Analysis and Optimization of Channel Capacity Based on Modified IFR Algorithm

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Abstract. Message passing can be communicated over different frequency channels at the same time. With the rapid development of the wireless system, more and more wireless applications have to compete for limited spectrum resources. These days, however, the spectrum vacancy is a serious issue that has aroused many studies. Therefore, how to make use of the resource properly has become a very significant problem to be mitigated. In this paper, we first study the frequency allocation by analyzing the capacity through using the Soft Frequency Reuse (SFR) system model applied in the Cellular Networks and building up a basic SFR model. Then we analyze the influence of the temperature by modifying the interference temperature model into a basic IFR model to find the impact on the environment. Finally, this result for IFR is extended to our SFR model to study the influence of the environment for SFR.

In this model, as our expectation, with the ratio of cell radius over the center radius grows, the network capacity increases. However, due to the spectrum's shortage, this upward trend does not emerge significantly when the ratio is over 0.75. Considering factors related to temperature, even in the simplest environment, the influence of thermal noise cannot be ignored. Therefore, it is crucial to put temperature into account when simulating a more complex model in an environment similar to the real world.

1. Introduction
The idea of frequency reuse is initially proposed by Bell Laboratories in 1947 [2], which is the cornerstone of cellular mobile communication. Because of the spectrum shortage, usually, the number of channels is not sufficient in wireless communication. In this case, this problem can be solved by frequency reuse. Due to the attenuation characteristics of electromagnetic wave propagation in space, when a frequency is used in an area, the power has been attenuated a lot far away from the area. The interference has been reduced to an acceptable level so that the frequency can be reused. With the development of OFDM technology, the FFR technique is proposed aiming to mitigate average Co-channel interference [1][3][4]. But there are still many defects in frequency reuse. In practice, the distribution of users will affect the capacity of the network. However, to achieve higher data rates, LTE deployments with smaller cell size are required, due to transmission power limitations in mobile terminals [2][5]. SFR is considered as one of the most representative approaches to solve this problem due to its effectiveness [6][7].

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But there are still some deficiencies in the SFR scheme that need to be improved. An improved SFR scheme named the Softer Frequency Reuse (SerFR) scheme was suggested in 2008 [8]. In SerFR scheme, the cell-edge users have access to all of the resource blocks (RB) using a proportional fairness scheduling algorithm to increase the cell-edge users’ throughput. Interference management has been proposed to improve network quality as well [9]. By allocating resources to inter-cell interference coordination (ICIC), interference can be minimized over time and space. Considering the multi-service requirement, the scheme has developed the SFR scheme at the point of quality of service (QoS) and distribution [10].

On the other hand, the temperature analysis is mainly based on the interference temperature model raised by the Federal Communications Commission (FCC) to improve the efficiency of the spectrum to be used [11]. In this paper, the analysis of the temperature especially focuses on the thermal noise with the utilization of the interference temperature model. This interference temperature model had many problems with the detection of the temperature by the year 2005. The same year, to overcome these troubles of detection, A. P. Hulbert and S. Mangold et al. (2005) proposed a new spectrum protocol to avoid the interference between the authorized users and unauthorized users [11]. This is a new turning point for analyzing the interference model, which has drawn more researchers’ attention to this topic.

The simulation in this paper on the influence of temperature only takes advantage of the concept of the authorized users and unauthorized users. Therefore, every two cells are grouped as one pair with one user each to simulate authorized users and unauthorized users respectively. Besides, the number of frequency channels is assumed to be 18. Boltzmann’s model is used as well to simulate the effect of temperature. In this way, the system can be influenced by the thermal noise and find its influence by analysing the magnitude of the system's quality as a result. With the use of the Rayleigh Fading, which has a better channel performance [12], the simulation firstly tests the IFR model for the origin (without the influence of the thermal noise) 19-cell Cellular Networks and have a comparison with the modified model, which considers the effects of the temperature.

The method we propose will bring some benefit in acknowledging the use of the spectrum and the value of the communication quality. Under this cognitive, it also benefits from determining whether the model is realistic by simulating the model under the interference of temperature.

2. Method
In this section, we will discuss our method in detail.

\section{SFR model}
In the proposed scheme, SFR is the basis for allocating frequency resources. In this model, frequency bands are divided into several parts. Each cell chooses a part of the frequency band as the main carrier, while the minor carrier is the remaining portion. Consider a cellular network system made up of M cells (the number of cells in network structure $m = 1, 2, 3, \ldots, M$) with each having a bandwidth divided into non-overlapping bands as shown in Fig. 1. According to the carrier's transmission range, each cell is divided into two parts: the center and the outer edge.

![Fig. 1 System model for SFR](image)
Different power is allocated with different bandwidth for each signal, which is shown in Fig. 2 below. Pmajor and Pminor is the power of the signal carrier, and Bmajor, Bminor is the bandwidth of the signal. The total system bandwidth B is the sum of the bandwidths belonging to the set of M cells.

Consider slow fading (path loss and shadowing) in signal transmission. Under the conditions that the channel between each base station is H. Based on these conditions, the signal-to-noise ratio for each user is:
\[ \text{SINR}_m = \frac{S}{I+N} = \frac{p_m |H_{i,m}|}{p_m \rho_{i,m} |H_{i,m}| + \sigma^2} \]  

(1)

Where \( p_m \) is the power of the transmitter in cell \( m \) and \( H_{i,m} \) is the channel coefficient from base station \( i \) to the cell \( m \). \( \rho_{i,m} \) stands for interference coefficient of base station \( i \) to the users in cell \( m \), which is inversely proportional to distance:

\[ \rho_{i,m} = d_{i,m}^{-\alpha} \]  

(2)

Where the \( \sigma^2 \) is the system thermal noise power and \( \alpha \) is the pathloss exponent.

In the SFR system, the minor carrier is the main carrier of its adjacent cell, so the minor carrier's interference may come from the major carrier or minor carrier of the adjacent cell. The interference signal strength on different subcarriers may be different, and the average throughput of the cell can be expressed as follows:

\[ C = B \log_2 (1 + \sum \text{SINR}) \]  

(3)

Where \( B \) is the bandwidth of the signal, \( \sum \text{SINR} \) is the sum of SINR of \( M \) cells in the whole network.

A simulation system has been developed to evaluate the cell prediction and its relationship with the area ratio and power ratio. The simulation parameter is provided in Table 1.

| Parameter name                  | Unit     |
|---------------------------------|----------|
| The number of cells             | 10       |
| Radius of cell center           | 100 m    |
| Radius ratio                    | 0.5      |
| Signal-to-noise ratio           | 0~10dB   |

In this scheme model, the power in the cell edge is larger than the power in the cell center due to the path loss at the edge is usually higher than that at the center. To observe the relationship between capacity and interference more clearly, the bandwidth coefficient of the above formula is discarded.

2.2. The analysis of the temperature (thermal noise)

To find the temperature's influence, we simplified the model and made the variable number of channels \( (Nc) \) to be 18. It can be written as \( fc = [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18] \). Also, we make the reuse number \( N \) be 10, which means that for every two adjacent cells, they use the same frequency set, and therefore the interference will only occur in these two cells. We have to keep the number of users in each cell to be 1 because for the single interference model, we can directly make use of the noise power formula if more than 1 authorized users connected to the authorized users, i.e., the cells are not grouped into 2, the thermal noise cannot be used directly, and we have to consider the nonlinear problem. The simplified model is illustrated below. The cells in the same color show that they share the same frequency set so that they are influenced by each other.
Fig. 3 The simplified system model for analysis of temperature

In this model, cell 1 and 2 share the frequency channel 1 while cell 3 and 4 share frequency channel 2. The rest can be done in the same manner. There is an inadequacy where for cell 19, the number of allocated frequency channels is not enough. Still, since this basic model will be used in the other simulation, and to make every simulation’s basic information the same, we will keep cell 19 being idle.

For the interference between each cell, we use the Rayleigh fading model, which means that the signal received will be affected by the interference between each user and the noise of the environment, and the Channel fading coefficient \( h \) (which indicates the interference generated between each user) obeys normal distribution. From the Shannon equation, we have:

\[
C = \log_2(1 + SINR)
\]  

(3)

Here, \( C \) represents the channel capacity and \( SINR \) is the Signal to Interference plus Noise Ratio, which is expressed as follows:

\[
SINR = \frac{P_t |h(m,n)|^2}{\sigma^2 + I}
\]  

(4)

The \( P_t \) in this formula is the transmit power, \( h(m,n) \) is the Channel fading coefficient between cell \( m \) and cell \( n \), where

\[
h(m,n) = \frac{randn + i \times randn}{\sqrt{2}}
\]  

(5)

\( \sigma \) is the noise power, and \( I \) indicates the interference between different cells and for different users.

In this model, the noise power is related to the SNR and \( P_t \), so it can be expressed as:

\[
\sigma = \sqrt{\frac{P_t}{SNR}}
\]  

(6)

For SNR, it is an experienced value that is set to be 10 here.

The interference here depends on many factors, including \( \rho(m,n) \), a parameter to adjust the amount of interference from cell \( m \) to cell \( n \), \( h(m,n) \) and the transmit power from the base station (cell) \( m \) (if we consider the cell \( n \) is the cell received the power transmitted from cell \( m \)). As every user and cell can have interference, so in formula (4), \( I \) is the sum of all the interference from the first cell to the last one (in this model is 1 to 19) and it is expressed as:

\[
I = \sum \rho(m,n)|h(m,n)|^2 P_m, m \neq n
\]  

(7)

For the IFR model without the interference temperature, both the transmit power are set to be 1 to simplify the model. However, the power is changed and the access user in cell \( n \) just reaches the interference temperature limit when accessing the frequency for the modified one, as a result. Moreover, since we choose to use the Rayleigh fading in the IFR model, the performance of the model (reflect by the result of the capacity magnitude) is optimal [12], so the interference of temperature can be illustrated.
more clearly. Equation (8) [1] is the optimal solution. Therefore, cell \( n \) will not disturb the working environment of cell \( m \).

\[
P_t = kTB \times \left( \frac{4\pi L}{\lambda} \right)^2
\]  

(8)

This equation uses a measuring point in the main base station (can be regarded as a cell) \( m \) and the \( L \) in this reference is the distance between the measuring point and the user who wants to access. Here I simplified the \( L \) to be the distance between the main cell \( m \) and the access cell \( n \). In figure 4, it is represented by the symbol ‘d’. Besides, \( k \) is the Boltzmann’s constant, which is \( 1.38 \times 10^{-23} \) JK\(^{-1} \), \( T \) is the noise temperature in Kelvin, \( B \) is the channel’s bandwidth. \( \lambda \) is the Carrier frequency wavelength and the term \( \left( \frac{4\pi L}{\lambda} \right)^2 \) in this expression can be seen as a coefficient because the value of them in the simulation is fixed [14].

There is also some small alternation on the parameters in equation (4) and (7). \( P_t \) in equation (4) is kept to be 1 and multiplied a coefficient to maintain the same order of magnitudes between the numerator and denominator. In fact, there should be a variable ‘r’ in equation (4) [1], but in our model, we assume the radius of the cell to be 1 [16].

![Fig. 4 Illustration of the distance parameter](image)

And for equation (7), \( \sigma^2 \) is replaced by \( P_t \) without the term \( \left( \frac{4\pi L}{\lambda} \right)^2 \), which is inverted and multiplied to the interference. The modified formula is expressed in equation (9). Here, the replacement happened because \( K^*T^*B \) is a kind of noise power in Boltzmann's model.

\[
\text{SINR} = \frac{1 \times |h(m,n)|^2}{P_t^2 + i^2} \quad (9)
\]

3. Results and Discussion

Using the same parameters as earlier, the simulation model of SFR is constructed. In this model, the number of cells is set to 10.

Network topology diagram and user distribution in randomly selected cells are shown in Fig. 5. With this diagram, Fig. 6 shows the average capacity versus signal-to-noise (SNR) relationship. It is noted that the network capacity increases with the increase of the SNR. With a high SNR, each cell has a high capacity because of its low noise level.
Fig. 5 Network topology

Fig. 6 Average capacity as a function of SNR

Fig. 7 shows the network's capacity when the ratio is different, where the ratio is the ratio of cell radius and center radius. The cases where ratio = 0.15, 0.25, 0.50, 0.75 are shown separately. The result shows that when the ratio increases, the network increases while its ratio remains the same. The network structure had turned out to be similar to Integer Frequency Reuse with reuse factor 1 (IFR1) when the ratio increased. As the ratio becomes lower, the edge part becomes the dominant part of the whole cell. Two-thirds of the spectrum is allocated to the edges. With the continuous decline in the ratio, the utilization of one-third of the spectrum is declining, resulting in a decline in network capacity.

When the ratio is set to 0.75, the capacity of the network does not increase because the frequency allocation to the cell center is only one-third of the total frequency band B. Therefore, the shortage of spectrum limits the growth of network capacity.
Fig. 7 Average capacity comparison ratio as a function of SNR

For the temperature, we first compare the model’s capacity and do not take the interference temperature and the one that contains it into account. As the parameter $h$ is selected randomly, the result here is the average capacity after 500 times simulations. In reality, the temperature is only meaningful during the 250K to 320K, so the simulation will not be extended to a higher or lower temperature.

In figure 8, the red line represents the modified model's data with the influence of temperature, while the blue one is for the original model. In the simulation, other parameters used are: $\text{SNR} = 10$; $L = 100\text{m}$; $\lambda = 0.25\text{m}$; $B = 6\text{GHz}$, the value of which is selected based on previous researches in 2010 [15][16].

![Network Capacity](image)

**Table 2. Simulation Result.**

| Parameter position (x-axis) | Red Capacity Magnitude (bps/Hz) | Blue Capacity Magnitude (bps/Hz) |
|----------------------------|---------------------------------|----------------------------------|
| 1                          | 97.72                           | 27.06                            |
| 35                         | 27.1                            | 27.3                             |
| 300                        | 26.83                           | 7.759                            |
The yellow line in figure 9 represents the error between the original model and the temperature consideration model. From the results shown in figure 9, we can see that under this situation, if the interference of temperature is not considered, the average capacity is stable at around 27 bp/Hz shown by the blue line. When the interference temperature is considered, the capacity decreases with the increase of the temperature (red line). Before these 2 lines meet, the ideal capacity magnitude is around 27 bps/Hz. Still, for the modified model, which considers the facility’s temperature, it is around 98bps/Hz, being about 71bps/Hz higher than that of the ideal model.

Figure 9 also shows the difference in the capacity between the two models in the yellow line. It grows with the increase of the temperature and will finally stay at around 20 bps/Hz. This difference is acceptable. However, if we use the multi-user interference model, which means that $N = 3$, $N_c = 18$, and the average user grows to 3. The result of the IFR is shown below in figure 10:

From the result above, we can see that the error is around 40 bp/Hz (yellow line), and this error is 2 times greater than the error in the result of the single user interference model. What’s more, the magnitude of capacity error here almost reaches the same level as the original model, which is
inappropriate. This interference temperature model we built is befitting only the single interference model where the user in each cell is 1.

The capacity of SFR and the capacity of IFR both rely on SNR. Under the same condition, the capacity will show the same tendency. The result in figure 9 is applied to the simplified IFR model. However, the same principle can also be applied to SFR. From the simplest IFR model, we can find that in equation (9), the term "environment noise $\sigma$" can be replaced by the thermal noise, therefore, in the model of SFR, since the same SINR calculation method is used as that of IFR, the noise term can also be replaced by thermal noise. This means if $\sigma$ in SFR is replaced by Boltzmann’s formula, the magnitude of the capacity concerning the temperature will be similar to the result in IFR. That is, as the temperature goes high, the capacity will reduce, and the trend is the same as before.

4. Conclusion
Initially, we build up an SFR model in the Cellular Networks and test its performance. As we expected, the network capacity grows as the ratio of cell radius over-center radius increases until 0.75. After 0.75, this increase gets less significant because of factors such as the shortage of spectrum. Besides that, we can say that under the simplified model we build, the temperature will be as a kind of noise and affect the capacity. Still, when the temperature is too small, which means that the temperature kept from 0 to around 35 K, the temperature is meaningless because of the facility, the working environment cannot reach that low and is unpractical. During the temperature period 250 to 300 K, the temperature is much more suitable for the equipment in real life to work, and we can calculate that the difference between them is around 15 bps/Hz to 21 bps/Hz. Therefore, we can say that the temperature will affect the quality of the capacity, and it, to some extents, can disturb the transmission of the information because even in the simplest environment, the difference between the capacity is around 20 bps/Hz, where the loss is around 74%. So, we can prove that in the simplest situation, thermal noise exists, so do in other situations.

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