Analysis of Discontinuous Reception Based Energy-Saving Techniques

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Abstract

Discontinuous reception (DRX) is one of the key energy saving techniques in 3GPP HSPA and LTE communication standards. This paper aims complex mathematical analysis of power consumption and message delay in DRX mode. The analysis is based on the bursty traffic model which could be used for approximation of real traffic.

Index Terms: Discontinuous reception, Power consumption, Bursty traffic.

I. INTRODUCTION

Nowadays the increase of computational capabilities leads to extreme power consumption of mobile user devices. Modern smartphones run numerous applications which extensively use internet connection. However typical smartphone applications produce bursty traffic [1], where periods of data exchange are followed by the silence periods. To reduce power consumption it is reasonable to turn off user transceiver within silence periods. This behavior is called discontinuous reception (DRX). In DRX mode the user transceiver is mostly turned off (does not listen to the channel) and periodically wakes up to monitor incoming messages. Different DRX algorithms are realized in most 3G and 4G communication standards, like HSPA, WiMAX and LTE [2, 3].

Analysis of DRX-based energy-saving techniques requires consideration of two main metrics: power consumption and quality of service (QoS). Here we assume that QoS is defined by delay of incoming messages. The longer time intervals between transceiver wakes up in DRX mode the more energy are economized, but the longer possible delay of incoming messages. Thus the following optimization problem could be defined: select DRX parameters to minimize power consumption under restrictions on maximal message delay. The solution of the problem depends on traffic characteristics and DRX algorithm. Here we analyze two-cycle DRX used in HSPA and LTE standards under typical bursty traffic model.

The rest of the paper is organized as follows. Section II describes energy-saving DRX algorithm and traffic model. Section III provides mathematical analysis of power consumption and delay. Finally numerical results for typical system parameters are presented in section IV.

II. SYSTEM MODEL

A. Energy-saving algorithm

Let us consider the simplest energy-saving strategy (Fig. 1). At the end of data reception the timer with timeout T_1 is started. If no messages arrive before timer expiration, the user starts DRX cycles. Each DRX cycle lasts L seconds and user transceiver is active (listen to the channel) only within B seconds at the beginning of each cycle. If new message arrives to the base station (BS) within silent period of DRX cycle, it is saved in BS memory and could be received by the user only at the beginning of the next cycle. Such mode is described by the set of three parameters (T_1, L, B).

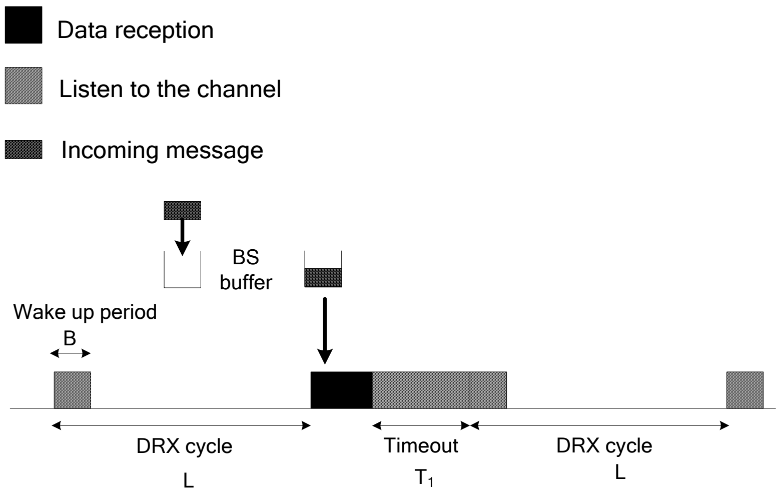

Fig. 1. Simple energy-saving strategy

To increase flexibility and efficiency, modern communication standards specifies DRX mode with two set of parameters – short and long DRX cycles. The operation of two-cycle DRX is depicted in Fig. 2. After expiration of T_1 timer the user equipment (UE) goes to the mode with short DRX cycles (with parameters L_1 and B_1) as well as starts second timer with timeout T_2. After second timer expiration the UE switch to the mode with long DRX cycles (with parameters $L_2 > L_1$ and $B_2 \leq B_1$). Note that if $L_2 = L_1$ and $B_2 = B_1$ the two-cycle DRX comes to the simplest one-cycle DRX scenario.

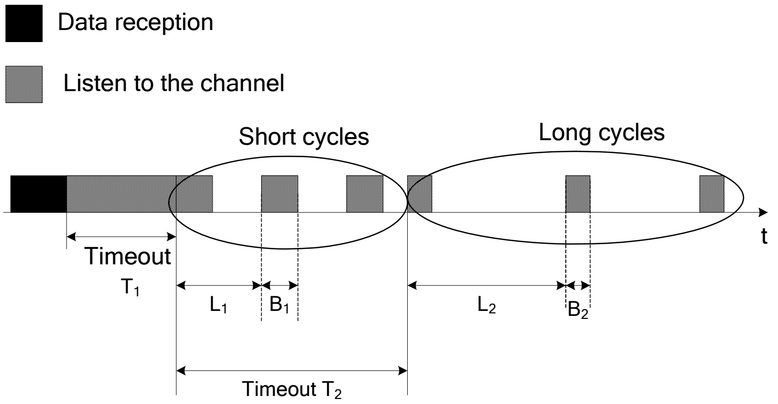

Fig. 2. Two-cycle DRX mode

Two-cycle DRX mode is used for energy saving in 3GPP HSPA and 3GPP LTE [2]. In this paper we analyze power consumption and message delay in two-cycle DRX mode.

B. Traffic model

Real smartphones generate complex traffic with mixture of data flows of different applications. For analysis the real traffic could be approximated by one of mathematical models whose parameters are calculated based on estimates of real traffic. For further analysis we will use bursy traffic model [4], proposed by 3GPP standard committee.

Bursty traffic model is defined by two parameters: mean burst size $\overline{s}$ and mean arrival rate λ. The exact burst size and inter-arrival time are random variables with log-normal and exponential distributions correspondingly. Burst arrival time is counted after the end of reception of the previous data burst. Thus at each time instant BS buffer could contain no more than one message. We assume that the user has constant data rate *R*, thus the expectation of burst reception time (T_b) is

$$\overline{T}_B \triangleq E[T_b] = \frac{\overline{s}}{R}.$$

III. ANALYSIS

In DRX mode the mobile device could be in one of two states: "OFF" state where user transceiver is turned off, and "ON" state, where user transceiver is turned on and listens to the channel or receives data. Let ζ_{ON} be power consumption in "ON" state and ζ_{OFF} be power consumption in "OFF" state ($\zeta_{OFF} << \zeta_{ON}$). Then the overall power consumption of UE is

$$P = \eta_{ON}\zeta_{ON} + \eta_{OFF}\zeta_{OFF}, \qquad (1)$$

where η_{ON} - portion of time the user stays in "ON" state; η_{OFF} - portion of time the user stays in "OFF" state. While exact values of ζ_{ON} and ζ_{OFF} are vendor specific, here we restrict analysis to the values of η_{ON} и η_{OFF}.

Let us define the portion of time the transceiver is turned off as

$$\eta_{OFF} \triangleq \lim_{T\to\infty} \frac{T_{OFF}(T)}{T},$$

where T – total operation time; $T_{OFF}(T)$ - the overall duration of "OFF" state within time *T*. Due to the fact that the user transceiver could only be in one of two states: "ON" or "OFF", η_{ON} could be found from normality condition

$$\eta_{ON} + \eta_{OFF} = 1.$$

Define T_R as a time interval between reception onsets of two consecutive data bursts. Note that in considered model new message could arrive only after the end of reception of the previous data burst. This leads to the fact that system behavior does not depend on the past since UE transceiver starts reception of the current data burst. Such process is called regenerative and T_R - regeneration cycle [5]. Using know results from regeneration theory η_{OFF} could be found by

$$\eta_{OFF} = \frac{\mathrm{E}\left[t_R^{OFF}\right]}{\mathrm{E}\left[T_R\right]}, \qquad (2)$$

where t_R^{OFF} - time in “OFF” state within regeneration cycle.

Let t_R^{DRX1} be overall duration short DRX cycles within regeneration cycle and t_R^{DRX2} be overall duration of long cycles. Remind that within one DRX cycle the user listens to the channel only *B* seconds. Then t_R^{OFF} could be found by the following equation

$$t_R^{OFF} = t_R^{DRX1} \frac{L_1 - B_1}{L_1} + t_R^{DRX2} \frac{L_2 - B_2}{L_2},$$

and its expectation

$$\mathrm{E}\left[t_R^{OFF}\right] = \mathrm{E}\left[t_R^{DRX1}\right] \frac{L_1 - B_1}{L_1} + \mathrm{E}\left[t_R^{DRX2}\right] \frac{L_2 - B_2}{L_2}. \tag{3}$$

Show how to calculate expectation of t_R^{DRX1}, t_R^{DRX2} and T_R. There are three possible events in regeneration cycle:

1. New message arrives before start of DRX mode (before expiration on T_1). Due to exponential distribution of inter-arrival time, the probability of event is
$$p_1 = P(t < T_1) = 1 - e^{-\lambda T_1}.$$
2. New message arrives within short DRX cycles (after expiration of T_1 but before expiration of T_2). The probability of event is
$$p_2 = P(T_1 < t < T_1 + T_2) = P(t > T_1) - P(t > T_1 + T_2) = e^{-\lambda T_1} - e^{-\lambda (T_1 + T_2)}.$$
3. New message arrives within long DRX cycles (after expiration of T_2). The probability of event is
$$p_3 = P(t > T_1 + T_2) = e^{-\lambda (T_1 + T_2)}.$$

Find $\mathrm{E}\left[t_R^{DRX1}\right]$. In the first case the user equipment does not start DRX and

$$\mathrm{E}\left[t_R^{DRX1} \mid t < T_1\right] = 0.$$

In the third case the UE stays in short DRX cycles exactly T_2 seconds, thus

$$\mathrm{E}\left[t_R^{DRX1} \mid t > T_1 + T_2\right] = T_2.$$

Let us consider the second case in details. In that case the user stays in the long-cycle DRX mode up to the time instant the UE starts receiving incoming data message. Then

$$\mathrm{E}\left[t_R^{DRX1} \mid T_1 < t < T_1 + T_2\right] = \mathrm{E}\left[t - T_1 \mid T_1 < t < T_1 + T_2\right] + \mathrm{E}\left[d \mid T_1 < t < T_1 + T_2\right], \tag{4}$$

where *d* – delay between time instant of message arrival and time instant of reception onset. Let us call *d* as initial delay. Due to memorylessness of exponential distribution [6]

$$\mathrm{E}\left[t - T_1 \mid T_1 < t < T_1 + T\right] = \mathrm{E}\left[t \mid t < T_2\right].$$

Let $f(t)$ be probability density function (PDF) of exponential distribution. Then

$$\mathrm{E}\left[t \mid t < T_2\right] = \int_0^{T_2} t f(t \mid t < T_2)dt = \int_0^{T_2} t\frac{f(t)}{P(t < T_2)}dt = \frac{\int_0^{T_2} t\lambda e^{-\lambda t}dt}{1 - e^{-\lambda T_2}} = \frac{-e^{\lambda T_2}(T_2 + 1/\lambda) + 1/\lambda}{1 - e^{-\lambda T_2}}. \quad (5)$$

Find $\mathrm{E}\left[d \mid T_1 < t < T_1 + T_2\right]$. Let random variable k ($0 \le k \le L_1$) describe the time instant of message arrival within regeneration cycle of length L_1. Then the initial delay d is

$$d = \begin{cases} 0, & \text{if } k \le B_1, \\ L_1 - k, & \text{if } k > B_1. \end{cases} \quad (6)$$

Note that according to Poisson process (a process in which the time between events is exponentially distributed) variable k has uniform distribution over the interval L_1 [6]. Omitting interim calculations, the expectation of (6) is

$$\bar{d}_1 \triangleq \mathrm{E}\left[d \mid T_1 < t < T_1 + T_2\right] = \frac{L_1}{2} - B_1 + \frac{B_1^{\,2}}{2L_1}. \quad (7)$$

Analogue

$$\bar{d}_2 \triangleq \mathrm{E}\left[d \mid t > T_1 + T_2\right] = \frac{L_2}{2} - B_2 + \frac{B_2^{\,2}}{2L_2}.$$

Inserting (5) and (7) in (4) we get

$$\mathrm{E}\left[t_R^{DRX1} \mid T_1 < t < T_1 + T_2\right] = \frac{-e^{-\lambda T_2}(T_2 + 1/\lambda) + 1/\lambda}{1 - e^{-\lambda T_2}} + \bar{d}_1,$$

and unconditional expectation of t_R^{DRX1} is

$$\mathrm{E}\left[t_R^{DRX1}\right] = \left(\frac{-e^{-\lambda T_2}(T_2 + 1/\lambda) + 1/\lambda}{1 - e^{-\lambda T_2}} + \bar{d}_1\right)\left(e^{-\lambda T_1} - e^{-\lambda(T_1 + T_2)}\right) + T_2 \cdot e^{-\lambda(T_1 + T_2)}. \quad (8)$$

Analogue the expectation of t_R^{DRX1} could be found as

$$\mathrm{E}\left[t_R^{DRX2}\right] = \left(\frac{1}{\lambda} + \bar{d}_2\right) \cdot e^{-\lambda(T_1 + T_2)}. \quad (9)$$

Mean initial delay could be found via equation

$$\bar{d} \triangleq \mathrm{E}\left[d\right] = \bar{d}_1 \cdot \left(e^{-\lambda T_1} - e^{-\lambda(T_1 + T_2)}\right) + \bar{d}_2 \cdot e^{-\lambda(T_1 + T_2)}. \quad (10)$$

Finally let us find mean regeneration cycle length. The regeneration cycle consists of three parts: current data reception, interim between the end of current data reception and the time instant of new data arrival, initial delay of new data. Then the expectation of T_R is

$$\mathrm{E}\left[T_R\right] = \mathrm{E}\left[T_B\right] + \mathrm{E}\left[t\right] + \mathrm{E}\left[d\right] = \bar{T}_B + \frac{1}{\lambda} + \bar{d}. \quad (11)$$

Insterting (8) and (9) in (3), and (3) and (11) in (2), we finally get the time portion of “OFF” state.

IV. NUMERICAL RESULTS

Note that functions of mean initial delay (10) and DRX time (8) and (9) are not linear. This means that in general case finding optimal DRX parameters (L_1, B_1, T_1, L_2, B_2 и T_2) may become a hard problem. However in real systems the DRX parameters are constrained and usually are defined by a list of possible values. Thus the problem could be reduced to the exhaustive search.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Traffic parameters	
Mean data burst size $\overline{S}$	10 KB
Mean inter-arrival time $1/\lambda$	2 s
Data rate R	12.5 KB/s
DRX parameters	
Short cycle length L_1	80 / 160 / 320 ms
Short cycle wakeup period B_1	10 ms
First timeout T_1	100 / 200 / 400 / 800 ms
Long cycle length L_2	640 / 1280 / 2560 / 5120 ms
Long cycle wakeup period B_2	2 / 4 / 6 / 8 / 10 ms
Second timeout T_2	0.5 / 1 / 2 / 5 s

Table I shows the set of typical parameters for low intensity traffic and DRX in HSPA [7]. Fig. 3 shows the dependence of "ON" time on constraint of initial delay. Each point on the curve corresponds to value of η_{ON} calculated for the optimal DRX parameters under given constraint (maximal value) of $\overline{d}$. According to (1) user power consumption is proportional to η_{ON}, thus each point on the curve corresponds to the minimal power consumption under given constraint on mean delay.

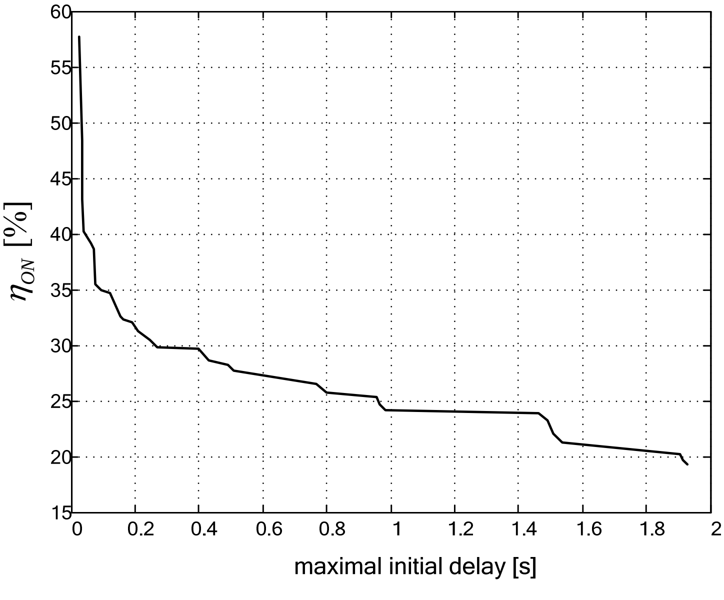

Fig. 3. Dependence of "ON" time on delay constraint

V. CONCLUSION

In this paper the typical energy-saving strategy based on discontinuous reception was considered. The analysis of power consumption and mean delay in DRX modes was described. It was shown that using proposed technique the optimal DRX parameters could be found under given constraints on mean delay.

The proposed technique replaces exhausting simulations by mathematical apparatus. However it should be noted that proposed analysis technique is based on the simple traffic model. Real data traffics are complex, but could be more or less approximated by defined model.

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