Hierarchical power control model for interference mitigation in a two – Tier heterogeneous network

O. I. Ladipo¹ and A. O. Gbenga-Ilori²

Abstract: The heterogeneous deployment of different base stations has increased the overall network capacity and reduced excess traffic from the macrocell network. However, this improved system performance is accompanied by several technical challenges which include interference management, power control, resource allocation, security, backhaul, and handover issues. This paper presents a single-leader, multi-follower power control game model that mitigates interference in a two-tier heterogeneous network where femtocells are densely deployed within the coverage area of the macrocell. In the proposed game, the femtocells act as the followers and update their respective transmission power based on the information received from the macrocell which is the leader of the Stackelberg game. The existence of the Stackelberg equilibrium (SE) in the formulated game was determined by the backward induction method and it showed the possibility of a stability point that is optimal and Pareto efficient. Extensive simulations were carried out to evaluate the performance of the proposed scheme and the effect of the set transmission cost and utility function on the base stations. Simulation results showed a reduced level of interference between the base stations, improved network capacity, and effective allocation of network resources among the users.

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PUBLIC INTEREST STATEMENT

The increased interference between the base stations in a heterogeneous network where femtocells and macrocells co-exist is a major concern in wireless cellular communication and has received a lot of attention from researchers. The traditional centralized power control schemes that have been proposed to solve the interference issue are known to result in overhead signaling as network capacity increases and this limitation has led to the application of game theory. In this paper, the Stackelberg game theory was applied to model the interaction among the base stations in a two-tier heterogeneous network. We defined a utility function that maximizes the performance of the devices in the network and a cost function that serves as a cooperation factor for the base stations. The cost function and utility function have a reliable physical interpretation and maximize the degree of satisfaction of the network users. The proposed scheme results in efficient utilization of network resources, reduced interference between the base stations, and improved network capacity.

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1. Introduction

The need to improve the services provided by the macrocells to their user equipment to meet up with the demand of the continuously growing subscriber has birthed the development of smaller networks such as microcells, picocells, and femtocells. Femtocells have been given a closer consideration among these small networks, because of its smaller coverage area (Chandrasekhar, Andrews, & Gatherer, 2008), cost-effectiveness, and its ability to improve voice and data reception in the indoor environment (Chandrasekhar et al., 2008; Saad, Ismail, & Nordin, 2013). Femtocells operate within the licensed spectrum strictly allocated by the network operator to provide data and voice services to user terminals and are easily deployed by customers with minimal or no radio frequency planning (Saad et al., 2013).

The interference between the communication devices in a two-tier heterogeneous network where femtocells are overlaid on the macrocell network is a major technical issue that limits the overall system performance. (Joshi & Malik, 2019; Adediran, Lasisi, & Okedere, 2017; Pawar & Trivedi, 2019; Yang, Zhao, Gao, & Gong, 2019). Therefore, the subject of interference in a wireless communication network has been the focus of several works of literature where several authors have proposed different techniques to mitigate and manage the issue of interference.

In the work of (Ho et al., 2015), a sum rate optimization problem with power control for uplink transmission in a heterogeneous network was considered by developing a distributed algorithm that can attain the global optimal transmit power values. However, their algorithm resulted in an increased information exchange which is inefficient in energy consumption unlike our work that factor the energy usage of the base stations into consideration. Price-based resource allocation strategies for two-tier femtocell networks were investigated in (Kang, Zhang, & Motani, 2012) while a power control mechanism was proposed in the work of (Tseng, Wang, Ting, Tsai, & Kuo, 2017) to mitigate the interference between femtocell and macrocell during the uplink transmission. The authors considered the joint utility maximization of the base stations subject to a maximum tolerable interference power constraints at the measurement points. In their work, the quality of service of the femtocell is not guaranteed because they gave utmost priority to the macrocell. This is in contrast to our work which considered both the co-tier and cross-tier interference.

A distributed iterative power control scheme was proposed in (Douros, Toumpis, & Polyzos, 2012), based on the assumption that macrocell only provides voice communication while femtocells provide data communication to their respective users. Their solution is not feasible because macrocells and femtocells provide both voice and data services at the same time based on the service requirement of the user. The limitations in these works of literature, coupled with the need to design a stable and reliable two-tier heterogeneous network with minimal interference level from the co-existing base stations, are the motivation for this research work.

In this paper, the interference problem in a two-tier heterogeneous network where femtocells are overlaid on the macrocell network is modeled using the Stackelberg game (SG) theory. The player that takes the first action in the game is referred to as the leader while the player that chooses its strategy based on the leader’s strategy is referred to as the follower (Jia, Xu, Sun, Feng, & Anpalagan, 2018; Solis, Clempner, & Poznyak, 2016; Zheng et al., 2016). The macrocell and the femtocells are the players in the proposed power control game, where the macrocell is the leader and the femtocells are the followers. The leader announces its strategy and the follower takes action based on the leader’s announced strategy (Xu et al., 2018; Han, Niyato, Saad, Başar, & Hjørungnes, 2012; MacKenzie & Wicker, 2001; Ladipo, 2018). As a result of this hierarchy in the
player’s decision-making, a Stackelberg equilibrium (SE) is determined which corresponds to the optimum strategy of the leader and the followers.

The major contributions of this paper are summarized as follows:

- Formulation of a hierarchical power control game that mitigates interference in a two-tier femtocell and macrocell network,
- Proposal of an appropriate utility and cost functions to maximize the degree of satisfaction of the network users, reduce the interference between the users, reduce their power consumption, and provide efficient energy usage,
- Determination of a Stackelberg Equilibrium (SE) point in the power control game by the backward induction method with a resultant algorithm that is fair, adaptive, flexible, and easy to implement in a cellular system.

The rest of this paper is organized as follows: The system model of the proposed scheme and assumptions are discussed in Section 2. Section 3 presents the power control game formulation and the existence of the SE while the algorithm and the simulation results that validate the effectiveness of the proposed scheme are discussed in Section 4. Lastly, Section 5 provides the conclusions of this paper and future research directions.

2. System model
A two-tier heterogeneous network that consists of a centralized macrocell and densely deployed femtocells within its coverage area as shown in Figure 1 is studied in this paper. It is assumed that both the macrocell and the femtocells utilize the orthogonal frequency division multiple access (OFDMA) in which the channels have been divided into different communication slots and each transceiver is assigned a set of orthogonal channel (Ladipo, 2018). The base stations (BSs) act as the players in the proposed model, each having a set of strategy corresponding to the choice of their transmission power. Each player competes in a non-cooperative manner to maximize its utility which we defined in terms of increased capacity, reduced interference, and good signal-to-interference plus noise ratio (SINR). The macrocell is denoted as $M$, the macrocell user equipment $M_{UE}$, the femtocell $F$ and its user equipment $F_{UE}$. The set of all the deployed femtocells is $F_N$, where $F_N = \{ F_1, F_2, F_3, \ldots, F_n \}$ and $F_{-1}$ represent all...
the femtocell in the set \( F_N \) except femtocell \( F_1 \). The transmission power of all the deployed femtocells forms the transmission power vector \( P_{F_n} = \{ P_{F_1}, P_{F_2}, \ldots, P_{F_n} \} \). \( P_{F_1} \) is the power of the other femtocells except for femtocell \( F_1 \). The power strategy of macrocell \( M \) is \( P_M \) since there is only one macrocell within the model network and \( P_M \) can range from 0 to \( P_M^{\text{max}} \). The strategy set of femtocell \( F_1 \) is given as \( P_{F_1} = \{ P_{F_1} : 0 \leq P_{F_1} \leq P_{F_1}^{\text{max}} \} \), where \( P_M \) and \( P_{F_1} \) are the transmission power of macrocell \( M \) and femtocell \( F_1 \), respectively. 0 is their inactive states, \( P_M^{\text{max}} \) and \( P_{F_1}^{\text{max}} \) are the maximum transmit power within their strategy profile. There are \( N \) base stations within the network and they form the set \( N_{BS} = \{ M, F_1, F_2, \ldots, F_n \} \). The strategy set of all the base stations \( P_{N_{BS}} \) is given as: \( P_{N_{BS}} = \{ P_M, P_{F_1}, P_{F_2}, \ldots, P_F, \ldots, P_{F_n} \} \).

The channel gain between the BSs and their respective user equipment is calculated from the modified path loss formula given in (Sun, Wang, Sun, & Zhang, 2016; Guruacharya, Niyato, Hossain, & Kim, 2010), and it is the product of the distance between each base station, its user equipment, and the random fading coefficient. The signal-to-interference-plus-noise ratio (SINR) of the macrocell is expressed as:

\[
\text{SINR}_M = \frac{P_M G_{M,i}}{\sum_{i' \in F_n} P_{F_1} G_{F_1,i' + \sigma_n}}
\]  

(1)

where \( P_M \) and \( P_{F_1} \) are the transmission power of the serving macrocell and femtocell \( F_1 \), \( \sigma_n \) is the noise power, \( G_{M,i} \) represent the channel gain between macrocell \( M \) and its user \( i \), \( G_{F_1,i} \) is the gain between femtocell \( F_1 \) and user \( i \). Similarly, the SINR of femtocell \( F_1 \) can be expressed as:

\[
\text{SINR}_{F_1} = \frac{P_{F_1} G_{F_1,i}}{P_M G_{M,i} + \sum_{i' \in F_n} P_{F_1} G_{F_1,i'} + \sigma_n}
\]  

(2)

where the parameters are as defined.

The macrocell is aware of the presence of the femtocells within its coverage area because it is assumed that the femtocells take their signaling from the macrocell (Han et al., 2012) since they are within the same network. It is assumed that all the BSs in the modeled network can adjust their transmission power dynamically, depending on the measured parameters in their environment. The achieved transmission rate of the base stations \( R_{BS} \) can be determined by Shannon’s formula as:

\[
R_{BS} = W \log_2(1 + \text{SINR}_{BS})
\]  

(3)

where \( W \) is the bandwidth in Hertz and \( \text{SINR}_{BS} \) is the signal to interference plus noise ratio for either the macrocell or any of the femtocell in the network.

### 3. Stackelberg game formulation

The Stackelberg power control game (SPCG) formulated in this paper represents a non-cooperative \( N_{BS} \) player game which is defined as:

\[
G_{N_{BS}} = \{ N_{BS}, \{ P_{N_{BS}} \}, \{ U_{N_{BS}} \} \}
\]  

(4)

where \( U_{N_{BS}} \) is the set of utility functions for the players. The macrocell and each of the femtocells aim to optimize their utilities denoted by \( U_M \) and \( U_{F_1} \) for macrocell \( M \) and femtocell \( F_1 \) respectively.

In our model, the base stations incurred a transmission cost \( TC \) per unit power during their active transmission. \( TC_M \) is the transmission cost for macrocell \( M \) and \( TC_{F_1} \) is the cost incurred by femtocell \( F_1 \). This transmission cost is defined as the interference the base stations cause the neighboring BS during their active transmission which is the measure of their received power. For ease of computation and comparison, the SINR and the transmission cost are expressed in decibel (dB). The utility \( U_{M} \) of macrocell \( M \) is defined as:
Similarly, the utility $U_{F_1}$ for femtocell $F_1$ is defined as:

$$ U_{F_1}(P_M, P_{F_1}) = \text{SINR}_{F_1} - TC_{F_1} $$

As seen in equation (5) and (6) the utility function depends on SINR, the transmission power of the base stations, and their transmission cost. The macrocell and each of the femtocells aim to find the optimal transmission power that achieves a good link quality and results in minimal interference to the neighboring BSs. This optimal transmission power of the base stations is obtained by solving the optimization problems defined in Problem A and B.

**Problem A**: 

$$ \max_{P_M} U_M(P_M, P_{F_1}) = \text{SINR}_M - TC_M $$

$$ \text{s.t. } 0 \leq P_M \leq P_M^{\text{max}} $$

**Problem B**: 

$$ \max_{P_{F_1}} U_{F_1}(P_M, P_{F_1}, P_{-F_1}) = \text{SINR}_{F_1} - TC_{F_1} $$

$$ \text{s.t. } 0 \leq P_{F_1} \leq P_{F_1}^{\text{max}} $$

Equation (7) and (9) form the proposed Stackelberg power control problem in this work.

### 3.1. The Stackelberg equilibrium (SE) in the formulated game

The solution of the single-leader multi-follower Stackelberg game proposed in this paper is analyzed below. The backward induction method is applied to solve the problems defined in equation (7) and (9) because of its capability to analyze the interaction between the decisions of the players in a game where hierarchy exists. The Stackelberg Equilibrium (SE) for the formulated game is defined as follows:

**Definition 1**: Let $U_M$ and $P_{F_1}$ be the Stackelberg equilibrium if $U_M$ maximizes the utility of macrocell $M$ and $P_{F_1}$ is the best response that maximizes the femtocell utility. Thus, the point $(U_M, P_{F_1})$ is a solution to the proposed game if the conditions in Equation (11) and (12) are satisfied, for $(U_M, P_{F_1})$, where $U_M \geq 0$ and $P_{F_1} \geq 0$:

$$ U_M(U_M, P_{F_1}) \geq U_M(U_M, P_{F_1}) \forall U_M $$

$$ U_{F_1}(P_{F_1}, P_{-F_1}, U_M) \geq U_{F_1}(P_{F_1}, P_{-F_1}, U_M) \forall U_M, P_{F_1} $$

**Problem B** is solved given transmission power $P_M$ for macrocell $M$, in order to get the optimum transmit power that maximizes the utility of the femtocells. The outcome of this maximization problem is applied in **Problem A** to get the optimum transmission power $P_M^*$ for macrocell $M$.

#### 3.1.1. Optimum response strategy of the femtocells

Let $P_M$ be the transmission power of macrocell $M$, therefore the optimum strategy $P_{F_1}^*$ of femtocell $F_1$ is computed by solving **Problem B** defined in (9).
**Definition 2:** Given the announced transmission power $P_M$ of the macrocell, a non-cooperative sub-game exists among the femtocells where they all compete to determine the optimal power that maximizes their transmission sum rate. This competition among the femtocell is referred to as a lower sub-game (Sun et al., 2016; Guruacharya et al., 2010) and it is expressed as:

$$G_N = \left[ F_N, \{ P_{F_i} \}_{i \in F_N}, \{ U_{F_i} \}_{i \in F_N} \right]$$

(13)

**Lemma 1:** The optimum response of femtocell $F_1$ is its optimal transmission power $P_{F_1}$ that maximizes its utility $U_{F_1}(P_M, P_{F_1}, P_{-F_1})$. Therefore, the maximum of $U_{F_1}$ with respect to $(P_M, P_{F_1}, P_{-F_1})$ is shown in proof 1.

**Proof 1:** Recall equation (9), $\max U_{F_1}(P_M, P_{F_1}, P_{-F_1}) = \text{SINR}_{F_1} - TC_{F_1}$

$$U_{F_1}(P_M, P_{F_1}, P_{-F_1}) = \frac{P_{F_1} G_{F_1,j}}{P_M G_{M,j} + \sum_{i \in F_N} P_{i,j} G_{i,j} + \sigma_n} - TC_{F_1}$$

(14)

$$\frac{\partial^2 U_{F_1}(P_M, P_{F_1}, P_{-F_1})}{\partial P_{F_1}^2} = \frac{G_{F_1,j}}{(P_M G_{M,j} + \sum_{i \in F_N} P_{i,j} G_{i,j} + \sigma_n)^2}$$

(15)

$$\frac{\partial^2 U_{F_1}(P_M, P_{F_1}, P_{-F_1})}{\partial P_{F_1}^2} = > 0$$

(16)

$$P_{F_1}^* = \frac{G_{F_1,j}}{(P_M G_{M,j} + \sum_{i \in F_N} P_{i,j} G_{i,j} + \sigma_n) 2G_{F_1,j}}$$

(17)

The optimal transmission power of femtocell $F_1$ is given in (17), after some mathematical deductions from (14) and (15). Any response strategy in the power allocation vector of $P_{F_1}$ that does not result in $P_{F_1}^*$ increases the transmission cost of its base station which reduces its SINR value with a tendency of being forced out of the game. The objective function is convex as seen in (16). The optimal power strategy of femtocell $F_1$ is $P_{F_1}^*$ and it is within the strategy space of $P_{F_1}$. It is non-empty, convex, and a compact subset of the Euclidean space $R^n$. Also, the utility $U_{F_1}(P_M, P_{F_1}, P_{-F_1})$ is non-zero, continuous, and quasi-concave in $P_{F_1}$ (Xu, Li, Gao, & Tao, 2014; Ladipo & Gbenga-Ilori, 2019). Therefore, Nash equilibrium exists for the femtocells sub-game where each femtocell play its best strategy.

3.1.2. Optimum strategy of the macrocell

The optimal response strategy of the macrocell is obtained by solving the optimization problem defined in Problem A based on the best response strategies of the femtocells.

**Lemma 2:** Macrocell $M$ is aware of the presence of the femtocells within its coverage as well as their optimal response strategies based on its announced strategy $P_M$. Thus, the optimum strategy that maximizes the utility $U_M(P_M, P_{F_1})$ of the macrocell based on $P_{F_1}$ is shown in proof 2.

**Proof 2:** Recall equation (7), $\max U_M(P_M, P_{F_1}) = \text{SINR}_M - TC_M$

$$U_M(P_M, P_{F_1}) = \frac{P_M G_{M,j}}{\sum_{i \in F_N} P_{F_i,j} G_{F_i,j} + \sigma_n} - TC_M$$

$$U_M(P_M, P_{F_1}) = \frac{P_M G_{M,j}}{\left( \frac{G_{F_1,j}}{(P_M G_{M,j} + \sum_{i \in F_N} P_{i,j} G_{i,j} + \sigma_n) 2G_{F_1,j}} \right) G_{F_1,j} + \sigma_n} - TC_M$$

(18)
The best strategy of the macrocell is given as:

\[
P^* = \frac{G_{M,j}}{\left( \frac{G_{F,j}}{\left( \frac{G_{M,j} + \sum_{i=1}^{n} P_i G_{F,j} + \sigma_n}{2G_{F,j}} \right) G_{F,j} + \sigma_n} \right) G_{M,j}}
\]

The optimum solution to Problem A is shown in (19) and it is the best strategy \( P^*_M \) that maximizes the utility \( U_M \) of the macrocell based on the optimal responses of the femtocells. Therefore, the Stackelberg equilibrium for macrocell \( M \) and the femtocells is \( (P^*_M, P^*_F) \). The proof of the uniqueness of the Stackelberg equilibrium is omitted in our work for brevity, but it follow the pattern seen in the work of (Sun et al., 2016) and (Xu et al., 2014).

### 4. Numerical results and analyses

The Stackelberg power control scheme proposed in this work was implemented in the MATLAB environment. The simulation scenario comprised of a single macrocell with an omnidirectional antenna located at the center of the cell and 10 femtocells randomly deployed within. The femtocell access points have a minimum of two (2) users and a maximum of four (4) users connected to it. The macrocell has 40 active user equipment which are randomly deployed within the coverage area of the femtocells, outside the femtocells’ coverage area, and at the cell edge. The transmit power of the macrocell is higher than that of the femtocells while the coverage radius of the femtocells is considerably smaller than that of the macrocell. The femtocell users are located at different distances within the FAP’s coverage area and are assumed to have the same bandwidth. The setup was analyzed from the point of view of network transmission sum rate, SINR, network capacity, transmission power, transmission cost, number of transmitting user equipment, and utilities of the base stations. The parameters used in the simulation are summarized in Table 1 and the algorithm is presented in Algorithm 1.

Figures 2 and 3 show the transmission cost of the femtocells and their signal to interference plus noise ratio. The transmission power of the femtocells was increased at an interval of 10mW from 0mW to 100mW and their characteristic was also observed at their respective optimum transmit power given the set macrocell power \( P_M \). It is observed in Figure 2 that transmission cost increases exponentially with increasing transmission power as against the incurred cost at optimum transmit power which is seen to reduce drastically.

### Table 1. Simulation parameters (Xu et al., 2014; Huawei, HiSilicon, CATR, CMCC, R1-130744, 2012)

| Parameters         | Macrocell | Femtocell |
|--------------------|-----------|-----------|
| Transmission power | 46 dBm    | 10 dBm—20 dBm |
| Bandwidth          | 10 MHz    | 2.5 MHz   |
| Number of base stations | 1       | 10       |
| Radius             | 500 m     | 20 m      |
| Noise power        | —174 dBm  | —174 dBm  |
| Number of users    | 40        | 2—4       |
Algorithm 1: The proposed Stackelberg Power Control Scheme

**Input variables:** $P_M, P_{F_i}, \forall BS \in N_{BS}$.

**Output variables:** The optimal transmission power that maximizes the utility of all BS $(P_M^*, P_{F_i}^*)$

1. Macrocell set its power strategy $P_M$ and broadcast it to all femtocells.
2. A lower sub-game exists among the femtocells based on $P_M$ and they determine their optimum transmit power that maximizes $U_{F_i}(P_M, P_{F_i}, P_{F_i})$.
3. Determine the Nash Equilibrium for the femtocells sub-game.
4. Obtain the responses of the femtocells given in eq. (17) and determine the optimum transmit power $P_M^*$ for macrocell $M$.
5. Arrive at $(P_M^*, P_{F_i}^*)$ and declare the Stackelberg Equilibrium.

**End.**

This implies that at high transmit power, the femtocells incur a high cost as their power increases which justified the set definition. The cost function introduced in this work served as a cooperative function in the game by discouraging the base stations from transmitting at any other transmit power apart from their optimum power value.

It is seen in Figure 3 that by increasing the transmitter power level of the femtocells, they achieved a higher value of SINR except for the femtocells that have more active macrocell users within its coverage as a result of increased interference. The higher SINR value does not result in a good utility value because of the increased transmission cost incurred. The utility is a measure of the sum transmission rate, network capacity, and SINR. The capacity of the femtocells was investigated as shown in Figure 4. The capacity
increases both with increasing value of transmitter power and at the optimum transmit power of the femtocells. The femtocells achieved a good transmission sum rate at optimum transmission values which conform to their achieved utility value. Therefore, it can be deduced that the proposed scheme is effective in the network resource allocation.

The locations of the femtocells were varied thrice as well as the number of their users as a numerical example to further evaluate the performance of the proposed power control scheme. At each of these locations, the macrocell optimum transmission power was seen to range from $41.51\,\text{dBm}$ to $46.33\,\text{dBm}$ and it resulted in an SINR value that is higher than their target SINR when
they operated at their nominal power. The capacity of the femtocells at these optimum power responses is shown in Figure 5. The estimated SINR and capacity of the macrocell at these optimum power levels far exceed when it operated at its nominal transmission power. This shows that the proposed scheme gives preference to the macrocell by allowing it to protect itself from increased interference from the femtocells. The cost incurred by the macrocell during its operation at the optimum power levels is almost negligible; therefore, the utility is seen to be directly proportional to the achieved SINR at the optimum power.

To further establish the validity and the performance of the work presented in this paper, the proposed scheme is compared with the scheme used in (Guruacharya et al., 2010) where a two-way pricing mechanism was integrated into the Stackelberg game to reduce the co-tier interference among femtocells. Their scheme reached an equilibrium point after several iterations which is seen as a limitation in terms of complexity time when compared to the scheme proposed in this research work which readily results in a Stackelberg equilibrium point.

The femtocell under the Stackelberg model in this research performed better in terms of transmission rate and capacity unlike what is seen in (Guruacharya et al., 2010) where the followers were discouraged from transmitting at a particular interference constraint. Likewise, their work only measured the interference among the femtocells while they considered the interference from the femtocells to the macrocell and vice versa as a background interference. This is not fair on the macrocell and its user equipment because they constitute a major percentage of the overall system network. An improvement on this is seen in the work we present in this study and the transmission sum rate of the femtocells under the two schemes is shown in Figure 6.

5. Conclusions
In this paper, the Stackelberg game theory was used to formulate a power control scheme that mitigates interference in a shared spectrum two-tier network where femtocells and macrocells co-exist. A system comprising a centralized macrocell with several femtocells randomly deployed
within its coverage area was modeled as an interfering link in order to measure the amount of interference between them and to evaluate their performance. A utility function and cost function with good physical interpretation were clearly defined and the optimal transmit power that maximizes the respective payoffs of the base stations was determined by the backward induction method. The performance of the proposed scheme was evaluated with extensive simulations and the numerical results showed a reduced interference among the base stations, good SINR value, increased transmission sum rate, and improved network capacity.

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