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Performance Analysis of Energy-Efficient Home Femto Base Stations

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Abstract—The energy consumption of home femto base stations (BSs) can be reduced, by turning off the Wi-Fi radio interface when there is no mobile station (MS) under the coverage of the BSs or MSs do not transmit or receive data packet for long time, especially in late night. In the energy-efficient home femto BSs, if MSs have any data packet to transmit and the Wi-Fi radio interface in *off* state, MSs wake up the Wi-Fi radio interface of home femto BSs by using additional low power radio interface. In this paper, the performance of the energy-efficient home femto BSs from the aspect of energy consumption and cumulative average delay, and show the effect of various parameters on energy consumption and cumulative average delay. From the results, the tradeoff relationship between energy consumption and cumulative average delay is shown and thus, appropriate operation should be needed to balance the tradeoff.

Keywords—energy consumption, power saving, femto base station.

I. INTRODUCTION

Recently, works on reducing energy consumption in mobile stations (MSs) have been carried out significantly in order to extend the battery lifetime of MSs [1]-[3]. In these works, MSs stay in power save mode or sleep mode, by turning off radio interface when there is no data transmission with BSs or access points (APs). Then, MSs wake up periodically to check whether there is any incoming data packet towards them and stay awake if there is any incoming data packet. Otherwise, MSs return to power save mode or sleep mode to save energy.

Although a lot of attentions have been paid to energy saving of MSs, only a few works have been carried out regarding energy saving of BSs, to the best of our knowledge, because BSs have stable power sources normally and also should support MSs always. However, home femto BSs installed in home environment can turn off their radio interfaces and save energy when there is no MS under the coverage of the BSs or MSs do not transmit or receive data packet for long time, especially in late night, as proposed in [4]. In [4], the authors use additional low power radio interface to wake up the radio interface of BSs in power saving mode [5] when MSs have any data to transmit via BSs. By doing this, BSs can stay in low power state and serve MSs when the MSs request data transmission by waking up the radio interface with the help of additional low power radio interface.

Although the performance of the proposed energy-efficient BSs was analyzed using a testbed, a detailed analysis of the effect of various parameters on the performance was not dealt with in [4]. In this paper, we propose state model for BSs in [4] consisting of *active*, *idle (Wi-Fi ON)*, and *idle (Wi-Fi OFF)*, and analyze the performance of the energy management scheme for BSs from the aspect of energy consumption and delay, which is an essential first step to design a better power saving scheme for BSs. The rest of this paper is organized as follows: In Section II, state model for home femto BS is modeled and analyzed; In Section III, numerical examples are provided; Finally, conclusions and further works are drawn in Section IV.

II. MODELING AND ANALYSIS OF STATE TRANSITIONS FOR HOME FEMTO BASE STATION

A. Modeling of State Transitions

Figure 1 shows a state transition model of home femto BS in this paper. The state of home femto BS is divided into *active*, *idle (Wi-Fi ON)*, and *idle (Wi-Fi OFF)* states. In *active* state, Wi-Fi interface of home femto BSs is awake and thus, BSs are sending or receiving data packets with MSs. *Active* state is further divided into sub-states, where the value of state in these sub-states represents the total number of active sessions of all the MSs and transitions between the sub-states are modeled as $M/M/\infty$ queuing model.

After completing service for the data session in *active* state, the state moves to *idle (Wi-Fi ON)* state and an *inactivity timer* is started. If there is no data transmission until the *inactivity timer* expires, the state moves to *Wi-Fi OFF* state and the BSs turn off their Wi-Fi radio interface. In *Wi-Fi OFF* state, the energy of BSs can be saved significantly. Otherwise, *inactivity timer* is reset and the state returns back to *active* state. If there is any data packet from MSs when BS is in *idle (Wi-Fi OFF)* state, MSs must send reverse paging signal to wake up the BS by using additional low power radio interface. As mentioned in [4], the low power radio interface uses different radio channel with very low power and thus, it does not consume battery energy of MSs significantly.

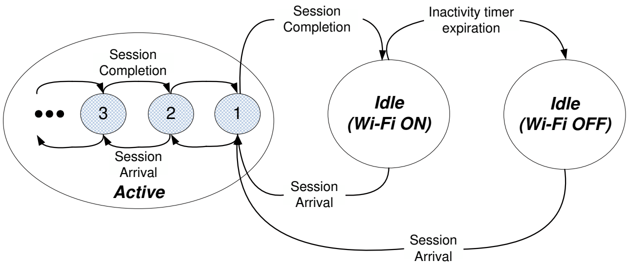

Fig. 1: *State transition model of home femto base station.*

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B. Performance Analysis

For performance analysis, we have made the following assumptions regarding the density functions of random variables in each state:

- Session arrivals at an MS occur according to a Poisson process and session arrivals at a BS from all the MSs in the coverage of the BS occur according to a Poisson process with parameters λ_s;
- The time duration that a BS remains in *active* states follows a busy period of $M/M/\infty$ queuing model;
- The value of *inactivity timer* is assumed as constant and is denoted by T_I.

We denote *active*, *idle (Wi-Fi ON)*, and *idle (Wi-Fi OFF)* states as states $1, 2,$ and3, respectively, for notational convenience. Since the residence times of an BS in *active* and *idle (Wi-Fi ON)* states do not follow an exponential distribution, the BS state transition behavior is analyzed using a semi-Markov process approach [6].

The steady state probability of each BS state can be obtained as:

$$P_k = \frac{\pi_k \overline{t_k}}{\sum_{i=1}^{3} \pi_i \overline{t_i}}, \qquad k = 1, 2, \text{and } 3, \tag{1}$$

where π_k denotes the stationary probability of state k and $\overline{t_k}$ is the mean residence time of the BS in state k. The stationary probability is obtained by solving the following balancing equations [6]:

$$\begin{aligned} \pi_j &= \sum_{k=1}^{3} \pi_k P_{kj}, \qquad j = 1, 2, \text{and } 3, \quad &(2)\\ 1 &= \sum_{k=1}^{3} \pi_k, &(3) \end{aligned}$$

where P_{kj} represents the state transition probability from state k to state j. The state transition probability matrix $P = [p_{kj}]$ of the state transition model is given by:

$$P = \begin{pmatrix} 0 & P_{12} & 0 \\ P_{21} & 0 & P_{23} \\ P_{31} & 0 & 0 \end{pmatrix}.$$

Then, stationary probabilities can be solved as:

$$\begin{aligned} \pi_1 &= \frac{1}{D}; &(4)\\ \pi_2 &= P_{12}\pi_1 = \frac{P_{12}}{D}; &(5)\\ \pi_3 &= P_{12}P_{23}\pi_1 = \frac{P_{12}P_{23}}{D}; &(6)\\ & &(7) \end{aligned}$$

where D is obtained by:

$$D = 1 + P_{12} + P_{12}P_{23}. \tag{8}$$

State transition probability P_{kj} can be derived based on the distribution of time from states k to j, T_{kj}. In *active* and *idle (Wi-Fi OFF)* states, since exits from these states occur due to only one event, i.e., session completion and session arrival, respectively, $P_{12} = P_{31} = 1$. In *idle (Wi-Fi ON)* state, exit from the *idle (Wi-Fi ON)* is caused by any of the following events:

- Session arrival (T_{21});
- *inactivity timer* expiration (T_{23}).

Then, the state transition probabilities P_{21} is derived as:

$$\begin{aligned} P_{21} &= \int_0^\infty f_{T_{21}}(t) Pr(T_{23} > t) dt \\ &= \int_0^\infty \lambda_s e^{-\lambda_s t} \int_t^\infty \delta(u - T_I) du dt \\ &= \int_0^\infty \lambda_s e^{-\lambda_s t} U[T_I - t] dt \\ &= \lambda_s \int_0^{T_I} e^{-\lambda_s t} dt \\ &= 1 - e^{-\lambda_s T_I}; \end{aligned} \tag{9}$$

Then, P_{23} is obtained as:

$$1 - P_{21} = e^{-\lambda_s T_I}. \tag{10}$$

The mean residence time in the *active* state is as follows, which is a busy period of $M/M/\infty$ model:

$$\overline{t_1} = \frac{e^{-\lambda_s/\mu_s} - 1}{\lambda_s} \tag{11}$$

The mean residence time in the *idle (Wi-Fi ON)* state is derived as:

$$\begin{aligned} \overline{t_2} &= \mathrm{E}[t_2] = \mathrm{E}[\min\{T_{21}, T_{23}\}] \\ &= \int_0^\infty \Pr(\min\{T_{21}, T_{23}\} > t) dt \\ &= \int_0^\infty e^{-(\lambda_s t} U(T_I - t) dt = \int_0^{T_I} e^{-(\lambda_s t} dt \\ &= \frac{1 - e^{(-\lambda_s T_I)}}{\lambda_s}. \end{aligned} \tag{12}$$

The mean residence time in the *idle (Wi-Fi OFF)* state is derived as:

$$\overline{t_3} = \frac{1}{\lambda_s}. \tag{13}$$

Based on the values of π_k and $\overline{t_k}$ obtained from Equations (4) - (6) and Equations (11) - (13), respectively, we finally derive the steady state probability of each BS state using Equation (1). Now, we can obtain the energy consumption of an BS per unit hour by using the steady state probability as:

$$E = \sum_{k=1}^{3} \psi_k P_k, \tag{14}$$

where ψ_k is the power consumption of BS in state k.

Although transitions into *idle (Wi-Fi OFF)* state can save energy, additional delay is introduced for session initiation, since MSs must wake up BSs and obtain new IP address using DHCP [4]. Therefore, there is tradeoff between energy saving and delay and thus, the effect of delay introduced by turning off the radio interface of BSs should be analyzed. In this paper, cumulative average delay per unit hour is defined as:

$$D = D_{off} P_3 / \overline{t_3} + D_{on} \frac{P_2 P_{21}}{\overline{t_2}}, \tag{15}$$

where D_{off} and D_{on} are the delay needed to initiate a new session in *idle (Wi-Fi ON)* and *idle (Wi-Fi OFF)* states, respectively.

III. NUMERICAL EXAMPLES

Figure 2 shows steady state probability of BS state by varying the values of *inactivity timer* T_I with $\lambda_s = 10(/h)$ and $\mu_s = 100(/h)$. The probability of *idle (Wi-Fi ON)* state increases as the values of *inactivity timer* increase due to less transitions into *idle (Wi-Fi OFF)* state. On the other hand, the probability of *idle (Wi-Fi OFF)* state decreases as the values of *inactivity timer* increase. Also, the probability of *active* is constant and does not depend on the values of *inactivity timer*. From the results, we can see that the value of *inactivity timer* has a significant effect on the steady state probability of BS state, and appropriate *inactivity timer* values should be selected for proper operation of power saving of home femto BSs.

Figure 3 shows energy consumption by varying the values of *inactivity timer* T_I with $\mu_s = 100(/h)$, $\psi_1 = 3.604(W)$, $\psi_2 = 3.604(W)$, and $\psi_3 = 2.637(W)$ [4]. The energy consumption increases as the values of *inactivity timer* increase since the probability of *idle (Wi-Fi ON)* state increases, which has higher power consumption than *idle (Wi-Fi OFF)* state. For a fixed value of *inactivity timer*, the energy consumption increases as the rate of session arrival increases, since it causes more transitions into *active* state.

Figure 4 shows cumulative average delay by varying the values of *inactivity timer* T_I with $\mu_s = 100(/h)$, $D_{off} = 10(s)$ [4], and $D_{on} = 1(s)$. The cumulative average delay decreases as the values of *inactivity timer* increase since the probability of *idle (Wi-Fi ON)* state increases, which has smaller delay than *idle (Wi-Fi OFF)* state. For a fixed value of *inactivity timer*, the cumulative average delay increases as the rate of session arrival increases. For small values of *inactivity timer*, the effect of long delay in *idle (Wi-Fi OFF)* state is more dominant. Otherwise, the effect of short delay in *idle (Wi-Fi ON)* state is more dominant. From the results, we show that there is tradeoff between energy consumption and cumulative average delay and thus, appropriate operation should be needed to balance the tradeoff.

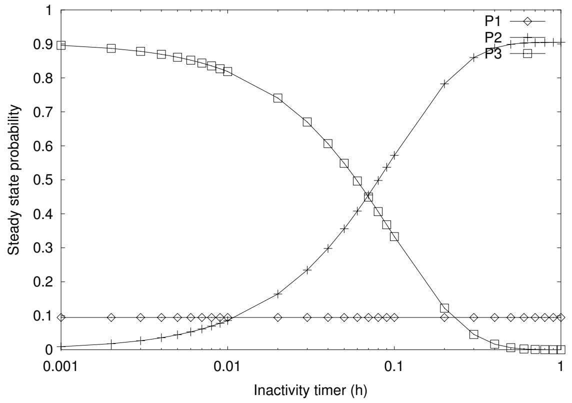

Fig. 2: Steady state probability by varying *inactivity timer*.

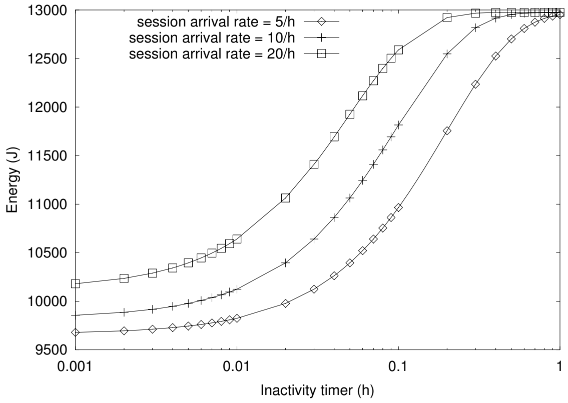

Fig. 3: Energy consumption by varying *inactivity timer*.

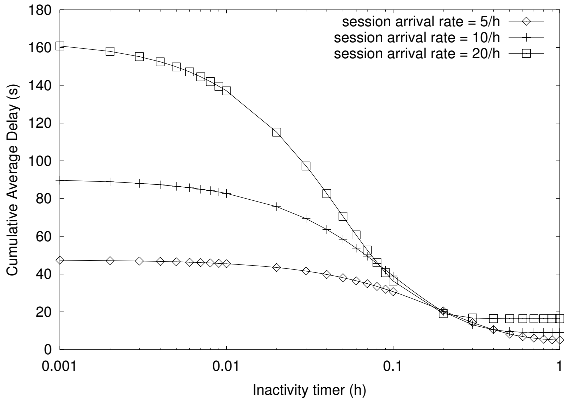

Fig. 4: Cumulative average delay by varying *inactivity timer*.

Figure 5 shows energy consumption by varying the values of session arrival rate with $\mu_s = 200(/h)$, $\psi_1 = 3.604(W)$, $\psi_2 = 3.604(W)$, and $\psi_3 = 2.637(W)$ [4]. The energy consumption increases as the values of session arrival rate increase due to more transitions into *active* state. For a fixed value of session arrival rate, the energy consumption increases as the values of *inactivity timer* increase due to less transitions into low power *idle (Wi-Fi OFF)* state .

IV. CONCLUSIONS AND FURTHER WORKS

In this paper, we analyzed the performance of energy-efficient home femto BSs, from the aspect of energy consumption and cumulative average delay, and show the effect of various parameters on energy consumption and cumulative average delay. From the results, the tradeoff relationship between energy consumption and cumulative average delay is shown and thus, appropriate operation should be needed to balance the tradeoff.

In our further works, power saving of MSs should be considered together with that of BSs, and thus, integrated power saving of MSs and BSs should be analyzed.

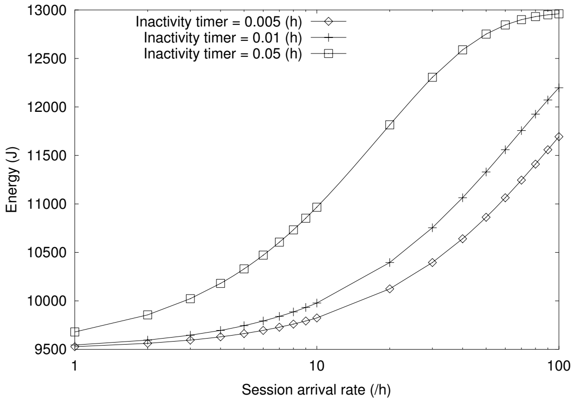

Fig. 5: Energy consumption by varying session arrival rate.

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