Traffic-Aware Base Station Sleeping Control with Cooperation for Energy-Delay Tradeoffs in Multi-cell Cellular Network

JIA WANG

KTH Electrical Engineering

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Abstract

From an energy efficiency viewpoint of improving the cellular access networks, the power consumption of the whole system needs to be tracked. In this project, a theoretical model is studied which jointly encompasses sleep control strategy and Base Station (BS) cooperation polices, our goal is to obtain a Pareto Optimal tradeoff between energy consumption and average delay time. Based on the traffic load variation, the sleep control strategy is proposed by adjusting the BS working mode. This project focuses on the multi-cell network which is more close to the real world. In multi-cell scenario, except for the design of the sleep control, the issues of BS cooperation and the inter-cell interference also need to be covered. Furthermore, based on the multi-cell network, three types of energy saving strategies are considered: In case I, users only can be served by their own Base stations (BSs) which go to sleep mode when there is no active user and will not wake up until N users need to be served. This strategy leads to a good energy performance but the long delay. To reduce the average delay, therefore, in case II, we introduced the user association policies that the network handover the user to his adjacent BSs when his own BS is in the sleep mode. Furthermore, the relay-assisted network was studied in the case III. Finally, Based on theoretical and simulation results, we compared these tree cases under the given traffic conditions from the perspective of achieving the optimal average energy-delay tradeoff. And also we found out that sacrificing network throughput can yield the energy saving if we carefully design the network.

abstrakt

Ur energieffektivitetssynpunkt att frbttra de cellulra accessnten, mste effektfrbrukningen fr hela systemet som ska spras. I detta projekt r en teoretisk modell studerat vilka tillsammans omfattar smnkontrollstrategi och basstationen (BS) samarbetspolitiken, r vrt ml att f en Pareto Optimal avvgning mellan energifrbrukning och genomsnittlig frdrjning. Baserat p trafikbelastning variationen r smnkontrollstrategi fresls genom att justera BS arbetslge. Detta projekt fokuserar p multicellntverk som r mer nra den verkliga vrlden. I flercells scenario, med undantag fr utformningen av smnkontroll, frgor om BS samarbete och intercell interferens mste ocks tckas. Dessutom bygger p flercellsntverk, r tre typer av sparenergistrategier beaktas: I fall jag, anvndarna endast kan betjnas av egna Basstationer (BSS) som gr till vilolge nr det inte finns ngon aktiv anvndare och kommer inte vaknar tills N anvndare behver delges. Denna strategi leder till en god energiprestanda men den lnga frseningen. Fr att minska den genomsnittliga frseningen drfr ifall II infrde vi de anvndar freningens policy att ntverket lmnandet anvndaren att hans intilliggande BS nr hans egen BS r i vilolge. Vidare relet assisterade nt studerades i fallet III. Slutligen Baserat p teoretiska och simuleringsresultat, jmfrde vi dessa trd ml enligt de givna trafikfrhllandena ur perspektivet att uppn den optimala genomsnittliga energifrdrjnings avvgning. Och ven vi fick reda p att offra ntverksgenomstrmning kan ge energibesparingar om vi noggrant utforma ntverket.

Acknowledgment

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Contents

Chapter 1

Introduction

1.1 Motivation

The fast growth of mobile communication industry and ICT (information and communication technology) industry has increased the demand for cellular data traffic by mobile customers, which emerged as one of the major sources of the world energy consumption. The consumption rising in a global scale reaches an annual rate of 15-20% and doubles every five years[1]. Increased energy consumption is not only harmful to the environment due to CO2 emissions, but also has an economic impact on revenue, e.g. the wireless network operators are estimated to spend more than ten billion dollars for electricity [1]. Therefore, in the future, one of the hottest research topics from both economic and environmental point of views is to design the energy-efficient green cellular network.

For the case of cellular networks, BSs dominate in the energy consumption and drain approximately 60-80%of the total network energy [2]. Currently, most operators run the BS at the full capacity all the day that the power resource allocation is mainly designed for meeting the peak hour traffic load requirement. Therefore, most of the BSs are largely underutilized during the low-traffic period such as nighttime. Actually, in the 'micro' or the 'pico' cellular networks, this the energy consumption problem is crucially severe. The reason is that the traffic load in the such cellular network varied dynamically [3], the much power is wasted if the BS works with the full capacity power all the day.

So far, there are many efforts that focusing on the design of the sleeping model [4-6] and the power adaptation strategy [7] to reduce energy consumption. From the sleeping model design viewpoint, in [4], the BS sleep policy is introduced where the problem was solved in a mathematical way. In [5] the author studied the vacation policy and considered the issues like how to utilise the vacation time and how to switch working mode would benefit the system most. In our project, M/G/1 queuing model is applied to describe the system . Based on this N-police M/G/1 queuing model, In [6], the author derived closed-form formulation revealing the tradeoff between power consumption and average response time. In addition, From the traffic-aware power adaptation design viewpoint, in [7], the authors proposed a predictive power management scheme attempting to reduce the energy consumption based on the traffic load variation. Recently in [8], the author considered these two standpoints jointly to design the system. The author not only discussed the criterion under which the energy efficiency would be obtained, but provided the optimal system parameters for the sleep control design. However, the references mentioned above only considered the single-cell scenario where there is no BSs cooperation strategy involved. Therefore, in this project, we focus on the multiple cell scenario in which the situation is more closed to the real-word. Therefore, in this project, apart from the design of the sleep control, the issues like BS station cooperation and the inter-cell interference are also covered. Since in the multi-cell network, the user's data rate is affected not only by the noise but by the interference from BSs around it.

1.2 Objectives and problem formulation

In this report, sleeping control method is studied to reduce the total energy consumption of the system while meet the Quality of Service (QoS) requirements. The issues of energy-efficiency design and user association are covered. Additionally, based on the multi-cell network, three types of energy saving strategies are proposed and the optimal one is found.

- In this repot, we study the theoretical proposed model that jointly encompasses sleep control strategy and Base Station (BS) cooperation polices , trying to obtain a Pareto Optimal tradeoff between energy consumption and average delay time.

- We focus on the multiple cell scenario and propose the mathematic model trying to analyse network cooperating at the BS level. We monitor the related parameters, such as network throughput, average power consumption, providing in which case that optimal delay-energy tradeoff can be achieved.

- Build the Matlab simulation platform that explicitly involves the inter-cell interference. Compare with the simulation results so as to improve the validity of our theoretical models.

Chapter 2

Background

The astonishing achievements of the communication industry as well as the users demand of high speed data access has resulted in the deployment of dense and tremendous power consuming networks [1]. Conventionally, communication systems was mainly designed for meeting the users demanding requirement. However, with the incredible growth of the users, the power consumption starts to be the burden to the environment and also has the bad impact on the operating cost. Therefore, the communication industry has pledged to reduce carbon emission of wireless network by up to50% by the end of 2020[13]. Since Base Stations (BSs) dominate in energy consumption and drain approximately $60-80\%$ of the total network energy [3]. More recently, there is growing focus on energy-efficient operation of cellular BSs. So far, there are several ways to evolve the current cellular networks into more environmental-friendly and economic networks, green cellular networks [4]. A few methods are:

- Link level: network resource management schemes and energy-aware transmission, such as power control and user association.

- Network level: topological approaches from deployment to operation, such as BS sleeping control.

Figure 2.1 [4] above shows some of the main issues studied in this project. X-axis illustrates what elements are considered for the networks operation in each time slot. Y-axis presents the key components of the network. Z-axis lists some of the key performance metrics examined. In this report, the X-axis elements are manipulated and their effect on the Z-axis metrics is in depth investigated and analyzed.

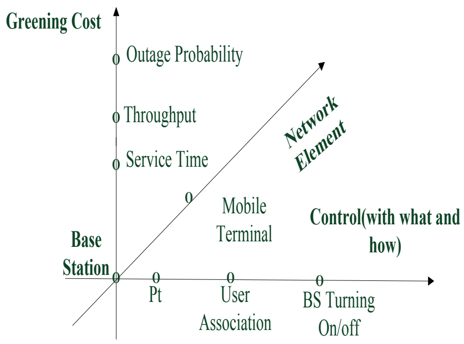

Figure 2.1: Example of N-police sleep control mechanism

Chapter 3

Methodology

In order to tackle with the above problems, some key theoretical topics have to be investigated. In this section, all the mathematical modes involved in this project are briefly described as below.

3.1 Signal to Interference and Noise Ratio Calculation

The most important feature that characterizes a communication link is the Signal to Interference and Noise Ratio (SINR). SINR combines the three essential elements of a link, the received signal strength (signal power), the interference power and the noise power. The expression of SINR is as follows:

$$SINR = \frac{P_r}{I + N} \tag{3.1}$$

where P_r is the received signal power, I is the interference power and N is the power of noise. The received power P_r at distance d according to link budget equation is described as the follow equarion:

$$P_r(d) = \frac{P_t G_t G_r}{L_p + L} \tag{3.2}$$

Where P_r is the received signal power at distance $d(inmeters)$, P_t is the transmitted power and $G_r$and G_t are the gains of the antennas. Additionally, L_p is the distance dependent path loss which could be replaced by various propagation path loss models. L is the system loss that is independent of the distance, such as cable loss, filter loss, antenna loss. For simplicity, it is assumed that the examined system is ideal and does not suffer such losses. Hence, combined with Eq.(3.1), the expression of SINR is given as below:

$$SINR = \frac{\frac{P_t G_t G_r}{L_p + L}}{I + N} \tag{3.3}$$

For simplicity, Here the constant C is used to represent the interference and noise part. Since densely populated wireless network is studied here, the noise power is small compared to its the interference, on the other hand, since all users in each cell are uniformly distributed, the interference for one user is almost the same for the others. Thus, I+N is a constant value.

Another important characteristic of a wireless link is its capacity. Usually we use the shannonHartley theorem (or Shannons law) to calculate the maximum error-free data rate which the user can achieve in the examined system. Here for simplicity, we use Shannons law to calculate the throughput of each link. Shannon's law is stated as follows:

$$R = W \log_2(1 + SINR) \tag{3.4}$$

where R is the capacity or maximum rate of the link, W is the available bandwidth and SINR is the signal to noise ratio as discussed in the equation 3.1.

3.2 Time Division Multiple Access (TDMA)

An interesting challenge in modern wireless communication networks is the ability to serve simultaneously multiple users. Key issues of this technology involve the limited resources needed to be shared and the interference caused by the multi-users. Until now the telecommunication community has created many channel access methods and multiplexing techniques. Some of the most common examples are Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), Orthogonal Frequency Division Multiple Access (OFDMA) and a few variations of them.[13]

TDMA is a digital transmission technology that enables users to transmit on the same shared medium using the entire signal bandwidth available [13]. This is achieved by allocating the resources (radio-frequency channel) to different users for short, not overlapping time intervals (Time slots) [14]. The idea behind TDMA relies on the fact that the audio signal is digitized, fragmented into packets of small time duration. In this way, the user can exploit his allocated time intervals and transmit his packets. Moreover, TDMA is a successful technology and is introduced in many wireless systems such as D-AMPS, GSM and DECT.

In this project, TDMA is applied in our system due to its simplicity of implementation and handover handling. The system configuration is illustrated in the figure 3.1, where the BSs are densely deployed in the certain area. Given that there are several users simultaneously arrive to a cell, then these users share the resources(bandwidth) in a TDMA way where the BS only serves one user in a one time slot. Therefore, during a certain time interval, this user is able to transmit the package with the entire bandwidth.

3.3 Round Robin scheduling

As discussed in the previous subsection, TDMA allocates time intervals to the users for transmission. Moreover, a process is needed to schedule the users, i.e. assign a user to a specific time slot. Many scheduling techniques have been designed such as Round Robin, Maximum Throughput, and Proportional Fair[18]. Most of the scheduling techniques consider the variation in the channel

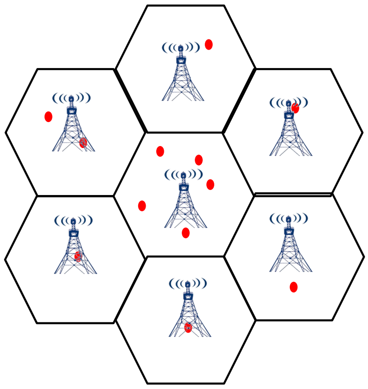

Figure 3.1: The micro cellular network

characteristics in an opportunistic way and they try to achieve higher network performance without increasing the additional spectrum.

Round Robin Scheduler (RR) is investigated further. RR is one of the most common scheduling algorithms designed for time-sharing systems. The fairness of this technique resides to the fact that all users have access to the same resources in a cyclic order manner. However, RR does not consider the quality information of the channel which might result in low throughput of the system. The basic idea behind the RR is that it selects the user that has not been served for the longest period of time has the highest priority to transmit. This procedure is executed iteratively until all the users have finished their transmission. For the development of the simulator, a combination of TDMA and RR is implemented in this project.

3.4 Traffic Model

The procedure that the system handles the arriving traffic per cell can be modeled as a M/M/1 queuing process [7]. According to queuing theory[19], the M/M/1 queuing model consists of a single server (BS) with infinite buffer, customer arrival follows the Poisson distribution with rate λ and the time interval between two arrive users is exponentially distributed with the intensity $\frac{1}{\lambda}$. Moreover, the packet size for non-realtime download transmission is also considered exponentially distributed with mean value equaling to L. The Basic knowledge for the M/M/1 queuing model is described as below:

- Server utilization: An important factor of a queuing system is the servers utilization. The servers utilization of a M/M/1 queuing model represents the servers stability and is calculated according to the following formula.

$$\rho = \frac{\lambda}{\mu} = \frac{\lambda L}{R} \tag{3.5}$$

where the λ is the average data rate. In order to maintain stability in the system, it is required < 1.

- Littles Law

  Furthermore, in order to estimate the number of customers in the system without blocking, Littles law is applied. The average number of customers in the system is equal to the arrival rate , times the average time a customer spends in the system. It is expressed with the formula:

$$N_q = \lambda T \tag{3.6}$$

where T is the service time which is considered to be the average service time for the each user in the system.

3.5 Power consumption model

Usually, the power consumption model of a BS consists of two parts, static power consumption and dynamic power consumption[4]. The first part is a constant value caused by the circuit power consumption. While, the second part is a dynamic value mainly depending on the dynamical traffic load. Thus, the total power consumption in the BS can be expressed as:

$$P_{bs} = P_{stactic} + P_{dynamic} \tag{3.7}$$

Depending on the working mode of BS, there are two types of power consumption models considered in our project. The model for the active BSs consists both the statistic part due to circuit power consumption $P_{stactic}$ and the dynamic part due to the wireless transmission consuming power $P_{dynamic}$. While, the model applied for the sleep mode only has the constant part caused by the circuits power consumption $P_{stactic}$. Finally, the power consumption model is expressed in the Eq.(3.8):

$$Pbs(i) = \begin{cases} p_0 + p_{user}, & BS\ is\ in\ the\ active\ mode \\ p_{sleep}, & BS\ is\ in\ the\ sleep\ mode \end{cases} \tag{3.8}$$

Where p_0 is the circuit power consumption in the active mode, and p_{user} is the load variation based cost. Moreover, the expression of the load-dependent power consumption is given as:

$$p_{user} = p_c + \Delta p.p_t \tag{3.9}$$

In Eq.(3.9), p_c is the base power keeping the user connected with BSs, and Δp is the slope of load-dependent power consumption. p_t is the average power consumption of each user. In addition, the relation of $p_{sleep} < p_0$ makes network save energy in the sleep mode.

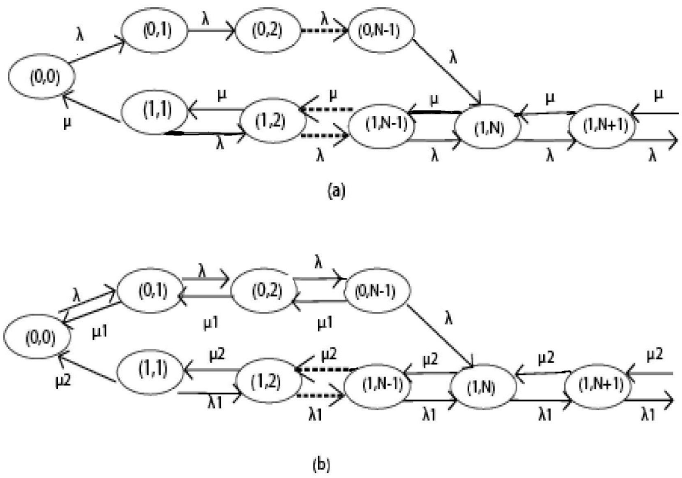

Figure 3.2: System extended-Markov-chain State Diagram (a) N-police sleep control without BS cooperation. (b) N-police sleep control with BS cooperation.

3.6 Energy-Delay tradeoff based on the N-police sleep control

The examined system in this project is an urban micro-cell wireless cellular network with multiple base stations. For tractability, our work focuses on the downlink link data transmission, however, our scheme also can be applied to the uplink scenario provided the inter-cell inference from each user can be considered as a static value. In this project, we consider a set of BS β cover the area $L \in R^2$ and let $x \in L$ denote the position of the current user and i$\in \beta$ is the corresponding BS index to which the user is connected. In addition, we assume all the users in the cells are uniformly distributed and the user arrival is a Poisson process with mean rateλ, where the arrival interval satisfies the exponentially distribution with mean value $\mu = 1/\lambda$. Furthermore, the traffic load is defined by $\rho = \lambda/\mu$.

when the BS i is in an active mode, $c_i(x)$ denotes the data rate for the user at the position x served by BS i, we used Shannon capacity to calculate the data rate, i.e.

$$c_i(x) = Wlog_2(1 + SINR_i(x)) \tag{3.10}$$

where W is the available bandwidth and $SINR_i(x)$is signal to interference and noise ratio for the user at location x served by BS i. AS we assumed that inference form each BS is static, the sum of total interference power just depends on the amount of active BSs. The $SINR_i(x)$is thus provided as

$$SINR_i(x) = \frac{P_i(x)c}{N_r I + N} \tag{3.11}$$

Where $c = \frac{G_t G_r}{L_p(x)}$. $P_i(x)$ represents the transmit power of BS_i . And $G_t G_r$ are the antenna gains.L_p is the distance dependent path loss. From the Eq.(3.11), we could find The number of active BS denoted by N_r has the impact on the performance of whole network as more BSs in the active mode may result in greater interference, as a result it would reduces the throughput of the total network.

The Eq.(3.12) gives the model of the network total power consumption.

$$P_{BS}(i) = P_{active}(i) + P_{sleep} \tag{3.12}$$

In this section, we study the basic models used to describe the system. Below , the three specific cases of energy-saving strategy are analysed respectively.

3.6.1 Case I: N-police sleep control without BS cooperation

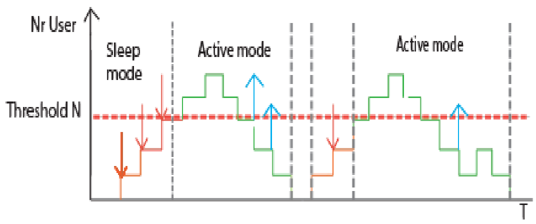

Figure 3.3: Example of N-police sleep control mechanism

First we focus on the design of N-police sleep control where the transmit power is adapted to the traffic load variation. The mechanism of the N-police Sleep control is illustrated in the Fig 3.3, the BS keeps in the sleep state when there is no user in the network and the state will be changed when more than N users arrived in the network. if in the active state, the BS continues serving the users even if the user number drop down below than N. But the BS won't change to the sleep mode until there is no user in the coverage area.

As illustrated in the Fig 3.4, in this no user cooperation scenario, when BS_i switched to the sleep mode, all users belonging to the cell i have to be temperately disconnected and wait in the certain cell i until the BS_i turns on. although saving the energy, apparently, this strategy makes users suffer from the long time waiting.

For the simplicity of analysis, given the users are stationary and randomly uniform distributed in each cell. Thus, the statistical result got from a single cell is identical to the average metrics got from the whole network system. Based on this assumption, M/G/1 processor sharing model[8-9] illustrated in Fig 3.1 (a) is applied to model the user arrival process in the each cell. The $P_r(i, j)$ where $i \in 0, 1, j \in 0, 1, 2, 3...$ defines the state space, where $P_r(0, j)$ denotes there are j users in the system when the BS is in the sleeping mode, whereas $P_r(1, j)$ refers

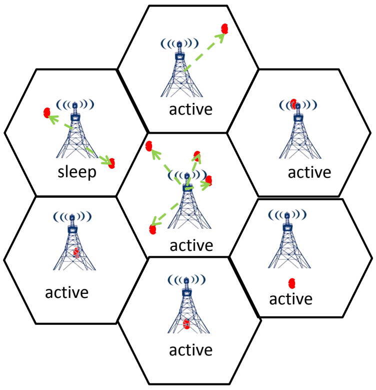

Figure 3.4: Case I strategy

to there are totally j users in the cell whose BS is in the active mode.

Let $D_{N,\mu}, F_m, P_{N,\mu}$ represent the average delay, the mode transition frequency [10], the average power consumption of the network system respectively[8]. By solving the extended-Markov-chain shown as Fig 3.1(a) first we obtain the possibility of each state shown in the Eq.((3.13). Here, the probability state $P_r(i,j)$ refers to the number of users in the each state, where i is the working mode of each BS. Also j denotes how many users are there in the such state.

$$P_r(i,j) = \begin{cases} P_r(0,j) = (\frac{x-\lambda l}{Nx}), & if \quad i=0; \\ P_r(1,j) = \frac{\lambda l}{Nx}(1-\frac{\lambda l}{Nx}^{j}), & if \quad i=1, 1 \le j \le N; \\ P_r(1,j) = \frac{\lambda l}{Nx}(\frac{\lambda l}{Nx}^{j-N}) - (\frac{\lambda l}{x})^{j}, & if \quad i=1, j > N; \end{cases} \tag{3.13}$$

And then the BS sleep probability is calculated by sum up all the probability in the sleep state, as expressed in the Eq.((3.14):

$$P_{rsleep} = \sum_{i=0}^{N-1} P_{r(0,j)} = 1 - \frac{\lambda l}{x} \tag{3.14}$$

Since the average queue length is calculated by summing up all the products of the number of users and its corresponding probability , we can obtain the average queue length as shown in the Eq.((3.15):

$$N = \sum_{j=0}^{N-1} jP_{r(0,j)} + \sum_{j=1}^{\infty} jP_{r(0,j)} = \frac{\lambda l}{x} \tag{3.15}$$

By applying the Little theory described in the section 3.4, the average delay is given in the Eq.(3.16):

$$D_{N,\mu} = \frac{N}{x-\lambda} D_{N,\mu} = \frac{l}{x-\lambda l} + \frac{N-1}{2\lambda} \tag{3.16}$$

Here, the BS mode changing power consumption is taken into account in this project. The BS always works until there is no user in the cell with the average working time $\frac{N}{\mu-\lambda}$, And then the BS begins to sleep whose duration is from the system is empty to there are more than N users needs to be served, thereby the average sleep time for the BS is $\frac{N}{\mu}$. Thus , the mode transition Fm which is defined as the transitions times between active mode and sleep mode per time unit[1], is:

$$F_m = \frac{2}{\frac{N}{\lambda} + \frac{N}{\mu-\lambda}} = \frac{2\lambda}{\mu}(1 - \frac{\lambda}{\mu}) \tag{3.17}$$

By combining the power consumption as described in the in Eq.(3.8) with the average service time in the Eq.(3.15) , we can get the relation between the power consumption and the average delay, as in the Eq. (3.16):

$$P_{N,\mu} = \frac{D\lambda - \frac{N-1}{2}}{D\lambda + 1 - \frac{N-1}{2}} [p_0 + \frac{\Delta p}{c}(2^{\frac{\mu l}{W}})] + \frac{1}{D\lambda + 1 - \frac{N-1}{2}} [P_{sleep} + \frac{2\lambda E_s}{N}] \tag{3.18}$$

Where E_s is the power consumption caused by the mode transition.

The figure 3.3 shows that the variation of the delay-power consumption tradeoff curve depends on the value of the threshold N. The small N leads to a relatively small delay but yields large power consumption. This is because that the small threshold N for waking up the BS is easier to reach than the large N. Therefore, the small threshold N makes BS more easily work in the active mode. As being mentioned in sector 3.7.2, the strategy of case I only allows the user to be served by its own BS, as the result from the figure 3.3 we could observe it causes the long delay when large threshold N is applied.

3.6.2 Case II: N-police sleep control with BS cooperation

Though Case I reaches the energy-saving requirement, from the viewpoint of QoS, the Case I mentioned above leads to the long delay which extremely annoys the users. Therefore, if the system continuously works like this, the operators would pay a heavy price like for losing customers. In this section, we proposes the new analytical model that focuses on the users cooperation at the BS level. As illustrated in Fig .2(b). The network hands over the use to the adjacent BSs, when his own BS is switched off. On the other hand, if the BS wakes up by counting the number of the waiting users in the cell reaches the threshold N, the handed-over users will immediately be handed back and get served by their own BS. Finally, the N-policy sleeping scheme mentioned above is also adopted

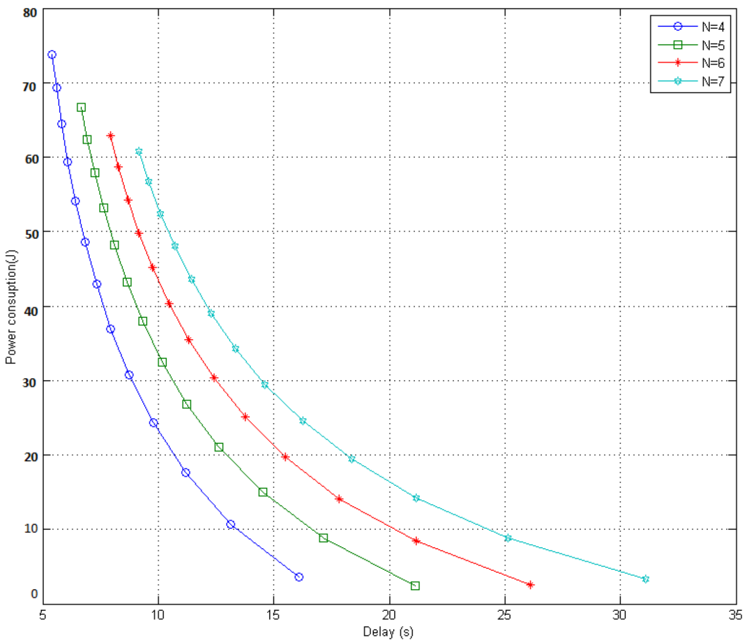

Figure 3.5: The power-delay tradeoff for Case I

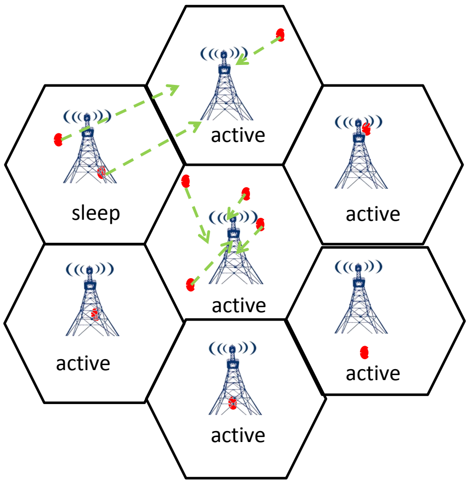

Figure 3.6: Case II strategy

in this case.

The main idea of the model in the case II is that, at a particular instant, the working modes of each BS in the network are Bernoulli distributed with probability P_{rsleep} if the BSs are in the sleep mode. Given there are n cells deployed in the area, the number of BSs currently in the sleep mode is nP_{rsleep}. Moreover, we introduced the user association policies that, during the 'night time,' the minimum QoS is handled by a fraction x of active base stations, and the remain$1 - x$ fraction remains in the sleep mode. Thus, the arrive rate λ_1 of the active BS consists its own arrive rate λ and handover user arrive rate $\lambda_{handover}$ where $\lambda_{handover} = \frac{1-x}{x}\lambda$. Therefore, the arrive rate of the network system $\lambda_{network}$ is given by the following Eq.(3.17):

$$\lambda_{network} = \begin{cases} 0, & i = \lambda \\ \lambda + \frac{nP_{rsleep}}{n - nP_{rsleep}} = \frac{1}{nP_{rsleep}}\lambda, & i = 1 \end{cases} \tag{3.19}$$

As illustrated in Fig 3.2 (b), the embedded Markov-Chain model, which consists of the two conventional M/G/1 queues working in parallel is adopted in the case II. The user could be served by its own BS with the service rate μ_1 as well as could be handed-over and get the new service rate μ_2. In addition, According to the definition of traffic load, to make the system more stable, the

$$\sum_{j=0}^{N-1} P_r(1,j) = -\frac{N\mu^2 - 2\lambda^2 N - 2\lambda\mu + \sqrt{-Ns(\lambda - s)(Ns^2 - 4\lambda^2 N - 4\lambda\mu + 4\lambda\mu(\frac{\mu}{\lambda})^N + 3\lambda\mu N))}}{2(\lambda\mu + \lambda^2 N - \lambda\mu(\frac{\mu}{\lambda})^N - N\lambda\mu)} \tag{3.21}$$

constraint of the traffic load is $C, C < 1$. And the relation between $\lambda 1$ and μ_2 is $\lambda = \mu_2 C, 0 < C < 1$. As illustrated in Fig 3.6, therefore, if the BS is in the sleeping mode, the users in the such cell will be served by the N_{on} BSs around it with the service rate μ_1. Therefore,the relationship between μ_1 and μ_2 is $\mu_2 = N_{on} P_{rsleep} \mu_1$ where N_{on} is the total number of the neighbour BSs that the users can be handed-over. Since hexagon cell is considered, here, we set the $N_{on} = 6$.

First we obtained the probability of the network in the each state, as shown in the Eq.(3.18):

$$P_r(i,j) = \begin{cases} P_r(0,j) = (\frac{1-b^{j-N}}{b-1}) P_r(1,1) \\ P_r(1,j) = (\frac{1-a^j}{1-a}) P_r(1,1), & j \leq N \\ P_r(1,j) = a^{j-N} (\frac{1-a^N}{1-a}) P_r(1,1), & j > N \end{cases} \tag{3.20}$$

Where $a = \frac{\lambda}{\mu_1}$ is the traffic load for the sleep cell and $b = \frac{\lambda_1}{\mu_2}$ is the traffic load for the active cell. Since the sum of each state's probability $\sum_{i=0,j=0}^{N-1} \sum_{i=1,j=1}^{\infty} P_r(i,j) = 1$ and all the $P_r(i,j)$ can be represented by the $P_r(1,1)$. Thus, $P_r(1,1)$ can be obtained from $\sum_{i=0,j=0}^{N-1} \sum_{i=1,j=1}^{\infty} P_r(i,j) = 1$. And then we have the sleep probability $P_r(sleep) = \sum_{j=0}^{N-1} P_r(0,j)$ as given in the E.q (3.20).

As mentioned in the Eq.(3.18), the user arrive rate of the active BSs is shown in the Eq.(3.21):

$$\lambda 1 = \frac{1}{nP_{rsleep}} \lambda \tag{3.22}$$

Since the average queue length can be calculated by summing up all the products of the user number and its probability , we can obtain the average queue length as in the Eq.(3.22):

$$N = \sum_{j=0}^{N-1} j P_{r(0,j)} + \sum_{j=1}^{\infty} j P_{r(0,j)} \tag{3.23}$$

Because the BS has two working modes, there are two parts need to be considered when calculating the average service time. the first part is the average time for the users served by their own BS with the probability $1 - p_{rsleep}$ and the second part is for the handed-over user with the probability p_{rsleep}. Therefore, by using the little theory$D = \frac{N}{\lambda}$ as mentioned in the section 3.4. The average service time is given in the Eq. (3.23):

$$Delay = (1 - p_{rsleep}) \frac{1}{\mu_1 - \lambda 1} + p_{rsleep} \frac{1}{6\mu_1 - \lambda 1} \tag{3.24}$$

where μ_1 is the service rate of the BS, and $\lambda 1$ is the user arrive rate of the active cell.

The mode transitions energy consumption, as defined in the case I, is also involved. For each BS, the sleeping period starts when there is no user in the cell until the cell amasses least N users with the assembling time $\frac{N}{\mu 1-\lambda 1}$. As is calculated in the similar way, the average working time of the BS is $\frac{N}{\mu 2-\lambda 1}$. Therefore, The mode transition frequency defined as the change times between the two modes per time unit, can be calculated in the Eq. (3.24):

$$F_m = \frac{2}{\frac{N}{\mu 1-\lambda 1} + \frac{N}{\mu 2-\lambda 1}} \tag{3.25}$$

The average power consumption model in case II is represented in the Eq.(3.25):

$$P_{N,\mu} = (1 - p_{rsleep})[p_0 + \frac{\Delta p}{c}(2^{\frac{\mu l}{W}})] + p_{rsleep}P_{sleep} + F_m E_s \tag{3.26}$$

The average power consumption in case II consisted of the three parts. the first part dues to the active mode power consumption, the second part is the cost in the sleeping mode, and the last part dues to the mode transitions energy consumption, where p_0 and Δp are the circuit and slope of the load-dependent power consumption, p_{sleep} is the static power consumption in the sleeping mode, c is the traffic load of the network and E_s is the cost for the BS mode transition.

By combining the equation (3.23) and the equation(3.25)together, the relationship between power consumption and average delay in case II, is represented in the Eq.(3.26)

$$P_{N,\mu} = \frac{(1-c)D\lambda}{c}[p_0 + \frac{\Delta p}{c}(2^{\frac{\lambda 1 l}{WC}})] + \frac{c - D\lambda - cD\lambda}{c}[P_{sleep} + FmE_s] \tag{3.27}$$

Where D refers to the average delay and W is the bandwidth.

As shown in the Fig 3.5, compared with the Case I, the case II (N-police sleep control with BS cooperation) can significantly reduces the average delay. However, Case II is not the eventually energy efficiency strategy. Due to the large-scale shadowing, if there are some handed-over users exist in the cell, the BS has to increase its transmit power in order to guarantee the data rate of the hand-over users which are geographically far away from it. Thus, the criterion under which the case II could benefit the network is discussed as below.

By solving the inequation $P_{t,case2} - P_{t,case1} > 0$, we obtained the quadratic inequations is given in the Eq.(3.27) :

$$ap_{r,2}^2 + (c-a)p_{r,2} + (c-b) > 0 \tag{3.28}$$

where

$$\begin{cases} a = p_{sleep} - p_{active}; \\ b = \lambda D_2; \\ c = D_1\lambda + P_{rsleep}p_{active} - p_{sleep}; \end{cases} \tag{3.29}$$

Here, P_{sleep} and p_{active} are the BS's power consumption depending on the BS working mode respectively. $P_r sleep$ is the BS sleeping probability which is decided by the threshold N. In addition, D_1 is the average delay for the case I and D_2 is the average delay for the case II. By solving this inequation, we can find that the power deference of the case I and the Case II is decided by the P_{rsleep} ($0 < P_{rsleep} < 1$). Thus, if the P_{rsleep} lies in the range $[0, \beta]$, the case II preformed much better. otherwise, if the P_{rsleep} lies in the range $[\beta, 1]$, case

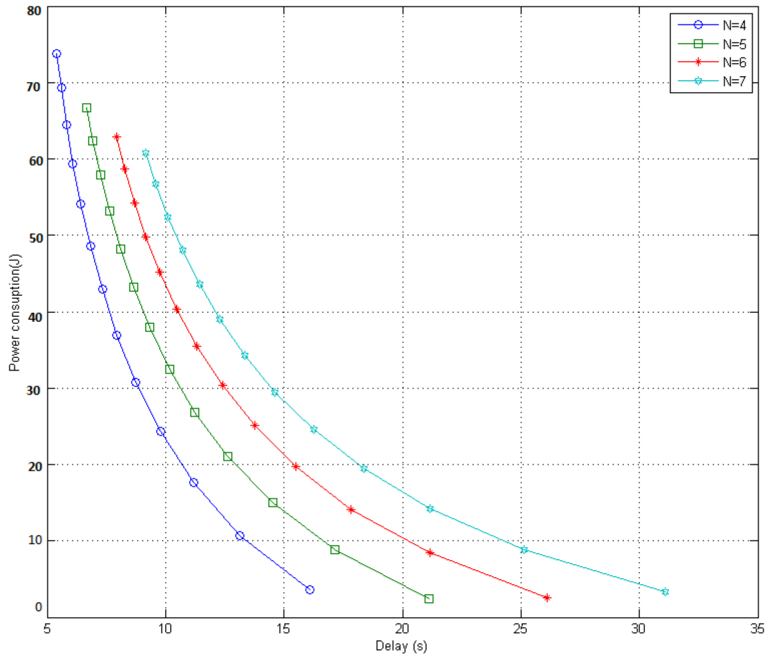

Figure 3.7: The power-delay tradeoff for Case II

I should be chosen for the both power and time saving . Finally, because the probability P_{rsleep} depends on the value of the threshold N ($N = f^{-1}(P_{rsleep})$), the scheme choosing is eventually influenced by the selection of the threshold N.

Example: if we set the system parameters $\lambda = 0.25, p_{open} = 100, p_{sleep} = 10$ by adopting the mathematical model described in section 3.5 and section 3.6 respectively,then we will obtain $D_1 = 10, D_2 = 4.2$, and then we can get the β=0.8041. After solving the Eq. (3.27), the result is shown in Fig. 3.9. When the P_{rsleep}lies in the range (0,0.8041), Case II could let the network consume less power and the threshold N obtained by $\mathcal{N} = f^{-1}(P_{rsleep})$ turns out to be the condition for the cases selection. That is if $N < \mathcal{N}$ we'd better to use the Case II, otherwise, Case I is used in the network.

3.7 N-police sleep control with BS cooperation relay assisted-network

In this section, we introduce relay assisted strategies in the wireless cellular network where the Case III can be applied to further improve the network performance. As being discussed in the section 3.6.2, if the threshold $N > \mathcal{N}$, this threshold would force a lot of the BSs work in the sleep mode which leads many users to handed-over to the active BSs. Therefore, under this condition,

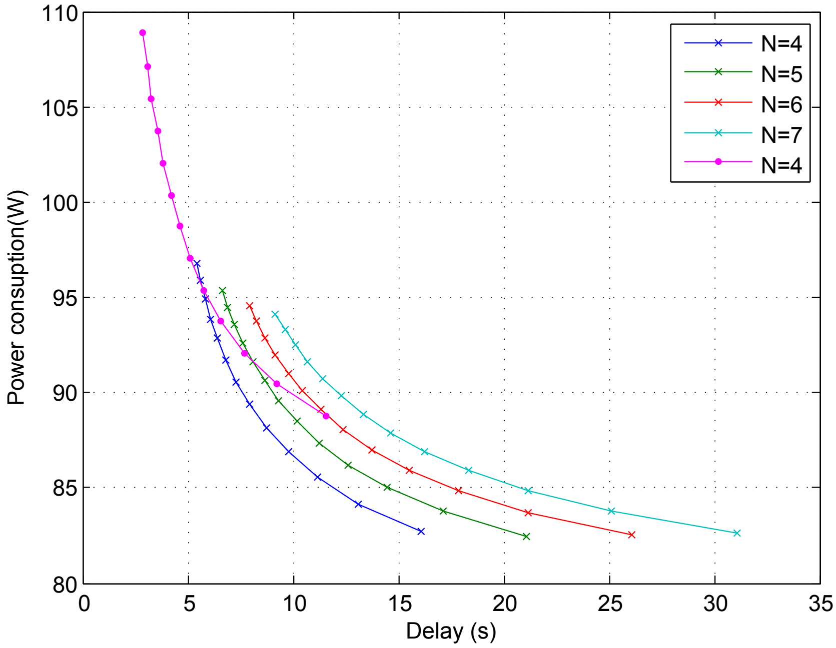

Figure 3.8: The comparison between Case I and Case II

the case II consumes much more power. To solve this issue, in this new strategy, serval users from the different relay-groups could get the transmitted package in the same time slot. Based on this, the case III cuts down the average time which the users spend in the waiting buffer, and then the transmission rate is acceptably purposely reduced for the exchange of the low cost.

As illustrated in Fig 3.10, The whole transmission process consists of the two steps, the first step is the BS combines and encodes the transmitted signal and then broadcasts the information to all relay notes set in the active cells. And then in the same time slot, each user from the different relay groups simultaneously get the package from the relay nodes.

In this case, the Markov-chain model used to describe the traffic load change is optical to the one we used in the case II, where the BS constantly count the number of users in the cell. If the BS turns to the sleep mode, the users will be handed over to their adjacent BSs. However, contract to the strategies we mentioned in the sections 3.6.2 , in the case III, the users in the active cells are separated into 6 relay groups according to the minimum distance to the relay nodes. In addition, there are deployed 6 relay notes in each active cells. If S source's messages $S_{6\times 1} = [X_1, X_2...X_6]^T$ are to be sent to the users. A complete transmission consists 2-hops: First, the B-R (from the BS to relay nodes) broadcasts transmission. Second, the R-U (from the relay nodes to the

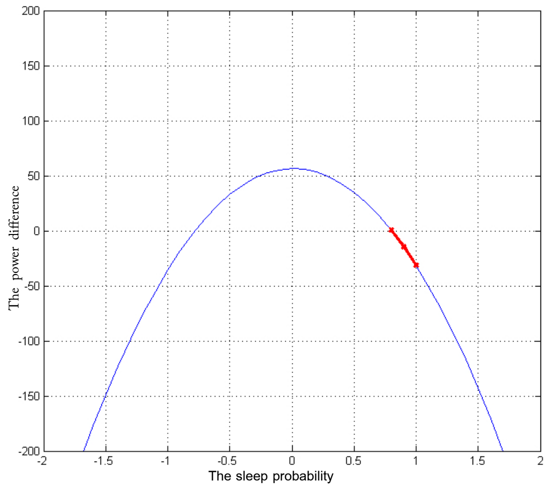

Figure 3.9: The power difference

users) multi-access at the BS side. At the agency of the network coding, S source's messages could be sent simultaneously. For simplicity, we assume the channel condition of S-R and R-B along with the transition rate are the same. Hence, we have the following formula to describe this model:

$$Delay = (1 - p_{rsleep})\frac{1}{6\mu_1 - \lambda 1} + p_{rsleep}\frac{1}{36\mu_1 - \lambda 1} \tag{3.30}$$

where λ_1 is the user arrive rate of the active cell, and μ_1 is the service rate of the BS. Since S source's messages could be sent simultaneously. Therefore, in this case, the service rate of the hand-over users is six times higher than the service rate of the native users.

The average power consumption model of the Case III is given, as below in the Eq.(3.30)

$$P_{N,\mu} = \frac{l\lambda}{x}[p_0 + \frac{\Delta p}{c}(2^{\frac{\mu l}{W}})] + (1 - \frac{l\lambda}{x})[P_{sleep} + \frac{2\lambda E_s}{N}] \tag{3.31}$$

where p_0 and Δp are the circuit and slope of the load-dependent power consumption, λ is the user arrive rate, x is the transmit rate, l is the average length of the package and E_s is the cost for the BS mode transition.

By inserting the Eq.(3.29) into the Eq.(3.30), the relation between the power consumption and the time delay in the Case III can be obtained:

$$P_{N,\mu} = \frac{D\lambda - \frac{N-1}{2}}{D\lambda + 1 - \frac{N-1}{2}}[p_0 + \frac{\Delta p}{c}(2^{\frac{\mu l}{W}})] + \frac{1}{D\lambda + 1 - \frac{N-1}{2}}[P_{sleep} + \frac{2\lambda E_s}{N}] \tag{3.32}$$

The power-delay tradeoff of the Case III is illustrated in the Fig 3.11, the

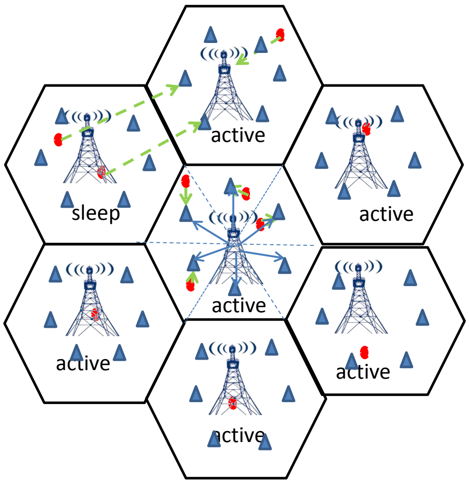

Figure 3.10: Case III strategy

Case III reduces the user average delay compared with the first two cases. Thus, the case III can be adopted to improve the QoS of the network.

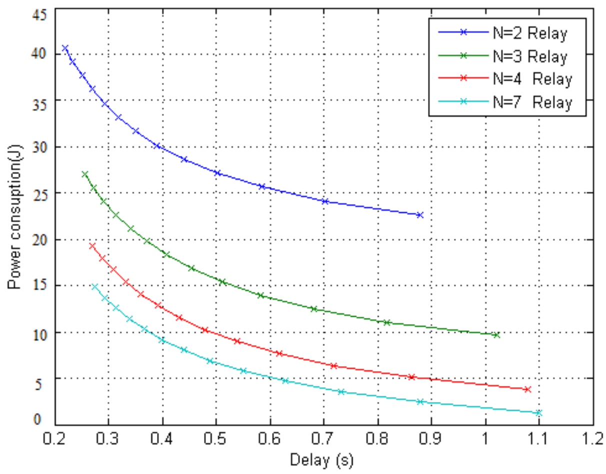

Figure 3.11: The power-delay tradeoff for Case III

Chapter 4

Simulation Analysis Result

In this section, the simulation result for mathematical model is presented, the system-level performance in terms of average power consumption ,average delay, and energy-delay tradeoff is evaluated for each scenario. Here, our strategy is applied to the micro cell scenario where we assume the radium of hexagonal cell is 100m, the system under is studied under the realistic conditions according to the 3GPP release[11] , the system bandwidth is 10 MHZ, the Noise power density $N_0 = -174dBm/HZ$ and the loss path model $L_d = 34.53 + 38log10(d)$. And as [8] did, we set the BS power consumption parameters $P_0 = 100W, \Delta P = 7W, Psleep = 30W andEs = 25W$[12].For simplicity, we considered users arrive to the system satisfied the Passion distribution and each user only transmits single package whose size is exponential distributed with the mean value $l = 1M$, additionally, we set the traffic load variate from 0.1 to 0.4 specified the system is in the low traffic state. Since the system performance of non-cooperation scheme has been deeply discussed in the [8], here we mainly focus on evaluating the cooperation scheme and the differences between these three scenarios.

For this procedure, the implementation of the MATLAB based simulation platform is considered. The examined scenario in this project is an urban micro-cell wireless cellular network. The simulation focuses on the down-link data transmission and the inner cluster for better accuracy of the results. The users of the network are uniformly distributed and arrive according to a Poisson process with mean variated from 0.1 to 0.4 . Furthermore, the arrival time difference of the users is exponentially distributed with mean value = 1/ and their transmission follows exponential distribution with mean value $l = 1M$.

4.1 Case I

The algorithm 1 below shows the process of the Case I. In this case, the users suspended their transmission when the BS of their own is in the sleep mode. Therefore, only the users in the active cells need to be scheduled in a 'Round Robin' way. To begin with, we generate the user matrix with the three rows to collect the user's information (such as arrival time instant, user location, user package length) of all users in the 37 Cells.

Since the user's arrival is poisson distribution and interval between the two time points is the exponential distribution. To generate the user arrival time instant, first the exponential distributed array $\overrightarrow{A}$ is created with the intention λ, and then the cumulative sum of items in the $\overrightarrow{A}$ is collected in the array $\overrightarrow{arrival}$. Finally, we cut down the $\overrightarrow{arrival}$ to make sure all the items in it are less than 3599s. Therefore, $\overrightarrow{arrival}$ represents all the user arrive the cell within one hour.

In each time slot (1s), the BSs checked how many users had arrived. After that, the BS sleeping pattern is generated by comparing the number of active users with the threshold N. According to this sleeping pattern, by applying the XOR calculation, we divided the BS into two sets, active set and sleep set. To make our platform more effective, we only consider the user transmission in the active set. As soon as the users arrived to the active cell, their corresponding transmit rate was calculated by the Shannon theory as well as the transmitted power of the BS was adaptively changed. After that, each user obtained the channel sources and get served by applying the 'Round Robin' scheduling. While, for users in the sleep sets, their information table doesn't change. The procedure mentioned above is executed iteratively every hour while the network performance metrics are collected and analysed at the end of each hour.

Algorithm 1 Simulation Framework for case I.

Create the Users arrival according to poisson distribution with the intensity λ;
Generate the users package whose average length is L;
Generate the User's geographic Information
Collect the network performance results at the end of each hour, E_n;
initialize the time $T_i = 1$; $T_i = 1 \leq 3599$ $T_i = T_i + 1$; each $Cell_j \in [1, 37]$ $thenumberofuserinthecell < thresholdN$ Set the small transmit power to the sleep BS; $thenumberofuserinthecell > thresholdN$ Allocate the Pt to each user accoding to the current traffic load; Caculate all user's SINR along with the data rate; Apply the Round Robin Scheduling ; the network performance metrics ;

4.2 Case II

The algorithm diagram below illustrates the procedure of the N based sleep scheme with the handover strategy. To begin with, all the 37 BSs generate the arrival time instant for the new customers according to and the corresponding packet size based on the L. Then BSs check if there are customers remaining from the previous hour. If there are users left, the BSs save the location and the remaining packet size of the users that have not finished their transmission. After that, the sleep pattern is generated per time slot according to the comparison of the number of active users with N. With the sleep pattern, the BSs can be divided into two sets, active set and sleep set. For all the BSs in the sleep set, the users are handover to the adjacent active BSs according to distance.

As soon as each active BS receives information table (location and packet size) from the handover customers, a Routing table is created to save their home BS number. Afterwards, the users SINR and data rate are calculated for all the users in the active BSs as well as channel resources are allocated to each user by applying Round Robin Scheduling. Furthermore, once the work mode of the sleep BS is changed, the information table of handover users will returned to their corresponding home BSs in the next time slot. The work mode of the BS is checked each time slot and the procedure mentioned above is executed iteratively every time slot.

Algorithm 2 Simulation Framework for case II.

Create the Users arrival according to poisson distribution with the intensity λ;
Generate the users package whose average length is L;
Generate the User's geographic Information
Collect the network performance results at the end of each hour, E_n;
initialize the time $T_i = 1$; $T_i = 1 \leq 3599$ $T_i = T_i + 1$; each $Cell_j \in [1, 37]$ $thenumberofuserinthecell < thresholdN$ Handover the user to its adjacent BS; Create a 'routing table' to save home BS number; Set the small transmit power to the sleep BS; $thenumberofuserinthecell > thresholdN$ Allocate the Pt to each user according to the current traffic load; Caculate all user's SINR along with the data rate; Round Robin Scheduling ; the network performance metrics ;

4.3 Case III

The algorithm diagram below illustrates the procedure of N based sleep scheme with the relay network strategy. In abstract to case II, where the user always occupied the whole channel recourse when getting connected to the BS. In this case, six relay station nodes are placed in the each hexagonal cell,with the help of network-coding, the relay-assisted strategy could let the users from the different groups jointly transmit their message.

At the beginning, the information table is generated which involves user's information such as arrive instant and package length. and then by comparing the number of the user in the network with the threshold N, the BS sleep pattern is saved in the new array for recording the working mode of each BS. And the user handover strategy is identical to the approach adopted in the Case II.

In Case III, a complete transmission consists of the two steps, first from the BS to the RS and then from the RS to the users. Once the user arrives, the users are to be separated into the six relay group according to the minimum distance with the relay stations. And then the BS encodes and broadcasts the information to those relay stations. Furthermore, the data rate of the group users is decided by the 'lowest' data rate of all users in group. with the such speed, the relay stations send decoded information to the group users in the one time slot. For our procedure, the substraction between the package length and the group data rate represents the users transmission in the one time slot. And also the remaining package length is updated to the user information table.

The procedure mentioned above is executed iteratively every hour while the network performance metrics are collected and analysed at the end of each hour.

Algorithm 3 Simulation Framework for case III.

Create the Users arrival according to poisson distribution with the intensity λ;
Generate the users package whose average length is L;
Generate the User's geographic Information
Collect the network performance results at the end of each hour, E_n;
initialize the time $T_i = 1$; $T_i = 1 \leq 3599$ $T_i = T_i + 1$; each $Cell_j \in [1, 37]$ $thenumberofuserinthecell < thresholdN$ Handover the user to its adjacent BS; Create a 'routing table' to save home BS number; Set the small transmit power to the sleep BS; $thenumberofuserinthecell > thresholdN$ Allocate the users to the 6 relay group; Allocate the Pt to each user according to the current traffic load; Calculate all user's SINR and the data rate R(i) ; Rate R=R(1) ; i=1:6 $R(i) < R$ R=R(i) The data rate for S-R(From source to relay link) ; Round Robin Scheduling; Each time the relay station processed the information from 6 users jointly ; the network performance metrics ;

4.4 Simulation result

The simulation result of Case I is illustrated in the Figure 4.1, where we can find the that, the average service time of the case I was relatively longer compare to the other strategies, since in this case the users only can get service from its own BS of the cell. Moreover, when the larger threshold N is chosen, the network could save more energy consumption because there are more BSs are in the Sleep mode. And the long service time can be satisfied to yield the energy consumption in return.

The curves of the power-delay tradeoff for Case II are shown in the Figure 4.2. whose trends are exactly identical to the trade-off curves that we got from the numerical result as shown in the Fig. 3.5 .

The figure below (Figure 4.3: The power-delay tradeoff in the Case III)is the power-delay tradeoff curve for the Case III. This relay-assisted strategy obviously has advantages over the first two strategies. On the one hand, the strategy adopted in the case III could help the network to reduce the unbearable service time. on the other hand, this strategy could achieve the power consumption efficiency even if the large threshold N is chosen, which overcomes the drawback of the case II. Again, the curve trend of simulation result in the Figure 4.3 is similar to its numerical result shown in the Figure 3.6

The comparison between these three strategies is illustrated in the Fig 4.4(The comparison of these three strategies), where we can see that the Case III with relay assisted strategy always played the best performance among these three strategies. Regardless of the threshold N, the case III always consumes the minimum power as well as has the shortest delay. On the contrary , the case II, its PC performance is related to the threshold N, where the large N makes the case II worse in the energy efficiency perspective. For example, when N is small(N =3), with the same traffic load, the case II consumes less power if we chose the Case I as a benchmark. While, as the threshold N increases, more

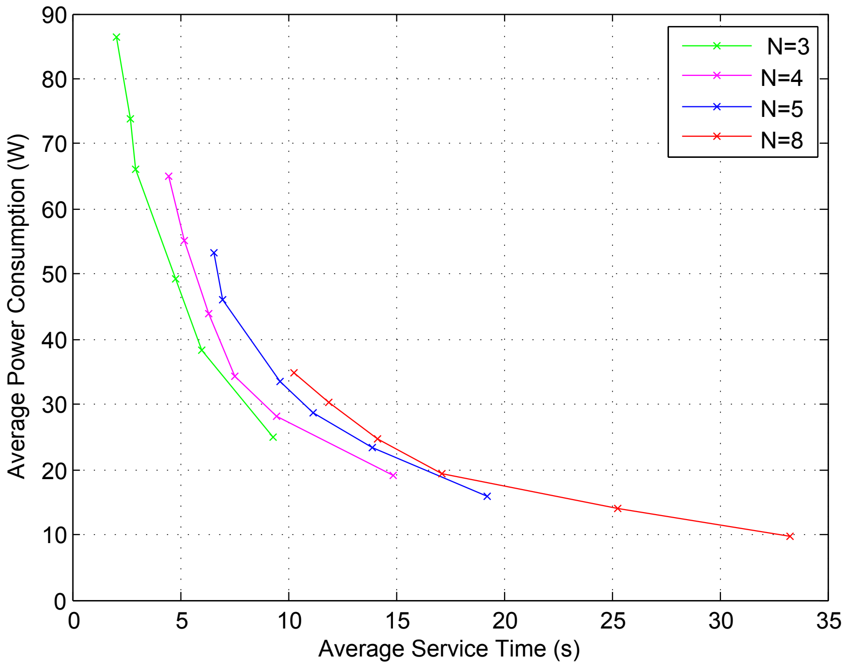

Figure 4.1: The power-delay tradeoff in the Case I

power is consumed in the Case II.

To have a deep understanding for the performances of these three strategies, from the Fig 4.5, we can observe the relation between the threshold N and the average delay from these three cases according to the variation of the traffic load. The simulation result shows that the Case III (with the relay assisted approach) typically played the best performance in getting the shortest service time. Since with the help of the network coding, the Case III can let the use from the different relay groups complete transmission together. In addition, compare with the case I (N-sleep only) where if the BS is turned off, all its corresponding users have to wait in the buffer until the BS of its own works, the Case II with user association strategy has a better performance in the short delay. Because the Case II makes the users always be served by the active BS. What's more, in our simulation platform, by adaptively increasing the transmission power of active BSs, we set all users' transmitted rate is above the minimum value($R > R0$) which means there are no outage users in the system. And also the figure shows that the average service time increases with the increase of the threshold N. Because the large N makes more BSs into a sleep mode, then the network will take the longer delay .

From Fig 4.6, we are about to compare these three strategies from the energy saving perspective. According to the previous assumption for avoiding the interruption, the translated power is adaptively increased according to the traffic

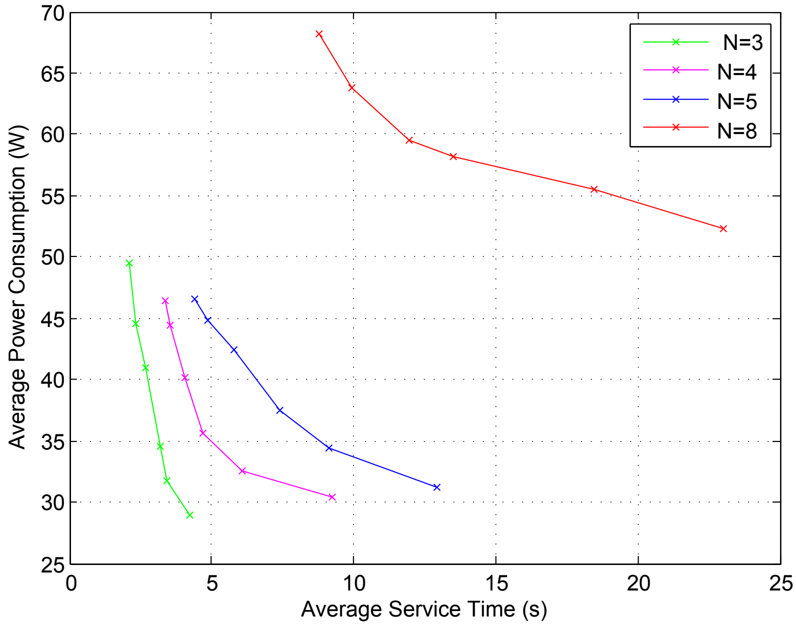

Figure 4.2: The power-delay tradeoff in the Case II

load of the network. Moreover, for case III, since several users' information can be merged and transmitted together, we can intentionally reduce the transmission rate of each link so as to reduce the overall power consumption. It can be seen that when Threshold N is small, and traffic load is low, the case II could save more energy. However, when the threshold N is increased, adopting Case I and Case III would be more energy efficient because the energy consumption of each single link is low. In addition, the average power consumption decreases with the increase of the threshold N for the more BSs might get into a sleep mode, the more energy would be saved.

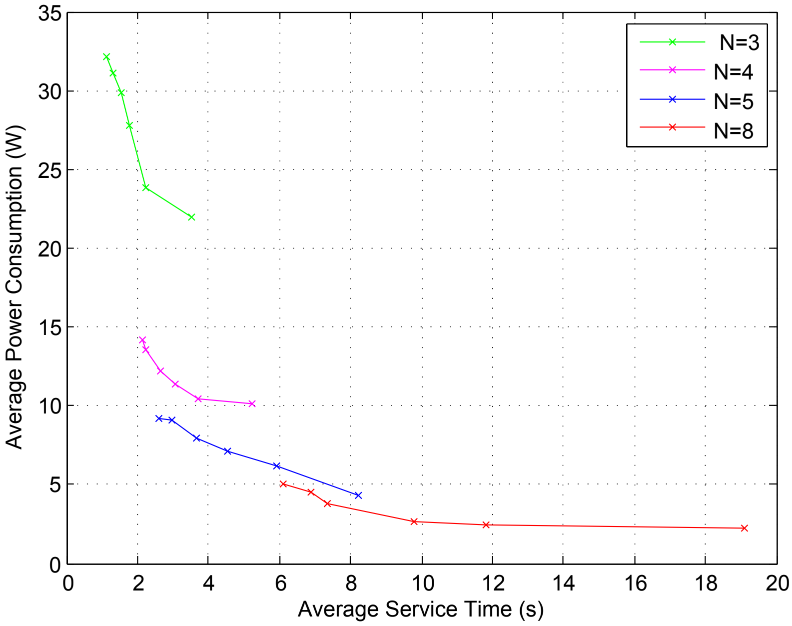

Figure 4.3: The power-delay tradeoff in the Case III

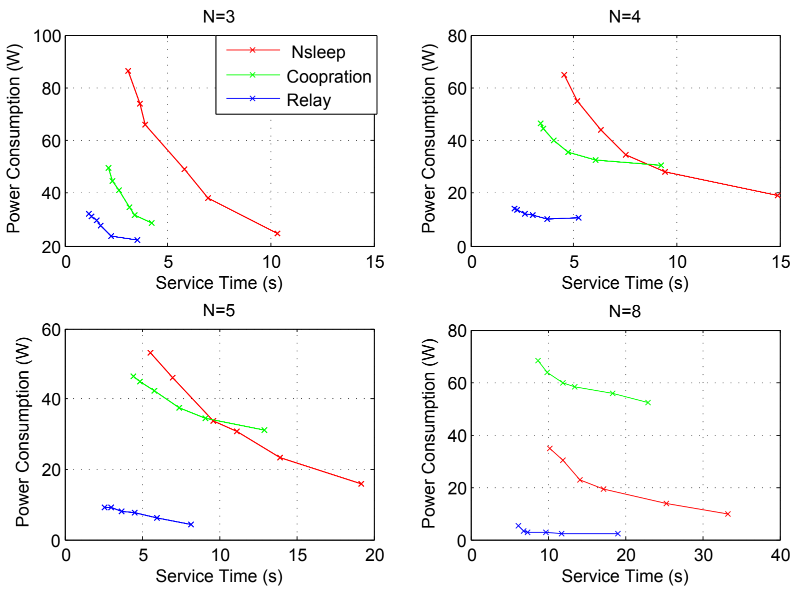

Figure 4.4: The comparison of these three strategies

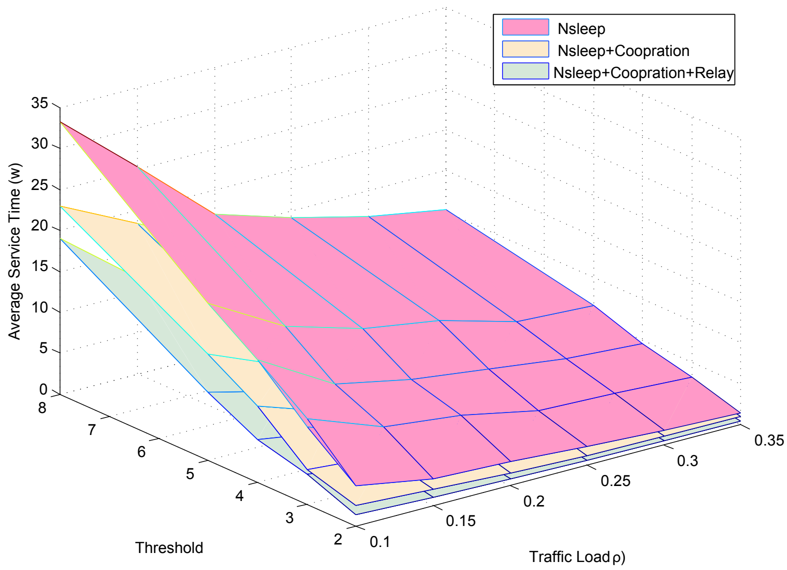

Figure 4.5: The comparison among these three strategies in term of average service time

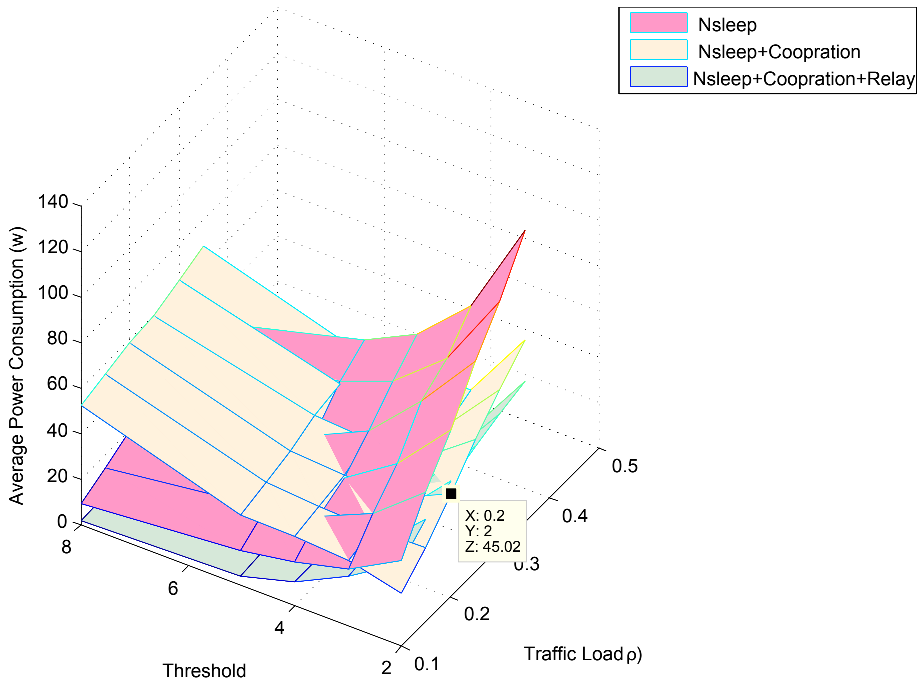

Figure 4.6: The comparison among these three strategies in term of average power consumption

Chapter 5

conclusion

The objective of this project is to propose a sleeping control method that increase the EE and reduce the delay to assist the mobile stakeholder to evaluate the benefits of BS sleeping technology. After a deep research, we study N-base sleep scheme as a baseline and implement an adaptive Power Control. Deeping into this, we found that the lager threshold N will increase the EE. However, it leads to the high latency. Furthermore, we design the N based user association strategy as an upgrade for N based adaptive Power Control. In this new mode, when the BS is in the sleep mode, its corresponding users would be handed-over to its adjacent BSs in getting contiguously service and reduce the latency. This mode gives us a satisfied service time. However, the shortcoming of this one is that Pt allocation adjusts to the number of users requests, so that when many handed-over users exist, the power consumption is increased. Furthermore, if the handed-over user is far away from the destination BS, more transmission energy is needed to avoid interruption but decreases the EE. To solve this EE issue, after a deep research, we upgrade the system by introducing the relay-assisted nodes in our system. With the help of these relay stations, if there are several users request the transmission in the same time slot, the transmitted messages are merged together and then transmitted to the relay nodes with network-encoding. When receiving these merged information from relay nodes, the BSs decode and process these information together. In this mode, the EE is compensated by slightly reducing the transmission rate of each link as long as keeping the QOS at the satisfied level.

Exploring these three schemes and comparing the performance among power consumption, EE and average service time, we find that N based no handover Control scheme has an excellent power consumption performance but the highest latency. With the increase of the threshold N. In the beginning, considering system complexity, EE and latency, the N based user association scheme is the best choice. However, when Threshold N reaches a big value or user arrival rate increases, more BSs will turn into the sleeping mode, N based user association scheme will still have the tolerant latency but the worst EE and power consumption performance. N based relay-assisted scheme is the best scheme since it has the best EE and power consumption performance but the highest latency.

Based on the comparison, we made the conclusion that when threshold N and arrival rate is small, N based user association scheme is recommended because of the highest EE and the lowest latency. otherwise, we can consider case III (N based relay-assisted scheme)to be the best choice. From the simulation platform, it can be observed that the simulation results are satisfied with our numerical result, and our there is a tradeoff between power consumption and service time. In order to improve EE or power consumption, we need to sacrifice the average service time.

Chapter 6

Appendix

6.1 Appendix I

Proof of the equation (3.9)

From the extended Markov-chain illustrated in the(....), the probability in each state (3.9) is obtained by solving the balanced equation jointly:

$$\begin{cases} \lambda P_r(0,j) = \mu P_r(1,1), & j = 0, ..., N-1; \\ (\lambda+\mu)P_r(1,1) = \mu P_r(1,2); & \\ (\lambda+\mu)P_r(1,j) = \lambda P_r(1,j-1) + \mu P_r(1,j+1), & j \neq 0,1,N; \\ (\lambda+\mu)P_r(1,N) = \lambda[P_r(1,N-1) + P_r(0,N-1) + \mu P_r(1,N+1)]; & \end{cases} \tag{6.1}$$

So we can obtain average queue length by doing the calculation as follows :

$$N = \sum_{j=0}^{N-1} jP_{r(0,j)} + \sum_{j=1}^{\infty} jP_{r(0,j)} = 1 - \frac{\lambda l}{x} \tag{6.2}$$

$$= \sum_{j=N+1}^{\infty} j\frac{\lambda l}{Nx}[\frac{\lambda l}{x}^{j-N} - \frac{\lambda l}{x}^{j}] + \sum_{j=1}^{N-1} j\frac{x-\lambda l}{Nx} + \sum_{j=1}^{N} j\frac{\lambda l}{Nx}[1 - \frac{\lambda l}{x}^{j}] \tag{6.3}$$

$$= \frac{x-\lambda l}{Nx}\frac{(N-1)N}{2} + \frac{\lambda l}{Nx}[\frac{N(N+1)}{2} + \sum_{j=1}^{\infty}(j+N)(\frac{\lambda l}{x})^j - \sum_{j=1}^{\infty} j(\frac{\lambda l}{x})^j] \tag{6.4}$$

6.2 Appendix II

Proof of the equation (3.9)

From the extended Markov-chain illustrated in the Fig. 3.3, the probabilities of each state (3.9) can be obtained by solving the balanced equation jointly:

$$\begin{cases} \lambda P_r(0,j) = \mu_1 P_r(0,j+1), & j = 0,...,N-2; \\ (\lambda+\mu_1)P_r(0,N-1) = \lambda P_r(0,N-2); \\ (\lambda)P_r(0,0) = \mu_2 P_r(1,1) + \mu_1 P_r(0,1); \\ (\lambda+\mu_2)P_r(1,j) = \lambda P_r(1,j-1) + \mu_2 P_r(1,j+1), & j \neq 0,1,N; \\ (\lambda_1+\mu_2)P_r(1,N) = \lambda_1 P_r(1,N-1) + \lambda P_r(0,N-1) + \mu_2 P_r(1,N+1)]; \end{cases} \tag{6.5}$$

Then we can get the possibilities for each states are:

$$\begin{cases} P_r(1,j) = a^{j-N}(\frac{1-a^N}{1-a})P_r(1,N), & j > N; \\ P_r(1,j) = (\frac{1-a^j}{1-a})P_r(1,1), & j < N; \\ P_r(0,j) = (\frac{1-b^{j-N}}{1-b^{-1}})P_r(0,N-1), & j < N; \end{cases} \tag{6.6}$$

Since $\sum_{j=1}^{\infty} P_r(1,j) + \sum_{i=0}^{N-1} P_r(0,i) = 1$, solving the equation array above together with Matlab, we can get the sleep probability as below:

$$P_{rsleep} = -\frac{N\mu^2 - 2\lambda^2 N - 2\lambda\mu + \sqrt{-Ns(\lambda-s)(Ns^2 - 4\lambda^2 N - 4\lambda\mu + 4\lambda\mu(\frac{\mu}{\lambda})^N + 3\lambda\mu N))}}{2(\lambda\mu + \lambda^2 N - \lambda\mu(\frac{\mu}{\lambda})^N - N\lambda\mu)} \tag{6.7}$$

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