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Capacity Analysis and Hybrid Power Allocation for Multi-cell Cellular Networks

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Outline

- The booming data transmission leads to a rapidly **increasing demand for data services with limited power and spectrum resources.** Therefore, it would be of great significance to utilise the spectrum resources efficiently and adjust the power allocation to improve the energy efficiency and achieve higher capacity.
- Among all these heterogeneous cellular networks, the basic structure is the hexagonal grid for the BS. **And by applying frequency reuse methods, the utilisation of spectrum resources will be more efficient and serve a larger area with these methods.**
- Fractional Frequency Reuse (FFR) and Soft Frequency Reuse (SFR)[1] schemes have been evaluated as **inter-cell interference (ICI) mitigation methods** to increase network capacity in a two-tier Orthogonal Frequency Division Multiple Access (OFDMA) based multi-cell deployed next generation wireless network[2].

[1] (Abbas et al. 2020; Novlan et al. 2011)

[2] (Han et al. 2017; Garcia-Morales, Femenias, and Riera-Palou 2019)

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The major contributions are summarized as follows:

- Introduce a method for constructing an multi-cell network that allows an arbitrary number of cells in a network.
- Propose Hybrid Power Allocation method in FFR combining SWF, FWF and IFR to get high network capacity and serve as many users as possible.
- The comparison between the sFFR and SFR schemes validated through Monte-Carlo simulation.

Abbreviations

SWF: Simultaneous Water-Filling; FWF: Forward-Looking Game Water-Filling;
sFFR: Strict Fractional Frequency Reuse; SFR: Soft Frequency Reuse.

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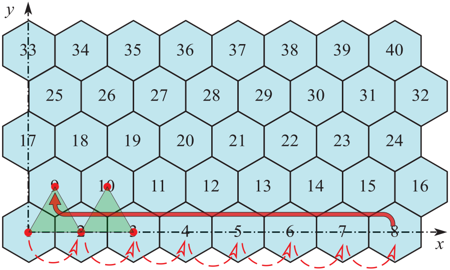
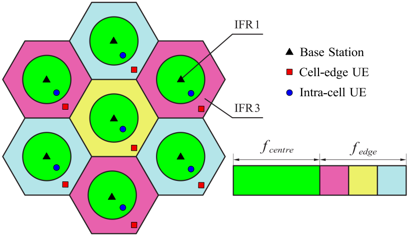
Here is a method of multi-cell generation



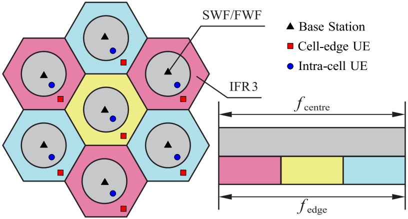
- A network consists M cells $M = R(row) \times C(column)$;
- From left to right, from bottom to the top;
- Use the mathematical relation between adjacent cell centres.

The green triangle shows the relation between each cell centre and also help to find the relation between the odd and even rows.

Strict FFR Scenario



SFR Scenario



- Apply IFR1 (IFR3) for cell centre (edge) in a typical 7-cell network;
- No co-channel interference between cell centre and cell edge for sFFR;
- SFR scenario serves more users at the expense of the network capacity.

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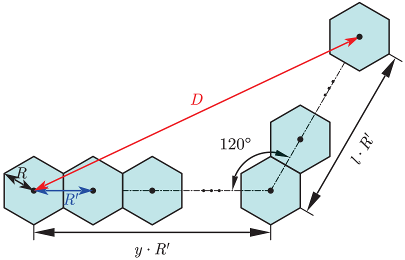
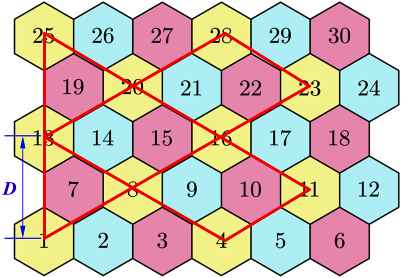
The schematic of identifying IFR cell groups





- The Frequency Reuse Factor (FRF), $N = \frac{D^2}{3R^2}$;
- Based on cosine law for sides, $D = \sqrt{3N}R$;
- Apply **Deep-First-Search** algorithm to get corresponding group information.

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The capacity analysis of IFR with different FRF

Consider a M-cell network, the capacity for the frequency channel f in the cell i can be calculated by

$$C_f^{i,u} = \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{\left|h_{i,i}\right|^2 p_i^u}{\sum_{j=1}^{M} \rho_{j,i} \left|h_{j,i}\right|^2 p_j + \sigma^2} \right) (i \neq j). \tag{1}$$

Thus, the capacity of a network using IFR can be derived as

$$C_{\mathsf{IFR}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i} C_f^{i,u}. \tag{2}$$

$h_{i,i} \rightarrow$ channel coefficient, $\rho_{j,i} = D_{j,i}^{-\alpha}$ ($D_{j,i} \rightarrow$ distance between cell j and i)

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The network capacity analysis of sFFR

The capacity of all cell centres in the network is given by

$$C_{\text{centre}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i^1} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{|h_{i,i}|^2 p_1^f}{\sum_{j=1}^{M} \rho_1^{j,i} |h_{j,i}|^2 p_1^f + \sigma^2} \right). \tag{3}$$

The capacity of all cell edges in the network is given by

$$C_{\text{edge}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i^2} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{|h_{i,i}|^2 p_2^{u,f}}{\sum_{j=1}^{M} \rho_2^{j,i} |h_{j,i}|^2 p_2^{u,f} + \sigma^2} \right). \tag{4}$$

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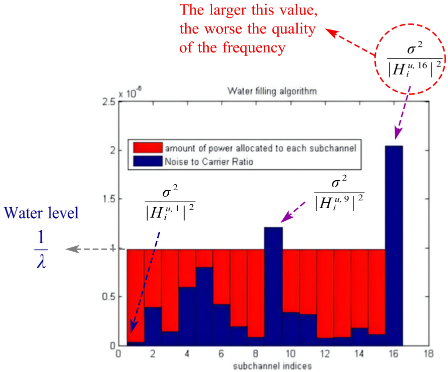
The network capacity analysis of SFR

$$C_{\mathsf{SFR}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{|h_{i,i}|^2 p_i^{u,f}}{I_1 + I_2 + \sigma^2} \right),$$
$$I_1 = \sum_{j=1}^{M} \rho_1^{j,i} |h_{j,i}|^2 p_1, I_2 = \sum_{j=1}^{M} \rho_2^{j,i} |h_{j,i}|^2 p_2^{u,f}, \tag{5}$$

Both IFR and FFR are still rigid and inflexible

- Some cells may not have enough frequency channels to serve their users even if some other cells do not need their frequencies;
- Even if there are abundant frequency resources, they cannot be used to improve the capacity for the active users.



Start with cell 1

Start with user 1

$$\text{Repeat}\begin{cases} p_i^{u,f} = \left(\frac{1}{\lambda} - \frac{\sigma^2}{|H_i^{u,f}|^2}\right)^+, \\ \sum_{f=1}^{N_i} \left(\frac{1}{\lambda} - \frac{\sigma^2}{|H_i^{u,f}|^2}\right)^+ = P_{\max}, \\ \text{Move to another user} \end{cases}$$

Until convergence

Get the optimal power allocation scheme

- The total capacity with constraining for one user is given by
- $\max_{\{p_i^{u,f}\}} C_{\mathsf{SWF}}^u = \sum_{f=1}^{N_i} \log_2\left(1 + \frac{p_i^{u,f}|H_i^{u,f}|^2}{\sigma^2}\right)$, s.t. $\sum_{f=1}^{N_i} p_i^{u,f} \leq P_{\max}$.

Forward-looking Water-filling constructs a self-optimising OFDMA cognitive radio network that approaches forward-looking equilibrium(FE) (Ren and Wong 2018) The power allocation for user u at time t is updated by (6) using the previous power allocation information,

$$
\begin{aligned}
p_u^t[f] &= \left(w_u^t - \frac{\left(c_u^t[f]\right)^2 + \varphi_u^t[f]\left(p_u^{t-1}[f]\right)^2}{c_u^t[f] - \varphi_u^t[f] p_u^{t-1}[f]} \right)^+, \\
\varphi_u^t[f] &= -\sqrt{\frac{c_u^t[f]}{2c_u^t[f] + p_u^{t-1}[f]}} \quad \forall u.
\end{aligned} \tag{6}
$$

where $c_u[f] \triangleq \sigma_u[f] + I_u[f]$ corresponds to the overall noise on the frequency channel f for user u.

Forward-Looking Game Water-Filling (FWF)

Based on the above power updating scheme, the network capacity using FWF for user u is

$$\begin{aligned} \max_{\{p_i^{u,f}\}} \; & C_{\mathsf{FWF}}^{u} = \sum_{f=1}^{N_i} \log_2\left(1 + \frac{p_u^t[f]|H_i^{u,f}|^2}{\sigma^2}\right), \\ \text{s.t.} \; & \sum_{f=1}^{N_i} p_i^{u,f} \le P_{\max}. \end{aligned} \tag{7}$$

As for the entire network, the capacity maximization problem can be formulated as

$$\begin{aligned} \max_{\{p_i^{u,f}\}} \; & C_{\mathsf{FWF}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i} C_{\mathsf{FWF}}^{u}, \\ \text{s.t.} \; & \sum_{f=1}^{N_i} p_i^{u,f} \le P_{\max}. \end{aligned} \tag{8}$$

Hybrid Power Allocation Algorithm

To serve more user and reduce the co-channel interference.
In this paper, we design a hybrid FFR power allocation iterative algorithm, as shown in Algorithm 1.

Algorithm 1 Proposed hybrid power allocation algorithm

Initialize system parameters M, $P_{\max}$, N, U, $p_{\max}$, ρ, h, σ^2

Set the maximum iteration times $T_{\max}$ and the convergence accuracy δ, set the initial iteration index $t = 0$.

while $\sum_{u=1}^{U_i} \sum_{k=1}^{N_i} \left| p_u^{t+1}[k] - p_u^t[k] \right| \geq \delta$ and $t \leq T_{\max}$ **do**

  Calculate $p_u^t[k]$ using (6) for all the cell centre.

  Calculate the capacity in all the cell centre,

$$C_{\text{centre}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{p_u^t[f] |H_i^{u,f}|^2}{\sigma^2} \right).$$

  Calculate the capacity in all the cell edge,

$$C_{\text{edge}} = \sum_{i=1}^{M} \sum_{u=1}^{U_i^2} \sum_{f=1}^{N_i} \log_2 \left(1 + \frac{\left| h_{i,i} \right|^2 p_2^{u,f}}{\sum_{j=1}^{M} \rho_2^{j,i} \left| h_{j,i} \right|^2 p_2^{u,f} + \sigma^2} \right).$$

  Calculate the overall network capacity: $C_{\text{FFR}} = C_{\text{centre}} + C_{\text{edge}}$.

  $t = t + 1$.

end while

- First, find the optimal values of all variables of (6) or (7) in each iteration.
- After that, the network capacity can be calculated based on the power allocation scheme.
- And to find the optimal capacity, we get into the next iteration with former information until it converges.

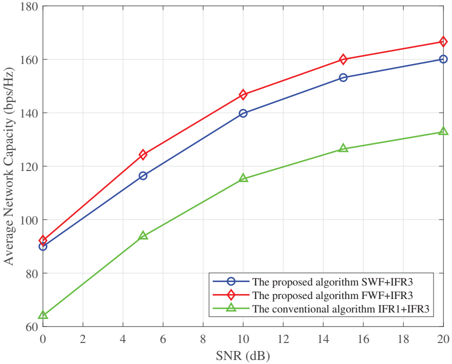
Parameter Settings

- A 30-cell network
- Six frequency channels for a cell centre (edge)
- Radius of the cell centre (edge): 150 m (200 m)(Sun et al. 2018)[1]
- $U_c = 12$, $\alpha = 3$, $T_{\max} = 300$
- With 12 UEs:
  $p_{\max} = 35.2$ dBm, $P_{\max} = 46$ dBm(Saleh, Le, and Sesay 2018)

Algorithm Comparisons

- FWF (cell centre) + IFR3 (cell edge)
- SWF (cell centre) + IFR3 (cell edge)
- IFR1 (cell centre) + IFR3 (cell edge)

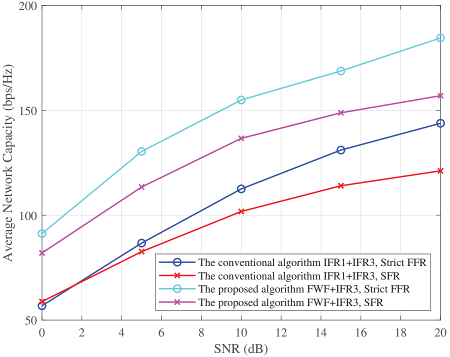
[1] This cell radius setting has weaker interference but has lower spectral efficiency in most cases.



- ✓ SWF+IFR3 is **20% higher** than IFR1+IFR3;
- ✓ FWF+IFR3 has a **3%** improvement compared to SWF+IFR3;

Also, the simulation results reveal that with the same amount of frequency channels, **the FWF+IFR3 can reach a higher network capacity and serve more users simultaneously.**

Capacity comparison between sFFR and SFR



- ✓ Highest capacity→FWF+IFR3;
- ✓ Capacity: FWF+IFR3 (SFR) >IFR1+IFR3 (sFFR);
- ✓ With 50% of spectrum resources, the algorithm reaches nearly 80% of the original capacity.

By applying the FWF+IFR3 for SFR scenario, the network capacity is found to be smaller than the sFFR scenario but still greater than applying a conventional algorithm for both scenarios.

Conclusion

- Introduce a construction method for an multi-cell network that allows an arbitrary number of cells;
- Apply DFS in indentifying the cell group and allocate the frequency channel more efficiently.
- Proposed hybrid power allocation methods combining SWF, FWF and IFR to get high network capacity and serve more users with fast, flexible and intelligent supply.

Outlook

- The results provided intriguing insights into an Multi-cell power allocation behaviour, which might be beneficial in designing and implementing future power allocation.

Reference I

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Thank You
Q & A

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