Performance Analysis of a Power Saving Mechanism in WLANs

Kiril Kassev

***Abstract* – Traditional WLANs consume significant amount of power to contend to the shared wireless medium as well as to periodically broadcast special beacons for identifying themselves to mobile nodes within the service area. Improving energy efficiency can be achieved by adopting power saving mechanism if no data is transferred for a particular amount of time. This paper aims at investigating such a mechanism, employed in WLANs. The performance analysis is carried out by analytical modelling under different service time distributions and inactivity timer values using a semi-Markov process. Numerical results demonstrate the trade-off relationship between energy consumption and cumulative wake-up delay performance.**

***Keywords* – Energy consumption, Performance analysis, Power saving, Wireless access networks, WLAN.**

I. Introduction

Energy consumption in communication networks is a crucial issue, which is paid an increasing attention. The global communication infrastructure comprises various kinds of network domains implemented by different technologies. It is reported that more than 3 % of the worldwide energy consumption is driven by the ICT sector, and it is expected to increase in future [1]. Nowadays wireless communications are fundamental part of the modern networks. Such wireless access networks are widely deployed worldwide in order to meet customers' demands for broadband access to a rich variety of services. Over the years many efforts have been made towards network throughput enhancement, which is related to the energy consumption increase. Energy efficiency in telecommunication networks is a still open issue, which aims at reducing energy consumption while meeting QoS criteria [2], [3]. With the growing popularity of broadband wireless access technologies, research activities are focused on reducing energy consumption in battery-driven mobile devices [4]. Moreover, the worldwide mass deployment of 3G and 4G cellular networks requires adequate actions aimed at energy consumption reduction, since more than 50 % of total energy is consumed by the radio access network [5]. It largely depends on the mobile stations (MSs) density in the area covered by the base station.

Heterogeneous wireless access networks are considered to be a promising solution for supporting dense and hyper-dense traffic loads and providing cost-effective services. Different technologies coexist in the same geographical area and often cells of small sizes are installed either indoor or outdoor for better coverage and cellular traffic offload. The latter is an area of great interest and is usually realized by WLANs (Wi-Fi AP) [6].

WLANs are widely available in urban areas either deployed by operators as commercial hotspots or deployed by users for private or business usage. A common weakness is that they consume significant amount of energy as periodically broadcast special beacons for identifying themselves to MSs within the service area [7]. Thus, lack of data activity would lead to energy waste. This paper aims at investigating a power saving mechanism applied to WLANs with respect to traffic characteristics.

The rest of the paper is organized as follows: Section 2 describes the system and the analytical model for performance analysis of a power saving mechanism incorporated in a WLAN. Numerical studies in Section 3 reveal the influence of various parameters on system performance. Some conclusion remarks and suggestions for future work are presented in Section 4.

II. System Model and Performance Analysis

The system under investigation is represented by a Wi-Fi Access Point (AP) operating in infrastructure mode. Medium access control is done by the CSMA/CA protocol at the data link layer. AP operation can be in one out of three possible states (Fig. 1). During active state (denoted as *Active*) the AP transfers data with MSs after establishing packet data sessions. The total number of active sessions of all the MSs is a random variable. The AP is intended to serve various kinds of data traffic. Thus, sessions arrivals and completions are modeled as an M/G/1 queuing model. After completing the last active session, the AP turns to *Idle ON* state where an inactivity timer is launched. If a new session arrives before timer expiration, the process turns back to *Active* state for session service and inactivity timer is reset to its initial value. In order to avoid energy waste a power saving mechanism is incorporated. If there is not either MSs within the AP coverage or data activity for a predefined amount of time (inactivity timer expires), the AP switches to low power state (denoted as *Idle OFF*), and turning off the beacons. The interface will be able to serve a user request for a new connection (session) by employing an additional wake-up mechanism based on reverse paging and low-power radio module [8]. Such module uses different technology and operates on separate channel to avoid interference. In such case the AP directly moves to the *Active* state for session service.

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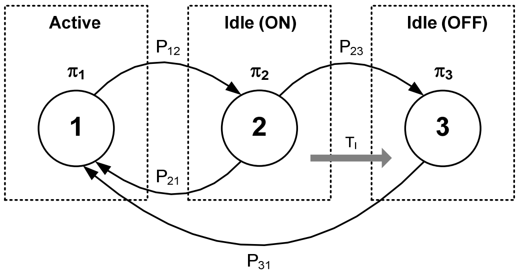

Fig. 1. State transition diagram of the AP operation

The performance analysis is based on the following assumptions with respect to traffic flow characteristics. Offered traffic A is generated by a Poisson arrival process. The active MSs within the AP coverage generate sessions with mean arrival rate λ_S. Time duration of the AP in *Active* state follows the busy period of M/G/1 queuing system. The holding time follows an arbitrary time distribution. During the busy period at least one session is served. The value of inactivity timer is denoted by T_I and is assumed to be constant (deterministic time intervals). Since not all the states of the stochastic process follow the exponentially distributed residence times, the AP behavior can be analyzed as a semi-Markov process. The focus is on steady-states probabilities calculation and proportion of time the process is in a given state.

Suppose that the process can be in any one of three possible states. Each time it enters the state i it remains there for a random amount of time. If an event occurs the process makes transition into state j with probability P_{ij}. Based on the state-transition diagram the transition probability matrix $P=[P_{ij}]$ of the semi-Markov chain is given as

$$P=\begin{bmatrix} 0 & P_{12} & 0 \\ P_{21} & 0 & P_{23} \\ P_{31} & 0 & 0 \end{bmatrix}. \qquad (1)$$

Let $\pi_i \ (i\in\{1,2,3\})$ denotes the stationary (limiting) probability that the semi-Markov process is in state $S_i \ (i\in\{1,2,3\})$. In general, π_i is derived by using the balance equation [9]

$$\pi_i=\sum_{j=1}^{3}\pi_j\cdot P_{ji}, \quad i=1,2,3 \qquad (2)$$

$$\sum_{i=1}^{3}\pi_i=1$$

By solving balance equations and using normalization constant, the stationary probabilities can be obtained as

$$\begin{aligned} \pi_1 &= \frac{1}{P_{12}+P_{12}\cdot P_{23}+1} \\ \pi_2 &= P_{12}\cdot\pi_1=\frac{P_{12}}{P_{12}+P_{12}\cdot P_{23}+1} \\ \pi_3 &= P_{12}\cdot P_{23}\cdot\pi_1=\frac{P_{12}\cdot P_{23}}{P_{12}+P_{12}\cdot P_{23}+1} \end{aligned} . \qquad (3)$$

Since the process spends an expected time $\overline{t_i}$ in state i, the proportion of time the process is in state i, and hence the AP's steady state probabilities, should be a weighted average of the π_i, i.e.

$$P_i=\frac{\pi_i\cdot\overline{t_i}}{\sum_{j=1}^{3}\pi_j\cdot\overline{t_j}}, \quad i=1,2,3 \ , \qquad (4)$$

where π_i is given as the solution to (3) [9].

The probability that a new session begins before T_I expiration, and hence the state transition probability P_{21}, is

$$P_{21}=1-\exp(-\lambda_s\cdot T_I)=\Pr[t<T_I]\,. \qquad (5)$$

Then, the probability of entering the power saving state is

$$P_{23}=1-P_{21}=\exp(-\lambda_s\cdot T_I)=\Pr[t\geq T_I] \qquad (6)$$

In both *Active* and *Idle OFF* states exit transitions are driven by one event only – session completion and session arrival, respectively. Thus,

$$P_{12}=P_{31}=1\,. \qquad (7)$$

During data activity the mean number of active sessions is obtained by the Polaczek-Khintchine formula for arbitrary service time distributions [10], [11]. For M/G/1 model the time duration $\overline{t_1}$ in *Active* state is derived by the Little's theorem

$$\overline{t_1}=\frac{[(c^2)^2-1]A^2+2A}{2\lambda_s(1-A)}, \qquad (8)$$

where c^2 is the coefficient of variation, which is normalized dimensionless measure for the irregularity of the holding time distribution. It is defined as the ratio between the standard deviation σ and the mean value τ of the session's holding time. The larger c^2, the more irregular (dispersive) is the service time distribution. Typical values of c^2 for M/M/1 and M/D/1 systems are 1 and 0 respectively.

The mean residence time $\overline{t_2}$ in *Idle ON* state is governed by the inactivity timer value T_I. If a new session occurs before T_I expires, the timer is cancelled and *Active* state is entered. Otherwise the AP enters the power saving mode at *Idle OFF* state. Therefore $T_I = \min(T_{21}, T_I)$ is obtained as

$$\begin{aligned} \overline{t_2} &= E[\min(T_{21},T_{23})]=\int_0^{\infty}\Pr[\min(T_{21},T_I)>t]dt= \\ &= \int_0^{T_I}\Pr[T_{21}>t]dt= \\ &= \int_0^{T_I}\exp(-\lambda_s t)dt=\frac{1-\exp(-\lambda_s T_I)}{\lambda_s}, \end{aligned} \qquad (9)$$

where $E[X]$ is the expected value operator [12].

The mean residence time in the *Idle OFF* state follows the session arrival rate (Fig. 1)

$$\overline{t_3} = \frac{1}{\lambda_s}\,. \tag{10}$$

Based on the values of steady states probabilities, obtained by (4), the energy consumption of the AP can be calculated. If AP's power consumption in state i is denoted as φ_i, its mean value is derived by

$$\overline{E} = \sum_{i=1}^{3} \varphi_i \cdot P_i\,. \tag{11}$$

The energy consumption is generally expressed in Joules (J), by having knowledge on power consumption for a unit of time.

As stated above, in order to decrease energy consumption AP turns off its radio interface during power saving mode. When a new session arrives, AP must be woken up and move to active state. Unfortunately, this procedure introduces an additional delay since AP must allocate and assign a new IP address to the MS initiated the data session. Therefore, there is a trade-off between energy saving and the delay to obtain a new IP address by DHCP when AP wakes up. This could be quantitatively expressed by the cumulative average delay $\overline{D_c}$, which is defined as

$$\overline{D_c} = D_{OFF} \cdot \frac{P_3}{\overline{t_3}}\,, \tag{12}$$

where D_{OFF} is the delay to initiate a new session in case AP has been in *Idle OFF* state.

III. Numerical Results

This section presents numerical results of the performance analysis the power saving mechanism applied to a WLAN.

The basic unit of time is one hour. It is assumed the AP serving rate μ_s of 200 sessions per hour ($\mu_s = 200\,h^{-1}$). In general, the service (holding) time distribution is assumed to be an arbitrary. Different systems can be analyzed by setting the coefficient of variation c^2. The power consumption in all the states is as follows: $\varphi_1 = 3{,}604$ W, $\varphi_2 = 3{,}604$ W, and $\varphi_3 = 2{,}637$ W. These are average values obtained by measuring on a prototype with a popular Wi-Fi AP [8]. The complete wake-up time comprises the following processes – an application request; a message sending to the AP, which let the interface to be activated; DHCP process starting and completing after assigning an IP address to the MS. Thus, the delay to initiate a new session D_{OFF} is 10 s., as measured in [8].

It is expected that the energy consumption will increase as the inactivity timer value increase, as well, since the probability of staying at *Idle ON* state increases. For a fixed value of inactivity timer, the energy consumption depends on the offered traffic, in terms of Erlangs (Fig. 2). It increases as the traffic load is rising due to frequent transitions into *Active* state. On the other hand, the coefficient of variation c^2 may have a clear impact, especially for high traffic loads and small values of inactivity timer (right-hand side of Fig. 2). In order to maintain energy consumption constant an admission control mechanism should be adopted. It could be seen that dispersive service time distributions can lead to throughput degradation.

The design of power saving mechanisms for WLANs requires proper setting of the inactivity timer value, since a number of parameters influence on the system performance. Fig. 3 reveals how energy consumption changes with respect to the inactivity timer value and the dispersive nature of the service time distribution. For a fixed value of offered traffic flow, the more higher value of inactivity timer results in increase of energy consumed by the AP due to less number of transitions into power saving (*Idle OFF*) state. Again, these values are considerable for higher traffic loads, since more transitions into *Active* state occur. For sessions with constant (deterministic) service times ($c^2 = 0$) AP achieves the best energy efficiency performance.

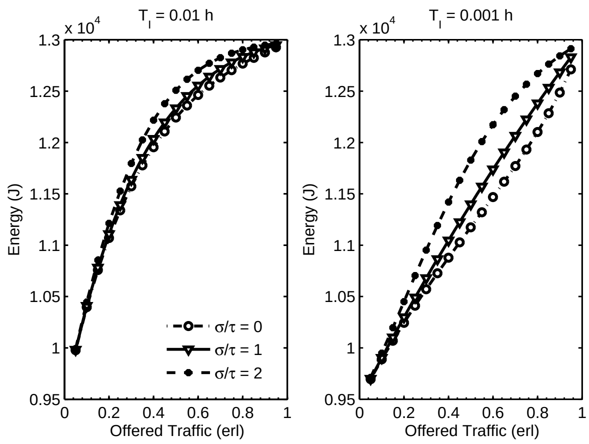

Fig. 2. Energy consumption variation as a function of offered traffic and coefficient of variation

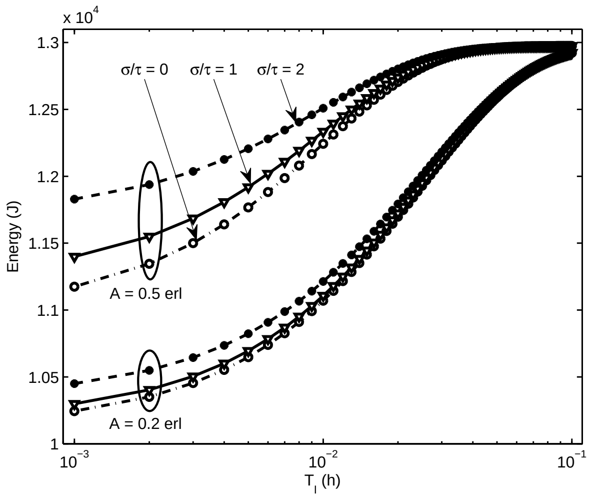

Fig. 3. Inactivity timer value influence on the energy consumption

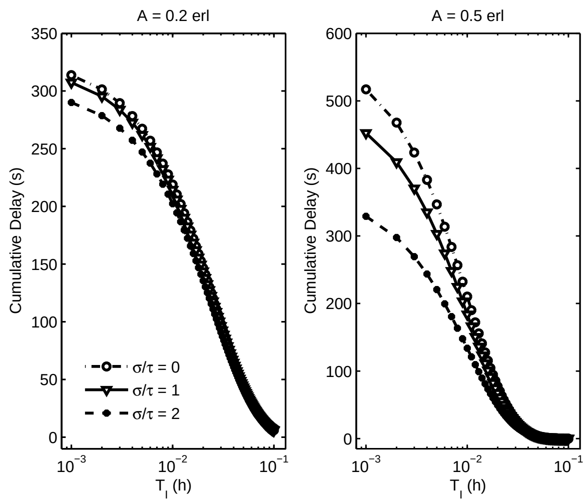

Fig. 4. Inactivity timer value influence on the cumulative delay

As shown, the smaller inactivity timer value, the greater energy efficiency can be achieved. Another interesting aspect of the analysis is the assessment of the average cumulative delay, quantitatively expressed by (12) and depicted on Fig. 4. From the results on both Fig. 3 and Fig. 4 is evident that there is a trade-off between the energy consumption and the cumulative delay. For small values of inactivity timer reasonable energy consumption is achieved (Fig. 3), but frequent transitions into power saving state incur long delays for session reestablishment. Heavy traffic loads and large variations of service time distributions are unfavorable. Thus, an appropriate setting of inactive timer value is necessary in order to balance the above mentioned trade-off.

IV. Conclusion

In this paper an analytical evaluation of a power saving mechanism in WLANs has been carried out. The system performance under different service time distributions and inactivity timer values is investigated. The tradeoff between energy consumption and cumulative wakeup delay has been demonstrated, which is important for optimal setting of the inactivity timer value under specific traffic load and service time distributions.

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