

# Energy-Efficient Base Station Operation in Heterogeneous Cellular Networks

Hoang-Hiep Nguyen<sup>†</sup>, Won-Joo Hwang<sup>††</sup>

## ABSTRACT

In this paper, we study the ON/OFF control policy of base stations in two-tier heterogeneous cellular networks to minimize the total power consumption of the system. Using heterogeneous cellular networks is a potential approach of providing higher throughput and coverage compared to conventional networks with only macrocell deployment, but in fact heterogeneous cellular networks often operates regardless of total power consumption, which is a very important issue of modern cellular networks. We propose a policy that controls the activation/deactivation of base stations in heterogeneous cellular networks to minimize total power consumption. Under this policy, the total power consumed can be significantly reduced when the traffic is low while the QoS requirement is satisfied.

**Key words:** Energy-efficient, optimal control, cellular networks, heterogeneous cellular networks, dynamic programming.

## 1. INTRODUCTION

Nowadays, energy efficiency in wireless cellular networks has become a very important aspect in addition to improving the total throughput of the system. This is because of the huge amount of energy consumed and the  $CO_2$  emissions caused by the operation of the networks. It is reported that the information and communication technology industries accounts for 2% and 3% of global  $CO_2$  emissions and energy consumption respectively, [1], this consumption is expected to grow by three times by 2030. In particular, nearly 60% of this use

belongs to users and devices in mobile networks and this is still increasing explosively. Much attention has focuses on reducing the energy consumption of mobile cellular networks, and solutions range from backhaul networks to radio access networks [2].

In this paper, we focus on increasing the energy efficiency of base station (BS) operation since they account for nearly 60% of the total energy consumed. We study the dynamic on/off operation of BSs in two-tier heterogeneous networks. we specifically consider networks that consist of a macrocell as the first tier and picocells overlaid on the coverage area of the macrocell as the second tier. Our work can also expand to a network of microcells or femtocells as the second layer, the latter only has effects on energy efficiency in case of dense femtocell deployed because the power consumption of a femto BS is quite small, e.g., 5 W. Our goal is to reduce the total power consumption of the system. For this purpose, we propose a policy that chooses the optimal actions which are activation, deactivation or doing nothing on picocells and radio resources of the macrocell that lead to

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※ Corresponding Author : Won-Joo Hwang, Address : 621-749, Obangdong, Gimhae, Gyeongnam, Korea, TEL : +82-55-320-3847, FAX : +82-55-322-6275, E-mail : ichwang@inje.ac.kr

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<sup>†</sup> Department of Information and Communication Engineering, HSV-TRC, Inje University  
(E-mail: hoanghiep.hut@gmail.com)

<sup>††</sup> Department of Information and Communication Engineering, HSV-TRC, Inje University

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minimum power consumed with acceptable users QoS perceived. For example, in the scenario in Fig. 1, users are leaving picocell 1, when traffic in picocell 1 decreases to a level in which the macro BS can handle the current traffic of this picocell while keeping an acceptable level of QoS. Then we can turn it off to save power, and ongoing calls in picocell 1 will be handed over to the macro BS. However, there may be the case that when we put picocell 1 off, the macro BS has to serve additional traffic that leads to degradation of the QoS requirement, e.g., the blocking rate exceeds a certain threshold or the macro BS has to activate additional radio resources to serve that traffic with acceptable QoS which causes more power consumption, then doing nothing is the optimal action. We formulate this problem as a dynamic programming problem, the optimal action is deduced based on the traffic profile that results in the minimum total power consumption and satisfies the QoS requirements. Our main contributions can be summarized as follows:

- We model the system and formulate the problem of choosing the optimal policy as a dynamic programming problem. (Section III.A and III.B).
- We propose an algorithm that minimizes the power consumption of the system and satisfies the QoS requirement. (Section III.C).
- In section IV, we evaluate the proposed algorithm with numerical analysis.

The remainder of this paper is organized as follows. We present related works in section II. In section III, we describe our system model, the problem formulation and the solution. Section IV gives the evaluation of the proposed algorithm and section V eventually concludes the paper.

## 2. RELATED WORKS

There are various ways to improve the energy efficiency of cellular networks. An approach that can significantly reduce the amount of energy

consumed is the dynamic load aware on/off operation of BSs [3,4] (this idea can be found in [5] for home networks). Since BSs usually operate regardless of traffic load, they are often underutilized. In [6], it was observed that real traffic patterns are highly periodic and there are long periods in which traffic is below 10% of the peak hour, however, the energy consumption of the BSs is nearly unchanged even when traffic is very low. Real data measurements show that the power consumption of BSs varies about 2%-3% over the time when traffic varies between no load to peak load level [7]. This is due to the presence of pilot channels and the fixed power consumed of BSs is very large, therefore it is essential to entirely or partly turn off BSs in the period of low loads to save energy. In [3] they proposed a scheme that allows BSs to turn on/off their radio resources based on the traffic information and users perceived QoS, but in networks with hierarchy cell structure, the authors considered that the smaller cells or relays were the radio resources of macro BS. This assumption does not capture the impacts of switching on/off smaller cells on macro BS. Another mechanism was proposed in [8] that femto BSs activate or deactivate their radio transmissions according to the presence or absence of users within its coverage. This required modification of femto BSs so they were able to detect active calls from users to the overlaid macrocell.

Another approach was using hierarchy cell structures by deploying low-cost, low-power, small-range coverage micro/pico base stations that covered dense traffic areas, e.g., shopping malls, office buildings or cell-edge areas to improve users performance instead of increasing macro BSs. Networks with such heterogeneous cell structures improve not only network capacity and coverage but also energy efficiency such as improvement in term of the total throughput over the total power consumption [9]. However, this work only analyzed the inherent energy efficiency

of heterogeneous cellular networks. To further reduce the power consumption of heterogeneous cellular networks, we consider the dynamic on/off operation of heterogeneous cellular networks according to real traffic patterns, we also investigate the impacts of switching off smaller cell on the macrocell.

### 3. SYSTEM MODEL AND PROBLEM FORMULATION

#### 3.1 A. System model

In this paper, we consider a system consists of traditional macrocell, which is the first tier equipped with  $R$  radio resources such as the number of transmitters for GSM, carriers for 3G, HSDPA or LTE, and  $N$  picocells forming the second tier within the macrocell coverage area (Fig. 1). Users within the coverage area of picocells can communicate with both the macro and pico BSs, we assume in this case they will be automatically connected to the pico BSs because of the short distance to pico BSs. When users leave a picocell, on going calls of users will be transferred to the macro BS by hand over. We also assume that cross-tier and inter-tier interference are mitigated by the interference coordination and cancellation techniques [10].

Next, let's consider the scenario in Fig. 1 in which the traffic in picocell 1 is decreasing, traffic in macro and picocell 2 are increasing. The macro

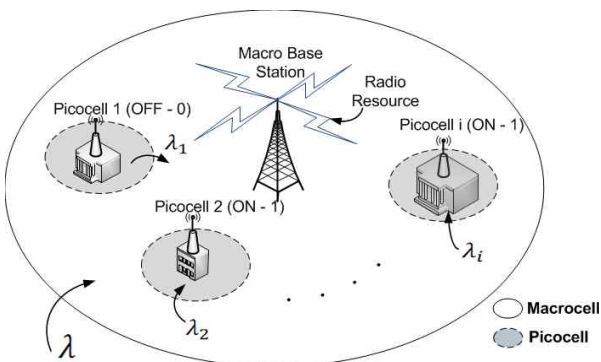


Fig. 1. Macrocell with overlaid picocells.

BS knows about the traffic information of system and will decide: if the traffic in picocell 1 decreases to a level that macro BS can handle that traffic with acceptable users perceived QoS, it will turn off picocell 1 to save energy. In this case, ongoing calls of users in picocell 1 will be handed over to the macrocell. If the macro BS can serve the handed over traffic from picocell 1 but has to activate additional radio resources to serve that traffic, which in turn requires more power or the QoS degrades due to the increasing of users in the macrocell, then clearly doing nothing is the optimal action.

To calculate the power consumption of BSs, we use a power consumption model of macro and pico BSs that consists of two parts, the static part which is consumed even if there is no user in the system and the dynamic part that depends on the load (BS's utilization), the energy consumption function of macro BS is given by [3]

$$P_m = P_{cst} + \sum_{j=1}^R (P_{trx} + \rho_j P_{max}/\omega),$$

where  $P_{cst}$  is the power consumed due to transport and processing units,  $P_{trx}$  is the fixed power of the transceiver and  $P_{max}$  is the maximum output signal of the power amplifier,  $\omega$  is the direct current to radio frequency conversion factor,  $\rho_j$  is the utilization (load) of radio resource  $j$ . We assume that each pico BS is equipped with one radio resource and the energy consumption is given by [4]

$$P_p = \rho P_{dynamic} + P_{fixed}. \tag{1}$$

Similar to macro BS,  $P_{fixed}$  here is the fixed power consumption and  $P_{dynamic}$  is the power consumption that is proportional to the utilization (load) of pico BSs,  $P_{fixed} + P_{dynamic} = P_{p,max}$  where  $P_{p,max}$  is the maximum power consumption of pico BSs (when operating with full load).

#### 3.2 B. Problem formulation

To choose the optimal actions on radio resources of macro BS and picocells to serve current traffic

with minimum consumed energy and acceptable QoS, we formulate the problem as a Dynamic Programming Problem with components as follows:

**(i) Time:** In this paper, we consider time is divided into equal periods in which the traffic is considered as constant. It is clear that the traffic pattern varies over time and space, but it can be considered unchanged for a certain period of time (e.g., one hour as in [4]).

**(ii) System state:** Let  $s_t \subset S$  be the vector that represents system state at period  $t^{th}$ ,  $S$  is the state space,  $s_t$  is defined as

$$s_t = (r_t, l_{t,1}, l_{t,2}, \dots, l_{t,N}),$$

where  $r_t$  is the number of active radio resources and  $l_{t,(.)}$  represents the state of pico BSs, i.e.,

$$l_{t,i} = \begin{cases} 1 & \text{if pico BS } i \text{ is activated} \\ 0 & \text{if pico BS } i \text{ is deactivated} \end{cases}.$$

**(iii) Decision variable:** At the beginning of each period, we define the control variable  $a_t \subset A$  associated with state  $s_t$ ,  $A$  is the action space,  $a_t$  is defined as

$$a_t = (m_t, p_{t,1}, p_{t,2}, p_{t,3}, \dots, p_{t,N}),$$

where  $m_t$  and  $p_{t,(.)}$  are actions corresponding to the radio resources of macro BS and pico BSs respectively, the values of  $m_t$  and  $p_{t,(.)}$  are as follows:

$$m_t = -1, 0, +1, \\ p_{t,i} = \begin{cases} 0 \text{ or } +1 & \text{if } l_{t,i} = 0 \\ 0 \text{ or } -1 & \text{if } l_{t,i} = 1 \end{cases}.$$

The value “+1” means activation, “-1” means deactivation and “0” means do nothing.

**(iv) Transition function:** The system evolution is described as

$$s_{t+1} = s_t + a_t.$$

**(v) Traffic information:** Due to the dynamic on/off operation of BSs, it is very hard to obtain completely and exactly traffic information of the system, but based on the real traffic profile, the controller can obtain the traffic distribution of the

system in each period.

**(vi) Cost per stage:** We define the cost per stage  $C_t(s_t, a_t)$  is the power consumption of the system in state  $s_t$  knowing the distribution of traffic load in period  $t^{th}$ , i.e.,

$$C_t(s_t, a_t) = P_m(s_t) + P_p(s_t),$$

where  $P_m(s_t)$  and  $P_p(s_t)$  are the total power consumption of macro BS and pico BSs knowing state  $s_t$  and traffic information in period  $t^{th}$  respectively. When system state is  $s_t$ , the macro BS is using  $r_t$  radio resources, thus  $P_m(s_t)$  is given by (1), replacing  $R$  by  $r_t$  radio resources

$$P_m(s_t) = P_{cst} + \sum_{j=1}^{r_t} (P_{trx} + \rho_j P_{max}/\omega). \quad (2)$$

The total power consumption of all pico BSs depends on the state of those pico BSs and can be calculated as

$$P_p(s_t) = \sum_{i=1}^N l_{t,i} P_{p,i}. \quad (3)$$

Here  $l_{t,i}$  and  $p_{p,i}$  are the state and the energy consumption of pico BS  $i^{th}$ , respectively and  $p_{p,i}$  is given by (2). Our aim is to find the actions that minimize the total power consumption of the system over a period  $T$  and satisfy QoS requirement, i.e.,

$$\min_{a_t} \sum_{t=0}^T C_t(s_t, a_t), \quad (4)$$

s.t. QoS requirements,

$$s_{t+1} = s_t + a_t.$$

Here we just consider the QoS of macrocell as picocells are designed to serve users with acceptable QoS even in peak traffic.

### 3.3 C. Optimal policy

The pure problem (4) (without QoS requirements) is a dynamic programming problem over a finite horizon with finite, discrete states and action space, solving this problem is equivalent to solving the following equation [10]

Table 1. The algorithm

<p><b>Step 1:</b> Initiating the termination cost <math>J_T(s_T)</math>. Set <math>t = T - 1</math>.</p> <p><b>Step 2:</b> For all <math>s_t \in S</math>, <math>a_t \in A</math> calculate:  <b>2a:</b> <math>J_t(s_t) = \min_{a_t} \{C_t(s_t, a_t) + J_{t+1}(s_{t+1})\}</math>.  Set <math>a_t^* = \operatorname{argmin} \{C_t(s_t, a_t) + J_{t+1}(s_{t+1})\}</math>.  <b>2b:</b> Calculating the corresponding QoS.  <b>2c:</b> If QoS meets requirement then go to step 3.  Else Set <math>A = A \setminus \{a_t^*\}</math> and return to 2a.</p> <p><b>Step 3:</b> If <math>t &gt; 0</math>, decrement <math>t</math> and return to step 1. Else stop.</p>
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$$J_t(s_t) = \min_{a_t} \{C_t(s_t, a_t) + J_{t+1}(s_{t+1})\}, \tag{5}$$

where  $J_t(s_t)$  is the cost-to-go starting from state  $s_t$ , this problem can be solved by the “backward induction” algorithm in [11] by setting the termination cost  $J_T(s_T)$  and calculating (5) recursively backward in time for  $t = T - 1, T - 2, \dots, 1, 0$ . Problem (4) with the QoS requirement can be solved by this algorithm with a little modification as shown in Table. 1.

This framework can be applied, for example in a typical day, time is divided into 24 periods (each lasts one hour), the load of base station for each period is calculated as

$$\rho_t = \frac{\lambda_t F_t}{R}.$$

Where  $\lambda_t$  and  $F_t$  are the arrival rate and average file size in period  $t^{th}$  (note that  $(\lambda_t F_t)$  is the average offered traffic in period  $t^{th}$ ) and  $R$  is the total transmission rate. Substituting this into (1), (2) and (3), calculating the cost according (5) and following “backward induction” algorithm to obtain the optimal actions, QoS here can be considered in case of a network with admission control as the blocking probability that new call requests will be blocked when there are the maximum  $M$  active users in the system to achieve a required throughput and is given by (Erlang B formula)

$$P_{t, blocking} = \frac{\rho_t^M / M!}{\sum_{i=0}^M \rho_t^i / i!}.$$

The maximum allowable number of users  $M$  in the system is given by

$$M = \lfloor \frac{R}{T_{target}} \rfloor.$$

Where  $T_{target}$  is the target throughput. It is desirable that the blocking probability is less than a certain threshold (e.g., 5%).

#### 4. NUMERICAL ANALYSIS

In this section, we evaluate and compare our proposed scheme in heterogeneous cellular networks with the “sleep mode” policy in [3] and when system operates in normal way (i.e., all resources are activated). We consider a network consists of a macro BS and 5 picocells, the total power consumption of macro BS and pico base stations are 523 W and 38 W (with  $P_{fixed} = 6$  W and  $P_{dynamic} = 32$  W) respectively (these parameters were used in [7]). We assume each radio resource of the macro BS has a bandwidth of 5 Mhz in the 2.6 Ghz band that leads to a total throughput of 13.5 Mbps when there is one user served in the cell (e.g., LTE-advance networks). Bandwidth of each picocell is 5 Mhz and results in a total throughput is 15 Mbps when there is one user served in the cell. The target throughput for each user is 500 Kbps. The offered traffic pattern (Fig. 2) within a day (24 hours) is categorized by three main groups: peak, medium

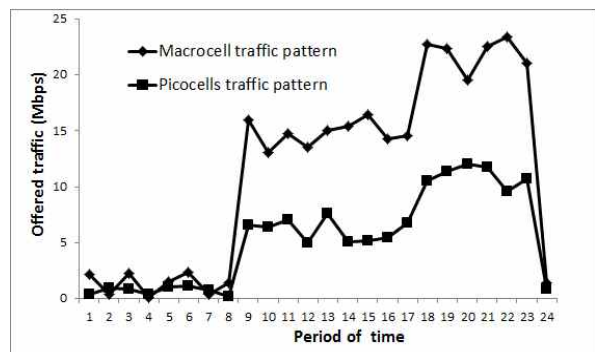


Fig. 2. Traffic pattern.

and low with normalized values of 1, 0.5 and 0.1 of peak traffic, the corresponding periods are 19 h – 22 h, 9 h – 19 h and 23 h – 08 h respectively, details are given in Table 2.

We run our algorithm over 24 periods, blocking probability threshold is 5%, for each period the offered traffic is generated randomly. In Fig. 3, we plot the total power consumption when the system is operating in our proposed scheme, in the “sleep mode” policy and in normal way. We observe a

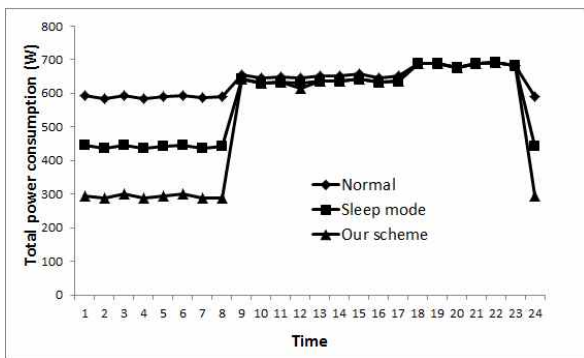


Fig. 3. Total power consumption.

Table 2. Parameters for numerical analysis

Parameters	Value
Number of radio resources	2
Bandwidth of each radio resource	5 Mhz
Throughput of each radio resource	13.5 Mbps
Target throughput	500 Kbps
$P_{cst}$	127 W
$P_{max}$	20 W
$\omega$	0.4
Total power consumption of macro BS	523 W
Number of picocells	5
Bandwidth of each picocells	5 Mhz
Throughput of each picocell	15 Mbps
Total power consumption of each picocell	38 W
Macrocell peak traffic	24 Mbps
Picocell peak traffic	12 Mbps
Low traffic period (10% of peak traffic)	23h – 08h
Medium traffic period (50% of peak traffic)	9h – 19h
Peak traffic period	19h – 22h

large reduction in power consumption when the offered traffic of the system is very low (i.e., in the first group of traffic patterns). In this period, our proposed scheme can reduce the power consumption by approximately 50% compared to nearly 25% reduction when system operates in the “sleep mode” policy, this is because “sleep mode” policy considers smaller cells as the same as the radio resources of macro BS and the system state is just the number of activated radio resources of macro BS. Thus it allows just only one radio resource or pico BS to be deactivated at a certain time while in our scheme, multiple radio resources and pico BSs can be deactivated simultaneously. For example, in this group of traffic, the optimal system state in our scheme in the first period is (1, 0, 0, 0, 0, 0), which means that we can turn off all pico BSs, the system just needs one remaining radio resource to serve the whole traffic. In contrast, the optimal state when the system operate in sleep mode policy in the first period is (1, 1, 1, 1, 1, 1), meaning that just one radio resource of macro BS can be deactivated. The power consumption reduction is negligible when the system operates in medium traffic period as in this period, just some pico BSs can be turned off, and there is no reduction when the system operates in peak traffic as all radio resources and all pico BSs have to be activated, any deactivation will result in the violation of QoS constraint. Over the whole day, the average power reduction in our scheme is nearly 20%. In Fig. 4, we plot the blocking probability of the system in our scheme which demonstrates that the QoS is guaranteed (less than 5% for all periods).

## 5. CONCLUSION

In this paper, we considered the dynamic operation of two-tier heterogeneous networks, using dynamic programming framework to save energy consumption, we proposed a scheme that based on

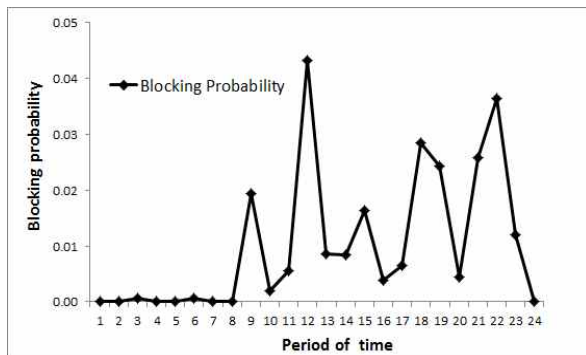


Fig. 4. Blocking probability.

traffic information, the controller will choose best action on macro and pico base stations that results in the minimum total power consumption while satisfies the QoS requirement. Numerical results showed that the total power consumption significantly depends on the behaviour of the traffic pattern and can be strongly reduced when the offered traffic is low and the duration is long. In future, we will consider the optimal policy when there is incomplete traffic information or with networks of multi-macro multi-pico cells.

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Hoang-Hiep Nguyen

Received his bachelor's degree in Electronic and Telecommunications from Hanoi University of Science and Technology, Vietnam in 2009. He is now Master student of the Department of Electronic and Tele-

communications Engineering, Inje University, Gimhae, Republic of Korea. His research interests are green cellular networks



Won-Joo Hwang

He received the Ph.D Degree from Osaka University Japan in 2002. He received his bachelor's degree and M.S. degree in Computer Engineering from Pusan National University, Pusan, Republic of Korea, in 1998 and

2000. Since September 2002, he has been an associate professor at Inje University, Republic of Korea. His research interests are in Network Optimization and Ubiquitous Sensor Networks