Analyzing Energy Efficiency for IoT Devices with DRX Capability and Poisson Arrivals

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Abstract—**Energy-efficient communications is one important consideration for Internet of Things (IoT) devices, and it can be achieved via the discontinuous reception (DRX) technology. In this paper, we consider an IoT device with the DRX capability. The device is functioning based on the LTE standard and it is communicating with the base station over a Nakagami-m fading channel. Data are generated with fixed length and Poisson processes. Under these settings, we develop a cross-layer analytical model to analyze 1) the energy efficiency, 2) stationary probability and 3) state holding time of this device. Simulation results show that the proposed model can approximate the three performance of a IoT device accurately.**

I. INTRODUCTION

The number of Internet of Things (IoT) devices grows rapidly and is expected to exceed the number of human user devices [1]. Most of the devices will be battery operated and require long life time with minimal maintenance. Therefore, it is important to save power consumption for better battery life. The discontinuous reception (DRX) is a core technology in mobile systems [2]; and It can dynamically switch off parts of the circuits from active state to short or long sleep state, resulting in significant energy savings.

Many researches have investigated DRX mechanisms under various traffic patterns or constraints to improve energy efficiency. Liang *et al.* [3] investigated a DRX optimization problem with the consideration of UEs' QoS requirements by maximizing UEs' sleep periods under a guaranteed bit rate. Feng *et al.* [4] introduced a playout buffer and proposed a DRX aware scheduling scheme to meet video streaming QoS requirements. Wang *et al.* [5] studied modeling and optimizing LTE DRX operations under self-similar traffic. Chu *et al.* [6] investigate the DRX mechanism in a batch server system, which allocates the resources according to the number of UEs, the number of backlog packets, quality of service (QoS) requirements and the wireless channel conditions of the UE. However, the above DRX models optimize DRX under the assumption that the channel quality is static. This assumption is in general not true for time-varying wireless fading channels.

An IoT device or a UE is in an active state if the device has data to transmit in its buffer. Therefore, we argue that the probability of a device being in a active state is associated with the non-empty buffer probability, when a wireless system is modeled as a queueing system. This probability over a wireless fading channel can be characterized by the effective capacity model [7] and was first derived in [8]. Based on the work of [8], Xu et al. [9], [10] considered a two-mode circuitry with an idle mode and an active mode, and further develop a two-mode energy efficiency analysis model. Their work considered the traffic model with a Bernoulli arrival process and exponentially distributed packet length. However, the data size for IoT applications is relatively fixed and their arrivals are better modeled as Poisson processes.

The aim of this paper is to find a way to analyze energy efficiency for IoT applications with DRX capability. In particular, we take LTE system as an example. Considering an uncorrelated Nakagami-m fading channel, we model the IoT data packets as the Poisson arrival process with a fixed packet length. According to our proposed model, stationary probability and state holding time can be accurately calculated. Furthermore, energy efficiency can be analyzed and optimized by our proposed model.

The remainder of this paper is organized as follows. Section II describes the wireless DRX system model. In section III, we analyzed the stationary probability and energy efficiency of our proposed DRX model. Simulation results validate our proposed IoT energy efficiency model in Section IV, followed by a conclusion in Section V. The notation used in this paper is shown in table I.

II. WIRELESS DRX SYSTEM MODEL

A. DRX mechanism

The DRX mechanism in LTE is enabled in both the RRC_Idle and the RRC_Connected states. This is specified in the 3GPP standard TS 36.321 [11]. In this paper, we consider that the UE is always in the RRC_Connected state.

As shown in Fig.1, in RRC_Connected state, the whole data transmission process can be divided into four states, namely the active state, the DRX awake state, the short DRX state, and the long DRX state. In the active state, the UE receives data continuously from the base station and have a highest battery consumption. When there is no traffic arrival, the UE enters the DRX awake state and the Inactivity time t_i begins. In the DRX awake state, the UE continuously monitors the PDCCH until the inactivity timer exceeds the limit value. Then the UE shuts down its transceiver circuitry and enters into short sleep

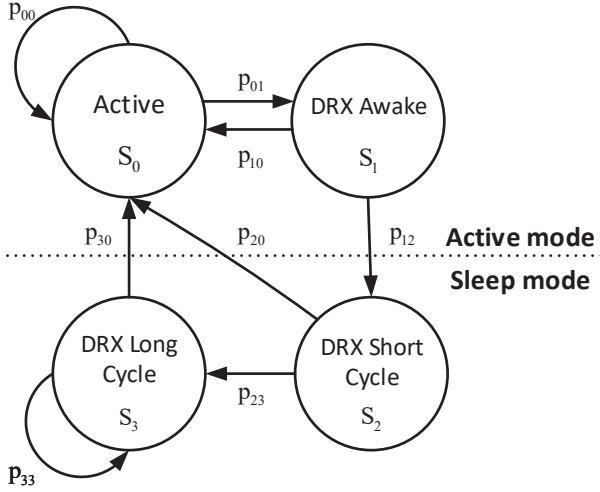| Parameters	Values
p_b	nonempty buffer probability
S_0	active state
S_1	DRX awake state
S_2	short DRX state
S_3	long DRX state
π_i	stationary probability at S_i
H_i	state holding time at S_i
$p_{i,j}$	transition probability from S_i to S_j
t_i	Inactivity Timer
t_s	Short DRX Cycle Timer
t_l	Long DRX Cycle Timer
T	average system time
E	total energy consumption
P_c	circuit power
P_{tx}	transmission power
p_{tx}	transmission probability

Fig. 1: State Transition

state with low power consumption. It wakes up and listens to PDCCH periodically in the short DRX state. If there is no packet received within the short DRX timer t_s expires, which indicates the number of short DRX cycles has expired, the UE enters in the the long DRX state.

In the short DRX state and the long DRX state, the UE powers off transceiver circuitry and has lower energy consumption comparing to the UE in the active state and the DRX awake state.

B. Traffic Model

We consider an IoT device working in a block-fading wireless channel, as shown in Fig.2. The time slot of the device is T_s seconds, which is equal to the fading time. Due to IoT devices typically have a small packet size but a fixed packet length, we assume that

1) the source arrival packet confirms to a Poisson distribution with parameter λ;
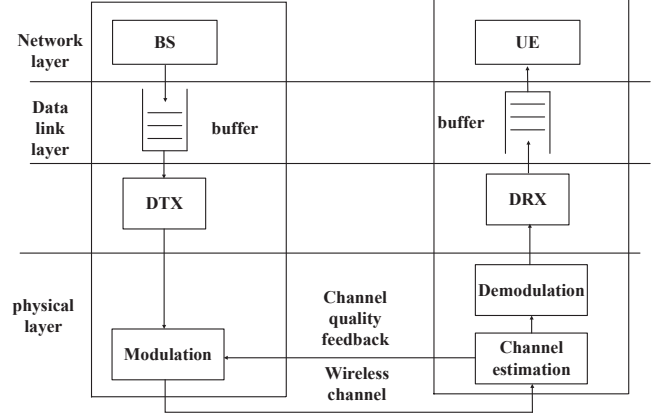2) and the packet length is fixed with L bits.

Fig. 2: Cross-layer system model

The data arrivals for the IoT device is denoted by $A[n]$ ($n = \{1, 2, 3, \ldots\}$), which is independent and identically distributed. Therefore, the probability of the $k(k = 1, 2, \ldots)$ packets arrival is

$$P(A = k \text{ packets per slot}) = \frac{\lambda^k}{k!} e^{-\lambda}. \quad (1)$$

Then the average arrival rate μ is

$$\mu = \lambda L / T_s. \quad (2)$$

The data arrival probability p is

$$p = 1 - P(A = 0) = 1 - e^{-\lambda}. \quad (3)$$

III. CROSS-LAYER ANALYTICAL MODEL WITH DRX

A. Nonempty Buffer Probability Analysis

Nakagami-m block-fading channel extensively used for wireless channel modeling. The parameter m is the shape parameter. When $m = 1$, the signal experiences Rayleigh fading; when $m > 1$, the signal experiences Rician fading. The probability distribution of signal-to-noise ratio (SNR) γ in Nakagami-m fading channel is [12]

$$f_\gamma(\gamma) = \frac{\gamma^{m-1}}{\Gamma(m)} \left(\frac{m}{\bar{\gamma}}\right)^m \exp\left(-\frac{m}{\bar{\gamma}}\gamma\right) (\gamma \geq 0), \quad (4)$$

where $\Gamma(\cdot)$ is the Gamma function, $\bar{\gamma}$ is the average SNR.

If the channel capacity $C[n]$ can be determined by Shannon's capacity, then the services $S[n]$ within a slot can be expressed as

$$S[n] = T_s C[n] = T_s B_c \log_2(1 + \gamma[n]), \quad (5)$$

where B_c is the channel bandwidth. Let $Q(n)$ denote the backlog size of the base station. Then

$$Q(n+1) = \max(Q(n) + A(n) - S(n), 0) \quad (6)$$

The complementary cumulative distribution function of backlog size Q can be expressed as [7]

$$P(Q > q) \approx p_b \exp(-u^* q). \quad (7)$$

where p_b is the nonempty buffer probability and u^* is a QoS exponent.

From previous work such as [8] and [9], the QoS exponent can be derived by using effective bandwidth and effective capacity model. The QoS exponent u^* satisfies the effective bandwidth $\alpha^{(b)}(u)$ equals to the effective capacity $\alpha^{(c)}(u)$, where

$$\alpha^{(b)}(u) = \frac{\log(E[\exp(uA)])}{T_s u} \tag{8}$$

and

$$\alpha^{(c)}(u) = -\frac{\log(E[\exp(-uS)])}{T_s u}. \tag{9}$$

As for the nonempty buffer probability in (7), it can be obtained by the following proposition.

Proposition 1: Consider a Poisson data arrival process with a fixed packet length and a Nakagami-m fading channel, the nonempty buffer probability p_b can be approximated by

$$p_b \approx \frac{\sum\limits_{k=0}^{+\infty} \int_0^{kL} \frac{\lambda^k}{k!} f_S(s) ds}{\sum\limits_{k=0}^{+\infty} \int_{kL}^{+\infty} \frac{\lambda^k}{k!} e^{-(s-kL)u^*} f_S(s) ds}. \tag{10}$$

The proof is attached to the Appendix A.

B. Stationary Probability and State Holding Time

Denote $p_{i,j}$ and π_i as the transition probability from S_i to S_j and the stationary probability of state S_i respectively. The transition between states can happen in the following situations:

1) S_0 to S_1 happens when the buffer is empty and no traffic arrival at the base station;
2) S_1 to S_2 happens when the there is no traffic arrival until Inactivity timer t_i expires;
3) S_2 to S_3 happens when there is no traffic arrival until short DRX timer t_s expires;
4) $S_i (i = 0, 1, 2, 3)$ to S_0 happens when the UE monitor traffic arrival indicated by PDCCH in state i.

The transition between states can be modeled as the discrete-parameter markov chains. Denote $\mathbf{P}$ as the state transition matrix, then $\mathbf{P}$ can expressed as

$$\mathbf{P} = \begin{pmatrix} p_{0,0} & p_{0,1} & 0 & 0 \\ p_{1,0} & 0 & p_{1,2} & 0 \\ p_{2,0} & 0 & 0 & p_{0,3} \\ p_{3,0} & 0 & 0 & p_{3,3} \end{pmatrix} \tag{11}$$

For a DRX system, the data arrival at base station and buffer status are mutually independent, $p_{0,1}$ and $p_{0,0}$ can be expressed as

$$\begin{aligned} p_{0,1} &= (1-p)(1-p_b) \\ p_{0,0} &= 1 - (1-p)(1-p_b). \end{aligned} \tag{12}$$

The other transition probabilities can be calculated as following

$$\begin{aligned} p_{1,2} &= (1-p)^{t_i} \\ p_{1,0} &= 1 - (1-p)^{t_i} \\ p_{2,3} &= (1-p)^{t_s} \\ p_{2,0} &= 1 - (1-p)^{t_s} \\ p_{3,3} &= (1-p)^{t_l} \\ p_{3,0} &= 1 - (1-p)^{t_l} \end{aligned} \tag{13}$$

Since the stationary vector $\pi = (\pi_0, \pi_1, \pi_2, \pi_3)$ satisfy $\pi\mathbf{P} = \pi$ and $\pi_0 + \pi_1 + \pi_2 + \pi_3 = 1$. There exist a unique stationary distribution to ensure the autonomous DRX scheme has steady and consistent behavior. Based on the above notations for the statistical distributions, the stationary probabilities are

$$\begin{aligned} \pi_0 &= \frac{p_{3,0}}{p_{3,0}(1 + p_{0,1} + p_{0,1}p_{1,2}) + p_{0,1}p_{1,2}p_{2,3}} \\ \pi_1 &= \frac{p_{0,1}p_{3,0}}{p_{3,0}(1 + p_{0,1} + p_{0,1}p_{1,2}) + p_{0,1}p_{1,2}p_{2,3}} \\ \pi_2 &= \frac{p_{0,1}p_{1,2}p_{3,0}}{p_{3,0}(1 + p_{0,1} + p_{0,1}p_{1,2}) + p_{0,1}p_{1,2}p_{2,3}} \\ \pi_3 &= \frac{p_{0,1}p_{1,2}p_{2,3}}{p_{3,0}(1 + p_{0,1} + p_{0,1}p_{1,2}) + p_{0,1}p_{1,2}p_{2,3}} \end{aligned} \tag{14}$$

Since the total energy consumption depends on the time duration in each state, it is important to evaluate the holding time of different states. At S_0, the packet arrivals are the data stored in the buffer during the sleep cycle. We assume the UE can receive these data in T_s seconds. This assumption is based on the fact that the peak rate of the LTE systems is more than 120 Mb/s [5]. Then H_0 is

$$H_0 = T_s. \tag{15}$$

At S_1, the new packet arrives before the expiry of inactivity timer t_i. We assume t_i expires at K subframes (that is $t_i = KT_s$), the probability that the time packet arrives at the ith subframe is $p(1-p)^i$ and the holding time is iT_s seconds, then the holding time at S_1 is

$$H_1 = \sum_{i=1}^{K} p(1-p)^i iT_s. \tag{16}$$

The calculation of the H_2 and H_3 are similar to that of H_1. The main differences are we assume t_s expires at L subframes and t_l expires at M subframes respectively. Then the holding time at S_2 and S_3 are

$$H_2 = \sum_{i=1}^{L} p(1-p)^i iT_s. \tag{17}$$

and

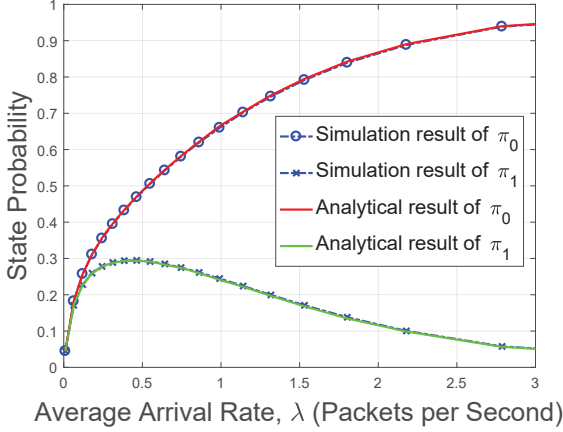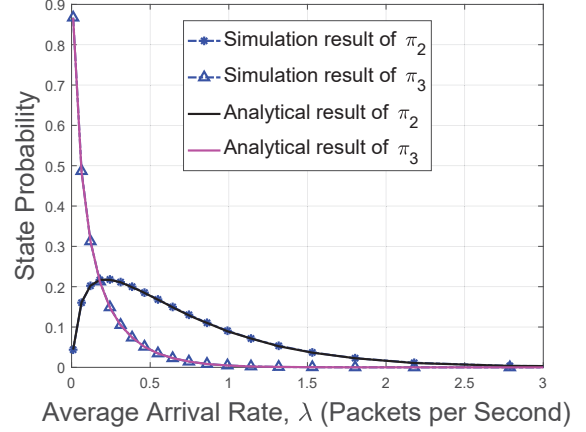$$H_3 = \sum_{i=1}^{M} p(1-p)^i iT_s. \tag{18}$$

C. Energy Efficiency Analysis

In a DRX system, the IoT device works either in the active mode with high energy consumption or in the sleep mode otherwise. In the active mode, the total power consumption P_{active} includes circuit power consumption P_c and transmission power consumption P_{tx}. In the sleep mode, the IoT device only have circuit power consumption. Then P_{active} and P_{sleep} are

$$P_{active} = P_c + P_{tx} \tag{19}$$

and

$$P_{sleep} = P_c. \tag{20}$$

(a) π_0 and π_1

(b) π_2 and π_3

Fig. 3: State probability under different average arrival rate λ

Denote T as the average system time, then T can be expressed as

$$T = \pi_0 H_0 + \pi_1 H_1 + \pi_2 H_2 + \pi_3 H_3. \qquad (21)$$

In S_0 and S_1, the transmitter is in active mode and in S_2 and S_3, the transmitter is in sleep mode. Then the total energy consumption E in average system time is

$$\begin{aligned} E &= (\pi_0 H_0 + \pi_1 H_1)(P_c + P_{tx}) + (\pi_2 H_2 + \pi_3 H_3)P_c \\ &= P_c T + (\pi_0 H_0 + \pi_1 H_1)P_{tx}. \end{aligned} \qquad (22)$$

Bits per Joule is an effective measurement to measure a system energy efficiency. For our proposed DRX system, the energy efficiency η is the total power consumption E in average system time

$$\eta = \frac{\mu T}{E} = \frac{\mu T}{P_c T + (\pi_0 H_0 + \pi_1 H_1)P_{tx}}. \qquad (23)$$

IV. RESULT AND DISCUSSION

In this section, a simulation model is constructed to validate against the analytical model by using MATLAB as a simulation tool. For the result here, the parameters used in the simulations are $t_i = 1ms$, $t_s = 3ms$, $t_l = 5ms$ and $t_i = 3ms$, $t_s = 5ms$, $t_l = 10ms$ respectively. The other parameters are listed in Table II.

Table II: Simulation Parameters

Parameter	Value
Time duration of a slot, T_s	1ms
Packet length, L	500bit
Spectral bandwidth, B	180KHz
Average SNR, $\overline{\gamma}$	10dB
Data arrival probability, p	0.1, 0.2, ..., 1.0
active power consumption, P_{tx}	46dBm
circuit power, P_c	0.1W

Fig.3 shows the state stationary probability under different λ. The simulation curves and analytical curves coincide with
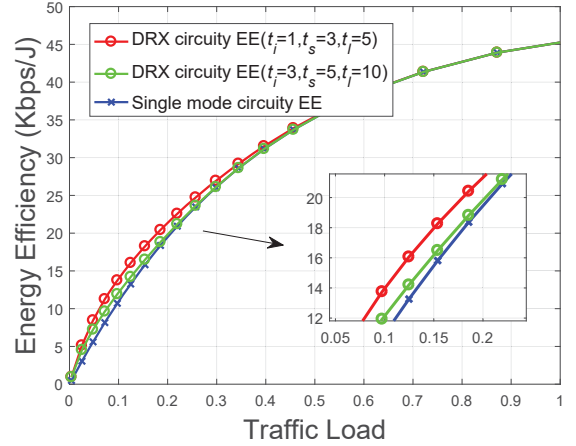

Fig. 4: Achieved energy efciency under different traffic load

each other, which verifies the accuracy of our proposed model. We can observe how the active state, DRX awake state, short DRX state, and long DRX state vary according to the different parameter λ. As λ increases, the data arrival probability in (2) increases accordingly. From the figures, we can find π_0 is an increasing function of the data arrival probability, π_3 is a decreasing function of the data arrival probability. But π_1 and π_2 firstly increase and then decrease, so they have marked peak values at a certain data arrival rate.

Fig.4 shows a comparison of our proposed DRX model energy efficiency (t_i=1ms, t_s=3ms, t_l=5ms and t_i=3ms, t_s=5ms, t_l=10ms) and single mode circuitry energy efficiency. From the figure, we can observe that the energy efficiency improvement compared with single mode circuitry. As the traffic load increases, the rate of growth decreases accordingly. The energy efficiency improvement is remarkable in low traffic load.

Fig.5 shows the energy efficiency improvement under different traffic load. This figure shows the energy efficiency
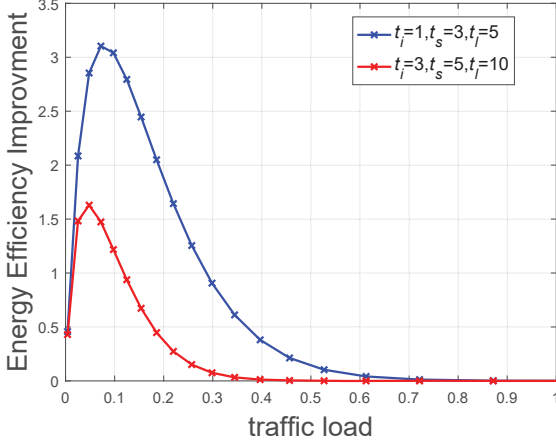
Fig. 5: Energy efciency improvement under different traffic load

improvement has a peak point at a certain traffic load. There exists an optimal traffic load that maximize the energy efficiency improvement.

V. CONCLUSION

It is important to understand the energy efficiency of Internet of Thing (IoT) devices. In this paper, a cross-layer analytical model is developed to analyze this property in LTE systems, and other two properties: stationary probability and state holding time. This model is based on the nonempty buffer probability of the effective capacity model and suitable for time-varying fading channels and data arrivals modeled as a Poisson process. Simulation results verify our analytical model and indicate the IoT device has a maximum energy efficiency improvement under a specific traffic load with DRX capability.

VI. ACKNOWLEDGEMENT

APPENDIX A

When the data arrival process confirms the Poisson distribution and have a fixed packet length, the effective bandwidth $\alpha^{(b)}(u)$ can be expended as

$$\alpha^{(b)}(u) = \frac{\log(\mathrm{E}[\exp(uA)])}{T_s u} = \frac{\lambda(e^{uL} - 1)}{T_s u}. \quad (24)$$

The effective capacity $\alpha^{(c)}(u)$ under Nakagami-m fading channel is

$$\alpha^{(c)}(u) = -\frac{1}{T_s u} \log\left(\int_0^{+\infty} e^{-uT_s B_c \log_2(1+\gamma)} f_\gamma(\gamma) d\gamma\right). \quad (25)$$

Since the QoS exponent u^* that satisfies:

$$\begin{aligned} &\alpha^{(b)}(u^*) = \alpha^{(c)}(u^*) \\ \Rightarrow\ &E(e^{u^*A})E(e^{-u^*S}) = 1 \\ \Rightarrow\ &\sum_{k=0}^{+\infty} e^{ku^*L} \frac{\lambda^k}{k!} e^{-\lambda} \int_0^{+\infty} e^{-u^*s} f_S(s) ds = 1, \end{aligned} \quad (26)$$

where $\Rightarrow$ is the implies symbol.

The nonempty buffer probability p_b can be approximated by the method in [14]

$$p_b \approx \frac{P(A > S)}{1 - P(Q^+ + A > S) + P(A > S)}, \quad (27)$$

where Q^+ is the auxiliary variable and its probability density function $f_{Q^+}(b)$ is defined as

$$f_{Q^+}(b) = \begin{cases} u^* e^{-u^*b} & (b \geq 0), \\ 0 & (b < 0). \end{cases} \quad (28)$$

$P(Q^+ + A > S)$ in (27) can be expended as

$$\begin{aligned} P(Q^+ + A > S) &= P(Q^+ + A > S | A \leq S) + P(A > S) \\ &= \sum_{k=0}^{+\infty} \int_0^{kL} P(A = kL) P(Q^+ > s - kL) f_S(s) ds + P(A > S) \\ &= \sum_{k=0}^{+\infty} \int_0^{kL} \frac{\lambda^k}{k!} e^{-\lambda} e^{-(s-kL)u^*} f_S(s) ds + P(A > S) \\ &= 1 - \sum_{k=0}^{+\infty} \int_{kL}^{+\infty} \frac{\lambda^k}{k!} e^{-\lambda} e^{-(s-kL)u^*} f_S(s) ds + P(A > S) \end{aligned} \quad (29)$$

and $P(A > S)$ is

$$\begin{aligned} P(A > S) &= \int_0^{\infty} P(A > s) f_S(s) ds \\ &= \sum_{k=0}^{+\infty} \int_0^{kL} \frac{\lambda^k}{k!} e^{-\lambda} f_S(s) ds. \end{aligned} \quad (30)$$

Therefore the nonempty buffer probability p_b can be expressed by (26), (29) and (30)

$$p_b \approx \frac{\sum\limits_{k=0}^{+\infty} \int_0^{kL} \frac{\lambda^k}{k!} f_S(s) ds}{\sum\limits_{k=0}^{+\infty} \int_{kL}^{+\infty} \frac{\lambda^k}{k!} e^{-(s-kL)u^*} f_S(s) ds} \quad (31)$$

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