Performance Analysis for RF Energy Harvesting Mobile Edge Computing Networks with SIMO/MISO-NOMA Schemes

Dac-Binh Ha1,*, Van-Truong Truong2, Yoonill Lee3

1Faculty of Electrical-Electronic Engineering, Duy Tan University, Da Nang, 550000, Vietnam and the Institute of Research and Development, Duy Tan University, Da Nang
2Faculty of Electrical-Electronic Engineering, Duy Tan University, Da Nang, 550000, Vietnam and the Institute of Research and Development, Duy Tan University, Da Nang
3Faculty of Electrical Engineering Technology at the College of Lake County, Grayslake, IL, USA

Abstract

In this paper, we study an RF energy harvesting mobile edge computing network based on a SIMO/MISO system and NOMA schemes over Nakagami-$m$ fading. Specifically, a multi-antenna user harvests RF energy from a power station by using a selection combining/maximal ratio combining scheme and offload its tasks to two MEC servers through downlink NOMA by employing transmit antenna selection/maximal ratio transmission scheme. Accordingly, we investigate the performance of six schemes, namely SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, and MRC-MRT, for this considered system. To evaluate the performance, exact closed-form expressions of successful computation probability are derived. We further propose the optimal algorithm to find the best parameter sets to achieve the best performance. Moreover, the impacts of the network parameters on the system performance for these schemes are investigated. Finally, the simulation results are also provided to verify the accuracy of our analysis.

Received on 29 March 2021; accepted on 19 April 2021; published on 28 April 2021

Keywords: radio frequency energy harvesting, mobile edge computing, non-orthogonal multiple access, Nakagami-$m$ fading, multi-antenna

1. Introduction

Indeed, the next-generation wireless communication networks (NGWCN) (e.g., beyond 5G or 6G) will accommodate a massive number of user devices (e.g., Internet of Things (IoT)) and fulfill their capacity and computation demands [1]. However, it is beyond the possibility for existing wireless communication technologies with limited radio resources (e.g., spectrum and transmit power) and limited computation ability (i.e., computing and storing) to cope with such ever increasing capacity and computation demands.

Therefore, multiple candidate technologies (e.g., 3D MIMO, massive MIMO, mmWave, cognitive radio, cooperative communications, NOMA, intelligent reflecting surfaces, MEC, and so on) are needed be integrated into NGWCN to solve the rapidly growing problem of users. Among these technologies, the NOMA technique has been also recognized as an emerging technique for NGWCN because it can improve spectral efficiency and user fairness, and low transmission latency and higher cell-edge throughput [1–3]. This technique allows multiple users to share the same resource (e.g., a time/frequency domain) and separate the users in the power domain by exploiting successive interference cancellation (SIC) scheme at the receiver. Recently, many studies on the advancements needed in the transmitter and receiver sides for adopting NOMA schemes have been published [4–7].

Besides, some link-level and system-level performance evaluations have shown the potential of applying NOMA schemes in NGWCNs [8–10]. In addition, applications
of multiple antennas selection or combination schemes to NOMA systems have also been exploited to improve system performance [11–13]. The technique of transmit antenna selection (TAS) or maximal ratio transmission (MRT) can be deployed at the transmitter to assist the data transmission. The adaptive transmission mode switching between minimum mean square error beamforming and NOMA-based MRT for a system with one multi-antenna base station and two single-antenna users is investigated in [11]. In the work of [12], the system performance of a two-user cooperative multiple-input single-output (MISO) NOMA network with simultaneous wireless information and power transfer was investigated, where multiple antennas at source are exploited by utilizing TAS. The authors in [13] examined a TAS scheme and a user selection method to enhance the secrecy performance of the downlink MISO NOMA system.

Mobile edge computing (MEC) has been seen as a new evolution of cloud computing, in which the function of servers or access points moves towards the network edges to support the intensive computation needs of wireless devices in NGWCNs [14–18]. In this kind of computing approach, the edge servers serve as the computational access points to help accomplish the computation tasks of mobile computation-constrained devices through wireless links. There are two modes of computation offloading for mobile users: binary computation offloading and partial computation offloading. In binary computation offloading mode, the computation task that 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, one executed at the mobile device and the other offloaded to edge servers or access points. Some studies have investigated the combination of MEC with the NOMA technique to improve system performance in NGWCNs [19–22].

An uplink NOMA MEC system consisting of one multi-antenna base station (BS) and multiple single-antenna users is studied in [19]. In [20], the authors proposed a model that multiple users simultaneously offload their workload to one multi-antenna BS. The Lagrange method is used to solve the problem of optimizing the user’s energy consumption. The offloading scheme in three different modes, namely the partial computation offloading, the complete local computation, and the complete offloading, was proposed in [21] for a NOMA MEC network, in which two users may partially offload their respective tasks to a single antenna MEC server through the uplink NOMA. The optimal solutions for an optimization problem to maximize the successful computation probability were obtained by jointly optimizing the parameters of this proposed scheme. The work of [22] studied NOMA MEC networks for both uplink and downlink transmissions in a general MEC communication scenario with multiple single-antenna users and multiple single-antenna access points. 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) schemes.

Meantime, due to the energy-constrained wireless devices, the radio frequency energy harvesting (RF EH) technique is proposed and deployed in applications with quality-of-service requirements to prolong mobile users lifetime and maintain the coverage of wireless networks [23–25]. The prior research results have shown that the user computation performance can be improved by integrating RF EH and NOMA techniques into MEC networks [26-29]. Specifically, the IoT sensor nodes in [26] and the smart wearable devices in [27] can harvest RF energy and offload the heavy computation workload to the MEC server to satisfy the allowed delay under limited energy conditions. A similar model is proposed in [28], in which each user device can execute its task either locally at the mobile or by offloading to MEC using the energy harvesting from a single antenna base station. The joint computation offloading and resource allocation scheme is developed for the MEC system supporting multiple EH mobiles. 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 [29]. The iterative algorithm and alternative optimization algorithm were proposed to solve the computation efficiency non-convex problem. The NOMA-MEC model is particularly suitable for applications with demanding time and energy requirements such as autonomous vehicles [30], Industrial Internet [31], Wearable Virtual Reality device [32].

Besides, receiver can employ selection combining (SC) or maximal ratio combining (MRC) technique for combining signals to improve the system performance [33, 34]. In work [34], the authors proposed a MEC network in which two multi-antenna computational access points support computation for a user under Nakagami- $m$ fading. The operating protocol for the system is a combination of employ receiver antenna selection (RAS) or maximal ratio combining (MRC) at the receiver and implement selection combining (SC) or switch-and-stay combining (SSC). The paper concludes that the increased number of antennas helps improve system performance, i.e., reduce the latency and energy consumption effectively.

To the best of our knowledge, there is no prior work to study the integration of RF EH, multi-antenna technique, and downlink NOMA into MEC system.
this work, we consider the scenario that a single multi-
antenna user harvests the energy from the power station
by using SC/MRC schemes and partially offloads its
tasks to two MEC access points by applying TAS/MRT
downlink NOMA schemes. We compared the system
performance under protocols in term of successful
computation probability (SCP). The main contributions
of our paper are as follows.
• Six quadra-phase protocols for RF EH downlink
NOMA mobile edge computing system based on
SC/MRC and TAS/MRT schemes are proposed.
• Exact closed-form expressions of successful com-
putation probability for these protocols of the
considered system are derived.
• Two algorithms are proposed to find the optimal
parameter set to achieve the best performance for
this proposed system.
• The impact of the network parameters, e.g.,
transmit power, time switching ratio, power
allocation ratio, and task bit allocation, on the
system performance is examined by numerical
results to verify the efficiency and effectiveness of
deployment of RF EH, multi-antenna, and NOMA
in MEC network.

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

2. System and Channel Model
We define the notations used in the next part of this
work in Table 1.

Fig. 1 depicts an RF EH NOMA MEC system in which
an energy-constrained K-antenna user (S) harvests RF
energy from a single antenna power station (P) to
offload its task to two MEC servers located at single
antenna access points (APs). Specifically, S has tasks
with L bits/task to be executed. Due to the constraint of
latency requirement and its limited computation ability,
may not execute its tasks locally. Therefore, it offloads
its tasks to MEC servers, which have more strong
computation ability. However, due to the limited battery
problem, S has to harvest RF energy by exploiting
SC/MRC schemes and uses it to offload its tasks. After
RF energy harvesting, it transmits its task data using
all harvested energy based on TAS/MRT and downlink
NOMA schemes. We assume that the task follows data-
partition model and can be arbitrarily divided into
different subtasks [35–37] to apply NOMA. For instance,
L_1 = \epsilon L \ (0 \leq \epsilon \leq 1) \text{ bits are offloaded to} \ AP_1, \text{ and
the remained} \ L_2 = (1 - \epsilon)L \text{ bits are offloaded to} \ AP_2.
Finally, \ APs \text{ return the computing results to the user
by the uplink NOMA scheme. The time flowchart of this
considered RF EH NOMA MEC system is shown as Fig.
2.

![Figure 1. System Model for RF Energy Harvesting NOMA
MEC Network](image1)

![Figure 2. Time flowchart of the considered RF EH NOMA
MEC system](image2)

Table 1. Notations

| Notation | Meaning |
|----------|---------|
| m_0, m_1, m_2 | Fading severity factor of Nakagami-m |
| g_0, g_1, g_2 | Channel power gain of the wireless links of P-S, S-AP_1, S-AP_2 |
| \alpha | Time switching ratio |
| a | Power allocation coefficient |
| K | Number of antennas of S |
| P_0 | Transmit power of power station P |
| \gamma_0 | Average transmit SNR |
| \eta | Energy conversion efficiency |
| f_i | CPU-cycle frequency of AP_i |
| \epsilon | Task bit allocation coefficient |
| c_i | The number of required CPU cycles for each bit of AP_i |
| B | Channel bandwidth |
| T | The threshold of latency |
| L | The length of task |
| Ps | Successful computation probability |
| \delta | The algorithm accuracy factor |
where the channel power gain \( g \) for RF EH to maximize the power harvesting. Therefore, \( g \) is very small compared to \( \tau_0, \tau_1 \) as well as \( \tau_2 \) and thus is neglected [21, 29].

Assuming that all the channels have block Nakagami-\( m \) fading, i.e., the channel power gain is constant over each block but vary independently between different block and follows Nakagami-\( m \) distribution with parameter \( m \). We also assume that \( P, S, A \) operate in half-duplex mode and all harvested energy is used for offloading transmission. Let \( h_0 = [h_{01}, ..., h_{0K}]^T \), \( h_1 = [h_{11}, ..., h_{1K}]^T \) and \( h_2 = [h_{21}, ..., h_{2K}]^T \) denote the channel vectors of the wireless links \( P - S, S - A \) and \( S - A \), respectively.

Given the energy harvested from the harvested energy of \( S \) during the duration of \( \alpha T \) is given by

\[
E = \eta P_0 g_0 \alpha T, \tag{1}
\]

where \( 0 < \eta \leq 1 \) stands for the energy conversion efficiency of the energy receiver [24], \( P_0 \) denotes the transmit power of power station, \( g_0 \) is the channel power gain of link \( P - S \).

For the SC technique, an antenna at \( S \) is selected for RF EH to maximize the channel gain of the link \( P - S \). Thus, the channel power gain \( g_0 \) is written as

\[
g_0 = \max_{1 \leq k \leq K} (|h_{0k}|^2). \tag{2}
\]

For the MRC technique, all of \( K \) antennas of \( S \) are used for RF EH to maximize the power harvesting. Therefore, the channel power gain \( g_0 \), in this case, is calculated as

\[
g_0 = ||h_0||^2. \tag{3}
\]

Without loss of generality, we assume that the transmit power allocated to \( A \) is greater than that allocated to \( A \), thus \( a \) is selected to satisfy the condition: \( 0.5 < a \leq 1 \) to apply the NOMA scheme. \( S \) broadcasts the signal to \( A \) by exploiting TAS/MRT schemes with transmit power \( P_T \) calculated as follows

\[
P_T = \frac{E}{(1 - \alpha)T} = \frac{\eta P_0 g_0 \alpha}{(1 - \alpha)} = bP_0g_0, \tag{4}
\]

where \( b = \frac{\eta}{(1 - \alpha)} \).

During the offloading phase, \( S \) uses harvested energy to transmit a superimposed message signal

\[
x = \sqrt{a P_T} s_1 + \sqrt{(1 - a) P_T} s_2, \tag{5}
\]

to \( A \), where \( s_1 \) and \( s_2 \) are the messages for \( A_1 \) and \( A_2 \), respectively; \( a \) stands for the power allocation coefficient.

Thus, the received signals at \( A_1 \) corresponding to the \( k \)-th antenna of \( S \) is written as

\[
y_{k} = \left( \sqrt{a P_T} s_1 + \sqrt{(1 - a) P_T} s_2 \right) h_k + n_{ik}, \tag{6}
\]

where \( n_{ik} \) is the additive white Gaussian noise (AWGN) with mean 0 and variance \( \sigma^2 \) at \( A_i \), \( i \in \{1, 2\} \).

For applying the TAS scheme, an antenna at \( S \), denoted as \( k^* \), is selected for transmission to maximize the channel gain of the link \( S - A_1 \), namely TAS1 case:

\[
k^* = \arg \max_{1 \leq k \leq K} (|h_{1k}|^2). \tag{7}
\]

Thus, in this TAS1 case, the channel power gains for the selected transmit antenna \( k^* \) of links \( S - A_1 \) and \( S - A_2 \) are given by

\[
(g_1, g_2) = (|h_{1k^*}|^2, |h_{2k^*}|^2). \tag{8}
\]

Similarly, an antenna at \( S \), denoted as \( k^{**} \), can be selected to maximize the channel gain of the link \( S - A_2 \), namely TAS2 case, in which \( k^{**} \) is obtained by

\[
k^{**} = \arg \max_{1 \leq k \leq K} (|h_{2k}|^2). \tag{9}
\]

In this TAS2 case, the channel power gains corresponding to the selected transmit antenna of links \( S - A_1 \) and \( S - A_2 \) are written as

\[
(g_1, g_2) = (|h_{1k^{**}}|^2, |h_{2k^{**}}|^2). \tag{10}
\]

For applying the MRT scheme, all of \( K \) antennas of \( S \) are used for communication. Therefore, the channel power gains, in this case, are expressed as

\[
g_i = ||h_i||^2, i \in \{1, 2\}. \tag{11}
\]

The instantaneous signal-to-interference-noise ratio (SINR) at \( A_1 \) to detect \( s_1 \) is given by

\[
\gamma_{A_1} = \frac{ab \gamma_0 g_0 g_1}{(1 - a) \gamma_0 g_0 g_1 + 1}, \tag{12}
\]

where \( \gamma_0 \) is the average transmit signal-to-noise ratio (SNR).

By applying successive interference cancellation (SIC) technique, \( A_2 \) detects message \( s_1 \) and subtracts this component from the received signal to obtain its message \( s_2 \). Therefore, the instantaneous SINR at \( A_2 \) to detect
Loop:

Setup:

Proposed quadra-phase schemes for RF

Algorithm 1

where $B$ is the channel bandwidth.

The transmission latencies of offloading to AP$_1$ and AP$_2$ are respectively expressed as

\[ t_1 = \frac{\epsilon \lambda}{(1 - \alpha)B \log_2 \left(1 + \gamma_{s1}^n\right)}, \]

\[ t_2 = \frac{(1 - \epsilon) \lambda L}{(1 - \alpha)B \log_2 \left(1 + \gamma_{s2}^n\right)}, \]

where $\epsilon$ denotes the task bit allocation coefficient.

The execution time $\tau$ of this system is calculated as follows

\[ \tau = \max \left\{ t_1 + \frac{c_1 \epsilon \lambda}{f_1}, t_2 + \frac{c_2(1 - \epsilon) \lambda L}{f_2} \right\}, \]

where $c_i$ denotes the number of required CPU cycles for each bit of AP$_i$, and $f_i$ stands for the CPU-cycle frequency at the AP$_i$, $i \in \{1, 2\}$.

The SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, MRC-MRT schemes for this considered system are summarized as Algorithm 1.

Algorithm 1 Proposed quadra-phase schemes for RF EH NOmA MEC system

1: procedure RF EH NOmA MEC Protocol
2: Setup:
3: Selection: SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, MRC-MRT
4: Loop:
5: Phase-1: S harvests energy from P by exploiting SC/MRC scheme.
6: Phase-2: S broadcasts its tasks to APs by applying TAS1/TAS2/MRT and NOMA schemes. AP$_2$ uses SIC technique to detect $s_2$.
7: Phase-3: S waits for APs execute the received tasks.
8: Phase-4: S downloads the computed results from APs.
9: end procedure

Notice that the wireless links of P - S, S - AP$_1$ and S - AP$_2$ undergo the Nakagami-m fading which is a generalized fading model for practical communication scenarios. Therefore, the cumulative distribution function (CDF) and probability density function (PDF) of channel power gains, i.e., $|h_{ik}|^2$, $(i \in \{0, 1, 2\}$ and $1 \leq k \leq K$) are respectively given by

\[ F_{|h_{ik}|^2}(x) = 1 - e^{-\frac{x}{\lambda_i}} \sum_{l=0}^{m_i-1} \frac{m_i}{l!} \left( \frac{x}{\lambda_i} \right)^l, \]

\[ f_{|h_{ik}|^2}(x) = \frac{1}{(m_i-1)!} \left( \frac{x}{\lambda_i} \right)^{m_i-1} e^{-\frac{x}{\lambda_i}}, \]

where $\lambda_i = \mathbb{E}(|h_{ik}|^2)$, $m_i \geq 1/2$ is the fading severity factor, in which $m_i = 1$ corresponds to Rayleigh fading and $m_i = (V + 1)^2/(2V + 1)$ approximates Rician fading with parameter $V$, $\mathbb{E}(.)$ stands for expectation operator.

For SC scheme, the CDF and PDF of $g_0$ can be respectively written as

\[ F_{g_0}(x) = \left(1 - \sum_{l=0}^{m_0-1} \frac{m_0}{l!\lambda_0} x^l e^{-\frac{m_0}{\lambda_0} x} \right)^K, \]

\[ f_{g_0}(x) = \sum_{k=0}^{K} \sum_{\sigma_0=\sigma_k} \Phi_0 \left( \frac{x}{\sigma_k} - \frac{m_0 \sigma_0}{\lambda_0} \right) e^{\frac{-m_0 \sigma_0}{\lambda_0} x}, \]

where $\Phi_0 = \left( \begin{array}{c} K \\ k \end{array} \right) \left( \begin{array}{cccc} k_0 & k_1 & \ldots & k_{m_0-1} \end{array} \right) (-1)^{k_1} \prod_{l=0}^{m_0-1} \frac{m_0^l}{l!\lambda_0^l} \delta_l$, $\sigma_0 = \sum_{l=0}^{m_0-1} \delta_l$, and $\varphi_0 = \frac{m_0-1}{l!} \delta_l$ [13].

Similarly, for TAS1 case, the CDF and PDF of $g_1$ can be respectively written as

\[ F_{g_1}(x) = \left(1 - \sum_{l=0}^{m_1-1} \frac{m_1}{l!\lambda_1} x^l e^{-\frac{m_1}{\lambda_1} x} \right)^K, \]

\[ f_{g_1}(x) = \sum_{k_1=0}^{K} \sum_{\sigma_1=\sigma_{k_1}} \Phi_1 \left( \frac{x}{\sigma_1} - \frac{k_1 m_1}{\lambda_1} \right) e^{\frac{-k_1 m_1}{\lambda_1} x}, \]

where $\Phi_1 = \left( \begin{array}{c} K \\ k_1 \end{array} \right) \left( \begin{array}{cccc} k_0 & k_1 & \ldots & k_{m_1-1} \end{array} \right) (-1)^{k_1} \prod_{l=0}^{m_1-1} \frac{m_1^l}{l!\lambda_1^l} \delta_l$, $\sigma_1 = \sum_{l=0}^{m_1-1} \delta_l$, and $\varphi_1 = \frac{m_1-1}{l!} \delta_l$. It follows that the CDF and PDF of $g_2$ can be respectively given by

\[ F_{g_2}(x) = 1 - e^{-\frac{m_2}{\lambda_2} x} \sum_{l=0}^{m_2-1} \frac{1}{l!} \left( \frac{m_2}{\lambda_2} x \right)^l, \]

\[ f_{g_2}(x) = \frac{1}{(m_2-1)!} \left( \frac{m_2}{\lambda_2} x \right)^{m_2-1} e^{-\frac{m_2}{\lambda_2} x}, \]
Dac-Binh Ha, Van-Truong Truong, Yoonill Lee

\[ f_{g_2}(x) = \frac{1}{(m_2 - 1)!} \left( \frac{m_2}{\lambda_{2}} \right)^{m_2} x^{m_2-1} e^{-\frac{m_2 x}{\lambda_{2}}} \cdot (27) \]

Similarly, for TAS2 case, the CDF and PDF of \( g_1 \) can be respectively expressed as

\[ F_{g_1}(x) = 1 - e^{-\frac{m_1 x}{\lambda_{1}}} \sum_{l=0}^{m_1-1} \frac{1}{l!} \left( \frac{m_1}{\lambda_{1}} \right)^{l}, \]

\[ f_{g_1}(x) = \frac{1}{(m_1 - 1)!} \left( \frac{m_1}{\lambda_{1}} \right)^{m_1} x^{m_1-1} e^{-\frac{m_1 x}{\lambda_{1}}} \cdot (28) \]

It follows that the CDF and PDF of \( g_2 \) in this case can be respectively written as

\[ F_{g_2}(x) = \sum_{k_2=0}^{K} \sum_{\sigma_2=k_2} \Phi_2(x^2 \alpha) e^{-\frac{k_2 m_2 x^2}{\lambda_{2}}} \cdot (30) \]

\[ f_{g_2}(x) = \sum_{k_2=0}^{K} \sum_{\sigma_2=k_2} \Phi_2(x^2 \alpha) x \left( \alpha - \frac{k_2 m_2 x^2}{\lambda_{2}} \right) \cdot (31) \]

where \( \Phi_2 = \left( \frac{K}{k_2} \right) \left( \frac{k_2}{2} \right) \left( \delta_{2} \right) \cdot \left( \delta_{2} - l_0 \right) \]

\[ \sigma_2 = \sum_{l=1}^{m_2-1} \delta_{l}, \text{ and } \varphi_2 = \sum_{l=1}^{m_2-1} l_0. \]

For MRT/MRC scheme, the CDF and PDF of \( g_i \) can be respectively expressed as

\[ F_{g_{MRT/MRC}}^i(x) = 1 - \frac{m_i K - 1}{l!} \left( \frac{m_i}{\lambda_{i}} \right)^l x e^{-\frac{m_i x}{\lambda_{i}}} \cdot (32) \]

\[ f_{g_{MRT/MRC}}^i(x) = \frac{1}{(m_i K - 1)!} \left( \frac{m_i}{\lambda_{i}} \right)^{m_i K} x^{m_i K - 1} e^{-\frac{m_i x}{\lambda_{i}}} \cdot (33) \]

where \( i \in \{0, 1, 2\} \).

3. Performance Analysis and Optimization

In this section, we present the performance analysis of this proposed system in terms of the successful computation probability \( P_s \) and the optimization of the parameter set to achieve the optimal performance.

3.1. Performance analysis

In order to characterize the performance of a MEC system, \( P_s \) is defined as the probability that all tasks are successfully executed within a given time \( T_{th} > 0 \) [21]. Therefore, \( P_s \) of this proposed system is written as

\[ P_s = Pr(\tau < T_{th}) = Pr(\tau < (1 - \alpha)T) \cdot (34) \]

where \( \tau \) is calculated as (19).

In order to evaluate the performance of six schemes, i.e., SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, MRC-MRT, for this considered RF EH NOMA MEC system, we obtain the following theorem.

**Theorem 1.** Under Nakagami-\( m \) fading, the exact closed form expressions of the successful computation probability \( P_s \) for this considered RF EH MEC system based on SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, MRC-MRT downlink NOMA schemes, respectively, is given by formula SCP.

\[ \Psi_1 = \frac{2^{m \frac{1}{m(1-\alpha)}} - 1}{2^{m \frac{1}{m(1-\alpha)}} - \frac{1}{m(1-\alpha)}}, \]

\[ \Psi_2 = \frac{2^{m \frac{1}{m(1-\alpha)}} - 1}{2^{m \frac{1}{m(1-\alpha)}} - \frac{1}{m(1-\alpha)}}, \]

\[ \Omega_1 = (1 - \alpha)T - \frac{\epsilon L}{\alpha}, \]

\[ \Omega_2 = (1 - \alpha)T - \frac{\epsilon L}{\alpha} \]

\[ v_1 = \varphi_0 - \varphi_1 - l, \]

\[ v_2 = \varphi_0 - \varphi_2 - l, \]

\[ v_3 = m_o K - \varphi_1 - l, \]

\[ v_4 = m_o K - \varphi_2 - l, \]

\[ v_5 = \varphi_0 - l_1 - l_2, \]

\[ v_6 = m_o K - l_1 - l_2, \]

\[ K_{\alpha}(x) \] is the modified Bessel function of the second kind and \( \theta \)th order.

**Proof.** See in Appendix A. \( \square \)

**Remark 1.** The condition \( a > \rho = 1 - \frac{1}{2^{m \frac{1}{m(1-\alpha)}}} \) in Equation SCP is constraint of three key parameters: data offloading ratio \( (\epsilon) \), time switching ratio \( (\alpha) \), and power allocation ratio \( (\rho) \). This constraint can be rewritten as follows:

\[ (1 - \alpha) \left( \frac{e L}{\alpha} \right) \left( \frac{e L}{\alpha} \right) < 1. \]

3.2. Optimization: Problem formulation and solution

According to the above analysis, we formulate the optimization problem to maximize \( P_s \) as follows:

\[ (SCPMP) : \max_{\epsilon, \alpha} P_s \] (36a)

subject to \( 0 \leq \epsilon \leq 1 \) (36b)

\( 0 < \alpha \leq 1 \) (36c)

\( 0.5 < \alpha \leq 1 \) (36d)

Note: SCPMP stands for successful computation probability maximization problem. Constraint (36b) describes the data offloading ratio for APs. Constraint (36c) describes the time switching ratio for energy harvesting. Constraint (36d) means that the power allocation ratio is chosen to apply NOMA and maximize \( P_s \). To solve (36), we propose two optimal algorithms: Algorithm 2 - SCPMS and Algorithm 3 - SPCMGS, which is used to find the optimal set \( (P_{s_{\text{max}}}, \epsilon^*, \alpha^*, \rho^*) \) in the entire solution space.

The **Algorithm 2** - SCPMS is based on search method and is divided into two simple steps. We use
As such, the complexity of the SCPM algorithm is \( O\left(\frac{1}{\delta^3}\right) \).

We propose the second algorithm for the SCPM based on the Golden section search algorithm, i.e., the SCPMG. Algorithm 3 – SCPMG consists of four main steps:

- **Step 1**: Similar to SCPMS algorithm, SCPMG chooses the \( P_s \) formula according to the scheme that the system is operating.

- **Step 2 (Initialization)**: Determine lower bound \( x_l \equiv (e_l, \alpha_l, a_l) \) and upper bound \( x_u \equiv (e_u, \alpha_u, a_u) \). We define \( \delta \) is an accuracy factor. Normalize the variable \( a \) by using the equation

  \[ \hat{a} = \frac{a - a_l}{a_u - a_l} \]

  Thus, the interval of each parameter \( (e, \alpha, \hat{a}) \) is \([0,1]\). Determine two intermediate points \( x_1 \equiv (e_1, \alpha_1, a_1) \) and \( x_2 \equiv (e_2, \alpha_2, a_2) \) such that:

  \[ x_1 = x_l + (x_u - x_l)/G, \]

  \[ x_2 = x_u - (x_u - x_l)/G \]

  \( (39) \)

  where \( G = \sqrt[5]{\frac{e_x+1}{2}} \) is the golden ratio.

- **Step 3 (Evaluation)**: Next, we evaluate \( P_s \) at \( x_1 \) and \( x_2 \). In case \( P_s(x_1) > P_s(x_2) \), we update \( x_1, x_2 \). If \( x_1, x_2 \rightarrow x_l \), and \( x_1 \rightarrow x + (x_u - x_l)/G \). In the opposite case, we update \( x_u \rightarrow x, x_1 \rightarrow x, \) and \( x_2 \rightarrow x_u - (x_u - x_l)/G \).

- **Step 4**: We run step continuously in the loop until \( x_u - x_l < \delta \). Then, the algorithm terminates and the \( P_{s_{\text{max}}} \) occurs at \( \frac{x_u + x_l}{2} \).

So, SCPMG use three loops that cut the interval in \( \frac{1}{\mathcal{G}} \) each time they run; hence, its time complexity is \( O(\log^2\frac{1}{\mathcal{G}}) \).

### 4. Numerical Results and Discussion

In this section, we provide numerical results in terms of successful computation probability \( P_s \) for SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, and MRC-MRT schemes to reveal the impacts of key system parameters (data offloading ratio, time switching ratio, and power allocation coefficient) to the system performance. Furthermore, the simulation results are also provided to verify analytical results. The parameters used in this work are provided in TABLE 2.
Algorithm 2 Successful computation probability maximization searching (SCPMS) algorithm

Input: \( \gamma_0, L, c_1, c_2, f_1, f_2, T \)

Output: Optimalset \( (P_{s_{\text{max}}}, \epsilon^*, \alpha^*, a^*) \)

1: \textbf{Initialize:} Optimalset \((0, 0, 0, 0)\)

2: Parameters: \((\epsilon, \alpha, a) \leftarrow (0.01, 0.01, \max\{0.5, \rho\} + 0.01)\)

3: Step: \(\delta \leftarrow 0.01\)

4: while \(\epsilon \leq 1\) do

5: \hspace{0.5cm} while \(\alpha \leq 1\) do

6: \hspace{1cm} switch (Scheme)

7: \hspace{1.5cm} case SC-TAS1: Calculate \(P_s\) using SCP (a).

8: \hspace{1.5cm} case SC-TAS2: Calculate \(P_s\) using SCP (b).

9: \hspace{1.5cm} case MRC-TAS1: Calculate \(P_s\) using SCP (c).

10: \hspace{1.5cm} case MRC-TAS2: Calculate \(P_s\) using SCP (d).

11: \hspace{1.5cm} case SC-MRT: Calculate \(P_s\) using SCP (e).

12: \hspace{1.5cm} case MRC-MRT: Calculate \(P_s\) using SCP (f).

13: \hspace{1cm} end switch

14: \hspace{0.5cm} if \((P_s > P_{s_{\text{max}}})\) then

15: \hspace{1cm} Update \((P_{s_{\text{max}}}, \epsilon^*, \alpha^*, a^*) \leftarrow (P_{s_{\text{max}}}, \epsilon, \alpha, a)\)

16: \hspace{1cm} end if

17: \hspace{0.5cm} Update \(\epsilon \leftarrow \epsilon + \delta\)

18: \hspace{0.5cm} end while

19: \hspace{0.5cm} Update \(\alpha \leftarrow \alpha + \delta\)

20: \hspace{0.5cm} end while

21: \hspace{0.5cm} Update \(a \leftarrow a + \delta\)

22: \hspace{0.5cm} end while

23: 24: Return Optimalset \((P_{s_{\text{max}}}, \epsilon^*, \alpha^*, a^*)\)

4.1. Impacts of average transmit SNR and the number of antennas

Figs. 3-8 depict the impacts of average transmit SNR \(\gamma_0\) and the number of antennas \(K\) on \(P_s\) with \(\epsilon = 0.6, \alpha = 0.3, \) and \(a = 0.8\). Obviously, from these figures we can observe that \(\gamma_0\) or/and \(K\) increase leading \(P_s\) increases. It means that the computing performance of this considered system can be improved by increasing the average transmit SNR or/and the number of antennas. However, when \(\gamma_0\) gets too large, \(P_s\) will tend to be saturated. So in the proposed model, it is not necessary to increase the transmit power of the user too large.

As expected, in above figures, we observe that the \(P_s\) of the NOMA scheme significantly outperforms that of the OMA scheme.

Algorithm 3 Successful computation probability maximization Golden searching (SCPMG) algorithm

Input: \( \gamma_0, L, c_1, c_2, f_1, f_2, T \)

Output: Optimalset \( (P_{s_{\text{max}}}, \epsilon^*, \alpha^*, a^*) \)

1: \textbf{Initialize:} Optimalset \((0, 0, 0, 0)\)

2: Parameters: \(x_1 \triangleq (\epsilon, \alpha_1, a_1), x_u \triangleq (\epsilon_u, \alpha_u, a_u)\)

3: Step: \(\delta \leftarrow 0.01\)

4: Normalize \(a\) using (38)

5: Determine \(x_1 \triangleq (\epsilon, \alpha_1, a_1)\) and \(x_2 \triangleq (\epsilon_2, \alpha_2, a_2)\)

6: while \(\epsilon_u - \epsilon > \delta\) do

7: \hspace{0.5cm} while \(\alpha_u - \alpha > \delta\) do

8: \hspace{1cm} switch (Scheme)

9: \hspace{1.5cm} case SC-TAS1: Calculate \(P_s\) using SCP (a).

10: \hspace{1.5cm} case SC-TAS2: Calculate \(P_s\) using SCP (b).

11: \hspace{1.5cm} case MRC-TAS1: Calculate \(P_s\) using SCP (c).

12: \hspace{1.5cm} case MRC-TAS2: Calculate \(P_s\) using SCP (d).

13: \hspace{1.5cm} case SC-MRT: Calculate \(P_s\) using SCP (e).

14: \hspace{1.5cm} case MRC-MRT: Calculate \(P_s\) using SCP (f).

15: \hspace{1cm} end switch

16: \hspace{0.5cm} if \((P_s(x_1) > P_s(x_2))\) then

17: \hspace{1cm} Update \((P_{s_{\text{max}}}, x_1, x_2, x_1 + (x_u - x_1)/G)\)

18: \hspace{1cm} else

19: \hspace{1cm} Update \((P_{s_{\text{max}}}, x_1, x_2, x_2 - (x_u - x_1)/G)\)

20: \hspace{1cm} end if

21: \hspace{0.5cm} end while

22: \hspace{0.5cm} end while

23: \hspace{0.5cm} end while

24: \hspace{0.5cm} end while

25: \hspace{0.5cm} Return Optimalset \((P_{s_{\text{max}}}, \epsilon^*, \alpha^*, a^*)\) at \(\frac{x_u + x_2}{2}\)

4.2. Impacts of the data offloading ratio

In Fig. 9, we examine \(P_s\) as a function of the data offloading ratio \(\epsilon\) with \(\gamma_0 = 10dB, K = 2, \alpha = 0.3, \) and \(a = 0.8\) for different schemes. From this figure, we can see that when \(\epsilon\) increases from 0 to \(\epsilon^*\), \(P_s\) upgrades. However, if \(\epsilon\) continuously increases from \(\epsilon^*\) to 1, \(P_s\) degrades. This can be easily explained that applying NOMA AP1 is allocated more transmit power than AP2, therefore when \(\epsilon\) increases, \(P_s\) upgrades. However, when \(\epsilon\) continuously increases the load allocated for AP1 increases. This leads the offloading and computing time of AP1 longer and makes \(P_s\) degrades, meanwhile the AP2’s time is wasted.
TABLE 1. Simulation Parameters

| Parameters                        | Notation | Typical Values |
|----------------------------------|----------|----------------|
| Environment                      | $Nakagami-m$ | 3, 2, 1         |
| Fading severity factor of $Nakagami-m$ | $m_0, m_1, m_2$ | 3, 2, 1         |
| Number of antennas of $APs$      | $\gamma_0$ | 0-30dB          |
| Average transmit SNR             | $\eta$   | 0.75            |
| Energy conversion efficiency     | $f_1$    | 5 GHz           |
| CPU-cycle frequency of $AP_1$    | $f_2$    | 10 GHz          |
| The number of CPU cycles for each bit | $c_1, c_2$ | 10              |
| Channel bandwidth                | $B$      | 100 MHz         |
| The threshold of latency         | $T$      | 0.5s            |
| The length of task               | $L$      | 80 Mbits        |

4.3. Impacts of the time switching ratio

The impacts of the time switching ratio $\alpha$ on $P_s$ are depicted as Fig. 10 with $\gamma_0 = 10 dB$, $K = 2$, $\epsilon = 0.6$, and $\alpha = 0.8$ for different schemes. From this figure, we can observe that when $\alpha$ increases from 0 to $\alpha^*$, $P_s$ upgrades, when $\alpha$ continuously increases from $\alpha^*$ to 0.5, $P_s$ degrades. When $\alpha \geq 0.5$, $P_s$ is approximately 0 due to the condition (35). It can be explained that when $\alpha$ increases from 0 to $\alpha^*$, the more harvested energy the better SNR and the better $P_s$. However, if $\alpha$ continuously increases the remained time for transmission and computation is less, this makes $P_s$ degrades.

4.4. Impacts of the power allocation coefficient

In Fig. 11, we investigate $P_s$ as a function of the power allocation coefficient $\alpha$ with $\gamma_0 = 10 dB$, $K = 2$, $\epsilon = 0.6$, and $\alpha = 0.3$ for different schemes. From this figure, we can see that when $\alpha$ increases from $\alpha^*$ to 1, $P_s$ degrades. This can be easily explained that due to the offloading data for $AP_1$ is larger the $AP_2$, thus when $\alpha$ continuously increases the power allocated for $AP_2$ decreases and makes $P_s$ degrades.

Remark 2. From Figs. 3-11, we can see that the MRC-MRT scheme is the best one, meantime the SC-TAS1 scheme is worst one. This is reasonable because the MRC-MRT scheme employs all antennas to harvest RF energy and offload tasks to $AP$s, meanwhile in SC-TAS1 scheme only the best antenna is selected to harvest RF energy and offload task to $AP$s, but it is simplest one.

Remark 3. From Figs. 3-11, we can observe that the analysis and simulation results are matching very well. It means that the correctness of our analysis has been verified.

4.5. Impacts of the length of task and the bandwidth

Figure 12 presents the $P_s$ by the length of the task under different bandwidth. We fixed the power allocation to 0.8. We observe that $P_s$ decreases when $L$ increases. It can be explained as the time that spent on the offloading phase increases when $L$ increases (follow a formula (17),...
(18)), which reduces the time remaining for the data computing phase. Thus, both user and APs will likely not have enough time to handle all of their tasks, so the $P_s$ decreases.

Figure 12 shows the apparent effect of bandwidth on system performance. The case where the bandwidth is sufficiently large ($B = 100 \text{ MHz}$) offers much better performance than the lower bandwidth case ($B = 50 \text{ MHz}$). In case the length of task is short, the effect of bandwidth is not significant, but the longer the task, the impact of bandwidth is very pronounced.

Figure 5. Impacts of the number of antennas $K$ on $P_s$ of MRC-TAS1 scheme

Figure 6. Impacts of the number of antennas $K$ on $P_s$ of MRC-TAS2 scheme

Figure 7. Impacts of the number of antennas $K$ on $P_s$ of SC-MRT scheme

Figure 8. Impacts of the number of antennas $K$ on $P_s$ of MRC-MRT scheme

4.6. Optimization for successful computation probability

In Fig. 13, we verify the two optimization algorithms, i.e., SCPMS and SCPMG, to achieve the optimal performance in terms of $P_s$ for different schemes. We can easily see that both algorithms achieve the same optimum effect for the proposed model. In order to comparison, we also plot the $P_s$ with $\epsilon = 0.4$, $\alpha = 0.3$, and $a = 0.6$ in the non-optimal case. From this figure, we can see that when the optimization algorithm is deployed the values of $P_s$ is higher than non-optimal ones. In other words, the computing performance of this considered system can achieve the optimal value by using the optimal set $(P_{s_{\text{max}}}, \epsilon^*, \alpha^*, a^*)$ for corresponding schemes.
5. Conclusion

In this paper, we have studied the RF energy harvesting NOMA mobile edge computing network. Six schemes, namely SC-TAS1, SC-TAS2, MRC-TAS1, MRC-TAS2, SC-MRT, and MRC-MRT are proposed for this system based on multi-antenna selection of user. We have also derived the exact closed-form expressions of successful computation probability for these corresponding schemes. Moreover, the optimization algorithm has been proposed to obtain the optimal performance. Finally, the numerical results have been provided to reveal the impacts of system parameters on performance. From these results, we observe that the performance of this considered system can be improved by increasing the transmit power and/or the number of antennas and by selecting the optimal set of key parameters: data offloading ratio, time switching ratio, and power allocation coefficient.

In our future work, we will study the case of multiple input multiple output RF EH NOMA MEC system with imperfect channel state information. We also consider the system equality and scalability to expand the scope for the study.

Appendix A. Proof of Theorem 1

Here, from equation (34) we derive the closed-form expression of $P_s^{SC}$ as (A-1) and (A-2) on the top of the next page.

This ends our proof.
References

[1] O. Maraqa, A. S. Rajasekaran, S. Al-Ahmadi, H. Yanikomeroglu, and S. M. Sait, “A survey of rate-optimal power domain NOMA with enabling technologies of future wireless networks,” *IEEE*, 2020.

[2] L. Dai, B. Wang, Y. Yuan, S. Han, C. Lin I, and Z. Wang, “Nonorthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends,” *IEEE Communications Magazine*, vol. 53, no. 9, pp. 74–81, 2015.

[3] A. Anwar, B.-C. Seet, M. A. Hasan, and X. J. Li, “A survey on application of non-orthogonal multiple access to different wireless networks,” *Electronics*, vol. 8, p. 1355, 2019.

[4] Z. Ding, M. Peng, and H. V. Poor, “Cooperative non-orthogonal multiple access in 5G systems,” *IEEE Communications Letters*, vol. 19, no. 8, pp. 1462–1465, 2015.

[5] A. H. Gendia, M. Elsabrouty, and A. A. Emran, “Cooperative multi-relay non-orthogonal multiple access for downlink transmission in 5G communication systems,” in *2017 Wireless Days*. Porto, Portugal: IEEE, 2017.

[6] S. M. R. Islam, N. Avazov, O. A. Dobre, and K. sup Kwak, “Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges,” *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 721–742, 2017.

[7] S. Lee, “Cooperative non-orthogonal multiple access for future wireless communications,” *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems*, vol. 5, no. 17, pp. 1–8, 2018.

[8] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, “On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users,” *IEEE Signal. Process. Lett.*, vol. 21, no. 12, pp. 1501–1505, 2014.

[9] D.-D. Tran, H.-V. Tran, D.-B. Ha, and G. Kaddoum, “Cooperation in NOMA networks under limited user-to-user communications: Solution and analysis,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, 15-18/4/2018, Barcelona, Spain.

[10] D.-D. Tran and D.-B. Ha, “Secrecy performance analysis of QoS-based non-orthogonal multiple access networks over nakagami-m fading,” in *The International Conference on Recent Advances in Signal Processing, Telecommunications and Computing (SigTelCom)*, HCMC, Vietnam, 2018.

[11] Z. Zhao and W. Chen, “An adaptive switching method for sum rate maximization in downlink MISO-NOMA systems,” in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, 2017.

[12] T. N. Do, D. B. da Costa, T. Q. Duong, and B. An, “Improving the performance of cell-edge users in MISO-NOMA systems using TAS and SWIPT-based cooperative transmissions,” *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 1, pp. 49–62, 2018.

[13] T. N. Kieu, D.-D. Tran, D.-B. Ha, and M. Voznak, “On secure QoS-based NOMA networks with multiple antennas and eavesdroppers over nakagami-m fading,” *IETE Journal of Research*, pp. 1–13, 2019.

[14] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, “A survey on mobile edge computing: The communication perspective,” *IEEE Communications Survey Tutorials*, vol. 19, no. 4, pp. 2322–2358, 2017.

[15] H. Sun, F. Zhou, and R. Q. Hu, “Joint offloading and computation energy efficiency maximization in a mobile edge computing system,” *IEEE Transactions on Vehicular Technology*, vol. 68, no. 3, pp. 3052–3056, 2019.

[16] Y. Zhang, X. Lan, Y. Li, L. Cai, and J. Pan, “Efficient computation resource management in mobile edge cloud computing,” *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3455–3466, 2019.

[17] Q. Li, J. Zhao, and Y. Gong, “Computation offloading and resource allocation for mobile edge computing with multiple access points,” *IET Communications*, vol. 13, no. 17, pp. 2668–2677, 2019.

[18] W. Lu, B. Yin, G. Huang, and B. Li, “Edge caching strategy design and reward contract optimization for uAV-enabled mobile edge networks,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2020:38, pp. 1–10, 2020.

[19] F. Wang, J. Xu, and Z. Ding, “Optimized multiuser computation offloading with multi-antenna NOMA,” in *2017 IEEE Globecom Workshops (GCWkshps)*, Singapore, 4-8 Dec. 2017, pp. 1–7.

[20] ——, “Multi-antenna NOMA for computation offloading in multiuser mobile edge computing systems,” *IEEE Transactionson Communications*, vol. 67, no. 3, pp. 2450–2463, 2018.

[21] Y. Ye, G. Lu, R. Q. Hu, and L. Shi, “On the performance and optimization for MEC networks using uplink NOMA,” in *IEEE International Conference on Communications Workshops (ICC Workshops)*, Shanghai, China. IEEE, 2019.

[22] Z. Ding, P. Fan, and H. V. Poor, “Impact of non-orthogonal multiple access on the offloading of mobile edge computing,” *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 375–390, 2019.

[23] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, “Wireless networks with RF energy harvesting: A
\[ P_{S_{TAS1}}^{SC} = \Pr \left( \max \left\{ t_1 + \frac{c_1 L}{f_1}, t_2 + \frac{c_2 (1 - \epsilon) L}{f_2} \right\} < (1 - \alpha)T \right) \]
\[ = \Pr \left( t_1 + \frac{c_1 L}{f_1} < (1 - \alpha)T, \quad t_2 + \frac{c_2 (1 - \epsilon) L}{f_2} < (1 - \alpha)T \right) \]
\[ = \Pr \left( \gamma_{AP1}^{a} > 2^{\frac{\beta \gamma_{0} g_{1}}{\epsilon_{0} (1 - \alpha) T f_1}} - 1, \gamma_{AP2}^{a} > 2^{\frac{\beta \gamma_{0} g_{2}}{f_2}} - 1 \right) \]
\[ = \Pr \left( \frac{a b \gamma_{0} g_{1}}{(1 - \alpha) b \gamma_{0} g_{2} + 1} > 2^{\frac{\beta \gamma_{0} g_{2}}{f_2}} - 1, \frac{(1 - \alpha) b \gamma_{0} g_{2} > 2^{\frac{\beta \gamma_{0} g_{2}}{f_2}} - 1} \right) \] (A-1)
\[ = \begin{cases} 0, & \text{if } a < \rho \\
\int_{0}^{\infty} \left[ 1 - F_{g_1} \left( \frac{\Psi_1}{x} \right) \right] \left[ 1 - F_{g_2} \left( \frac{\Psi_2}{x} \right) \right] f_{g_0}(x) \, dx, & \text{if } a > \rho 
\end{cases} \]
\[ \int_{0}^{\infty} f_{g_0}(x) \, dx, \quad \text{if } a > \rho \]

where \( \rho = 1 - \frac{1}{2^{\frac{\beta \gamma_{0} g_{2}}{f_2}}} \), \( \Psi_1 = \frac{2^{\frac{\beta \gamma_{0} g_{2}}{f_2} - 1}}{(1 - \alpha) \gamma_{0} \left( 2^{-\frac{\beta \gamma_{0} g_{2}}{f_2}} \right) - 1} \), \( \Psi_2 = \frac{2^{\frac{\beta \gamma_{0} g_{2}}{f_2} - 1}}{(1 - \alpha) \gamma_{0} \left( 2^{-\frac{\beta \gamma_{0} g_{2}}{f_2}} \right) - 1} \), \( \Omega_1 = (1 - \alpha)T - \frac{c_1 L}{f_1} \), \( \Omega_2 = (1 - \alpha)T - \frac{c_2 (1 - \epsilon) L}{f_2} \).

Substituting (23), (24) and (26) into the integral \( \int_{0}^{\infty} f_{g_0}(x) \, dx \), after some manipulation, we obtain

\[ \int_{0}^{\infty} f_{g_0}(x) \, dx = \sum_{k_0=1}^{K} \sum_{k_1=1}^{K} \sum_{l=0}^{m_2-1} \sum_{t=0}^{m_1-1} \frac{1}{\gamma_{0} \sigma_{k_0}^{a} \sigma_{k_1}^{a}} \left( \frac{m_2}{\lambda_2} \right)^{l} \int_{0}^{\infty} e^{x \varphi_0 - \varphi_1 - l - 1} e^{-\frac{(1 + m_1 e_{k_1} + m_2 e_{k_2})}{\lambda_2} x} - k_{m_2}^{\frac{\beta_1}{\mu_1}} \left( \varphi_0 - k_{m_2}^{\frac{\beta_1}{\mu_1}} \right) dx \]
\[ = \sum_{k_0=1}^{K} \sum_{k_1=1}^{K} \sum_{l=0}^{m_2-1} \sum_{t=0}^{m_1-1} \frac{1}{\gamma_{0} \sigma_{k_0}^{a} \sigma_{k_1}^{a}} \left( \frac{m_2}{\lambda_2} \right)^{l} \left[ 2 \varphi_0 - \frac{\beta_1}{\mu_1} \right]^{\frac{l+1}{\mu_1}} K_{v_{1}} \left( 2 \sqrt{\beta_1 \mu_1} \right) \]
\[ - \frac{\beta_1}{\mu_1} \left( \frac{\beta_1}{\mu_1} \right)^{\frac{l+1}{\mu_1}} K_{v_{1+1}} \left( 2 \sqrt{\beta_1 \mu_1} \right) \] (A-2)

where \( v_1 = \varphi_0 - \varphi_1 - l \), \( \beta_1 = \frac{k_{m_1} e_{k_1}}{\lambda_1} + \frac{k_{m_2} e_{k_2}}{\lambda_2}, \mu_1 = \frac{k_{m_2}}{\lambda_2} \), and \( K_{v_{1}}( \cdot ) \) is the modified Bessel function of the second kind and \( v_{1} \)th order. Note that step (a) is obtained by the aid of [38, Equation (3.471.9)].

contemporary survey,” IEEE Communications Surveys and Tutorials, 17(2), pp. 757–789, 2014.
[24] D.-B. Ha, D.-D. Tran, V. Tran-Ha, and E.-K. Hong, “Performance of amplify-and-forward relaying with wireless power transfer over dissimilar channels,” Elektronika ir Elektrotechnika Journal, vol. 21, no. 5, pp. 90–95, 2015.
[25] D.-B. Ha and Q. S. Nguyen, “Outage performance of energy harvesting DF relaying NOMA networks,” Mobile Networks and Applications, 2017.
[26] X. Pei, W. Duan, M. Wen, Y.-C. Wu, H. Yu, and V. Monteiro, “Socially-aware joint resource allocation and computation offloading in non-orthogonal energy harvesting massive iot,” IEEE Internet of Things Journal, 2020.
[27] C. Li, J. Tang, Y. Zhang, X. Yan, and Y. Luo, “Energy efficient computation offloading for nonorthogonal multiple access assisted mobile edge computing with energy harvesting devices,” Computer Networks, vol. 164, p. 106890, 2019.
[28] F. Wang and X. Zhang, “Dynamic computation offloading and resource allocation over mobile edge computing networks with energy harvesting capability,” in IEEE International Conference on Communications (ICC), Kansas City, MO, USA, May 2018.
[29] F. Zhou, Y. Wu, R. Q. Hu, and Y. Qian, “Computation efficiency in a wireless-powered mobile edge computing network with NOMA,” in IEEE International Conference on Communications (ICC), Shanghai, China, 20-24 May 2019, 2019.
[30] F. Giust, V. Sciancalepore, D. Sabello, M. C. Filippou, S. Mangiante, W. Featherstone, and D. Munaretto, “Multi-access edge computing: The driver behind the wheel of 5g-connected cars,” IEEE Communications Standards Magazine, vol. 2, no. 3, pp. 66–73, 2018.
[31] P. Varga, J. Peto, A. Franko, D. Balla, D. Haja, F. Janký, G. Soos, D. Ficzere, M. Maliszcz, and L. Toka, “5G support for industrial iot applications-challenges, solutions, and research gaps,” Sensors, vol. 20, no. 3, p. 828, 2020.
[32] L. Tao, Z. Li, and L. Wu, “Outlet: outsourcing wearable computing to the ambient mobile computing edge,” IEEE Access, vol. 6, pp. 18408–18419, 2018.
A. Dogay and K. K. Gunes, “Diversity combining for RF energy harvesting,” in IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, NSW, Australia, Jun. 2017, pp. 1–5.

J. Xia, L. Fan, N. Yang, Y. Deng, T. Q. Duong, G. K. Karagiannidis, and A. Nallanathan, “Opportunistic access point selection for mobile edge computing networks,” IEEE Transactions on Wireless Communications, 2020.

Y. Ye, R. Q. Hu, G. Lu, and L. Shi, “Enhance latency-constrained computation in mec networks using uplink noma,” IEEE Transactions on Communications, vol. 68, no. 4, pp. 2409–2425, 2020.

Q. Gu, G. Wang, J. Liu, R. Fan, D. Fan, and Z. Zhong, “Optimal offloading with non-orthogonal multiple access in mobile edge computing,” in 2018 IEEE Global Communications Conference (GLOBECOM). IEEE, 2018, pp. 1–5.

Y. Wu, L. P. Qian, K. Ni, C. Zhang, and X. Shen, “Delay-minimization nonorthogonal multiple access enabled multi-user mobile edge computation offloading,” IEEE Journal of Selected Topics in Signal Processing, vol. 13, no. 3, pp. 392–407, 2019.

I. Gradshteyn and I. Ryzhik, Table of Integrals, Series, and Products, D. Zwillinger, Ed. Elsevier Academic Press, 2007.

Van-Truong Truong received a B.S. degree in Electronics and Telecommunication journals, such as IEICE Transactions, Journal of Communications and Network, Wireless Communications and Mobile Computing, IETE Journal of Research, Elektronika ir Elektrotechnika, Wireless Personal Communications, IET Communications, Mobile Networks and Applications, IEEE Access, and IEEE System. Engineering and an M.Sc. in Electronic Engineering from the University of Da Nang, Vietnam. He is currently a Ph.D. student and lecturer of the Faculty of Electrical and Electronics Engineering, Duy Tan University, Da Nang, Vietnam. His research interests include non-orthogonal multiple access, wireless sensor networks, mobile edge computing and the IoT.

Yoonill Lee is currently a faculty of Electrical Engineering Technology at the College of Lake County, Grayslake, IL. He earned his B.S. and M.S. in Electrical Engineering from Yonsei University in Seoul, South Korea, in 1984, 1986, respectively, and M.S. in Electrical Engineering from Oklahoma State University in Stillwater, OK in 1992, and Ph.D. in Electrical Engineering from the University of South Florida in Tampa, FL in 2001. He worked at Cisco Systems as a communications engineer. His research interests include CDMA, Multi-Carrier Systems, MIMO Technology, and Physical Layer Security in Wireless Communication Systems. He has published several papers for IEEE and holds a U.S. patent.

Dac-Binh Ha received the B.S. degree in Radio Technique, the M.Sc. and Ph.D. degree in Communication and Information System from Huazhong University of Science and Technology (HUST), China in 1997, 2006, and 2009, respectively. He is currently the Dean of Faculty of Electrical and Electronics Engineering, Duy Tan University, Da Nang, Vietnam. His research interests include secrecy physical layer communications, MIMO systems, combining techniques, cooperative communications, cognitive radio, wireless energy harvesting networks and image processing. He has published several papers on ISI/SCI/SCIE index