A Novel Utility Function of Power Control Game in Multi-Channel Cognitive Femtocell Network

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Abstract: Importance of power control is associated with distributed user characteristics, which is self-organized and non-cooperative in multi-channel cognitive femtocell network. Power control on Proposed PCG was based on the use of game theory method by generating a novel utility function that referred to the provision of solutions to the weakness of previous methods (KG and TB methods) that were the inability to achieve the SINR target. The results showed that the Proposed PCG was able to achieve SINR of 5.4 dB and above the SINR target 5 dB, so that the quality of service in this system can be fulfilled properly.

Keywords: power control game (PCG), game theory, utility function, non-cooperative, multi-channel, cognitive femtocell network.

1. Introduction

The development of wireless communication demands high speed data transmission, ability to support a different QoS, and wide bandwidth usage to satisfy users’ high mobility. Since the bandwidth is a limited resource, the spectral efficiency is needed in wireless communication. The use of spectrum to the maximum often create interference between users, therefore a technology that can provide high bit rate is required, such as the multi-carrier modulation (MCM). In MCM, the bandwidth is split into several sub-channels. Orthogonal Frequency Division Multiplexing (OFDM) is MCM form that provides the advantages of high bandwidth spectrum efficiency due to the use of orthogonal symbols, resistance to ISI (inter symbol interference) and easier data recovery through the channel estimation method [1]. To accommodate the increasing number of users, Orthogonal Frequency Division Multiple Access (OFDMA) is needed as multiple access technology. The use of OFDMA has several advantages such as high spectrum efficiency, reducing the effects of ISI and ability to provide high data rate. However, OFDMA is sensitive to co-channel interference (CCI) from neighboring cells which use similar frequency. The use OFDMA on the uplink direction is easier to do if it is developed from multiple access techniques of FDMA [2], but it takes a frequency synchronization and more accurate scheduling because the transmitted symbols come from several different users [3].

To reduce the density of the spectrum, we need a technique where parts of the spectrum that are not used by the primary user (PU) then used by the secondary user (SU) in order to increase the utility of the use of the frequency spectrum as a whole. This principle is contained in cognitive radio technology. Cognitive radio can also be implemented into an adaptive system that enables application of many parameters such as frequency spectrum, transmit power, modulation scheme and others [4]. The utilization of cognitive radio technology on mobile network (cognitive radio network, CRN) strongly supports the development of mobile communication technology, especially in the femtocell network.

Femtocell appears as data access network solution that can be installed by the customer to increase the coverage area. Development of cognitive femtocell network (CFN) is able to provide solutions to improve the cost effectiveness in several scenarios related to spectrum scarcity because the femtocell network can be implemented to share the spectrum with the macrocell network [5]. Even though femtocell provides the significant benefits for users of mobile operators, its existence generates a lot of challenges, including the interference either between users on the same level of femtocell network (co-tier interference) or between femtocell user and macrocell user at the tiered level (cross-tier interference) [6]. Inter-user interference occurs in some users either in similar femtocell or in different femtocell yet they are in the same channel at one time [7]. This interference is caused by disproportionate use of transmit power by each user. On the use of OFDMA, interference within a cell (intra-cell interference) is very small, even negligible compared to the interference between cells (inter-cell interference), so that interference between cells dominate the system performance. Therefore, the need for uplink power control system is applied to the side of the user to control the amount of interference between cells in order to minimize the interference [8], since the purpose of power control is to ensure that the transmit power of the transmitter will be able to reach high enough level to be detected by the receiver yet sufficiently low to avoid the interference with other users.

Power control does not only reduce interference, but also enhance the system capacity and quality of communication, so that power control can be used as one of the key techniques of resource management in mobile communication system. Power control system has been widely applied in mobile networks but much remains to be centralized. However, centralized power control system is no longer considered suitable to be applied since current users are growing in distributed characteristics. Since in the centralized power control system, power control process is handled by the base station so that the user does not need to do anything, which means that the user does not have independent power control. In addition, the complexity of the centralized power control system affects the overall quality of the communication system. To reduce the complexity of centralized system, a method of power control that is compatible to the cognitive radio system with the
characteristics of the self-organized user uses game theory approach is needed. Some theories such as Selectorate theory [9] and Deterrence theory [10] are only suitable for systems that are centralized, cooperative and extensive [11]. The selection of methods of game theory is motivated by conflict between self-organized power control users and non-cooperative. Therefore, research on the power control system independently by the user in cognitive femtocell network using game theory approach becomes important nowadays. Femtocell communication main problem is the interference between users as a result of their transmit-power inefficiency. Transmit power inefficiencies of user on femtocell communication has more effects particularly on the uplink communication than the user of femtocell access point (FAP), since transmission power inefficiencies is more often occurs in the uplink direction. In addition, uplink interference management is more difficult than downlink because management interference should count interference as the impact of all uplink sources [12]. Apart from disturbing other user-related interference, it will also affect the user itself in terms of its battery life. Complexity of the centralized network is influenced by the large number of computing process in the base station related to information processing of the overall environment and user [13]. The distributed network can become an option to reduce this complexity since the user in distributed network is no longer requires shared information from all relevant users regarding their environmental conditions. However, the system with the user characteristics such as this requires self-organized power control. Implementation of the power control system on a distributed network is able to reduce the complexity of the base station and also adapts to the characteristics of dynamic network where the users have high mobility. One of the problems in distributed network is the absence of power control by the base station as each user has an incentive to increase the maximum transmit-power based on self-interest to obtain the high SINR (signal to interference and noise ratio). This selfish user characteristic creates the interference to others and also wasteful use of the user’s battery. The use of game theory in power control systems considers user behavior as non-cooperative with each user in a distributed network. It makes every user does not have complete information of the environmental conditions, therefore efficient and flexible approach of distributed self-organized approach is required [14]. Game theory is very easy to adapt to non-cooperative (competitive) environments, but it focuses more on the achievement of NE so less concern on the process how users interact to achieve equilibrium [15].

Related to the latest research on power control in cognitive femtocell network, the research conducted by Thalabani [16] has proven that when it reaches a convergent condition, power usage by the user is smaller, but it did not achieve the target SINR. This becomes a disadvantage of Thalabani, so that the appropriate term to describe the results of this research is converging at an inconvenient time because it has not reached the SINR target. However, in the previous studies, particularly in Thalabani’s, it only features low power and high convergence, but not in compliance with good quality which is marked by the achievement of the SINR target. Consideration of good quality in addition of low power and high convergence in this study was the objective of this study that had not been met by other studies. This study proposed novel approach to develop power control model independently by the user (distributed power control) that used multi-channels on cognitive femtocell network using game theory approach. In addition, the evaluation of the feasibility and convergence as well as the development of utility function was also conducted to improve the user performance on cognitive femtocell network.

The organization of this paper is shown as follows. The system model is described in Section II, and section III explains the power control game in multi-channel femtocell network. Section IV shows the results of the power control game performance, and conclusions are given in section V.

2. Related Work

Research conducted by Koskie Gajic or known as KG algorithm [17] still used uplink single cell CDMA so as not to accommodate the channel addition of multi user (multi-channel multi-user) for the purpose of channel sharing, or in other words it has not yet accommodating the effect of channel addition to SINR and transmit power of the user. In KG algorithm, change of user distance has no effect on capacity, nor does the AWGN value change have no effect on the SINR value [18]. Although the convergence rate is almost the same, but unable to achieve the SINR target [19],[20]. Properly like KG, research by Al Gumaei [21] is also unable to achieve SINR target especially when the value of exponential factor (β) is small, but increasing in β will also increase user power. Increased β also slows down the convergence rate. The additions of pricing factor (α) here actually decrease the SINR of user.

Related to recent research on power control of the cognitive femtocell network, research conducted by Thalabani [16] has proven that when it reaches convergent conditions, the user's power usage is smaller than KG, but it does not achieve the SINR target even smaller than KG algorithm. This is the weakness of this research.

The proposed method of Zhao Chenglin [22] and Luyong Zhang [23] has a very high SINR value and goes far beyond the SINR target value, but also consumes a high power. In this research, quality of service (QoS) that is too much for communication systems that do not need high quality is not essential, because the power required will also be greater than it proper be. Both of these methods improve KG in terms of the achievement of SINR target, but the achieved SINR is too high so it unreliable. Most of these studies have not shown the efficiency in the use of user transmit power associated to the achievement of SINR target by each user and the required convergence rate. The inefficiency of transmit power can cause losses to user themselves related to battery life or loss to other users due to interference caused. So in this case, it takes something new in this research that can be used as a solution of the research. The new thing will do in this research is to develop a self-organized power control model by users who use multi-channel on cognitive femtocell network using game theory.
The contribution of this research is the proposed novel utility function based on SINR and channel sharing factor which is useful for users who share the channel. This is because SINR becomes an important performance parameter besides the power-transmit. In addition, the evaluation of convergence of Nash equilibrium is also done to determine the stability of the system on cognitive femtocell network.

3. System Model

Co-tier network (homogeneous network) is a type of network with similar system characteristic whether it is in macrocell, picocell or femtocell network. In this study, co-tier network focused on the femtocell network by taking the case of the inter-user femtocell network (inter-femto). Fig. 1 shows a power control model of cognitive femtocell in co-tier network which is emphasized in the communication system between the secondary users (SUs), which has a lower priority than the primary user (PU). In the system model, there are femtocell user equipment (FUE) as a secondary user transmitter (SU-Tx) and femtocell access point (FAP) as a secondary user receiver (SU-Rx). A solid line on the system model shows the main signal, while the dashed line shows the resulting interference when the user uses the same channel.

\[ I_{ij} = \sum_{k=1}^{P} \sum_{n=1}^{N} p_{i,j,n} g_{n,f,i} \delta_{k_{ij}}^{(x)} \delta_{k_{ij}}^{(y)} + \sigma_0^2 \]

Based on the interference that occurs as a result:

\[ I_{ij} = \sum_{k=1}^{P} \sum_{n=1}^{N} p_{i,j,n} g_{n,f,i} \delta_{k_{ij}}^{(x)} \delta_{k_{ij}}^{(y)} + \sigma_0^2 \]

Where \( I_{ij} \) and \( \sigma_0^2 \) are interference perceived by user i on FAP j and the average noise level is assumed to be the same for all users respectively. Notation of \( \delta_{k_{ij}}^{(x)} \) is used to indicate whether there is same channel usage from both the femtocell \( r_{ij} \) and \( r_{nf} \) or not, where \( r_{ij} = (k_{ij}^{(0)}, k_{ij}^{(1)}, \ldots, k_{ij}^{(L-1)}) \) with L is number of available channel (RB). If both are of the same value, \( k_{ij}^{(x)} = k_{n,f}^{(y)} \), so \( \delta_{k_{ij}}^{(x)} \delta_{k_{ij}}^{(y)} = 1 \) and if both are different then \( \delta_{k_{ij}}^{(x)} \delta_{k_{ij}}^{(y)} = 0 \).

4. Power Control Game in Multi-Channel Cognitive Femtocell Network

4.1. Utility Function of Proposed Power Control Game

In the concept of power control by using game theory, every user is considered as a player with a utility function that is formed by the transmit power of all users in cognitive radio networks. The utility function is a formula that is determined to achieve a desired condition player (payoff) through the selection of some of the strategies that will be used. In general, the utility function is designed to simultaneously maximize network performance and capacity of the whole system. From these assumptions, the obtained identification to the modeling needs to be made to the characteristics of self-organized power control.

Determining the utility function is adapted to the proposed model and supported by consideration of several factors such as interference perceived by the user is basically due to the use of the same channel. As can be seen on Fig.1, in channel 1 (Ch1), when the transmitter FUE\(_{1,1}\) (SU-TX\(_{1,1}\)) sends a signal to the receiver FAP\(_1\) (SU-RX\(_{1}\)), it will cause interference on receiver FAP\(_2\) (SU-RX\(_{2}\)). This interference then forces the transmitter FUE\(_{2,2}\) (SU-TX\(_{2,2}\)) to increase transmit power to achieve a fix value of target SINR. This condition also applies to channel 2 (Ch2) and will always be sustainable, hence the use of power control techniques is necessary.
as the channel usage, determining a target SINR, maximum power, and others. Channel usage in this case would be comparable to the use of power, so that in the multi-channel systems of cognitive femtocell network, the more the channels are used, the greater the transmitted power.

Utility function in this study focused on the channel of each user, so that every user can have an accumulative utility function consisting of several utility functions of each channel. Suppose the user is using channel 1 and channel 2, and then the accumulated power of the user is total power on channel 1 and channel 2. If more users are using the channel then the required power is also growing, since each channel has its own power and SINR that may affect the value of the utility function. The formulation of the proposed utility function is as follows:

\[ U_i = a_i p_i^2 - 2b_i \lambda_k y_i + c_i (y_i^{tar} - y_i)^2 \]  \hspace{1cm} (4)

### 4.2. Power Update Scheme of Proposed Power Control Game

Convergence and uniqueness have similar meaning. If the iteration system is convergent, it will reach the certain unique point [16]. Convergence characteristic of the algorithm with full information can be applied to the distributed systems.

Equation of power update is derived from utility function equation that is predetermined according to the proposed model in this study. From the utility functions, the derivative process of the power function is performed in order to obtain the power update formula. Mathematically, it can be formulated as follows:

\[ \frac{dU_i}{dp_i} = 0 \]  \hspace{1cm} (5)

Results of the derivatives showed the best response value, so that the equation (5) will be:

\[ \frac{dU_i}{dp_i} = 2a_i p_i - 2b_i \lambda_k y_i + 2c_i (y_i^{tar} - y_i) \left( \frac{dy_i}{dp_i} \right) = 0 \]  \hspace{1cm} (6)

Since \( \frac{dy_i}{dp_i} = \frac{b_i \lambda_k}{c_i} \), the equation becomes:

\[ \frac{dU_i}{dp_i} = 2a_i p_i - 2b_i \lambda_k \frac{b_i \lambda_k}{c_i} + 2c_i (y_i^{tar} - y_i) \left( -\frac{b_i \lambda_k}{c_i} \right) = 0 \]  \hspace{1cm} (7)

\[ \frac{dy_i}{dp_i} = \frac{b_i \lambda_k}{c_i} \]  \hspace{1cm} (8)

\[ y_i = y_i^{tar} - \frac{a_i p_i}{c_i} \frac{b_i \lambda_k}{c_i} \]  \hspace{1cm} (9)

Then, by substituting \( y_i = \frac{b_i \lambda_k}{c_i} \), the equation becomes:

\[ y_i = y_i^{tar} - \frac{a_i p_i}{c_i} \]  \hspace{1cm} (10)

\[ p_i = \left( y_i^{tar} + \frac{b_i \lambda_k}{c_i} \right) \frac{a_i p_i}{c_i} \frac{b_i \lambda_k}{c_i} \]  \hspace{1cm} (11)

By substituting \( \frac{b_i \lambda_k}{c_i} = \frac{p_i}{y_i} \), the equation becomes:

\[ p_i = \left( y_i^{tar} + \frac{b_i \lambda_k}{c_i} \right) \frac{p_i}{y_i} - \frac{a_i p_i^2}{c_i} \]  \hspace{1cm} (12)

\[ p_i = \left( y_i^{tar} + \frac{b_i \lambda_k}{c_i} \right) \frac{p_i}{y_i} - \frac{a_i p_i^3}{c_i} \frac{b_i \lambda_k}{c_i} \]  \hspace{1cm} (13)

If \( b_i = c_i \) then the power update equation on the Proposed PCG will be as follows:

\[ p_i^{(t+1)} = (y_i^{tar} + \lambda_k) \frac{p_i^{(t)}}{y_i^{(t)}} - \frac{a_i (p_i^{(t)})^3}{c_i (y_i^{(t)})^2} \pm f(p_i) \]  \hspace{1cm} (14)

### 4.3. Nash Equilibrium (NE)

#### 4.3.1 Existence NE

Requirements of a Nash Equilibrium’s existence on the Proposed PCG will be fulfilled if it meets the following conditions [17], [21]–[23]:

a. Distance of strategy \( p \) is limited, closed, nonempty convex set for Euclidean distance \( R \)

b. Utility function of \( U_i(p) \) is continuous and quasi convex in \( p \). Continuous in the range of \( (0, P_{max}) \) and quasi convex proven by the value of the second derivative of the utility function:

\[ \frac{d^2 U_i}{dp_i^2} > 0 \]  \hspace{1cm} (15)

#### 4.3.2 Uniqueness NE

Uniqueness NE can be determined based on the proposed power update. This part will proof the requirements of uniqueness of NE that converges at a certain fixed point and meets some of the following properties:

1. Positivity: \( f(p_i) > 0 \). It is easily obtained from (14) when we choose \( a_i/c_i \ll 1 \) and \( y_i^{tar} \gg \lambda_k \) and \( \lambda_k > 0 \) (positive).

2. Monotonicity:

\[ p_1 > p_2 \rightarrow f(p_1) > f(p_2) \quad \Leftrightarrow \quad f(p_1) - f(p_2) > 0. \]

To prove this property, the term \( f(p_1) - f(p_2) \) is equal to

\[ \frac{y_i^{tar} + \lambda_k}{g_i} (l_1 - l_2) - \frac{a_i}{c_i \lambda_k} (p_i 1_l - p_i 2_l). \]

Since \( p_1 > p_2 \), then \( l_1 > l_2 \). Next, we assume that \( a_i/c_i \ll 1 \), then \( \frac{a_i}{c_i \lambda_k} \ll \frac{y_i^{tar} + \lambda_k}{g_i} \) thus \( f(p_1) - f(p_2) \) would be a positive value.

3. Scalability:

\[ \delta f(p_i) > f(\delta p_i), \forall \delta > 1 \rightarrow \delta f(p_i) - f(\delta p_i) > 0 \]

If this condition is satisfied, the algorithm converges to a unique fixed point. Assume that \( (y_i^{tar} + \lambda_k) = \eta \) thus we can get the formula as follows:

\[ \delta f(p_i) = \delta \left( \frac{y_i^{tar}}{\eta} - \frac{a_i p_i^3}{c_i \eta^3} \right) = \left( \delta \frac{y_i^{tar}}{\eta} - \frac{a_i p_i^3}{c_i \eta^3} \eta^2 \right) \]  \hspace{1cm} (16)

\[ f(\delta p_i) = \eta \delta \frac{a_i p_i^3}{c_i \eta^3} \]  \hspace{1cm} (17)

Therefore, the equation of \( \delta f(p_i) - f(\delta p_i) \) becomes:

\[ \delta f(p_i) - f(\delta p_i) = \left( \delta \frac{y_i^{tar}}{\eta} - \frac{a_i p_i^3}{c_i \eta^3} \right) \frac{y_i^{tar}}{\eta} - \left( \frac{y_i^{tar}}{\eta} - \frac{a_i p_i^3}{c_i \eta^3} \right) \]  \hspace{1cm} (18)

\[ \delta f(p_i) - f(\delta p_i) = \frac{a_i p_i^3}{c_i \eta^3} (\delta^3 - \delta) \]  \hspace{1cm} (19)

The result from (19) shows that the scalability condition is satisfied due to \( \delta > 1 \).

### 4.4. Algorithm of Proposed Power Control Game

Power control algorithm used in the study is universal for all user scenarios. In general the power control algorithm can be described as follows:
a. User initialization.
b. Calculating the value of the initial SINR
c. User renewing power using the equation of power updates that have been determined based on proposed utility function.
d. If $|P(t+1) - P(t)| > \varepsilon$ then back to step 2, with $\varepsilon$ is very small values that reflect the accuracy of computing.
e. If $|P(t+1) - P(t)| \leq \varepsilon$ then update power iteration process stops and the condition of Nash equilibrium is reached.

5. Simulation Result

This study used multi-user and multi-channel schemes with three users and four channels. In particular, channel gain $g_i$ was generated by the attenuation model $g_i = \frac{\Delta_i}{d^\alpha}$ where $d$ was the distance between the user and the base station, which was uniformly and randomly generated. Value of $A = 10^{-8}$ and $\alpha = 4$ with value of $a_i/c_i = 0.25$ or $a_i = 1$ and $c_i = 4$, SINR target ($y_{i\text{tar}}$) 5 dB with $\Delta_{\text{tar,i}}$ and $\lambda_k$ made with a uniform and static value for all users which was equal to 0.5 which referred to the value chosen in [0,1] according to the scenario of Thalabani [16].

A comparison was performed between the Proposed PCG with the existing algorithms: KG algorithm [17] (see (20)) and the TB algorithm [16] (see (21)). Their iterative algorithms were as follows:

- **KG algorithm**
  \[
  p_{i(t+1)} = y_{i\text{tar}} \left( \frac{y_{i(t)}}{y_{i(t)}} - \frac{a_i}{2c_i} \frac{y_{i(t)}^2}{y_{i(t)}} \right)^2
  \]  

- **TB algorithm**
  \[
  p_{i(t+1)} = \left( y_{i\text{tar}} - \Delta_{\text{tar,i}} \right) \frac{y_{i(t)}}{y_{i(t)}} - \frac{a_i}{c_i} \frac{y_{i(t)}^2}{y_{i(t)}}
  \]  

This section will show some of the results of Proposed PCG related to these parameters: transmit power, SINR achievement and convergence rate. Three of these parameters indicate the performance of each PCG method.

5.1 Transmit power

Transmit power in these PCG methods were distinguished by the way of getting the transmit power i.e. the utility function was determined initially, and then the derivatives process yielded the power update equation. Power measurements conducted at the same time, i.e. when it reached the convergent condition.

![Figure 3. Transmit power of Proposed PCG](image)

Fig. 4 shows a comparison of power usage in user 1 channel 1 (U1C1), the character representing the user with other channel. As can be seen in Fig. 4, the power usage of proposed PCG converged in a higher power, but it was used to meet the specified target SINR. This result was the opposite of the result of previous methods, namely KG and TB, where they had a relatively lower power but were not able to achieve the target SINR as shown in Fig. 5.

5.2 SINR Achieved

SINR calculation at the PCG methods was conducted when they reached the convergent condition and then their SINR were compared to each other. In addition, the value of SINR achieved on PCG method not always the same as the target SINR, but it can be above or below the SINR target. PCG that was unable to achieve the target SINR usually prioritized its efficiency (TB) or its convergence rate (KG), but most were still within tolerable limits of allowed SINR.

![Figure 5. SINR of Proposed PCG](image)

Fig. 5 shows the SINR achievement, which exceeded the target SINR for all users of a Proposed PCG. All users were able to achieve SINR of 5.4 dB and above the target SINR. This showed that when the system was convergent, user on the Proposed PCG was able to get better quality of service compared to the two other methods (KG and TB), as shown in Fig. 6.

As can be seen in Fig. 6, the KG and TB were only able to achieve respective SINR of 4.8 dB and 4.9 dB, which were lower than the target SINR of 5 dB, hence their quality were still below the Proposed PCG.
5.3 Convergence Rate

The convergence rate or the required speed of these methods to achieve convergence was measured by the required number of iterations to achieve convergence. Fig. 7 shows the convergence rate of these three methods, in terms of the number of iterations required by each user to achieve convergence, from user 1 channel 1 (U1C1) to user 3 channel 3 (U3C3). As displayed in Fig. 7, each of them had nearly similar convergence rate, but in the case of user-1 channel 4, the KG method was faster in achieving convergence than TB and Proposed PCG.

As can be seen in Table 1, each method had its own advantages, where Proposed PCG was superior in terms of achievement of the SINR target, TB method was superior in power consumption and KG method was excelled in the speed of convergence.

6. Conclusions

The Proposed PCG was able to achieve the target SINR so that the quality of service can be fulfilled properly. This achievement has not been met by other methods. The Proposed PCG was superior in terms of achievement of the SINR target, while TB method was superior in power consumption and KG method was excelled in the speed of convergence. In general, each of the method had nearly similar convergence rate, thus it can be concluded that the stability of these three methods were similar.

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