

Heterogenous Networks

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Introduction

- It is envisioned that there will be **50 billion** connected devices by **2020**.
- Demands for higher data rates continues to increase multi-fold. .
- Major shift towards transporting mobile multi-media data applications.
- High-quality video streaming, social networking and **M2M** communication over wireless networks are growing exponentially.
- Providing real-time voice and high-speed data services without considering energy saving is a big challenge.

- Hence, a new paradigm called heterogeneous networks (**HetNet**) are being considered by network operators.
- Considered as the basis of evolution to fifth generation (**5G**), that can cost-efficiently improve system coverage and capacity [1].
- Some other emerging technologies which may make up future 5G are:- Software Defined Cellular Networks (**SDN**), Massive **MIMO** and 3D **MIMO**, **M2M** Communications
- **HetNet** is expected to play an important role to create an optimal customer experience, especially in crowded areas.

[1] V. Chandrasekhar, et. al., "*Femtocell Networks: A Survey*", in IEEE Communications Magazine, vol. 46, September 2008.

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- **HetNet** involves a mix of radio technologies and cell types working together seamlessly.
- Deploys short-range, low-power, and low-cost base stations operating in conjunction with the main macro-cellular network infrastructure.
- Low power nodes (**LPNs**) are deployed to eliminate coverage holes in outdoor and indoor environments.
- Also increases the capacity/area of the network.
- **LPNs** include micro, pico, Remote Radio Heads (**RRH**), relay and femto nodes.

HetNet: System Overview

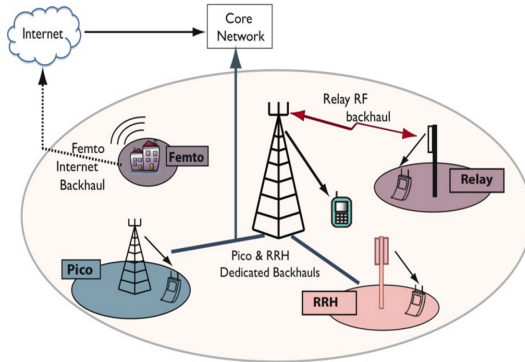


Figure 1: System model of a Heterogeneous Network.

- Macro base stations (**MBSs**) are high power nodes (**HPNs**) that supports extended coverage and high mobility.
- **LPNs** supports high achievable data rates in the local coverage of some hot spots and spectrum holes.
- Macro cell maintains connectivity and mobility (**Control plane**) using lower frequency bands [2].
- Small cell provides high throughput data transport (**User plane**) using higher frequency bands[2].

[2] T. Nakamura, et. al., "*Trends in Small Cell Enhancements in LTE Advanced*", IEEE Communications Magazine, vol. 51, 2013.

- With the separation of control plane and user plane, small cells can now be switched off when there is no data to transmit.
- Thus provides additional benefits such as lower interference and energy saving.
- **HetNets** can operate with open access (small cell resources open for all users) and closed access (small cell resources restricted for closed group) modes.
- Technical requirements and corresponding work items have been recommended in **3GPP** Releases **10** and **11**.

[3] C. Hoymann, et. al., "*A Lean Carrier for LTE*", IEEE Communications Magazine, vol. 51, 2013.

- If **HPNs** and **LPNs** are located in same coverage area, access strategies used :- Overlay, Underlay & mixed.
- Overlay Strategy [4]
 - Allocates orthogonal frequency resources to **HPNs** and **LPNs** for the data transmission.
 - **LPNs** are allocated subchannels, not being used by the **HPNs**.
 - Co-channel interference (**CCI**) can be thus avoided under the low frequency resource utilization ratio.
- Underlay Strategy [4]
 - Spectral resources are shared between **HPNs** and **LPNs** for the data transmission.
 - Inter-tier interference (**ITI**) between the **HPNs** and **LPNs** is a challenge.

[4] Q. Zhao and B. Sadler, "A survey of dynamic spectrum access: Signal processing, networking, and regulatory policy", IEEE Signal Process. Mag., May 2007.

Underlay Strategy

- Spectral utilization ratio is enhanced.
- **ITI** is mitigated utilizing interference coordination and cancelation (**ICC**) in the PHY layer.
- **ITI** for underlay **HetNets** is strictly related to the access modes (open/closed).
- Constrained backhaul capacity and privacy concerns for UEs are the key challenges under open access mode.
- Non-listed closed subscriber group (**CSG**) members may face coverage hole under closed access modes.

- To overcome the disadvantages of these two access modes, hybrid model is used.
 - Some resources in **LPNs** are reserved for registered UEs.
 - Other resources are open and can be shared by roaming UEs

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- Developing practical techniques for managing interference (e.g, Inter-cell Interference (**ICI**)).
- Radio resource allocation and management.
- Degree of integration that can be achieved throughout the **HetNets**.
- Impact of deployment of femtocells and relays in the same cell.
- Robust Precoder design for non-ideal channel state information (**CSI**) and limited feedback scenarios.

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Interference Coordination and Cancellation

- Inter-tier and intra-tier interference are the technological bottlenecks to improve Spectral and energy efficiency (**SE**, **EE**).
- **Inter-Tier Coordinated Multiple Point (COMP) Transmission**

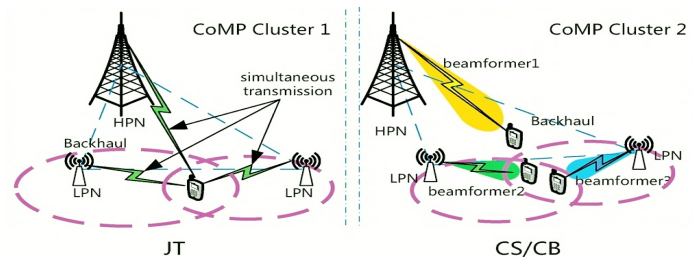


Figure 2: Main CoMP techniques (JT, CS/CB) in underlay HetNets

- **CoMP** technique is used for mitigation of inter-cell interference and **QoS** improvement for cell-edge UEs.
- Downlink **CoMP** is classified into joint transmission (**JT**), coordinated scheduling and coordinated beamforming (**CS/CB**).
- In a **JT** the data traffic is jointly transmitted by all transmission nodes within the same **CoMP** cluster.
- In **JT**, data for each UE needs to be shared among multiple BSs through the capacity-limited backhaul.
- If the number of cooperative BSs is large, this data exchange will result in a huge backhaul signaling overhead.

- For **CS/CB**, data traffic is transmitted only by serving BS.
- Corresponding beamformer is jointly calculated in a coordination to control the interference for a **CS/CB**.
- **JT** achieves higher average spectral efficiency than **CS/CB** but at the expense of more backhaul consumption.
- The performance of inter-**CoMP** highly depends on perfect knowledge of **CSI** and tight synchronization.

Inter-Tier Interference Alignment (IA)

- Multiple interfering signals are aligned within a reduced dimensional subspace at each receiver.
- Desired signal is left to transmit in an interference-free subspace.
- To mitigate interference, beamforming matrices for **LPNs** and **HPNs** are aligned to the nullspace of each others effective channels.
- However, **IA** requires perfect **CSI** knowledge and tight synchronization between cooperative transmitters

Interference Rejection Combining in Receiver

- Linear receivers improve capacity by suppressing multiple access interference, and also mitigates multipath fading.
- Some typical linear receivers are zero-force (**ZF**), maximal ratio combining (**MRC**), minimum mean square error (**MMSE**) and interference rejection combining (**IRC**).
- **ZF** and **MRC** receivers are interference-unaware.
- **MMSE** and **IRC** receivers account for the effect of co-channel interference and noise.
- When the interference is strong at the desired UE, then **MMSE** and **IRC** outperforms the **ZF** and **MRC** receivers.
- Successive interference cancellation (**SIC**) is another effective technique to combat interference.

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Resource Allocation in Underlay HetNets

- To maximize **SE** and **EE** performances radio resources should be optimized.
- Suppression of **ITI** in the PHY layer and adaptation to the traffic time-delay features should be crosslayer designed.
- Multi-Dimensional Radio Resource Allocation Optimization
 - Unplanned topology along with much higher interference magnitude and variability exists in **HetNets**.
 - Joint optimization including resource allocation, user scheduling, and cell association is necessary.
 - If the transmit power is fixed, the joint optimal resource allocation is a convex problem.
 - Under the adaptive power control situation, the problem is non-convex.

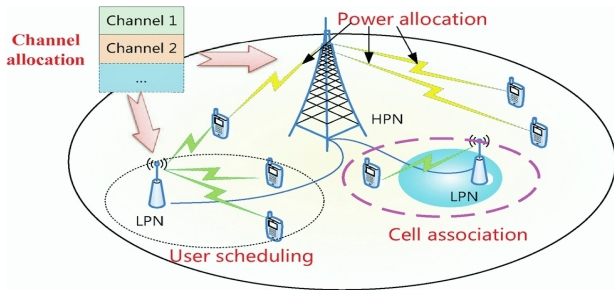


Figure 3: System model of multi-dimensional radio resource optimization.

• Cross-Layer Radio Resource Allocation Optimization

- To consider the **QoS** as well as mitigate interference at the PHY layer.
- Three main approaches to cross-layer optimization for underlay **HetNets**: Equivalent rate constraint, Lyapunov optimization and Markov decision process (**MDP**).
- The equivalent rate constraint approach is used to solve the cross-layer optimization problem by converting the average delay constraints (or objectives) into equivalent average rate constraints (or objectives) using queuing theory or large deviation theory.
- The Lyapunov optimization approach is used to solve the cross-layer optimization problem by converting the average delay constraints (or objectives) into minimizing the Lyapunov drift-plus-utility function.
- The **MDP** approach is a systematic approach in dealing with delayaware cross-layer resource optimization by solving the derived Bellman equation in a stochastic learning or differential equation manner.

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Self-Organizing Underlay HetNets

- Manually adjusting parameters in a multi-Dim. resource scenario becomes a complex, inefficient, error prone and costly task.
- May thus introduce large delays between parameter updates and resulting network-triggered events.
- Hence, future cellular networks may be equipped with intelligence and autonomous adaptivity.
- Self-organizing capability can be classified into self-configuration, self-optimization and self-healing.

- Self-configuration
 - Automated configuration of physical cell identity (**PCI**).
 - Automatic neighbor relation (**ANR**).
- Self-optimization
 - Coverage and capacity optimization.
 - Inter-cell interference coordination.
 - Energy Savings.
- Self-healing
 - Outage detection.
 - Outage compensation.
- Self organizing Networks related algorithms and approaches
 - Reinforcement Learning.
 - Multi-Objective Optimization.

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Quality of service over HetNet in 5G

- In [5], an end-to-end **QoS** support to application services over the **HetNet** is proposed.
- The proposed solution operates as per below framework
 - Traffics from different networks are identified and classified based on application type and **QoS** requirements.
 - Traffics are mapped to the most appropriate integrated **QoS** classes.
 - A suitable scheduling policy is then implemented.
 - Finally, the outgoing traffic is mapped back to the next set of network **QoS** classes.
- The proposed solution was showed to, improve performance of both real time and non-real time applications.

[5] A. Al-Shaikhli, et. al., "*Quality of Service Interworking over Heterogeneous Networks in 5G*", ICC , Malaysia, 2016.

- In [6], authors have presented the criteria of selecting cooperation strategies among Decode-Forward (**DF**), Compress-Forward (**CF**), and Amplify-Forward (**AF**) schemes in the Receiver Frequency Division Relay Channel(**RFDRC**).
- A joint power and bandwidth allocation optimization problem was considered for
 - a hybrid DF-CF scheme.
 - a hybrid DF-AF scheme.

[6] Z. Chen; et. al., "Cooperation in 5G Heterogeneous Networking: Relay Scheme Combination and Resource Allocation", IEEE Transactions on Communications

Interference Alignment and Cancellation (IAC)

- In [7], authors have proposed an **IAC** scheme for the uplink of **HetNets**.
- Random deployment of small cells and the heterogeneous deployment of macro cells and small cells results in complex interference.
- This makes the optimal **IAC** scheme hard to determine.
- Optimization problem is to maximize the number of data streams that can be transmitted in the network.
- The optimization problem formulated is an **MILP** problem which was solved by **MOSEK** solver in **CVX**.

[7] M. Sheng; et. al., "*Interference Alignment and Cancellation for the Uplink of Heterogeneous Networks*", in IEEE TVT 2016.

Network Flow and Resource Allocation

- In [8], authors have considered a **HetNet** consisting of a number of BSs and network routers connected via a backhaul network.
- An efficient distributed algorithm for joint resource allocation across the wireless links and flow control within backhaul network is proposed.
- Optimization problem is to maximize the minimum rate among all the users and/or flows.
- The proposed algorithm is based on a decomposition approach that leverages both the Alternating Direction Method of Multipliers (**ADMM**) and the **WMMSE** algorithm.

[8] W. C. Liao; et. al., "Max-min Network Flow and Resource Allocation for Backhaul Constrained Heterogeneous Wireless Networks", in ICASSP, Florence, 2014.

Interference Cancellation for HeNet with Massive MIMO

- In [9], authors have analyzed the user performance in a heterogeneous network with macro BS equipped with massive **MIMO**.
- High **DoF** introduced by massive **MIMO** can be utilized for interference cancellation .
- Thus, macro BS can project signals for macro users to the null space of interference channels from macro BS to pico users.
- An algorithm based on statistical **CSI** is proposed to maximize the overall network transmission rate by selecting the interference-free pico users.

[9] Y. Liu, et. al., "*Performance Analysis and Interference Cancellation for HetNet with Massive MIMO*", IEEE GlobalSIP, FL, 2015,

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Joint IA and Power Allocation in HetNet

- Macrocell and small cells reuse the same spectrum resources.
- UEs experiences severe co-channel interference (**CCI**).
- As the cell density increases classical resource management techniques are unable to cope with the additional interference.
- An advanced beamforming technique has been proposed for **IA** in [10].
- A **HetNet** can be configured into either closed subscriber group (**CSG**) or the open subscriber group (**OSG**) mode.

[10] V. R. Cadambe and S. A. Jafar, "*Interference Alignment and Spatial Degrees of Freedom for the K-User Interference Channel*", in International Conference on Communications, Beijing, 2008

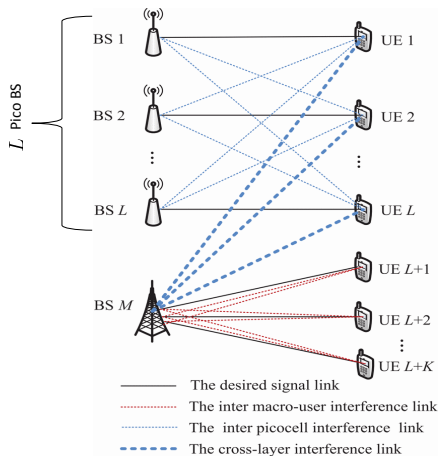
- **IA** schemes for **CSG** mode for a **HetNet** are proposed in [11]-[12].
- An **IA** scheme for the case of downlink **MIMO HetNet OSG** mode is proposed in [13].
- A power allocation scheme for the macro BS has also been proposed.
- System throughput is thus improved as the interference to pico UEs is further reduced due to power allocation scheme.

[11] H. H. Lee and Y. C. Ko, "*Linear Transceiver Design based on Interference Alignment for MIMO Heterogeneous Networks*", in PIMRC, Sydney, 2012.

[12] T. Akitaya and T. Saba, "*Hierarchical multi-stage Interference Alignment for Downlink Heterogeneous Networks*", in APSIPA, 2013

[13] Q. Niu; Z. Zeng; et al., "*Joint Interference Alignment and Power Allocation in Heterogeneous Networks*", in PIMRC, Washington DC, 2014

System Model



- N_{MT} Tx. antennas at BS M
- N_{PT} Tx. antennas at pico BS
- N_R Rx. antennas at UEs
- $\mathbf{V}_k$ Normalized Precoding Matrix
- $\mathbf{x}_k$ is the d-dim. transmitted symbols to UE
- $\mathbf{U}_k$ -Interference suppression matrix of UE
- $\mathbf{H}_{k,M}$ -channel matrix from BS M to UE k
- $\mathbf{n}_k \in \mathcal{CN}(0, \mathbf{I})$

Figure 4: Open Access Mode Underlay Heterogeneous Network

Interference to Macro UEs

- Each UE receives d -independent streams from its corresponding BS.
- Cross-layer interference from pico BS's to macro UEs can be negligible in **OSG** mode compared to **CSG** mode [14].
- Thus, inter macro-user interference is the main interference to macro UEs.
- Hence, received signal at UE k ($\forall k = \{L+1, \dots, L+K\}$) is given by

$$\mathbf{y}_k = \underbrace{\mathbf{U}_k^H \mathbf{H}_{k,M} \mathbf{V}_k \mathbf{x}_k}_{\text{desired signal}} + \underbrace{\sum_{j=L+1, j \neq k}^{L+K} \mathbf{U}_k^H \mathbf{H}_{k,M} \mathbf{V}_j \mathbf{x}_j}_{\text{inter macro - user interference}} + \underbrace{\mathbf{U}_k^H \mathbf{n}_k}_{\text{noise}} \quad (1)$$

[14] W. Shin et al., "Hierarchical Interference Alignment for Heterogeneous Networks with Multiple Antennas", in ICC, Kyoto, 2011

IA Scheme: Transceiver design for the Macro-cell

★ Design of the precoding matrix for macro BS

- Let,

$$\bar{\mathbf{H}}_{k,M} = [\mathbf{H}_{L+1,M}^T, \dots, \mathbf{H}_{L+k-1,M}^T, \mathbf{H}_{L+k+1,M}^T, \dots, \mathbf{H}_{L+K,M}^T]^T \quad (3)$$

- The singular value decomposition (SVD) of $\bar{\mathbf{H}}_{k,M}$ is

$$\bar{\mathbf{H}}_{k,M} = \bar{\mathbf{U}}_{k,M} \begin{bmatrix} \bar{\Sigma}_{k,M} & 0 \\ 0 & 0 \end{bmatrix} [(\bar{\mathbf{V}}_{k,M})^{(1)} (\bar{\mathbf{V}}_{k,M})^{(0)}]^H \quad (4)$$

- where column vectors of $(\bar{\mathbf{V}}_{k,M})^{(0)}$ are orthogonal basis for the null space of $\bar{\mathbf{H}}_{k,M}$
- Now, the SVD of $\mathbf{H}_{k,M}(\bar{\mathbf{V}}_{k,M})^{(0)}$ is

$$\mathbf{H}_{k,M}(\bar{\mathbf{V}}_{k,M})^{(0)} = \mathbf{U}_{k,M} \begin{bmatrix} \Sigma_{k,M} & 0 \\ 0 & 0 \end{bmatrix} [(\mathbf{V}_{k,M})^{(1)} (\mathbf{V}_{k,M})^{(0)}]^H \quad (5)$$

- So the precoding matrix of UE k is designed as

$$\mathbf{V}_k = (\overline{\mathbf{V}}_{k,M})^{(0)} (\mathbf{V}_{k,M})^{(1)} \begin{pmatrix} \mathbf{I}_d \\ 0 \end{pmatrix} \quad (6)$$

- The precoding matrix of BS M is $\mathbf{V}_M = [\mathbf{V}_{L+1}, \dots, \mathbf{V}_{L+K}]$
- To guarantee the existence of the null space of $\tilde{H}_{k,M}$, $N_{MT} > (K-1)N_R$.

★ Design of the interference suppression matrices for macro UEs

- To nullify the inter-stream interference and maximize the capacity of macro UEs, suppression matrix is required
- The interference suppression matrix can be designed as

$$\mathbf{U}_k^H = \mathbf{U}_{k,M}^H \quad (7)$$

Interference to Pico UEs

- Interference at pico UEs are due to inter pico-cell interference and the cross-layer interference from macro BS.
- So, the received signal at UE l ($\forall l = \{1, \dots, L\}$) is given by

$$\mathbf{y}_l = \underbrace{\mathbf{U}_l^H \mathbf{H}_{l,l} \mathbf{V}_l \mathbf{x}_l}_{\text{desired signal}} + \underbrace{\sum_{j=1, j \neq l}^L \mathbf{U}_l^H \mathbf{H}_{l,j} \mathbf{V}_j \mathbf{x}_j}_{\text{inter picocell interference}} + \underbrace{\sum_{k=L+1}^{L+K} \mathbf{U}_l^H \mathbf{H}_{l,M} \mathbf{V}_k \mathbf{x}_k}_{\text{cross-layer interference}} + \underbrace{\mathbf{U}_l^H \mathbf{n}_l}_{\text{noise}} \quad (8)$$

IA Scheme: Transceiver design for the picocells

★ Design of the precoding matrices for pico BSs

- Inter picocell interference is aligned onto the space of the strongest cross-layer interference, produced by the macro BS.
- Find a macro UE that receives the signal from BS M producing the strongest cross-layer interference to UE l .

$$l_m = \arg \max_{k \in \{L+1, \dots, L+K\}} \|\mathbf{H}_{l,M} \mathbf{V}_K\|_2^2$$

- Align the inter picocell interference to UE l onto the column space of $\mathbf{H}_{l,M} \mathbf{V}_{l_m}$.
- To ensure the solution exists, $N_{PT} \geq (L-1)N_R$ should be satisfied.

★ Design of the interference suppression matrices for pico UEs

- Interference suppression matrix should be in the left null space of the $\mathbf{ICI}$.
- Thus, interference suppression matrix is an orthogonal basis for the null space of $[\mathbf{H}_{l,M} \mathbf{V}_{l_m}]^H$.

Power Allocation Scheme for the macro BS

- Rest interference although relatively weak, still has a great impact on the rate of pico UE's.
- The proposed power allocation scheme consists of the following two steps.
 - Step 1. For each macro UE k , find certain pico UEs, to which BS M transmitting data to macro UE k leaks the strongest cross-layer interference.
 - Step 2. Allocate the power of BS M to the macro UEs, ensuring that the weighted sum of macro UEs receiving power and the eliminated cross-layer interference power is maximized.

★ Optimization problem of the proposed power allocation scheme is

$$\begin{aligned} & \max_{\{P_k\}, k \in \{L+1, \dots, L+K\}} \sum_{k=L+1}^{L+K} \lambda_k P_k \\ & s.t. \quad \sum_{k=L+1}^{L+K} P_k = P_M \\ & \quad P_k \geq 0 \end{aligned} \tag{9}$$

- where λ_k is the weighted sum of macro UEs receiving power and the eliminated crosslayer interference power
- P_M denotes the total power of BS M .
- (9) is a linear programming (**LP**) problem and can be solved efficiently with the Simplex method.