CONNECT
Networks of the Future

Mobile operators, service providers, and the virtualisation of wireless networks

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Vision

Wireless networks of the future will be characterised by heterogeneity

- of spectrum usage regimes
- of ownership models
- of radio access technologies

where resources are shared and orchestrated to create bespoke, virtual networks designed for specific services

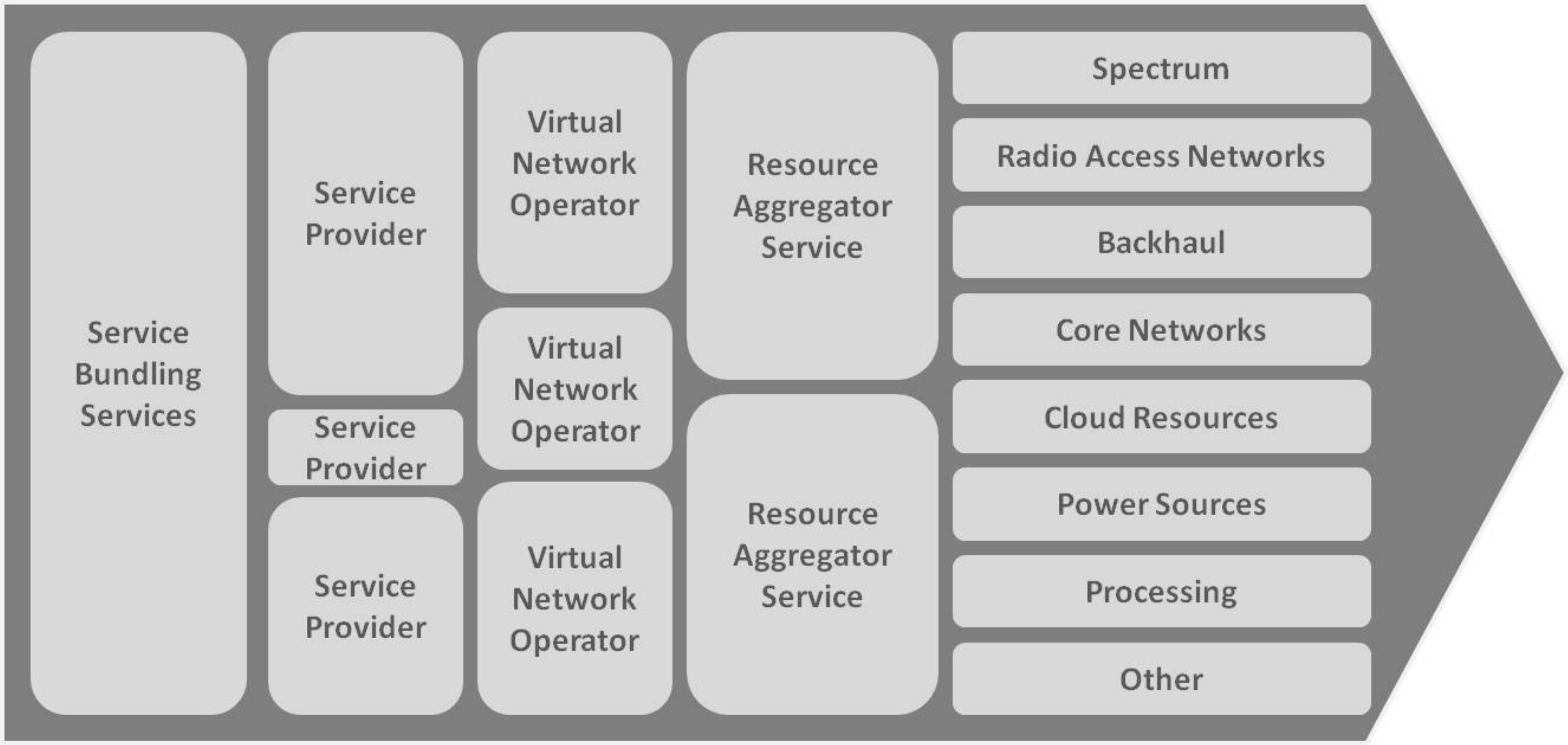
Inter-operator RAN and spectrum sharing is a key step towards that future

- cost efficiencies, tempered by
- competitive advantage considerations
- regulatory constraints

Virtualisation = the illusion of exclusive access to physical resources that are, in fact, shared

A virtual wireless access network feels to the user like a traditional network operated by a single entity but is in fact orchestrated out of a diverse pool of resources with different ownership models

A set of physical resources can host several virtual networks



Future wireless networks will rely on ***sharing*** and ***virtualisation***

… and this requires the ability to slice and trade resources

Doyle, Forde, Kibilda, DaSilva, Proc. of IEEE, 2014

Increased efficiency and lower costs through:

1. Incentives for the deployment of localised (small cell, primarily) infrastructure by medium-sized and small operators.

2. The ability to provide service over infra-structure that employs heterogeneous technologies, and has different properties and ownership.

3. Improved service in currently under-served areas.

4. The ability to offer virtual wireless networks with different associated quality of experience, at different price points.

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BUSINESS

ESPN Eyes Subsidizing Wireless-Data Plans

New questions…

1. How to select physical resources to meet the needs of a virtual operator?

2. How to dynamically manage these virtual networks?

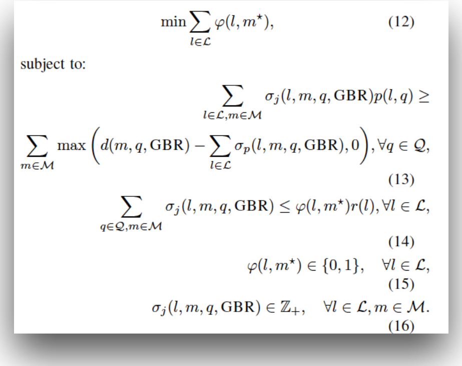
3. How to ensure security, and privacy?

4. What economic and public policy models will support this new model?

(…)

Approaches

optimization



$$\min \sum_{l \in \mathcal{L}} \varphi(l, m^\star), \tag{12}$$

subject to:

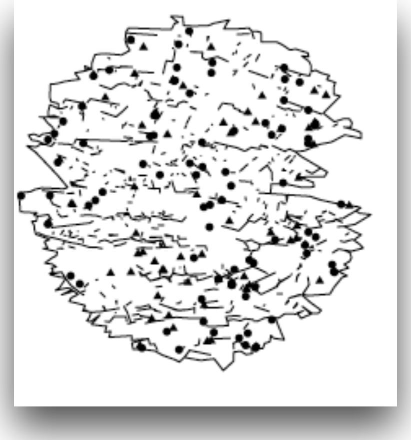
$$\sum_{l \in \mathcal{L}, m \in \mathcal{M}} \sigma_j(l, m, q, \text{GBR}) p(l, q) \geq \sum_{m \in \mathcal{M}} \max\left(d(m, q, \text{GBR}) - \sum_{l \in \mathcal{L}} \sigma_p(l, m, q, \text{GBR}), 0\right), \forall q \in \mathcal{Q}, \tag{13}$$

$$\sum_{q \in \mathcal{Q}, m \in \mathcal{M}} \sigma_j(l, m, q, \text{GBR}) \leq \varphi(l, m^\star) r(l), \forall l \in \mathcal{L}, \tag{14}$$

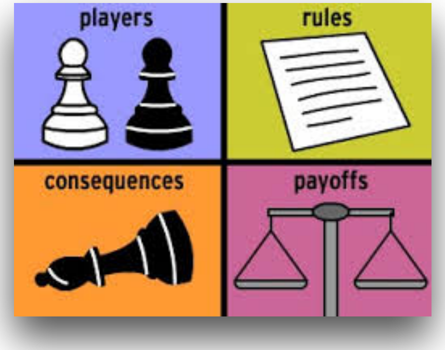
$$\varphi(l, m^\star) \in \{0, 1\}, \quad \forall l \in \mathcal{L}, \tag{15}$$

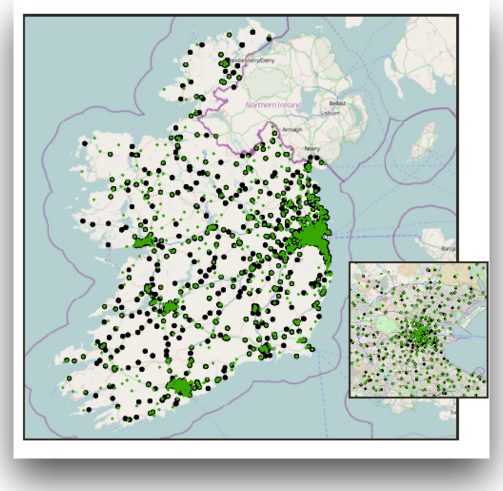
$$\sigma_j(l, m, q, \text{GBR}) \in \mathbb{Z}_+, \quad \forall l \in \mathcal{L}, m \in \mathcal{M}. \tag{16}$$

stochastic geometry



game theory

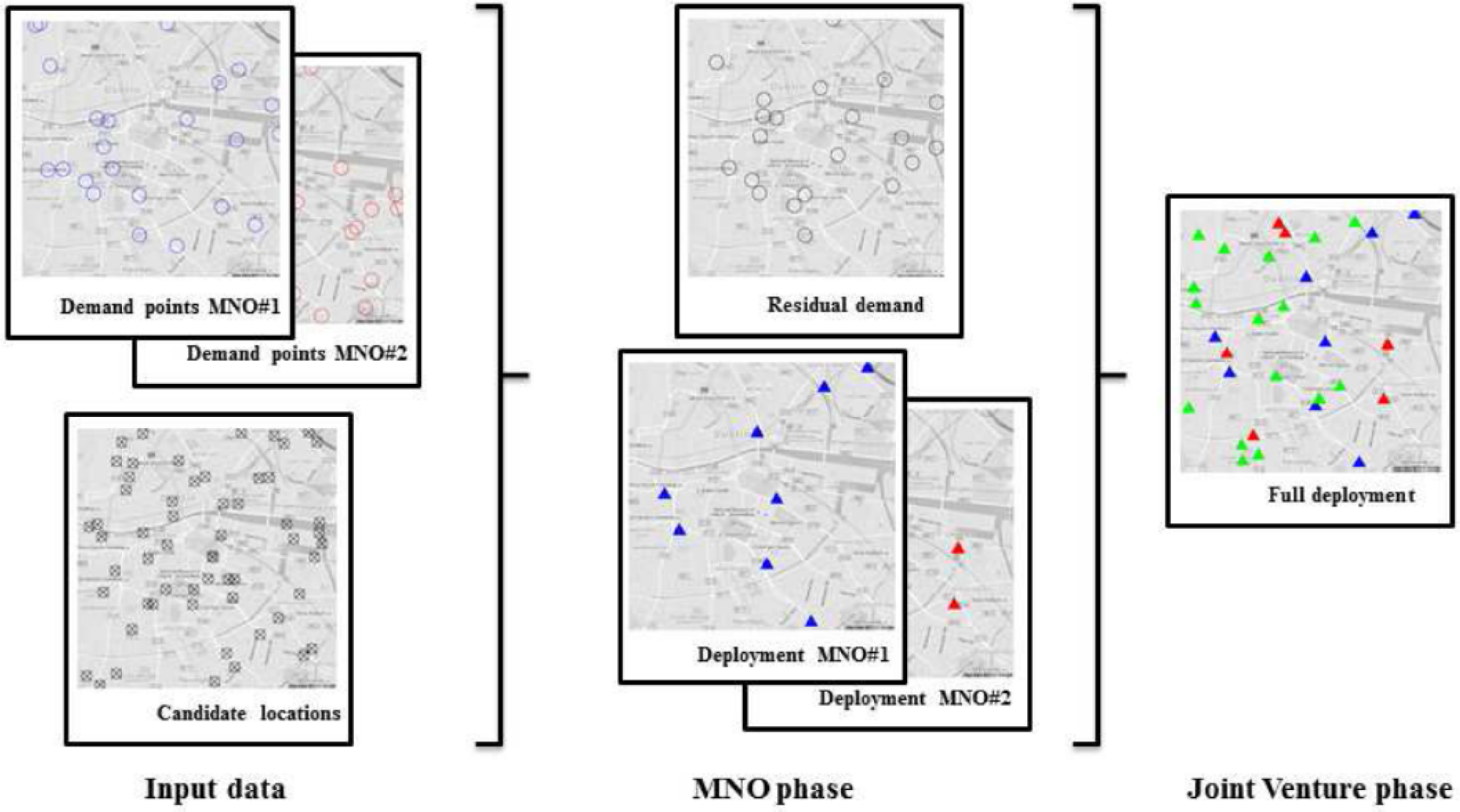




real data

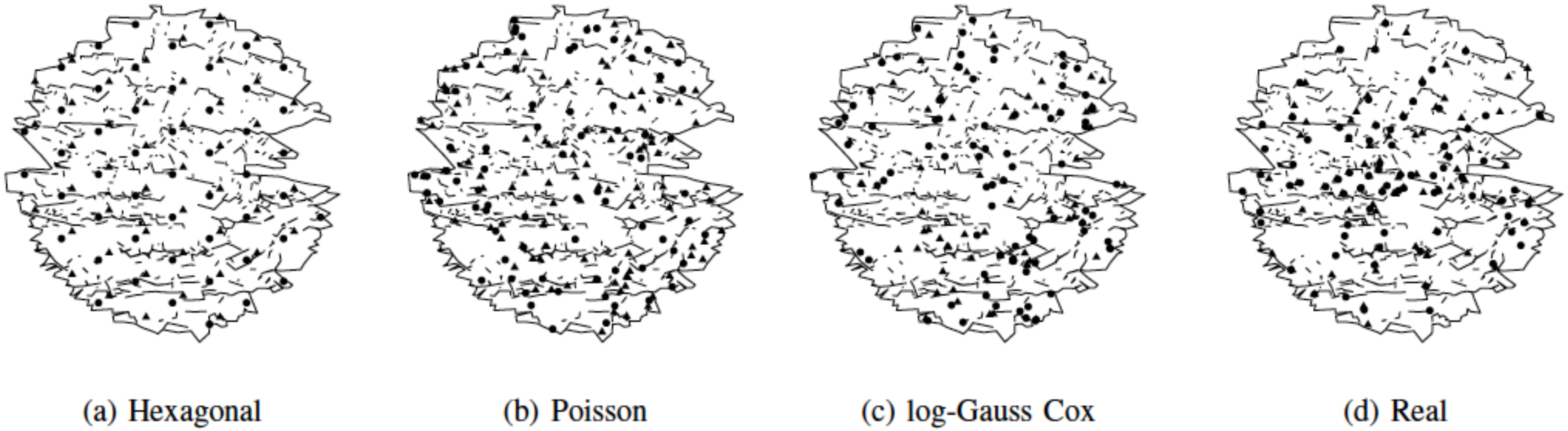
Optimization

To assess gains from resource sharing under diverse sets of technical, market, and regulatory constraints



Stochastic Geometry

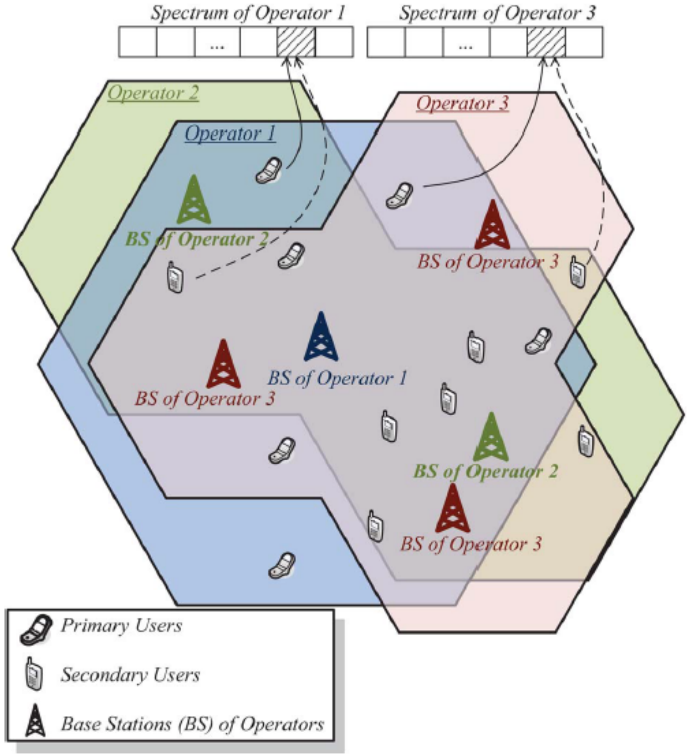
To find appropriate stochastic models for combined network deployments by multiple operators, and to assess the resulting performance of shared networks

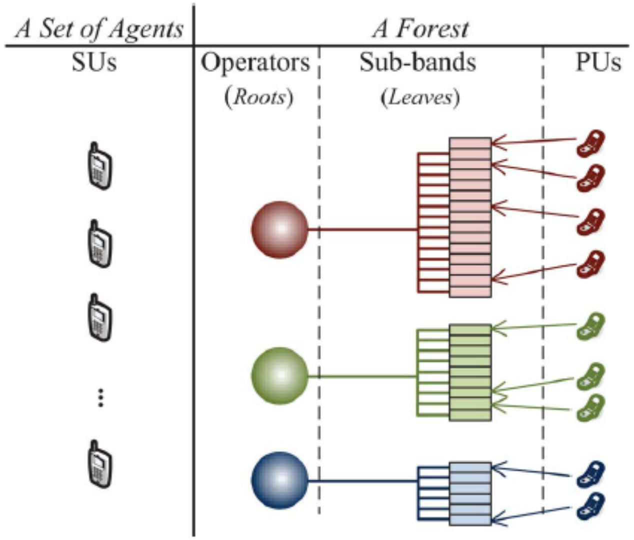


(a) Hexagonal (b) Poisson (c) log-Gauss Cox (d) Real

Game Theory

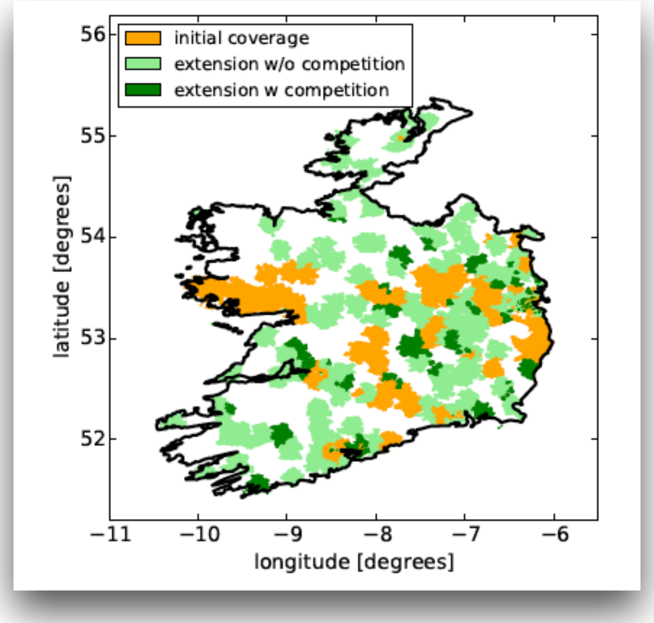
To assess the effect of possibly conflicting objetives among independent decision makers and to design mechanisms that lead to socially desirable outcomes



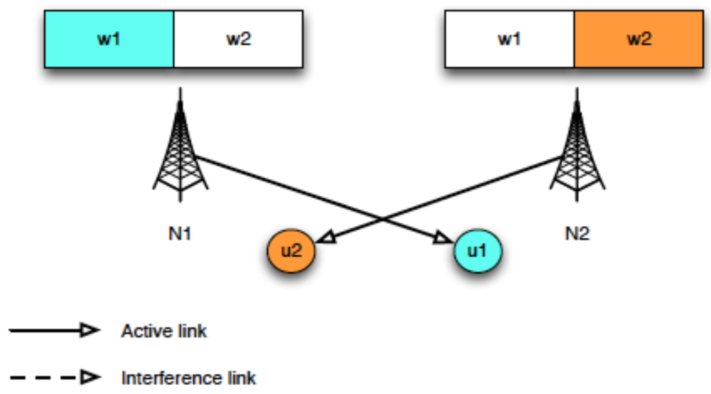


Our starting point…

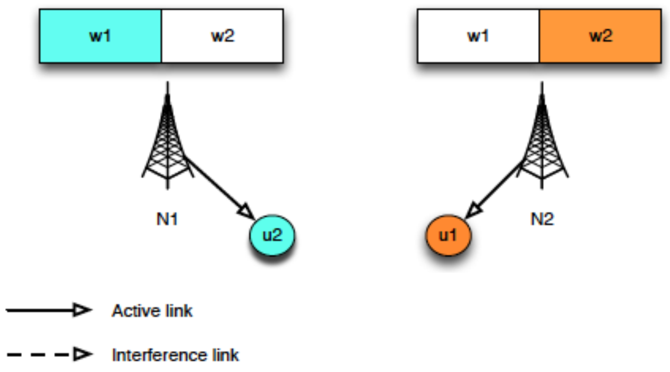
Sharing decisions
among network
operators



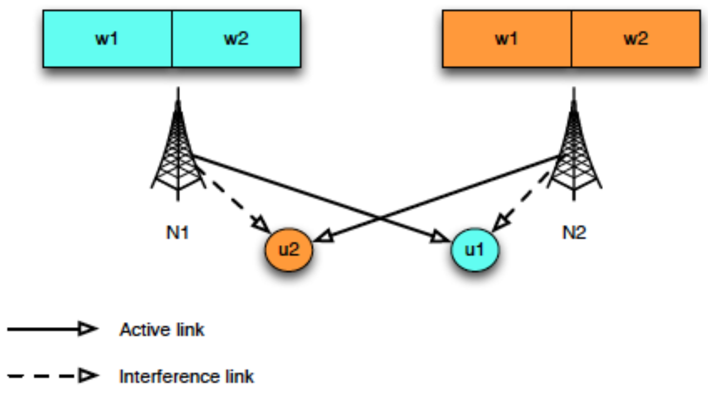
Illustrative problem: can infrastructure sharing be traded for spectrum sharing?



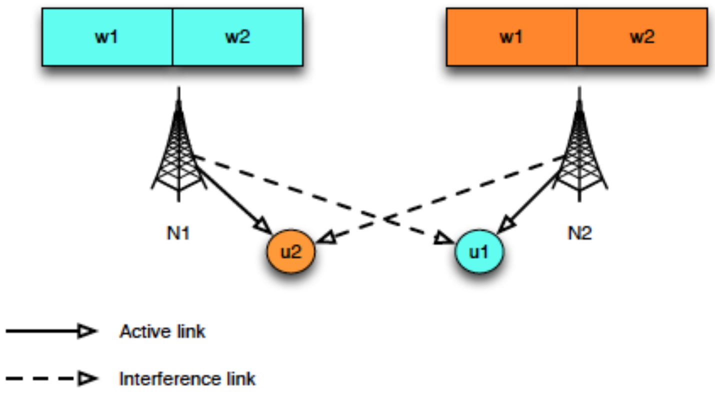
No sharing



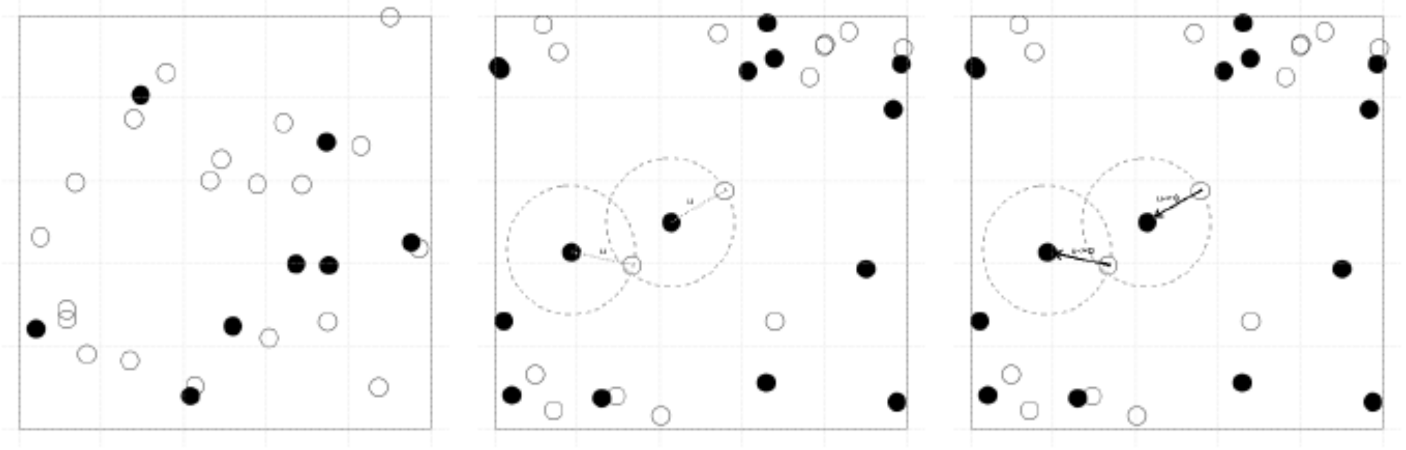
Infrastructure only



Spectrum only



Infrastructure + Spectrum



(a) PPP (b) GPP ($u > 0$) (c) GPP ($u \leftarrow 0$)

[Kibilda, Di Francesco, Malandrino, DaSilva, IEEE DySPAN 2015]

Some results…

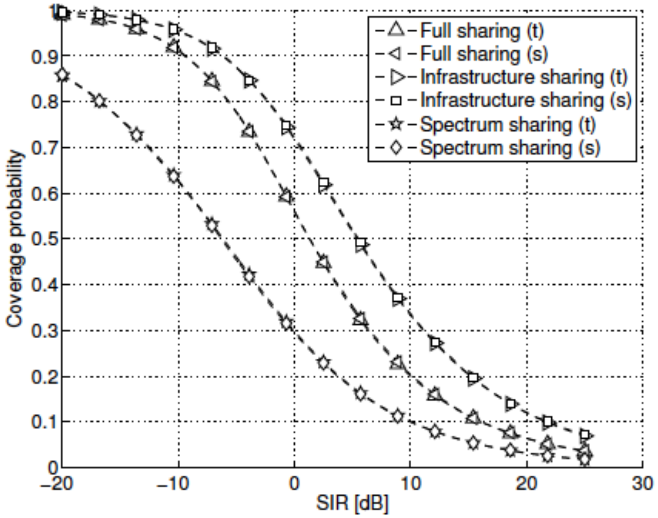
Coverage probability

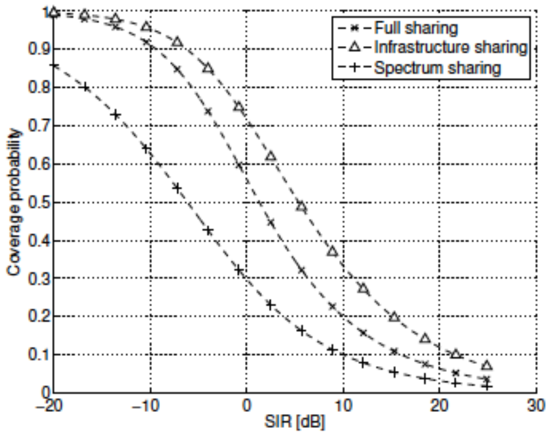
Full sharing	p_c^{ns}
Infrastructure sharing	$\sum_{i\in\mathcal{N}} \frac{\lambda_i}{\lambda+\lambda_i\theta^{\frac{1}{2}}(\frac{\pi}{2}-\arctan(\theta^{-\frac{1}{2}}))}$
Spectrum sharing	$\frac{\lambda_i}{\lambda_i+\lambda_i\theta^{\frac{1}{2}}(\frac{\pi}{2}-\arctan(\theta^{-\frac{1}{2}}))+\frac{\pi}{2}\theta^{\frac{1}{2}}\sum_{j\in\mathcal{N}\setminus\{i\}}\lambda_j}$

Average user rate

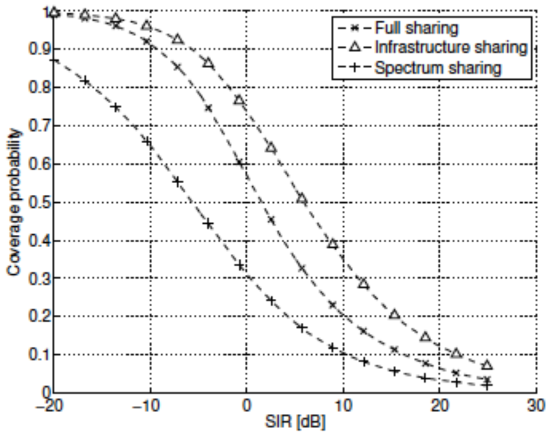
Full sharing	$\frac{\sum_{i\in\mathcal{N}} w_i}{w_i}\mathcal{T}^{ns}$
Infrastructure sharing	$w_i \int_{0+}^{\infty} p_c^{is}(\gamma)\exp(-\log(\gamma-1))d\gamma$
Spectrum sharing	$\left(\sum_{j\in\mathcal{N}} w_j\right)\int_{0+}^{\infty} p_c^{ss}(\gamma)\exp(-\log(\gamma-1))d\gamma$

- Validation of closed-form expressions for coverage probability (hPPP)

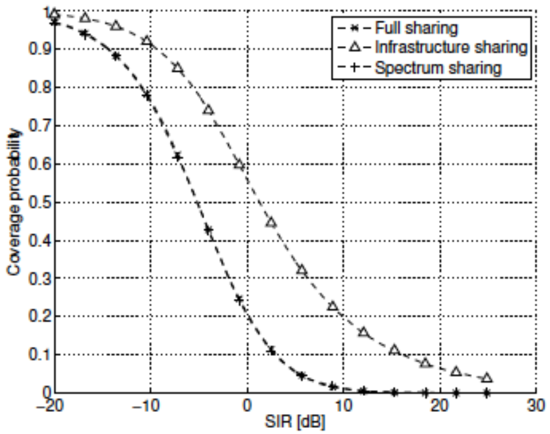




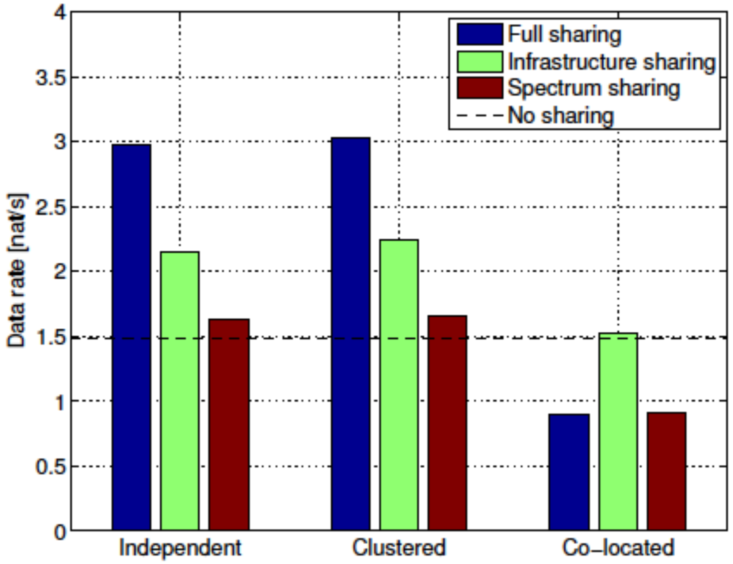
Independently deployed infrastructure



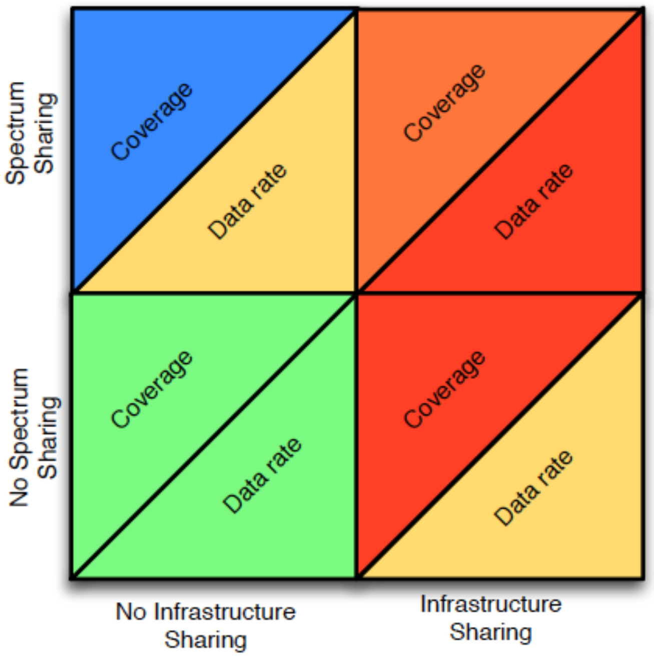
Clustered infrastructure



Co-located infrastructure



Effects on data rate



- Infrastructure and spectrum cannot be simply substituted for each other, as they bring a tradeoff in coverage and capacity

- The combination of infrastructure and spectrum sharing does not bring linearly scaling gains

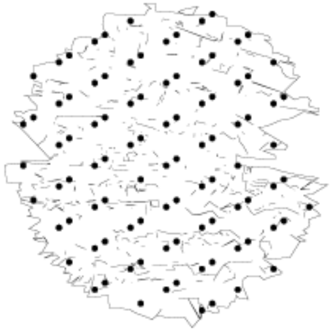
- The spatial distribution of the networks has a significant impact on the gains brought about by sharing

- The respective densities of the networks of the two operators influences how each perceives the sharing gains

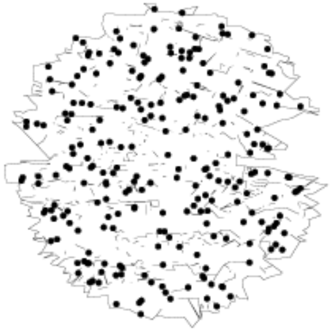
- Results of spectrum sharing are overly pessimistic as they consider no spectrum management or frequency planning

Clustered point processes to model multi-operator deployments

- Premise: multi-operator RAN deployments exhibit significantly more clustering than single-operator
- Investigate goodness of fit of log-Gaussian Cox process (LGCP), Matern cluster process (MCP) and Thomas process (TP)
- Deployment data from Ireland, Poland, and the UK

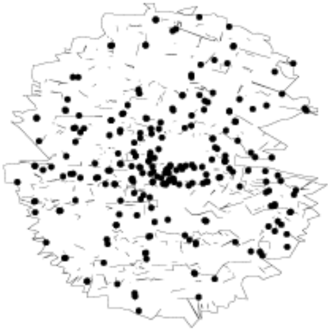


Hexagonal

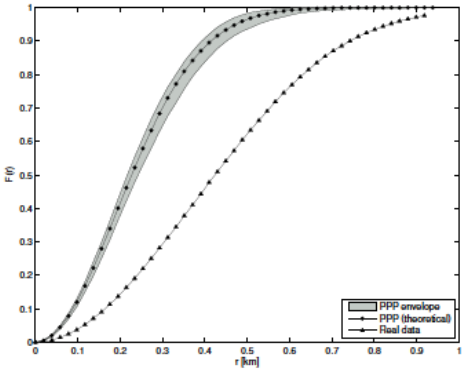


PPP

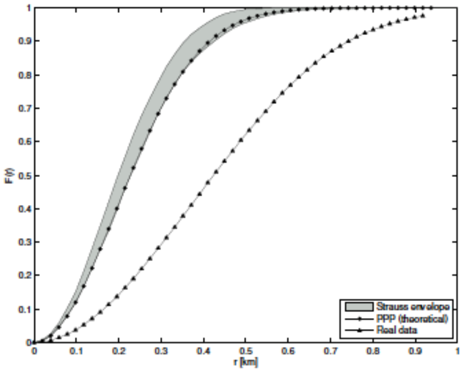
LGCP



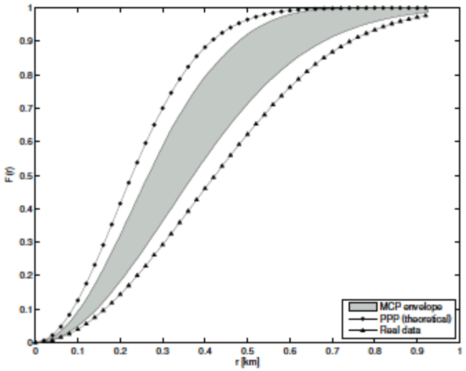
Dublin (real data)



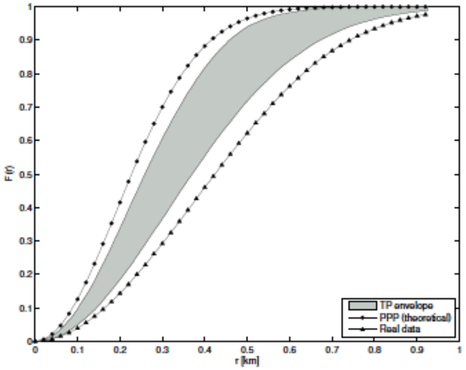
(a) hPPP



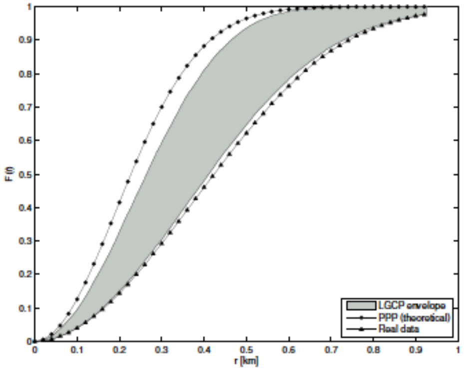
(b) N realizations Strauss



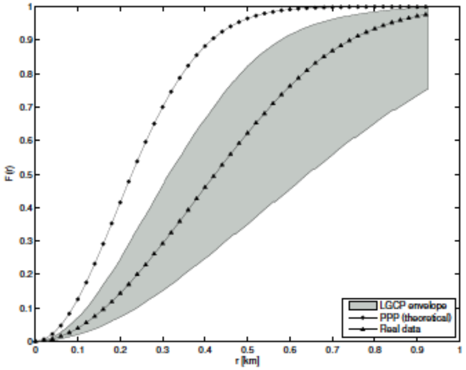
(c) MCP



(d) TP

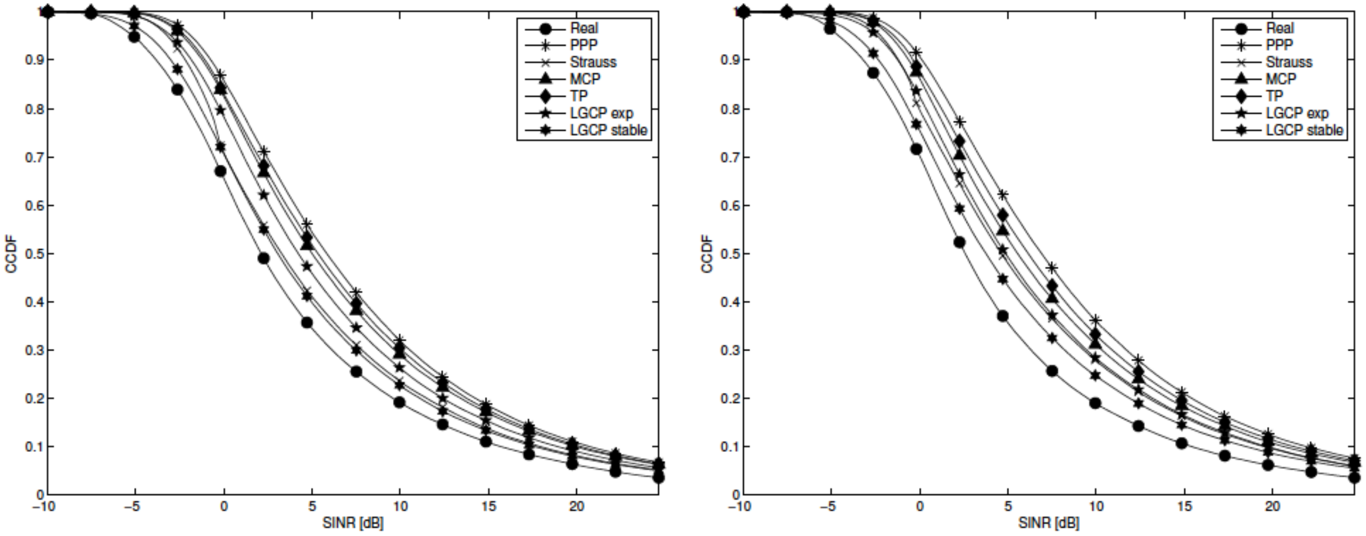


(e) LGCP exponential



(f) LGCP stable

- Empty space function (F function), fitted with a second-order statistic (pair-correlation function)
- Fit shown for UMTS deployments in Dublin (Three, Vodafone, Meteor)
- Envelope of 99 realisations of the fitted point process model shown in grey
- Similar results for other urban areas investigated



(a) GSM (b) UMTS

- Coverage probability: again LGCP provides the closest match to real data
- Combined multi-operator deployments seem to cluster at shorter distances (high demand areas) and repulse at longer
- LGCP and cluster point processes provide a reasonable fit to such multi-operator deployments
- Results are robust to various countries tested for in Europe

[Kibilda, Galkin, DaSilva, TMC (under review)]

Modelling resource sharing through game theoretic models…

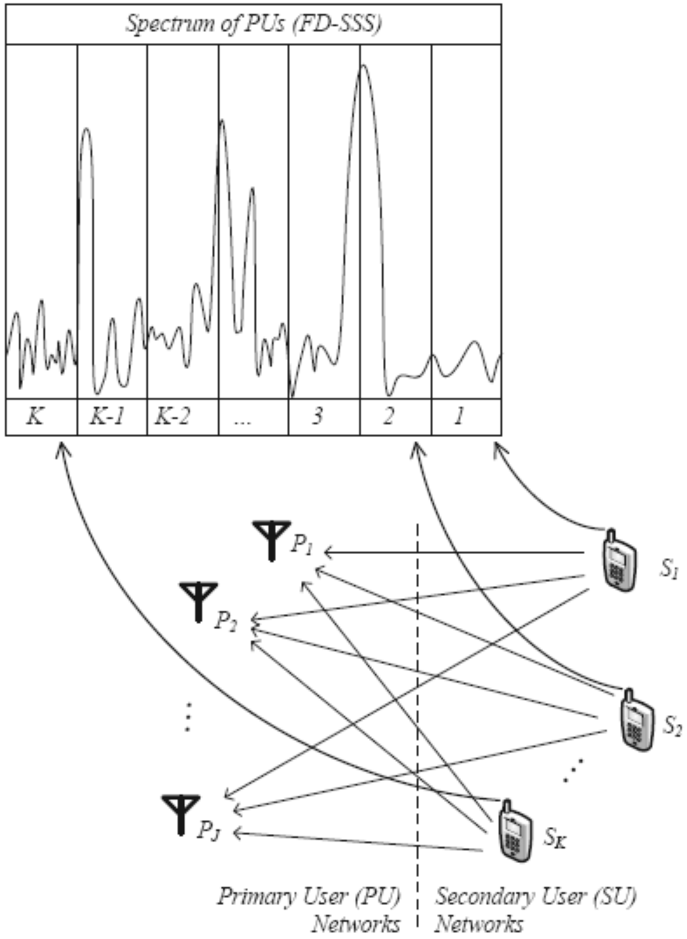
- Hierarchy of decision makers
- Stackelberg games

- Uncertainty as to player types
- Bayesian games

- Sub-set of players cooperating
- Coalition games

- Setting the rules of the game
- Mechanism design

Hierarchical spectrum sharing



[Xiao, Bi, Niyato, DaSilva, JSAC'12]

❶ Primary users (PUs) can charge secondary users (SUs) for access to spectrum

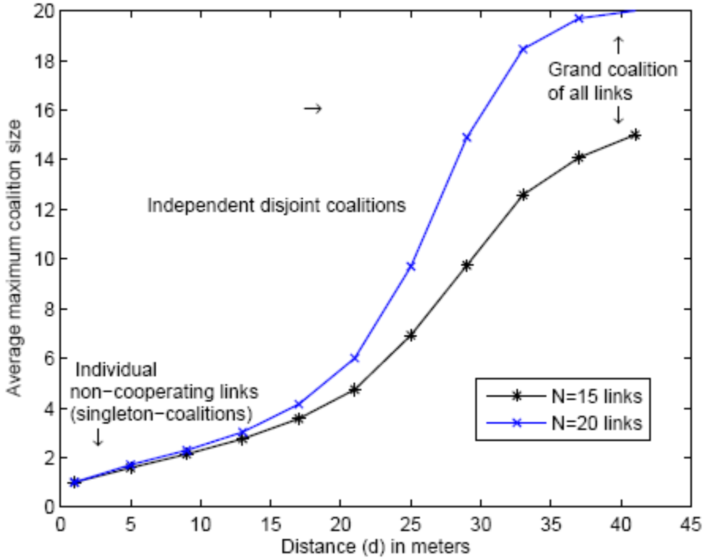
❷ SUs distributedly select on which sub-bands to operate
  - Multiple SUs can occupy the same sub-band and cooperate in communicating

❸ SUs control their transmit power

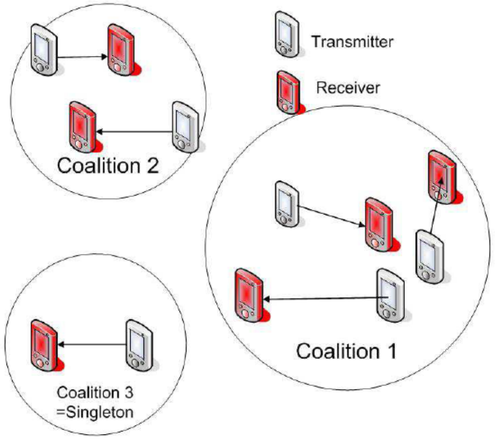
- Model as inter-related Stackelberg game and coalition formation game

- Derive an algorithm to arrive at the NE for the individual games and the SE for the hierarchical game

Resource-sharing coalitions

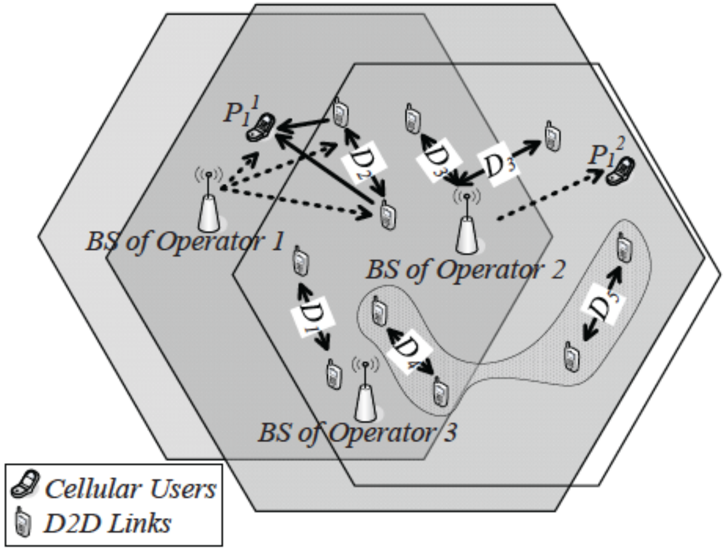


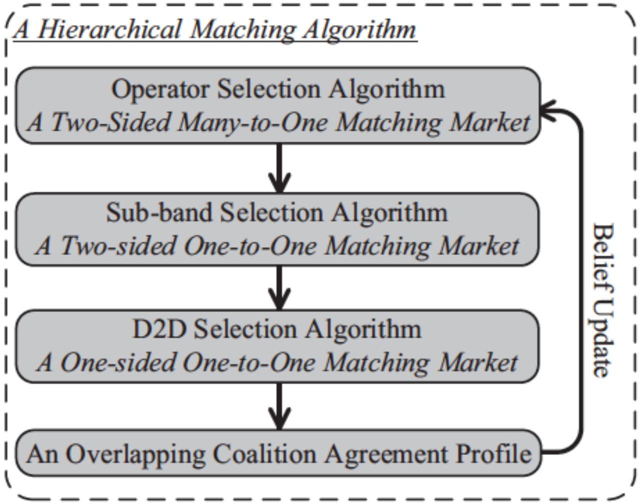
- N transmitter/receiver pairs [players]
- Channel selection and transmit power [actions]
- Utility can include network-wide spectrum efficiency, fairness, network connectivity
- Study the coalition formation process and the stability of coalitions



[Khan, Glisic, DaSilva, Lehtomakki, TCIAIG'10]

Supporting D2D communications in cellular bands





A Hierarchical Matching Algorithm

Operator Selection Algorithm
A Two-Sided Many-to-One Matching Market

Sub-band Selection Algorithm
A Two-sided One-to-One Matching Market

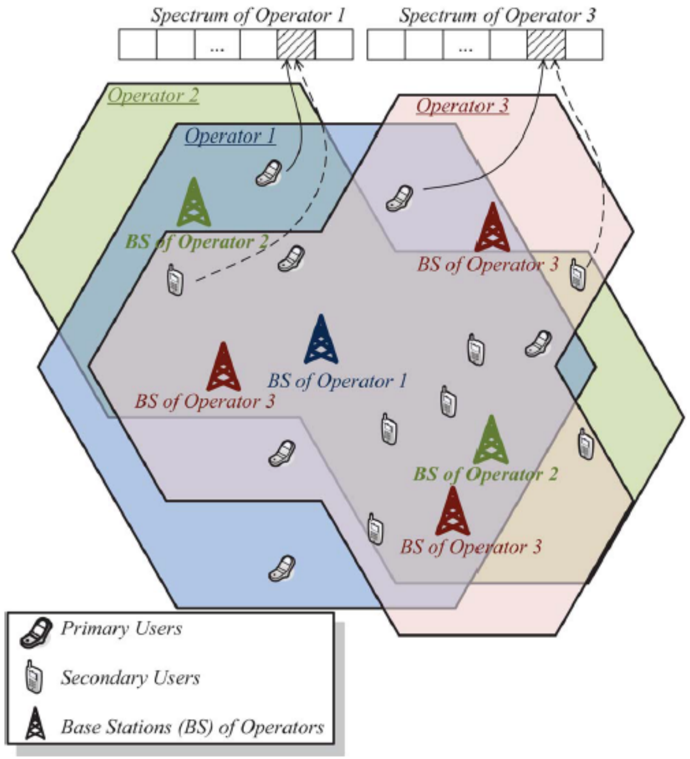
D2D Selection Algorithm
A One-sided One-to-One Matching Market

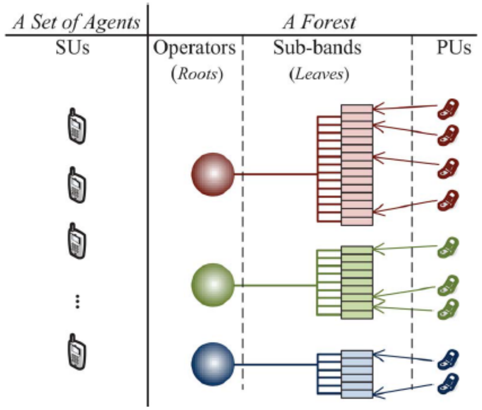
An Overlapping Coalition Agreement Profile

- D2D links [players] compete for sub-bands occupied by a cellular subscriber (if interference is tolerable) or for a sub-band for exclusive use (otherwise)
- Multiple D2D links can share a sub-band
- D2D links do not know about others' preferences, location, link conditions
- Bayesian non-transferable utility overlapping coalition formation game
- Propose a hierarchical matching algorithm to achieve a stable, unique matching structure

[Xiao, Chen, Yuen, Han, DaSilva, TWC'15]

Dynamically matching subscribers to operators





- Subscribers [players] dynamically request channels of operators
- Bayesian game: subscribers are unaware of each other's preferences
  - Belief functions, learning
- Matching market: subscribers are matched to operators, then to sub-bands controlled by the operator
- Design a mechanism that incentivises truth-telling

[Xiao, Han, Chen, DaSilva, JSAC'15]

- Sharing (of infrastructure, spectrum, processing, …) will be increasingly important as wireless networks evolve
- Optimisation, game theory, stochastic geometry are complementary approaches to better understand the effects and limitations of sharing
- Significant cost savings are in play, even when competitive concerns and regulatory constraints are present
- Recent research on SDN, NFV, etc. will be helpful in designing the mechanisms for the virtualisation of wireless networks
- Next: mathematical extensions of infrastructure and spectrum sharing analysis to account for clustering, management of shared resources, etc.

Acknowlegements

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