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On performance of mobile edge computing network with non-orthogonal multiple access and radio frequency energy harvesting

Hiệu năng mạng điện toán biên di động sử dụng cơ chế đa truy cập phi trực giao và thu năng lượng sóng vô tuyến

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Abstract

Mobile edge computing is an emerging trend of cloud computing that enables terminal users, which have limited computing ability, to offload their tasks to the edge servers. In this paper, we study the performance of mobile edge computing system using non-orthogonal multiple access (NOMA) and radio frequency energy harvesting techniques. Specifically, a user harvests energy and offloads tasks to the edge servers by using NOMA scheme over wireless channels. The exact closed-form expression of successful computation probability is derived to evaluate the system performance. In addition, the numerical results are also provided based on system parameters to investigate system behaviors. The analytical results are verified by Monte-Carlo simulation.

Keywords: Mobile edge computing; NOMA; RF energy harvesting; successful computation probability.

Tóm tắt

Điện toán biên di động là một xu hướng phát triển của điện toán đám mây giúp cho người dùng đầu cuối hạn chế về khả năng tính toán có thể chuyển việc tính toán cho các máy chủ gần đầu cuối. Trong bài báo này, chúng tôi nghiên cứu hiệu năng hệ thống mạng điện toán biên di động sử dụng phương thức đa truy cập phi trực giao (NOMA) và kỹ thuật thu năng lượng vô tuyến. Cụ thể, máy người dùng thu năng lượng vô tuyến và giảm tải các tác vụ cho các máy chủ biên sử dụng cơ chế NOMA qua các kênh truyền không dây. Biểu thức xác suất tính toán thành công được tìm ra để đánh giá hiệu năng của hệ thống. Ngoài ra, bài báo còn cung cấp các kết quả số theo các thông số hệ thống kiểm chứng các hành vi của hệ thống. Các kết quả phân tích còn được kiểm chứng thông qua mô phỏng Monte-Carlo.

Từ khóa: Điện toán biên di động; NOMA; thu năng lượng vô tuyến; xác suất tính toán thành công.

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1. Introduction

Mobile edge computing (MEC) has been seen as a new paradigm of cloud computing in the last few years, in which the function of servers or access points moves towards the network edges to support the intensive computation needs of the next-generation wireless networks. In this kind of computing network, the edge servers serve as the computational access points to help in accomplishing the computation tasks of mobile computation-constrained devices through wireless links [1-6]. The mobile users can perform computation offloading via two modes: binary computation offloading and partial computation offloading. In binary computation offloading mode, the computation task which is highly integrated or relatively simple cannot be divided and has to be executed locally by itself or offloaded to the MEC servers. Meanwhile, in partial computation offloading mode, the computation task can be divided into two parts with one executed at the mobile device and the other offloaded to edge servers or access points for execution.

Meantime, due to the energy-constrained battery of wireless devices, a number of powering techniques have proposed and deployed to provide the energy to users, i.e., solar energy, wind energy, thermal energy, magnetic energy, and radio frequency energy. The radio frequency energy harvesting (RF EH) technique can prolong the lifetime of mobile devices and maintain the coverage of wireless networks. The prior research results have shown that the user computation performance can be improved by integrating RF EH technique into MEC networks [7-12]. This technique is expected to deploy in next-generation networks.

Besides RF EH technique, NOMA technique has been also recognized as an emerging technique for future wireless networks due to its ability to serve multiuser by using the same time and frequency resources. It was shown that network capacity can be improved by employing NOMA [13-17].

Naturally, the combination of RF EH technique and NOMA technique in MEC is considered in a few works to improve the performance of MEC networks [18-21]. In [18], the offloading scheme in three different modes, namely the partial computation offloading, the complete local computation, and the complete offloading was proposed for a NOMA MEC network, in which two users may partially offload their respective tasks to a single MEC server through uplink NOMA. The optimal solutions for an optimization problem to maximize the successful computation probability were obtained by jointly optimizing the parameters of the proposed scheme. A computation efficiency maximization framework was proposed for wireless-powered MEC networks based on uplink NOMA according to both partial and binary computation offloading modes in [19]. The iterative algorithm and alternative optimization algorithm were proposed to solve the computation efficiency non-convex problem. In [20], the authors proposed the efficient algorithms to solve the weighted sum-energy minimization problems under both cases with partial and binary offloading for multi-antenna NOMA multiuser MEC system. The work of [21] studied NOMA MEC networks for both uplink and downlink transmissions. The studied results have shown that the use of NOMA can efficiently reduce the latency and energy consumption of MEC offloading compared to their conventional orthogonal multiple access (OMA) counterparts.

Different from above works, in this work we consider the scenario that a single user harvests the energy from power station and partially offloads its tasks to two MEC access points by applying downlink NOMA scheme. The main contributions of our paper are as follows.

- A novel quadra-phase protocol for mobile edge computing system based on downlink NOMA scheme is proposed.
- We derive the exact closed-form expression of successful computation probability for this considered system.
- Numerical results are provided to investigate the impact of the network parameters, i.e., transmit power, time switching ratio, power allocation ratio, and data fraction on the system performance to verify the efficiency of deployment of NOMA in MEC network.

The rest of this paper is organized as follows. Section II presents the system model. The performance analysis of this considered system is provided in Section III. The numerical results and discussion are presented in Section IV. Finally, we draw conclusion for our work in Section V.

2. System model

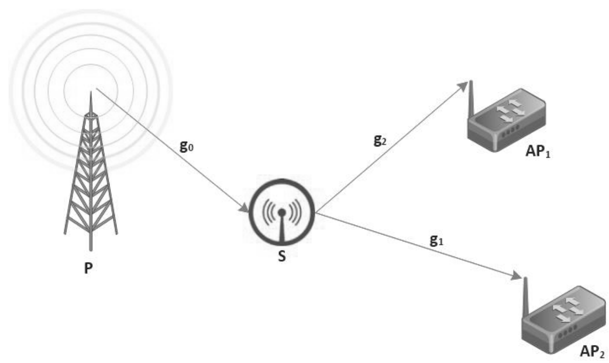

Figure 1. System model for RF EH NOMA MEC network

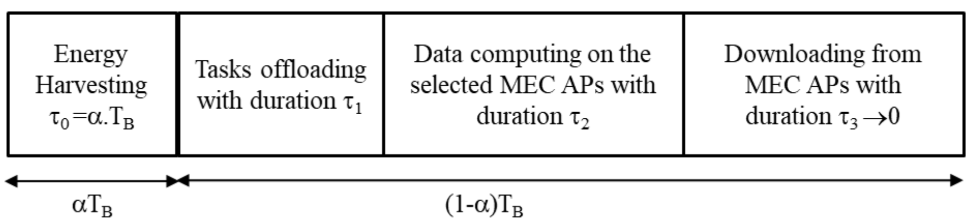

Figure 2. Time flow chart for proposed protocol

The Fig. 1 depicts the system model for an RF EH NOMA mobile edge computing network, in which a single user (S), harvests the energy from power station (P) and partially offloads its tasks to two MEC access points (APs), through downlink NOMA scheme. All the nodes are assumed to have a single antenna and operate in the half-duplex mode. We assume that the task-input bits are bit-wise independent and can be arbitrarily divided into different groups [18]. Therefore, S divides its total task into two tasks: L_1-bit task (Task 1) and L_2-bit task (Task 2). This user may not be able to execute its tasks locally within the latency budget due to the limited computational ability. Therefore, S needs the help from APs through wireless links subject to quasi-static Rayleigh fading. S offloads Task 1 and Task 2 to AP_1 and AP_2, respectively. In this work, we propose a quadra-phase protocol for this RF-EH NOMA MEC system as shown in Fig. 2, consisting of four phases presented as below.

(1) In the first phase (power transfer phase): P transfers RF energy to the users with power P_0 in the time $\tau_0 = \alpha T_B$ ($0 < \alpha < 1$: time switching ratio; T_B: block time for each transmission).

(2) In the second phase (data offloading phase): S uses harvested energy to transmit superimposed message signal

$$x = \sqrt{a_1}s_1 + \sqrt{a_2}s_2, \quad (1)$$

to the access point pair (AP_1, AP_2) in the time of τ_1, where s_1 and s_2 are the messages for AP_1 and AP_2, respectively; a_1 and a_2 are the power allocation coefficients satisfied the conditions: $0 < a_1 < a_2$ and $a_1 + a_2 = 1$ by following the NOMA scheme. By applying NOMA, AP_1 uses successive interference cancellation (SIC) to detect message s_2 and subtracts this component from the received signal to obtain its own message s_1.

(3) In the third phase (data computing phase): After successful offloading, the offloaded tasks are computed at the corresponding MEC APs during duration τ_2.

(4) In the last phase (result downloading phase): After successful computation, the MEC APs feedback the computed results to S within τ_3. Notice that τ_3 is assumed very small and thus is neglected [18].

Given the RF energy harvesting stage, the energy harvested at S during the duration of αT_B in the first phase is given by

$$E = \eta P_0 g_0 \alpha T_B, \quad (1)$$

where $0 < \eta \le 1$ stands for the energy conversion efficiency of the energy receiver (which depends on the rectification process and the energy harvesting circuitry), P_0 denotes the transmit power of power station, g_0 is the channel power gain of link P-S, $0 < \alpha < 1$ denotes the time fraction dedicated for energy harvesting process, T_B is the transmission block time.

Once the power transfer process is finished, the user broadcasts superimposed message signal x as (1) to the access point pair by applying NOMA. AP_1 uses SIC to detect message s_2 and subtracts this component from the received signal to obtain its own message s_1. Therefore, the instantaneous signal-to-noise ratio (SNR) at AP_1 to detect s_1 is given by

$$\gamma_{AP_1}^{s_1} = \frac{a_1 P_s g_1}{N} = a_1 b \gamma_0 g_0 g_1, \quad (2)$$

where $P_s = \frac{E}{(1-\alpha)T_B} = \frac{\eta P_0 \alpha g_0}{1-\alpha}$, N is the average power of additive white Gaussian noise, $b = \frac{\eta\alpha}{1-\alpha}$, $\gamma_0 = \frac{P_0}{N}$ is the average transmit SNR, g_1 is the channel power gain of link S-AP_1.

At AP_1, the instantaneous signal-to-interference-plus-noise ratio (SINR) to detect s_2 is written as

$$\gamma_{AP_2}^{s_2} = \frac{a_2 P_s g_2}{a_1 P_s g_2 + N} = \frac{a_2 b \gamma_0 g_0 g_2}{a_1 b \gamma_0 g_0 g_2 + 1}, \quad (3)$$

where g_2 is the channel power gain of link S-AP_2.

The channel capacity of link S-AP_1 and link S-AP_2 are respectively expressed as

$$C_1 = (1-\alpha)B\log_2\left(1+\gamma_{AP_1}^{s_1}\right), \quad (4)$$

$$C_2 = (1-\alpha)B\log_2\left(1+\gamma_{AP_2}^{s_2}\right), \quad (5)$$

where B is the channel bandwidth.

The transmission latencies from S to AP_1 and S to AP_2 are respectively obtained by

$$t_1 = \frac{L_1}{(1-\alpha)B\log_2\left(1+\gamma_{AP_1}^{s_1}\right)}, \quad (6)$$

$$t_2 = \frac{L_2}{(1-\alpha)B\log_2\left(1+\gamma_{AP_2}^{s_2}\right)}. \quad (7)$$

The execution time τ of this system is calculated as follows.

$$\tau = \max\left\{t_1 + \frac{\rho L_1}{f_1}, t_2 + \frac{\rho L_2}{f_2}\right\}, \quad (8)$$

where ρ denotes the number of required CPU cycles for each bit, and f_i stands for the CPU-cycle frequency at the AP_i, $i = \{1, 2\}$.

The i.i.d. quasi-static Rayleigh channel gain g_k, $k = \{0, 1, 2\}$, follows exponential distributions with parameters λ_k. Therefore, the probability density function (PDF) and cumulative density function (CDF) of g_k are respectively given by

$$f_{g_k}(x) = \frac{1}{\lambda_k} e^{-\frac{x}{\lambda_k}}, \tag{9}$$

$$F_{g_k}(x) = 1 - e^{-\frac{x}{\lambda_k}}. \tag{10}$$

3. Performance analysis

In order to characterize the performance of a MEC system, we use the successful computation probability which defined as the probability that all tasks are successfully executed within a given time $T > 0$, which is expressed as [18]

$$\Pr_s = \Pr(\tau < T). \tag{10}$$

Next, in order to evaluate the performance of this considered RF EH NOMA MEC system, we obtain the following theorem.

Theorem 1.

Under quasi-static Rayleigh fading, the exact closed-form expression of the successful computation probability for this considered MEC system is given by

$$\Pr_s = \begin{cases} 0, & \frac{a_2}{a_1} < \left(2^{\Omega_2} - 1\right) \\ 2\sqrt{\frac{1}{\lambda_0}\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)} \mathrm{K}_1\left(2\sqrt{\frac{1}{\lambda_0}\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)}\right), & \frac{a_2}{a_1} > \left(2^{\Omega_2} - 1\right) \end{cases} \tag{11}$$

where $\beta_1 = \frac{2^{\Omega_1} - 1}{a_1 b \gamma_0}$, $\beta_2 = \frac{2^{\Omega_2} - 1}{\left[a_2 - \left(2^{\Omega_2} - 1\right) a_1\right] b \gamma_0}$, $\Omega_1 = \frac{L_1}{(1-\alpha) B\left(T - \frac{\rho L_1}{f_1}\right)}$, $\Omega_2 = \frac{L_2}{(1-\alpha) B\left(T - \frac{\rho L_2}{f_2}\right)}$,

K_ν is the modified Bessel function of the second kind and ν^{th} order [22].

Proof. See APPENDIX A.

4. Numerical results and discussion

In this section, the numerical results are provided in terms of successful computation probability $\Pr_s$ to reveal the impact of key system parameters, i.e., transmit power, power allocation ratio, energy harvesting time switching ratio, the length of tasks, on the system performance. The simulation parameters used in this work are presented in TABLE 1.

TABLE 1. Simulation parameters

Parameters	**Notation**	**Typical Values**
Environment		Rayleigh
Transmit power of power station	P_0	0 – 30dB
Time switching ratio	α	$0 < \alpha < 1$
CPU-cycle frequency of AP_1	f_1	5 GHz
CPU-cycle frequency of AP_2	f_2	10 GHz
The number of CPU cycles for each bit	ρ	10
Channel bandwidth	B	100 MHz
The threshold of latency	T	0.5s
The number of data bits of Task 1	L_1	48 Mbits
The number of data bits of Task 2	L_2	32 Mbits
Power allocation ratio	a_1	$0 < a_1 \leq 0.5$
Energy conversion efficiency	η	0.75

Fig. 3 depicts the curve of successful computation probability $\Pr_s$ versus the average transmit SNR γ_0 with different power allocation ratio a_1. As we observe from this figure that $\Pr_s$ increases when the transmit power increases.

In other words, the performance of this considered system can be improved by increasing of the power at the station. Meanwhile, the impact of power allocation ratio on the system performance is different from above. This we can see from both figures, i.e., Fig. 3 and Fig. 4, that Pr_s upgrades when a_1 increases from 0 to a^* and Pr_s degrades when a_1 increases from a^* to 1. It is explained that when a_1 increases from 0 to a^*, the transmit power allocated for AP_1 increases, thus the SNR to detect s_1 increases. When a_1 increases from a^* to 1, the interference affected the detection of s_2 at AP_2 is much more serious, thus it makes Pr_s degrade. Notice that a^* is the optimal value of a_1 that makes Pr_s achieve the maximum value. Furthermore, the Fig. 4 also shows that a_1 must satisfy the condition: $a_1 < \frac{a_2}{2^{\Omega_2}-1}$, otherwise $Pr_s = 0$.

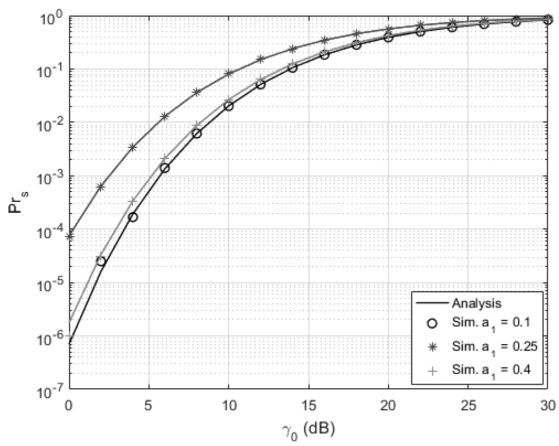

Figure 3. Pr_s versus the average transmit SNR with different power allocation ratio

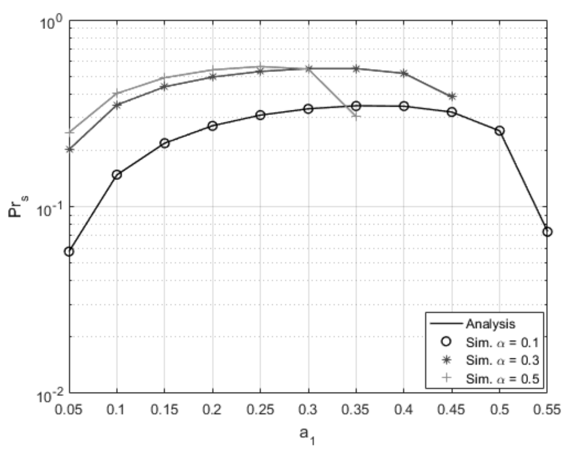

Figure 4. Pr_s versus the power allocation ratio with different time switching ratio

The impact of energy harvesting time switching ratio α on the system performance is depicted in Fig. 4 and Fig. 5. As we see from these figures that Pr_s upgrades when α increases from 0 to α^* and Pr_s degrades when α changes from α^* to 1. It is explained that when α increases from 0 to α^*, the user hartvests more energy to transmit the signals, thus the SNRs to detect s_1 and s_2 increases. However, when α increases from α^* to 1, the time for offloading and computation is less, thus it makes Pr_s degrade. Notice that there exists an optimal value of α (α^*) that makes Pr_s achieve the maximum value.

In order to study the impact of the length of tasks on the performance, we let $\varepsilon = \frac{L_1}{L}$, where ε denotes the data allocation, $L = L_1 + L_2$ is a fixed number of bits of task. Fig. 5 and Fig. 6 plot the curves of Pr_s versus the data fraction. From these figures we can see that the data fraction impacts on the system performance. In other words, there exists an optimal value of ε (ε^*) that makes Pr_s achieve the maximum value.

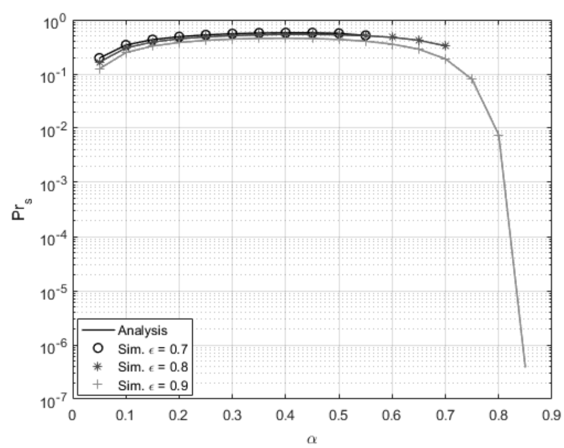

Figure 5. Pr_s versus the time switching ratio with different data fraction

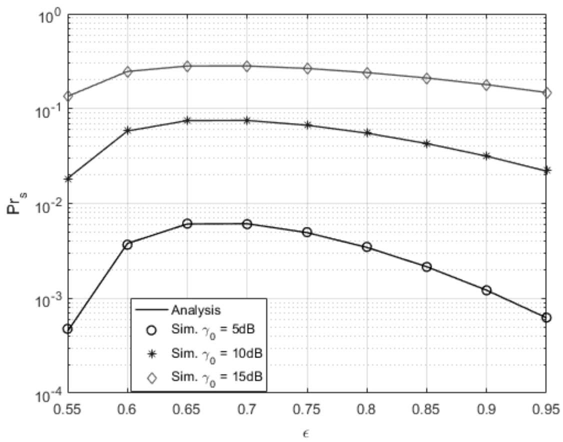

Figure 6. Pr$_s$ versus the data fraction with different average transmit SNR

Finally, we can observe from above figures that the analytical successful computation probability is in good agreement with the simulation one, which verifies the derived analytical expression of successful computation probability.

5. Conclusion

In this paper, we have analyzed the performance of a radio frequency energy harvesting NOMA MEC network by deriving the exact closed-form expression for successful computation probability. By using this expression, we have investigated the impact of system parameters on the system performance. The numerical results have shown that the system performance can be improved by increasing the transmit power of power station or by selecting an optimal value set of time switching ratio, power allocation ratio, and data fraction. The optimization problem will be solved in our future works.

APPENDIX A: PROOF OF THEOREM 1

$$\begin{aligned}
\Pr_s &= \Pr\left(\tau < T\right) = \Pr\left(\max\left\{t_1 + \frac{\rho L_1}{f_1}, t_2 + \frac{\rho L_2}{f_2}\right\} < T\right) \\
&= \Pr\left(t_1 + \frac{\rho L_1}{f_1} < T, t_2 + \frac{\rho L_2}{f_2} < T\right) \\
&= \Pr\left(\frac{L_1}{(1-\alpha)B\log_2\left(1+\gamma_{AP_1}^{s_1}\right)} < T - \frac{\rho L_1}{f_1}, \frac{L_2}{(1-\alpha)B\log_2\left(1+\gamma_{AP_2}^{s_2}\right)} < T - \frac{\rho L_2}{f_2}\right) \\
&= \Pr\left(\log_2\left(1+\gamma_{AP_1}^{s_1}\right) > \frac{L_1}{(1-\alpha)B\left(T - \frac{\rho L_1}{f_1}\right)}, \log_2\left(1+\gamma_{AP_2}^{s_2}\right) > \frac{L_2}{(1-\alpha)B\left(T - \frac{\rho L_2}{f_2}\right)}\right) \\
&\overset{(a)}{=} \Pr\left(a_1 b\gamma_0 g_0 g_1 > 2^{\Omega_1} - 1, \frac{a_2 b\gamma_0 g_0 g_2}{a_1 b\gamma_0 g_0 g_2 + 1} > 2^{\Omega_2} - 1\right) \\
&= \Pr\left(g_1 > \frac{2^{\Omega_1} - 1}{a_1 b\gamma_0 g_0}, \left[a_2 - \left(2^{\Omega_2} - 1\right)a_1\right] b\gamma_0 g_0 g_2 > 2^{\Omega_2} - 1\right) \\
&= \begin{cases} 0, & \frac{a_2}{a_1} < \left(2^{\Omega_2} - 1\right) \\ \underbrace{\Pr\left(g_1 > \frac{2^{\Omega_1} - 1}{a_1 b\gamma_0 g_0}, g_2 > \frac{2^{\Omega_2} - 1}{\left[a_2 - \left(2^{\Omega_2} - 1\right)a_1\right] b\gamma_0 g_0}\right)}_{I}, & \frac{a_2}{a_1} > \left(2^{\Omega_2} - 1\right) \end{cases}
\end{aligned} \tag{12}$$

Denote $\Omega_1 = \dfrac{L_1}{(1-\alpha)B\left(T - \dfrac{\rho L_1}{f_1}\right)}$, $\Omega_2 = \dfrac{L_2}{(1-\alpha)B\left(T - \dfrac{\rho L_2}{f_2}\right)}$, $\beta_1 = \dfrac{2^{\Omega_1} - 1}{a_1 b \gamma_0}$,

$\beta_2 = \dfrac{2^{\Omega_2} - 1}{\left[a_2 - \left(2^{\Omega_2} - 1\right)a_1\right] b\gamma_0}$, we calculate I as follows.

$$\begin{aligned} I &= \Pr\left(g_1 > \frac{\beta_1}{g_0}, g_2 > \frac{\beta_2}{g_0}\right) \\ &= \int_0^\infty \left[1 - F_{g_1}\left(\frac{\beta_1}{x}\right)\right]\left[1 - F_{g_2}\left(\frac{\beta_2}{x}\right)\right] f_{g_0}(x)dx \\ &= \frac{1}{\lambda_0}\int_0^\infty e^{-\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)\frac{1}{x} - \frac{1}{\lambda_0}x} dx \\ &= 2\sqrt{\frac{1}{\lambda_0}\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)} \mathrm{K}_1\left(2\sqrt{\frac{1}{\lambda_0}\left(\frac{\beta_1}{\lambda_1} + \frac{\beta_2}{\lambda_2}\right)}\right). \end{aligned} \tag{13}$$

Substituting (13) into (12), we obtain (11). This concludes our proof.

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