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Edge Weight Power and Frequency Assignment Algorithm

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***Abstract*—In cellular networks, cells are grouped more densely around highly populated areas to provide more capacity. Antennas are pointed in accordance with local terrain and clutter to reduce signal shadows and interference. Hardware parameters are easily set during installation but difficult to change thereafter. In a dynamic environment of population migration, there is need to continuously tune network parameters to adapt the network performance. Modern mobile equipment logs network usage patterns and statistics over time. This information can be used to tune soft parameters of the network. These parameters may include frequency channel assignment or reuse, and transmitter radiation power assignment to provide more capacity on demand. The paper proposes that by combining the frequency and power assignments, further optimisation in resource allocation can be achieved over a traditional frequency assignment. The solution considers the interference, traffic intensity and use of priority flags to bias some edges. An Edge Weight Power and Frequency Assignment Algorithm is presented to solve the resource allocation problem in cellular networks. The paper also analyses the performance improvements obtained over that of the Edge Weight Frequency Assignment Algorithm. The results show that the proposed algorithm improves the performance of the Edge Weight Frequency Assignment Algorithm depending on the initial structure of the graph.**

***Keywords*—Channel allocation, Interference and Traffic Intensity Score, Priority Flags, Edge Weight, Power and Frequency Assignment, Algorithm, Optimisation.**

I. Introduction

THE basic component of a cellular network structure is a base station (BS) and a mobile terminal pair. A cell is made up of one or more BSs usually housing omnidirectional transceivers. A mobile is served by the BS whose received signal is the strongest. In urban areas where population is concentrated in a small area, smaller cells with a high concentration of BS are used. Overall network quality is reduced by co-channel interference. Co-channel interference occurs when nearby transmitters use the same channel and their signal coverages overlap. Often network providers have to re-use their channels to optimise the available bandwidth, and strictly control signal power to avoid the overlap. Cell splitting involves sub-dividing a larger cell in to several smaller cells, each with a BS and a much reduced transmit power. Cell sectoring uses a transmitter with a directional antenna to cover a sector of the intended area. In both cases, the cell is covered by more BSs with a reduced signal overlap, resulting in an increased cell channel capacity. This makes it important to consider the frequency and power assignment problems together in order to achieve improved cellular network optimisation.

An Edge Weight Frequency Assignment Algorithm (EWFAA) was proposed to solve the frequency assignment problem [1]. The algorithm used traffic intensity, measured interference and priority settings to calculate edge weights of the network. The use of edge weights in frequency assignment offers a practical optimisation solution. The solution reduces cost by re-directing resources to where they are most needed in a network. A network provider is offered an opportunity to predict the overall network deficiency before committing to a solution. The paper proposes that combining EWFAA with power assignment can result in further optimisation. In addition, an Edge Weighted Power and Frequency Algorithm is proposed and analysed in this paper.

II. The Power Assignment Problem

In densely populated areas where traffic intensity is heavy, cells are usually much closer together to provide enough resources. This leads to many channels being re-used in a smaller physical space which requires that the transmission power of BSs, have to be reduced and strictly controlled so that their signals do not overlap. In areas where traffic is light, the network provider uses fewer BSs each with a coverage over a much larger area. This leads to direct reduction in costs for hardware and bandwidth. As population migrates such as from industrial areas during working hours to residential areas after working hours, the network provider may re-allocate resources to follow the migration. This is done by increasing the coverage of inadequately used BSs and reducing that of heavily used BSs to enable a higher degree of channel re-use.

Consider 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 are connected by an edge if some interference is experienced in that link.

Using the network graph as defined above, transmission power levels can be assigned to vertices to mitigate interference. Edges can be broken or created by reducing (breaking signal overlaps) or increasing the transmission power of a vertex. Each time an edge is created or removed the structure of the graph changes, meaning that the previously optimal frequency assignment solution may no longer apply. This necessitates a re-colouring of the graph on each change of its structure.

Power control in cellular networks is adopted mainly to reduce interference hence increase system quality, to prolong the battery life of a mobile device, to reduce cost in power charges, and to reduce the near-far effect [2]. Due to propagation signal losses mobiles further from a BS are at a disadvantage to

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those closer. To correct this, the BS can increase the transmit power of a mobile device. Power control schemes broadly fall in two categories: constant receive power control (CRPC), and quality receive power control (QRPC) [3]. In CRPC the transmitter adapts its signal power to meet the expected power level at each receiver. In QRPC the transmitter employs a closed feedback loop that measures the carrier-to-interference ratio (CIR) and adjusts its radiated power to keep the CIR above the required level to maintain the quality expected at the receiver.

The power control schemes can either be centralised or distributed [4]. Lee [5] proposed a fast converging centralised power control scheme, which aimed to keep the CIR balanced throughout the system. A central collector was used to monitor the CIRs from different cells and balancing techniques continuously applied until CIRs were within 1dB of each other. The CIR balancing algorithm was found to be quick and led to less power consumption when compared to more distributed schemes.

Zander [6] developed a model that found that dynamic power control is an efficient tool for managing co-channel interference thereby improving the capacity of cellular systems. They noted that Code-Division Multiple Access systems suffer from adjacent code interference. Minimum transmitter power was used to acquire the desired transmitted signal quality, with an advantage of prolonging battery life for mobile devices. The optimum transmitter power configuration was found through solving the Eigen value problem. Their findings also noted that dynamic channel allocation and power control closely interact. The optimum power control schemes (minimising the outage probability) effectively switched certain links off which indicated that these links should move to other channels. Notice that even though Lee [5] and Zander [6] manipulate the transmitted power, they do it with different objectives. Lee focuses on the speed of bringing a systems CIR back to an accepted stability in the event of a disturbance, while Zander focuses on minimising transmitter power to achieve the desired CIR.

III. THE OPTIMISATION PROCESS

To optimise network performance, actual interference information obtained from drive tests and cell traffic intensity statistics logged into network servers can be used. The information is reflected on the edges of the graph to be used by a network optimisation algorithm. In addition, priority settings can be used to bias the algorithm for or against some of the input information.

A. *Improving Network Performance with Power Level Assignments*

Network performance can be improved by combining the power level allocation algorithm and the frequency assignment algorithm (FAA). Each algorithm models the network as a graph comprising of vertices (BSs) and edges. A pair of vertices with interference is connected by an edge. The FAA uses the concept of graph colouring to allocate channels to all vertices. Although no two BSs in the same cluster should use the same channel, in practice this is not always possible. The number of channels available is usually less than the number of BSs to be allocated requiring that some channels must be re-used. When BSs in close proximity share a channel, interference is experienced in areas where their signals overlap. If the channels are also not spaced adequately, interference is present in that link, however not as severe as co-channel interference. The FAA takes into account interference, traffic load, and priorities imposed by the network provider when allocating channels. However, the completion of channel allocation may leave some links still unusable. By running the power assignment algorithm before FAA, transmission power of BSs can be adjusted to break any unusable links. This results in an improvement in the overall network performance. The resulting graph submitted to the frequency assignment algorithm is already semi-optimised. The power assignment algorithm selects the best option to adjust transmission power of a BS to either break a bad link or increase coverage. This is done to service more users that require additional resources or had no previous service at all.

1) The Power Penalty Model: The power assignment model takes three variables: Interference matrix *F*, Traffic load matrix *T*, and the Priority flags matrix *P*. The interference matrix comprises of the observed resultant interference in edges from network statistics or drive tests after customer complaints. From experience, the worst possible value of interference that leads to all calls being dropped can be assigned a score of $f_{ij} = 1$.

The edge traffic penalty is

$$t_{ij} = \frac{\text{cell pair traffic}}{\text{cluster traffic}} = \frac{t_i + t_j}{t_i}$$

Priority matrix takes values in the range 0 ... 1, with 1 indicating the highest priority where no interference is tolerated. All matrices *F*, *T* and *P* are symmetrical square matrices. Using the Poisson distribution to model the arrival of random variables being traffic and interference in a BS [7], the power edge weight can be modelled as

$$u_{ij} = p_{ij} e^{t_{ij}} e^{f_{ij}} \tag{1}$$

It follows that the power penalty matrix

$$U = P e^{T} e^{F} \tag{2}$$

The network power deficiency $D_p^{(n)}$, at any point is a summation of the power edge weights divided by 2 since every edge is counted twice in the symmetrical square matrix *U*,

$$D_p^{(n)} = \frac{1}{2} \sum_{i=1}^{j} u_{ij} \tag{3}$$

Two adjacent BSs are connected by an edge if interference exists in an area where their signals overlap; otherwise there is no edge as $f_{ij} = 0$. If no edge exists between a pair of BSs, it follows that penalties for traffic or set a priority on a non-existing edge hence t_{ij} and p_{ij} is also zero. However, traffic at the individual BSs would still have a non-zero value for as long as the BS covers some population.

2) Threshold Value for Edge Breaking Decision: The power penalty matrix is used by the power assignment algorithm to determine whether or not to break an edge. A threshold value for this decision can be obtained by considering the levels of priority p_{ij}, traffic t_{ij} , and interference f_{ij} values. The values in the range [0,0.25], [0.25,0.74], and [0.75,1] are classified as low (L), mid-range, and high (H) respectively. Considering values that represent a high level of permutations for values of p_{ij}, t_{ij} and f_{ij} on the L and H scale forming a 3-tuple, the power penalty matrix is obtained as shown in Figure 1.

Figure 1 shows that for a value of $u_{ij} = 0.68$, at least one of the parameters of interest has a rating of high i.e. ≥ 0.75. This justifies a threshold value of 0.68 for the optimisation by the power assignment algorithm. This means all edges with weight ≥ 0.68 are broken before applying the FAA on the resultant network graph.

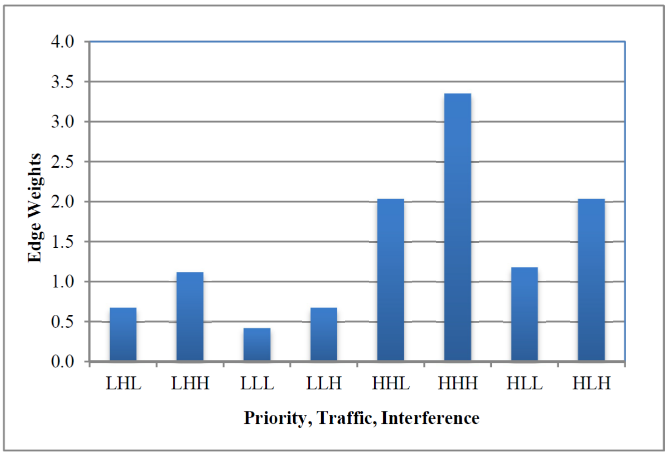

Fig. 1. Effect of Priority, Traffic and Interference tuple on Edge Weights

3) Blind Spots: Blind spots are positions within a networks geographical area where no signal coverage exists or the signal is too weak. If an area of the network was covered by a bad link that must be broken i.e. $u_{ij} \geq 0.68$, then a blind spot results. When breaking a bad link, done by reducing the coverage of the vertex with more traffic (ensuring a reduction in its traffic burden) until there is no signal overlap with the other concerned vertex. Having blind spots in a network is equally unacceptable as an unusable link. To remedy this situation, a BS has to be identified whose coverage can be increased to eliminate the current blind spot (the traffic lost by the reduced station is absorbed by the one being increased).

At any point in time, the vertex with the least degree has the least negative impact on network performance. Increasing the power level i.e. coverage area of a vertex with the least degree enough to remove blind spots is an attractive option. However, this operation has the potential of creating other links which could potentially result in degrading network performance.

With the above in mind, traffic gained and lost by vertices on increasing and decreasing their signal coverages can be modelled. This setup can take into account the fact that population generally migrates from one part of the network to another. If a vertex with no potential of interference with another exists (i.e. on a different channel to all other vertices), then the choice is to increase its coverage to remove the blind spot. Trial coverage increments of other vertices excluding the edge just broken, and those with an edge connection to the vertex reduced is performed. Otherwise the action is undone to maintain the bad edge. A maintained edge connection implies no blind spot has been created in that area. This indicates how the variation over time in gained traffic ($\triangle$), affects the vertex degrees of increased vertices. The increment that leads to the least negative impact on the network for a particular value of $\triangle$ is confirmed.

If no trial increment can be confirmed the network is better off being left the way it was. In this case, the current trial is terminated and the current network is accepted as the most optimised. A situation can exist where it becomes impossible to break an edge because the coverage of one of the vertices is more than the distance between the vertices. In this case, the next heaviest edge of the highest degree vertex is selected and the action continued.

4) Estimating Traffic Re-Distribution: In estimating the value of t_{ij}, note that before their signals overlap, each BS has a population that it is serving. There are up-link and down-link channels available to service each call. When signals overlap, users in that area have available to them a pool of channels from the BSs. If one BS was heavily loaded and the other had light load, then in effect the users from the previously heavily loaded BS are at an advantage as they can now connect using the extra unused channels from the other BS.

Link penalty due to traffic can be estimated as $t_{ij} = \frac{t_i + t_j}{t_t}$, where t_i and t_j are traffic levels at BSs i and j that now have a link between them. t_t is the total cluster traffic such that

$$t_t = t_1 + t_2 + ... + t_n \tag{4}$$

To derive an expression for the network score $D_p^{(n)}$ in terms of Δ, where Δ is the amount of traffic gained or lost by a BS as its coverage increases or reduces. Consider an arbitrary network of 5 vertices as shown in Figure 2.

Assuming the following: All vertices are initialised to the same channel c_1, to ensure that interfering pairs exist. A is the heaviest degree vertex with edge AD being its heaviest. This

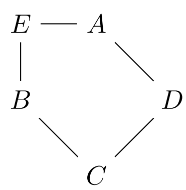

Fig. 2. An arbitrary network with 5 vertices

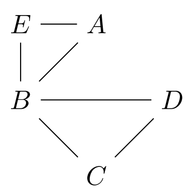

Fig. 3. Resultant network after reducing A and increasing B

means of all edges of A with $0.68 < u$, AD is the heaviest of them all. The traffic of A is much greater than that of D.

Breaking edge AD by reducing the coverage of A and increasing the coverage of B to absorb some of the population left uncovered by reducing A. This breaks the edge AD and leads to new edges BD and AB, as shown in Figure 3. Traffic at A is $t_a - \Delta$ and traffic at B is $t_b + \Delta/2$ ($\Delta/2$ because the Δ lost by A is evenly shared out by all existing edges connecting to A).

The power penalty of an edge is calculated as $u_{ij} = p_{ij} e^{t_{ij}} e^{f_{ij}}$ from equation (1). Normalizing t_i to 1 gives $t_a + t_b + t_c + t_d + t_e = 1$.

It follows that

$$t_{ab} = t_a - \Delta + t_b + \frac{\Delta}{2} \Rightarrow u_{ab} = p_{ab} e^{f_{ab}} e^{\frac{2t_a + 2t_b - \Delta}{2}} \tag{5}$$

$$t_{ae} = t_a - \Delta + t_e + \frac{\Delta}{2} \Rightarrow u_{ae} = p_{ae} e^{f_{ae}} e^{\frac{2t_a + 2t_e - \Delta}{2}} \tag{6}$$

$$t_{eb} = t_b + \frac{\Delta}{2} + t_b + \frac{\Delta}{2} \Rightarrow u_{eb} = p_{eb} e^{f_{eb}} e^{\frac{2t_e + 2t_b + 2\Delta}{2}} \tag{7}$$

$$t_{bd} = t_b + \frac{\Delta}{2} + t_d \Rightarrow u_{bd} = p_{bd} e^{f_{bd}} e^{\frac{2t_b + 2t_d + \Delta}{2}} \tag{8}$$

$$t_{bc} = t_b + \frac{\Delta}{2} + t_c \Rightarrow u_{bc} = p_{bc} e^{f_{bc}} e^{\frac{2t_b + t_c + \Delta}{2}} \tag{9}$$

$$t_{cd} = t_c + t_d \Rightarrow ucd = p_{cd} e^{f_{cd}} e^{t_c + t_d} \tag{10}$$

Note: All values of I, P and T are known, the only unknown is Δ.

The network score is obtained from

$$\begin{aligned} & u_{ab} + u_{ae} + u_{bd} + u_{bc} + u_{cd} + u_{eb} \\ &= (p_{ab} e^{f_{ab}} e^{\frac{2t_a + 2t_b - \Delta}{2}}) + (p_{ae} e^{f_{ae}} e^{\frac{2t_b + 2t_e - \Delta}{2}}) \\ &+ (p_{bd} e^{f_{bd}} e^{\frac{2t_b + 2t_d + \Delta}{2}}) + (p_{bc} e^{f_{bc}} e^{\frac{2t_b + 2t_c + \Delta}{2}}) \\ &+ (p_{cd} e^{f_{cd}} e^{t_c + t_d}) + (p_{eb} e^{f_{eb}} e^{\frac{2t_e + 2t_b + 2\Delta}{2}}) \\ &= (p_{cd} e^{f_{cd}} e^{t_c + t_d}) + (p_{ab} e^{f_{ab}} e^{\frac{2t_a + 2t_b - \Delta}{2}}) \\ &+ (p_{ae} e^{f_{ae}} e^{\frac{2t_a + 2t_e - \Delta}{2}}) + (p_{bd} e^{f_{bd}} e^{\frac{2t_b + t_d + \Delta}{2}}) \\ &+ (p_{bc} e^{f_{bc}} e^{\frac{2t_b + 2t_c - \Delta}{2}}) + (p_{eb} e^{f_{eb}} e^{\frac{2t_b + 2t_d + 2\Delta}{2}}) \end{aligned} \tag{11}$$

The bracketed terms represents: interaction of all other edges whose vertices neither absorb nor lose Δ (referred to as an ordinary vertex); edges that the vertex losing Δ interacts with the vertex that absorbs a fraction of Δ; edges where the vertex absorbing a fraction of Δ interacts with other ordinary vertex; and an interaction between edges that are both absorbing a fraction of Δ respectively.

Considering a set of three elements losing absorbing ordinary, there are six possible permutations namely: (losing, losing), (losing, absorbing), (losing, ordinary), (absorbing, absorbing), (absorbing, ordinary) and (ordinary, ordinary). All permutations are covered above except for the two (losing, losing) and (losing, ordinary). (losing, losing) is not a possible combination because the coverage of only a single vertex is reduced at a time. Note that (losing, ordinary) is also not a possible interaction because as soon as a vertex loses Δ, the other vertex which shares an edge with it absorbs a fraction of that Δ.

In order to generalise the expression, let a generally mean the vertex whose coverage is reduced because of its worst effect i.e. the one that loses Δ. Let b generally mean the vertex that absorbs a fraction of Δ lost by a (either because its own coverage has been increased or it maintained an edge connection with a even after reducing coverage of a). Let z be the number of signal overlaps with other vertices of the vertex whose coverage is just reduced (those overlaps might be edges in a case where a channel is shared or might not be edges in a case where different channels are used); For instance vertex a and in the previous example 'z' would be 2. Let m be the set of all ordinary vertices i.e. $[C \; D]$. Let h be the set of all vertices absorbing D i.e. $[B \; E]$.

Let

$$S = \begin{cases} 1 & \text{if an edge exists between considered vertices,} \\ 0 & \text{otherwise} \end{cases}$$

then, equation (11) reduces to:

$$\begin{aligned} & u_{ab} + u_{ae} + u_{bd} + u_{bc} + u_{cd} + u_{eb} \\ &= S \sum_{j \in \binom{m}{2}} (e^{t_j} p_j e^{f_j}) + S \sum_{j \in h} (e^{\frac{zt_a + zt_j - \Delta(z-1)}{z}} p_{aj} e^{f_{aj}}) \\ &+ \sum_{i \in h} S \sum_{j \in m} (e^{\frac{zt_i + zt_j + \Delta}{z}} p_{ij} e^{f_{ij}}) + S \sum_{j \in \binom{h}{2}} (e^{\frac{zt_j + 2\Delta}{z}} p_j e^{f_j}) \end{aligned} \tag{12}$$

Note: For $m = [C \; D]$, $\binom{m}{2} = [C \; D]$ and likewise for $h = [B \; E]$, $\binom{h}{2} = [B \; E]$ etc. z can never equal zero because at least the increased vertex overlaps with the reduced vertex.

For testing the effect of reducing one vertex coverage and increasing that of any other, a, b and z are substituted in the expression above. Other terms are kept and deleted based on the value of S.

In practice, the values of Δ are obtained from network statistics as population migrates around the network and pick the best vertex option to increase its coverage leading to a least negative impact on the network.

5) Incorporating the Signal Propagation Mode: The Okumura model [8], gives the median field strength as,

$$\begin{aligned} E(dB\mu V/m) &= E_{fs} - A_{mu}(f, d) + H_{tu}(h_{te}, d) \\ &+ H_{ru}(h_{re}, f) + \Sigma K_{correction} \end{aligned} \tag{13}$$

where, E_{fs} is the received field strength under free space conditions, A_{mu} is the urban area excess loss assuming BS height of 200 m and mobile station (MS) height of 3 m as a function of the operational frequency (allocated channel), f and the distance between the BS and MS (BS coverage) d. H_{tu} is the BS gain factor as a function of BS effective height h_{te} and d. H_{ru} is the MS gain factor as a function of the MS antenna height h_{re}. A_{mu}, H_{tu} and H_{ru} are read off pre-existing graphs.

Furthermore,

$$E_{fs} = 78.78 + 20 \; log \text{ eirp } - \; 20 \; log \; d \tag{14}$$

eirp can further be expressed as,

$$EIRP \text{ (dBW)} = P_t \text{ (dBW)} + G_t \text{ (dB)} - L_t \text{ (dB)} \tag{15}$$

where P_t is the transmitter output power, L_t is the loss between transmitter and receiver and G_t is the antenna gain. To find the median field strength exceeded for a certain percentage of location up to where the receiver is,

$$E\ (x\%L) = E\ (\text{dB}\mu\text{V/m}) - k(x\%L)L_v \tag{16}$$

where L_v is the location variability which is graphed as a function of f. Table I shows practical values of $k(x\%L)$ versus $x\%L$ locations.

TABLE I
$k(x\%L)$ VERSUS $x\%L$ [8]

$x\%L$	$k(x\%L)$
50	0.00
75	0.67
90	1.28
95	1.64

From the frequency assignment, the frequency that each BS uses f is known. From the power assignment, the signals coverage distance with at-least a median of 90% transmitted signal strength is also known. Using these parameters and the terrain features, the amount of transmit power required for the signal can be calculated.

The model at default estimates coverage of at least 50% of coverage locations. It is ideal to use a higher coverage percentage, therefore starting with the desired median field strength in at least 90% of coverage locations i.e. $E\ (x\%L) = 1.28$ in Table I, equation (16) can be used to find E (dBμV/m), with $A_{mu}(f,d)$, $H_{tu}(h_{te},d)$, and $H_{ru}(h_{re},f)$ obtained off Okumuras graphs [8] as functions of operational frequency, BS and MS distance, transmitter and receiver effective heights all being constants, therefore E_{fs} can be found by substituting E (dBμV/m) in equation (13).

$EIRP$ (dBW) is found by substituting E_{fs} in equation (14). From the known antenna gains G_t (dB), and the total losses depending on the environment and terrain L_t (dB), the required transmitter power P_t (dBW) can be obtained using equation (15).

B. The Edge Weight Power Frequency Assignment Algorithm

The EWCPFA algorithm is as follows:

1) Calculate the power penalty matrix U, add up the edge weights to calculate the score of the current power plan $D_{p1}^{(n)}$.
2) If all edges have a weight $u_{ij} < 0.68$, then terminate at this point here.
   Otherwise, pick the highest degree vertex to break its heaviest edge. If BS X has more traffic than BS Y, then reduce the signal coverage of BS X until it no longer overlaps with that of Y, in effect X loses a section of population it was serving i.e. Δ, causing a blind spot.
3) If there exists a vertex that has no potential of interfering with any other, then arbitrarily increase its coverage to remove the blind spot and jump to the next step.
   Otherwise derive $N-(2+Q)$ expressions of equation (12) in terms of Δ, where N is the number of vertices in the graph, 2 excludes the vertices whose edge is currently being broken and Q is a count of all the vertices that still maintains to share an edge with the vertex being reduced.
   By observing the network statistics over a period of time, the value of Δ can be determined. Substitute for Δ, in the equations and choose the best vertex to increase its coverage in order to absorb the population lost by X, in effect removing the blind spot.
   Update the network score to be $D_{p2}^{(n)}$ and confirm the new network graph only if $D_{p2}^{(n)} < D_{p1}^{(n)}$, otherwise proceed to 4) below with the original network graph from 1) above.
4) Perform a frequency allocation of the current network graph using the Edge Weight Frequency Assignment algorithm.
5) Re-calculate the power penalty matrix and the score of the next power plan as $D_{p1}^{(n+1)}$.
6) Repeat 2) to 5) until $D_{p1}^{(n)} \leq D_{p2}^{(n)}$, or $u_{ij} < 0.68\ \forall\ u_{ij} \in U$, or if only one edge remains with $u_{ij} \leq 0.68$ and is not breakable.

IV. RESULTS AND DISCUSSION

The EWPFAA algorithm was converted into a Python program to simulate sample network structures. The simulation performance indicators were: Final score vs. Number of Base Stations, Number of Iterations vs. Number of Channels, Number of Iterations vs. Number of Base Stations, Final Score vs. Priority Variance, and Final Score vs. Traffic Variance. A performance comparison of EWPFAA and EWFAA is given using simulation results for EWFAA [1]. Note that ECWPFAA encapsulates the EWFAA algorithm therefore the major performance indicators are similar to those of EWFAA. However, ECWPFAA places a much greater emphasis on signal power levels or signal coverage.

Figure 4 shows the Final score vs. Number of Base Stations performance comparison of the EWPFAA and EWFAA. The final score increases as the number of BSs increase for both algorithms, with EWPFAA having a higher score than EWFAA. When the number of BSs is 4 or 5 EWPFAA and EWFAA scores converge to almost the same value. Recall that EWPFAA starts with a power plan to break the heaviest edge, close blind spots, and then the normal channel assignment similar to that in EWFAA follows. It is possible that after the power plan, the resulting network structure (which is easier to optimise further) is similar to that obtained after the first iteration of EWFAA. The following normal channel assignment leads to a similar final score as for EWFAA.

Figure 5 shows the effects of variation of the Number of channels on the Number of iterations for EWFAA and EWPFAA. For EWFAA, the number of iterations is low for a small number of channels; however this increases with an increase in the number of channels settling at a value of 4. For a few channels, the EWFAA converges faster to a final score since its optimisation is limited by the available channels. When more channels become available EWFAA takes advantage of the extra channels to archive further optimisation. For a sufficient number of channels, EWFAA assigns each vertex on its own channel and no edges exist giving a network score of zero. Increasing channels beyond this point leads to no further

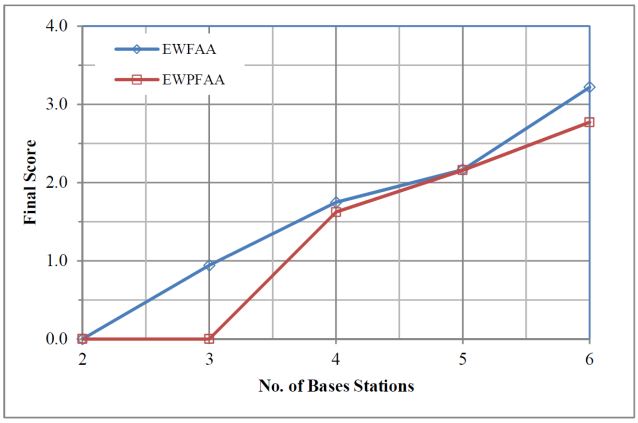

Fig. 4. Final Score vs. No. of Base Stations

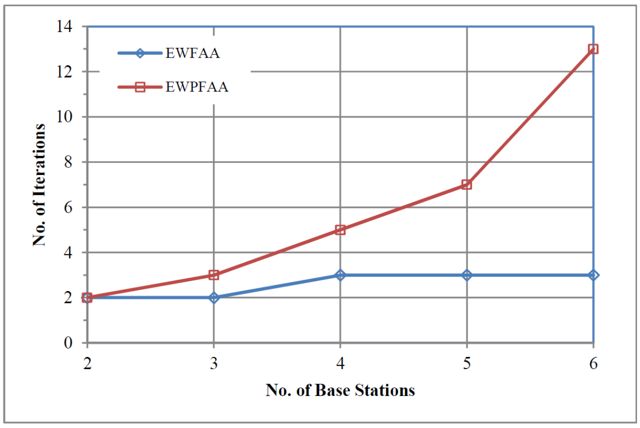

Fig. 6. No. of Iterations vs. No. of Base Stations

benefit; this wastage translates directly to un-necessary costs as the right to use these channels is paid for.

For EWPFAA, the number of iterations is high at a small number of channels; this number reduces as the number of channels is increased and settles at a value of 4. The number of iterations is affected by two actions, the power plan assignment followed by the channel re-assignment. The number of iterations depend largely on how many power plan cycles the algorithm goes through to converge to a final score. Initially, EWPFAA goes through several power plan cycles for a small number of channels. When the Numbers of channels increase, EWPFAA does only the initial power plan cycle and the final score is converged to by the following channel re-assignment hence reducing the number of iterations. The number of iterations also settles at a constant value beyond a certain number of channels as maximum optimisation is reached for the network.

With a small Number of channels, EWFAA outperforms EWPFAA by converging in fewer iterations since EWFAA does very little optimisation as compared to EWPFAA at this point. EWFAA has only a single approach, which is to assign a different channel, whereas EWPFAA uses both channel assignment and signal transmission power adjustment. For instance for a network with a single channel c1, regardless of the number of base stations, EWFAA iterates only once and

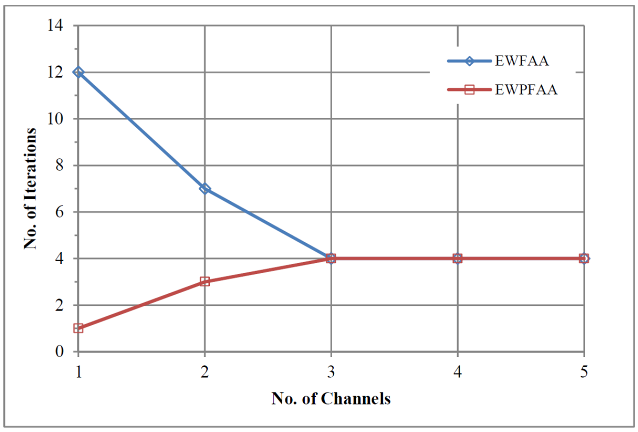

Fig. 5. No. of Iterations vs. No. of Channels

exits since no more channels are available for optimisation. This leaves the network score unchanged from the original. For the same network, EWPFAA does not achieve much through channel assignment too, but it manipulates the transmission signal power of the different BS, hence in the end it manages some optimisation. In this case, an increase in the number of iterations leads to a reduction in the final network score.

Figure 6, shows the effect of variation of the Number of BSs on the Number of iterations. For a small number of BSs both EWFAA and EWPFAA give a low number of iterations. F or instance of just two BS in a network, only a single edge can possibly exist. This edge is cleared out in a single iteration for both algorithms. As the number of BS increase, EWFAA slightly increases the number of iterations and then settles off at a constant. This is because an increase in the number of BS leads to an increase in the number of iterations for EWFAA, since it depends on other factors such as coverage of the BSs. As an example, two more BSs can be added to a network but each with a very small coverage area. This does not lead to any more edges than before, and since EWFAA does not manipulate BS coverage in any way, it takes a similar number of iterations to converge to a final score. Note that the number of iterations for EWFAA is less than the number of BS. This validates the results as expected following the steepest path. The iterations for EWPFAA however continue to increase with the increasing number of BS. This is because for EWPFAA more BSs lead to more edges available to break. EWPFAA manipulates BS coverage by breaking heavy weight edges and increasing coverage of small degree vertices to remove blind spots. Even if a BS is added that initially does not form any edges, it becomes a good candidate to close a blind spot after another heavy edge is broken. This ultimately contributes to the number of edges in the network as well.

Figure 7 shows the effect of variation of Priority variance settings of edges on the Final score. The average score is low at low values of Priority variance. The Final score then increases with increase in Priority variance for both EWFAA and EWPFAA. This is due to the algorithm at a high priority variance always favours breaking a high priority edge in exchange of creating several lower weight edges. This deliberately reduces traffic and interference in special areas but introduces a problem in other areas resulting in

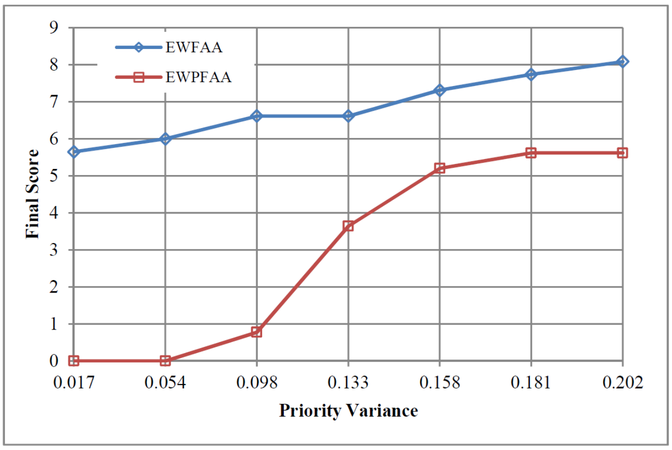

Fig. 7. Final Score vs. Priority Variance

poor performance for the whole network. Low variance in priority leads to a lower final score because the algorithm provides the optimal solution by equally considering edges mainly influenced by traffic and interference values, and not priority. It is also worth noting here that EWPFAA continues to outperform EWFAA.

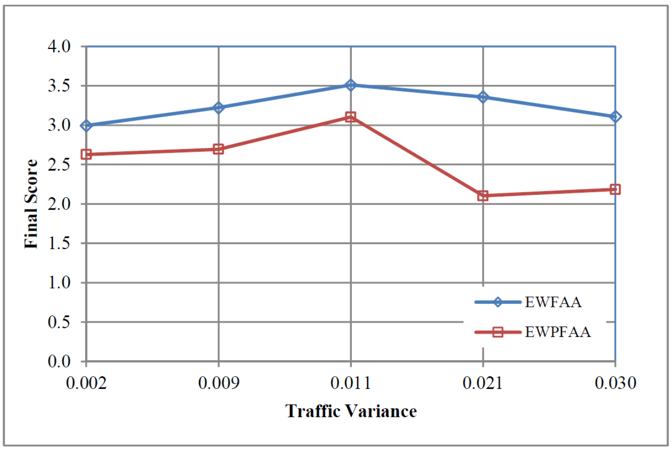

Fig. 8. Final Score vs. Traffic Variance (normalize network traffic values)

Figure 8 shows the effect of variation of Traffic variance on the Final score. Note that EWPFAA still continues to outperform EWFAA. Traffic load variance turns out to be too unstable a parameter to measure its influence since the plots do not show any meaningful trend. Low variance can mean one of two things, that all traffic values are close to each other but high, or that all traffic values are close to each other but low. In this case for low traffic variance the values are close to each other but low because the total network traffic is normalised to 1. Since the power edge weights are calculated from $u_{ij} = p^{ij} e^{t_{ij}} e^{f_{ij}}$, the effect of low traffic values on u_{ij} leads to a seemingly low network score at low traffic variance. In a practical scenario where the total network traffic would not be normalised, then one can have low variance being all traffic values high, leading to a different trend. Also for EWPFAA in particular, the starting traffic variance does not matter since the algorithm moves the traffic between different BS stations with each power plan, actually going through a number of traffic variances before converging to a final value.

V. Conclusion

An Edge Weight Frequency Assignment Algorithm was proposed to solve the frequency assignment problem [1]. The paper has shown that if EWFAA is combined with power assignment it is possible to obtain further optimisation. An EWPFAA algorithm has been proposed and its performance analysed. The paper has also shown that EWPFAA performance is better than that of EWFAA. EWPFAA algorithm calculates edge weights from traffic, interference, and priority. A power plan is derived by breaking the heaviest edge of the highest degree vertex, re-colouring the resulting network graph by following the FAA. Breaking network edges leads to network traffic being moved from one BS to another. An equation was derived to model the traffic movements and predict their network deficiency score. With these predictions, a decision can be made whether breaking an edge leads to a more optimised network, or is worse off than before.

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