Self-Organizing Small Cell Networks

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Outline

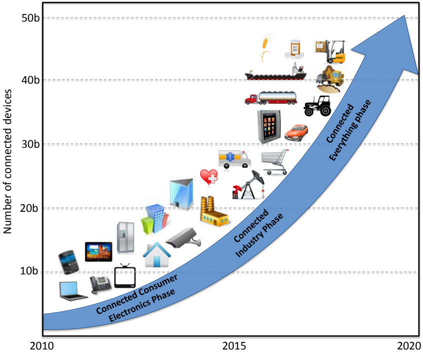
- Overview of small cell networks (SCNs)
- Self-organization in SCNs
- Survey on self-organization in SCNs
- Cognitive spectrum access by small cells
- Future research directions

Overview of SCNs

- Introduction and motivation - small cells and HetNet
- Use cases for small cells
- Small cell specifications
- Licensed small cells vs. Wi-Fi
- Access modes (e.g., closed, open, and hybrid)
- Small cells in LTE/LTE-Advanced architecture
- Small cell deployment models
- Technical challenges in small cell deployment

Introduction and motivation

- Exponential increase of the population of wireless devices with ubiquitous Internet connectivity (which is expected to reach 50 billion by 2020)
- Evolution phases: connected consumer electronics phase, connected industry phase, and connected everything (IoT) phase



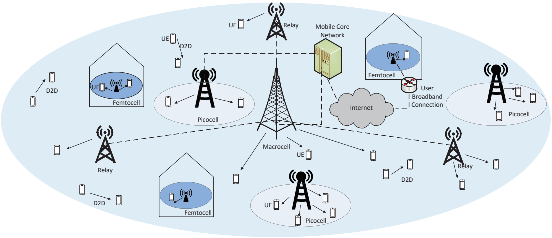
Introduction and motivation

- Significant challenge to the existing cellular wireless infrastructure
- Traditional capacity expansion techniques (e.g., cell splitting) are insufficient and introduce a huge CAPEX.
- **Small cells** may provide a fast, flexible, and cost-efficient solution to fulfill the gap between capacity and demand to cope with the fast growth in wireless traffic.
- Low-powered radio access nodes which can operate in licensed and/or unlicensed spectrum bands and have a transmission range of several tens to several hundreds of meters

Introduction and motivation

- Small cells include **femtocells**, **picocells**, **microcells**, and **metrocells**.
- Small cells can support wireless applications for homes and enterprises as well as metropolitan and rural public spaces.
- **Heterogeneous networks (HetNets)** including macrocells and small cells of all types will provide improved spectrum efficiency (bps/Hz/km^2), capacity, and coverage.
- Small cells are traffic offloading spots in the radio access network to decrease the congestion in macrocells, and enhance users' QoS experience.
- Small cells in the licensed bands for cellular networks standardized by 3GPP, 3GPP2, and WiMAX forum

A heterogeneous cellular wireless network:



E. Hossain, M. Rasti, H. Tabassum, and A. Abdelnasser, "Evolution towards 5G multi-tier cellular wireless networks: An interference management perspective," *IEEE Wireless Communications*, vol. 21, no. 3, pp. 118–127, 2014

Different types of small cells:

- **Femtocell**: small area covered by a small base station, called the femto access point (FAP), intended for residential indoor applications, installed and managed by the customers
- **Key attributes**: IP backhaul, self-optimization, low power consumption, ease of deployment (user-deployed), closed/open/hybrid access
- **Picocell**: low-power compact base stations, used in enterprise or public indoor areas, sometimes encompasses outdoor small cells as well
- **Key attributes**: wired or wireless backhaul, operator deployed, self-optimization, open access

Different types of small cells:

- **Microcell**: outdoor short-range base station aiming at enhancing coverage for both indoor and outdoor users
- **Key attributes**: wired or wireless backhaul, self-optimization, low power consumption, open access
- **Metrocell**: small cell technologies designed for high-capacity metropolitan areas, typically installed on building walls, lampposts; can include technologies such as femtocells, picocells, and microcells
- **Key attributes**: wired or wireless backhaul, operator deployed, self-optimization, open access
- **Relays**: operator deployed, open access, wireless backhaul

- Due to their limited coverage, small cells will have unplanned deployment with high densities (hence complete centralized control may be infeasible).
- Small cells need to have the Self-Organizing Network (SON) capabilities (through **cognition**) for efficient operation with limited centralized control.
- Cognitive **small cell base stations (SBSs)** will be capable of monitoring the surrounding environment, locate major interference sources, and avoid them by opportunistically accessing the orthogonal channels.
- To be robust and adaptive to topological changes, the design parameters (e.g., spectrum sensing threshold) for cognitive SBSs should be independent from the topology and account for the topological randomness.

Use cases for small cells

- **Residential**: femtocell concept (a standalone self-configuring, low-power compact BS connected through broadband Internet), 4-8 active users per BS
- **Enterprise**: larger BSs with higher RF power (longer range) and higher traffic capacity, 8-32 concurrent users per BS
- **Metro and public space**: for urban and rural environments to serve the hotspots, higher traffic capacity (16-64 concurrent users per BS), relatively short range

Small cell specifications

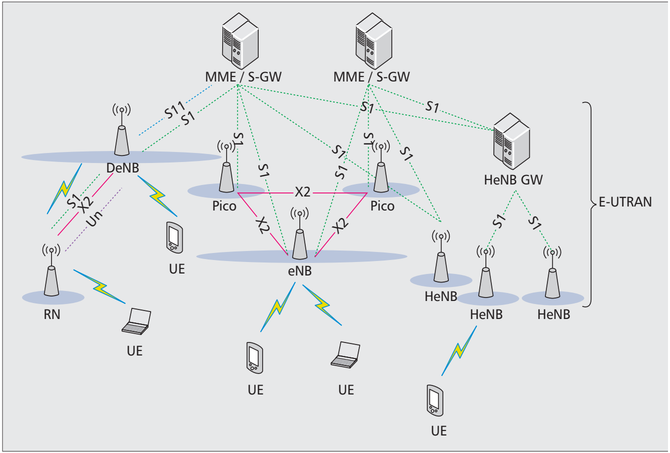
Attribute	MeNB	Picocell	HeNB	Wi-Fi
Coverage	Wide area	Hot spot	Hot spot	Hot spot
Type of coverage	Outdoor	Outdoor, indoor	Indoor	Indoor
Density	Low	High	High	High
BS installation	Operator	Operator	Subscriber	Customer
Site acquisition	Operator	Operator	Subscriber	Customer
Tx. range	300-2000m	40-100m	10-30m	100-200m
Tx. power	40W (approx.)	200mW- 2W	10-100mW	100-200mW
Band license	Licensed	Licensed	Licensed	Unlicensed
System bandwidth	5, 10, 15, 20MHz (upto 100MHz)	5, 10, 15, 20MHz (upto 100MHz)	5, 10, 15, 20MHz (upto 100MHz)	5, 10, 20MHz
Tx. rate	upto 1Gbps	upto 300Mbps	100Mbps-1Gbps	upto 600Mbps
Cost (approx.)	$60,000/yr	$10,000/yr	$200/yr	$100-200/yr
Power consump.	High	Moderate	Low	Low
Backhaul	S1 interface	X2 interface	IP	IP
Mobility	Seamless	Nomadic	Nomadic	Nomadic
QoS	High	High	High	Best-effort

Small cell specifications

- Heterogeneous (small cell) networks operate on licensed spectrum owned by the mobile operator
- Fundamentally different from macrocells since they need to be autonomous and self-organizing and self-adaptive to maintain low costs
- Femtocells are connected to the operator through DSL/cable/ethernet connection.
- Picocells have dedicated backhauls since deployed by operators
- Relays are essentially used for coverage extension.
- Heterogeneous (wired,wireless, and mix) backhauls are envisioned.

Small cells in the LTE/LTE-Advanced architecture

LTE/LTE-A HetNet:



A. Damnjanovic et al., "A survey on 3GPP heterogeneous networks," *IEEE Wireless Comm.*, June 2011.

Small cells in the LTE/LTE-Advanced architecture

LTE-A HetNet:

- OFDM for downlink (DL) and single-carrier FDM (SC-FDM) waveform for uplink (UL) communications (20 MHz bandwidth)
- The eNB serving the RN (i.e., scheduling RN backhaul traffic) is denoted donor eNB (DeNB). The same eNB can be the DeNB for one RN and the regular serving node for UE.
- X2 interface, defined as a direct eNB-to-eNB interface, allows for inter-cell interference coordination (ICIC)
- S1 and S11 interfaces support transfer of user and data traffic between the corresponding nodes.
- Un interface refers to an air interface between DeNB and RN. Un is based on a modified interface between the eNB and UE in order to allow half duplex operation for the RN.

Licensed small cells vs. Wi-Fi

- Support for legacy handsets
- Operator managed QoS
- Seamless continuity with the macro networks through better support for mobility/handoff
- Improved security
- Increased development of small cells that **combine both licensed and unlicensed technologies**

Access modes for small cells

- *Closed access mode*: A set of registered users belonging to Closed Subscriber Group (CGS) is allowed to access a femtocell (e.g., residential deployment scenario).
- Co-channel deployments of closed femtocells cause coverage holes.
- *Open access mode:* Any user can connect to a small cell (e.g., can be used for public places like airports, shopping malls etc.).
- *Hybrid access mode:* A small cell may allow up to N non-registered mobile users to access it (to limit the load on the base station and its backhaul connection); can be used in small business or enterprise deployment scenario
- Femtocells generally use closed, open, or hybrid access mode while picocells usually use the open access mode.

Small cells in the LTE/LTE-Advanced architecture

LTE-A HetNet:

- OFDM (SC-FDM) symbols are grouped in subframes of 1 ms duration. Each subframe is composed of two 0.5 ms slots.
- Minimum scheduling unit for the DL and UL of LTE is referred to as a resource block (RB).
- One RB consists of 12 subcarriers in the frequency domain (180 kHz) and one subframe in the time domain (1 ms).
- Subframes are further grouped in 10 ms radio frames.
- A reference or pilot signal, referred to as a common reference signal (CRS), is used for mobility measurements as well as for demodulation of the DL control and data channels.
- CRS transmission is distributed in time and frequency.

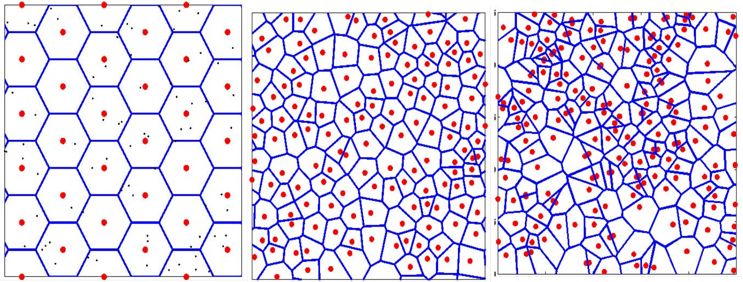
LTE HetNet:

- LTE Rel-10 (or LTE- Advanced) supports improved MIMO operation as DL MIMO support is enhanced (8 Tx, 8Rx is supported), and UL MIMO (4Tx, 4 Rx) is introduced to improve link spectral efficiency.
- Up to five 20-MHz component carriers can be aggregated, offering a peak data rate of more than 1 Gb/s
- Do not translate into significant improvements in terms of system spectral efficiency in bits per second per Hertz.
- System gains are only achievable through increased node density and deployment of low-power nodes, such as pico, femto, and relay base stations.

Macrocell network modeling:

- Hexagonal grid model (easy to simulate) along with outdoor channel model (path-loss, shadowing, and fading) for macrocells
- Random i.i.d. placements of macrocell base stations (analytically tractable, easy to integrate femtocells, relays etc.)
- Real-world macrocell deployment is in between a fully deterministic grid and a fully random placement.

Macrocell network modeling:



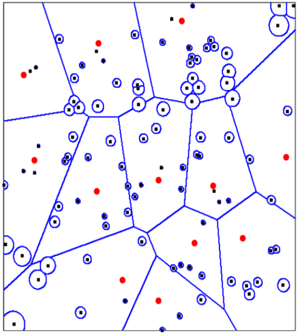
Traditional grid model | Actual 4G macrocells today | Completely random BSs

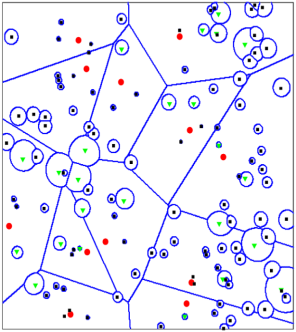
J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. C. Reed, "Femtocells: Past, present, and future," *IEEE Journal on Selected Areas in Communications*, Special Issue on "Femtocell Networks", April 2012.

Small cell channel and deployment models

Multi-tier network modeling:

Zoom w/ femtocells





Zoom w/ picocells too

J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. C. Reed, "Femtocells: Past, present, and future," *IEEE Journal on Selected Areas in Communications*, Special Issue on "Femtocell Networks", April 2012.

Small cell channel and deployment models

Femtocell and heterogeneous network modeling:

- K-tier network, each tier has BS locations taken from independent Poisson Point Processes (PPP)
- Base station density: λ_i BS$/m^2$, transmit power: P_j Watts, SINR target: β_j, path-loss exponent: α_j
- Tier 1 BSs (macrocells) are not really "random", they are carefully planned.
- Picocells typically clustered, not iid either
- May be fine for femtocells, which are truly scattered

Technical challenges in small cell deployment

- Resource allocation and interference management
- Cell association and admission control
- Network performance analysis
- Handoff and mobility management
- **Self-configuration, self-optimization, self-healing**
- Backhaul for small cells
- Security
- Timing and synchronization

Technical challenges in small cell deployment

Self-configuration, self-optimization, self-healing:

- Self-organizing small cells will reduce the operational expenditure (OPEX)
- Efficient methods are required for automatic channel selection, power adjustment, and frequency assignment for autonomous interference coordination and coverage optimization.
- Also, procedures for automatic registration and authentication, neighbor discovery, cell ID selection will be required for small cells.

Technical challenges in small cell deployment

Self-configuration, self-optimization, self-healing:

- Self-organizing and self-optimizing small cells can be referred to as *cognitive small cells*.
- Cognitive small cells should be able to dynamically sense spectrum usage by the macrocell and adapt their transmissions.
- Cognitive small cells should be able to optimize the network parameters for transmit power, physical resources, access modes, admission control, handoff control etc.

- Motivations of self-organization: scalability, stability, robustness, and agility
- Self-organizing network (SON) functionalities (**self-x** concept): self-configuration, self-optimization, and self-healing
- SONs in the LTE and LTE-Advanced standards
- Time-scales of self-organization
- Centralized, distributed, and hybrid SON architectures for small cells

Motivation of self-organization in small cell networks

- Scalability is a key requirement
- Network parameters are more uncertain ever than before due to the random deployment of small cells (e.g., femtocells, picocells).
- Users with different QoS parameters are to be served
- Manual operation, control and maintenance of a large number of network devices to meet the above requirements is not cost-effective to the operator
- Network operation is too fast and too complex for manual intervention
- Scalability, stability, robustness, agility

SON functionalities

- **Intelligence and autonomous adaptability**: to observe, optimize, decide and adapt to the network changes
- **Distributed control**: Ability to operate without (or limited) external control
- **Local interaction**: Exchanging information with nearby network elements
- **Emergent behavior capabilities**: Ability to respond to the environmental changes within a reasonable time

SON functionalities

Self-x concept:

- **Self-configuration**: Basic configuration of the network before operation (frequency selection, obtaining an IP address through the backhaul link, connecting to the OAM server etc.)
- **Self-optimization**: Automatic adaptation to the environment and network changes to optimize the network performances while providing the QoS requirements of the users.
- **Self-healing**: Recover automatically when failures occur.
- SON concepts were first included in the 3GPP release 8 for LTE and enhanced in latter releases.

Self-configuration aspects for eNodeB in the first release of SON (Release 8):

- Automatic inventory (to collect network parameters and characteristics)
- Auto configuration of Physical Cell ID (PCI)
- Automatic Neighbor Relations (ANR): helps automatic discovery of new neighbor eNodeBs via UE assistance (to guarantee continuity of cell coverage)
- Automatic software download (to upgrade and modify eNodeBs without human intervention)

Self-optimization aspects in Release 9 and beyond:

- Mobility Load Balancing (MLB): allows tuning the handover thresholds between macro and pico cells for traffic load balancing
- Coverage and capacity optimization
- Energy saving
- Mobility Robustness Optimization (MRO): monitors failed handovers to fine tune mobility parameters
- Inter cell interference coordination
- Interference reduction
- Random access channel (RACH) optimization
- Mobility optimization

Time scales of self-organization

- Very short time scale: e.g., adaptive modulation and coding, packet scheduling and power control with channel variations
- Short time scale: e.g., sub-band allocation and mobility management
- Medium time scale: e.g., load balancing and coverage optimization
- Large time scale: e.g., adoption of a new spectrum access policy

Centralized, distributed, and hybrid SON architectures for small cells

- In a centralized SON scenario, the components and algorithms will be performed at the operations, administration, and management (OAM) system or server, located at selected locations.
- In a distributed SON scenario, the components and algorithms are performed at the network elements (e.g., at the macro BSs, FAPs).
- In a hybrid SON scenario, some algorithms are executed at the OAM system, while the rest are executed at the network elements.

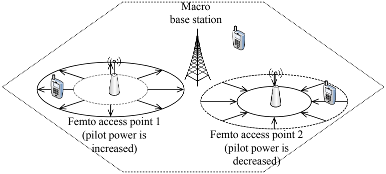
Survey on self-organization in SCNs

- Dynamic traffic offloading
- Coverage optimization
- Dynamic frequency allocation
- Distributed and coordinated spectrum assignment
- Resource allocation for service differentiation
- Self-organizing femtocell management architecture
- Evolutionary and learning-based power control
- Coordination mechanism for self-organizing femtocells
- Collaborative resource allocation for self-healing femtocells

Survey on self-organization in SCNs

Dynamic traffic offloading and ICIC:

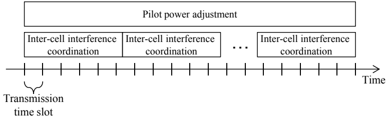
- Femtocells are self-configured to control the pilot power (and hence its coverage area) in an OFDMA system to optimize global network performance (e.g., maximize network capacity).
- Users connect to the BS with the strongest pilot signal.
- Self optimizing inter-cell interference coordination (ICIC) scheme is used to adjust the transmit power.



S. Akbarzadeh, R. Combes, and Z. Altman, "Network capacity enhancement of OFDMA system using self-organized femtocell off-load," in *Proceedings of IEEE WCNC*, pp. 1234–1238, April 2012.

Dynamic traffic offloading and ICIC:

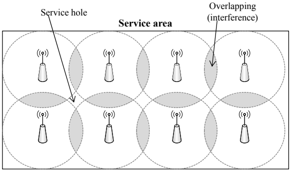
- Given that the pilot power is fixed, the transmit power for each station is updated distributively in order to maximize the utility of the station.
- Pilot power adjustment and inter-cell interference coordination work in different time scales.
- Multi time scale structure allows to configure the transmission parameters with flexibility.



Survey on self-organization in SCNs

Coverage optimization by pilot adjustment:

- Goal is to minimize the coverage holes and overlaps in the service area and to balance the traffic while minimizing the interference caused to the macro users (an enterprise femtocell environment).
- Pilot power adjustment based on a standard tree-based genetic algorithm
- Considers experienced load (L) and estimated coverage overlap (O) for a femtocell, and the probability of users entering a femtocell coverage hole (H)

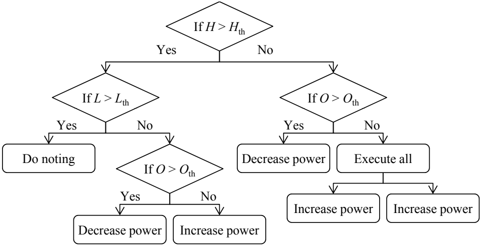


L. T. W. Ho, I. Ashraf, and H. Claussen, "Evolving femtocell coverage optimization algorithms using genetic programming," in *Proceedings of IEEE PIMRC*, pp. 2132–2136, September 2009.

Coverage optimization by pilot adjustment:

- Coverage overlap O is estimated by the ratio between the number of times that users receive the pilot signal from more than one femtocell and the total number of times that users receive any pilot signal.
- H is the ratio of time that the users are in the coverage hole to the total time that the users are in the coverage area of a femtocell.
- A fitness function is defined to quantify the suitability of a generated tree.
- The tree is revised based on the mutation and crossover processes.

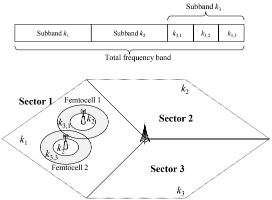
Coverage optimization:



- How to deign the thresholds L_{th}, O_{th}, H_{th}?
- The tree-based genetic algorithm uses a centralized approach, where the global network information is required to obtain the globally optimal solution.

Dynamic frequency allocation:

- A self configuration method for dense femtocell networks to decide which frequencies to be used in the operational phase
- Available spectrum band is divided into three equal parts, i.e., k_1, k_2, and k_3, which are allocated to sectors 1, 2, and 3 of the macrocell.
- Frequency subband k_2 allocated to the center of the femtocells in sector 1, and subbands $k_{3,1}$, $k_{3,2}$, and $k_{3,3}$ allocated for the edges of the adjacent femtocells



M. Z. Chowdhury, Y. M. Jang, and Z. J. Haas, "Interference mitigation using dynamic frequency re-use for dense femtocell network architectures," in *Proceedings of IEEE ICUFN*, pp. 256–261, June 2010.

Survey on self-organization in SCNs

Distributed and coordinated spectrum assignment:

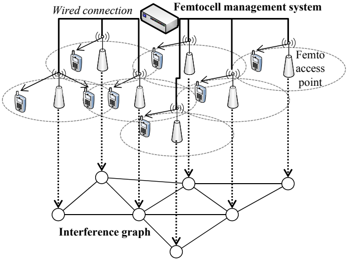
- A distributed method of spectrum allocation for dense femtocells (self configuration)
- Dedicated and shared subbands
- Coordinated spectrum assignment in two steps: autonomous **dedicated subbabnd** selection for basic connectivity (phase 1), and cooperative **shared subband** selection for high data capacity (phase 2)
- Femtocells periodically exchange information about the interfering femtocells (interference cell list)
- A femto access point selects the subband with the best channel quality and broadcasts a message to the femtocells in the interference list.

Y. Wu, H. Jiang, and D. Zhang, "A novel coordinated spectrum assignment scheme for densely deployed enterprise LTE femtocells," in *Proceedings of IEEE VTC Spring*, May 2012.

Survey on self-organization in SCNs

Resource allocation for service differentiation:

- A self-configuration and self-optimization framework to provide service differentiation among different service classes
- Femtocells are connected to a femtocell management system (FMS), which collects global network information and performs interference mitigation among femtocells.



Y.-S. Liang, W.-H. Chung, G.-K. Ni, I.-Y. Chen, H. Zhang, and S.-Y. Kuo, "Resource allocation with interference avoidance in OFDMA femtocell networks," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 5, pp. 2243–2255, Jun 2012.

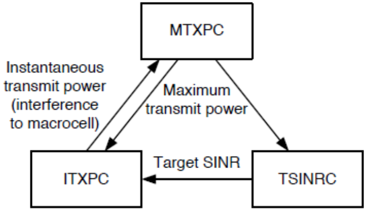
Survey on self-organization in SCNs

Resource allocation for service differentiation:

- Initialization phase and resource allocation phase
- During the initialization phase, the femtocells collect information about their neighbors and report to FMS.
- During the resource allocation phase, the FMS performs physical resource block allocation based on an optimization formulation.
  1. Objective: maximize the utilization of the the resource blocks
  2. Constraints: the same resource block cannot be assigned to multiple femtocells which have a direct interference link, and utilization ratio for the transmission frame must be less than or equal to one.
  3. Rate constraint and L2 packet delay constraint are also considered.
- A binary interference model is used and impact of interference due to macro users is not considered.

Self-organizing femtocell management architecture:

- "Tri-control loop architecture" to protect uplink transmissions at macrocells and femtocells.
- Three control loop components: maximum transmission power control loop (MTXPC), target SINR control loop (TSINRC), and instantaneous transmission power control loop (ITXPC).



J.-H. Yun and K. G. Shin, "Adaptive interference management of OFDMA femtocells for co-channel deployment," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 6, pp. 1225–1241, June 2011.

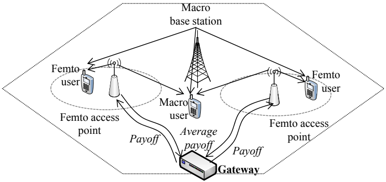
Self-organizing femtocell management architecture:

- MTXPC determines the maximum transmit power of a femto user based on the load margin of the macrocell uplink (solution of a steady state tracking problem in control theory).
- TSINRC decides the target SINR for femto users using maximum transmit power (Nash equilibrium solution in a noncooperative game setting).
- ITXPC allocates the actual transmit power to achieve the target SINR under the constrained maximum transmit power (solution of a control problem).

Survey on self-organization in SCNs

Evolutionary game and learning-based power control:

- Due to limited capacity of backhaul links, the femto access points may not be able to communicate and exchange information for resource management and interference mitigation.
- FAPs make decisions independently.
- Interaction among FAPs is modeled using evolutionary game.



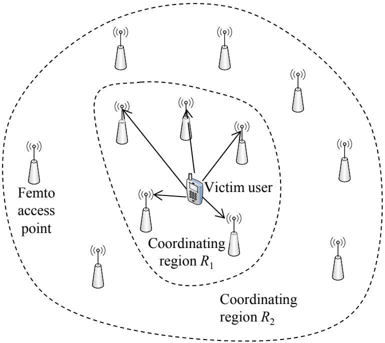
M. Bennis, S. Guruacharya, and D. Niyato, "Distributed learning strategies for interference mitigation in femtocell networks," in *Proceedings of IEEE GLOBECOM*, December 2011.

Evolutionary game and learning-based power control:

- Reinforcement learning (e.g., Q-learning) can be used for channel access and transmission power selection.
- Q-learning aims at finding a policy that maximizes the observed rewards (i.e., payoffs) over a certain time period.
- Every FAP explores the environment, observes its current state s, and takes a subsequent action a, according to a decision policy $\pi : s \rightarrow a$, which is a mapping from state s to action a. With the ability to learn, knowledge about other FAPs' strategies is not needed.
- **Cooperative Q-learning**: Instead of learning by themselves, FAPs can learn from an expert.
- A given FAP modifies its Q-values and learns from a small group of other FAPs that it considers as the expert. The exchange of information between FAPs is performed periodically.

Coordination mechanism for self-organizing femtocells:

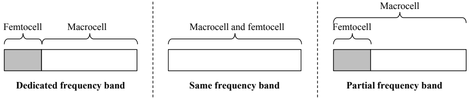
- FAPs creating co-channel interference to a macro user ("victim") can use a coordination mechanism (e.g., to reduce transmission power, switch to different subband).



C. H. M. de Lima, M. Bennis, and M. Latva-aho, "Coordination mechanisms for stand-alone femtocells in self-organizing deployments," in *Proceedings of IEEE GLOBECOM*, December 2011.

Coordination mechanism for self-organizing femtocells:

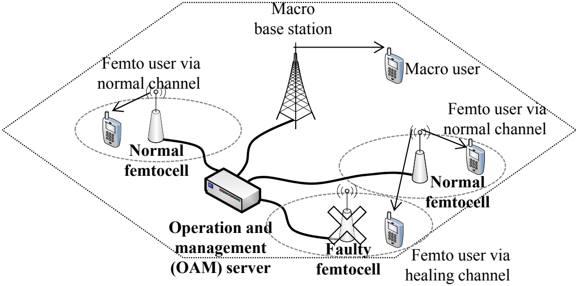
- A macro user is identified to be a "victim" user if this user experiences an aggregate co-channel interference which is higher than a predefined threshold.
- The victim user sends a signaling message to the nearby FAPs (e.g., in coordinating region R_1).
- Only the FAPs with strong interference adapt their transmission parameters.
- FAPs in the coordinating region R_1 can switch the subband and FAPs in region R_2 may also reduce their transmission power.



Survey on self-organization in SCNs

Collaborative resource allocation for self-healing femtocells:

- A joint self-healing and self optimization scheme
- All femtocells periodically transmit a message to the server; message not received $\longrightarrow$ failure
- Nearby femtocells support the users of the failed femtocell.



K. Lee, H. Lee, and D.-H. Cho, "Collaborative resource allocation for self-healing in self-organizing networks," in *Proceedings of IEEE ICC*, June 2011.

Collaborative resource allocation for self-healing femtocells:

- K_H = set of healing channels, K_N = set of normal channels
- Selection of the worst subchannel k^*:

$$k^* = \arg\min_{k \in K_N} \left(\frac{U_{x(f,k),k} - U_{x(f,-k),-k}}{U_{x(f,k),k}} \right) \quad (1)$$

  where $U_{x(f,k),k}$ = network throughput when the subchannel k is allocated to a user, $U_{x(f,-k),-k}$ = network throughput when the subchannel k is not allocated to a user

- Subchannel k^* is assigned to be the healing channel to the user with the highest transmission rate in the faulty femtocell, if the gain

$$g = \frac{U_{x(f^*,k^*),k^*} - U_{x(f,k),k}}{U_{x(f,k),k}} \quad (2)$$

  is greater than zero. That is, $K_N = K_N \setminus k^*$ and $K_H = K_H \cup K^*$.

- Spectrum sensing range and spectrum reuse efficiency
- Spectrum access schemes by cognitive small cells
  1. Performance gain due to opportunistic spectrum access
  2. Effect of channel allocation at the macro tier
- Clustering-based spectrum access by cognitive small cells

Spectrum sensing range and spectrum reuse efficiency

- **Interference** is the most performance limiting parameter in HetNets
- Infeasible to use traditional centralized techniques to coordinate spectrum access by a large number of small cells (hence **distributed SON**)
- A cognitive small cell will not access a channel unless the power received on that channel from any other network entity is less than the spectrum sensing threshold.
- Due to the distance-dependent signal power decay, the spectrum sensing threshold defines an area where no interference source exists.

Spectrum sensing range and spectrum reuse efficiency

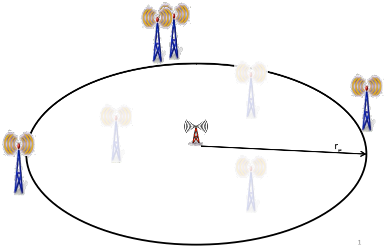
- A channel used by a network entity (i.e., an MBS or an SBS) located at $x \in \mathbb{R}^2$ can be reused by a cognitive SBS located at $y \in \mathbb{R}^2$ if and only if

$$\|x - y\| \geq \left(\frac{P_{tx} h(x,y)}{\gamma} \right)^{\frac{1}{\eta}} \tag{3}$$

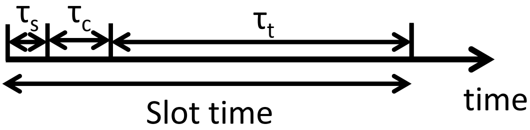
  where $h(x,y)$ = random channel gain between the two locations x and y, P_{tx} = transmit power of the network entity located at x, γ = **spectrum sensing threshold**, $\|.\|$ = Euclidean norm, and η = path-loss exponent.
- γ is the design parameter that controls the minimum frequency reuse distance $r_e = \left(\frac{P_{tx} h(x,y)}{\gamma} \right)^{\frac{1}{\eta}}$ and hence the spatial reuse efficiency.

Spectrum sensing range and spectrum reuse efficiency

- Higher the value of γ, lower is the frequency reuse distance and more aggressive will be the cognitive SBSs in spectrum access (hence increased mutual interference leading to a higher outage probability, and vice versa).
- Tradeoff between spatial frequency reuse efficiency and outage probability that can be optimized by carefully tuning the spectrum sensing threshold



Spectrum access by cognitive small cells:

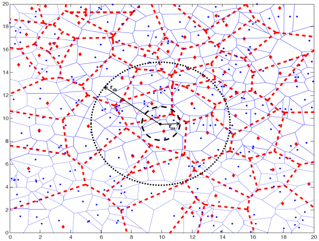


H. ElSawy and E. Hossain, "Two-tier HetNets with cognitive femtocells: Downlink performance modeling and analysis in a multi-channel environment," *IEEE Transactions on Mobile Computing*, vol. 13, no. 3, March 2014, pp. 649-663.

Spectrum access schemes by cognitive small cells

- A cognitive small cell will not access a channel which is being used by nearby macocell and small cells.
- Unavailability of radio channels may lead to outage.
- Each time slot is divided into three main parts (**scheme-1**).
  1. *First part*: each cognitive small cell senses the available spectrum to detect the channels which are not used by the MBS.
  2. *Second part*: each cognitive small cell contends to access one of the available channels (e.g., using a random backoff process while persistently sensing the channel).
  3. *Third part*: if the sensed channel was available during the entire backoff duration (i.e., not used by a nearby small cell), the cognitive small cell transmits on that channel for the rest of the time slot. Otherwise, the small cell is considered to be in outage due to channel unavailability.

- Due to the unified sensing threshold γ each cognitive SBS (e.g., FAP) will have two spectrum sensing regions (SSR).
  1. *macro SSR*
  2. *femto SSR*
- A cognitive SBS (e.g., FAP) should avoid using any channel used by a macro BS in the *macro SSR* and any channel used by any FAP in the *femto SSR*.



Spectrum access schemes by cognitive small cells

- For downlink transmission, total outage probability for a small cell user can be expressed as

$$
\begin{aligned}
P_{out} &= (1 - \mathbb{P}\{\text{opportunistic access}\}) + \\
&\quad \mathbb{P}\{\text{SINR} \leq \beta\}\, \mathbb{P}\{\text{opportunistic access}\}
\end{aligned}
$$

  where SINR is the signal-to-interference-plus-noise ratio and β is the threshold defined for correct signal reception.

- Both the opportunistic spectrum access probability and the SINR outage depend on the network geometry.

Spectrum access schemes by cognitive small cells

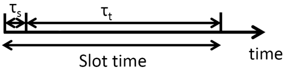
- Outage could be due to channel unavailability for opportunistic access and/or due to SINR violation (i.e., resulting from aggregate interference).
- Spectrum sensing threshold controls the tradeoff between the two outages.
- Increasing the spectrum sensing threshold decreases the frequency reuse distance and increases the opportunistic channel access, however, it increases the aggregate interference and hence the SINR outage.

Spectrum access schemes by cognitive small cells

- For a given spectrum sensing threshold, since the opportunistic spectrum access performance of the small cells will deteriorate when the intensity of the deployed small cells is high, introducing spectrum awareness at a small cell with respect to the spectrum usage at the other small cells may not be the best solution.
- Instead, cognition can be introduced only with respect to the macro-tier. That is, each SBS senses the spectrum to locate the channels which are not used by the MBS and uses any of them without considering the other SBSs (**scheme-2**).

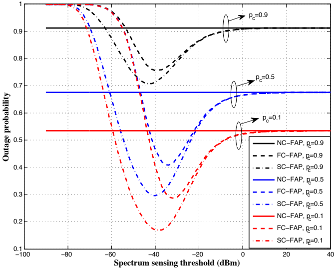
Spectrum access schemes by cognitive small cells

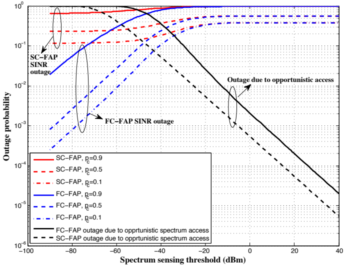
- Each time slot is divided into two main parts (**scheme-2**).
  1. *First part*: each cognitive small cell senses the available spectrum to detect the channels which are not used by the macrocell.
  2. *Second part*: each cognitive small cell selects one of the available channels and transmits in that channel.
- Channels will be aggressively used in the small cell tier to increase their opportunistic spectrum access performance at the expense of higher mutual interference in the small cell tier.



Performance gain due to cognitive spectrum access:

- Outage probability (of small cell users) vs. spectrum sensing threshold for cognitive techniques and different values p_c (= percentage of SBSs operating in the closed access mode)
- Outage due to SINR violation and outage due to unavailability of channel for opportunistic spectrum access for small cell users vs. spectrum sensing threshold for different cognitive techniques and different values p_c





Spectrum access schemes by cognitive small cells

- There exists an optimal spectrum sensing threshold that depends on the network parameters and the cognition technique.
- A higher value of spectrum sensing threshold results in shorter frequency reuse distances and more spectrum opportunities, however, the aggregate interference increases and dominates the outage probability. This results in a degraded outage performance.
- For very high values of spectrum sensing threshold, the cognitive small cells become very aggressive and their performance matches with that of the non-cognitive small cells.
- Lower values of spectrum sensing threshold result in higher frequency reuse distance and lower aggregate interference; however, the opportunistic spectrum access probability decreases and dominates the outage probability.

Summary of observations:

- For **scheme-1**, the decreased SINR outage probability is wasted by the outage probability due to the channel unavailability.
- The degraded SINR outage probability of **scheme-2** is balanced by the improved spectrum access probability.
- Cognition is an important feature that can significantly enhance the HetNet performance.
- Introducing cognition w.r.t. the macro-tier only is more beneficial than introducing cognition w.r.t. the two network tiers (due to uncoordinated access among densely deployed coexisting small cells).

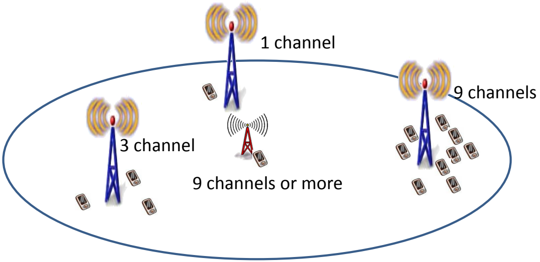
Spectrum access schemes by cognitive small cells

<u>Effect of channel allocation at the macro tier</u>:

- Two channel assignment techniques for the MBSs in in a two-tier network with cognitive SBSs: random channel assignment (RCA) and sequential channel assignment (SCA)
- RCA: each MBS randomly and uniformly chooses one channel for each of its associated users
- SCA: the available channels have a specific order and each MBS assigns the channels to its associated users in a sequential manner.
- RCA deteriorates the opportunistic spectrum access performance for cognitive SBSs.
- SCA minimizes the number of unique channels used by the coexisting MBSs (hence maximizes the opportunistic spectrum access performance for cognitive SBSs)

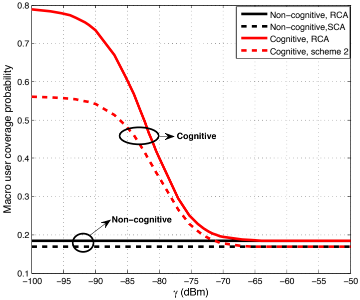
Spectrum access schemes by cognitive small cells

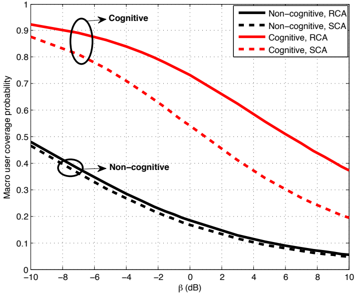
Channels available to a cognitive SBS for opportunistic access:



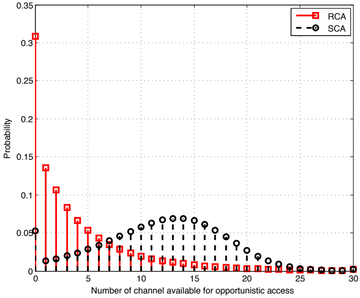
Effect of channel allocation at the macro tier:

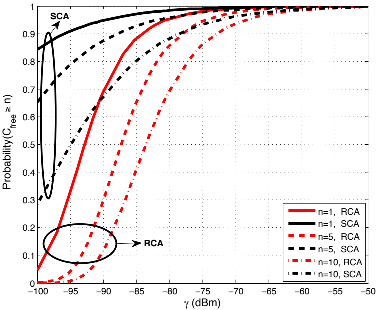
- SINR performance for macro users





- Opportunistic spectrum access for small cells





Clustering-based spectrum access by cognitive small cells

- The concept of clustering may be used to optimize the tradeoff between the outage due to opportunistic spectrum access and outage due to the aggregate interference.
- In clustering, adjacent small cells group together and elect a cluster head to coordinate the spectrum access within the cluster.
- Many challenges need to be addressed to implement clustering.
    1. What is the optimal cluster size
    2. What information is to be exchanged among the cluster members
    3. How to elect the cluster head
    4. What is the allocation strategy that maximizes the throughput in the small cells while maintaining fairness among the cluster members.

Future research directions

- Self-organization in presence of multiple radio access technology (multi-RAT) and inter-RAT cooperation (e.g., LTE and Wi-Fi integration)
- Self-organization by exploiting carrier aggregation in both access and backhaul links
- Backhaul-aware self-organization
- Context-aware self-organization
- Self-organization for energy efficiency
- Self-organization of small cell networks in the TV band
- Reliability analysis and redundancy design for self-organizing small cell networks
- Security issues in the self-organization of small cells

Book on small cell networks