

Comparison of Different Frequency Allocation Methods for Suburban Areas based on Capacity Analysis

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Abstract: From the first generation (1G) to the fifth generation (5G), an upward trend in demand has been witnessed as wireless technology contributes to more aspects in the daily life of ordinary people. A similar pattern is likely to be seen in the next decade as sixth generation (6G) networks are deployed. Researchers are having a stronger incentive in frequency planning in order to bring a better experience to users. Therefore, by collecting capacity data for a network of nineteen cells with an average of five users and twelve channels per cell, different frequency allocation methods from 1 decibel (dB) to 20 dB (dB) are investigated for their superiority in suburban areas based on the comparison of capacity. The experiments conducted in this paper show that cellular networks outperform Fractional Frequency Reuse (FFR) and that the more intelligent the frequency allocation method, the higher the capacity. Therefore, telecommunication providers may consider prioritizing the 19-cell Forward Looking Game (FLG) method in areas with low population density.

Keywords: Frequency Allocation, Fractional Frequency Reuse.

1. Introduction

Since 1980, when the first mobile phone (1G) was invented, wireless communication has rapidly evolved, with one generation per decade. The majority of the world's population uses 4G and 5G networks, and 5G+ and 6G networks may be available in ten years. People now utilize voicemail, text messaging, and Internet-based data communication in their daily lives. With faster internet and less interference, drones could serve as taxis instead of cars [1], cognitive radios could sense the environment and adjust operating parameters dynamically [2], and the internet of things (IoT) connected disparate technologies to support intelligent decision making and enable new applications [3]. Therefore, smarter frequency allocation methods must be implemented. Because of the absence of overlap, the hexagonal cellular network [4] is utilized more than a single base station serving a large area. The smallest unit of a hexagonal cellular network is OFDMA (Cell). The experiment will employ a network of hexagonal cells. The following topics will be discussed: reuse cells, reuse factor, Pathloss loss, shadowing, Signal-to-Interference-plus-Noise-Ratio, and Thermal noise.

Due to spectrum constraints, information signals are transmitted over multiple frequency channels. Spectrum conservation requires frequency reuse across cells. Procedure for selecting reuse cells: Choose a cell. Move k hexagonal cells in any direction perpendicular to the edge of the hexagonal cell. Next, turn 120 degrees counterclockwise and advance l cells. The destination cell uses the source cell's frequency set.

The Frequency Reuse factor (N) is defined as the number of channel sets (cells) in a reuse pattern, which is related to the numerical number of k and l .

$$N = \frac{A}{a} = (k^2 + kl + l^2) \quad (1)$$

N is the reuse factor, A is the area of the group, a is the area of the cell, k and l are the distance moved before and after tilting anti-clockwise. The allowable reuse pattern is 1, 3, 4, 7, 9, 12, 13, ...

According to the Pathloss formula, the received power has positively related to P_t (transmit power), G_t (transmit antenna gain), G_r (receive antenna gain), and λ (wavelength) and inversely related to d (the distance traveled). The formula can be generalised as below:

$$P_r = P_0 d^{-\alpha} \quad (2)$$

P_r is the received power, P_t is the transmit power. The α here is the Pathloss Exponent. Different values can be taken for different scenarios and environments.

The SIR in a more realistic situation, the user may lie on the cell edge, a more accurate method of calculating SIR is:

$$SIR = \frac{R^{-\alpha}}{\sum_l D_l^{-\alpha}} = \frac{1}{\frac{2(Q+1)^{\alpha} + (Q-1)^{\alpha}}{(Q^2-1)^{\alpha}} + \frac{(Q+0.5)^{\alpha} + (Q-0.5)^{\alpha}}{(Q^2-0.25)^{\alpha}}} \quad (3)$$

R is the radius of cell, D is the distance between reuse cells, α is the Pathloss Exponent. l is the total number of other reuse cells. Q is the ratio of the distance between reuse cells and the radius of cell. Fractional Frequency Reuse (FFR), which is purposed as a ICIC technique based on the cellular network [5] could reduce the interference due to cell-edge users are using different sets of channels and the SINR for interior users are reduced as well [6] by separating the centre and edge of cells physically.

2. Method

2.1 The structure of cellular network

In the experiment, the 19-cell network shown below is used.

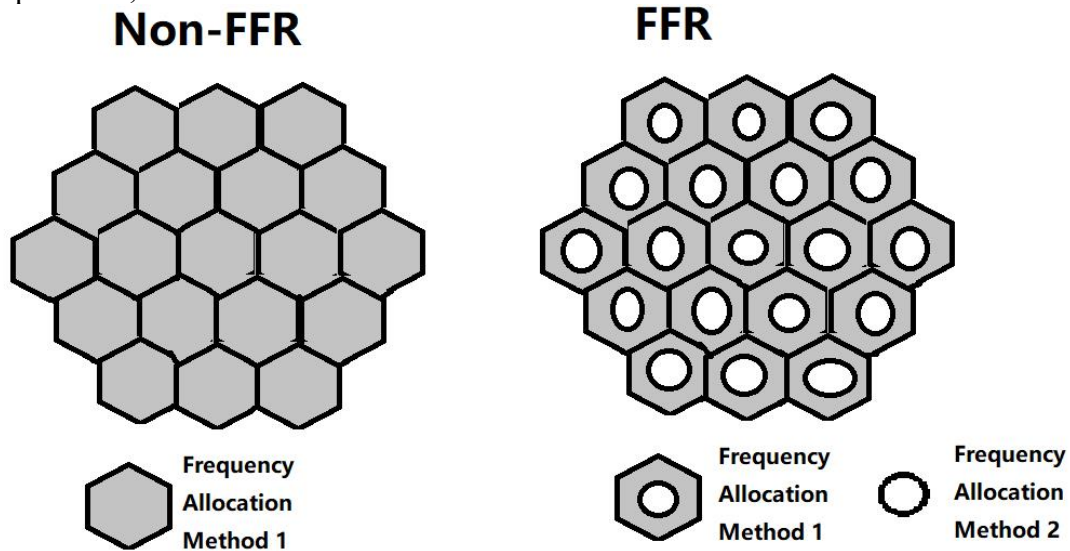


Figure 1. Assumed 19 cell network

For Non-FFR methods, all the cells use the same frequency methods. For FFR methods, the frequency allocation methods at the centre and the edge are not the same. The rho value in the rho matrix is determined according to the distance between the two cells (k and l). The rho values are summarised in the below table.

Table 1. rho value and k and l respectively

(k, l) or (l, k)	Forecasting
(1, 0)	0.8
(1, 1)	0.6
(2, 0)	0.4
(2, 1)	0.2
(3, 0)	0.1
(2, 2)	0.05

2.2 The frequency allocation method utilized

In this paper, Integer Frequency Reuse [7], Simultaneous Water-Filling [7], Transmit Interference Temperature Limit [8] and Forward-Looking Game [9] are used and comparison is made. The Shannon's limit suggests that:

$$C = W \log_2(1 + \text{SINR}) \quad (4)$$

C is the capacity. W is the bandwidth. SINR is the Signal-to-Interference-and-Noise Ratio.

2.2.1 Introduction to IFR1

IFR1 is the Integer Frequency Reuse with $N=1$, the frequencies are reused in neighboring cells which leads to the most interference. The total capacity formula is shown:

$$C_{\text{total}} = \sum_n C_n = \sum_n \log_2 \left(1 + \frac{|h_{n,n}|^2 P_n}{\sum_{m \neq n} |h_{m,n}|^2 P_m + \sigma^2} \right) \quad (5)$$

Where P_n is the transmit power from the base station 'n', $h_{n,n}$ is the channel from base station 'n' to the user 'n', $h_{m,n}$ is the channel from base station 'm' to the user 'n', P_m is the transmit power from the base station 'm', σ^2 is the noise power.

2.2.2 Introduction to IFR3

IFR3 divides total number of channels in a cluster into 3 sets equally which leads to slightly less interference than IFR1. The formula is shown as following:

$$C_{\text{total}} = \sum_n C_n = \sum_n \log_2 \left(1 + \frac{|h_{n,n}|^2 P_n}{\sum_{m \neq n} |h_{m,n}|^2 \rho_{m,n} P_m + \sigma^2} \right) \quad (6)$$

Where P_n is the transmit power from the base station 'n', $h_{n,n}$ is the channel from base station 'n' to the user 'n', $h_{m,n}$ is the channel from base station 'm' to the user 'n', P_m is the transmit power from the base station 'm', σ^2 is the noise power, $\rho_{m,n}$ means the parameter that adjusts the amount of interference from cell m to cell n

2.2.3 Introduction to Simultaneous Water-Filling (SWF)

SWF is a method which users are free to access all channels allocates power inversely related with the Noise-to-carrier ratio. The total capacity is:

$$C_{\text{total}} = \max_{\{P_f\}} \sum_{f=1}^{N_c} \log_2 \left(1 + \frac{P_f |H[f]|^2}{\sigma^2} \right) \quad (7)$$

Where N_c is the number of channels, P_f is the transmit power at frequency f, $|H[f]|^2$ is the channel for each frequency, σ^2 is the noise power. S.t. $P_1 + P_2 + P_3 + \dots + P_{N_c} \leq P$. The formula for the water-level is:

$$\sum_{n=1}^{N_c} \left(\frac{1}{\lambda} - \frac{\sigma^2}{|H[f]|^2} \right)^+ = P \quad (8)$$

Where N_c is the number of channels, $|H[f]|^2$ is the channel for each frequency, σ^2 is the noise power. The notion is defined as $(x)^+ = \max\{0, x\}$. However, users tend to use the same channels for SWF which leads to interference. [10].

2.2.4 Introduction to tx-ITL

By introducing a parameter named interference temperature limit (S_k), meaning the average channel interference power which enables users to control interference level through comparing it with $c[n]$ while using tx-ITL. The formula is as following:

$$\text{Repeat} \begin{cases} p_k[n] = \begin{cases} (w_k - c_k[n])^+ & \text{if } c_k[n] \leq S_k, \forall n \\ 0 & \text{if } c_k[n] > S_k \end{cases} \\ \sum_{n=1}^N (w_k - c_k[n])^+ = P_k \\ \text{Move to another user until convergence} \end{cases} \quad (9)$$

w_k , is the water-level for the k-th user, $c_k[n]$ is the inverse SINR on the n-th frequency for the k-th user, P_k is the power budget for the k-th user. A more advanced tx-ITL is then proposed that the S_k could self-optimize to a reasonable value for each user. S_k could be calculated in the following method:

$$\tilde{S}_k = \max \left(S_k, \frac{\sum_{n=1}^N I_k[n] \text{sgn}(p_k[n])}{\sum_{n=1}^N \text{sgn}(p_k[n])} \right) \quad (10)$$

$I_k[n]$ is the interference power for user k in frequency channel n , $\text{sgn}(p_k[n])$ is the sign power for user k in frequency n . It is one if the channel is used. Otherwise, it would be zero.

2.2.5 Introduction to Forward-Looking Game (FLG)

FLG is a method utilising the game theory that could help to self-optimize so users could have minimum interference. The formula is addressed below:

$$\begin{cases} p_k[n] = \left(w_k - \frac{c_k^2[n] + \varphi_k[n] p_k^2[n]}{c_k^2[n] - \varphi_k[n] p_k[n]} \right)^+ \\ \varphi_k^*[n] \geq -\sqrt{\frac{c_k^*[n]}{2c_k^*[n] + p_k^*[n]}} = -\sqrt{\frac{1}{2 + \frac{p_k^*[n]}{c_k^*[n]}}} \end{cases} \quad (11)$$

$c_k[n]$ is the sum of the noise power and the interference power over the channel. $p_k[n]$ on the Right-hand-side of the first formula is the old power for user k in channel n . $p_k[n]$ on the Left-hand-side of the first formula is the new power for user k in channel n . φ_k is a chosen value depends on $c_k[n]$ and $p_k[n]$.

3. Results

3.1 The establishment of simulation model

It was chosen due to Matlab's ease of use and utility. When the main programme code is executed, 100 simulations are generated for each data point. Separate code plots the capacity (bps/Hz) versus average SNR (dB). The simulation assumes that each cell has 12 channels. In FFR systems, there are the same number of central and peripheral channels. Five users are assigned to each cell on average, and there is an equal chance of being in the centre or on the perimeter. Actual users in a cell may deviate from the average number and adhere to a Poisson distribution. The maximum transmit temperature is 3.5, and the alpha value is 0.9 for all txITL methods.

3.2 Analysis of experimental results

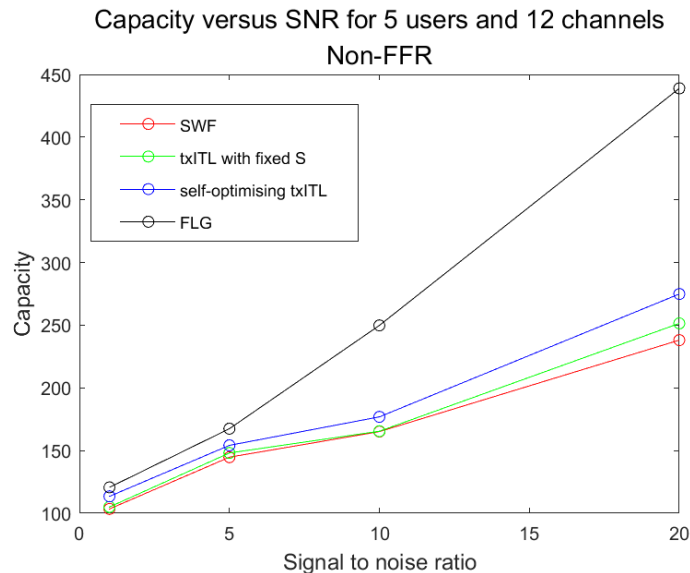


Fig 2. The capacity versus SNR for Non-FFR methods

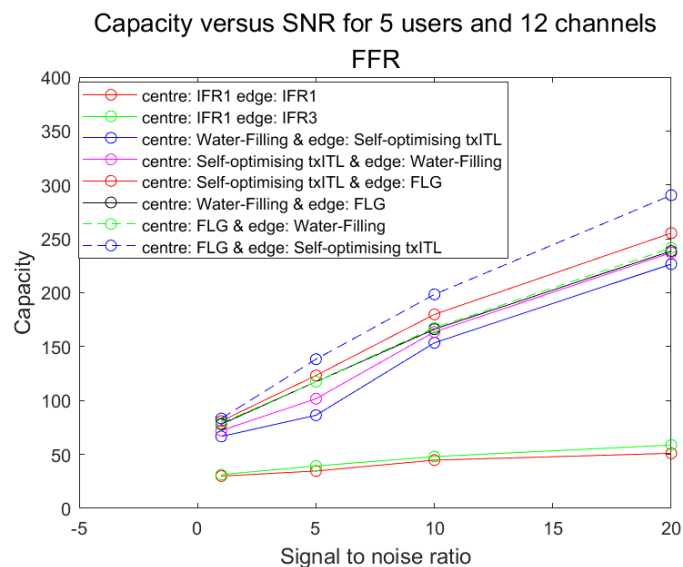


Fig 3. The capacity versus SNR for FFR methods

The graph reveals a positive correlation between capacity and SNR, which can be attributed to the interference reduction capabilities of SNR. In terms of capacity, Non-FFR methods perform better than FFR methods on average. Even if users are not separated by cell and edge, there are sufficient channels for the use. If more users are located in the centre or on the edge while channels are distributed equally, users may have to compete for a limited number of channels while others remain unused. The FLG outperforms all other methods, indicating that the more intelligent a method is, the greater its capacity, assuming that all other parameters remain constant. Those FFRs with centre as IFR1 and IFR1 or IFR3 have much lower capacities than the remaining methods due to the fact that IFR can only simultaneously serve one user per channel, making them the two methods with the lowest capacity. For other FFR, the smarter the chosen method (FLG txITL SWF), the greater the capacity (assume the method chosen for another part of the cell is fixed). If an FFR employs two methods and another FFR employs the same two methods but swaps the centre and edge methods, the FFR with the smarter method in the centre has a higher capacity. This is because the central users are closer to the base station, resulting in stronger channels.

4. Conclusions

To conclude, the FFR are not necessary to be implemented in low population dense areas, Since FLG performs the best among all the frequency allocation methods, FLG is the most recommended technique for telecommunication providers.

References

- [1] Yun, Won & Jung, Soyi & Kim, Joongheon & Kim, Jae-Hyun. (2021). Distributed deep reinforcement learning for autonomous aerial eVTOL mobility in drone taxi applications. *ICT Express*. 7. 10.1016/j.ict.2021.01.005.
- [2] S. Haykin, "Cognitive radio: brain-empowered wireless communications," in *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, Feb. 2005, doi: 10.1109/JSAC.2004.839380.
- [3] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," in *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 2347-2376, Fourthquarter 2015, doi: 10.1109/COMST.2015.2444095.
- [4] Wu, Shengna & Yang, Jun & Peng, Rui & Zhai, Qingqing. (2020). Optimal design of facility allocation and maintenance strategy for a cellular network. *Reliability Engineering System Safety*. 205. 107253. 10.1016/j.res.2020.107253.

- [5] Himayat, N. & Talwar, Shilpa & Rao, Anil & Soni, Robert. (2010). Interference management for 4g cellular standards [WIMAX/LTE update]. Communications Magazine, IEEE. 48. 86 - 92. 10.1109/MCOM.2010.5534591.
- [6] T. D. Novlan, R. K. Ganti, A. Ghosh and J. G. Andrews, "Analytical Evaluation of Fractional Frequency Reuse for OFDMA Cellular Networks," in IEEE Transactions on Wireless Communications, vol. 10, no. 12, pp. 4294-4305, December 2011, doi: 10.1109/TWC.2011.100611.110181.
- [7] H. Chen, B. Huang and C. Wu, "Simulation and Analysis of Simultaneous Water-Filling Allocation Based on Fractional Frequency Reuse for 19-Cell Network," 2021 International Conference on Electronics, Circuits and Information Engineering (ECIE), 2021, pp. 240-244, doi: 10.1109/ECIE52353.2021.00058.
- [8] Ren, J., Wong, KK., Khandaker, M.R.A. (2019). Autonomous Spectrum Sharing by Well-Designed Games. In: Zhang, W. (eds) Handbook of Cognitive Radio. Springer, Singapore. https://doi.org/10.1007/978-981-10-1394-2_14
- [9] J. Ren and K. -K. Wong, "Cognitive Radio Made Practical: Forward-Lookingness and Calculated Competition," in IEEE Access, vol. 7, pp. 2529-2548, 2019, doi: 10.1109/ACCESS.2018.2886607.
- [10] S. Liu, X. Zheng and B. Wang, "Analysis of the Capacity of Different Frequency Channel Allocation Method in the Simulated Amusement Park," 2021 International Conference on Wireless Communications and Smart Grid (ICWCSG), 2021, pp. 168-178, doi: 10.1109/ICWCSG53609.2021.00041.