Performance Analysis of Energy Consumption of AFECA in Wireless Sensor Networks

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***Abstract*—Energy consumption is one of the most important problems to be solved in wireless sensor networks, since sensor nodes are operated with battery power. Therefore, it is necessary to put the wireless interface of sensor nodes into low power *sleep* state as much as possible when communication with neighbor sensor nodes is not required, in order to save battery power. In this paper, we analytically derive the steady state probability of sensor node states, *sleep*, *listen*, and *active* states, in Adaptive Fidelity Energy-Conserving Algorithm (AFECA), which belongs to duty cycling scheme for energy conservation in wireless sensor networks. Then, we analyze the energy consumption of AFECA in detail for varying the number of neighboring nodes, *sleep timer*, *listen timer*, and *active timer* values. The performance of AFECA is compared with that of Basic Energy Conservation Algorithm (BECA) in detail via mathematical analysis. The analysis results show that AFECA achieves significant improvement of energy conservation over BECA, even for a small number of neighboring nodes, when the values of *sleep timer* and *active timer* are not very large. The result of this paper can provide sensor network operators guideline for selecting appropriate timer values for AFECA.**

***Index Terms*—BECA, AFECA, energy consumption, power consumption, sensor network.**

I. Introduction

Energy consumption is one of the most important problems to be solved in wireless sensor networks, since sensor nodes are operated with battery power and battery in sensor nodes cannot be replaced easily [1], [2], [3], [4]. Although energy is consumed to sense information or process sensed information, significant portion of energy is consumed to communicate with other sensor nodes [4]. Also, since just listening to air interface, without transmitting or receiving data with other sensor nodes, consumes comparable energy to receiving data, it is necessary to put the wireless interface of sensor nodes into low power *sleep* state as much as possible when communication between neighbor sensor nodes is not required, in order to save battery power [5], [6].

Although there have been numerous schemes to save energy in wireless sensor networks [4], duty cycling scheme is one of the most representative schemes, where sensor nodes alternate between *active* and *sleep* states. Basic Energy Conservation Algorithm (BECA) and Adaptive Fidelity Energy-Conserving Algorithm (AFECA) belong to duty cycling scheme. As shown in Fig. 1, operating states in BECA consist of *active*, *listen*, and *sleep* states. Initially, sensor nodes stay in *sleep* state when communication is not required, by putting the communication interface in the low power *sleep* state. In *sleep* state, sensor node periodically wakes up for every *sleep timer*, T_s. At the expiration of *sleep* timer, it moves to *listen* state and listens to air interface in order to check any incoming data to the sensor node until *listen timer*, T_l, is expired. In *listen* state, if there is no incoming data until the expiration of the *listen timer*, it moves back to *sleep* state again. Otherwise, sensor node changes its state to *active* state and communicates with another sensor node via air interface. In *active* state, data are transmitted or received, and if there is no further data to be transmitted or received until the expiration of *active timer*, T_a, after completing transmitting or receiving any data, it moves to *sleep* state.

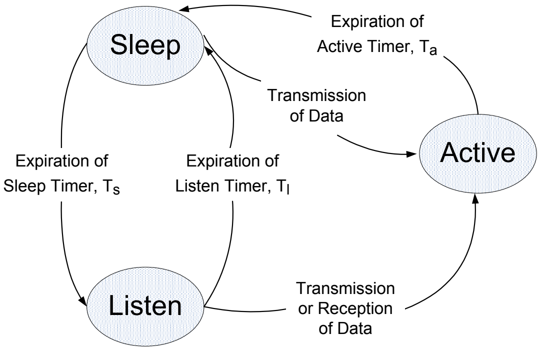

Fig. 1. *State transition model of BECA.*

As shown in Fig. 2, AFECA [7] improves energy conservation of BECA by increasing residence duration in *sleep* state when neighbor nodes are available. In AFECA, sleep timer value is defined as $U(1, N) * T_s$, where U denotes uniform distribution and N is the estimated number of neighbor nodes. A subset of sensor nodes awake to forward data to neighboring sensor nodes on behalf of neighboring sensor nodes, which stay in *sleep* state and save battery power, where a subset of sensor nodes are selected alternatively. Thus, if there are more neighbor nodes, it is more likely for a sensor node to stay in *sleep* state longer and thus, achieve more energy conservation. Other state transition conditions in AFECA are the same with those in BECA.

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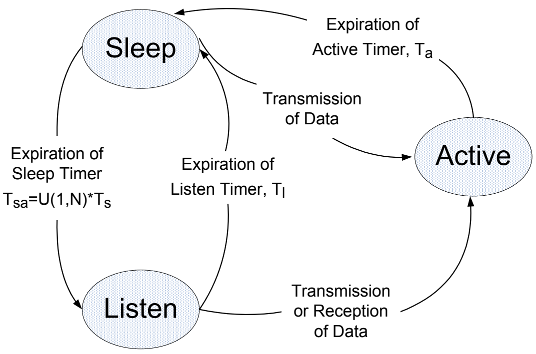

Fig. 2. *State transition model of AFECA.*

Although the performance of BECA and AFECA was analyzed in detail in [7], it was carried out via simulation approach, and thus, it is not feasible to reuse the analysis results and extend the results to analyze other duty cycling schemes and gain insight on general duty cycling schemes. In our previous work on BECA [8], we derived the steady state probability of sensor node states in BECA via mathematical analysis and analyzed the energy consumption in BECA in detail. Also, since state transitions are controlled by timer values and traffic characteristics, the effect of timer values and traffic characteristics on the steady state probability and energy consumption was analyzed thoroughly.

As an extension to our previous work in [8], we derive the steady state probability of sensor node states in AFECA via mathematical analysis and analyze the energy consumption in AFECA in detail for varying timer values. Then, we compare the performance of AFECA with BECA and show the performance improvement of AFECA over BECA. The effect of the number of neighbor nodes and timer values on energy consumption is analyzed, too.

The remainder of this paper is organized as follows: Section 2 develops analytical model of sensor nodes in AFECA for deriving steady state probability of sensor node states and obtains energy consumption. Numerical examples are presented in Section 3. Finally, Section 4 summarizes this work and presents further works.

II. Modeling and Analysis of AFECA State Transition Model

In this section, we develop an analytical methodology for deriving steady state probability of sensor node states in AFECA, based on that developed for BECA in our previous work [8].

A. Modeling of Sensor Node State Transition

Figure 3 shows a modified state transition model of AFECA, where *active* state in Fig. 2 is divided into four sub-states; *active-transmit*, *active-receive*, *active-forward*, and *active-idle* states, for ease of mathematical derivation, as was proposed in [8]. In *active-transmit*, *active-receive*, and *active-idle* states, a sensor node transmits locally generated sensing data to a sink node, relays sensing data from other sensor nodes to neighbor sensor nodes, and receives sensing data from neighbor sensor nodes, respectively [9]. In *active-idle* state, the sensor node does not receive or transmit any sensing data. For notational convenience, *Sleep*, *listen*, *active-transmit*, *active-receive*, *active-forward*, and *active-idle* states are denoted as states $1, 2, 3, 4, 5$, and 6, respectively.

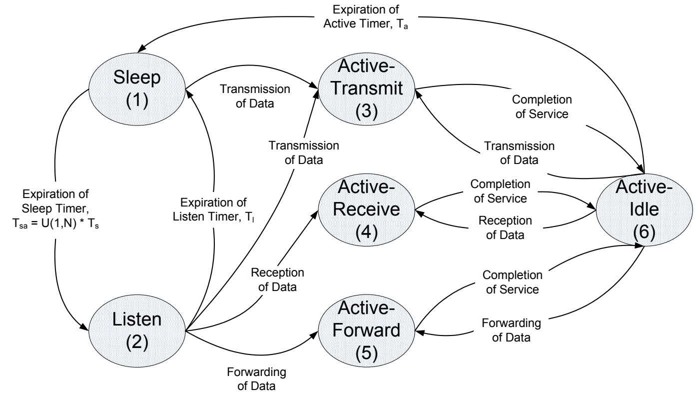

Fig. 3. *A modified state transition model of AFECA.*

B. Derivation of Steady State Probability and Energy Consumption

For analysis, we adopt the same assumptions from [8], regarding the density functions of random variables as follows:

- Transmitting, receiving, and forwarding data packets at a sensor node occur according to a Poisson process with parameters λ_t, λ_r, and λ_f, respectively;
- The time duration that a sensor node remains in *active-transmit*, *active-receive*, and *active-forward* states follows an exponential distribution with a mean value of $1/\mu_t$, $1/\mu_r$, and $1/\mu_f$;
- The values of *sleep timer*, *listen timer*, and *active timer* are assumed as constant and they are denoted by T_s, T_l, and T_a, respectively;
- $\lambda_f = w_f \lambda_t$, $\lambda_r = \lambda_f$, and $1/\mu_t = 1/\mu_r = 1/\mu_f$ are assumed, where w_f is the weighting factor for forwarding data traffic to local transmitting data traffic, and The activity of a sensor node is defined as $\rho = \frac{\lambda_t + \lambda_r + \lambda_f}{\mu_t} = \frac{(1+2w_f)\lambda_t}{\mu_t}$.

The steady state probability of each sensor node state can be obtained as [10]:

$$P_k = \frac{\pi_k \overline{t_k}}{\sum_{i=1}^{6} \pi_i \overline{t_i}}, \qquad k = 1, 2, 3, 4, 5, \text{and } 6, \tag{1}$$

where π_k denotes the stationary probability of state k and $\overline{t_k}$ is the mean residence time of the sensor node in state k. The stationary probability is obtained by solving the following balancing equations [10]:

$$\pi_j = \sum_{k=1}^{6} \pi_k P_{kj}, j = 1, 2, 3, 4, 5, \text{and } 6, \tag{2}$$

$$1 = \sum_{k=1}^{6} \pi_k, \tag{3}$$

where P_{kj} represents the state transition probability from state k to state j. Since the stationary probabilities of AFECA are the same with those of BECA, we reuse the derivation results from [8] and detailed derivation results are omitted here due to the limitation of space.

State transition probability P_{kj} can be derived based on the distribution of time from states k to j, T_{kj}. Since the state transition from *sleep* to *listen* state of AFECA is different from that of BECA, we newly derive the values of P_{12} and P_{13}. Exit from the *sleep* state is caused by any of the following events:

- *Sleep* timer expiration (T_{12});
- A transmitting data packet arrival (T_{13}).

Then, the state transition probabilities P_{12} and P_{13} are obtained as:

$$\begin{aligned} P_{12} &= \int_0^\infty f_{T_{12}}(t) Pr(T_{13} > t) dt \\ &= \int_0^\infty f_{T_{12}}(t) \int_t^\infty \lambda_t e^{-\lambda_t u} du dt \\ &= \int_{T_s}^{NT_s} \frac{1}{(N-1)T_s} e^{-\lambda_t t} dt \\ &= \frac{e^{-\lambda_t T_s} - e^{-\lambda_t N T_s}}{\lambda_t (N-1) T_s} \end{aligned} \tag{4}$$

$$P_{13} = 1 - P_{12}, \tag{5}$$

where the probability density function of T_{12} is defined as:

$$f_{T_{12}}(t) = \begin{cases} \frac{1}{(N-1)T_s} & \text{if } T_s \le t \le NT_s \\ 0 & \text{otherwise} \end{cases}$$

Since other state transitions are the same in both schemes, we reuse the results obtained in [8] for the other state transition probabilities.

Based on the derived state transition probabilities, the mean residence time of the sensor node in each state is calculated. Similar to the above derivation, we only derive the values of the mean residence time in *sleep* state and reuse the results obtained in [8] for the other mean residence time values. The mean residence time in the *sleep* state in AFECA is derived using the newly derived state transition probabilities P_{12} and P_{13} as follows:

$$\begin{aligned} \overline{t_1} &= \mathrm{E}[t_1] = \mathrm{E}[\min\{T_{12}, T_{13}\}] \\ &= \int_0^\infty \Pr(\min\{T_{12}, T_{13}\} > t) dt \\ &= \int_0^\infty \Pr(T_{12} > t) \Pr(T_{13} > t) dt \\ &= \int_0^{T_s} e^{-\lambda_t t} dt + \int_{T_s}^{NT_s} \frac{NT_s - t}{(N-1)T_s} e^{-\lambda_t t} dt \\ &= \frac{1 - e^{-\lambda_t T_s}}{\lambda_t} - \frac{NT_s (e^{-\lambda_t N T_s} - e^{-\lambda_t T_s})}{(N-1) T_s \lambda_t} \\ &- \frac{T_s e^{-\lambda_t T_s} - NT_s e^{-\lambda_t N T_s}}{\lambda_t} - \frac{e^{-\lambda_t T_s} - e^{-\lambda_t N T_s}}{{\lambda_t}^2}. \end{aligned} \tag{6}$$

Based on the values of π_k and $\overline{t_k}$, we can obtain the steady state probability of each sensor node state using Eq. (1) [10]. The energy consumption of a sensor node per unit time is obtained by using the steady state probability as follows:

$$E = \sum_{k=1}^{6} \psi_k P_k, \tag{7}$$

where ψ_k is the power consumption in state k.

III. Numerical Examples

For numerical examples, we use the same default parameter values assumed in [8], i.e., $T_s = \frac{10}{3600}h$, $T_l = \frac{10}{3600}h$, $T_a = \frac{10}{3600}h$, $\rho = 0.1$, $w_f = 10$, $\frac{1}{\mu_t} = \frac{10}{3600}h$, $\frac{1}{\mu_r} = \frac{10}{3600}h$, $\frac{1}{\mu_f} = \frac{10}{3600}h$, $\lambda_t = \frac{3600}{210}/h$, $\lambda_r = \frac{3600}{21}/h$, $\lambda_f = \frac{3600}{21}/h$, $\psi_1 = 0.025W$, $\psi_2 = 1.155W$, $\psi_3 = 1.6W$, $\psi_4 = 1.2W$, $\psi_5 = 1.6W$, and $\psi_6 = 1.5W$.

Figure 4 shows the effect of N for steady state probability of BECA and AFECA. We note that instead of showing the probabilities of four sub-states; *active-transmit*, *active-receive*, *active-forward*, and *active-idle* states, respectively, we show the probability of *active* state collectively, in order to simplify and strengthen the result. Since BECA is irrelevant to N, steady state probabilities of BECA does not change. On the other hand, the probability of *sleep* state of AFECA increases as the value of N increases, and the probabilities of other states decreases as the value of N decreases. As shown in Fig. 5, the energy consumption of AFECA is significantly less than that of BECA and the energy consumption of AFECA decreases as the value of N increases. However, the rate of decrease of energy consumption of AFECA decreases as N increases, since the probability of *sleep* state of AFECA saturates as the value of N increases. From Fig. 5, it can be shown that AFECA achieves significant improvement of energy conservation over BECA, even for a small values of N.

Figure 6 shows the effect of *sleep timer* on the steady state probability for $N = 5$. From the results, it is shown that the shape of steady state probabilities of AFECA is very similar to that of BECA presented in [8]. However, the probability

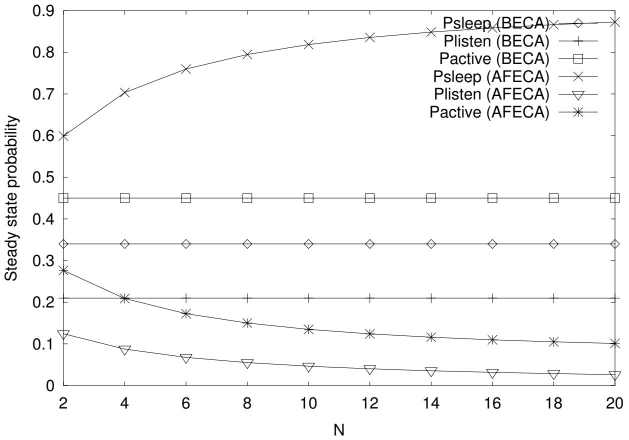

Fig. 4. *Steady state probability for varying N.*

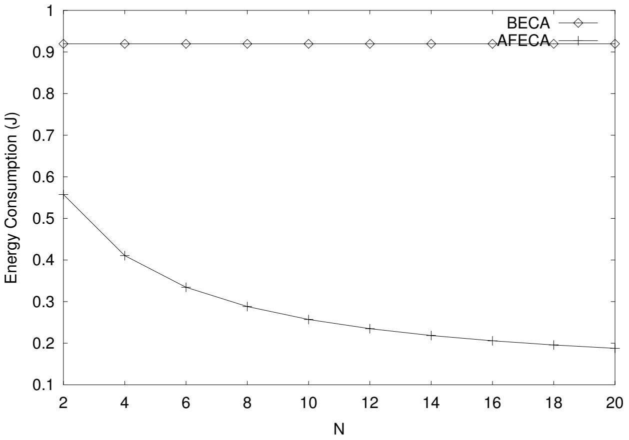

Fig. 5. *Energy consumption for varying N.*

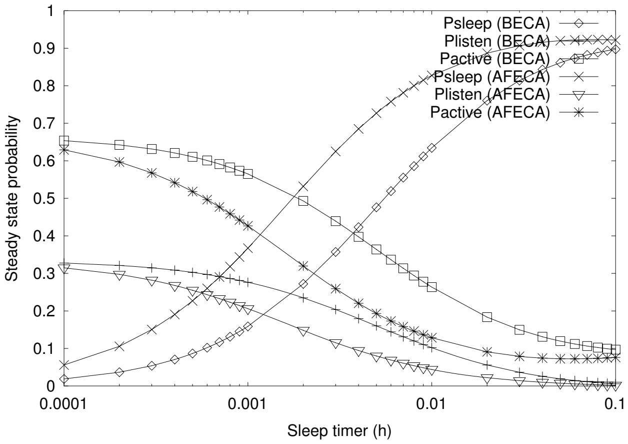

Fig. 6. *Steady state probability for varying sleep timer.*

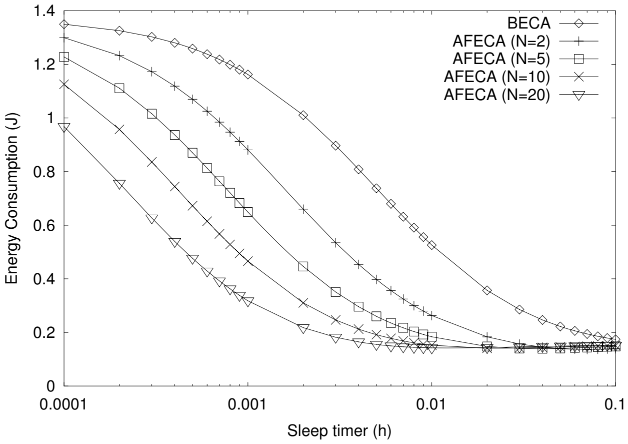

Fig. 7. *Energy consumption for varying sleep timer.*

of *sleep* state of AFECA is larger than that of BECA due to increased *sleep timer* value, and the probabilities of *listen* and *active* states of AFECA are less than those of BECA. Also, we note that the probabilities of the same state in both AFECA and BECA converge to the same value when the value of *sleep timer* is very large, since the effect of N is negligible for very large value of *sleep timer*. The energy consumption of AFECA is smaller than that of BECA because of the increased probability of *sleep* state and decreased probability of *listen* and *active* states, as shown in Fig. 7. Also, the energy consumptions of both schemes converge to the same value for very large values of *sleep timer*, where the effect of N is negligible. Similar to Fig. 5, it is shown that AFECA achieves significant improvement of energy conservation over BECA, even for a small values of N, when the value of *sleep timer* is not very large.

Figures 8 and 10 show the effect of *listen timer* and *active timer*, on the steady state probability, respectively, for $N = 5$. Figures 9 and 11 show the effect of *listen timer* and *active timer*, on the energy consumption, respectively, for varying the values of N. Similar to Fig. 6, the shape of steady state probabilities of AFECA is very similar to that of BECA in [8], as shown in Figs. 8 and 10, and the probabilities of *sleep* state in AFECA are larger than those in BECA. Therefore, the energy consumption of AFECA is smaller than that of BECA, as shown in Figs. 9 and 11. We note that the steady state probability of all the states of both schemes saturates for large values of *sleep timer* since there is few transition from *listen* to *sleep* state, and thus, energy consumption of both schemes also saturate. In Fig. 11, on the other hand, the energy consumptions of both schemes converge to the same value for very large values of *active timer*, where the effect of N is negligible since states remain in *active* state almost always. Similar to Figs. 5 and 7, it is shown that AFECA achieves significant improvement of energy conservation over BECA, even for a small values of N, when the values of *active timer* are not very large.

IV. Conclusions and Further Works

In this paper, we developed an analytical methodology of state transition model of AFECA based on analytical methodology developed for BECA in our previous work and derived both steady state probability of sensor node states and energy consumption. Then, the effects of N, *sleep timer*, *listen timer*, and *active timer* on the steady state probability and energy consumption have been analyzed and compared with those

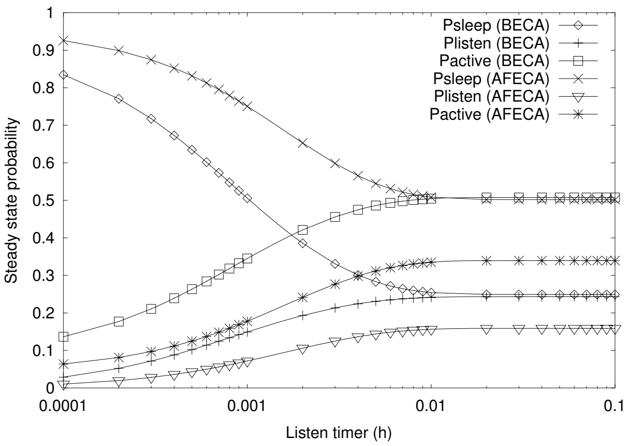

Fig. 8. *Steady state probability for varying listen timer.*

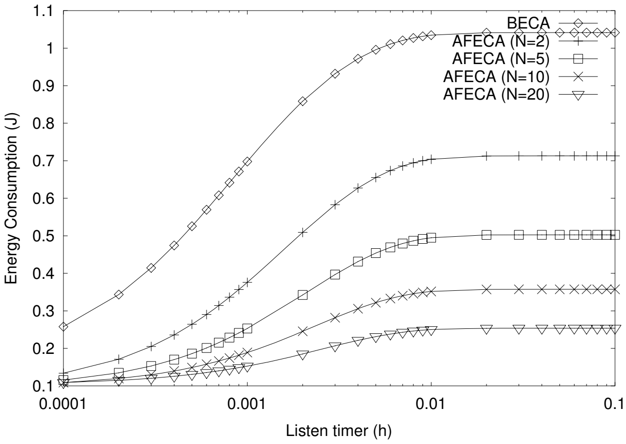

Fig. 9. *Energy consumption for varying listen timer.*

of BECA in detail. The results show that AFECA achieves significant improvement of energy conservation over BECA, even for a small values of N, when the values of *sleep timer* and *active timer* are not very large. The result of this paper can provide sensor network operators guideline for selecting appropriate timer values for AFECA.

We note, however, that the reduction of energy consumption in AFECA is possible, at the expense of increased packet delivery delay due to increased probability of *sleep* state. In our further works, the increased packet delivery delay in AFECA will be investigated analytically in detail, based on the estimation of the number of neighboring nodes and traffic characteristics. Also, an adaptive algorithm for selecting either BECA or AFECA, depending on the quality of service (QoS) requirement of requested packet delivery, will be proposed and analyzed as our further works, too.

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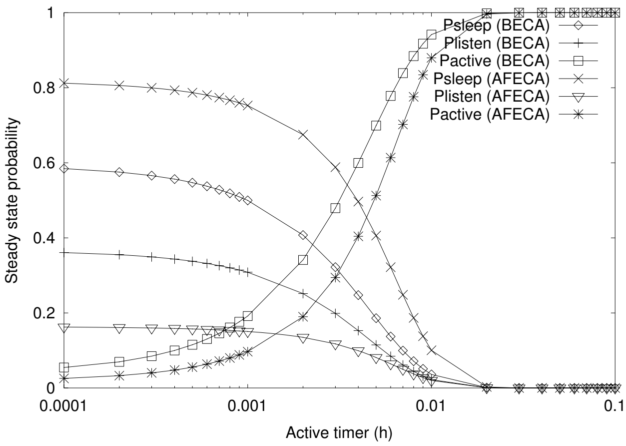

Fig. 10. *Steady state probability for varying active timer.*

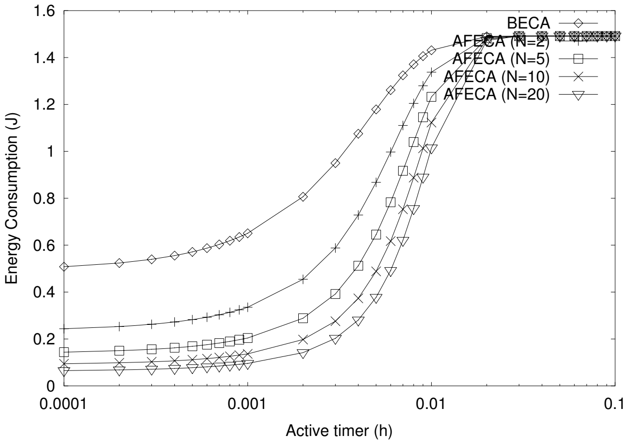

Fig. 11. *Energy consumption for varying active timer.*

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