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Power control in LTE based on heuristic game theory for interference management

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ABSTRACT
In the conventional LTE homogeneous network, sufficient transmit power of user equipment (UE) is determined by open-loop power control (OL-PC) and closed-loop power control (CL-PC) schemes. However, in a Het-Net environment, setting the UE's transmit power requires delicate responsiveness to handle the severe and complicated uplink interference. In this paper, an interference-aware uplink power control mechanism based on Heuristic game theory approach is proposed for devices coexisting in a heterogeneous wireless network. Various wireless constraints like channel response, path loss, fading, shadowing, interference and metrics like SNR, SINR, throughput and bit rates are considered. Uplink power is controlled by suitably selecting the penalization factor (β) based on a simple Heuristic game theory approach considering the possible wireless constraints of each user depending on its location in the cell under consideration. The algorithm is framed in such a way to reduce inter-cell interference, limit transmit power, enhance bit rates and throughput of users. A significant improvement of 5.2% in the user coverage/distribution is achieved as a result of interference management compared to conventional power control scheme and power control with convex pricing.

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Het-net; heuristic game theory approach; inter-cell interference; power control; wireless network

1. Introduction

If a device transmits a signal at too low power, the base station would not be able to detect it; if it transmits at too high power, it causes interference with the other communication devices in its proximity. So, there is an urge to decide the suitable transmit power level which has to be strong enough to be accurately decoded by the base station and weak enough not to cause interference. Hence, power control plays an important role in providing sufficient transmission power to achieve the necessary system quality, throughput and battery life of the mobile terminal with reduced interference. In the case of 4G, the power control strategy is primarily used in uplink, because the UE's battery is power limited compared to eNodeB's power in downlink [1–3]. To achieve the required transmission goals, uplink power has to adjust to the time-varying channel conditions, which includes path loss, shadowing, slow and fast fading, reflections, inter- and intra-cell interference. The motive of this paper is to decide an acceptable uplink transmit power considering the various channel impairments. There are two ways of power control mechanisms discussed in the literature: Open Loop Power control (OL-PC) and Closed Loop Power Control (CL-PC) schemes [4,5]. In OL-PC, the UE determines its transmit power by its power setting algorithm which takes higher layer signalling information, initially received target power, reference signal power, path loss and other factors. There is no feedback input from eNodeB. In CL-PC, eNodeB measures the power of the signal from the UE; if it is too low or high, the receiver sends a special command (called TPC – Transmit Power Control command) and the UE readjusts the transmit power accordingly. The TPC commands include target SNR/SINR, measured SNR/SINR and PH report to adjust the transmit power with the power setting algorithm that runs in the UE. The CL-PC scheme along with the fractional path loss compensation factor (discussed in Section 3) fixes the target SINR dynamically based on the path loss measurements, while the conventional closed-loop uses a single SINR for all the users in a cell irrespective of the users' location [6–9]. Also, LTE supports frequency reuse techniques to maximize the effective utilization of radio spectrum. But this results in interference, which cannot be ignored. Moreover, with many networks running concurrently, interference between networks/devices is inevitable [10]. This paper aims to manage the effect of such interference, by adjusting the uplink power. However, inter-cell interference has a significant impact on the whole system throughput.

Recently, game theory has drawn attention in the design of adaptive wireless networks due to its mathematical capability and analytical decision-making

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ability. Decision-making in a wireless environment is a complex problem whenever the information is asymmetric. However, an efficient decision-making can be made with heuristic approaches [11–13]. LTE and Wi-Fi systems affect negatively with each other and within themselves and this interaction can be modelled as a "Heuristic Game theory" framework to promote their mutual benefits [14–16]. The process of representing the strategy and pay-off between the players in the game is similar to the problem of power control considering SNR, SINR, path loss and interference.

Some techniques discussed in the literature to manage interference by controlling the transmit power in heterogeneous networks are Game theoretic approach based on Nash bargaining solution, autonomous transmission with power adjustment strategy, Machine learning-based algorithm for joint improvement in power and capacity, opportunistic and adaptive power control scheme, distributed reinforcement learning for uplink power control, etc. Reference [17] addresses the problem in distributed power control method via convex pricing. A distributed iterative Multi-Service Uplink Power Control game with Convex Pricing (MSUPC-CP) is proposed where users aim selfishly at maximizing their utility-based performance. This paper estimates the trade-off between QoS and the corresponding power consumption. A Pareto optimal solution for the formulated approach is obtained analytically and its performance is evaluated via modelling and simulation and compared against linear pricing. In [18], an adaptive power control technique through game theory also known as Power Control Game (PCG) is put forward to resolve the interference issues. The system arrives at the optimal power by determining the appropriate utility function and by the power update iteration process. In [5], the network performance is evaluated for different maximum transmitted uplink power, $P_{\max}$. The $P_{\max}$ limit is evaluated for both homogenous and heterogeneous networks in the uplink. In [19], the problem of joint user association in terms of uplink power allocation and resource orchestration, in NOMA heterogeneous 5G wireless networks, is looked on with the Base Stations (BSs) having only statistical information of the users' channel condition. To deal this inadequacy, the uplink power allocation is formulated with a Contract Theory-based approach, where the users make a contract with the corresponding BS. The optimal uplink power is obtained by optimizing each BS and its associated users' utility function. Also a Reinforcement Learning mechanism is adopted to obtain the association between users and BS, and the users individually select the BS to transmit their data. For the resource orchestration procedure, an assessment phase based on Bayesian Truth Serum (BTS) is introduced, where the users acquire their personal assessment regarding the service provided by the BS that they are associated with and each user selects the most beneficial BS. The proposed framework is modelled, simulated and its operation and benefits are illustrated, in a densely deployed heterogeneous environment under both complete and incomplete Channel State Information (CSI) scenarios. In [20], the joint optimization problem of user association and power control in OFDMA heterogeneous wireless network is resolved. The problem is treated as a mixed-integer, non-linear and non-convex problem and to solve this a multi-agent Deep Q-learning Network (DQN) method is proposed which requires only less statistical knowledge on the communication environment. The proposed algorithm is simulated with a two-tier het-net with few macro and micro base stations. The convergence speed of the multi-agent DQN algorithm is analysed and simulation results infer that the proposed algorithm performed better than the classical Q-learning algorithm. A significant improvement in the energy efficiency of all UEs is noted under the constraints of UEs' maximum transmit power and QoS requirements as users were able to intelligently make their adaptive decisions in selecting their suitable BSs. References [21–23] are based on strategies for non-cooperative games, which aim at maximizing QoS, in terms of SINR. In [21], a game theoretical framework for optimal uplink power allocation for small cells, i.e. femto-cell deployed under laid macro cell, is proposed to overcome the co-channel interference. The sum rate of the system is maximized based on an iterative QoS-aware game theory-based power control (QoSGTPC) to optimize the femto-cell users' power taking into macrocell users' QoS requirements. Reference [22] describes heuristic methods for generating "good" solutions and computational results for solving "hard" problems. The shortcomings of the literature works are: QoS is considered as the main performance metric [24] and the uplink power allocation is done, considering a fixed multiple access technology. Moreover, linear price for the penalization factor in the UE transmit power equation is used, even though path loss and SNR measurements are done. Most power control algorithms aim at reducing power wastage for users at the cell centres that usually have good radio conditions. But unfortunately, this increases the downlink transmission power for cell-edge users that suffer the most from interference and path loss problems. So, it is equally necessary to consider the interference issues of cell-edge users by keeping a check on the uplink transmit power.

The following are the contributions of the work:

- Create a heterogeneous network with LTE and Wi-Fi devices placed at different locations and distances and allowing them to communicate simultaneously
- Analyse the OL-PC and CL-PC schemes
- Evaluate the performance of Fractional Power Control (FPC) scheme and compare its performance

against conventional power control scheme with linear and convex pricing

- Reduce intra-cell and inter-cell interference by limiting the UE transmission power by properly selecting the penalization factor (β), based on Heuristic game theory approach
- Enhance user coverage/distribution, bit rate and throughput.

2. Power control in LTE

The LTE uplink power control contains a CL-PC term and an OL-PC term. The open loop term compensates for path loss and shadowing. The fractional path loss compensation is done in the closed loop and controlled by a factor I_c [23]. The closed loop component of the Physical Uplink Shared Channel (PUSCH) in LTE is defined by

$$PSD = P_0 + I_c * PL \tag{1}$$

where PSD is the transmitted power spectral density in dB, PL is the estimated path loss and P_0 is a parameter used to control the target SNR [8]. In 3GPP LTE-A specification, the UE transmitted power; P_{tx} for the uplink transmission in dB is defined as

$$P_{tx} = \min\{P_{\max}, P_0 + 10\log(m) + \alpha PL + \delta mcs + \Delta\}, \tag{2}$$

where P_{max} is the maximum transmitted uplink power allowed by UE. The uplink power control is separated into five parts. First is the amount of additional power needed by the UE based on the number (m) of physical resource blocks (PRBs). Higher the number of PRBs; higher is the power requirement. The second is P_o, which is a cell-specific parameter, i.e. the power contained in one PRB. The third is the product of path loss and the path loss compensation factor α. The fourth is δ_{mcs} (Modulation and Coding Scheme) which is UE specific and the power is adjusted based on the MCS assigned by the eNodeB. Lastly, Δ is the closed loop correction value. It is the extra powers added to UE for transmission based on feedback from the eNodeB to set its initial transmit power [25].

Conventional power control is employed at the receiver to maintain a constant SINR. The compensation for any increase in path loss is met by increasing the transmit power level at the UE, thereby maintaining the constant SINR. Whereas the fractional power control scheme allows the received SINR to decrease whenever there is an increase in path loss, with the certainty that path loss increases when UE moves towards the cell edge, and when SINR is increased at this time, it causes inter-cell interference. So it is essential that the UE should transmit power at a reduced level, as the path loss increases. Fractional power control scheme improves air-interface efficiency and average cell throughput by reducing inter-cell interference [26,27]. The path loss measured at UE along with P_o and α is broadcasted by the eNodeB to set the initial transmit power for OL-PC.

In general, according to 3GPP LTE-A specification, the transmit power P_{tx} of UE for uplink data transmission using PUSCH in terms of P_{OL} and P_{CL} is

$$P_{tx}(i) = \min\{P_{\max}(i), P_{OL}(i) + P_{CL}(i)\}, \tag{3}$$

where $P_{tx}(i)$ is the UE transmit power in dB/PRB, $P_{max}(i)$ is the maximum transmit power allowed by UE in UL, and $P_{OL}(i)$ and $P_{CL}(i)$ are the open loop and closed loop transmit power components for subframe i.

$$P_{OL}(i) = P_{\max}(i) + a(j)(SNR_0 - SNR_{\max}), \tag{4}$$

where $a(j)$ is the cell-specific parameter, SNR_0 is the target SNR and $\mathrm{SNR}_{\max} = \mathrm{P}_{\max}\text{-PL}$ is the SNR achieved with $P_{\max}$.

$$P_{CL}(i) = \Delta TF(i) + \Delta TPC(i), \tag{5}$$

where ΔTF is the MCS dependent component and ΔTPC is the TPC command. Equations (3), (4) and (5) give a complete understanding of the open loop and closed loop terms. From Equation (2), for simplicity and to concentrate more on the path-loss compensation factor, the correction function (Δ) is not considered in this work. The UE transmitted power in the uplink is now

$$P_{tx} = P_0 + 10\log(M) + \alpha PL + \delta_{mcs}, \tag{6}$$

where P_{tx} is linearly dependent on P_o and PPL. Parameters P_o and α are constant for the users in a cell while the term αPPL in Equation (6) varies for each UE according to the path loss [6]. A controlled decrease in LTE UL transmit power is carried out according to interference measurements at the eNodeBs, giving an opportunity to Wi-Fi transmissions. A power operating point (P_{OP}) as a function of interference and channel conditions is considered. The P_{OL} defines the P_{OP}, and the P_{CL} adjusts the transmit power to operate around the open loop operating point. Now

$$Pop(i) = P_{\max} + a(j)(SINR_0 - SINR_{\max}), \tag{7}$$

where

$$SINR_{\max} = P_{\max} - PL - 10\log_{10}\left(\beta.10^{\frac{I}{10}}\right). \tag{8}$$

where I is the interference power in dBm measured at eNodeB and β $(0 < \beta < 1)$ is the penalization of power operating point with respect to interference. The difference between Equations (4) and (7) is that P_{OL} is changed to P_{OP} taking interference into account. When the value of β is between 0 and 1, it means that a fraction of the path loss compensation factor is used to control the UE transmit power. This work is focused on evaluating the performance of fractional power control by properly selecting the β value. The uplink power is altered based on the measured interference power.

3. Game model for interference and power control

A heuristic game theory approach is used to determine the optimal power level that reduces the interference and maximizes the bit rate and throughput of users [23]. The work is modelled based on the three main ingredients.

- *the players*: LTE and Wi-Fi users in a heterogeneous network having conflicting interests
- *set of strategies* that determine what each player has to look on. In this work, transmission power, interference and path loss are considered
- *a utility function* that maximizes the bit rate and throughput of users.

The mathematical model for the above approach is expressed as

$$\Phi = \{\mathrm{P}, \{\mathrm{S}\eta\}, \{\cup\eta\}\}, \eta \in \mathrm{P}\}, \tag{9}$$

where P represents the players, i.e., LTE and Wi-Fi users. $\{S\eta\}$ represents the strategic choice of power level, SNR, the degree of acceptance of interference and path loss of user η, i.e. $S\eta = \{Ptx, SNR_{\max}, \alpha PL, I\}$. $\{\cup\eta\}$ represents the utility function that maximizes the bit rate and throughput of user η.

$$\Phi = \begin{cases} \cup = \max\limits_{\eta\in p}\{\cup_\eta\} \\ \arg\max\limits_{\eta\in p} f(\eta) = \{S\eta|\{SNR\max\} \\ \eta \geq \{SNR\max\} - \eta\} \end{cases} \tag{10}$$

The problem is formulated as in Equation (10) and best-response strategies for interference and power is reached when the condition is met; the strategy chosen by the current player is η and the strategy of the other players -η. The optimal solution is reached when the utility function is maximum, i.e. path loss and interference are minimum; SNR for the current player, η is $\geq$ SNR of other players, -η. Each user competes among other users in the game such that each user attains $SNR_{\max}$.

4. Proposed uplink power control scheme using heuristic approach

It is evident from Section 3 that the parameter β should be chosen wisely so that the interference is reduced, PL is minimized, SINR is acceptable and many possible users could meet the desired QoS requirements. The algorithm or the implementation steps for the proposed heuristic game theory approach is as follows:

Algorithm

```
Initialization: Fix the users $\eta \in \mathrm{P}$ at random
  positions in the cells.
while (1)
for each $\eta$ do
      Assign a $\beta$ value initially as $0 \leq \beta \leq 1.0$,
  and $\Delta$ ƕ $= 0.2$
      //Sort the UEs in descending order
according to the interference power level
and path loss.//
i.e. $a = \max(Pathloss_1, pathloss_2 \ldots .pathloss_\eta)$and
$b = \min(Pathloss_1, pathloss_2 \ldots .pathloss_\eta)$
          if
          PL $> (\frac{a+b}{2} + \frac{a}{2}) * \frac{1}{1.5}$ then PL > > min && $\beta =$
  $\beta+\Delta$ ƕ;
                                //where $\Delta$
  ƕ $= 0.2$//
          end
          else if
          PL$\cong \left(\frac{a+b}{2}\right)$ then
                    PL $\sim$ 'Strategic choice'&&
  $\beta = 0$
          end
          else
     PL $< \left(\frac{a+b}{2} + \frac{b}{2}\right) * \frac{1}{1.5}$ then PL > min && $\beta = \beta - \Delta$ ƕ;
     end
     end if
       Adjust $P_0$ and hence $p_{tx}$ using eqns (6),
 (7), (8)
     if
       $\{U_n\}_{n\in p} = \Phi$, continue with the same $\beta$
  value.
     else
       $\beta =$ 0.5
     end
end for
```

A heuristic is a technique that is used to solve a problem faster and finds an approximate solution with limited resources and time and make quick decisions by shortcuts than the classic methods. The following are the mathematical aspects and analytical decision-making involved in the heuristic game theory model:

Step 1: Let η be the no. of players as per Game theory approach. Fix the no. of users η at random positions in the cells and sectors as per the descriptions in Table 1.
Step 2: Assign an initial β value between $0 \leq \beta \leq 1.0$.
Step 3: Let Δ ƕ $= 0.2$.
Step 4: Do interference, channel quality and path loss measurement tests at the UEs/ENB.
Step 5: Sort the UEs in descending order according to the test results as shown in Figure 5.
Step 6: From the measured path loss results, note the maximum and minimum values. Let "a" and "b" represent the maximum and minimum path loss values.

i.e. $a = \max(Pathloss_1, pathloss_2 \ldots .pathloss_\eta)$ and
$b = \min(Pathloss_1, pathloss_2 \ldots .pathloss_\eta)$

Step 7: Calculate $\left(\frac{a+b}{2} + \frac{a}{2}\right) * \frac{1}{1.5}$, $\left(\frac{a+b}{2}\right)$ and $\left(\frac{a+b}{2} + \frac{b}{2}\right) * \frac{1}{1.5}$.

Table 1. Dependent and independent simulation parameters.

Simulation parameters	Description
Total no. of users, η	45
Cell radius, *r*	67m
Cell layout	Hexagonal, cells:5, 3-sectors, 15 sectors in total
Power contained in one PRB, P_0	−50 dBm
Noise PSD, $\text{NoisePower}_{\text{dB}}$	−174 dBm Hz
System Bandwidth, BW	10 MHz
Resource block allocation for different BW options, m	1.4 MHz = 6; 3 MHz = 15; 5 MHz = 25; 10 MHz = 50; 15 MHz = 75; 20 MHz = 100;
Path loss, PL	PL = 35.3 + 37.6·log(d), distance in m
UE power class, $P_{\max}$	250 Mw (Max UE output Power)
Maximum antenna gain, *G*	15 dBi
Modulation and coding, δ_{mcs}	QPSK & 16QAM, continuous coding
No. Receiver Antenna	2 for diversity in Rayleigh fading
SNR	Target SNR, SNR_0: 5 dB $\text{SNR}_{\max}$: 20 dB
Path loss compensation factor, α	0.7
Convergence rate, *CLBoostRatio*	0.3

Let $\left(\frac{a+b}{2} + \frac{a}{2}\right) * \frac{1}{1.5} = X$, $\left(\frac{a+b}{2}\right) = Y$ and $\left(\frac{a+b}{2} + \frac{b}{2}\right) * \frac{1}{1.5} = Z$

Step 8: Classify the users based on the path loss measurements.

Case 1: Users with path loss measurements greater than X belong to worst case condition, i.e. the path loss is much greater than minimum and $\beta = \beta + \Delta$ hυ.

Case 2: Users with path loss measurements approximately equal to Y belong to average case condition, i.e. the path loss is in the strategic choice and $\beta = 0$, i.e. no pricing is done.

Case 3: Users with path loss measurements less than Z belong to best case condition, i.e. the path loss is minimum and $\beta = \beta - \Delta$ hυ.

Step 9: Determine the β value from step 8 and obtain the open loop power operating point P_0, required transmit power P_{tx}, and hence the closed loop UE transmit power using Equations (6), (7), (8), (12), (13), (15), (16) and (17).

Step 10: Calculate the throughput using Equation (18)

Step 11: Check for the optimal condition. Continue with the same β value if the optimal condition in Equation (10) is met.

i.e. $\{U_n\}_{n \in p} = \Phi$. Else, choose $\beta = 0.5$.

4.1. System parameters

The system parameters as listed in Table 1 are assumed/initialized.

4.2. Creation of network map with cells and sectors

A cellular network map is created with five cells and three sectors. Users in each sector are varied and the maximum number depends on the bandwidth selected. The network map simulated in Matlab is shown in Figure 1. Each sector is hexagonal in shape and red dot markings shows the 45 users which are randomly positioned in every sector. The network map with the bold number markings represents the cells and the normal number markings represent the sectors. The symbol “x” denotes the BS with directional antennas of 120° directivity.

- Cell position

To get the cell position, the angle of each cell and the distance between cells is identified.

Angle of each cell is calculated by taking the first cell as a reference. An axis is created starting from 30° and incremented for every 60° up to 360°.

Using cell number and cell inter-site distance, the distance of each user from the BS is calculated.

4.3. Positioning of users in the sectors

Three users per sector is assumed. A random signal generator is used to place users randomly in each sector. LTE users are made to transmit with LTE standards and Wi-Fi users with Wi-Fi standards as defined in 3GPP [825]. Users are positioned in such a way that the x- and y-positions are known, from which distance from the centre of the cell is found. The angle of each user is also calculated from the distance. This information is enough to determine the position of each user in every cell.

4.4. Calculating path loss in each sector for each RB

It is for path-loss calculation the distance of each user from the base station is calculated. Path loss due to shadowing, distance and fading is considered.

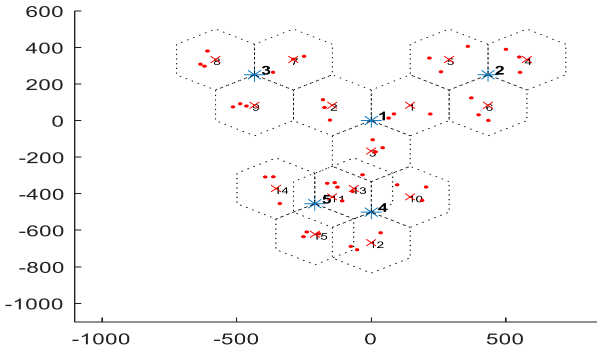


Figure 1. Created network map.

4.5. Allocation of PRB and SNR to users for each RB

The resource allocation is done using round-robin scheduling algorithm. Resource block allocation is done based on the bandwidth according to LTE standards. In a cellular network, each user's equipment has particular noise, and a suitable signal-to-noise ratio is allocated for every user in a target bound as per Equation (11). The lower and upper bounds of Channel Quality Indicator (CQI) are fixed as 3 and 15 and for SNR it is −6 and 20 dB (as per 3GPP standards). From these the possible SNR is found.

$$PossibleSNR(dB) = \frac{\begin{array}{c} SNRUpperbound \\ -SNRLowerbound \end{array}}{\begin{array}{c} (CQIUpperbound \\ -CQILowerbound) \end{array}} \begin{array}{c} *[(CQILowerbound: \\ CQIUpperbound) - 1] \\ +SNRLowerbound \end{array} \tag{11}$$

4.6. Calculation of SINR, transmitted and received power

The calculation of transmitter and receiver power is carried out for both closed loop and open loop conditions.

Open Loop: First, the transmitting power of each user should be known. Every sector is selected and the user in each sector is given a particular index. From the calculated path loss, the transmitting power of each user is found by substituting it in Equation (6). Receiver power is then calculated from the transmitter power by eliminating the path loss. Due to frequency reuse, interference is created between the cells/sectors. To compute the SINR, the interference power from the users of other cells is also calculated. Interference power is calculated by eliminating the path loss between the users from different sectors.

Closed Loop: Calculation of transmitting power, receiver power and SINR is the same as in open loop. But the power of the user is adjusted in such a way that the target SINR is reached. The SINR that is obtained is compared with the target SINR; if the computed value is below the target value; the base station asks the user to boost the power to have successful transmission. Else lowers the power to the particular target level. The required transmission power and the closed Loop UE transmit power are calculated as per Equations (12) and (13) referring Table 1.

$$\begin{aligned} requiredTXPower = {} & NoisePowerdB - 10\log 10(m) \\ & + \alpha * PLdB + ClosedLoopSNRdB \end{aligned} \tag{12}$$

$$\begin{aligned} UETXPower = {} & \min\{requiredTxPower, \\ & 10\log 10(\max UEOutputPower)\} \end{aligned} \tag{13}$$

5. Results and discussion

This section discusses the results obtained under each steps of implementation. Figure 2 shows the channel gain of all the 45 users in the cell and the corresponding path loss, shadow loss and interference power measured in dB. Each user's channel gain is calculated from the path loss and the distance from the base station. The channel gain, path loss, shadow loss and hence the interference power for each user is dissimilar/uncertain as it depends on the location in the cell with respect to the BS. The standard deviation of the shadowing is kept at 8 dB. Figure 2(b) shows the path loss due to distance and (c) shows the path loss due to shadowing.

Figure 3 shows the received uplink average SINR in dB for both open loop and closed loop for $\beta = 1$ for 10 iterations. The blue line shows the performance of open-loop system; it allows the users which have good channel conditions to have high uplink SINR and users with bad channel conditions to have low SINR. Open-loop scheme does not compensate for the interference caused by the other cells, so its cell-edge bit rate is poor. The red line in the plot shows the performance of closed loop power control algorithm. In this all the users are directed to a particular SINR since the closed loop operates within the target SINR which is fixed to be 5 dB. Closed loop scheme offers better performance as it compensates for the interference and its cell-edge bit rate is better and no user is allowed to transmit when its SNR is below the target level.

The improvement in bitrates is based on the proper selection of target SINR. If this selection is not proper, it would result in loss of information as all users are directed to a particular SINR. Figure 4 shows the closed loop and open loop CDF of SINR for different target SNRs. It is seen from the figure that the deviation in the distribution function of effective SINR for a fixed target SNR is more for open loop scheme compared to closed loop as a result of interference. For instance, the deviation in effective SINR for an SNR of 0 dB is 7 and 2 dB for open loop and closed loop respectively. It gets worse as the target SNR increases beyond 10 dB. It is more than 10 dB for open loop and 5 dB for closed loop scheme.

The received power of each user is calculated by neglecting the path loss from the closed loop UE transmit power as shown in Equation (14). The UE transmit power is calculated from Equation (13). The path loss is calculated as a function of distance as shown in Equation (15).

$$RXPowerdB = ClosedLoopUETXPower - PL, \tag{14}$$

where

$$PL = \Omega(\mathrm{d})35.5 + 3.6 * \log 10(\mathrm{d}). \tag{15}$$

Figure 5 shows the interference power and path loss measured in dB of all the users. It is then arranged in

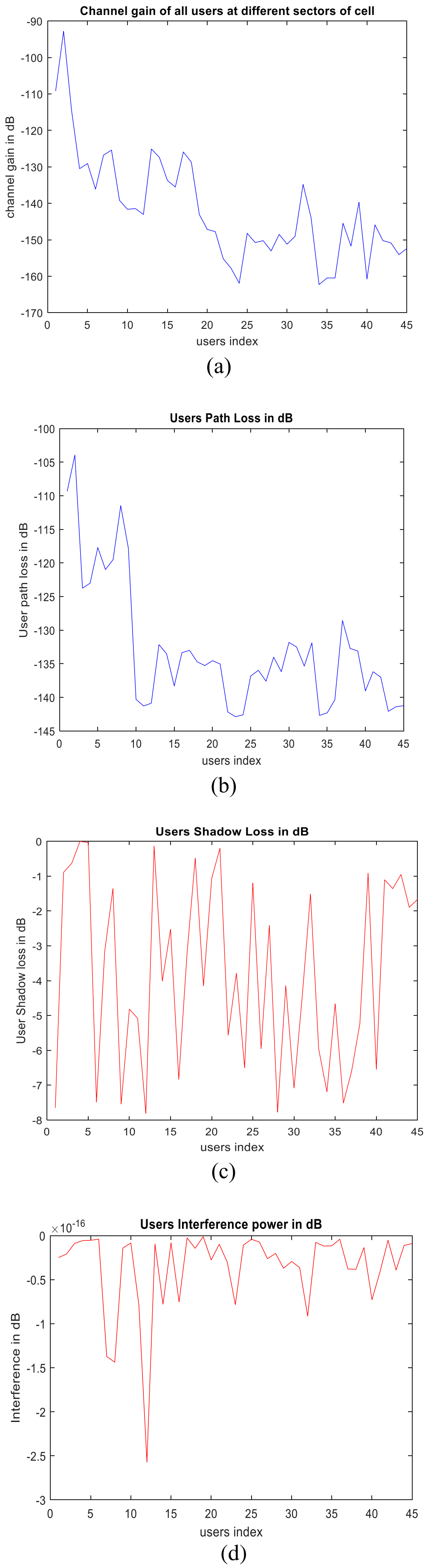


Figure 2. Each users' (a) channel gain, (b) path loss, (c) shadow loss and (d) interference power measured in dB.

descending order and the penalization factor β is then added to each user index depending on the measured values at the UEs/ENB as discussed in Section 4. Results may not be optimal; however, acceptable and economic.

The users are divided into three cases as per the channel gain and the path loss model to fix the β value. Users with CQI values of 10–15 have been assigned for good channel condition, 3–6 for worst channel condition and 6–10 for average channel condition. In the worst case, where the channel conditions are poor, both the interference power and path loss of the users are high, i.e. path loss above 114 dB. To compensate for this path loss, β is fixed to be $\beta +\Delta$ hυ. However, a very high value of β yields a lower bit rate. Henceforth, to manage the interference and to have an acceptable bit rate, the worst-case users are allotted a β value as β $+\Delta$hυ which is ~ 0.7. Under the average case, where the channel conditions are better, the interference power and path loss are neither high nor low. So no pricing is done in this case to have better results on the bit rate. The range is selected in such a way that more users are placed under this case to increase the bit rate of more number of users (nearly 60%). In the best case, the interference power and path loss are considerably low, i.e. the channel conditions are good and there exists only a little interference.

The β value in this case is assumed to be β-Δ hυ which is ~ 0.3, and very few users fall under this category. From the calculated β values, $\mathrm{SINR}_{\mathrm{max}}$ is computed from Equation (8) and P_{op} is computed from Equation (7) and hence the P_{CL} adjusts the uplink transmit power. Figure 6 shows the SNR and power variations of each user with respect to user's location in the created network. The power levels are maintained such that the target SINR is attained. If not, the power will be boosted as per Equations (16), (17) and (18) and the UE transmit power will be calculated again from the boosted closed loop UE transmit power. The equations are modified with respect to CL-PC scheme.

$$CLBoostPowerdB = CLrequiredSNR - CLRBSINR \tag{16}$$

$$\begin{aligned} CLUETXPower = {} & CLUETXPower \\ & + CLBoostPowerdB \\ & * CLBoostRatio \end{aligned} \tag{17}$$

Now,

$$\begin{aligned} UETXPower = {} & \min(CLUETXPower, \\ & 10\log 10(\max UEOutPower)) \end{aligned} \tag{18}$$

The interesting fact here is that there is a decrease in CL UE transmit power of about 15 dB and an increase in SNR of about 5 dB in CL schemes than the required transmit power and SNR respectively. This is possible as

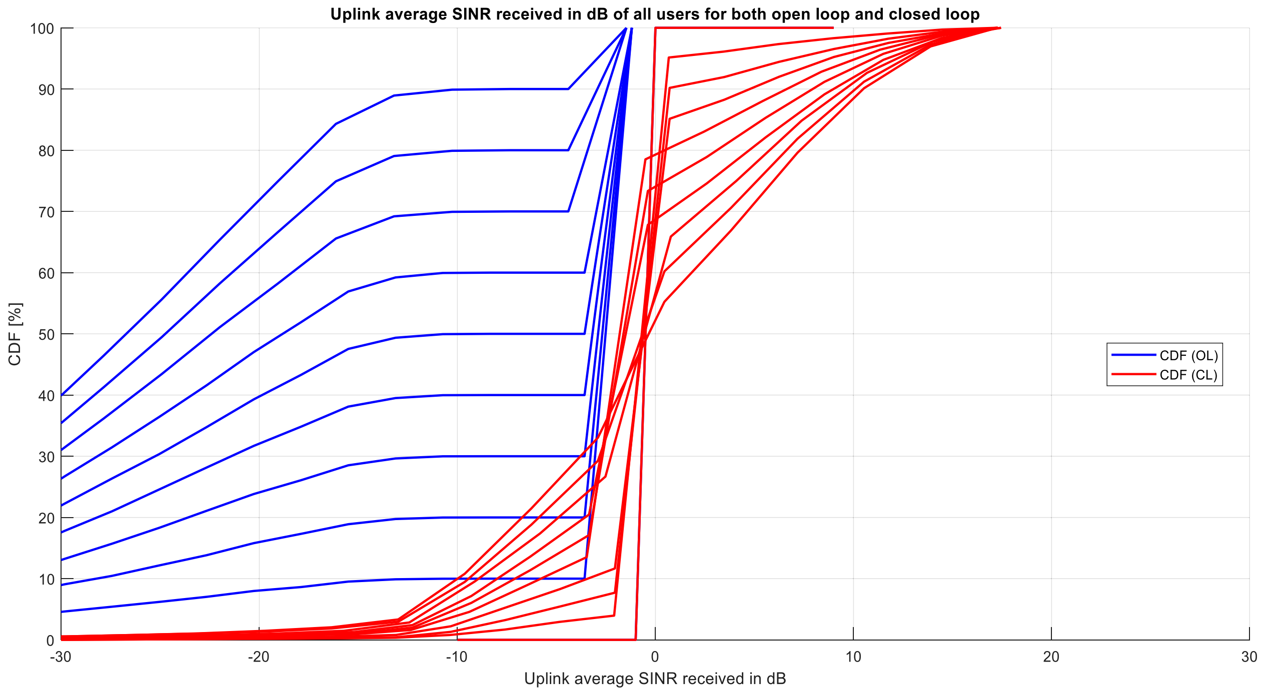


Figure 3. Uplink SINR for both open and closed loop.

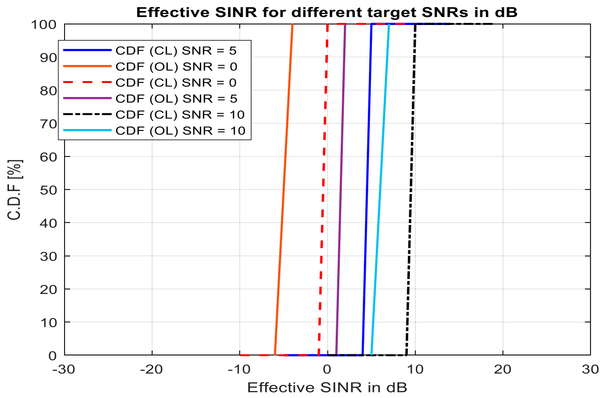
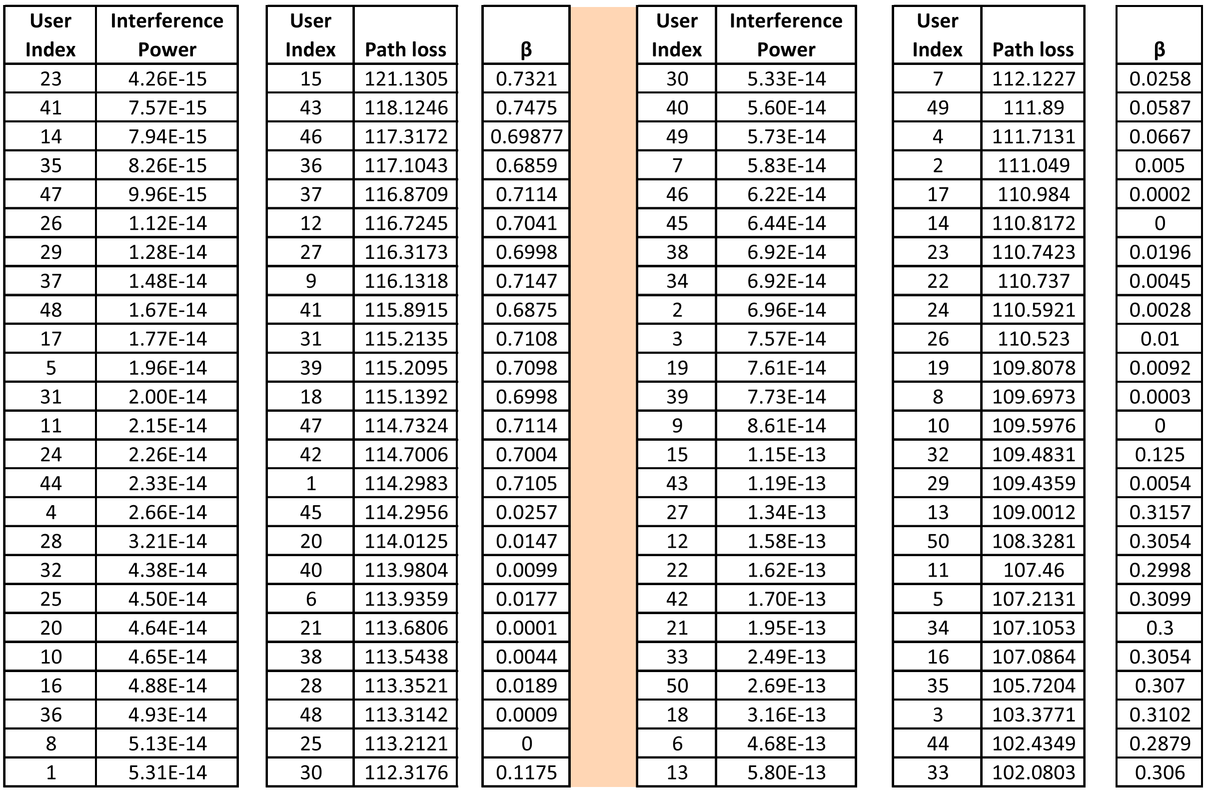


Figure 4. Effective SINR for different target SNRs in dB.

there would be reduction in the interference at the cell edges due to decreased CL UE transmit power levels [9]. The UE transmit power is adjusted based on the PHP report along with the path-loss measurement results. It is inferred from Figure 5 that the path loss is high for the user with index 15 and minimum for 33. However, their measured interference power levels are less which is 1.15E-13 and 2.49E-13 respectively. The decrease in the CL UE transmits power levels compared to the required TX level is only -33.4075 dBm for index 15 and -25.4075 dBm for 33. The CL UE transmit power is reduced at a greater level for user with high interference, i.e. the users at the cell edges. This is the reason for the reduced interference power and increased SNR/SINR. The CL UE power levels are maintained such that the interference power levels are reduced and the target SINR is maintained. The algorithm perfectly withstands the strategic choice which includes interference power and path loss. Figure 7 shows the graph that compares the performance of conventional power control scheme for $\beta = 1$, against MSUPC-CP game with convex pricing and the proposed fraction power control scheme. For MSUPC-CP, a simple usage-based pricing policy with linear iterative method has been adopted towards obtaining the pricing factor. The pricing function $c_i(p_i, p_{-i})$ is appropriately defined as convex function of transmission power [17]. However, for demonstration purposes, an exponential pricing function is adopted in the work as $c_i(p_i, p_{-i}) = c(e^{p_i} - 1)$. Analysing the performance, it is evident that the closed-loop algorithm with fractional compensation for the path-loss performs better. At every point in the graph, it is clear that the closed loop with fractional compensation has more users distributed (above 95%) than the power control with convex pricing and full compensation. But the drawback is in the computational complexity; as it involves running both open loop and closed loop power control algorithms to find the desired SINR along with Heuristic algorithm to adjust the uplink transmit power. It took a total simulation time of 16.736949 s for the entire system to work. On excluding (which are not relevant to real-time) the time for fixing the system parameters and creating the network with 45 users, which took 3.487837s and the time for plotting the graphs which took 1.211053 s; the exact time for running the open loop, closed loop and Heuristic algorithms is 12.038059 s.

The real-time implementation could be feasible as heuristically fixing the β value is simple compared to convex and linear pricing as game theory approaches are included. The algorithm performs better in improving the users' bit rates of all users even in heavy path loss and interference conditions, and also in deciding



User Index	Interference Power	User Index	Path loss	β	User Index	Interference Power	User Index	Path loss	β
23	4.26E-15	15	121.1305	0.7321	30	5.33E-14	7	112.1227	0.0258
41	7.57E-15	43	118.1246	0.7475	40	5.60E-14	49	111.89	0.0587
14	7.94E-15	46	117.3172	0.69877	49	5.73E-14	4	111.7131	0.0667
35	8.26E-15	36	117.1043	0.6859	7	5.83E-14	2	111.049	0.005
47	9.96E-15	37	116.8709	0.7114	46	6.22E-14	17	110.984	0.0002
26	1.12E-14	12	116.7245	0.7041	45	6.44E-14	14	110.8172	0
29	1.28E-14	27	116.3173	0.6998	38	6.92E-14	23	110.7423	0.0196
37	1.48E-14	9	116.1318	0.7147	34	6.92E-14	22	110.737	0.0045
48	1.67E-14	41	115.8915	0.6875	2	6.96E-14	24	110.5921	0.0028
17	1.77E-14	31	115.2135	0.7108	3	7.57E-14	26	110.523	0.01
5	1.96E-14	39	115.2095	0.7098	19	7.61E-14	19	109.8078	0.0092
31	2.00E-14	18	115.1392	0.6998	39	7.73E-14	8	109.6973	0.0003
11	2.15E-14	47	114.7324	0.7114	9	8.61E-14	10	109.5976	0
24	2.26E-14	42	114.7006	0.7004	15	1.15E-13	32	109.4831	0.125
44	2.33E-14	1	114.2983	0.7105	43	1.19E-13	29	109.4359	0.0054
4	2.66E-14	45	114.2956	0.0257	27	1.34E-13	13	109.0012	0.3157
28	3.21E-14	20	114.0125	0.0147	12	1.58E-13	50	108.3281	0.3054
32	4.38E-14	40	113.9804	0.0099	22	1.62E-13	11	107.46	0.2998
25	4.50E-14	6	113.9359	0.0177	42	1.70E-13	5	107.2131	0.3099
20	4.64E-14	21	113.6806	0.0001	21	1.95E-13	34	107.1053	0.3
10	4.65E-14	38	113.5438	0.0044	33	2.49E-13	16	107.0864	0.3054
16	4.88E-14	28	113.3521	0.0189	50	2.69E-13	35	105.7204	0.307
36	4.93E-14	48	113.3142	0.0009	18	3.16E-13	3	103.3771	0.3102
8	5.13E-14	25	113.2121	0	6	4.68E-13	44	102.4349	0.2879
1	5.31E-14	30	112.3176	0.1175	13	5.80E-13	33	102.0803	0.306

Figure 5. Interference power and path loss measured in dB arranged in descending order and allocation of β value.

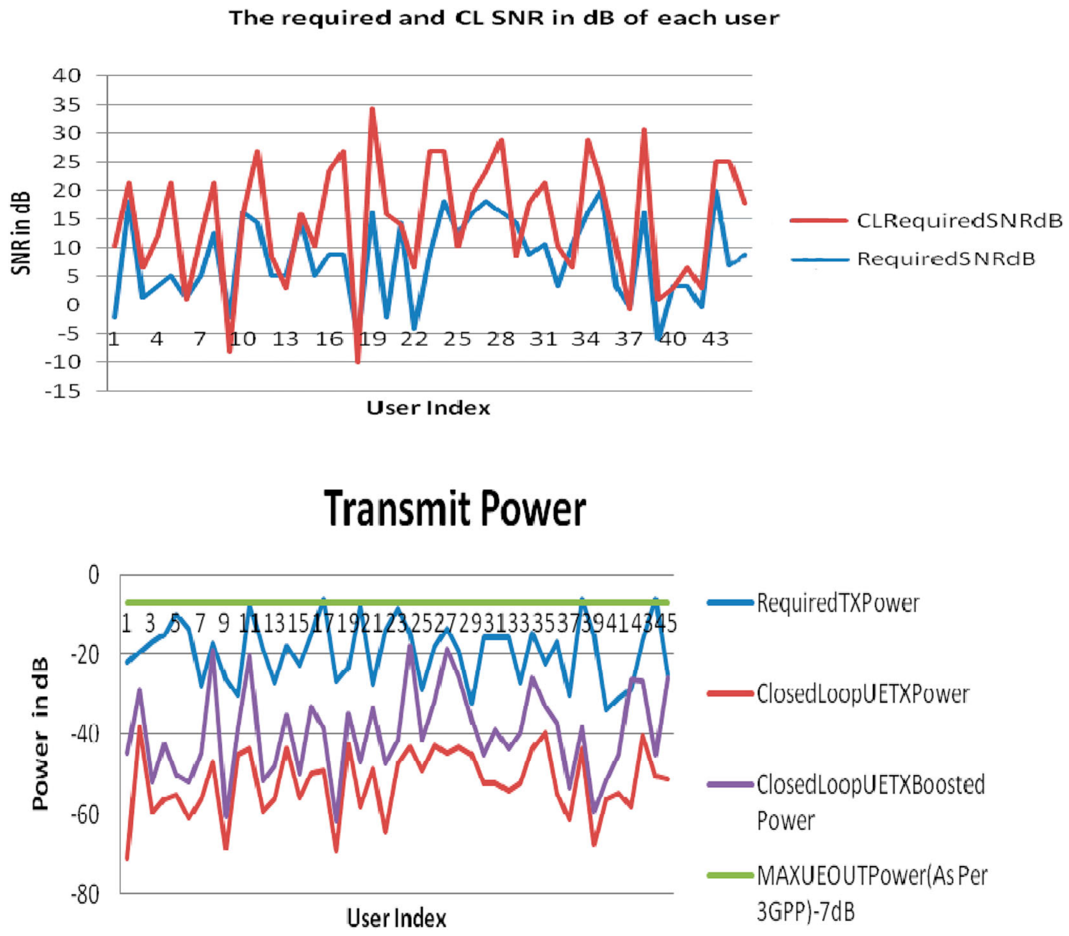


Figure 6. SNR and power variations of each user.

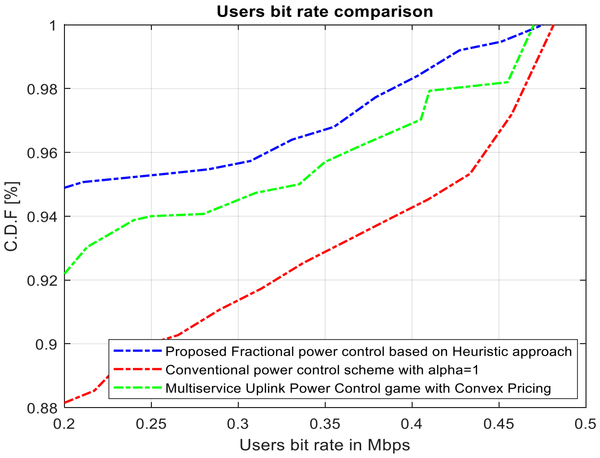


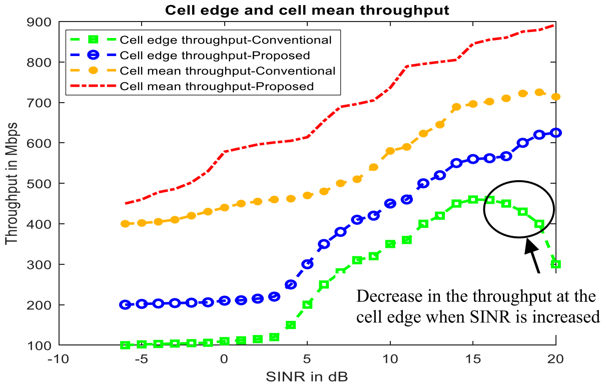
Figure 7. Users bit rate comparison of proposed power control scheme with the existing conventional power control scheme and power control scheme with convex pricing.

the desired uplink transmitter power. It is clear that on an average there is an increment of 5.2% in the coverage of users upon proper selection of penalization factor, β and hence the $P_{OP.}$ This percentage can even be more if wide ranges of β values are selected. However, Heuristics by definition are imprecise, and these quick fixes or provide optimal solutions only for the time being. Game theory approach requires adequate knowledge about the players/users in the game which is not always possible. There are different 3GPP LTE releases and they differ in many aspects. In the work only the LTE UE specification under release 10 is considered with limited channel impairments. A flexible Closed Loop Power Control strategy that takes into account the coordination among multiple beams and the limitation from 3GPP standards is not considered as in reference [28].

Variation in the throughput at the cell edge and the cell center for the proposed closed loop power control schemes with fractional compensation and the conventional power control scheme is shown in Figure 8. The SINR is varied between lower and upper bound respectively for the modulation to happen. The modulation type shifts between QPSK and 16-QAM based on the SINR. The proposed fractional power control scheme performs better in the cell centre and even at the cell edges. This is possible by dynamically changing the CL UE transmit power based on the location of UE. But in the conventional scheme there is a dip in the throughput at the edges due to increase in the path loss and the interference power, thereby reduces the SINR.

$$Throughput = \frac{BW}{Rbnumber * \log 2(1 + 10^{0.1*SINRdb})} \tag{19}$$

The closed loop and open loop throughput is calculated from Equation (19) which is similar to Shannon's formula. Thus the utility function is maximized as per Equation (10).



Decrease in the throughput at the cell edge when SINR is increased

Figure 8. Throughput at the cell edge and cell centre.

6. Conclusion and future scope

The system performance is evaluated for closed loop power control schemes with full compensation, fractional compensation and compensation with convex pricing. The simulation results are obtained for the cellular network environment with 45 random LTE and Wi-Fi users for a given bandwidth. The performance of the open loop and closed loop power control schemes is compared with the uplink SINR ratio. It is found that the closed loop power control scheme performs better than the open-loop scheme as it compensates for the interference in terms of throughput across the entire network area. As we look into interference aware power control scheme, the closed loop power control scheme with fractional compensation is found to be a better choice and its performance is analysed with respect to bit rate with full compensation and convex pricing schemes by fixing β values heuristically. An increment in the throughput at the cell edges and cell centre is achieved as a result of optimal power allocation as the algorithm fixes the β value based on the position of the users, measured interference and path loss, and checks if the optimal condition is met. From the β value, the uplink transmit power is calculated which apparently increases the throughput of the users in the cell edge and cell centre. Nearly 99% of the users were able to achieve a bit rate of 0.45 Mbps. An overall acceptable increment of 5.2% in the user coverage/distribution is achieved. In the future, it is planned to extend this work with an increased cell structure, accommodating more users, and allocating a wide range of β values between 0 and 1 with reduced computational time. Also the mobility aspect in a cellular network environment has to be considered which dynamically changes the measured interference power and the path loss. This reality is considered the prime limitation of the work.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix

```
Initialize simulation parameters and constants
      for each iteration:
Generate network map with cells and sectors
      for each user in sector:
Generate random user positions within the sector
Calculate users' distances, angles, and path loss for each user in sectors:
usersPathlossdB = pathloss_func(usersDistance)
usersShadowdB = shadowStddB ∗ rectpulse(rand(usersNumber, cellsNumber).', 3).'
totalPathLossdB = zeros(usersNumber, sectorsNumber, ResourceblockNumber)
Perform resource allocation based on scheduling algorithm
AllocMatrix = zeros(sectorsNumber, ResourceblockNumber)
          if strcmpi(schedulingAlg, 'roundrobin'):
            if usersPerSector ≤ ResourceblockNumber:
              for cnt = 1: sectorsNumber:
                usersIndex = (cnt-1) ∗ usersPerSector+(1:usersPerSector)
                    userCnt = 1
              for cnt2 = 1: ResourceblockNumber:
                AllocMatrix(cnt, cnt2) = usersIndex(userCnt)
                  if userCnt < usersPerSector:
                          userCnt = userCnt + 1
                  else
                            userCnt = 1
                  end
                end
              end
            end

Generate random or fixed SNR values for each resource block
      if strcmpi(requiredSNRdB, 'random') || strcmpi(requiredSNRdB, 'fixed'):
          elseif strcmpi(requiredSNRdB, 'adaptive'):
          end
        end
Determine the UE transmit power and calculating SINR for each resource block and sector
        for rb = 1: ResourceblockNumber
            if alpha = = 1
              RequiredTxPowdB = maxUEOutPow ∗ ones(ResourceblockNumber, 1)
            else
              RequiredTxPowdB = noisePowdB - 10 ∗ log10(ResourceblockNumber) + alpha ∗ CurrenttotalPathLossdBdB(:) + RequiredSNRdB(:)
            end
      for rb = 1: ResourceblockNumber
CurrenttotalPathLossdBdB(rb) = totalPathLossdB(userIndex(rb), cnt, rb)
          end
Determine the Receiver power and CL UE transmit power
RxPowdB = closedLoopUETransmitPower(cnt,:) - CurrenttotalPathLossdBdB(:).'
InterferePow = InterferePow + 10 .∧ (0.1 ∗ (UETransmitPower(cnt2,:).' - CurrenttotalPathLossdBdB2(rb))
closedLoopUETransmitPower(cnt, :) = min(RequiredTxPowdB, 10 ∗ log10(maxUEOutPow)).'
Heuristic Algorithm
usersPathlossdB = usersPathlossdB(:, 1);
PL = sort(usersPathlossdB);
SortedInterferePow = InterferePow(:, 1);
IntPower = sort(SortedInterferePow);
A = max(PL);
B = min(PL);
High_PL = ((((A + B) / 2) + (A / 2))) ∗ (1 / 1.5);
Low_PL = ((((A + B) / 2) + (B / 2))) ∗ (1 / 1.5);
Medium_PL = (A + B) / 2;
beta = 0.1 + (1 - 0.1) ∗ rand();
        for upl = 1: userIndex
          if usersPathlossdB(upl) > High_PL
      beta = beta + 0.2;
      end
        elsif usersPathlossdB(upl) < Low_PL
        beta = beta – 0.2;
      end
        else usersPathlossdB(upl) > Medium_PL
            beta = beta + 0;
        end
      end
Adjust closed-loop SINR based on the calculated beta and interference
closedLoopRbSINRdB = UETransmitPower – UETransmitPower – 10 ∗ log10(beta ∗ 10 .∧ (InterferePow / 10));
if nI ∼ = closedLoopNumOfIterations + 1
//Calculate the difference between required SNR and calculated SINR//
closedLoopPowerBoostdB = closedLoopRequiredSNRdB – closedLoopRbSINRdB;
//Adjust the transmit power based on the boost ratio//
closedLoopUETransmitPower = closedLoopUETransmitPower + closedLoopPowerBoostdB ∗ closedLoopBoostRatio;
//Ensure the transmit power does not exceed the maximum allowed power//
closedLoopUETransmitPower = min(closedLoopUETransmit Power, 10 ∗ log10(maxUEOutPow));
End
```

(*continued*)