Energy-Delay Tradeoff Analysis and Enhancement in LTE Power-Saving Mechanisms

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***Abstract*— We propose a modified power-saving mechanism (PSM) that reversely applies the state transition of legacy LTE PSM by considering the attributes of network propagation delay. We analyze the PSM with respect to the energy consumption and the buffering delay, and characterize them as a simple energy-delay tradeoff (EDT) curve according to the operational parameters. The resulting EDT curves clearly show that the proposed PSM enhances the legacy PSM in various network environments and also guide to select an optimal parameter for maximizing the energy conservation while ensuring the quality of service.**

I. Introduction

Third-Generation Partnership Project (3GPP) Long-Term Evolution (LTE) wireless networks provide power-saving mechanism (PSM) called *discontinuous reception* (DRX) operation [1]. In viewpoint of energy consumption, the DRX operation can be divided into two operational states: *active* and *sleeping* states. The active-state user equipment (UE) keeps awake to receive packets with an activated transceiver. In contrast, the sleeping-state UE inactivates its transceiver and hence needs to periodically wake up to receive an indication message. Prior to the beginning of sleeping state, the active-state UE initiates an *inactivity timer* to monitor new packet arrivals. If no new packets arrive before the timer's expiration, the UE transits into sleeping state. Otherwise, the UE restarts the timer whenever receiving newly arrived packets. This is the basic operation of legacy PSM, part of which is shown in Fig. 1.

It has been recognized that there is a tradeoff between the energy conservation of a UE and the delay performance of the transmitted packets in the PSM. The tradeoff between the energy consumption and the downlink buffering delay has been studied [2], [3]. This tradeoff arises from the fact that the longer the UE stays in the sleeping state, the more power is saved, but an additional buffering delay occurs. Moreover, the off period, during which no packet is transmitted and so the UE can sleep, is usually modeled as exponential distribution because it is originated from user behaviors, such as reading and silencing [4].

In this paper, we consider a network propagation delay as another factor that induces the traffic off period. Considering the attributes of network propagation delay, we propose a modified PSM that reversely applies the state transition of legacy PSM in the LTE standard. We analyze the legacy and proposed PSMs with respect to the energy consumption and the buffering delay, and characterize them as a simple *energy-delay tradeoff* (EDT) curve according to the value of inactivity timer.

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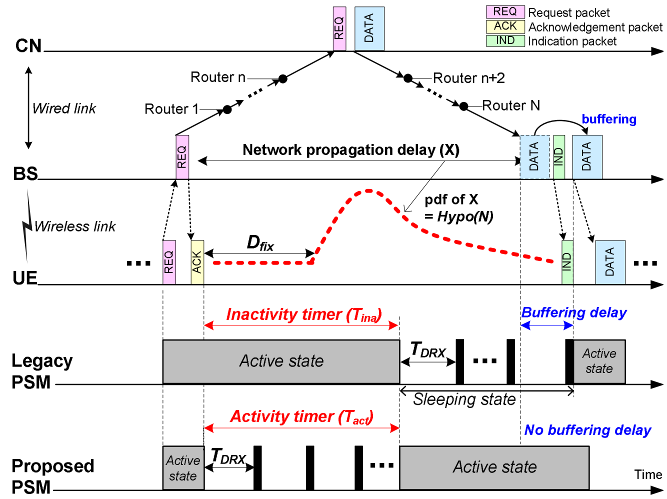

Fig. 1. Operations of legacy and proposed PSMs according to the traffic distribution with network propagation delay.

II. Network Propagation Delay Model

We consider request-response-based applications, such as web browsing and email synchronization. Fig. 1 illustrates an example of traffic arrivals of these applications. This traffic distribution involves the network propagation delay, which is defined as the time interval from the time when the base station (BS) sends the correspondence node (CN) a request packet to the time when it receives the data packet as a response. The network propagation delay is the sum of delays happening in each hop on the packet transmission path. Delay in each hop can be divided into minimal network delay and queueing delay. The minimal network delay consists of the propagation delay (5 μs/km), the transmission delay (which depends on the packet size and the link rate), and the route lookup delay. We denote this delay as D_{mnet}. Since D_{mnet} has a small variation compared to the entire propagation delay, its value is assumed to be fixed. On the other hand, the queueing delay in the n-th router, denoted as D^n_{que}, is variable and modeled as an exponential distribution based on empirical measurements [4], [5].

Let X be the random variable of network propagation delay. Then, X is expressed as

$$X = \sum_{n=1}^{N} (D_{mnet} + D^{n}_{que}) = \sum_{n=1}^{N} D^{n}_{que} + D_{fix} = Hypo(N) + D_{fix} \quad (1)$$

where D_{fix} is a fixed delay given by $N{\cdot}D_{mnet}$. Therefore, X follows a *hypoexponential* distribution composed of N exponential distributions with different rates in series. The probability density function (pdf) of X is given by

$$f_X(t)=\begin{cases}\sum_{n=1}^{N} C_n \lambda_n e^{-\lambda_n (t-D_{fix})} & \text{if } t \ge D_{fix} \\ 0 & \text{if } t < D_{fix}\end{cases} \quad (2)$$

where λ_n is a rate parameter of exponential distribution D^n_{que} and C_n is a constant given by $\prod_{m\neq n} \lambda_m/(\lambda_m-\lambda_n)$.

III. Proposed Power-Saving Mechanism

As shown in Fig. 1, the network propagation delay conforms to a heavy-tailed asymmetric distribution (i.e., hypoexponential distribution) with a certain constant delay. Thus, the proposed PSM is motivated by the fact that there is no packet arrival during a certain time period after the BS sends the request packet to the CN. So, it can simply change the PSM operation from the conventional active-to-sleeping state transition into the sleeping-to-active state transition, as shown in Fig. 1. To do this, the proposed PSM additionally makes the UE go into the sleeping state immediately when the UE receives the acknowledgement packet for its request. Compared with the inactivity timer (T_{ina}), we similarly introduce *activity timer* (T_{act}) to control the period of sleeping state. Note that the standard LTE PSM is not flexible enough to support this proposed technique.

IV. Energy-Delay Tradeoff Analysis

First, the probabilities that the data packet arrives in the active state and sleeping state are respectively calculated as

$$P_{act}=\int_0^{T_{ina}} f_X(t)dt, \quad P_{slp}=\int_{T_{ina}}^{\infty} f_X(t)dt = 1-P_{act}. \quad (3)$$

Let T_{DRX} be the length of DRX cycle. Since the data packet arrives uniform-randomly from a viewpoint of the given state's period, the average buffering delay is a half of DRX length when the DRX length of each cycle is constant. Therefore, the average buffering delay of legacy PSM is given by

$$\overline{D}_{legacy} = P_{slp} T_{DRX}/2. \quad (4)$$

Let E_{act} and E_{slp} be the costs of energy consumption when the UE stays in the active state and sleeping state, respectively. By calculating the conditional expectation of network propagation delay given that the data packet arrives in the sleeping state ($\overline{T}_{arr}$), the average energy consumption of legacy PSM is obtained as

$$\overline{T}_{arr} = E[t \mid t > T_{ina}] = \int_{T_{ina}}^{\infty} \frac{t f_X(t)}{P\{t > T_{ina}\}} dt = \int_{T_{ina}}^{\infty} \frac{t f_X(t)}{P_{slp}} dt, \quad (5)$$

$$\overline{E}_{legacy} = P_{act} E_{act} + P_{slp} \left\{ \frac{E_{act} T_{ina} + E_{slp}(\overline{T}_{arr} - T_{ina})}{\overline{T}_{arr}} \right\}. \quad (6)$$

Since the proposed PSM is the opposite of the legacy PSM, its buffering delay and energy consumption can be obtained by changing P_{slp} into P_{act} in (4) and by exchanging the cost value between E_{act} and E_{slp} in (6), respectively.

V. Results and Discussions

We use T_{DRX}=1.28 s, E_{act}=20 and E_{slp}=1 as relative energy costs, D_{mnet}=10 ms, and λ_n=(mean of 100 ms, variance of 1 ms) [1], [4]. We vary the number of routers (N) within 1~8 and the timer values within 0~5 s.

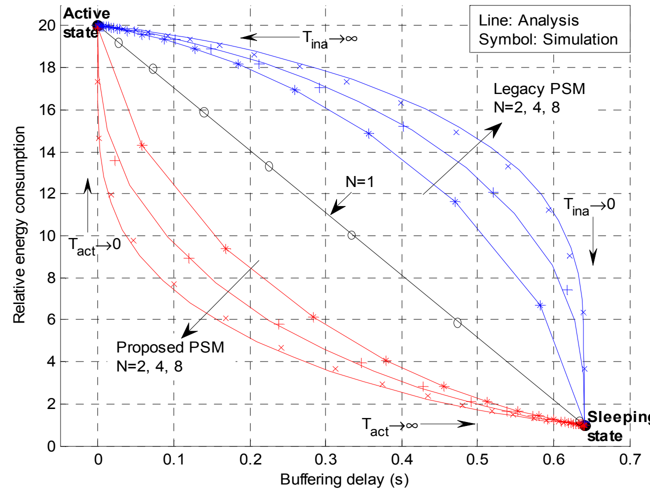

Fig. 2. Energy-delay tradeoff curves.

Fig. 2 plots the energy-delay tradeoff (EDT) curves. Every point on each curve can be achieved by adjusting the inactivity or activity timer. Therefore, based on this EDT curve, we can select an optimal timer value that minimizes the energy consumption while satisfying the requirement of buffering delay. An inner curve shows better tradeoff performances than outer one, i.e., both energy consumption and buffering delay become smaller at the same time. So, the proposed PSM significantly outperforms the legacy PSM from the perspective of EDT. As the number of routers (N) increases, the EDT of proposed PSM becomes improved, but the EDT of legacy PSM becomes degraded. This is because the pdf of network propagation delay moves to the right and so it gives more opportunity to sleep before awake as N increases. Notably, when N=1 (i.e., the network propagation delay just follows the exponential distribution), the tradeoff curve becomes a linear line connecting the energy-delay costs of two states, regardless of the PSM type.

VI. Conclusions

The proposed PSM modifies the legacy LTE PSM by considering the attribute of network propagation delay. The derived EDT curves clearly show that the proposed PSM outperforms the legacy PSM in various network environments and also facilitate to select an optimal parameter in order to minimize the energy consumption of mobile CE device while guaranteeing its quality of service (QoS).

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