Modeling and Understanding Burst Transmission Algorithms for Energy Efficient Ethernet

Jinli Meng, Fengyuan Ren, Wanchun Jiang, Chuang Lin
Tsinghua National Laboratory for Information Science and Technology
Department of Computer Science and Technology, Tsinghua University, Beijing, China 100084
Email: {mengjl08, renfy, jiangwc, chlin}@csnet1.cs.tsinghua.edu.cn

Abstract*—Recently, the energy consumption of Ethernet has become one of the hottest topics focused by both academic committee and industry, especially with the increase of the link speed from 1Gbps to 10Gbps nowadays or even 40/100/200Gbps in the near future. To save the energy consumed by the Ethernet, the Energy Efficient Ethernet (EEE) is developed and standardized by the IEEE 802.3az work group. When there is no incoming traffic, the EEE can saves 90% of its energy consumption by entering into the Low Power Idle (LPI) mode. To maximize the energy saving of Ethernet, the Burst TRansmission (BTR) algorithm, which defines a new way to utilize the LPI mode, is developed as a policy for EEE. Prior work theoretically shows that the BTR algorithm makes a tradeoff between the energy saving and the queuing delay. However, the traffic pattern, on which the performance of EEE greatly depends, is assumed to be deterministic in their analyses. Besides, their models made estimation for many situations. In this paper, assuming that the arrival time of packets can be modeled by Poisson process, we build Markov model for EEE with the BTR algorithm and provide analytical understanding on the BTR algorithm. We propose two actual models: one focuses on the buffer size limit, the other concentrates on tolerable packet delay additionally. We draw some guidelines of parameter selection and policy design for EEE from combination of theory conclusions and simulation results. The results show that the saved energy can be constrained by link occupancy even though the buffer size is variational. The other policy buffer full triggered wake-up can achieve ideal ratio of energy consumption and arrival rate within the scope of the buffer as well. However, the tolerable delay can not be guaranteed by any policies. The buffer size is even fixed, which affects the flexibility of demanded delay for different business. The policy considering tolerable delay is supposed to be a little better than the other policy, with a little more complicated design. Thus we design an adaptive policy: detect the load utilization, apply the buffer full triggered wake-up policy for higher load utilization link, while applying the buffer full and timeout triggered wake-up policy for the delay sensitive business and tiny arrival rate.

I. Introduction

Ethernet is widely deployed from 1980s. It is not only the main structure of Data Center Network (DCN), but also the most used access network in the world. The power consumption of Data Center is 2.3% of total power consumption in US [3]. With the growth of the Data Center scale, its power consumption doubles every five years [17]. Among these power consumption of IT infrastructure in Data Center, the network equipment consumes 20% approximately, which can not be ignored [6]. Moreover, the increase of the link speed leads to great power demand. For instance, the Network Interface Cards (NIC or interface) consumes 0.5W for 1Gbps link, while the number is 5W for 10Gbps [10]. The 10Gbps Ethernet is the main trend recently. The speed will reach 40/100/200Gbps in the near future [13]. No matter from the angle of environment sustainable development, or from the view of reducing the costs of power consumption, lowering the energy expenditure of the Ethernet devices is imperative.

The average load factors of the Ethernet is low in most time. The figure is 5% for the general computers, up to 30% for busy servers [2][16]. Therefore, reducing the power consumption of idle interface can save energy effectively. A norm called Energy Efficient Ethernet (EEE in short) absorbs such a mechanism of reducing power consumption in Ethernet routers, switches and hosts during periods of low link utilization. It is issued by the IEEE as a related industry standard, and officially approved just in September 2010. Nowadays, the manufacturers, such as HP, Broadcom and Asus, have their productions supporting the EEE standard. The Cisco 500 series stackable managed switches integrate a variety of power-saving features across all models, and EEE is absorbed as one of them soon [14].

EEE provides the mechanism of saving energy by powering off the unused elements of the interface when no transmission is required. Then the interface is in a low level of power consumption, which is called Low Power Idle (LPI) mode. Comparing with the normal transmission mode, the interface consumes only 10% energy of that in LPI mode. We name the normal work state as active in the article. The states of the interface can be active or LPI. From active to LPI, it takes some time to power off some elements while powering on them during the opposite transition. The sender end of the link decides to powered off or powered on and signals the other end of the link during the two transition periods. These two periods are called sleep and wake-up respectively. The standard also provides the protocol of coordinating the transitions between active and LPI.

However, EEE only supplies the mechanism of saving energy, but the algorithms of state transitions are not supplied in the final standard. Two algorithms of them are more practical and widely used [8][9][16]. The first one is **frame transmission** (**FTR**). Its main idea is to wake up the interface immediately once a new packet arrives in the LPI mode. In contrast, when a new packet arrives while the interface is in the LPI mode, it can be stored in the buffer until the buffer goes full. Then the interface is going to recover to the active state. The later algorithm is called **burst transmission** (**BTR**) or **packet**

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coalescing.

For the implementation of the BTR algorithm, various of policies are designed. When a new packet arrives while the interface is in the LPI mode, it can be stored in the buffer until the buffer contains enough packets. Then the interface is going to be waked up. The wake-up time depends on the buffer occupancy as well as the waiting time of the packets in the buffer. Thus the events of triggering wake-up operation include buffer occupancy and timeout of buffered packets. The first wake-up policy, which is called *buffer full triggered wake-up*, depends on the preset buffer size for the BTR algorithm. The second wake-up policy, which is called *buffer full and timeout triggered wake-up*, depends on both the preset buffer size and the minimum value of maximum delay of buffered packets. Different categories of the packets make different tolerable delays, which are also the maximum values for the specific category. The minimum one among all the maximum delays of the buffered packets can be set as the delay characteristics of the interface. This is the minimum value of maximum delay.

In this paper, we propose analytical models of the BTR algorithm and make comparison with FTR. FTR algorithm could be considered as a special case of BTR when buffer capacity for the LPI state is 0. Thus we only propose the general models and explain the performance analysis individually. The tradeoff between saved energy and performance degradation is discussed both for FTR and BTR. How to choose the practical parameters for advanced deployment of EEE is also advised in this paper. Based on the analysis of the models, we design policies of BTR algorithm for actual network environment.

The rest of the paper is organized as follows. In section II, we give more details and descriptions of the FTR and BTR algorithms, as well as introduce more motivations of our work. Besides, we refer to related works, compare them with our work in this section as well. Section III and section IV describe and solve the analytical models of the two algorithms, one model considers the buffer overflow, while the other considers packets' delay. Some practical conclusions are discussed according to the models. The models are compared in section V. We draw some guidelines of policy design for EEE from comprehensive of theory conclusions and simulation results. In the end, we conclude the analytical results, while address more details about the future work in section VI.

II. Background and Related Work

EEE for different speed links has different realization techniques [11][16]. Firstly, 100Mbps and 10Gbps links can be powered off in unidirectional links, while 1Gbps links should be powered off when both directions have no traffic. Secondly, transitions from the Active state to the LPI state cannot be interrupted in 10Gbps links, while immediate activation is caused by arriving packets when the interface is in sleep period for 100Mbps and 1Gbps links. Moreover, EEE for 10Gbps links becomes more and more widely used, the technology is more typical meanwhile. Therefore, we focus on EEE for 10Gbps links only.

As mentioned in section I, the interface of EEE has four operation states.

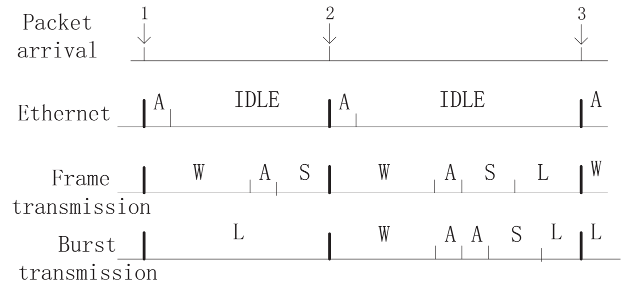


Fig. 1: An event line for Ethernet, frame transmission and burst transmission of EEE

- The state that the interface is transmitting packets is called **Active**, or **A** in short. In the Active state, when the buffer becomes empty and no other packet comes, the interface will take a **Sleep** (or **S** in short) operation.
- The Sleep process lasts for a period T_s. When a packet comes, the interface will continue to executive the Sleep operation; at the end of the Sleep operation, the interface will be waked up immediately. Or else, the interface will enter into the LPI state. The power consumption in the Sleep process is almost the same as that in the Active state.
- The state when the interface has been turned off is called **LPI**, or **L** in short. In the LPI state, the buffer is empty and no packet can be transmitting. Once a packet comes, the interface will start to be waked up. Besides, because the interface is turned off, the power consumption is 10% of that in the Active state.
- The **Wake-up** (or **W** in short) operation lasts for a period T_w; after the interface gets ready to transmit packets, the interface will turn into the Active state. In the Wake-up process, the power consumption is almost the same as that in the Active state.

EEE can save energy by keeping in the LPI state. Assume such a periodic traffic pattern: the first packet comes, the second packet arrives after $8.478\mu s$, then the third one arrives $11\mu s$ later, which is shown in Fig. 1. Obviously, the time length of each period is $19.478\mu s$. Without loss of generality, assume that all the packets are of length 1500 bytes. Accordingly, the time of transmitting a packet is $1.118\mu s$ for 10Gbps link.

In traditional Ethernet, the packet can be transmitted immediately when it arrives. Moreover, traditional Ethernet consumes the same power consistently no matter the link is Active or IDLE. The interval of the packets arrival is larger than the transmitting time, thus the state of Ethernet switches between Active and IDLE. In contrast, EEE can save energy in the way of entering into the LPI state when no packet is transmitting. During the second interval of packets arrivals, the proportion of the LPI state is 22.93% of the whole cycle, thus the energy consumption is 79.37% of that in Ethernet. Besides, the delay of the second packet is $4.48\mu s$. EEE saves huge energy with the tradeoff of tiny delay.

However, in the first interval of packet arrivals, the whole cycle of Wake-up, Active and Sleep takes $8.478\mu s$, leading to an immediate Wake-up operation when the second packet

TABLE I: An example comparing Ethernet, EEE and BTR

Transmission mechanism	Ethernet	EEE	BTR	Ideal
Link utilization (%)	11.48	11.48	11.48	11.48
Energy consumption (%)	100	88.35	54.34	20.33
Packet delay (μs)	0	4.48	12.96	

arrives. In the extra time T_w and T_s, the power consumes almost the same as that in the Active state. In the situation, EEE brings T_w delay for the second packet without any power saving. Therefore, we can come to a conclusion that EEE is worse than original Ethernet sometimes. For a long period in other packet arrival patterns, the frequent switching between the Active state and the LPI state can incur more delay and no power saving. To solve the problem, the burst transmission algorithm is proposed.

The BTR policy is based on EEE, adding an action of coalescing packets when the interface is in the LPI state. The policy uses the same buffer as the output buffer of the interface. The interface would not be waked up until the buffer reaches its threshold of buffer capacity, which is at least one packet length. The measurement of coalescing packets reduces the frequency of state transition. Take the example of Fig. 1, when the first packet arrives at the interface in the LPI state, it will be stored in the buffer. When the second packet arrives, the interface will be waked up. In the example, packet arrivals twice lead one cycle of Wake-up and Sleep. On contrast, one more Wake-up and Sleep action are taken in EEE. The LPI state accounts for 50.73% of the time scale in the whole cycle. The energy consumption is 54.34% of that in traditional Ethernet. Moreover, the delay is $12.958\mu s$ for the first packet in the buffer and $5.60\mu s$ for the later one. The delays are larger than EEE, but the energy consumption is lower than EEE. Thus BTR is a balance of delay and energy consumption comparing with EEE. If the increased delay is tolerable, it is a reasonable choice to select the BTR policy.

The results of the example list in table I. The link utilization is the fraction of the Active state in one circle. We set the energy consumption as the proportion of that Ethernet consumed. In other words, we assume the energy that Ethernet consumes is 1, then the numbers listed in the table are their respective energy consumption dealing with the same network flow. Coalescing makes different packets have different delays, among which we select the maximum one as the policy decided delay. For ideal situation, assume the buffer is infinite, the frequency of state transition is rare. In the other words, the interface transmits all the packets continuously, then it stays in the LPI state. The T_w and T_s can be ignored for they are tiny comparing with the sampling time. In this way, we get a theoretical limitation of energy consumption, which is also the minimum and ideal energy consumption for such a packet arriving pattern.

Performance analysis for EEE and even the burst transmission policy has been studied by many researchers. Reviriego et al. [10] firstly evaluated EEE performance with actual measurements of EEE Network Interface Cards which are manufactured by a major Ethernet vendor. Their work also showed the fundamental role of traffic patterns. However, the oversimplified simulation is just rough estimates for 1Gbps link and lower speed links. Marsan et al. [11] proposed a four-state Markov model to evaluate EEE, accurately predicted the proportion of each state in a cycle. Nevertheless, the BTR policy is not considered. In [9], Christensen et al. studied the burst transmission algorithm, the tradeoff between energy and delay was presented according to the simulation results. Herrería-Alonso et al. [16] presented analytical models for the FTR and BTR algorithms, then derived guidelines for parameter tuning of burst transmission. They said their work is the first work to derive guidelines for burst transmission. However, their work did not model the practical network behaviors, because they estimated the parameter tuning by plenty of average values. Thus we propose a new model of queue and Markov chain theory in order to get practical theoretical estimates which are more close to the actual situations. Moreover, the tradeoff decision of the energy consumption and packet delay is discussed in the paper, both considering the buffer full triggered wake-up and timeout triggered wake-up policies. We analyse parameters including the type of business, link occupation ratio, the tolerable delay, and buffer size. All of them play the decisive roles in the implementation process. The results of performance analysis give sound guidelines for parameter settings and policy design. In the following sections, we will describe and analysis the models for both FTR and BTR.

III. Burst Transmission Model Considering Buffer Full Triggered Wake-up

In BTR algorithm, arriving packets are put into the buffer if the interface has been powered off or is turning off. With the growth of the queue, the waiting time of the first arrived packets increases, the rest of the buffer space is less and less. On the other hand, the more coalesced packets lead the less frequent transitions between the Active and LPI state. The low frequent transitions can reduce the overhead time and unnecessary energy consumption. Above all, it is necessary to choose a proper opportunity to take Wake-up and Sleep operations in order to increase the duration of the LPI state and reduce the frequency of state transitions.

However, the simplest choice of the opportunity to take the Sleep operation is the moment when the interface becomes idle. Ignoring the short idle period and taking Sleep operation only for long idle periods can reduce the frequency of state transition. Due to the complicated traffic arrival mode, the waiting duration is unpredictable. Thus the power saving time for Sleep operation need a prediction mechanism, which is future work. Furthermore, one event to trigger the Wake-up operation is that the number of buffered packets reaches its upper limit or some packet in the buffer reaches its delay limit.

In this section, we propose the Markov model, list the mathematical descriptions, give analytical solutions and numerical analysis considering the buffer full triggered wake-up event. In the models, the effects of the measures, including packet delay, packet loss rate, burst and the amount of energy saving, are discussed. A more complicated model considering buffer size and packet delay is discussed in next section.

A. Symbols and Assumption

Without loss of generality, assume all the packets' size as 1500 bytes below, which is an integer near the Maximum Transfer Unit 1518 bytes. Although packets of different business arrive at the interface can be assumed as a mixed Poisson way. For the sake of simplicity, assume the data stream can last for a while for a specific category of business, the parameters of the models are different for different categories of business, including the arrival rate assumption of λ, while the interface transmits packets in a Poisson way with serving rate μ. In the article, $\mu = 10Gb/s$. Thus the interface can be modeled as M/M/1 queuing model. If $\lambda > \mu$ for a while, the system is unstable, the buffer is prone to overflow. Hence, we just discuss the situation $\lambda \leq \mu$ in statistical significance.

Assume the buffer size for output packet is $(n-1) * ps$ bytes. Here the average packet is $ps = 1500$. In the article, we use $n-1$ instead of $(n-1) * ps$ for buffer size.

The BTR algorithm shares the same buffer supplying for the interface. We set the buffer size as $(m-1) * ps$ or $m-1$ simply, m satisfies $m \leq n$. The assumption is reasonable for it remains some buffer space for upcoming packets during the Wake-up period T_w. On the other hand, the bigger the number m is, the longer the earlier packets wait in the buffer, which prolongs the waiting time and it is easy to over the delay time. Here m is tuned as one parameter according to different packet arrival situations and different delay requirements. Specially, $m = 1$ represents the FTR algorithm, which causes Wake-up operation immediately once a new packet arrives.

Assume A_i represents the interface stays in the Active state and i packets are waiting in the buffer. L_i represents the interface stays in the LPI state and i packets are waiting in the buffer. In the Markov model, it is important to analyze the stationary probability distribution of each states, which is one of the most important evaluation indicator. Thus we let the probability P with the state characters as subscript stands for the probability of each state: P_{A_i} stands for the stationary probability of A_i, P_S stands for the stationary probability of S, P_{L_i} stands for the stationary probability of L_i, and P_{W_i} stands for the stationary probability of W_i.

In fact, T_w is so small comparing with such a packet length 1500 bytes that packet arrives in T_w is practically impossible in 1Gbps, 100Mbps and 10Mbps. For 10Gbps link, the serving rate is $1342B/\mu s$. If the load is high, EEE is hardly deployed. Therefore, the opportunity of applying the EEE is in low load. As mentioned in section I, a normal link utilization is from 5% to 30%. We estimate as 10%, which means the average arriving rate is $134B/\mu s$. Thus the average number of arriving packet is 1. We ignore the small probability of arriving packets during the Wake-up operation. It means the transition is from L_i to A_k through W, and the only value of k is i. The expenditure of Sleep time T_s is also around T_w, which means no packet arriving in the transition from A_0 to L_0 through S. The same estimate can applies in section IV. This assumption hardly influences the analytical precision.

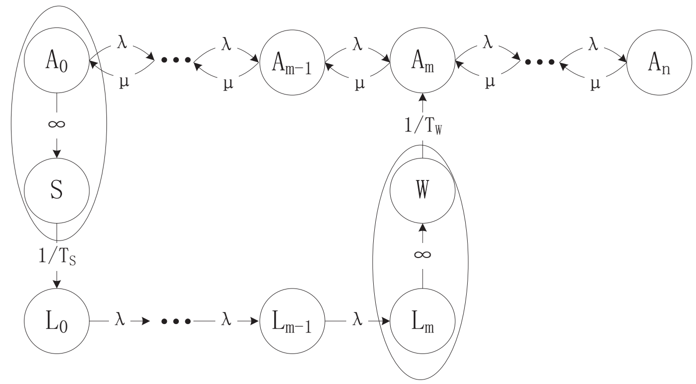


Fig. 2: Burst Transmission of EEE considering Buffer Full Triggered Wake-up

B. Modeling

$$\left(\lambda + \frac{1}{T_s}\right) P_{A_0} = \mu P_{A_1} \text{ for } A_0 \tag{1}$$

$$\frac{1}{T_s} P_{A_0} = \lambda P_{L_0} \text{ for } L_0 \tag{5}$$

$$\lambda P_{L_{m-1}} = \frac{1}{T_w} P_{L_m} \text{ for } L_m \tag{7}$$

$$\sum_{i=0}^{n} P_{A_i} + \sum_{i=0}^{m} P_{L_i} = 1 \tag{8}$$

In Fig. 2, we depict the Markov model for the BTR algorithm considering buffer full triggered wake-up. Until the waiting queue is empty, the interface will not be turned off and transferred into the LPI state. A_0 is a transient state, with a ∞ transition rate to the intermediate state S. It also means A_0 is the other symbol of state S, or implies that the probability of A_0 equals with S. The transition from S to L_0 takes some time which is the sleep time T_s, thus the transition rate is $1/T_s$. The only transition event is packet arrival along the chain of L_i which cannot backtrack. The only transition from L to other state happens in L_m when the m'th packet arrives. L_m is also a transient state, from which the only transition arc is to W with a rate ∞. It also means L_m is the other symbol of state W, or implies that the probability of L_m equals with W. The transition from W to A_m takes some time which is the Wake-up time T_w, thus the transition rate can be $1/T_w$. Considering all kinds of situations, there are several details about the relationship between the state transitions and the interface actions.

- Packets arrive back to back, the interface stays in the Active state, the buffer contains k packets.
  - $k < n$, a new packet arrives, then the state transfers from A_k to A_{k+1} with a state transition rate λ.
  - $k = n$, a new packet arrives, then the new packet will be abandoned, and the interface stays in A_n.
  - $k > 0$, a packet is transmitted, then the state transfers from A_k to A_{k-1} with a state transition rate μ. Especially when $k = 1$, after the packet has been

$$\begin{bmatrix} \lambda & -(\lambda+\mu) & \mu & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & \lambda & -(\lambda+\mu) & \mu & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda & -(\lambda+\mu) & \mu & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & \lambda & -(\lambda+\mu) & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \lambda & -(\lambda+\mu) & \mu \end{bmatrix} \begin{bmatrix} P_{A_0} \\ P_{A_1} \\ P_{A_2} \\ \vdots \\ P_{A_{m-1}} \\ P_{A_m} \end{bmatrix} = 0 \tag{2}$$

$$(\lambda+\mu) P_{A_m} = \lambda P_{A_{m-1}} + \mu P_{A_{m+1}} + \frac{1}{T_w} P_{L_m} \text{ for } A_m \tag{3}$$

$$\begin{bmatrix} \lambda & -(\lambda+\mu) & \mu & 0 & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & \lambda & -(\lambda+\mu) & \mu & 0 & \cdots & 0 & 0 & 0 & 0 \\ 0 & 0 & \lambda & -(\lambda+\mu) & \mu & \cdots & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & \lambda & -(\lambda+\mu) & \mu \\ 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & \lambda & -\mu \end{bmatrix} \begin{bmatrix} P_{A_m} \\ P_{A_{m+1}} \\ P_{A_{m+2}} \\ \vdots \\ P_{A_{n-1}} \\ P_{A_n} \end{bmatrix} = 0 \tag{4}$$

$$\lambda P_{L_0} = \lambda P_{L_1} = \lambda P_{L_2} = \cdots = \lambda P_{L_{m-2}} = \lambda P_{L_{m-1}} \text{for } L_1, L_2, \cdots, L_{m-1} \tag{6}$$

transmitted, the state transfers to transient state A_0, and then S immediately. The state transition rate from A_0 to S is ∞.

- The interface stays in the LPI state, the buffer contains k packets. a new packet arrives.
  - $k < m$, the new packet will be stored in the buffer, the model state transfers from L_k to L_{k+1} with a state transition rate λ.
  - $k = m$, the new packet will be stored in the buffer temporarily, the state transfers from transient state L_m to W immediately. Meanwhile, the interface begin to be woken up.
- The state S transfers to L_0 with a state transition rate $1/T_s$ consequentially.
- The state W transfers to A_m with a state transition rate $1/T_w$ consequentially.

We list the mathematical equations of Markov chain to determine the stationary probability of every state. The equations from 1 to 7 correspond to the transition details. Besides, the sum of probability for all states is 1, which is shown in equation 8. Solve the equations 1 to 8, let $g(m)$ satisfies 9, we get the stationary probability of every states in equations 10.

$$g(m) = \frac{\mu}{\mu-\lambda} + \frac{T_w}{T_s} + \frac{m\mu}{\lambda(\mu-\lambda)T_s} - \frac{\lambda}{(\mu-\lambda)^2 T_s}\left(\frac{\lambda}{\mu}\right)^{n-m} + \frac{\lambda[1-(\mu-\lambda)T_S]}{(\mu-\lambda)^2 T_S}\left(\frac{\lambda}{\mu}\right)^{n} \tag{9}$$

$$\begin{cases} P_{A_0} = \frac{1}{g(m)} \\ P_{A_k} = \frac{\left[1-\frac{1}{(\mu-\lambda)T_s}\right]\left(\frac{\lambda}{\mu}\right)^k + \frac{1}{(\mu-\lambda)T_s}}{g(m)}, \\ k = 1, 2, \cdots, m \\ P_{A_k} = \frac{\left[1-\frac{1}{(\mu-\lambda)T_s}\right]\left(\frac{\lambda}{\mu}\right)^k + \frac{1}{(\mu-\lambda)T_s}\left(\frac{\lambda}{\mu}\right)^{k-m}}{g(m)}, \\ k = m, m+1, \cdots, n \\ P_{L_0} = \cdots = P_{L_{m-1}} = \frac{1}{\lambda T_s g(m)} \\ P_{L_m} = \frac{T_w}{T_s g(m)} \end{cases} \tag{10}$$

The first useful result is the sum of probability of all $L_i, i = 0, 1, \cdots, m-1$ in equation 11. $\sum_{i=0}^{m-1} P_{L_i}$ is the proportion of the LPI state in a statistic cycle. Obviously, the duration of the LPI state reflects the saved energy. $\lambda, \mu, T_w, T_s, m, n$ are the impact factors in the equation.

$$\sum_{i=0}^{m-1} P_{L_i} = \frac{m}{\lambda T_s g(m)} \tag{11}$$

The second useful result is the packet delay affected by the BTR algorithm in equation 12. For packet coalescing can increase m packets' delay, we select the maximum delay as the BTR caused delay. As $\lambda \leq \mu$, the maximum waiting time belongs to the first packets in the queue. Assume all the packets carry out the same business, their delay limits are equals, thus the maximum delay t_d is the delay of the first arrived packet in the first-in-first-out buffer. λ, T_w, ps, m are the impact factors in the equation. Specially attention, t_d is linear with m .

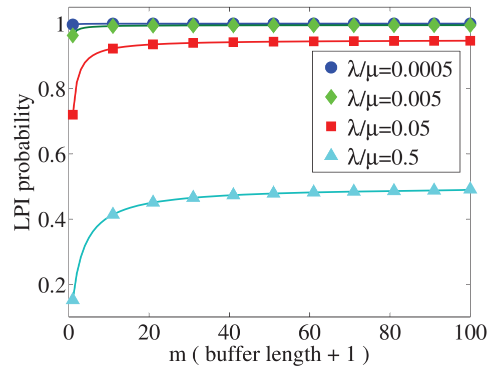
$$\begin{aligned} t_d &= \max\{\tfrac{(m-1)ps}{\lambda}+T_w, \tfrac{(m-2)ps}{\lambda}+T_w+\tfrac{ps}{\mu}, \\ &\quad \tfrac{(m-3)ps}{\lambda}+T_w+\tfrac{2ps}{\mu}, \cdots, T_w+\tfrac{(m-1)ps}{\mu}\} \\ &= \max\{\tfrac{(m-1)ps}{\lambda}+T_w, \tfrac{(m-1)ps}{\lambda}+T_w+\tfrac{ps(\lambda-\mu)}{\lambda\mu}, \\ &\quad \tfrac{(m-1)ps}{\lambda}+T_w+\tfrac{2ps(\lambda-\mu)}{\lambda\mu}, \\ &\quad \cdots, \tfrac{(m-1)ps}{\lambda}+T_w+\tfrac{(m-1)ps(\lambda-\mu)}{\lambda\mu}\} \\ &= \tfrac{(m-1)ps}{\lambda}+T_w \end{aligned} \tag{12}$$

C. Performance Analysis

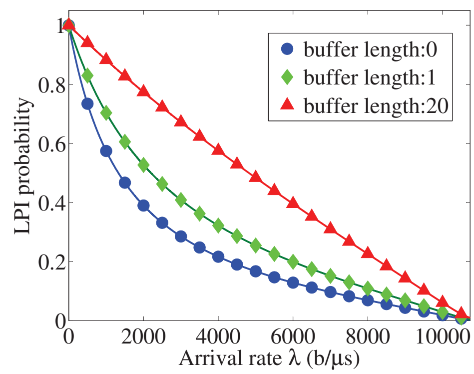
In order to validate the model and demonstrate effective guidelines, we simulate the model in MATLAB 7.11.0. The uncertain elements of the model include the kind of link which affects sleep time T_s, wake-up time T_w, transmission rate μ, packet arrival rate λ, the buffer size n for each interface. For 10GBASE-T, $\mu = 10485.76b/\mu s$ $T_s = 2.88\mu s$ and $T_w = 4.48\mu s$. SG500X-48 is a major product in Cisco 500, whose reference parameters are taken by our numerical simulation. SG500X-48 offers 48 Gigibit Ethernet Ports and 4 10Gigibit Ethernet ports, while containing an aggregated packet buffer of 12Mb*2 across all ports. Then the average buffer size is 1.36Mb per 10Gb port. It means it can contain about 119 packets of 1500 bytes at the most. Without affecting the simulation results, we set all of the buffer size $n-1$ as 99, which also increases the aesthetic feelings and consistency in our result figures 3, 4 and 5. The considerate options of buffer length $m-1$ is $0, 1, 20$. The first one 0 represents the FTR algorithm, while 1 is the first step from FTR to BTR. After repeated tests, the curves of the LPI probability vs. arrival rate λ are almost coincidence when the buffer length is no less than 20, thus 20 is the minimum value of maximum LPI probability of the buffer size.

All the representations related with $m = 1$, no matter the curves or point in these figures, are the simulation results for the FTR algorithm. Obviously, the improvement of the LPI probability is tremendous from FTR to BTR with buffer capacity increase of one packet according to Fig. 3(b). The price of significant increase of energy saving efficient is negligible increase of delay according to Fig. 4(b).

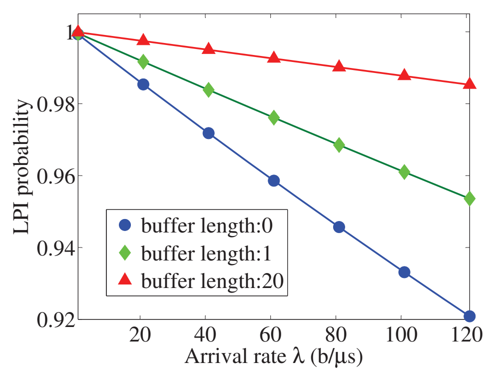
The figures in 3 show the variation trend of the probability of the LPI state. The configurable parameters include buffer size $m-1$ for the BTR algorithm and arrival rate λ. In order to evaluate the influence of m in kinds of load intensity, we set $\lambda = 0.0005\mu$, $\lambda = 0.005\mu$, $\lambda = 0.05\mu$ and $\lambda = 0.5\mu$ for comparison in figure 3(a). That means the arrival rate is $5Mbps$, $50Mbps$, $500Mbps$ and $5Gbps$ separately. From Fig. 3(b) to 3(d), the influence of λ is illustrated. The sub-figure 3(b) illustrates that no matter how long the buffer size is, $1(m = 2)$ or $20(m = 21)$, the value of the curve is down quickly to 0.5 in the first $\frac{1}{5}\mu$. The sub-figure 3(c) and 3(d) detail the first figure. The second sub-figure details the view from $\lambda = 1$ to $\lambda = 121$, which shows the LPI probability is more than 0.9. The last figure shows the detail from $\lambda = 524$ to $\lambda = 3146$, which stands for the Ethernet load from 5% to 30%. The curve of $\lambda = 0.05\mu$ and $\lambda = 0.5\mu$ in the first sub-figure is more instructive and meaningful, as well as the



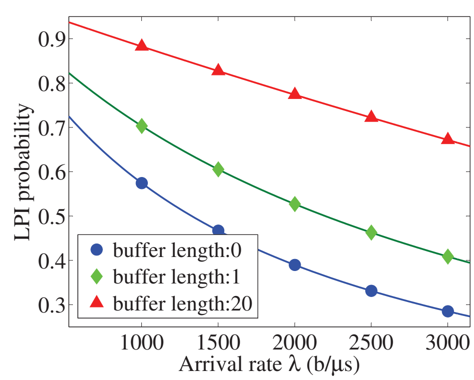
(a) The LPI probability vs. m



(b) The LPI probability vs. λ, $\lambda = 1 \sim \mu$

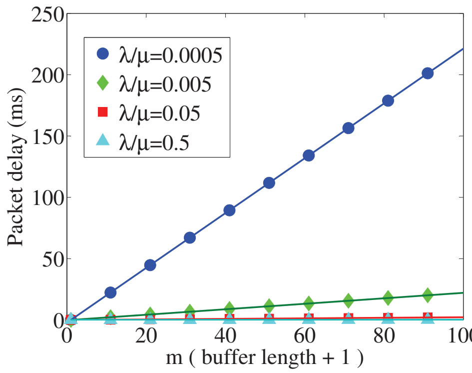


(c) The LPI probability vs. λ, $\lambda = 1 \sim 121$

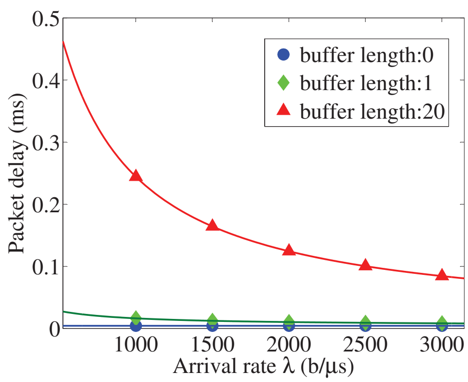


(d) The LPI probability vs. λ, $\lambda = 524 \sim 3146$

Fig. 3: Buffer full triggered wake-up for BTR: the parameters affection in the LPI probability in 10GBASE-T



(a) Delay vs. m



(b) Delay vs. λ

Fig. 4: Buffer full triggered wake-up for BTR: the parameters affection in packet delay in 10GBASE-T

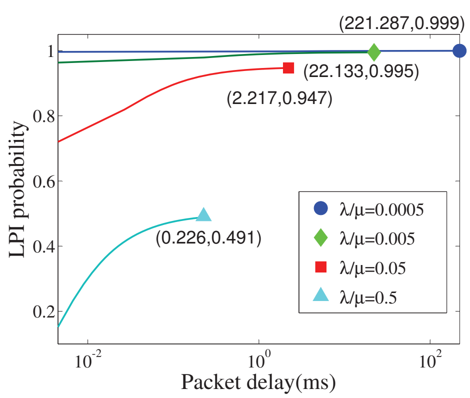


Fig. 5: Buffer full triggered wake-up for BTR: the LPI probability vs. delay in 10GBASE-T

forth sub-figure detailing the situation of the general Ethernet load.

The LPI probability increases along with m. The slope of the curve is high when m is small, while the trend is flatter and flatter with increase of m. We can safely infer that there is a limitation of steady-state probability distribution for a certain λ. The premise of such inference is that buffer size can be infinite or with a large upper limit. It means larger buffer capacity leads to less state transition with less overhead. If m is big enough, the LPI probability is close to the ideal value $1 - \lambda/\mu$.

Small arrival rate λ allows the LPI probability higher with a rapid decent speed. The probability and the arrival rate is almost the inverse relation in mid-load. The LPI state rarely appears in heavy load. It is easy to understand that the Active period can be longer in bigger arrival rate. With heavier arrival rate, the idle time is shorter, leading to unobvious energy saving effect. Comparing with the heavy load, the speed of the LPI probability is shrinking faster as the load increases in light load. Because the packet arrives in the form of clusters in heavy load, leading to low frequency of state transitions, the margin is not improved very much adopting the BTR algorithm.

According to the analysis results, when the load is less than 30%, the LPI probability is larger than 0.4 even buffer length is 1. It means the energy saving amount is larger than 36%. It is a huge fraction considering the global Ethernet energy consumption, thus the effect is very impressive.

Specially, the variation trend of delay and the LPI probability with the changes of independent variable m are shown in 5. The tail number of each curve is the delay and probability when m increases to 101. Obviously, the growth rate of the delay is higher than that of the probability.

IV. Burst Transmission Model Considering Buffer Full and Packets' Timeout Triggered Wake-up

In fact, packet delay is one of the main performance indicators in packet transmission, especially for Data Center Network. In actual network, different business has different time-sensitive demand, waiting in the queue increases the packets' delay. On the other side, we set buffer size $m-1$ for the policy in Fig. 2 without considering delay. If the buffer is high capacity, the first-in packets may be timeout. Based on model in Fig. 2, a new policy is designed. Packets' timeout is the other event to trigger Wake-up operation in the new policy. It gives each packet a threshold of delay. As time goes on, the event that some packet in the buffer reaches its threshold will trigger the Wake-up operation.

A. Modeling

Four reasons cause the timeout timing unpredictable: (1). the packets' waiting time is variational for the stochastic arriving; (2). the packets' tolerable waiting time is different for different business; (3). the leftover tolerable waiting time for the interface is unpredictable in a routing; (4). the route from source to destination is chosen freely for different packets of the same business. Therefore, in the range of allowable buffer size, tolerable waiting time may be exceeded in any buffer occupancy, which causes state transition. Moreover, when the interface is in the LPI state, the packets' arriving rate is stochastic, thus the buffer occupancy is uncertain in certain time. Videlicet, it means transition from L_i to W_i is possible in any of $i = 1, 2, \cdots, m$. The distinguish for different i is the transition rate. Larger buffer occupancy makes the packets' waiting time longer, then the Wake-up probability is larger, the transition rate is bigger as well. The tolerable waiting time is fixed at τ for all the packets of the long last business. tau is

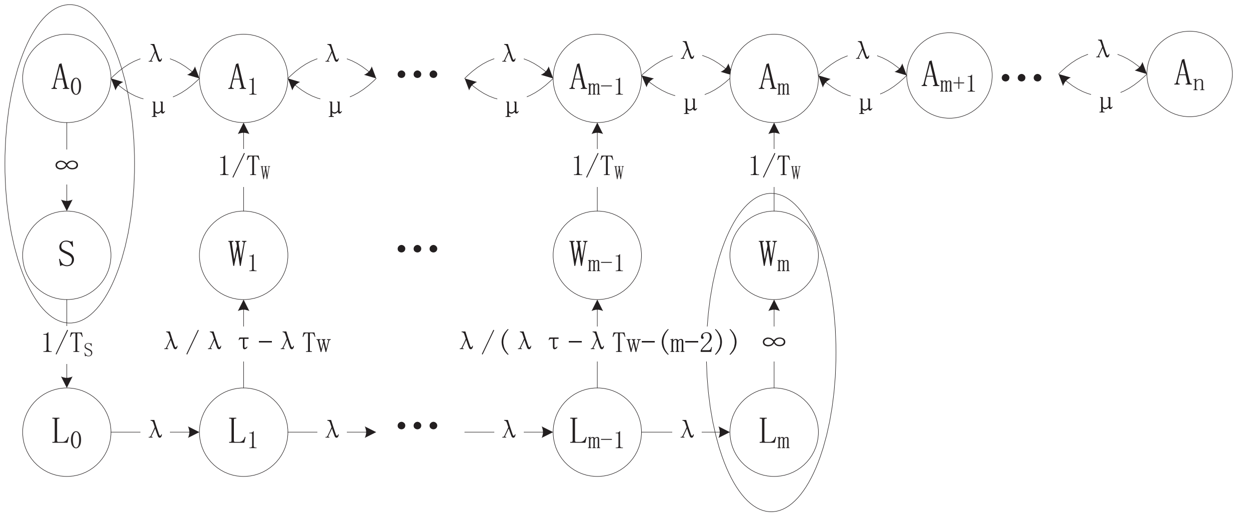


Fig. 6: Burst transmission algorithm considering buffer full and timeout triggered wake-up

only the tolerable waiting time in the interface, including the Wake-up time T_w when calculating the delay from the LPI state. The transition rate from L_i to $W_i, i = 1, 2, \cdots, m-1$ is related with specific τ and packet arrival rate λ. It can be estimated as $\frac{\lambda}{\tau*\lambda-\lambda*T_w-i+1}$ according to theorem 4.1. The last transition from L_m to W_m is unavoidable with transition rate ∞. Here, buffer size $m-1$ is decided by τ and λ as well. It satisfies $m = \min\{m_max, \lceil \lambda\tau - \lambda T_w + 1 \rceil\}$. In the right side of the equation, the first item m_max is human-determined for some other reasons except the BTR algorithm. The second item is used to make the transition rate from L to W positive, in another word, limit the delay in τ. From $W_i, i = 1, 2, \cdots, m$ to $A_i, i = 1, 2, \cdots, m$, the average transition time is the Wake-up time T_w, resulting in the transition rate $1/T_w$.

Theorem 4.1 (Timeout triggered state transition rate): In the Markov model for burst transmission algorithm of EEE considering buffer full and timeout triggered wake-up, the state transition rate from L_i to W_i is $\frac{\lambda}{\tau*\lambda-\lambda*T_w-i+1}$.

Proof: For the tolerable waiting time is τ, assume the average transition time from L_i to W_i is τ_i, then $\tau = (i-1)/\lambda + \tau_i + T_w$, so $\tau_i = \tau - T_w - (i-1)/\lambda$, thus the transition rate from L_i to W_i is $\frac{1}{\tau-T_w-\frac{i-1}{\lambda}}$, which also equals to $\frac{\lambda}{\tau*\lambda-\lambda*T_w-i+1}$. ■

The model is depicted in Fig. 6. Because τ is equivalent for every packets of the same business, a timer is necessary for the first arrival packet in the LPI state. It records the maximum waiting time of packets in the buffer. When the interface is in the LPI state, the only event to trigger the Wake-up operation is the packet arrival. For this reason, once a packet arrives, the timer is checked; if it is over τ, the interface should be waked up. However, if the buffer occupancy is not less than m/n when a new packet arrives, the Wake-up operation is taken absolutely. Considering all kinds of situations, there are several details about the relationship between the state transitions and the interface actions, we will not list them here due to the lack of space.

$$\begin{cases} P_{A_0}\left(\lambda + \frac{1}{T_s}\right) = P_{A_1}\mu \text{ for } A_0 \\ P_{L_0}\lambda = P_{A_0}\frac{1}{T_s} \text{ for } A_0 \\ P_{A_n}\mu = P_{A_{n-1}}\lambda \text{ for } A_n \\ P_{L_m}\frac{1}{T_w} = l_{m-1}\lambda \text{ for } L_m \\ P_{W_m} = P_{L_m} \\ P_{A_k}(\lambda+\mu) = P_{A_{k-1}}\lambda + P_{A_{k+1}}\mu + P_{W_k}\frac{1}{T_w}, \\ k = 1, 2, \cdots, m \\ P_{A_k}(\lambda+\mu) = P_{A_{k-1}}\lambda + P_{A_{k+1}}\mu, \\ k = m+1, m+2, \cdots, n-1 \\ P_{W_k}\frac{1}{T_w} = P_{L_k}\frac{\lambda}{\lambda\tau-\lambda T_w-(k-1)}, \ k = 1, 2, \cdots, m-1 \\ P_{L_k}\left(\frac{\lambda}{\lambda\tau-\lambda T_w-(k-1)} + \lambda\right) = P_{L_{k-1}}\lambda, \ k = 1, 2, \cdots, m-1 \end{cases} \tag{13}$$

For the model, we list the state transition equations in equation 13. Besides, $\sum_{i=0}^{n} P_{A_i} + \sum_{i=0}^{m} P_{L_i} + \sum_{i=1}^{m-1} P_{W_i} = 1$. We need to maximum the value of $\sum_{i=0}^{m-1} P_{L_i}$ while the parameters selection traverses the value space.

Solve the equations, we get the first useful results $\sum_{k=0}^{m-1} P_{L_k}$ in equation 14 which reflects how long the LPI state lasts in a statistic cycle. The second useful result is the packet delay affected by the packet coalescing policy shown in equation 15 according to the theorem 4.2. Although the energy could be saved by sacrificing a significant performance cost, the only thing we could do is to balance the tradeoff between saved energy and reduced performance. Because $\lambda \le \mu$, the maximum delay t_d is the delay of the first arrived packet in the first-in-first-out buffer.

$$\begin{aligned} t_d \quad = \quad & -\frac{1}{\lambda(\lambda\tau-\lambda T_w+1)}m^2 + \left(\frac{2}{\lambda} + \frac{1}{\lambda(\lambda\tau-\lambda T_w+1)}\right)m \\ & +T_w - \frac{2}{\lambda} \end{aligned} \tag{15}$$

Theorem 4.2 (The average delay): When the interface is in the LPI state, the average waiting time of the first packet in the

$$\sum_{k=0}^{m-1} P_{L_k} = \frac{-m^2 + (2\lambda\tau + 1)\, m}{\left(\frac{\lambda}{\mu}\right)^n \frac{2\lambda^2\mu}{(\mu-\lambda)^3} - \left(\frac{\lambda}{\mu}\right)^{n-m} \frac{2\lambda^2\mu}{(\mu-\lambda)^3} + \left(\frac{\lambda}{\mu}\right)^{n-m} \frac{2\lambda^2}{(\mu-\lambda)^2} m - \frac{1}{\mu-\lambda} m^2 + \frac{\mu}{\mu-\lambda} m + 2\lambda^2\tau T_s g(m)} \tag{14}$$

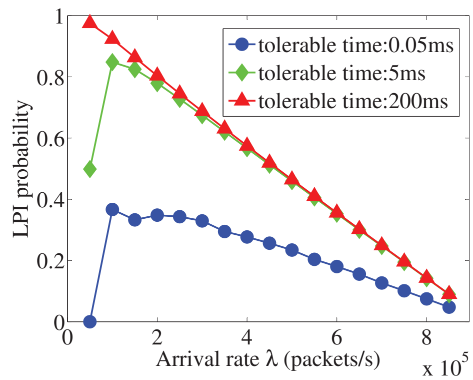


Fig. 7: Buffer full and timeout triggered wake-up model for BTR: the LPI probability vs. λ

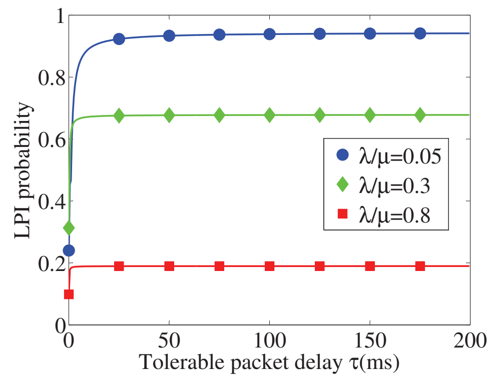


Fig. 8: Buffer full and timeout triggered wake-up model for BTR: the LPI probability vs. tolerable waiting time

buffer is $t_d = -\frac{1}{\lambda(\lambda\tau - \lambda T_w + 1)} m^2 + \left(\frac{2}{\lambda} + \frac{1}{\lambda(\lambda\tau-\lambda T_w+1)}\right) m + T_w - \frac{2}{\lambda}$.

Proof: In state $L_i, i = 1, 2, \cdots, m-1$, the transition rate to L_{i+1} is λ, while the rate is $\frac{\lambda}{\lambda\tau - \lambda T_w - i + 1}$ in the other outward direction to W_i.

Assume the probabilities to different directions are the ratio of rate. Hence the conditional probability from L_i to L_{i+1} is $P(L_i \to L_{i+1}|L_i) = \frac{\lambda\tau - \lambda T_w - i + 1}{\lambda\tau - \lambda T_w - i + 2}$, while it is $P(L_i \to W_i|L_i) = \frac{1}{\lambda\tau - \lambda T_w - i + 2}$ to W_i.

In fact, the conditional probability is not what we needed, the conditional assumption we needed is that the interface stays in the LPI state. Based on the hypothesis, the probability $P(L_i \to L_{i+1}) = \frac{\lambda\tau - \lambda T_w - i + 1}{\lambda\tau - \lambda T_w + 1}$, the other direction is $P(L_i \to W_i) = \frac{1}{\lambda\tau - \lambda T_w + 1}$.

For m, the probability $P(L_m \to W_m) = \frac{\lambda\tau - \lambda T_w - m + 2}{\lambda\tau - \lambda T_w + 1}$.

The waiting time is τ when the transition happens when buffer capacity is less than m. The time is $\frac{m-1}{\lambda} + T_w$ when the buffer contains m packets.

As above, the average waiting time is the weighted mean value $t_d = -\frac{1}{\lambda(\lambda\tau - \lambda T_w + 1)} m^2 + \left(\frac{2}{\lambda} + \frac{1}{\lambda(\lambda\tau-\lambda T_w+1)}\right) m + T_w - \frac{2}{\lambda}$. ■

B. Performance Analysis

We have listed the environment and parameters in section III. Extra parameter includes the tolerable delay τ. Because the buffer length m for the policy is decided by parameters τ, λ and T_w. It can be seen as an indirectly variable. Thus we consider the effect of τ and λ. For 10GBASE-T link, the application background is access network as well as Data Center Network, the general delay is from tens of microseconds to 200 milliseconds.

An intuitional impression is that lower link utilization leads to more energy saving. An ideal condition is the trend that the energy consumption increases linearly with arrival rate. As numerical analysis shows in Fig. 7, small tolerable waiting time $0.05ms$ and $5ms$ make the LPI probability small as well as a little oscillating when arrival rate λ is low. In other situations, no matter λ is high or τ is large, the LPI probability and the arrival rate maintain a linear relationship. The algorithm implementation selects the smaller buffer size between fixed maximum and delay restrained. Unless τ is big enough that $\lceil \lambda\tau - \lambda T_w + 1 \rceil > m\_max$, the buffer size is decided by $\tau - T_w$ and λ. With the growth of λ, the buffer size $m-1$ increases until a saltus step when $\lceil \lambda\tau - \lambda T_w + 1 \rceil > m\_max$, then m maintains in m_max. Small λ leads to unstable frequency of state transition, which is a waste of energy and an increase of delay. For m_max is big enough, once the buffer size keeps in m_max, the LPI probability can not be restrained by buffer size. However, smaller τ magnifies the transition rate, it is easy to get to the tolerable delay which makes distance between the curve and other curves of lager τ. For the same reason, when τ is big enough, the direct proportion of energy consumption and arrival rate match well. That is what the curve of $\tau = 200ms$ shown. The relationship between the LPI probability and τ is shown in Fig. 8 as well. Generally, when τ is bigger than $25ms$, the LPI probability is only decided by λ/μ. Nevertheless, in the subsegment when τ is smaller than $25ms$, the curve is rapidly slowed to 0 with the descending of τ. According to the analysis above, tolerable delay τ is the key factor in the LPI probability when arrival rate is small. As τ grows, when it will never be the limiting factor of maximum buffer size for the BTR algorithm, the LPI probability is absolutely decided by arrival rate λ. The probability equals to ideal saved energy $1 - \lambda/\mu$.

We don't pay much attention to the delay in the article due to the lack of space. In fact, the most important reason of concerning with the delay is to avoid timeout effect. In the buffer full and timeout triggered policy, the delay is limited by tau, else the interface will be waked up although the buffer do not reach its ceiling. Obviously, the timer of the interface is less than τ when the Wake-up event happens in buffer occupancy of m/n. Thus the timeout event could happen in infinitely small probability when buffer contains m packets in the LPI state.

V. Discussion and policy design

In this section, we will compare the numerical solutions in section III and IV. In the real environment, the model in section IV can be applied for the delay sensitive business; the model in section III can be applied for the business who does not require time-sensitive generally.

In fact, buffer full and timeout triggered wake-up policy can achieve ideal ratio of energy consumption and arrival rate in most available range of rate. For the normal rate range from 5% to 30%, the LPI probability is low and oscillating when tolerable delay is low, while, when the rate is above 10%, the LPI probability is stable and linear with arrival rate. For extreme low tolerable delay, the LPI probability is linear but disproportionately. While for normal tolerable delay the LPI probability is proportionate with arrival rate. However, the implementation of the policy is complicated because a timer should be maintained. The buffer size and the rest of the time recorded by the timer should be verified each packet arrives when the interface is in the LPI state. The other policy buffer full triggered wake-up can achieve ideal ratio of energy consumption and arrival rate within the scope of the buffer as well. However, the tolerable delay can not be guaranteed by any policies. The buffer size is even fixed, which affects the flexibility of demanded delay for different business.

The policies are alternatives which depends on the link utilization. When the interface is in the LPI state, and the load plays determinate role for a long while:

- If the link load is high, or the delay requirement is strict, frame transmission will be adopted.
- Else if the link load is low, buffer full and timeout triggered wake-up policy of burst transmission will be adopted.
- Else if the link load is medial, buffer full triggered wake-up policy of burst transmission will be adopted.

VI. Conclusion and future work

Frame transmission and burst transmission are two main policies for EEE deployment. In the paper, we design models of evaluating these policies. Guidance conclusions, including important parameters and energy-delay tradeoff, are obtained from the analysis results of the models. A new policy depending on load utilization is advised according to our analysis results.

This is an initial work for Energy Efficient Ethernet. A more practical model should be proposed in the future, since some situations have not been considered. Firstly, 1000BASE-T link could not transfer from the Active state to the LPI state until when there is no traffic in both directions, while the state of the interface will be transferred once unidirectional load is empty in our model. Secondly, the sleep operation can not be interrupted by packet arrival event until it finishes in 10GBASE-T, while an immediate transition would happen anytime for 100BASE-TX and 1000BASE-T link. The sleep operation is a unity in our model just adaptable for 10Gbps link. Thus models for the lower and higher speed link are needed for a larger-scale Ethernet infrastructure. Besides, our models suppose the packets are all 1500 bytes equally, which ignores the variation of packet size. Lastly, the packets are assumed coming in the Poisson process, which could be other processes for other application environments.

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