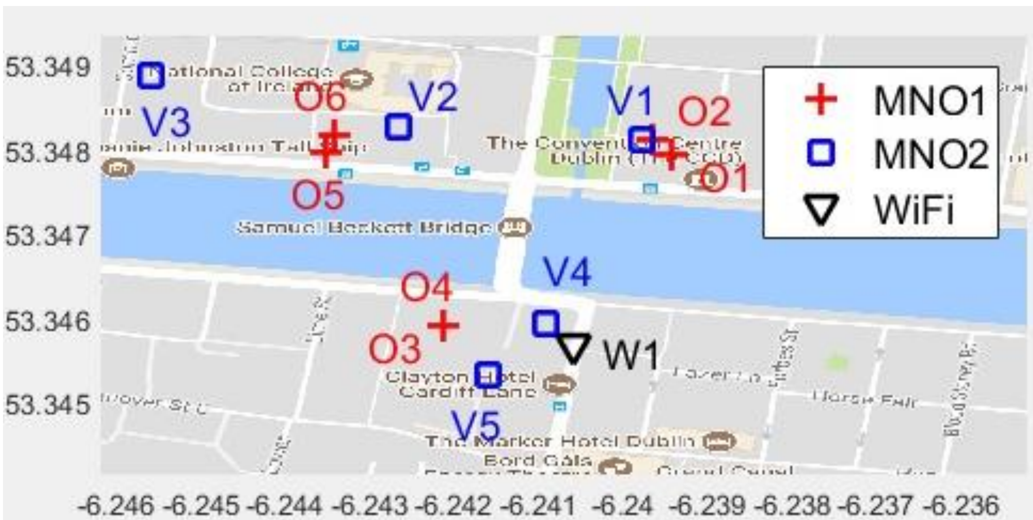
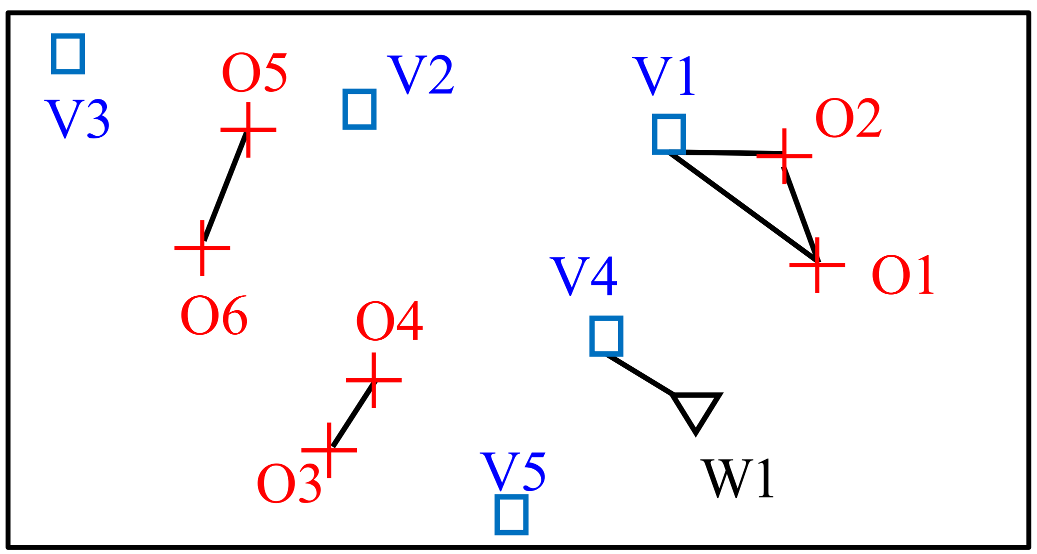
Example and Performance Validation





		CSIM Verif.	mBoE Estim.
MNO1	O1	0.3228	0.333
	O2	0.3192	0.333
	O3	0.4902	0.5
	O4	0.4959	0.5
	O5	0.4923	0.5
	O6	0.4938	0.5
MNO2	V1	0.3450	0.333
	V2	0.9828	1
	V3	0.9828	1
	V4	0.659	0.659
	V5	0.9825	1
Wi-Fi	W1	0.341	0.341

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 kth UE of MNO i in unlicensed band

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

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

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 kth UE of MNO i in unlicensed band

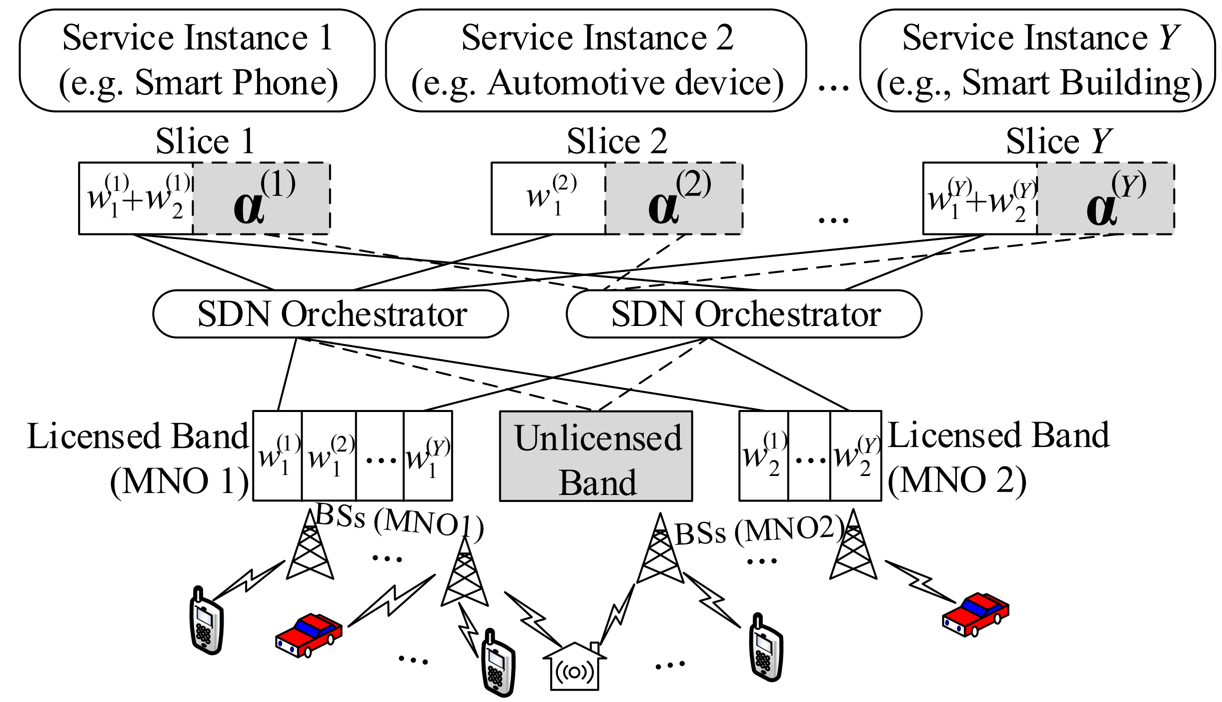
$$\max_{\boldsymbol{w}_i, \boldsymbol{\alpha}_i} \sum_{k \in \mathcal{L}_i} \sum_{l \in \mathcal{Y}} \varpi^{(l)}_{k,i}$$

$$\text{s.t.} \quad \sum_{l \in \mathcal{Y}} \alpha^{(l)}_{k,i} = \xi_{k,i \setminus \mathcal{D}} \text{ and } \sum_{l \in \mathcal{Y}} w^{(l)}_i \le B_i,$$

$$\Big(d^{(l)}_{k,i} \sum_{i \in \mathcal{C}^{(l)}} w^{(l)}_i + \alpha^{(l)}_{k,i} B^{(u)}\Big) R_{k,i} \ge \eta^{(l)}_i.$$

where $\varpi^{(l)}_{k,i} = \pi^{(l)}_{k,i} + \nu^{(l)}_{k,i}.$

Expected aggregated bandwidth that can be accessed by each MNO i for UE k's type l service



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):

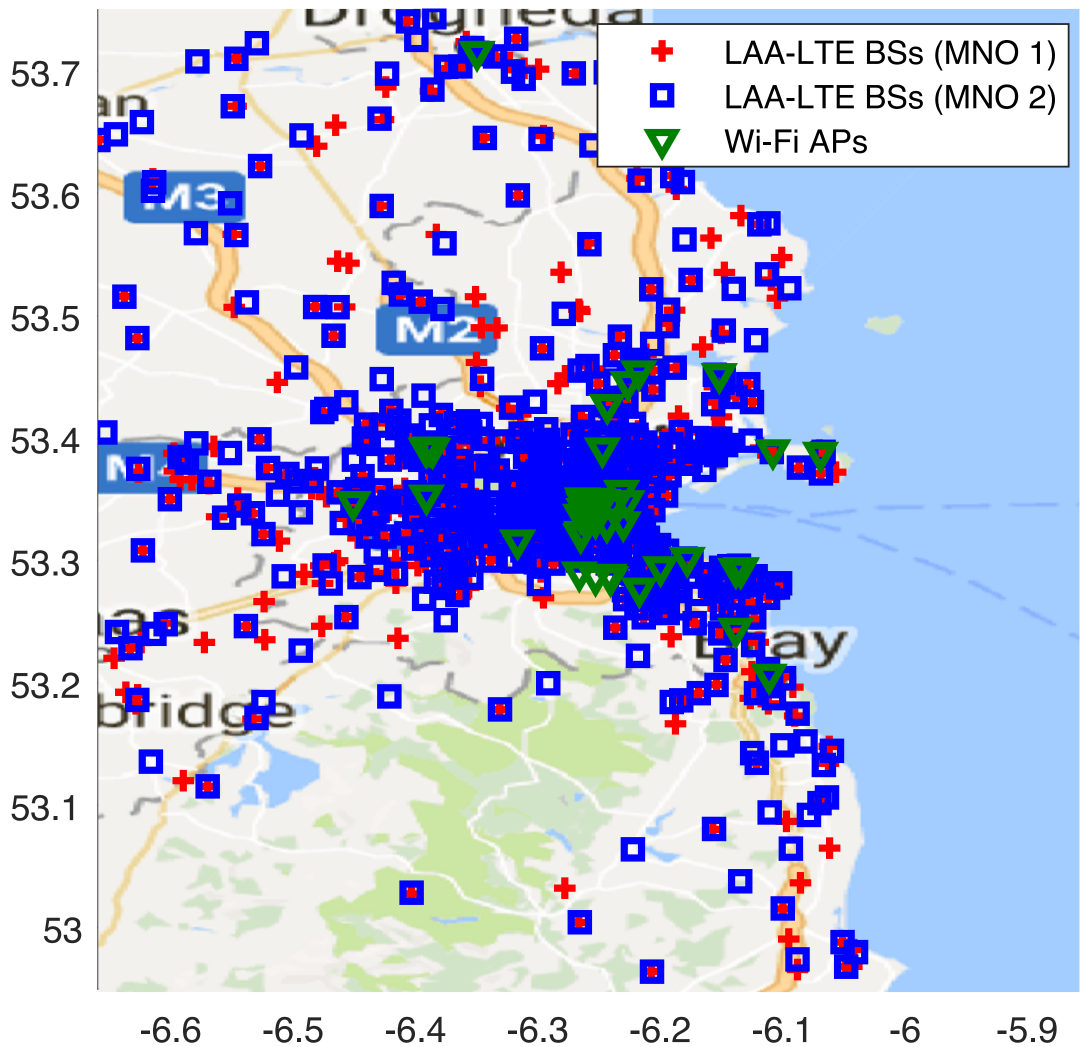
Given a network slicing game $A = \langle M, B, Y, \pi \rangle$ and a subset of MNOs $N \subseteq M$. Suppose $\langle c, x \rangle$ and $\langle c', x' \rangle$ are two network slicing agreements such that for any slice $c^{(l)} \in c$ either $\text{supp}(c^{(l)}) \subseteq N$ or $\text{supp}(c^{(l)}) \subseteq M \setminus N$. 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



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

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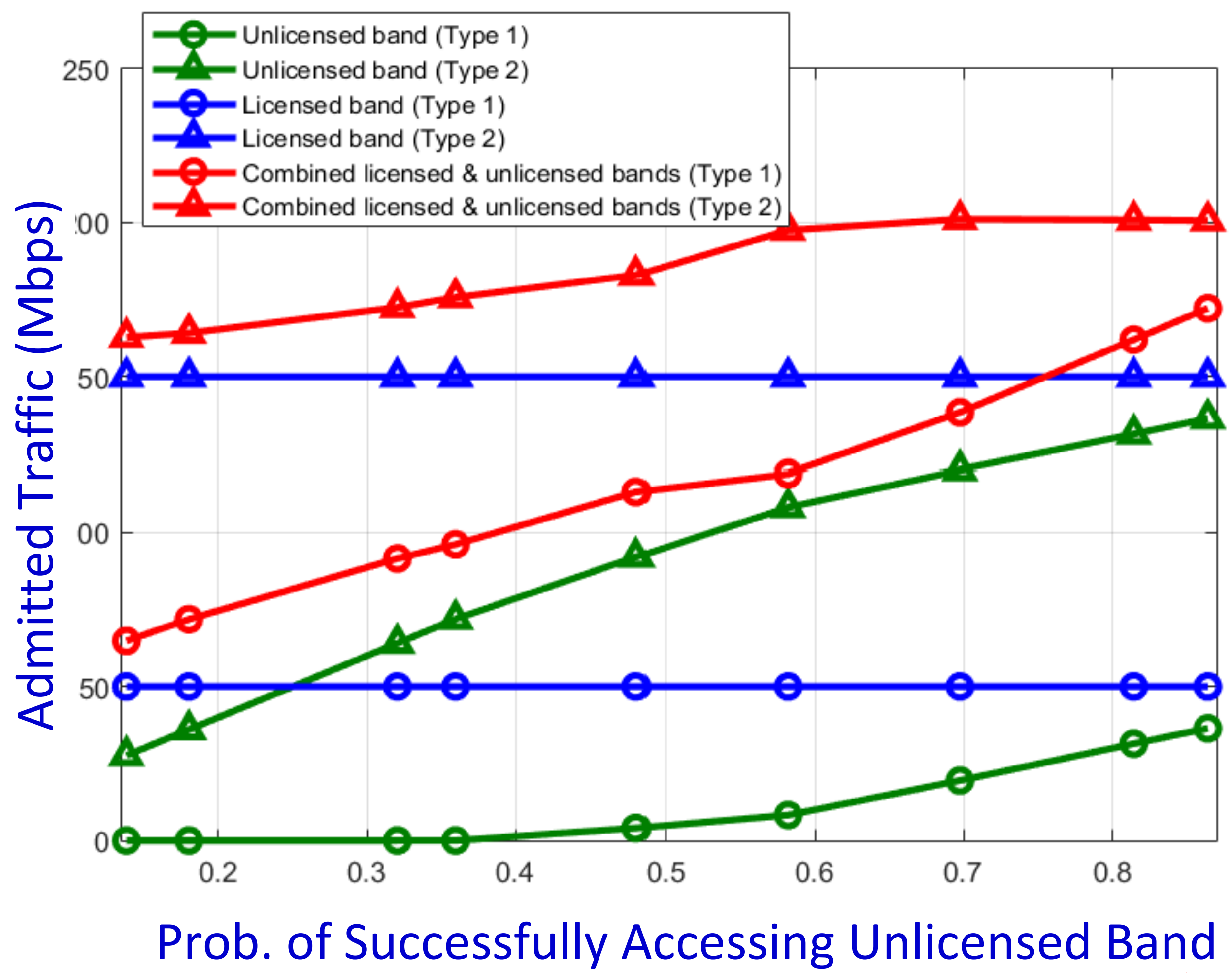
Simulation

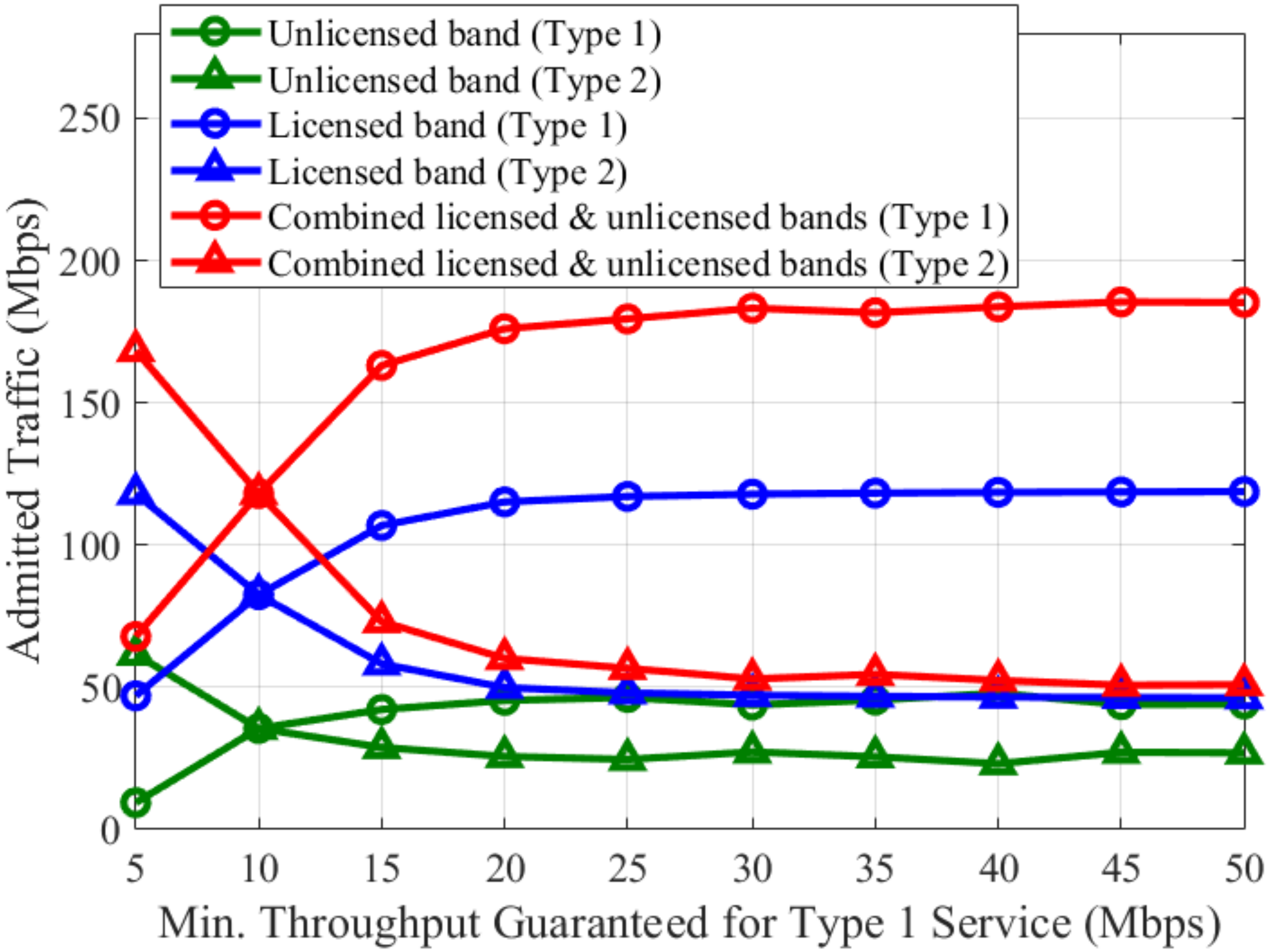


Setup:

- Two MNOs
- Two types:
  - Rate demand for Type 1 = 1 Mbps
  - Rate demand for Type 2 = 10 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



Unlicensed band (Type 1)
Unlicensed band (Type 2)
Licensed band (Type 1)
Licensed band (Type 2)
Combined licensed & unlicensed bands (Type 1)
Combined licensed & unlicensed bands (Type 2)
Admitted Traffic (Mbps)
0
50
100
150
200
250
5
10
15
20
25
30
35
40
45
50
Min. Throughput Guaranteed for Type 1 Service (Mbps)

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