

# Cellular Cluster Channel Allocation Using an Edge Weight Frequency Assignment Algorithm

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## Abstract

In cellular networks, the cells are grouped more densely around highly populated areas to provide more capacity with antennas pointed in accordance with local terrain and clutter to reduce signal shadows and interference. Hardware parameters are easily set during installation and hard to change afterwards. In a dynamic environment of population migration, parameters should be continuously tuned to adapt the network performance. Modern mobile network equipment logs network usage patterns and statistics over time, which can be used to tune soft parameters of the network. The tuned parameters may include frequency channel assignment or reuse and transmitter radiation power assignment to provide more capacity on demand with minimal interference. The paper proposes a practical solution to the frequency assignment problem which takes into account the interference, traffic intensity and edge biasing using priority flags. An edge weight frequency assignment algorithm is presented to solve the frequency assignment problem. The algorithm uses traffic intensity, measured interference, and priority settings to determine edge weights of the network. An edge represents a potential interference connection between a pair of base stations. With the edge weights the vertex degrees can be calculated and assigned or re-assigned a channel to the highest degree vertex leading to the lowest network deficiency score. An analysis of the performance of the algorithm is also provided. The use of edge weights in frequency assignment offers a practical optimization solution to a service provider keeping cost down by re-directing resources to where they are most needed in a network with priority settings.

**Keywords:** Channel allocation; Interference score; Traffic intensity score; Priority flags; Frequency assignment; Optimisation

## Introduction

In cellular networks the most limiting factor in the desired quality of service is usually interference. The interference is two forms: co-channel interference and adjacent channel interference. Co-channel interference arises from neighbouring transmitters using the same frequency channel. Adjacent channel interference is a result of practical filters being imperfect with a slow rise or fall around the pass and stop bands. Even when transmitters are assigned different channels, leakage into adjacent channels can still occur leading to interference. This interference is less severe in its nature and some level of service can still be achieved.

Radio spectrum is an expensive resource in many countries around the world. Usually, an operator buys bandwidth which is segmented into carrier channels. These channels need sufficient spacing between them to serve as a guard band against co-channel interference. The Global System for Mobile communications 900 up-links on a 890 MHz to 915 MHz band with a 200 KHz channel spacing is required which leads to only 124 carriers [1]. As the operator's customer base grows in particular areas, the 124 carriers will be insufficient to handle the traffic.

A base station (BS) and mobile terminal pair are the basic components of a cellular network structure. A mobile terminal is served by a BS whose signal is the strongest. When a mobile changes its location such that the strongest signal is now from another BS, a hand-off process is initiated such that the new BS now serves that mobile terminal. To cover the whole intended area, several BS's are placed at strategic points around that area forming a cell. Each cell uses a different set of frequency channels from the neighbouring cell to avoid interference. A group of cells using all the available frequencies in a network is referred to as a cluster of cells. The BS's normally houses omnidirectional transceiver with cells represented by hexagonal

shapes. As the number of users increase, the channel capacity of the cell decreases.

In order to increase channel capacity, the traditional solution involves subdividing large cells into smaller cells, each with its own base station with a much reduced transmit power. Directional antennas are used so that a transmitter covers some sector of an intended area. In addition, frequency re-use with transmitter power control can be used to mitigate co-channel interference. These solutions provide an increased capacity since the cell is now covered by more base stations.

In this paper we address the frequency assignment problem and offer its solution by proposing and analysing the performance of an Edge Weight Frequency Assignment Algorithm (EWFAA). We show that by using edge weights and assigned network priorities, resources can be directed to where they are needed thereby saving costs for service providers.

## The Frequency Assignment Problem

Considering a cluster of  $N$  cells as a graph  $G = (V, E)$  with  $N$  vertices  $v_i \in V$ , for,  $i \in [1, N]$ , where  $V$  is a set of vertices, and the edges connecting  $v_i$  and  $v_j$  represented as  $[v_i, v_j] \in E$ , for the edge set  $E$ . Vertex  $v_i$  and  $v_j$  will be connected by an edge if some interference is experienced

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in that link. Using graph colouring algorithms the available channels can be allocated with the objective that no adjacent vertices get the same colour. Classical graph colouring algorithms mainly tackled this hard interference constraint. However, when the chromatic number of the graph is greater than the available number of channels, no perfect solution can be found resulting in some residual interference being experienced. This is the case in practical systems hence the task now will be to minimize interference as much as possible. This motivated the need for another class of algorithms which solve this relatively soft interference model [2,3].

Modelling cellular networks as connected graphs in order to optimize them is not a new phenomenon. Taking this approach meant that the researchers instantly had available to them the rich area of mathematical graph theory to tackle such problems, especially frequency assignment. The frequency assignment problem has been treated as an extension of the graph-colouring problem [4]. Initially the biggest interest was in using the smallest number of colours to colour the graph such that no two adjacent vertices had the same colour. This is known as the chromatic number of a graph. This is a combinatorial problem, which falls in the class of problems known as NP-complete. Taking a step ahead of the chromatic number, we learn of the  $k$ -colouring problem of the graph. This is colouring a graph such that the sum of weights of the edges between the adjacent vertices with the same colour is minimized [4].

More advanced methods of sharing the limited channels have been developed. Multiple access techniques are further meant to allow many users to share the limited bandwidth in a most efficient manner and in a scalable way that would not compromise the quality of the system for already existing users. Frequency division multiple access (FDMA) is a type of narrow band system in which the available spectrum is divided into a large number of equal size smaller frequency bands or channels, with a guard band between adjacent channels to maintain satisfactory performance of the system. The data gets transmitted in parallel instead of serially hence making the most of the available bandwidth. A variation of this in the time domain is when users are put on the same channel but allocated unique time slots with some separation in time as a guard band. This means transmissions from separate users are never allowed to overlap. This is known as time division multiple access.

Throughput in dynamic FDMA systems can be increased by up to 15% for each mobile terminal when dynamic methods are applied as opposed to using a constant number of channels throughout [5]. Apart from demonstrating the use of multiple access schemes in channel assignment, the work also optimized the network channel assignment for the practical condition of fluctuating traffic.

## The Optimisation Process

To fine tune the network, input data must be based on measured data from drive tests (indicating the actual interference levels) and statistical data for traffic intensities per cell logged into servers. The influence of this data as inputs to the algorithm is then reflected on the edges of the graph. To bias the algorithm for or against some edges accordingly, one other input of priority settings will be required.

## Computing edge weights

Edge weights must place particular bias towards what is considered a major hindrance or advantage. For example, it may be that customers often complain about loss of signal in some unpopulated area. In that case the major concern would be to increase the signal-to-interference ratio while taking care not to divert the problem elsewhere. In another

case, it might be that customers around a heavily populated area have raised concerns about the network quality in which results of a drive test reveal interference as the cause. This presents a more sensitive case susceptible to the 'balloon effect'. In this case altering a single parameter can have adverse effects to neighbouring customers. Therefore the edge weight function must take into account interference levels, traffic intensity and priority flags between cells.

**Interference level scores:** Before defining a possible range of scores, it is worth establishing the different levels of effects a particular parameter can have on the network. The severity of interference can be grouped into three categories as observed from drive test results,

1. No significant interference with good quality reception.
2. Moderate interference; calls are possible, but have slightly poor quality.
3. Severe interference which nearly always results in dropped calls.

We can assign interference scores in two ways, either linearly or non-linearly. For instance in the linear case, for the green colour between cells say  $v_i$  and  $v_j$  we assign a value  $f_{ij} = 0$  to indicate that there is no observed interference. Then for yellow/orange  $f_{ij} = 0.5$  and finally for the red  $f_{ij} = 1$ . In the non-linear case, for the green it is  $f_{ij} = 0$ , whereas for the yellow/orange we may have  $f_{ij} = 0.25$  and for the adverse case  $f_{ij} = 1$ , which better highlights the discrepancy between no calls at all and somewhat poor quality calls. The choice largely depends on the drive test results. If most of the network experiences adverse interference levels, then the linear case can be adopted as most customers are affected anyway. The non-linear case tends to suit a case where very few people are experiencing poor coverage compared to others within the cell-cluster. Given  $N$  cells or vertices, the result is an  $N \times N$  interference matrix,

$$F = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1N} \\ \vdots & \vdots & & \vdots \\ f_{N1} & f_{N2} & \cdots & f_{NN} \end{pmatrix}$$

Where  $f_{ij} = f_{ji}$  due to symmetry that arises from considering interference between cell pairs. If the cell  $v_i$  is not connected to  $v_j$ , then  $f_{ij} = 0$ . Since we cannot consider the interference of a cell or antenna on itself,  $f_{ii} = 0 \forall i \in [1, N]$ .

**Traffic intensity score:** From the daily/weekly/monthly traffic statistics reports, it is possible to get a good estimate of the expected traffic intensity per cell. This value can assume a wide range; therefore it is best to assign a fraction less than unity to a particular pair of cells within a cluster, such as

$$t_{ij} = \frac{\text{cell pair traffic}}{\text{et cluster traffic}} = \frac{t_i + t_j}{t_i} \quad (3.1)$$

Note that the value  $t$  is the sum of traffic from cell  $v_i$  and cell  $v_j$  divided by the total traffic in the cluster of cells considered. This results in the traffic intensity matrix

$$T = \begin{pmatrix} t_{11} & t_{12} & \cdots & t_{1N} \\ \vdots & \vdots & & \vdots \\ t_{N1} & t_{N2} & \cdots & t_{NN} \end{pmatrix}$$

where  $t_{ij} = t_{ji}$  due to symmetry. If cell  $v_i$  is not connected to  $v_j$  then  $t_{ij} = 0$ . Since we cannot consider the interference of an antenna on itself,  $t_{ii} = 0 \forall i \in [1, N]$ .

**Priority flags:** The traffic intensity matrix  $T$  assumes an equal level of priority to all customers, yet there are those regions in the network that must always have good quality coverage. For example, it may be that some big company is on contract with the network provider in which case it is a must to make sure that they receive good service. A priority flag can be used to amplify/reduce an edge weight to place bias on the concerned cells. For  $N$  cells, this results in the  $N \times N$  matrix

$$P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1N} \\ \vdots & \vdots & & \vdots \\ p_{N1} & p_{N2} & \cdots & p_{NN} \end{pmatrix}$$

where  $p_{ij} = p_{ji}$  due to symmetry. If there is no priority to set, then the default value is  $p_{ij} = 0$ , whereas for high priority a value of 1 is used for  $p_{ij}$ . To emphasize less priority, then  $p_{ij} < 1$ .

**5.1.3 The Edge weight function:** Given that between the cells  $v_i$  and  $v_j$  the traffic intensity score is  $t_{ij}$  and these customers are affected by interference level of  $f_{ij}$  at a priority flag  $p_{ij}$  then the edge weight between these cells is given by

$$w_{ij} = p_{ij} e^{t_{ij}} p_{ij} e^{f_{ij}} \quad (3.2)$$

This means that the edge weight matrix  $E$  is a point-to-point multiplication of the interference matrix  $F$ , traffic intensity matrix  $T$  and the priority matrix  $P$ . We choose a non-linear model for interference level scores hence the exponentiation of that term. This is justified as most times its a few people in a network that experience adverse interference which rapidly degrades call quality, refer to section 3.1.1. The Poisson distribution is normally used to model the arrival rate of random variables; this model suits the arrival rate of calls in a BS [6].

## Radio network deficiency

A radio network is a communication system that comprises of multiple radio signal transmitters and receivers arranged to serve a small area known as a cell. These radio networks often do not perform to their optimal design capacity, it is under these situations that the network is said to have a deficiency. Current Network Deficiency is the level at which the network is under performing that can be measured or calculated at the present time, whereas predicted network deficiency is the level of under performance of the network that one can estimate will happen if the value of one or more current parameters were to change to another value. Using this concept of current and predicted network deficiency, the network provider can estimate ahead of time how changes in core parameters like frequency channels; traffic etc. can lead to improved or worse results using the edge weight function in equation (3.2).

**Current Network Deficiency:** From the computed edge weights, the vertex degree for cell  $v_i$  when assigned the frequency channel  $c_r$  for  $r \in [1, K]$ , given  $N$  cells is

$$D_{c_r}(v_i) = \sum_{j=1}^N w_{ij} = \sum_{j=1}^N p_{ij} e^{t_{ij}} p_{ij} e^{f_{ij}} \quad (3.3)$$

Which gives a measure of the deficiency associated with  $v_i$  in conjunction with other cells when it is assigned the frequency channel  $c_r$ . The net deficiency of the current frequency plan is thus

$$D = \frac{1}{2} \sum_{i=1}^N D_{c_r}(v_i), \quad r \in [1, K] \quad (3.4)$$

**Predicted network deficiency:** Given a set of frequency channels  $c_1, c_2, \dots, c_K$  to avoid adjacent-channel interference there is usually a

minimum frequency spacing  $|c_i - c_j| \geq s_{ij}$  such that the receiving unit can filter out signals from neighbouring cells (filter roll-off requires guard-bands), where  $s_{ij}$  is the required spacing between channels assigned to cells  $v_i$  and  $v_j$  for  $i, j \in [1, N]$ . Co-channel interference is avoided by spacing cells such that their coverage area does not overlap. Usually adjacent-channel interference results in moderate scores of say  $f_{ij} = 0.5$  for the linear case and 0.25 for the non-linear case when  $0 < |c_i - c_j| \leq s_{ij}$ . It is when cells with overlapping coverage areas are assigned the same frequency that it usually results in  $f_{ij} = 1$ . It is essential to predict the net frequency plan deficiency (based on the current measurements) to evaluate if a new assignment is beneficial or not. The predicted scores also serve as a check for the termination condition when there is no predicted improvement to the current plan.

Suppose from the current frequency plan it is cell  $v_i$  which has the highest vertex degree of the  $N$  cells. From a pool of available channels, we assign  $v_i$  a new channel that yields the minimum possible degree. This is done via a predicted vertex degree

$$D_{c_m}^{(n)}(v_i) = \sum_{j=1}^N p_{ij} e^{t_{ij}} p_{ij} e^{f_{ij}} \quad (3.5)$$

Where the superscript  $n$  indicates the number of frequency assignments so far. That is, there is a prediction with every new assignment. Using (3.3) and (3.4), the predicted deficiency of the possible new frequency plan is

$$D^{(n)} = \frac{1}{2} \sum_{i=1}^N D_{c_m}^{(n)}(v_i) \quad (3.6)$$

Where  $m \neq r$  and  $m \in [1, K]$ . A possible assignment is only approved if  $D^{(n)} > D^{(n+1)}$ , because the deficiency will be reduced. It is possible that the predicted vertex degree for the vertex of choice  $v_i$  be less than its current deficiency when assigned a different frequency channel, yet the net deficiency of the new frequency plan be worse. This is why the net measurement (3.6) is used to approve a possible assignment instead of the single vertex degree measure (3.5).

## 5.3 The Edge Weight Frequency Assignment Algorithm

The proposed algorithm steps are as follows:

1. Initialize all cells to the same frequency channel to pick out potential interfering pairs.
2. Compute the edge-weight matrix based on observed interference level, expected traffic and priority flags.
3. Compute the vertex degree  $D_{c_r}^{(n)}(v_i)$  for all  $i, j \in [1, N]$ . Also evaluate the net deficiency  $D^{(n)}$  of the  $n^{\text{th}}$  frequency plan.
4. For the vertex of highest degree, say  $v_p$ , evaluate  $D_{c_m}^{(n+1)}(v_i) \forall m \neq r$  and  $m \in [1, K]$ . Temporarily assign frequency  $c_m$  of lowest predicted vertex degree for  $v_p$ .
5. Also temporarily assign  $c_m$  to vertices whose predicted degree does not change upon updating the plan for  $v_i$  for frequency re-use.
6. Evaluate the net predicted deficiency of the possible frequency plan  $D^{(n+1)}$ . If  $D^{(n)} > D^{(n+1)}$ , confirm the assignments from steps 4 and 5.
7. Iterate steps 3 to 6 until  $D^{(n)} \leq D^{(n+1)}$  for all vertices at all frequency channels.

Step 1 of the proposed algorithm is applicable when there is no existing frequency plan. Otherwise steps 2 to 7 are used to fine-tune the network according to existing demands. Either way the results will converge to the same frequency plan which occurs when any new assignment does not better the existing plan, that is  $D^{(n)} > D^{(n+1)}$  for all cells and frequency channels. The choice of next vertex is by highest degree first as this allows maximum minimization of the network deficiency per iteration. Although this is not a requirement, it allows the algorithm to converge faster as it is the steepest path.

## Performance the EWFAA

To measure the performance of EWFAA, the algorithm was converted in to a python program and given input datasets representative of different network structures to run the simulation. The key performance indicators which were investigated where the final network score, the number of iterations taken by the algorithm to converge to the final score and the resultant average interference in the network. To simulate the algorithm, the datasets of a chosen number of base stations and channels also had to provide five critical inputs being a set of traffic levels at the individual base stations; values used to calculate the elements of  $T$ , a set of priority flags for each potential edge in the network i.e. elements of  $P$ , a set of interference penalties at each potential edge in the network i.e. elements of  $F$ , a set of signal coverage distances of each vertex in kilometres i.e.  $C_0$  and a set of distances between base stations  $K$ . Although the proposed EWFAA in 3.3 above does not rely on  $C_0$  and  $K$ , for the purposes of a simulation they are important to demonstrate signal overlap for better clarity and completeness.

Figure 1 shows that the final score increases with an increase in the number of BS's. As population grows, the size of the network will grow in terms of number of BS's in order to handle the increased traffic. The trend reveals that growing the number of BS's worsens the network quality by a factor of less than 1, this is important for the service provider as it tells them that the benefit of adding more BS's to deal with a clogged network far out-weighs the potential negative effects on the network as a whole.

Figure 2 show that the number of iterations the EWFAA algorithm takes to finish execution initially starts off low with a few channels available. The number of iterations then increases with increase in the number of channels until settling off at constant value. At a few number of channels, EWFAA tends to converge faster to a final score as the available channels limit its optimization ability. When more channels become available then the algorithm can take advantage of

the extra channels to achieve further optimization. For a sufficient number of channels, the algorithm can put each vertex on its own channel and hence no edges will exist in the network, this will translate to a perfect network score of zero. However increasing the number of channels beyond this point provides no further benefit; this in fact translates directly into un-necessary costs as the right to use the channels is paid for. Likewise, the trend in Figure 2 shows the network provider that there exist an optimal number of channels to achieve rapid optimization in terms of converging the EWFAA algorithm in a certain number of iterations.

Figure 3 shows that the number of iterations of EWFAA only slightly increases and quickly reaches a constant with an increase in the number of BS's. An increase in the number of BS's will not always lead to an increase in the number of iterations for EWFAA as it depends on other factors such as the coverage distance of the newly introduced BS's. As an example, two BS's can be added to an existing network but with their signal coverage areas small enough to not overlap with signals from any other BS. This essentially means the size of the optimization problem has remained the same hence a similar number of execution steps will be required to converge to a final score. It is also worth observing in Figure 3 that the number of iterations is always less than the number of BS's. This is an expected trend that validates our results. EWFAA follows the steepest path of execution by always going for a vertex with the heaviest degree first. This means that for a network with  $N$  vertices, in the worst case scenario the algorithm will visit all but one vertex, i.e. the last vertex, since the last edge will be eliminated one step before the last vertex is visited. This means at most, the EWFAA will have the number of iterations at most equal to the number of vertices in the network less one.

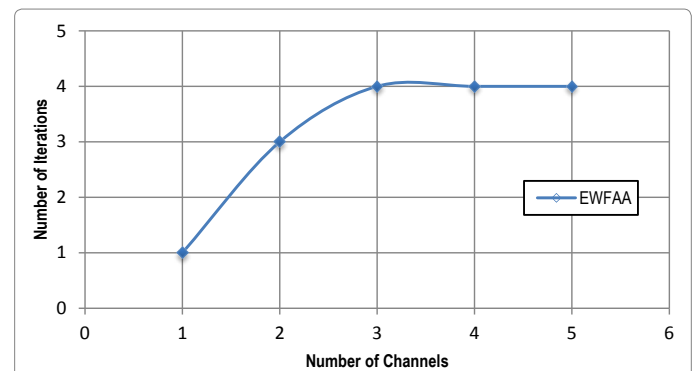


Figure 2: Number of Iterations vs. Number of Channels.

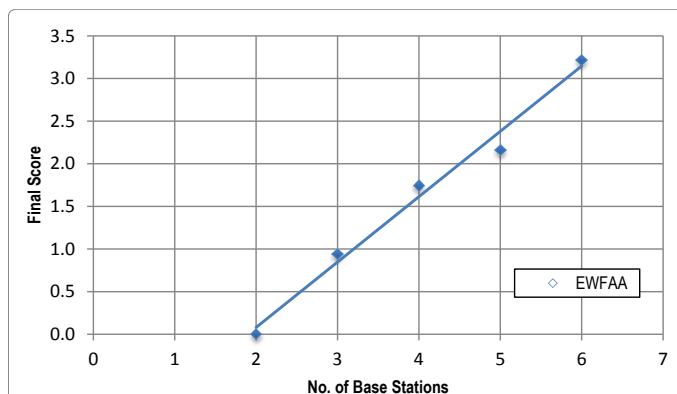


Figure 1: Final Score vs. No. of Base Stations.

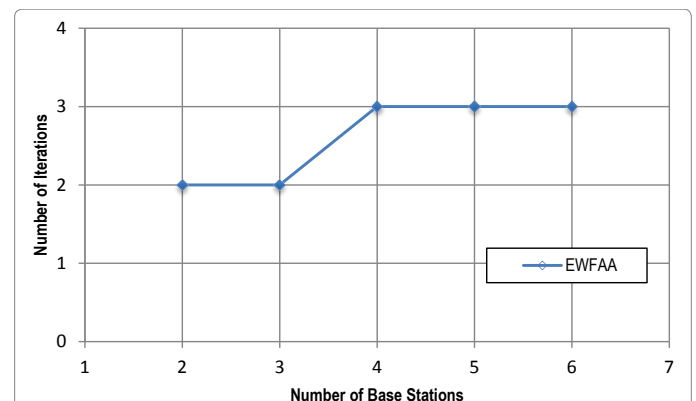


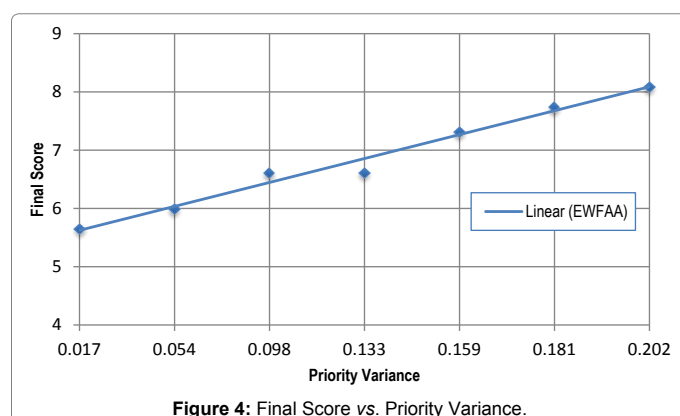
Figure 3: Number of Iterations vs. Number of Base Stations.



Figure 4 shows how the variance in priority settings of edges affects the final score rating in the optimized network. The figure shows that the average score is low at low values of priority variance. The final score then increases with increase in priority for EWFAA. This is an expected result because we know that the algorithm at a high priority variance will always favour breaking a high priority edge in exchange of creating several lower weight edges. This deliberately reduces traffic and interference in special areas but create more of a problem in non-special areas, which is a bad result for the network as a whole. Low variance in priority leads to a lower network score because the algorithm is allowed to come up with the best solution by equally considering edges mainly influenced by traffic and interference values, rather than priority.

## Discussion

To show how the performance of the proposed EWFAA algorithm scales with key parameters being number of BS's, number of channels and priority settings, the algorithm was implemented in Python code and the code ran for different input datasets. Figures 2 and 3 show that the number of iterations increases slightly with an increase in each parameter. Even though both trends eventually level off, it can be deduced that the optimisation speed of the EWFAA is heavily affected by the number of channels as opposed to the number of BSs. Additions of more channels will lead to a better quality network but it takes more steps in execution to get there. However, if the network provider was to choose to add more BS's instead, in such a way that they avoid signal overlap, then they can still keep execution time unchanged meaning as close to real time response to population migrations in their networks as possible. Figure 4 does however show that if BS's are added in such a way they form new edges in the network, then the quality of the network will be degraded in terms of the final score. However it is worth noting that the factor of the degradation is small enough to still justify the addition of new BS's as a positive move to deal with an already clogged network. Figure 4 further demonstrates that it is possible to bias the performance of the network using priority settings such that better quality of service is enjoyed in some geographical areas as opposed to others. However it is clear that making these biases too large will effectively neutralise the ability of the EWFAA to optimize on other variables of interference and traffic. This effectively means that the low priority areas (which there is more of) are far much worse, leading to an overall degraded network as a whole. The network provider must exercise high caution in using this feature.



## Conclusion

The paper has addressed the frequency assignment problem and offered its solution by proposing and analysing the performance of an Edge Weight Frequency Assignment Algorithm. The algorithm uses traffic intensity, measured interference and priority settings to calculate edge weights of the network. An edge represents a potential interference connection between a pair of base stations. With the edge weights the vertex degrees can be calculated and assigned or re-assigned a channel to the highest degree vertex leading to the lowest network deficiency score.

The paper has shown that the performance of the proposed EWFAA algorithm scales with the number of BS's, number of channels and priority settings. The results show that the number of iterations increase with an increase in each parameter. Although both trends eventually level off, we can deduce that the optimisation speed of the EWFAA will be more affected by the number of channels as opposed to the number of BS. Additions of more channels leads to a network with a better quality of service but this leads to an increase in the number of iterations required to reach convergence. However, if the network provider was to choose to add more BS's instead, in such a way that they avoid signal overlap, then they can still keep execution time unchanged as close to real time response to population migrations in their networks as possible.

The use of edge weights in frequency assignment offers a practical optimisation solution to a service provider which can keep costs down by re-directing resources to where they are most needed in a network with priority settings. The network provider gets an opportunity with EWFAA to predict through soft and less expensive means the effect of manipulating network parameters on the overall network deficiency before committing to a solution. This solution also offers the better quality of service to a user since it takes into account the measured interference and traffic intensities in the cellular network.

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