Performance Analysis of an Energy Efficient Femtocell Network Using Queuing Theory

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ABSTRACT

The energy expenditure of cellular networks is increasing rapidly due to high demand of data services by the subscribers. This subsequently gives rise to the CO_2 emission which is a critical issue nowadays. A hybrid cellular network comprised of macrocell and several femtocells is required to achieve reliability, continuous connectivity, and energy efficiency. To address the issue of energy efficiency, in this paper we present a queuing model of an energy efficient femtocell network. The transmission of data traffic in this type of network is modeled using M/M/1 queue where server FAP (Femtocell Access Point) takes vacation to save energy during inactivity period. The network model is solved using a MGM (Matrix Geometric Method). The performance of the system is evaluated in terms of average system delay and power savings for different sleep cycle durations. Results reveal that the maximum energy can be saved with higher sleep cycle duration at a cost of increased system delay.

Key Words: **Cellular Network, Energy Efficiency, Femtocell, Matrix Geometric Method, Sleep Cycle, Queuing, Quality of Service.**

1. INTRODUCTION

The capacity of wireless cellular networks can be increased by deploying small cells such as femtocells along with existing macrocells [1,2]. This kind of deployment has mainly two advantages: first high link reliability is achieved and second the spatial reuse is increased [3]. The femtocell networks support short range indoor communication hence the disadvantage of receiving weak signals from a macro-basestation can be avoided [4]. Moreover, the femtocell based deployment can enable a continuous wireless broadband communication in cellular dead zones [5].

Recently, a growing interest has been seen for reducing the carbon footprint. In this regard, the reduction of the CO_2 emission has been committed by various developed and developing economies [6]. For example the United Kingdom has decided to reduce its carbon emission level to only 20% by 2050. Currently the contribution of cellular communication to the total emission is only 1-2%. However, with rapid growth in the data service required by the cellular subscribers, the CO_2 emission is expected to increase with a pretty high pace. To address this issue, many researchers from academia and industry are putting

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their best efforts to make communication networks energy efficient. New architectures and protocols have been proposed and developed to achieve energy efficiency in these networks. A hybrid cellular network comprised of macrocell and femtocells is one of the possible solutions to achieve energy efficiency and reliability in current cellular network [7]. In [8] authors have studied the energy efficiency of spectrum sharing and power allocation using game theory for a heterogeneous network comprised of a cognitive macrocell and a cognitive femtocell. A measurement based study of energy expenditure of 3G (Third Generation) femtocell basestation for both voice and data application is presented in [9]. The energy efficiency using sleep mode in a dense femtocell network deployment is studied using a cluster-based energy efficient algorithm [10]. According to [11], energy efficiency in a cellular network can be achieved with deployment of small cells such as femtocells. Sleep mode, having small power consumption compared to transmission mode, can be useful to reduce energy consumption of a femtocell network.

Traditionally, queuing theory has been used to model packet switched networks [12]. However to the best of our knowledge, it is first time that a detailed queuing model with vacation for an energy efficient femtocell network has been developed. The performance of the system is evaluated in terms of both QoS (Quality of Service) parameter (i.e. average system delay) and energy efficiency (i.e. power savings).

Following the introduction the paper is organized as follows: Section 2 describes the studied scenario. A detailed mathematical model of a femtocell network is presented in Section 3. The performance evaluation of the system is carried out in Section 4. The paper concludes with Section 5.

2. STUDIED SCENARIO

A heterogeneous cellular network with coexistence of both macrocell and femtocells is shown in Fig. 1. In this paper, we consider a femtocell network with M communicating nodes. This femtocell network is a packet switched network, where each node transmits its packets to a femtocell basestation/access point. The FAP is connected to the main basestation (macrocell basestation) through backhaul to enable an end-to-end seamless communication. Without loss of generality, we only consider uplink transmission.

3. MATHEMATICAL MODELING

In scenario considered, each communicating node generates packets with a mean rate λ_n. The arrival process from M nodes becomes a multiple Poisson process with mean arrival rate $\lambda = M\lambda_n$. The received packets at the input of a FAP are then transmitted to the main BS through backhaul link. This backhaul link serves the incoming packets with a mean service rate of μ. Here, an Exponential distribution is considered to represent the packet length distribution. Hence, the service time of the server (the backhaul with a constant data rate R_b) follows an Exponential distribution. The FAP goes to sleep mode (low power state) during inactivity period and this phenomenon represents a server on vacation. This complete communication model for a femtocell network becomes an M/M/1 queue where server takes queue length dependent vacation to save energy when there is no packet to transmit (the system is empty) [13-15]. Server takes Negative Exponentially distributed vacation with mean vacation time $t_v = 1/\delta_v$, where δ_v is the arrival rate of server from vacation. On arrival from a vacation, if the server finds any packet in the system then the packet is served immediately otherwise the server takes another vacation. In this system, the variable mean availability time of the server is not present because the vacation is queue length dependent [13]. The state diagram of this system is shown in Fig. 2 with a lexicographical representation, where each state is represented by a pair *(j,k)*, where *j=0,1* represents the server on vacation or server availability and *k=1,2,...* is the number of packets in the system. In Fig. 2, the state (1,0), is inseparable with the state (0,0), because the server while returning from a vacation takes another vacation if there is no packet in the system.

The transition rate matrix *Q*, infinitesimal generator, of the model is represented as:

$$Q = \begin{bmatrix} a & b & & & \\ c & A & B & & \\ & C & A & B & \\ & & C & A & B \\ & & \ddots & \ddots & \ddots \end{bmatrix} \tag{1}$$

where the submatrices of *Q* are given by:

$$A = \begin{bmatrix} -(\lambda + \delta_V) & \delta_V \\ 0 & -(\lambda + \mu) \end{bmatrix}, B = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix}, C = \begin{bmatrix} 0 & 0 \\ 0 & \mu \end{bmatrix},$$

$$a = -\lambda, b = \begin{bmatrix} \lambda & 0 \end{bmatrix}, c = \begin{bmatrix} 0 \\ \mu \end{bmatrix}$$

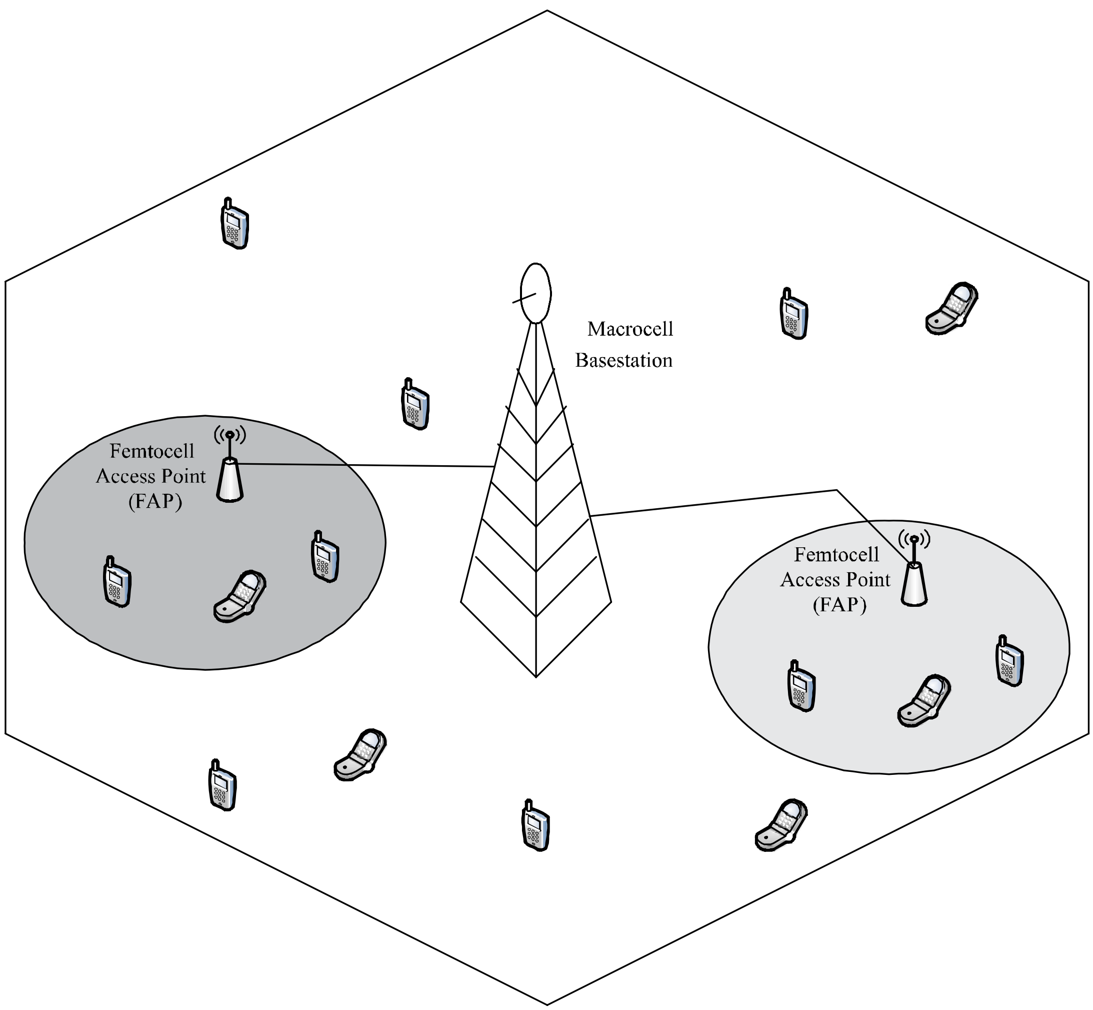

FIG. 1. CELLULAR NETWORK WITH BOTH MACROCELL AND FEMTOCELL DEPLOYMENT [8]

and the entries not mentioned in Q are null matrices [14]. For the state diagram in Fig. 2, the Q is an infinite block tri-diagonal matrix, where three blocks repeat after initial three states (representing 0 or 1 packet). This system follows a QBD (Quasi Birth and Death) process because transition from one state to the next state is not always a birth or a death but it can be the arrival of the server from a vacation [14]. Hence, the system model can be efficiently solved using MGM [14,15]. For this QBD process to be ergodic and positive recurrent, the stationary probability vector p of Q should have a matrix geometric form and must satisfy the following two systems of Equations (2-3):

$$pQ = 0 \tag{2}$$

$$pu = 1 \tag{3}$$

where 0 is a null row vector and u is a unit column vector, both having the same number of entries as that of p. Equation (3) states that the sum of all probabilities is unity [14]. The stationary probability vector p may be partitioned as $(p_0, p_1, p_2, \ldots)$ where $p_k=(p(0,k), p(1,k))$ is the probability vector of k packets in the system. By solving the set of Equation (2) using MGM method, an explicit solution for rate matrix R and initial probabilities p_0 and p_1 (representing probabilities of 0 and 1 packet in the system) [13], we obtain:

$$R = \begin{bmatrix} \frac{\lambda}{(\lambda+\delta_v)} & \frac{\lambda}{u} \\ 0 & \frac{\lambda}{u} \end{bmatrix}, \; p_0 = \frac{\delta_v(\mu-\lambda)}{\mu(\lambda+\delta_v)}$$

and

$$p_1 = [p_{01}\, p_{11}] = \begin{bmatrix} \frac{\lambda\delta_v(\mu-\lambda)}{\mu(\lambda+\delta_v)^2} & \frac{\lambda\delta_v(\mu-\lambda)}{\mu^2(\lambda+\delta_v)} \end{bmatrix}$$

The probability vector of k packets can be computed with the help of R and p_1 as:

$$p_k = p_1 R^{k-1};\; k \geq 1 \tag{4}$$

The steady state distribution, describing the number of packets in the system [15] is:

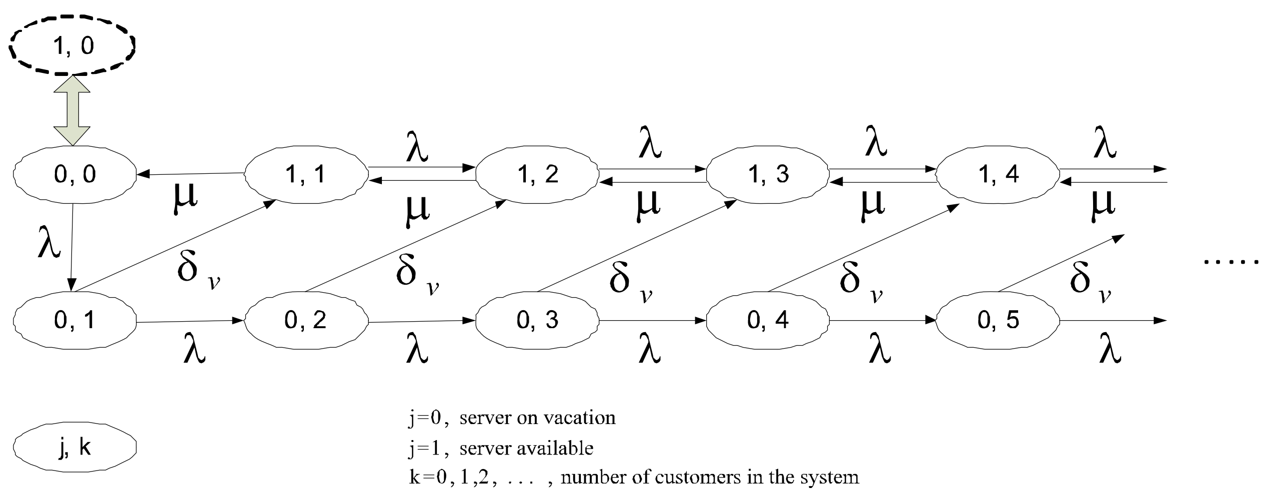

FIG. 2. STATE DIAGRAM OF M/M/1 SYSTEM WITH VACATION [15]

$$p_k = \begin{cases} p_k, & k = 0 \\ p_k u, & k \geq 1 \end{cases} \tag{5}$$

Thus, the mean queue length or system size (*N*) can be computed as [14]

$$N = \sum_{k=0}^{\infty} k p_k \tag{6}$$

The average system delay (*W*) for a packet can be computed using Little's theorem [14] as:

$$W = \frac{N}{\lambda} \tag{7}$$

The system utilization (*U*) is defined as [14]:

$$U = \frac{\lambda}{\mu} = \rho \tag{8}$$

where ρ is the offered load [13,14]. The energy efficiency in term of power savings at FAP, during inactivity period, is given by:

$$P_S = ((1\text{-}U) \times P_t) - (P_{OH}) \tag{9}$$

where P_t is the transmitter power and P_{OH} is the total overhead power required for switching from a transmit mode to a low power state mode [15].

4. PERFORMANCE EVALUATION

We evaluate the performance of a femtocell network in terms of average system delay and energy efficiency (i.e. power savings). We determine the values of these parameters with respect to the offered load (ρ) . The variation in the offered load can represent two cases: (a) The service rate is constant and the arrival rate is varying; (b) The arrival rate is constant and the service rate is varying. The arrival rate can increase because of higher data generation rates of nodes and also with increase in number communication nodes. The QoS parameter (i.e. system delay) and power savings are analyzed with and without sleep cycles. For simplicity and better understanding, mean sleep cycle durations of 5 and 10 ms are considered in this paper. These values are practical for small access points [15]. For each sleep cycle the value of the sleep duration are drawn for an Exponential distribution.

In Fig. 3, the average system delay for a packet is analyzed with respect to the offered load and sleep (no sleep) cycle durations. For system stability the service rate of FAP should be smaller than the combined arrival rate of the data. To cover complete range we consider values of offered load from 0.1 to 1. Fig. 3(a) represents the variation of average delay without sleep cycle. In this case the delay is only because of the service rate. It can be seen that with small offered load or higher service rate the delay of the system is small. However, it increases with an increase in the offered load. Delay becomes unbounded when the value of offered load reaches 1. Hence congestion occurs and system becomes unstable. Similarly Fig. 3(b-c) represent the delay variation with 5 and 10 ms sleep durations respectively. Delay in both cases is because of service rate and sleep durations. The delay with smaller offered load is dominated by the sleep duration as server is free most of the time. The difference between delays in all cases starts decreasing with increase in the offered load. It is because the server does not go to sleep mode that often with higher offered load. The optimum value of the sleep duration depends on the delay requirement of the data traffic type.

As can be realized from Equation (8) the utilization in all cases remains same. Utilization is less if the offered load of the system is small means that the server is less busy. If server is less busy then it is beneficial that it goes to a sleep mode (low power state) when there is no or small traffic to serve. In turn it will save the power consumed by the system. The power savings with varying offered load and different sleep cycles are shown in Figure 4. Please note that in case of no sleep there is no energy savings as server does not go to low power state. Fig. 4(a) shows power savings with mean sleep duration of 5 ms. Higher energy is saved with small number of packets in the system. It decreases with increase in offered load. The energy saving diminishes when arrival rate becomes approximately equal to service rate. It is because the server is very busy. The power savings in case of 10 ms sleep cycle duration is shown in Fig. 4(b). Higher energy savings are achieved with 10 ms sleep duration because of lower overheads for going to sleep. However, the higher sleep cycle duration causes higher system delay. In cases of 10 and 5 ms sleep durations the P_{OH} considered are 5 and 10% of P_t respectively.

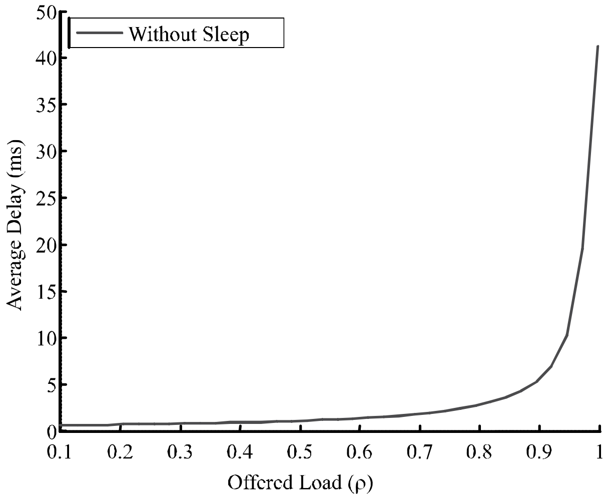

FIG. 3(a). AVERAGE SYSTEM DELAY WITHOUT SLEEP

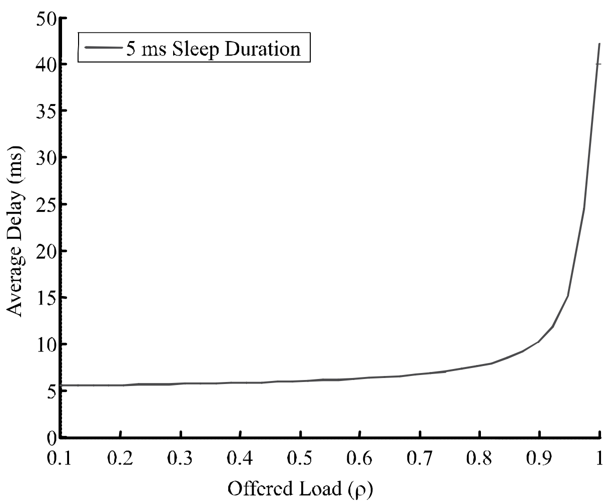

FIG. 3(b). AVERAGE SYSTEM DELAY WITH 5ms SLEEP DURATION

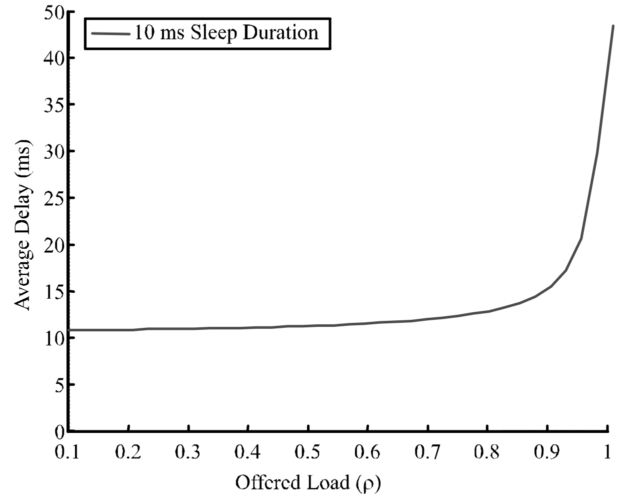

FIG. 3(c). AVERAGE SYSTEM DELAY WITH 10ms SLEEP DURATION

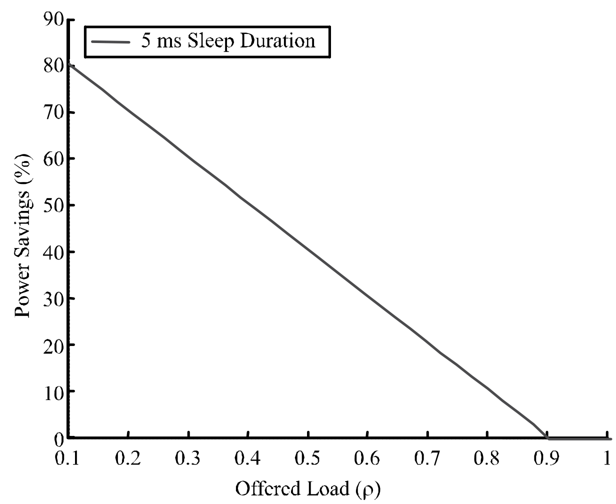

FIG. 4(a). POWER SAVINGS WITH 5ms SLEEP DURATION

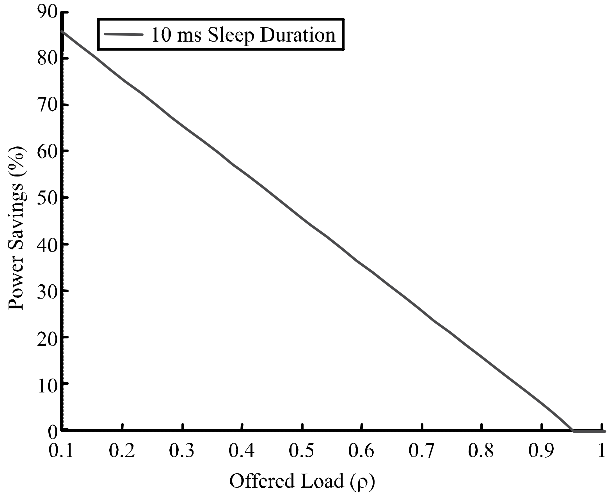

FIG. 4(b). POWER SAVINGS WITH 10ms SLEEP DURATION

5. CONCLUSION

In this paper, we presented a detailed queuing model for an energy efficient femtocell network. The system was modeled using an M/M/1 queue where server takes vacations (goes to a low power state) during inactivity period to save energy. The performance of the system was evaluated in terms of average system delay and power savings. Results revealed that for smaller values of the offered load the delay was dominated by the sleep cycle durations. The difference between delays with sleep and without sleep started diminishing as the offered load reached value of 1. Higher energy savings were achieved with smaller offered load and higher sleep cycle durations. However, when the offered load of the system was 1 there were no energy savings.

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