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Outage Analysis in SWIPT Enabled Cooperative AF/DF Relay Assisted Two-Way Spectrum Sharing Communication

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Abstract

This paper reports relative performance of decode-and-forward (DF) and amplify-and-forward (AF) relaying in a multi-antenna cooperative cognitive radio network (CCRN) that supports device-to-device (D2D) communications using spectrum sharing technique in cellular network. In this work, cellular system is considered as primary and internet of things devices (IoDs), engaged in D2D communications, are considered to be secondary system. The devices access the licensed spectrum by means of the cooperation in two-way primary communications. Furthermore, IoDs are energized by harvesting the energy from radio frequency (RF) signals, using simultaneous wireless information and power transfer (SWIPT) protocol. Closed form expressions of outage probability for both cellular and D2D communications are derived and the impact of various design parameters for both AF and DF relaying techniques are studied. Based on the simulation results, it is found that the proposed spectrum sharing protocol, for both DF relaying and AF relaying schemes, outperform another similar network architecture in terms of spectrum efficiency. It is also observed that the performance of the proposed system using DF relaying is better than AF relaying scheme in terms of energy efficiency at same transmit power.

Keywords : Spectrum sharing, simultaneous wireless information and power transfer, two-way relay network, cooperative cognitive radio network, energy efficiency.

I. INTRODUCTION

Internet-of-things (IoT) is now under extensive development phase to support the needs of short packet (few information bytes) delivery (through frequency access or sharing) at ultra-high reliability (low outage) and low latency (through efficient routing). Device-to-Device (D2D) communication looks promising in IoT networks due to enhanced battery life and service availability [1]. It also improves the proximity gain and pairing gain of radio spectrum without any involvement of cellular base station (BS), especially when the radio frequency spectrum is shared between D2D and cellular users [2]. Congestion due to proliferation of wireless networks in unlicensed band urges the essence of sharing of the spectrum, originally licensed to cellular users, so as to support future IoT communication [3].

Cooperative cognitive radio network (CCRN) refers to a network model that facilitates overlay mode of cognitive radio enabled spectrum sharing [4] and could be applied in D2D communication in 5G heterogeneous networks (HetNets). Following this, the pair of IoT devices (IoDs), using D2D communication as unlicensed users, may be viewed as secondary users (SUs), while cellular nodes (i.e. evolved Node-B (eNB) and user equipment (UE)) can be modelled as primary users (PUs). IoDs can access the licensed spectrum of cellular system while agreeing to relay the signals of the latter, thereby improving the reliability of their communication over the fading wireless channel. In literature, two-way communications [5] based on CCRN is studied to achieve higher spectrum efficiency (SE) over the one-way relaying [6]. The outage performance of the two-way CCRN is studied in [5] and the impact of different relaying schemes on spectrum efficient network operation is reported.

Recently, radio frequency energy harvesting (RF-EH) based relaying using simultaneous wireless information and power transfer (SWIPT) protocol has been under investigation to enhance network lifetime and reliability of wireless communication [7]-[9]. SU transmitter of CCRN may follow amplify-and-forward (AF) or, decode-and-forward (DF) relaying to support PU communication and send its own message to SU receiver using the energy harvested from the received PU signal. Relay node harvests the energy from the PU signal by following power splitting (PS) or, time switching (TS) based SWIPT protocols [10]. Performances of unidirectional or bidirectional communication using AF and DF relay aided SWIPT network are analysed in [11]-[13], [15]. The system outage performances of One-way DF relay assisted communication in CCRN is studied in [11] over a Nakagami fading channel. In [12], PU and SU outage performances are studied in two-way CCRN using AF relay assisted network. The authors of [12] also show the impact of energy conversion efficiency on the system energy efficiency (EE). The performance of similar network model is studied in [13] using DF relay. Based on the study of [13], it is shown that DF relay-assisted two-way communication is significantly more spectrum efficient than one-way communication [11] using PS relaying (PSR) protocol. However, privacy and security issues may be of concern as DF relay is required to decode PU message during the relaying process [14]. On the contrary, in AF relaying, PU signal does not need to be decoded at the relaying node, although, it is often

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TABLE I
SYMBOLS AND DEFINITIONS

Symbols	Definitions
X_s	Signal transmission between IoD ₁ (SU ₁) and IoD ₂ (SU ₂)
P_{p_1}, P_{p_2}	Transmission power of PU ₁ , PU ₂
$\mathbf{h}_i$	Channel gain of link PU _i → SU ₁ ($i \in 1, 2$)
$\mathbf{g}_i$	Channel gain of link PU _i → SU ₂ ($i \in 1, 2$)
D_i	Distance between PU _i and SU ₁ ($i \in 1, 2$)
D_j	Distance between PU _i and SU ₂ (for $i=1, j=4$ and $i=2, j=5$)
n_{su}, n_{pu}	Received noise at SU, PU, respectively
h_3	Channel gain of link SU ₁ → SU ₂
ρ	Power splitting factor of SU ₁
α	Power sharing factor at SU ₁
L	Distance between PU ₁ and PU ₂
D_3	Distance between SU ₁ and SU ₂
m	Path loss exponent
η	Energy conversion efficiency at SU ₁
R_{PU}, R_{SU}	Target rate of PU and SU communication, respectively

considered to be an energy inefficient approach as noise gets amplified by the relay node. The performance improvement of SU communication over [13] is studied in [15] using bidirectional SU communication. Needless to mention that the presence of multiple antennas at the source and or the relay in any SWIPT enabled relay assisted communication over fading channel would not only improve the reliability of information transfer, but also enhances in energy harvesting at the relay node. Motivated by this, a preliminary study on the performance of the same system model [13] with multiple antenna PUs is presented in [16]. In this paper, a comparative study between DF and AF relaying scheme is presented using PS protocol in CCRN.

Scope and Contributions:

The work in [13] follows three-phase communication using DF relaying with a single-antenna in a CCRN framework. However, it does not explore the impact of multi-antenna on SE and EE aspects of the proposed D2D operation in 5G HetNets. Two-phase communication is more preferable over three-phase to enhance the system throughput. This leads us to explore the problem of spectrum sharing for bidirectional cellular communication and unidirectional D2D communication simultaneously. To offer improved SE, the present cellular system use multiple antennas, the trend seen on 5G [17]. To make this study more general, non-identical number of antennas are considered at two ends of the PU system. The nodes engaged in D2D communication are equipped with necessary hardware to harvest energy from the RF signals of the cellular users. EH meets the energy requirement of the transmitting node for D2D communication to relay (AF/DF) the signals of cellular users and also its own message transmission over the cellular spectrum simultaneously. The main objective of this work is to highlight the relative improvements in SE and EE performances of AF and DF relaying as the PU system moves from single antenna to multi-antenna system. Our contributions can be summarized as follows.

- A novel CCRN architecture with multi-antenna PU system is proposed where two-phase protocol supports two-way SWIPT enabled communications between the pair of cellular users (PUs) and also one-way D2D (SU-to-SU) communication. Two fold benefits, the first one is the improved SE due to multi-antenna and the other one is the throughput improvement due to two-phase protocol are achieved.
- Closed form expressions of both PU and SU outage probability are derived for both DF and AF relay assisted communication using PSR protocol for multi-antenna CCRN framework. Simulation results closely match the analytical expressions.
- The exact dependence of the system performance on various parameters like power sharing factor, power splitting factor, transmission power is also shown through the simulation results. DF relaying mostly performs better than AF relaying. As we have used two-phase spectrum sharing protocol, therefore both of the relaying mechanisms show almost equally spectrum efficiency compared to the similar network architecture [13]. However, AF relaying is found to be better in terms of incremental improvement in SE with increase in the number of antennas.

The various symbols used are introduced in Table I. The remaining part of the paper is arranged as follows. The system model is described in Section II and communication protocol description is given in Section III. The outage performance of both PU and SU are analysed in Section IV. The necessary simulation and the numerical results in terms of the various system parameters is presented in Section V. Finally, the paper is concluded in Section VI.

II. SYSTEM MODEL

A. Assumptions and Notations

The system model consists of a pair of eNB and UE in long term evolution (LTE) network architecture as depicted in Fig. 1. The eNB and UE are equipped with multiple antennas N_a and N_b , respectively. In absence of direct communication link, the cellular nodes (eNB and UE) intend to exchange their information via a single antenna IoT device (IoD) (denoted as IoD₁ in Fig. 1.), aiming to achieve the target rate of R_{PU} at each side.

Simultaneously, IoD_1 sends its own message signal to IoD_2 to meet a target rate of R_{SU} . Both of them use single antenna for communication. Here eNB and UE are considered as PU_1 and PU_2 , respectively and IoD_1 and IoD_2 are modelled as SU_1 and SU_2 , respectively.

Fig. 1. System model

We assume that PU_i , ($i \in 1, 2$) uses fixed power supply, i.e., P_{p_i} , SU_1 is powered through harvested energy from PUs' RF signals, using SWIPT, for relaying PUs' messages and transmitting to SU_2 . We consider both DF and AF relaying mechanisms to support the two-way PU communications. $\mathbf{h}_i = [h_{i,1}, h_{i,2}, \dots, h_{i,N_p}]$, ($N_p \in N_a, N_b$) and $\mathbf{g}_i = [g_{i,1}, g_{i,2}, \dots, g_{i,N_p}]$, ($i \in 1, 2$) are the vector channel coefficients from the multiple-antenna PU_i to SU_1 and PU_i to SU_2 , respectively, where $h_{i,n} \sim \mathcal{CN}(0, 1)$ and $g_{i,n} \sim \mathcal{CN}(0, 1)$. Channel between $\text{SU}_1 \rightarrow \text{SU}_2$ is represented by h_3 , where $h_3 \sim \mathcal{CN}(0, 1)$. All the channel distribution between PU and SU links follow independent and identically distributed (i.i.d) Rayleigh fading. Due to short distance the link between SU_1 and SU_2 is considered as Nakagami- m fading. The instantaneous channel state information (CSI) is assumed to be unavailable at PU_i ($i \in 1, 2$). It is also considered that the full-diversity space-time codes (like GABBA codes [18]) are used at the PU nodes. Normally, in space-time code, power is uniformly distributed among the transmitting antennas. The distances between the users PU_1 – SU_1 , PU_2 – SU_1 , PU_1 – SU_2 , PU_2 – SU_2 and SU_1 – SU_2 are given by D_1, D_2, D_4, D_5 and D_3 , respectively with ' m ' as the path-loss exponent. Here n_{su} and n_{pu} indicate the received noise at SU and PU, respectively. These noises are additive white Gaussian noise (AWGN) with zero (0) mean and the variance σ^2 .

B. Protocol description

The two-way communications between PU_1 and PU_2 via SU_1 take place in two time phases viz., multiple access channel (MAC) and broadcast (BC) phase, as shown in Fig. 2. In the MAC phase, both PU_1 and PU_2 simultaneously transmit their information signals to SU_1 . SU_1 is able to harvest energy from part of the received signal using PSR protocol. In the case of AF relaying, SU_1 broadcasts an amplified PU signal superimposed with the SU signal X_s in the BC phase, using the total harvested energy. The PU receivers are able to receive the signals using the maximal-ratio-combining (MRC) and separate the desired signal using the self-interference cancellation (SIC). Now, decoding of SU_1 's message at SU_2 is performed in the two phases; first the stronger PU signal is decoded considering SU_1 's desired signal as interference. Once the strong PU signal is separated from the received signal in the first phase, SU_2 decodes the desired SU_1 's signal in presence of channel noise.

In the case of DF relaying, SU_1 first decodes the PUs' message signals received in the MAC phase, and then broadcasts a network coded primary signal superimposed on the secondary signal X_s in the BC phase. Both the PU nodes decode the network coded (XOR operation) PU signal in presence of SU interfering signal and noise. Thereafter, SU_2 decodes SU_1 signal by cancelling PU signal's based on the PUs' messages received previously in the MAC Phase.

Fig. 2. Transmission frame structure in the two-way PSR protocol

III. RATE AND OUTAGE ANALYSIS IN DF RELAYING

A. Rate Analysis

Now the received power in MAC phase at SU_1 from PU_1 and PU_2 can be expressed as follows¹ [19].

$$P_{SU_1}^{(1)} = \frac{P_{p1}}{N_a(D_1)^m} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{P_{p2}}{N_b(D_2)^m} \sum_{p=1}^{N_b} |h_{2,p}|^2 \quad (1)$$

where P_{p1} and P_{p2} are the transmit powers of PU_1 and PU_2 , respectively.

Similarly, the received power at SU_2 from PU_1 and PU_2 can be expressed as

$$P_{SU_2}^{(1)} = \frac{P_{p1}}{N_a(D_4)^m} \sum_{n=1}^{N_a} |g_{1,n}|^2 + \frac{P_{p2}}{N_b(D_5)^m} \sum_{p=1}^{N_b} |g_{2,p}|^2 \quad (2)$$

A part ρ (referred to as power splitting factor in the subsequent discussion) of the received signal power at SU_1 is used for energy harvesting, and the rest $(1-\rho)$ portion is used for information processing. The harvested energy in MAC phase is given by

$$E_s = \eta \rho \left(\frac{P_{p1}}{N_a(D_1)^m} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{P_{p2}}{N_b(D_2)^m} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right) \frac{T}{2} \quad (3)$$

where $0 < \eta < 1$ represents the energy conversion efficiency. After power splitting, the received power in MAC phase at the receiver of SU_1 for information processing is given by

$$P_{SU_1}^{(1,IT)} = (1-\rho) \left[\frac{P_{p1}}{N_a(D_1)^m} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{P_{p2}}{N_b(D_2)^m} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right] \quad (4)$$

Now following the linear EH model, the available power at SU_1 for transmission in the BC phase is given by

$$P_s = \eta \rho \left(\frac{P_{p1}}{N_a(D_1)^m} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{P_{p2}}{N_b(D_2)^m} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right) \quad (5)$$

In the MAC phase, the successful decoding of the received signals from PU_1 and PU_2 is possible at SU_1 , if $R_{SU_1}^{(1)} \geq R_{PU}$, $R_{SU_1}^{(2)} \geq R_{PU}$ and $R_{SU_1}^{\sum} \geq 2R_{PU}$ [20], where

$$Q_1 = \begin{cases} R_{SU_1}^{(11)} = \frac{T}{2T} \log_2 \left(1 + \frac{(1-\rho)P_{p1}}{N_a(D_1)^m \sigma^2} \sum_{n=1}^{N_a} |h_{1,n}|^2 \right), \\ R_{SU_1}^{(12)} = \frac{T}{2T} \log_2 \left(1 + \frac{(1-\rho)P_{p2}}{N_b(D_2)^m \sigma^2} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right), \\ R_{SU_1}^{\sum} = \frac{T}{2T} \log_2 \left(1 + \frac{(1-\rho)P_{p1}}{N_a(D_1)^m \sigma^2} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{(1-\rho)P_{p2}}{N_b(D_2)^m \sigma^2} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right) \end{cases} \quad (6)$$

Similarly, in the MAC phase, the successful decoding of the received signals from PU_1 and PU_2 is possible at SU_2 , if $R_{SU_2}^{(1)} \geq R_{PU}$, $R_{SU_2}^{(2)} \geq R_{PU}$ and $R_{SU_2}^{\sum} \geq 2R_{PU}$, where

$$Q_2 = \begin{cases} R_{SU_2}^{(11)} = \frac{1}{2} \log_2 \left(1 + \frac{P_{p1}}{N_a(D_4)^m \sigma^2} \sum_{n=1}^{N_a} |g_{1,n}|^2 \right), \\ R_{SU_2}^{(12)} = \frac{1}{2} \log_2 \left(1 + \frac{P_{p2}}{N_b(D_5)^m \sigma^2} \sum_{p=1}^{N_b} |g_{2,p}|^2 \right), \\ R_{SU_2}^{\sum} = \frac{1}{2} \log_2 \left(1 + \frac{P_{p1}}{N_a(D_4)^m \sigma^2} \sum_{n=1}^{N_a} |g_{1,n}|^2 + \frac{P_{p2}}{N_b(D_5)^m \sigma^2} \sum_{p=1}^{N_b} |g_{2,p}|^2 \right) \end{cases} \quad (7)$$

In DF relaying, SU_1 uses α ($0 < \alpha < 1$) fraction of its total transmit power P_s to relay the network-coded primary information and rest $(1-\alpha)$ fraction of P_s is used to send its own independent message X_s to SU_2 .

¹In absence of CSI, PU_1 and PU_2 are assumed to use suitable space-time coding techniques, the details of which are not within the scope of our current study.

After MRC and cancellation of self-interference terms by applying SIC technique, the received signal-to-interference-noise ratio (SINR) at PU_i ($i \in 1, 2; N_p \in N_a, N_b$) receivers in BC phase can be expressed as

$$\gamma_i^{DF} = \frac{\frac{\alpha P_s}{(D_i)^m} \sum_{w=1}^{N_p} |h_{i,w}|^2}{\frac{(1-\alpha)P_s}{(D_i)^m} \sum_{w=1}^{N_p} |h_{i,w}|^2 + \sigma^2} \quad (8)$$

It is assumed that SU_2 , like SU_1 , succeeds in decoding the PUs' signals received in MAC phase. Based on these prior knowledges, SU_2 is able to separate the desired SU signal from the PUs' interference received in BC phase [13]. Therefore, the received signal at SU_2 can be rewritten as

$$Y_{SU_2}^{(2,DF)} = \underbrace{\sqrt{\frac{(1-\alpha)P_s}{D_3^m}} h_3 X_s}_{\text{Required signal}} + \underbrace{n_{su}}_{\text{Noise}} \quad (9)$$

Now, the achievable rate at PU_i is given by (based on the SINR at PU_i) ($w \in n, p$)

$$R_{PU_i}^{(2,DF)} = \frac{1}{2} \log_2 \{1 + \gamma_i^{DF}\} = \frac{1}{2} \log_2 \left\{ 1 + \frac{a'_i (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{w=1}^{N_p} |h_{i,w}|^2}{b'_i (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{w=1}^{N_p} |h_{i,w}|^2 + 1} \right\} \quad (10)$$

where $a_1 = \eta \rho \frac{P_{p1}}{N_a (D_1)^m \sigma^2}$, $b_1 = \eta \rho \frac{P_{p2}}{N_b (D_2)^m \sigma^2}$, $a'_i = \frac{\alpha}{(D_i)^m}$, $b'_i = \frac{(1-\alpha)}{(D_i)^m}$.

Based on (9), the achievable rate at SU_2 is expressed as

$$R_{SU_2}^{(2,DF)} = \frac{1}{2} \log_2 \left\{ 1 + \frac{(\frac{1-\alpha}{D_3^m}) |h_3|^2}{\sigma^2} \right\} = \frac{1}{2} \log_2 \left\{ 1 + c (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) |h_3|^2 \right\} \quad (11)$$

where $c = \frac{(1-\alpha)}{D_3^m}$.

B. Outage Probability Analysis

An outage occurs when the achievable rate of data transmission on any transmission link falls below the target rate of data transmission.

1) *Outage Probability Analysis of Primary System:* Based on the definition, PU outage probability² using DF relaying mechanism can be determined as follows [13]:

$$\begin{aligned} \mathcal{P}_{out}^{(PU,DF)} &= 1 - \underbrace{\left[\underbrace{\mathcal{P}\{Q_1\}}_{\text{MAC phase}} \times \underbrace{\mathcal{P}\{\min(R_{PU_1}^{(2,DF)}, R_{PU_2}^{(2,DF)}) \geq R_{PU}\}}_{\text{BC phase}} \right]}_{\text{Success Probability}} \\ &= 1 - \left[\mathcal{P}\{Q_1\} \times \mathcal{P}\{R_{PU_1}^{(2,DF)} \geq R_{PU}\} \times \mathcal{P}\{R_{PU_2}^{(2,DF)} \geq R_{PU}\} \right] \quad (12) \end{aligned}$$

Applying (6), the success probability of data transmission between both of the PU nodes (PU_1 and PU_2) and SU_1 is expressed by following three conditions satisfied together.

$$Q_1 = \begin{cases} R_{SU_1}^{(11)} = \frac{1}{2} \log_2 (1 + A_1 X_1) \geq R_{PU}, \\ R_{SU_1}^{(12)} = \frac{1}{2} \log_2 (1 + A_2 Y_1) \geq R_{PU}, \\ R_{SU_1}^{\Sigma} = \frac{1}{2} \log_2 (1 + A_1 X_1 + A_2 Y_1) \geq 2R_{PU} \end{cases} \quad (13)$$

where $A_1 = \frac{(1-\rho)P_{p1}}{N_a (D_1)^m \sigma^2}$, $A_2 = \frac{(1-\rho)P_{p2}}{N_b (D_2)^m \sigma^2}$, $u_1 = 2^{(2R_{PU})} - 1$, $u_2 = 2^{(2R_{PU})} - 1$, $u_3 = 2^{(4R_{PU})} - 1$.

$X_1 = \sum_{n=1}^{N_a} |h_{1,n}|^2$ and $Y_1 = \sum_{p=1}^{N_b} |h_{2,p}|^2$ follow the same nature of gamma distribution with N_p degree of freedom. The probability density function (PDF) can be expressed as $f_X(x) = \frac{x^{N_p-1} \exp(-\frac{x}{1/N_p})}{\Gamma(N_p) (1/N_p)^{N_p}}$. Based on (13), $\mathcal{P}\{Q_1\}$ can be expressed as [21, Sec. 3.381.1, 3.381.3, 8.350.1, 8.352.1]

$$\begin{aligned} \mathcal{P}\{Q_1\} &= \int_{\frac{u_1}{A_1}}^{\infty} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a) (1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\infty} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b) (1/N_b)^{N_b}} dy_1 \right\} dx_1 - \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a) (1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\frac{u_3-A_1 x_1}{A_2}} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b) (1/N_b)^{N_b}} dy_1 \right\} dx_1 \\ &= \frac{1}{\Gamma(N_a) \Gamma(N_b)} \Gamma\left(N_a, N_a u_1 / A_1\right) \Gamma\left(N_b, N_b u_2 / A_2\right) - \left\{ \frac{1}{\Gamma(N_a)} - \frac{\gamma\left(N_b, N_b \frac{u_2}{A_2}\right)}{\Gamma(N_a) \Gamma(N_b)} \right\} \left\{ \gamma\left(N_a, N_a \frac{u_3-u_1}{A_1}\right) - \gamma\left(N_a, N_a \frac{u_1}{A_1}\right) \right\} \\ &+ \sum_{q_a=0}^{N_b-1} \frac{\exp\left(-\frac{N_b u_3}{A_2}\right) \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a-q}}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (1/N_b)^{q_a} A_2^{q_a}} \frac{A_1^q}{\left(N_a - \frac{A_1 N_b}{A_2}\right)^{(N_a+q)}} \left\{ \gamma\left[N_a + q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_3-u_1}{A_1}\right] - \gamma\left[N_a + q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_1}{A_1}\right] \right\} \quad (14) \end{aligned}$$

Proof : See Appendix A.

where $\Gamma(.,.)$ and $\gamma(.,.)$ are the upper and the lower incomplete gamma function, respectively.

²Since SU_1 is used as a relay to support PU communication, therefore the successful information transmission from both the PU nodes to SU_1 is essential in MAC phase for relaying the information in BC phase.

The probability of successful data transmission from SU_1 to PU_1 can be written as

$$R_{PU_1}^{(2,DF)} = \frac{1}{2} \log_2 \{1 + \gamma_1^{DF}\} = \frac{1}{2} \log_2 \left\{ 1 + \frac{a'_1 (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{n=1}^{N_a} |h_{1,n}|^2}{b'_1 (\sum_{n=1}^{N_a} a_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} b_1 |h_{2,p}|^2) \sum_{n=1}^{N_a} |h_{1,n}|^2 + 1} \right\} \quad (15)$$

$$\mathcal{P} \left\{ R_{PU_1}^{(2,DF)} \geq R_{PU} \right\} = \mathcal{P} \left\{ \frac{a'_1 (a_1 X_1 + b_1 Y_1) X_1}{b'_1 (a_1 X_1 + b_1 Y_1) X_1 + 1} \geq u_1 \right\} = \begin{cases} 1 - \mathcal{P} \left\{ X_1 \leq \frac{k'}{(a_1 X_1 + b_1 Y_1)} \right\}, & \text{for } u_1 < \frac{\alpha}{(1-\alpha)} \\ 1 - \mathcal{P} \left\{ X_1 \geq \frac{k'}{(a_1 X_1 + b_1 Y_1)} \right\} = 0, & \text{otherwise.} \end{cases} \quad (16)$$

where $k' = \frac{u_1}{a'_1 - u_1 b'_1}$. Now, the solution to (16) is obtained as (17) [21, Sec. 8.350.1, 8.352.1].

$$\mathcal{P} \left\{ X_1 \leq \frac{k'}{(a_1 X_1 + b_1 Y_1)} \right\} = \mathcal{P} \left(Y_1 \leq \frac{k'}{b_1 X_1} - \frac{a_1 X_1}{b_1} \right) = \frac{1}{\Gamma(N_a)} \gamma \left(N_a, \frac{\sqrt{\frac{k'}{a_1}}}{1/N_a} \right) - \left[\sum_{p_a=0}^{N_b-1} \frac{N_a^{N_a} N_b^{p_a}}{p_a! \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k'}{b_1} \right)^{p_a-r} \left(\frac{a_1}{b_1} \right)^r \sum_{l=0}^{\infty} \sum_{t_l=0}^l \binom{l}{t_l} \frac{(-1)^l}{l! (2r+N_a-p_a-l+2t_l)} \left(\frac{k' N_b}{b_1} \right)^{l-t_l} \left(N_a - \frac{a_1 N_b}{b_1} \right)^{t_l} \left(\sqrt{\frac{k'}{a_1}} \right)^{2r+N_a-p_a-l+2t_l} \right] \quad (17)$$

Proof : See Appendix B.

Similarly, the probability of successful data transmission from SU_1 to PU_2 can be written as

$$\mathcal{P} \left\{ Y_1 \leq \frac{k''}{(a_1 X_1 + b_1 Y_1)} \right\} = \mathcal{P} \left(X_1 \leq \frac{k''}{a_1 Y_1} - \frac{b_1 Y_1}{a_1} \right) = \frac{1}{\Gamma(N_b)} \gamma \left(N_b, \frac{\sqrt{\frac{k''}{b_1}}}{1/N_b} \right) - \left[\sum_{p_a=0}^{N_a-1} \frac{N_b^{N_b} N_a^{p_a}}{p_a! \Gamma(N_b)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k''}{a_1} \right)^{p_a-r} \left(\frac{b_1}{a_1} \right)^r \sum_{l=0}^{\infty} \sum_{t_l=0}^l \binom{l}{t_l} \frac{(-1)^l}{l! (2r+N_b-p_a-l+2t_l)} \left(\frac{k'' N_a}{a_1} \right)^{l-t_l} \left(N_b - \frac{b_1 N_a}{a_1} \right)^{t_l} \left(\sqrt{\frac{k''}{b_1}} \right)^{2r+N_b-p_a-l+2t_l} \right] \quad (18)$$

where $k'' = \frac{u_1}{a'_2 - u_1 b'_2}$.

The closed form solution to PU outage probability can be determined using (14), (17)-(18).

Closed form expression of PU outage probability using DF relaying is given in Appendix F.

2) *Outage Probability Analysis of Secondary System:* SU outage probability³ using DF relaying is shown as follows:

$$\mathcal{P}_{out}^{(SU,DF)} = 1 - \overbrace{\left[\mathcal{P}\{Q_1\} \times \mathcal{P}\{Q_2\} \times \mathcal{P}\{R_{SU_2}^{(2,DF)} \geq R_{SU}\} \right]}^{\text{Success Probability}} \quad (19)$$

MAC Phase BC Phase

Similar to (13), the probability of success due to data transmission from PU_i ($i \in 1, 2$) to SU_2 is defined by the following three conditions together.

$$Q_2 = \begin{cases} R_{SU_2}^{(11)} = \frac{1}{2} \log_2 (1 + B_1 X_2) \geq R_{PU}, \\ R_{SU_2}^{(12)} = \frac{1}{2} \log_2 (1 + B_2 Y_2) \geq R_{PU}, \\ R_{SU_2}^{\Sigma} = \frac{1}{2} \log_2 (1 + B_1 X_2 + B_2 Y_2) \geq 2R_{PU} \end{cases} \quad (20)$$

where $B_1 = \frac{P_{p1}}{N_a(D_1)^m \sigma^2}$, $B_2 = \frac{P_{p2}}{N_b(D_2)^m \sigma^2}$.

$X_2 = \sum_{n=1}^{N_a} |g_{1,n}|^2$ and $Y_2 = \sum_{p=1}^{N_b} |g_{2,p}|^2$ follow the same nature of gamma distribution like X_1 and Y_1 , respectively.

Based on (20), $\mathcal{P}\{Q_2\}$ can be expressed as follows

$$\mathcal{P}\{Q_2\} = \frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma \left(N_a, N_a u_1 / B_1 \right) \Gamma \left(N_b, N_b u_2 / B_2 \right) - \left\{ \frac{1}{\Gamma(N_a)} - \frac{\gamma \left(N_b, N_b \frac{u_2}{B_2} \right)}{\Gamma(N_a)\Gamma(N_b)} \right\} \left\{ \gamma \left(N_a, N_a \frac{u_3 - u_1}{B_1} \right) - \gamma \left(N_a, N_a \frac{u_1}{B_1} \right) \right\} \\ + \sum_{q_a=0}^{N_b-1} \frac{\exp \left(-\frac{N_b u_3}{B_2} \right) \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a} u_3^{-q}}{q_a! \Gamma(N_a) \left(1/N_a \right)^{N_a} \left(1/N_b \right)^{q_a} B_2^{q_a}} \left(\frac{B_1}{N_a - \frac{B_1 N_b}{B_2}} \right)^{(N_a+q)} \left\{ \gamma \left[N_a + q, \left(N_a - \frac{B_1 N_b}{B_2} \right) \frac{u_3 - u_1}{B_1} \right] - \gamma \left[N_a + q, \left(N_a - \frac{B_1 N_b}{B_2} \right) \frac{u_1}{B_1} \right] \right\} \quad (21)$$

Following (11), the probability of successful data transmission between the link SU_1 to SU_2 is expressed as

$$\mathcal{P}(R_{SU_2}^{(2,DF)} \geq R_{SU}) = \mathcal{P} \left(Z \geq \frac{u_4}{c(a_1 X_1 + b_1 Y_1)} \right) \quad (22)$$

where $u_4 = 2^{(2R_{SU})} - 1$. $Z = |h_3|^2$ and it follows the gamma distribution with Nakagami shaping parameter m_k . The

PDF of Z can be described as $f_Z(z) = \frac{z^{m_k-1} \exp(-\frac{z}{m_k})}{\Gamma(m_k) (1/m_k)^{m_k}}$.

³Since SU_2 needs to decode the message of SU_1 by removing PUs message in BC phase, therefore successful information transmission from both PUs to SU_1 is necessary in MAC phase.

Now (22) can be evaluated as follows [21, Sec. 3.471.9, 8.352.2]:

$$\begin{aligned} \mathcal{P}(R_{SU_2}^{(2,DF)} \geq R_{SU}) &= \sum_{p_a=0}^{N_b-1} \frac{\binom{N_b}{b_1}^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \frac{1}{\left(N_a - \frac{a_1 N_b}{b_1}\right)^{N_a+r}} \frac{\Gamma(N_a+r)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \\ &\left[2 \left\{ \frac{u_4 N_b}{c b_1 m_k} \right\}^{(m_k-p_a+r)/2} K_{m_k-p_a+r} \left\{ 2 \sqrt{\frac{u_4 N_b m_k}{c b_1}} \right\} - \sum_{j=0}^{N_a+r-1} \frac{1}{j!} \left[\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{c a_1} \right]^j 2 \left\{ \frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{c a_1 m_k} + \frac{u_4 N_b}{c b_1 m_k} \right\}^{\frac{(m_k-p_a+r-j)}{2}} \right. \\ &\left. K_{m_k-p_a+r-j} \left\{ 2 \sqrt{\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{c a_1} + \frac{u_4 N_b m_k}{c b_1}} \right\} \right] + \left[\sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{c a_1}\right)^{p_a} (m_k)^{m_k}}{p_a! \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{c a_1 m_k}\right)^{(m_k-p_a)/2} K_{m_k-p_a} \left(2 \sqrt{\frac{u_4 N_a m_k}{c a_1}}\right) \right] \end{aligned} \quad (23)$$

Proof : See Appendix C.

Finally, the closed form SU outage expression using DF relaying can be determined using (14), (21) and (23). Closed form expression of SU outage probability using DF relaying is given in Appendix G.

IV. RATE & OUTAGE ANALYSIS OF AF RELAYING

A. Rate Analysis

In the BC phase of AF relaying, SU_1 broadcasts an amplified version of the signal generated after combining the PU signals, received in the MAC phase. To include this in the analysis, harvested power P_s in (5) is normalized using the factor ξ^4 , expressed as

$$\begin{aligned} \xi &= \sqrt{\frac{1}{(1-\rho) \left[\frac{P_{p1}}{N_a (D_1)^m} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{P_{p2}}{N_b (D_2)^m} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right] + \sigma^2}} \\ &\approx \sqrt{\frac{1}{(1-\rho) \left[\frac{P_{p1}}{N_a (D_1)^m} \sum_{n=1}^{N_a} |h_{1,n}|^2 + \frac{P_{p2}}{N_b (D_2)^m} \sum_{p=1}^{N_b} |h_{2,p}|^2 \right]}} \end{aligned} \quad (24)$$

Based on the superposition coding and AF relaying principle SU_1 uses α ($0 < \alpha < 1$) the fraction of its total transmit power P_s to relay the combined signal of primary information and the rest $(1-\alpha)$ portion is used to send its own independent message X_s to SU_2 . As both PUs know their individual transmitted signals, consequently, they are able to cancel their self-interference terms. Therefore, the instantaneous end-to-end SINR at PU_i can be expressed using (25).

$$\gamma_i^{AF} = \frac{\frac{\xi^2 \alpha P_s (1-\rho) P_{pj}}{N_p' (D_i D_j)^m} \sum_{w=1}^{N_p} \sum_{w'=1}^{N_p'} |h_{i,w}|^2 |h_{j,w'}|^2}{\frac{(1-\alpha) P_s \sum_{w=1}^{N_p} |h_{i,w}|^2}{(D_i)^m} + \frac{\xi^2 \alpha P_s \sum_{w=1}^{N_p} |h_{i,w}|^2 \sigma^2}{(D_i)^m} + \sigma^2} = \frac{C_i \sum_{w=1}^{N_p} \sum_{w'=1}^{N_p'} |h_{i,w}|^2 |h_{j,w'}|^2}{H_i \sum_{w=1}^{N_p} |h_{i,w}|^4 + E_i \sum_{w=1}^{N_p} \sum_{w'=1}^{N_p'} |h_{i,w}|^2 |h_{j,w'}|^2 + F_i \sum_{w=1}^{N_p} |h_{i,w}|^2 + 1} \quad (25)$$

where $C_1 = \frac{\eta \rho P_{p2} \alpha}{N_b \sigma^2 (D_1)^m (D_2)^m}$, $C_2 = \frac{\eta \rho P_{p1} \alpha}{N_a \sigma^2 (D_1)^m (D_2)^m}$, $H_1 = \frac{(1-\alpha) \eta \rho P_{p1}}{N_a \sigma^2 (D_1)^{2m}}$, $H_2 = \frac{(1-\alpha) \eta \rho P_{p2}}{N_b \sigma^2 (D_2)^{2m}}$, $E_1 = \frac{(1-\alpha) \eta \rho P_{p2}}{N_b \sigma^2 (D_1 D_2)^m}$, $E_2 = \frac{(1-\alpha) \eta \rho P_{p1}}{N_a \sigma^2 (D_1 D_2)^m}$, $F_1 = \frac{\rho \alpha \eta}{(1-\rho) (D_1)^m}$, $F_2 = \frac{\rho \alpha \eta}{(1-\rho) (D_2)^m}$.

Similarly, SU_2 is able to detect PU signal by considering SU signal as an interference [22]. The instantaneous SINR can be expressed applying (26).

$$\begin{aligned} \gamma_{s,PU}^{AF} &= \frac{\frac{\alpha \eta \rho}{(D_3)^m \sigma^2} |h_3|^2 \left(\sum_{n=1}^{N_a} \frac{P_{p1}}{(D_1)^m N_a} |h_{1,n}|^2 + \sum_{p=1}^{N_b} \frac{P_{p2}}{(D_2)^m N_b} |h_{2,p}|^2 \right)}{\frac{(1-\alpha)}{(D_3)^m \sigma^2} \eta \rho |h_3|^2 \left(\sum_{n=1}^{N_a} \frac{P_{p1}}{(D_1)^m N_a} |h_{1,n}|^2 + \sum_{p=1}^{N_b} \frac{P_{p2}}{(D_2)^m N_b} |h_{2,p}|^2 \right) + \frac{\alpha \eta \rho |h_3|^2}{(1-\rho) (D_3)^m} + 1} \\ &= \frac{|h_3|^2 \left(\sum_{n=1}^{N_a} U_3 |h_{1,n}|^2 + \sum_{p=1}^{N_b} V_3 |h_{2,p}|^2 \right)}{|h_3|^2 \left(\sum_{n=1}^{N_a} U_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} V_1 |h_{2,p}|^2 \right) + U_2 |h_3|^2 + 1} \end{aligned} \quad (26)$$

where $U_1 = \frac{(1-\alpha)}{(D_3)^m \sigma^2} \eta \rho \frac{P_{p1}}{N_a (D_1)^m}$, $V_1 = \frac{(1-\alpha)}{(D_3)^m \sigma^2} \eta \rho \frac{P_{p2}}{N_b (D_2)^m}$, $U_2 = \frac{\alpha}{(D_3)^m (1-\rho)} \eta \rho$, $U_3 = \frac{\alpha \eta \rho P_{p1}}{(D_3 D_1)^m \sigma^2 N_a}$, $V_3 = \frac{\alpha \eta \rho P_{p2}}{(D_3 D_2)^m \sigma^2 N_b}$.

The PU signals being a strong one, SU_2 first decodes PU signals considering SU_1 signal as interference and removes it from the received signal. Then it decodes its own signal in the presence of noise. The instantaneous SNR at SU_2 can be expressed in (27).

$$\gamma_s^{AF} = \frac{\frac{(1-\alpha)}{(D_3)^m \sigma^2} \eta \rho |h_3|^2 \left(\sum_{n=1}^{N_a} \frac{P_{p1}}{(D_1)^m N_a} |h_{1,n}|^2 + \sum_{p=1}^{N_b} \frac{P_{p2}}{(D_2)^m N_b} |h_{2,p}|^2 \right)}{\frac{\alpha \eta \rho |h_3|^2}{(1-\rho) (D_3)^m} + 1} = \frac{|h_3|^2 \left(\sum_{n=1}^{N_a} U_1 |h_{1,n}|^2 + \sum_{p=1}^{N_b} V_1 |h_{2,p}|^2 \right)}{U_2 |h_3|^2 + 1} \quad (27)$$

Achievable rate at PU_i is given by (based on the SINR)

$$R_{PU_i}^{(2,AF)} = \frac{1}{2} \log_2 \{1 + \gamma_i^{AF}\} \quad (28)$$

The achievable rate for PU information decoding at SU_2 is as

$$R_{s,PU}^{(2,AF)} = \frac{1}{2} \log_2 \{1 + \gamma_{s,PU}^{AF}\} \quad (29)$$

The achievable rate at SU_2 is given by (based on the SNR at SU_2)

$$R_{SU_2}^{(2,AF)} = \frac{1}{2} \log_2 \{1 + \gamma_s^{AF}\} \quad (30)$$

⁴As noise power is negligible with respect to the power received for information processing, therefore noise power is neglected.

B. Outage Probability Analysis

1) *Outage Probability of Primary System:* PU outage probability using AF relaying is determined as follows:

$$\mathcal{P}_{out}^{(PU,AF)} = 1 - \overbrace{\left[\mathcal{P}\{R_{PU_1}^{(2,AF)} \geq R_{PU}\} \times \mathcal{P}\{R_{PU_2}^{(2,AF)} \geq R_{PU}\} \right]}^{\text{Success Probability}} \quad (31)$$

Following (25), the probability of success due to data transmission between the link SU_1 to PU_1 is expressed as [21, Sec. 3.471.9, 8.352.1]

$$\begin{aligned} \mathcal{P}\{R_{PU_1}^{(2,AF)} \geq R_{PU}\} &= \mathcal{P}\left[\frac{C_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 \sum_{p=1}^{N_b} |h_{2,p}|^2}{H_1 \sum_{n=1}^{N_a} |h_{1,n}|^4 + E_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 \sum_{p=1}^{N_b} |h_{2,p}|^2 + F_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 + 1} \geq u_1\right] \\ &= \mathcal{P}\left[\frac{C_1 XY}{H_1 X^2 + E_1 XY + F_1 X + 1} \geq u_1\right] = 1 - \mathcal{P}\left[Y < \frac{F_1 u_1}{(C_1 - E_1 u_1)} + \frac{H_1 u_1 X}{(C_1 - E_1 u_1)} + \frac{u_1}{(C_1 - E_1 u_1)X}\right] = \sum_{q_a=0}^{N_b-1} (N_b u_1)^{q_a} \\ &2 \left(\frac{N_b u_1 / (C_1 - E_1 u_1)}{N_a + \frac{N_b H_1 u_1}{C_1 - E_1 u_1}}\right)^{(N_a + q - 2l)/2} \frac{\exp\left(-\frac{N_b F_1 u_1}{(C_1 - E_1 u_1)}\right) \sum_{q=0}^{q_a} \binom{q_a}{q} \sum_{l=0}^q \binom{q}{l} F_1^{q_a-q} H_1^{q-l}}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (C_1 - E_1 u_1)^{q_a}} K_{N_a+q-2l} \left(2\sqrt{\frac{N_b u_1}{(C_1 - E_1 u_1)}} \left(N_a + \frac{N_b H_1 u_1}{C_1 - E_1 u_1}\right)\right) \end{aligned} \quad (32)$$

Proof : See Appendix D.

where $X = \sum_{n=1}^{N_a} |h_{1,n}|^2$, $Y = \sum_{p=1}^{N_b} |h_{2,p}|^2$. The symbol $K_v(\cdot)$ indicates the modified Bessel function. Similarly, it is also possible to determine the probability of successful data transmission between the link SU_1 to PU_2 .

Closed form expression of PU outage probability using AF relaying is given in Appendix H.

2) *Outage Probability Analysis of Secondary System:* SU outage probability, using AF relaying mechanism, can be determined as follows:

$$\mathcal{P}_{out}^{(SU,AF)} = 1 - \left[\underbrace{\mathcal{P}\{R_{SU_2}^{(2,AF)} \geq R_{SU}\}}_{\text{Success of } SU_1 \rightarrow SU_2} \times \underbrace{\mathcal{P}\{R_{s,PU}^{(2,AF)} \geq R_{PU}\}}_{\text{Successful decoding of PU signals at } SU_2} \right] \quad (33)$$

Following (27), the probability of successful data transmission between the link SU_1 to SU_2 is expressed using (34) [21, Sec. 3.471.9, 8.352.2].

$$\begin{aligned} \mathcal{P}\{R_{SU_2}^{(2,AF)} \geq R_{SU}\} &= \mathcal{P}\left\{\frac{|h_3|^2 \left(U_1 \sum_{n=1}^{N_a} |h_{1,n}|^2 + V_1 \sum_{p=1}^{N_b} |h_{2,p}|^2\right)}{U_2 |h_3|^2 + 1} \geq u_4\right\} \\ &= \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l \Gamma(N_a+l)}{p_a! \{(1/N_a)^{N_a}\} \left(N_a - \frac{U_1 N_b}{V_1}\right)^{N_a+l} \Gamma(N_a)} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \\ &\left[\frac{2 \left(\frac{u_4 N_b}{V_1 m_k}\right)^{\frac{m_k+l-r}{2}} K_{m_k+l-r} \left(2\sqrt{\frac{u_4 N_b m_k}{V_1}}\right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} - \sum_{j=0}^{N_a+l-1} \exp\left\{-\left(\frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right\} \right. \\ &\left. \frac{\left(N_a - \frac{U_1 N_b}{V_1}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_4 U_2}{U_1}\right)^{j-t_l} \left(\frac{u_4}{U_1}\right)^{t_l}}{j! \{(1/m_k)^{m_k}\} \Gamma(m_k)} - 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{\frac{m_k+l-r-t_l}{2}} K_{m_k+l-r-t_l} \left(2\sqrt{\frac{u_4 N_a m_k}{U_1}}\right) \right] \\ &+ \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{U_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_4 U_2 N_a}{U_1}\right)}{p_a! \Gamma(m_k)} \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r} 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{(m_k-r)/2} K_{m_k-r} \left(2\sqrt{\frac{u_4 N_a m_k}{U_1}}\right) \end{aligned} \quad (34)$$

Proof : See Appendix E.

Similar to (34), the probability of success for the decoding of the PU information in presence of SU interference and noise can be written as

$$\begin{aligned} \mathcal{P}\{R_{s,PU}^{(2,AF)} \geq R_{PU}\} &= \mathcal{P}\left\{\frac{Z(U_3 X_1 + V_3 Y_1)}{Z(U_1 X_1 + V_1 Y_1) + U_2 Z + 1} \geq u_1\right\} = \begin{cases} \mathcal{P}\{Z(S_1 X_1 + S_2 Y_1) \geq u_s U_2 Z + u_s\}, & \text{for } u_s < \frac{\alpha}{(1-\alpha)} \\ 0, & \text{otherwise.} \end{cases} \\ &= \begin{cases} \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_s U_2 N_b}{S_2}\right)^{p_a-r} \exp\left(-\frac{u_s U_2 N_b}{S_2}\right) \frac{\left(\frac{u_s N_b}{S_2}\right)^{r-l} \left(\frac{S_1 N_b}{S_2}\right)^l \Gamma(N_a+l)}{p_a! \{(1/N_a)^{N_a}\} \left(N_a - \frac{S_1 N_b}{S_2}\right)^{N_a+l} \Gamma(N_a)} \\ \left[\frac{2 \left(\frac{u_s N_b}{S_2 m_k}\right)^{\frac{m_k+l-r}{2}} K_{m_k+l-r} \left(2\sqrt{\frac{u_s N_b m_k}{S_2}}\right) - \sum_{j=0}^{N_a+l-1} \exp\left\{-\left(\frac{u_s U_2}{S_1}\right) \left(N_a - \frac{S_1 N_b}{S_2}\right)\right\}}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} K_{m_k+l-r} \left(2\sqrt{\frac{u_s N_b m_k}{S_2}}\right) - \sum_{j=0}^{N_a+l-1} \exp\left\{-\left(\frac{u_s U_2}{S_1}\right) \left(N_a - \frac{S_1 N_b}{S_2}\right)\right\} \right. \\ \left. 2 \left(\frac{u_s N_a}{S_1 m_k}\right)^{\frac{m_k+l-r-t_l}{2}} \frac{\left(N_a - \frac{S_1 N_b}{S_2}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_s U_2}{S_1}\right)^{j-t_l} \left(\frac{u_s}{S_1}\right)^{t_l}}{j! \{(1/m_k)^{m_k}\} \Gamma(m_k)} - K_{m_k+l-r-t_l} \left(2\sqrt{\frac{u_s N_a m_k}{S_1}}\right) \right] \\ + \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_s N_a}{S_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_s U_2 N_a}{S_1}\right)}{p_a! \Gamma(m_k)} \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r} 2 \left(\frac{u_s N_a}{S_1 m_k}\right)^{(m_k-r)/2} K_{m_k-r} \left(2\sqrt{\frac{u_s N_a m_k}{S_1}}\right), & \text{for } u_s < \frac{\alpha}{(1-\alpha)} \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \quad (35)$$

Fig. 3. Outage Probability vs. α : (a) DF relaying (b) AF relaying

where $S_1 = \frac{1}{(D_3)^m \sigma^2} \eta \rho \frac{P_{p1}}{N_a (D_1)^m}$, $S_2 = \frac{1}{(D_3)^m \sigma^2} \eta \rho \frac{P_{p2}}{N_a (D_2)^m}$, $u_s = \frac{u_1}{\alpha - u_1(1-\alpha)}$. Finally, the closed form SU outage expression using AF relaying can be determined using (34) and (35). Closed form expression of SU outage probability using AF relaying is given in Appendix M.

V. NUMERICAL RESULTS AND DISCUSSIONS

Numerical values for the system parameters used are enlisted in Table II. The constraint of the maximum PU outage limit (say 0.1) is found to be met at $\alpha=0.81$ by both AF and DF relaying for $N_a=2$. This value of α is used for the results shown in Fig. 4, Fig. 5 and Fig. 6. Considering the practicability of the number of transmitting antennas on mobile devices we set $N_b=1$ in our simulation results.

The outage performances of both PU and SU systems are shown as variation in power-sharing factor (α) for both DF and AF relaying in Fig. 3.a and Fig. 3.b. It is clearly seen that the analytical results match perfectly with the simulation results. For the small value of α , the higher fraction of the harvesting power is allocated to SU information transmission and small fraction of power is used for DF relaying of PU information. Thus SU outage is found to be low while PU outage to be high. The reverse situation is to be observed at high value of α . The small value of α (close to 0) causes PU outage of AF relaying same to that of DF relaying and SU performance is found to be the worst by following (33)-(35). Since 50% or more power is assigned to PU information transmission to detect PU signals perfectly in presence of SU interference, therefore the minimum value of α is shown as 0.5 for AF relaying in Fig. 3.b. The threshold limit of 10% PU outage is achieved at $\alpha=0.29$ and $N_a=1$ for DF relaying and the same outage limit is achieved at $\alpha=0.89$ and $N_a=1$ for AF relaying. If the number of antennas is increased then PU performance is improved accordingly. If N_a is increased from 1 to 2, about 46% improvement (reduction) in PU outage is observed for DF relaying and about 39% improvement of PU outage is observed for AF relaying. If N_a is increased from 1 to 2, about 58% improvement of SU outage is observed at $\alpha=0.27$ and $R_{SU}=1$ bps for DF relaying and about 42% improvement of SU outage is observed at $\alpha=0.81$ and $R_{SU}=1$ bps for AF relaying.

Fig. 4. and 5. show the outage performances of PU and SU, respectively with respect to power splitting factor (ρ) for both DF and AF relaying mechanisms. As depicted in the figures, the outage performances of both PU and SU are very poor for $\rho \rightarrow 0$ and $\rho \rightarrow 1$. Initially, the performances of PU and SU outage are improved with the increase in the value of ρ , and they attain their minimum values of outage at the optimal value of ρ^* . Thereafter, when the value of ρ is increased further, it leads to an increase in both PU and SU outage. The reason behind the characteristics of this graphical plot can be explained as follows. Initially, when ρ value is very low, the energy harvested at SU_1 is insufficient to broadcast the information at the BC phase and effectively the outage performance of both PU and SU are very poor. When the value of ρ increases, the harvesting energy at SU_1 is also increased and consequently both PU and SU outage performances improve accordingly. Further degradation on the outage performances are found due to major power allocation for EH and less power allocation for decoding the information received from PU to SU signal transmission. Performance of PU outage is significantly improved for DF relaying as compared to AF relaying mechanism whereas the SU outage performances are almost same for both the relaying mechanisms with respect to ρ . The overall outage performances for both PU and SU are improved with the increase in the number of antennas used at PU nodes.

Now SE and EE of the system can be defined as [13]

$$\eta_{SE} = 2 \times (1 - \mathcal{P}_{out}^{PU}) \times R_{PU} \times \frac{T}{2T} + (1 - \mathcal{P}_{out}^{SU}) \times R_{SU} \times \frac{T}{2T} \quad (36)$$

EE can be defined as the ratio of SE to the total energy consumed for PUs transmission [23].

TABLE II
SET OF NUMERICAL VALUES OF NECESSARY PARAMETERS

Name	Value
PU target rate of information transmission (R_{PU})	0.2 bps/Hz
SU target rate of information transmission (R_{SU})	1 bps/Hz
Distance between PU_1 and PU_2 (L)	20 m
Distance between SU_1 and SU_2 (D_3)	10 m
PU transmit power ($P_{p1}=P_{p2}=P_p$)	-23 dBm (Fig. 3 to Fig. 5), -50 dBm to -15 dBm (Fig. 6)
Average noise power ($n_{pu}=n_{su}=n_p$)	-100 dBm [11]
Path loss exponent (m)	2.7
Energy conversion efficiency (η)	0.9
Power splitting factor (ρ)	0.9
Power sharing factor (α)	0.81
$D_1 = D_4$ & $D_2 = D_5$	$L/2$

Fig. 4. PU Outage Probability vs. ρ : (a) DF relaying, (b) AF relaying

Fig. 5. SU Outage Probability vs. ρ : (a) DF relaying, (b) AF relaying

Fig. 6. System SE and EE vs. total PU transmit power : (a) DF relaying (b) AF relaying

The SE and EE performances of the DF and AF relaying protocols are shown with respect to the total PU transmit power⁵ in Fig. 6.a and Fig. 6.b, respectively. The performance of the proposed system using AF and DF relaying schemes are compared with similar system supporting two-way PU and one-way SU communication simultaneously [13]. As shown in figure, SE is improved and EE is deteriorated with the increase in PU transmit power. The characteristics of this graphical plot may be explained as follows. As transmission power of PUs are increased, the PU and SU outage probabilities are decreased accordingly following (14)-(18), (21), (23), (32), (34) and (35) for DF and AF relaying mechanisms, respectively. As inverse relationship is maintained between SE and the outage probability of both PU and SU system, the SE is improved with the increase in the transmission power of PU. Less increment of SE as compared to more energy consumption leads to a degradation of EE with the increasing value of PUs transmit power. Our proposed system using DF relaying mechanism is more efficient as compared to AF relaying mechanism and similar model of two-way PU and one-way SU communication. In terms of SE, our proposed system using DF relaying mechanism is performing 224%, 196% and 142% better as compared to [13] for $N_a=3$, $N_a=2$ and $N_a=1$, respectively at 52 dB transmit power. Our system using AF relaying is performing 34%, 31% and 22% better in terms of SE as compared to [13] for given value of $N_a=3$, $N_a=2$ and $N_a=1$, respectively at 70 dB transmit power. In terms of EE, our proposed system using DF relaying mechanism is performing 62%, 48% and 21% better as compared to [13] and on the other hand, the performance of [13] is 56%, 60% and 69% better as compared to the proposed system using AF relaying for given value of $N_a=3$, $N_a=2$ and $N_a=1$, respectively at 52 dB transmit power. However, the proposed model is less energy efficient at high transmit power as compared to [13].

VI. CONCLUSIONS

This paper has investigated the scope of SWIPT enabled IoT communication, on the licensed spectrum using overlay spectrum sharing mode of cognitive radio networks. Transmitting IoD node harvests energy from the information bearing RF signals of both eNB and UE transmission and this energy is used in relaying between eNB and UE. Apart from the close match between the analytical and simulation results on outage experiences in IoD and cellular systems, it is also to be noted that DF relaying mechanism is more efficient over AF relaying in terms of EE and AF relaying is more sensitive to the impact of the number of antennas used by the cellular system. The proposed network architecture and the spectrum sharing model can be extended further (i) to analyse the outage for more realistic non-linear RF-EH model, (ii) to improve the secrecy of the relay assisted cellular communication using the PUs' signals for friendly jamming in addition to EH and (iii) to study game theoretic modelling of the possible negotiations between cellular users and multiple IoT device pairs for efficient trading of the available radio resources of the former.

VII. IMPORTANT INTEGRALS AND THEIR SOLUTIONS

VII.1: [21, Sec. 3.471.9]

$$\int_0^{\infty} x^{v-1} \exp\left(-\frac{\beta}{x} - \gamma x\right) dx = 2 \left(\frac{\beta}{\gamma}\right)^{\frac{v}{2}} K_v(2\sqrt{\beta\gamma}), [\mathbf{Re}(\beta) > 0, \mathbf{Re}(\gamma) > 0] \quad (37)$$

VII.2: [21, Sec. 3.351.3]

$$\int_0^{\infty} x^{N_a} \exp(-\mu x) dx = N_a! \mu^{-N_a-1}, [\mathbf{Re}(\mu) > 0] \quad (38)$$

VII.3: [21, Sec. 3.381.1]

$$\int_0^u \frac{x^{v-1} \exp(-\mu x)}{\Gamma(\mu)} dx = \frac{\mu^{-v} \gamma(v, \mu u)}{\Gamma(\mu)}, [\mathbf{Re}(v) > 0] \quad (39)$$

VII.4: [21, Sec. 3.381.3]

$$\int_u^{\infty} \frac{x^{v-1} \exp(-\mu x)}{\Gamma(\mu)} dx = \frac{\mu^{-v} \Gamma(v, \mu u)}{\Gamma(\mu)}, [u > 0, \mathbf{Re}(\mu) > 0] \quad (40)$$

VII.5: [21, Sec. 8.352.1]

$$\gamma(1 + N_a, x) = N_a! \left[1 - \exp(-x) \left(\sum_{r=0}^{N_a} \frac{x^r}{r!} \right) \right], [N_a = 0, 1, \dots] \quad (41)$$

VII.6: [21, Sec. 8.352.2]

$$\Gamma(1 + N_a, x) = N_a! \exp(-x) \left(\sum_{r=0}^{N_a} \frac{x^r}{r!} \right), [N_a = 0, 1, \dots] \quad (42)$$

VII.7: [Taylor Series Expansion]

$$\exp(-x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^n}{n!} \quad (43)$$

VII.8: [Taylor Series Expansion]

$$\exp(x) = \sum_{n=0}^{\infty} \frac{x^n}{n!} \quad (44)$$

VII.9: [Binomial Series Expansion]

$$(x + a)^n = \sum_{r=0}^n \binom{n}{r} x^{n-r} a^r \quad (45)$$

⁵The transmit power is normalized with respect to average channel noise power.

1) *Appendix A: Proof of (14):* [21, Sec. 3.381.1, 3.381.3, 8.350.1, 8.352.1].

$$\begin{aligned}
\mathcal{P}\{Q_1\} &= \int_{\frac{u_1}{A_1}}^{\infty} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\infty} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 - \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\frac{u_3-A_1x_1}{A_2}} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 \\
&= \int_{\frac{u_1}{A_1}}^{\infty} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_{\frac{u_2}{A_2}}^{\infty} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 - \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_0^{\frac{u_3-A_1x_1}{A_2}} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 \\
&\quad + \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_0^{\frac{u_2}{A_2}} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 \\
&= \frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma\left(N_a, N_a u_1/A_1\right) \Gamma\left(N_b, N_b u_2/A_2\right) - \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)\Gamma(N_b)(1/N_a)^{N_a}} \gamma\left(N_b, N_b \frac{u_3-A_1x_1}{A_2}\right) dx_1 + \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)\Gamma(N_b)(1/N_a)^{N_a}} \gamma\left(N_b, N_b \frac{u_2}{A_2}\right) dx_1 \\
&= \frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma\left(N_a, N_a u_1/A_1\right) \Gamma\left(N_b, N_b u_2/A_2\right) \\
&\quad - \frac{1}{\Gamma(N_a)(1/N_a)^{N_a}} \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a}) \left[1 - \frac{\exp(-\frac{N_b u_3 - A_1 x_1}{A_2})}{q_a!} \sum_{q_a=0}^{N_b-1} N_b^{q_a} \left(\frac{u_3 - A_1 x_1}{A_2}\right)^{q_a} \right] dx_1 + \int_{\frac{u_1}{A_1}}^{\frac{u_3-u_1}{A_1}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)\Gamma(N_b)(1/N_a)^{N_a}} \gamma\left(N_b, N_b \frac{u_2}{A_2}\right) dx_1 \\
&\quad \text{(Using Binomial Series Expansion, we can write as follows)} \\
&= \frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma\left(N_a, N_a u_1/A_1\right) \Gamma\left(N_b, N_b u_2/A_2\right) - \frac{1}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_0^{\frac{u_3-u_1}{A_1}} x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a}) dx_1 - \int_0^{\frac{u_1}{A_1}} x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a}) dx_1 \right\} \\
&\quad + \sum_{q_a=0}^{N_b-1} \frac{\exp(-\frac{N_b u_3}{A_2})}{q_a! \Gamma(N_a)(1/N_a)^{N_a}} \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a-q} A_1^q \left\{ \int_0^{\frac{u_3-u_1}{A_1}} x_1^{N_a+q-1} \exp\left\{-\left(N_a - \frac{A_1 N_b}{A_2}\right)x_1\right\} dx_1 - \int_0^{\frac{u_1}{A_1}} x_1^{N_a+q-1} \exp\left\{-\left(N_a - \frac{A_1 N_b}{A_2}\right)x_1\right\} dx_1 \right\} \\
&\quad + \frac{\gamma\left(N_b, N_b \frac{u_2}{A_2}\right)}{\Gamma(N_a)\Gamma(N_b)(1/N_a)^{N_a}} \left\{ \int_0^{\frac{u_3-u_1}{A_1}} x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a}) dx_1 - \int_0^{\frac{u_1}{A_1}} x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a}) dx_1 \right\} \\
&= \frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma\left(N_a, N_a u_1/A_1\right) \Gamma\left(N_b, N_b u_2/A_2\right) - \left\{ \frac{1}{\Gamma(N_a)} - \frac{\gamma\left(N_b, N_b \frac{u_2}{A_2}\right)}{\Gamma(N_a)\Gamma(N_b)} \right\} \left\{ \gamma\left(N_a, N_a \frac{u_3-u_1}{A_1}\right) - \gamma\left(N_a, N_a \frac{u_1}{A_1}\right) \right\} \\
&\quad + \sum_{q_a=0}^{N_b-1} \frac{\exp(-\frac{N_b u_3}{A_2})}{q_a! \Gamma(N_a)(1/N_a)^{N_a}} \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a-q} A_1^q \left\{ \gamma\left[N_a+q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_3-u_1}{A_1}\right] - \gamma\left[N_a+q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_1}{A_1}\right] \right\} \\
&\quad \text{(46)}
\end{aligned}$$

2) *Appendix B: Proof of (17):* [21, Sec. 8.350.1, 8.352.1].

$$\begin{aligned}
\mathcal{P}\left\{X_1 \leq \frac{k'}{(a_1 X_1 + b_1 Y_1)}\right\} &= \mathcal{P}\left(Y_1 \leq \frac{k'}{b_1 X_1} - \frac{a_1 X_1}{b_1}\right) = \int_0^{\sqrt{\frac{k'}{a_1}}} \frac{x_1^{N_a-1} \exp(-\frac{x_1}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \int_0^{\frac{k'}{b_1 x_1} - \frac{a_1 x_1}{b_1}} \frac{y_1^{N_b-1} \exp(-\frac{y_1}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy_1 \right\} dx_1 \\
&= \frac{1}{\Gamma(N_b)} \int_0^{\sqrt{\frac{k'}{a_1}}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \gamma\left(N_b, N_b \left[\frac{k'}{b_1 x_1} - \frac{a_1 x_1}{b_1}\right]\right) dx_1 \\
&= \frac{1}{\Gamma(N_b)} \int_0^{\sqrt{\frac{k'}{a_1}}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \Gamma(N_b) \left[1 - \exp\left\{-N_b \left(\frac{k'}{b_1 x_1} - \frac{a_1 x_1}{b_1}\right)\right\} \sum_{p_a=0}^{N_b-1} \frac{\left\{N_b \left(\frac{k'}{b_1 x_1} - \frac{a_1 x_1}{b_1}\right)\right\}^{p_a}}{p_a!} \right] dx_1 \\
&\quad \text{Using Binomial Series Expansion, we can write as follows,} \\
&= \frac{1}{\Gamma(N_a)} \gamma\left(N_a, \sqrt{\frac{k'}{a_1}}\right) - \left[\sum_{p_a=0}^{N_b-1} \frac{(N_b)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k'}{b_1}\right)^{p_a-r} \left(\frac{a_1}{b_1}\right)^r \int_0^{\sqrt{\frac{k'}{a_1}}} (x_1)^{2r+N_a-p_a-1} \exp\left\{-\left(\frac{k' N_b}{b_1}\right) \frac{x_1}{x_1} - \left(N_a - \frac{a_1 N_b}{b_1}\right) x_1\right\} dx_1 \right] \\
&\quad \text{Using Taylor Series Expansion, we can write as follows,} \\
&= \frac{1}{\Gamma(N_a)} \gamma\left(N_a, \sqrt{\frac{k'}{a_1}}\right) - \left[\sum_{p_a=0}^{N_b-1} \frac{(N_b)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k'}{b_1}\right)^{p_a-r} \left(\frac{a_1}{b_1}\right)^r \sum_{l=0}^{\infty} \frac{(-1)^l}{l!} \int_0^{\sqrt{\frac{k'}{a_1}}} (x_1)^{2r+N_a-p_a-1} \left\{ \frac{\left(\frac{k' N_b}{b_1}\right)}{x_1} + \left(N_a - \frac{a_1 N_b}{b_1}\right) x_1 \right\}^l dx_1 \right] \\
&\quad \text{Using Binomial Series Expansion, we can write as follows,} \\
&= \frac{1}{\Gamma(N_a)} \gamma\left(N_a, \sqrt{\frac{k'}{a_1}}\right) - \left[\sum_{p_a=0}^{N_b-1} \frac{(N_b)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k'}{b_1}\right)^{p_a-r} \left(\frac{a_1}{b_1}\right)^r \sum_{l=0}^{\infty} \frac{(-1)^l}{l!} \sum_{t_l=0}^l \binom{l}{t_l} \left(\frac{k' N_b}{b_1}\right)^{l-t_l} \left(N_a - \frac{a_1 N_b}{b_1}\right)^{t_l} \int_0^{\sqrt{\frac{k'}{a_1}}} (x_1)^{2r+N_a-p_a-l+2t_l-1} dx_1 \right] \\
&= \frac{1}{\Gamma(N_a)} \gamma\left(N_a, \sqrt{\frac{k'}{a_1}}\right) - \left[\sum_{p_a=0}^{N_b-1} \frac{(N_a)^{N_a} (N_b)^{p_a}}{p_a! \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k'}{b_1}\right)^{p_a-r} \left(\frac{a_1}{b_1}\right)^r \sum_{l=0}^{\infty} \frac{(-1)^l}{l! (2r+N_a-p_a-l+2t_l)} \sum_{t_l=0}^l \binom{l}{t_l} \left(\frac{k' N_b}{b_1}\right)^{l-t_l} \left(N_a - \frac{a_1 N_b}{b_1}\right)^{t_l} \left(\sqrt{\frac{k'}{a_1}}\right)^{2r+N_a-p_a-l+2t_l} \right] \quad (47)
\end{aligned}$$

3) Appendix C: Proof of (23): [21, Sec. 3.471.9, 8.352.2], [24].

$$\begin{aligned}
\mathcal{P}(R_{SU_2}^{(2,DF)} \geq R_{SU}) &= \mathcal{P}\left(Z \geq \frac{u_4}{c(a_1 X_1 + b_1 Y_1)}\right) = \mathcal{P}\left(Y_1 \geq \frac{u_4}{cb_1 Z} - \frac{a_1 X_1}{b_1}\right) \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{ca_1 z}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \left\{ \int_{\frac{u_4}{cb_1 z}}^{\frac{a_1 x_1}{b_1}} \frac{\{y_1^{(N_b-1)}\} \exp(-\frac{y_1}{1/N_b})}{\{(1/N_b)^{N_b}\} \Gamma(N_b)} dy_1 \right\} dx_1 \right] dz + \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_{\frac{u_4}{ca_1 z}}^\infty \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} dx_1 \right] dz \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{ca_1 z}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \frac{\Gamma(N_b, \frac{u_4 N_b}{cb_1 z} - \frac{a_1 x_1 N_b}{b_1})}{\Gamma(N_b)} dx_1 \right] dz + I \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{ca_1 z}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \left\{ \exp\left(-\frac{u_4 N_b}{cb_1 z} + \frac{a_1 x_1 N_b}{b_1}\right) \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{u_4 N_b}{cb_1 z} - \frac{a_1 x_1 N_b}{b_1}\right)^{p_a}}{p_a!} \right\} dx_1 \right] dz + I \\
&= \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{N_b}{b_1}\right)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \int_0^\infty \frac{\{z^{(m_k-p_a+r-1)}\} \exp(-\frac{z}{1/m_k} - \frac{u_4 N_b}{cb_1 z})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \int_0^{\frac{u_4}{ca_1 z}} x_1^{N_a+r-1} \exp\left\{-\left(N_a - \frac{a_1 N_b}{b_1}\right) x_1\right\} dx_1 dz + I \\
&\quad \text{(Following Binomial Series Expansion)} \\
&= \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{N_b}{b_1}\right)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \int_0^\infty \frac{\{z^{(m_k-p_a+r-1)}\} \exp\left(-\frac{z}{1/m_k} - \frac{u_4 N_b}{cb_1 z}\right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \frac{1}{\left(N_a - \frac{a_1 N_b}{b_1}\right)^{N_a+r}} \gamma\left(N_a + r, \frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}\right) dz + I \\
&= \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{N_b}{b_1}\right)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \int_0^\infty \frac{\{z^{(m_k-p_a+r-1)}\} \exp\left(-\frac{z}{1/m_k} - \frac{u_4 N_b}{cb_1 z}\right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \frac{\Gamma(N_a + r)}{\left(N_a - \frac{a_1 N_b}{b_1}\right)^{N_a+r}} \\
&\quad \left\{ 1 - \frac{1}{j!} \exp\left(-\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}\right) \sum_{j=0}^{N_a+r-1} \left[\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}\right]^j \right\} dz + I \\
&= \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{N_b}{b_1}\right)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \frac{1}{\left(N_a - \frac{a_1 N_b}{b_1}\right)^{N_a+r}} \frac{\Gamma(N_a + r)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[2 \left\{ \frac{u_4 N_b}{cb_1 m_k} \right\}^{(m_k-p_a+r)/2} \right. \\
&\quad \left. K_{m_k-p_a+r} \left\{ 2 \sqrt{\frac{u_4 N_b m_k}{cb_1}} \right\} - \sum_{j=0}^{N_a+r-1} \frac{1}{j!} \left[\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}\right]^j \int_0^\infty \{z^{(m_k-p_a+r-j-1)}\} \exp\left\{-\frac{z}{1/m_k} - \frac{u_4 N_b}{cb_1 z} - \frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}\right\} dz \right] + I \\
&= \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{N_b}{b_1}\right)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \frac{1}{\left(N_a - \frac{a_1 N_b}{b_1}\right)^{N_a+r}} \frac{\Gamma(N_a + r)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[2 \left\{ \frac{u_4 N_b}{cb_1 m_k} \right\}^{(m_k-p_a+r)/2} \right. \\
&\quad \left. K_{m_k-p_a+r} \left\{ 2 \sqrt{\frac{u_4 N_b m_k}{cb_1}} \right\} - \sum_{j=0}^{N_a+r-1} \frac{1}{j!} \left[\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}\right]^j 2 \left\{ \frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1 m_k} + \frac{u_4 N_b}{cb_1 m_k} \right\}^{(m_k-p_a+r-j)/2} \right. \\
&\quad \left. K_{m_k-p_a+r-j} \left\{ 2 \sqrt{\frac{u_4 m_k \left(N_a - \frac{a_1 N_b}{b_1}\right)}{ca_1}} + \frac{u_4 N_b m_k}{cb_1} \right\} \right] + \sum_{p_a=0}^{N_b-1} \frac{\left(\frac{u_4 N_a}{ca_1}\right)^{p_a} (m_k)^{m_k}}{p_a! \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{ca_1 m_k}\right)^{(m_k-p_a)/2} K_{m_k-p_a} \left(2 \sqrt{\frac{u_4 N_a m_k}{ca_1}}\right) \quad (48)
\end{aligned}$$

I is possible to determine using (49) [21, Sec. 3.471.9, 8.352.2].

$$\begin{aligned}
I &= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{ca_1 z}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} dx_1 \right] dz = \frac{1}{\Gamma(N_a)} \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \Gamma\left(N_a, \frac{u_4 N_a}{ca_1 z}\right) dz \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\exp\left(-\frac{u_4 N_a}{ca_1 z}\right) \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{ca_1 z}\right)^{p_a}}{p_a!} \right] dz = \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{ca_1}\right)^{p_a} (m_k)^{m_k}}{p_a! \Gamma(m_k)} \int_0^\infty (z)^{m_k-p_a-1} \exp\left(-\frac{z}{1/m_k} - \frac{1}{z} \frac{u_4 N_a}{ca_1}\right) dz \\
&= \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{ca_1}\right)^{p_a} (m_k)^{m_k}}{p_a! \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{ca_1 m_k}\right)^{(m_k-p_a)/2} K_{m_k-p_a} \left(2 \sqrt{\frac{u_4 N_a m_k}{ca_1}}\right) \quad (49)
\end{aligned}$$

4) Appendix D: Proof of (32): [21, Sec. 3.471.9, 8.352.1].

$$\begin{aligned}
\mathcal{P}\left[Y < \frac{Fu_1}{(C-Eu_1)} + \frac{Hu_1 X}{(C-Eu_1)} + \frac{u_1}{(C-Eu_1)X}\right] &= \int_0^\infty \frac{x^{N_a-1} \exp(-\frac{x}{1/N_a})}{\Gamma(N_a)(1/N_a)^{N_a}} \left\{ \frac{\left[\frac{Fu_1}{(C-Eu_1)} + \frac{Hu_1 x}{(C-Eu_1)} + \frac{u_1}{(C-Eu_1)x}\right]}{\int_0^\infty \frac{y^{N_b-1} \exp(-\frac{y}{1/N_b})}{\Gamma(N_b)(1/N_b)^{N_b}} dy} \right\} dx \\
&= \int_0^\infty \frac{x^{N_a-1} \exp(-\frac{x}{1/N_a})}{\Gamma(N_a)\Gamma(N_b)(1/N_a)^{N_a}} \gamma\left\{N_b, \frac{Fu_1 N_b}{(C-Eu_1)} + \frac{Hu_1 N_b x}{(C-Eu_1)} + \frac{u_1 N_b}{(C-Eu_1)x}\right\} dx \\
&= \frac{1}{\Gamma(N_a)(1/N_a)^{N_a}} \int_0^\infty x^{N_a-1} \exp\left(-\frac{x}{1/N_a}\right) \left[1 - \frac{\exp\left\{-N_b \left(\frac{Fu_1}{(C-Eu_1)} + \frac{Hu_1 x}{(C-Eu_1)} + \frac{u_1}{(C-Eu_1)x}\right)\right\}}{q_a!} \sum_{q_a=0}^{N_b-1} N_b^{q_a} \left(\frac{Fu_1}{(C-Eu_1)} + \frac{Hu_1 x}{(C-Eu_1)} + \frac{u_1}{(C-Eu_1)x}\right)^{q_a} \right] dx \\
&\quad \text{(Using Binomial Series Expansion, we can write as follows)} \\
&= 1 - \sum_{q_a=0}^{N_b-1} (N_b u_1)^{q_a} \frac{\exp\left(-\frac{N_b F u_1}{(C-Eu_1)}\right) \sum_{q=0}^{q_a} \binom{q_a}{q} \sum_{l=0}^q \binom{q}{l} F^{q_a-q} H^{q-l}}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (C-Eu_1)^{q_a}} \left\{ \int_0^\infty x^{N_a+q-2l-1} \exp\left\{-N_a x - \frac{N_b H u_1 x}{(C-Eu_1)} - \frac{N_b u_1}{(C-Eu_1)x}\right\} dx \right\} \\
&= 1 - \sum_{q_a=0}^{N_b-1} (N_b u_1)^{q_a} \frac{\exp\left(-\frac{N_b F u_1}{(C-Eu_1)}\right) \sum_{q=0}^{q_a} \binom{q_a}{q} \sum_{l=0}^q \binom{q}{l} F^{q_a-q} H^{q-l}}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (C-Eu_1)^{q_a}} 2 \left(\frac{N_b u_1 / (C-Eu_1)}{N_a + \frac{N_b H u_1}{(C-Eu_1)}}\right)^{(N_a+q-2l)/2} K_{N_a+q-2l} \left(2 \sqrt{\frac{N_b u_1}{(C-Eu_1)}} \left(N_a + \frac{N_b H u_1}{C-Eu_1}\right)\right) \quad (50)
\end{aligned}$$

5) Appendix E: Proof of (34): [21, Sec. 3.471.9, 8.352.2], [24].

$$\begin{aligned}
\mathcal{P}(R_{SU_2}^{(2,AF)} \geq R_{SV}) &= \mathcal{P}\left\{\frac{Z\left(\frac{U_1 X_1 + V_1 Y_1}{U_2 Z + 1}\right)}{\geq u_4}\right\} = \mathcal{P}\left(Y_1 \geq \frac{u_4}{zV_1} + \frac{u_4 U_2}{V_1} - \frac{U_1 X_1}{V_1}\right) \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \left\{ \int_0^\infty \frac{\{y_1^{(N_b-1)}\} \exp(-\frac{y_1}{1/N_b})}{\{(1/N_b)^{N_b}\} \Gamma(N_b)} dy_1 \right\} dx_1 \right] dz \\
&\quad + \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} dx_1 \right] dz \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \frac{\Gamma(N_b, \frac{u_4 N_b}{zV_1} + \frac{u_4 U_2 N_b}{V_1} - \frac{U_1 x_1 N_b}{V_1})}{\Gamma(N_b)} dx_1 \right] dz + I' \\
&= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \left\{ \exp\left(-\frac{u_4 N_b}{zV_1} - \frac{u_4 U_2 N_b}{V_1} + \frac{U_1 x_1 N_b}{V_1}\right) \right. \right. \\
&\quad \left. \left. \frac{\left(\frac{u_4 N_b}{zV_1} + \frac{u_4 U_2 N_b}{V_1} - \frac{U_1 x_1 N_b}{V_1}\right)^{p_a}}{p_a!} \right\} dx_1 \right] dz + I' \\
&= \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k} - \frac{u_4 N_b}{zV_1})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_0^{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}} \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a} + \frac{U_1 x_1 N_b}{V_1})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} \right. \\
&\quad \left. \left\{ \frac{\left(\frac{u_4 N_b}{zV_1} + \frac{u_4 U_2 N_b}{V_1} - \frac{U_1 x_1 N_b}{V_1}\right)^{p_a}}{p_a!} \right\} dx_1 \right] dz + I'
\end{aligned}$$

(Using Binomial Series Expansion, we can write as follows)

$$\begin{aligned}
&= \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l}{p_a!} \int_0^\infty \frac{\{z^{(m_k-r+l-1)}\} \exp(-\frac{z}{1/m_k} - \frac{u_4 N_b}{zV_1})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \\
&\quad \left[\int_0^{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}} \frac{\{x_1^{(N_a+l-1)}\} \exp(-\frac{x_1}{1/N_a} + \frac{U_1 x_1 N_b}{V_1})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} dx_1 \right] dz + I' \\
&= \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l}{p_a!} \int_0^\infty \frac{\{z^{(m_k-r+l-1)}\} \exp(-zm_k - \frac{u_4 N_b}{zV_1})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \\
&\quad \frac{\gamma\left\{N_a+l, \left(\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right\}}{\{(1/N_a)^{N_a}\} \left(N_a - \frac{U_1 N_b}{V_1}\right)^{N_a+l} \Gamma(N_a)} dz + I' \\
&= \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l \Gamma(N_a+l)}{p_a! \{(1/N_a)^{N_a}\} \left(N_a - \frac{U_1 N_b}{V_1}\right)^{N_a+l} \Gamma(N_a)} \\
&\quad \left[1 - \exp\left\{-\left(\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right\} \sum_{j=0}^{N_a+l-1} \frac{\left[\left(\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right]^j}{j!} \right] \\
&\quad \int_0^\infty \frac{\{z^{(m_k-r+l-1)}\} \exp(-m_k z - \frac{u_4 N_b}{zV_1})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} dz + I' \\
&= \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l \Gamma(N_a+l)}{p_a! \{(1/N_a)^{N_a}\} \left(N_a - \frac{U_1 N_b}{V_1}\right)^{N_a+l} \Gamma(N_a)} \\
&\quad \left[\frac{2\left(\frac{u_4 N_b}{V_1 m_k}\right)^{\frac{m_k+l-r}{2}} K_{m_k+l-r}\left(2\sqrt{\frac{u_4 N_b m_k}{V_1}}\right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} - \sum_{j=0}^{N_a+l-1} \exp\left\{-\left(\frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right\} \frac{\left(N_a - \frac{U_1 N_b}{V_1}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_4 U_2}{U_1}\right)^{j-t_l} \left(\frac{u_4}{U_1}\right)^{t_l}}{j!} \right. \\
&\quad \left. \int_0^\infty \frac{\{z^{(m_k-r+l-t_l-1)}\} \exp\left\{-m_k z - \frac{u_4 N_b}{zV_1} - \left(\frac{u_4}{zU_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right\}}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} dz \right] + I' \quad (51)
\end{aligned}$$

Finally, above equation can be written as follows

$$\begin{aligned} \mathcal{P}\left(Y_1 \geq \frac{u_4}{ZV_1} + \frac{u_4 U_2}{V_1} - \frac{U_1 X_1}{V_1}\right) &= \sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l \Gamma(N_a + l)}{p_a! \left\{(1/N_a)^{N_a}\right\} \left(N_a - \frac{U_1 N_b}{V_1}\right)^{N_a+l} \Gamma(N_a)} \\ &\left[\frac{2 \left(\frac{u_4 N_b}{V_1 m_k}\right)^{\frac{m_k + l - r}{2}} K_{m_k + l - r} \left(2\sqrt{\frac{u_4 N_b m_k}{V_1}}\right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} - \sum_{j=0}^{N_a + l - 1} \exp\left\{-\left(\frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right)\right\} \frac{\left(N_a - \frac{U_1 N_b}{V_1}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_4 U_2}{U_1}\right)^{j-t_l} \left(\frac{u_4}{U_1}\right)^{t_l}}{j! \{(1/m_k)^{m_k}\} \Gamma(m_k)} \right. \\ &\quad \left. 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{\frac{m_k + l - r - t_l}{2}} K_{m_k + l - r - t_l} \left(2\sqrt{\frac{u_4 N_a m_k}{U_1}}\right) \right] \\ &+ \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{U_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_4 U_2 N_a}{U_1}\right) \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r}}{p_a! \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{(m_k-r)/2} K_{m_k-r} \left(2\sqrt{\frac{u_4 N_a m_k}{U_1}}\right) \quad (52) \end{aligned}$$

I' can be determined as follows [21, Sec. 3.471.9, 8.352.2].

$$\begin{aligned} I' &= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\int_{\frac{u_4}{zU_1} + \frac{u_4 U_2}{U_1}}^\infty \frac{\{x_1^{(N_a-1)}\} \exp(-\frac{x_1}{1/N_a})}{\{(1/N_a)^{N_a}\} \Gamma(N_a)} dx_1 \right] dz = \frac{1}{\Gamma(N_a)} \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \Gamma\left(N_a, \frac{u_4 N_a}{zU_1} + \frac{u_4 U_2 N_a}{U_1}\right) dz \\ &= \int_0^\infty \frac{\{z^{(m_k-1)}\} \exp(-\frac{z}{1/m_k})}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[\exp\left(-\frac{u_4 N_a}{zU_1} - \frac{u_4 U_2 N_a}{U_1}\right) \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{zU_1} + \frac{u_4 U_2 N_a}{U_1}\right)^{p_a}}{p_a!} \right] dz \\ &= \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{U_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_4 U_2 N_a}{U_1}\right) \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r}}{p_a! \Gamma(m_k)} \int_0^\infty (z)^{m_k-r-1} \exp\left(-m_k z - \frac{u_4 N_a}{zU_1}\right) dz \\ &= \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{U_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_4 U_2 N_a}{U_1}\right) \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r}}{p_a! \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{(m_k-r)/2} K_{m_k-r} \left(2\sqrt{\frac{u_4 N_a m_k}{U_1}}\right) \quad (53) \end{aligned}$$

6) Appendix F: Closed form PU outage expression for DF relaying:

$$\begin{aligned} \mathcal{P}_{out}^{(PU, DF)} &= 1 - \left[\mathcal{P}\{Q_1\} \times \mathcal{P}\{R_{PU1}^{(2, DF)} \geq R_{PU}\} \times \mathcal{P}\{R_{PU2}^{(2, DF)} \geq R_{PU}\} \right] \\ &= 1 - \left[\frac{1}{\Gamma(N_a) \Gamma(N_b)} \Gamma\left(N_a, N_a u_1 / A_1\right) \Gamma\left(N_b, N_b u_2 / A_2\right) - \left\{ \frac{1}{\Gamma(N_a)} - \frac{\gamma(N_b, N_b \frac{u_2}{A_2})}{\Gamma(N_a) \Gamma(N_b)} \right\} \left\{ \gamma(N_a, N_a \frac{u_3 - u_1}{A_1}) - \gamma(N_a, N_a \frac{u_1}{A_1}) \right\} \right. \\ &\quad \left. + \sum_{q_a=0}^{N_b-1} \frac{\exp\left(-\frac{N_b u_3}{A_2}\right) \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a-q} A_1^q}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (1/N_b)^{q_a} \left(N_a - \frac{A_1 N_b}{A_2}\right)^{(N_a+q)} A_2^{q_a}} \left\{ \gamma\left[N_a + q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_3 - u_1}{A_1}\right] - \gamma\left[N_a + q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_1}{A_1}\right] \right\} \right] \\ &\quad \times \left[\frac{1}{\Gamma(N_a)} \gamma\left(N_a, \sqrt{\frac{k'}{a_1}}\right) - \sum_{p_a=0}^{N_b-1} \frac{N_a^{N_a} N_b^{p_a}}{p_a! \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k'}{b_1}\right)^{p_a-r} \left(\frac{a_1}{b_1}\right)^r \sum_{l=0}^\infty \\ &\quad \sum_{t_l=0}^l \binom{l}{t_l} \frac{(-1)^l}{l! (2r + N_a - p_a - l + 2t_l)} \left(\frac{k' N_b}{b_1}\right)^{l-t_l} \left(N_a - \frac{a_1 N_b}{b_1}\right)^{t_l} \left(\sqrt{\frac{k'}{a_1}}\right)^{2r + N_a - p_a - l + 2t_l} \right] \\ &\quad \times \left[\frac{1}{\Gamma(N_b)} \gamma\left(N_b, \sqrt{\frac{k''}{b_1}}\right) - \sum_{p_a=0}^{N_a-1} \frac{N_b^{N_b} N_a^{p_a}}{p_a! \Gamma(N_b)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{k''}{a_1}\right)^{p_a-r} \left(\frac{b_1}{a_1}\right)^r \sum_{l=0}^\infty \\ &\quad \sum_{t_l=0}^l \binom{l}{t_l} \frac{(-1)^l}{l! (2r + N_b - p_a - l + 2t_l)} \left(\frac{k'' N_a}{a_1}\right)^{l-t_l} \left(N_b - \frac{b_1 N_a}{a_1}\right)^{t_l} \left(\sqrt{\frac{k''}{b_1}}\right)^{2r + N_b - p_a - l + 2t_l} \right] \quad (54) \end{aligned}$$

7) Appendix G: Closed form SU outage expression for DF relaying:

$$\begin{aligned}
\mathcal{P}_{out}^{(SU,DF)} &= 1 - [\mathcal{P}\{Q_1\} \times \mathcal{P}\{Q_2\} \times \mathcal{P}\{R_{SU_2}^{(2,DF)} \geq R_{SU}\}] \\
&= 1 - \left[\frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma\left(N_a, N_a u_1/A_1\right) \Gamma\left(N_b, N_b u_2/A_2\right) - \left\{ \frac{1}{\Gamma(N_a)} - \frac{\gamma\left(N_b, N_b \frac{u_2}{A_2}\right)}{\Gamma(N_a)\Gamma(N_b)} \right\} \right. \\
&\quad \left\{ \gamma\left(N_a, N_a \frac{u_3 - u_1}{A_1}\right) - \gamma\left(N_a, N_a \frac{u_1}{A_1}\right) \right\} + \sum_{q_a=0}^{N_b-1} \frac{\exp\left(-\frac{N_b u_3}{A_2}\right) \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a-q} A_1^q}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (1/N_b)^{q_a} \left(N_a - \frac{A_1 N_b}{A_2}\right)^{(N_a+q)} A_2^{q_a}} \\
&\quad \left. \left\{ \gamma\left[N_a + q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_3 - u_1}{A_1}\right] - \gamma\left[N_a + q, \left(N_a - \frac{A_1 N_b}{A_2}\right) \frac{u_1}{A_1}\right] \right\} \right] \\
&\quad \times \left[\frac{1}{\Gamma(N_a)\Gamma(N_b)} \Gamma\left(N_a, N_a u_1/B_1\right) \Gamma\left(N_b, N_b u_2/B_2\right) - \left\{ \frac{1}{\Gamma(N_a)} - \frac{\gamma\left(N_b, N_b \frac{u_2}{B_2}\right)}{\Gamma(N_a)\Gamma(N_b)} \right\} \right. \\
&\quad \left\{ \gamma\left(N_a, N_a \frac{u_3 - u_1}{B_1}\right) - \gamma\left(N_a, N_a \frac{u_1}{B_1}\right) \right\} + \sum_{q_a=0}^{N_b-1} \frac{\exp\left(-\frac{N_b u_3}{B_2}\right) \sum_{q=0}^{q_a} (-1)^q \binom{q_a}{q} u_3^{q_a-q} B_1^q}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (1/N_b)^{q_a} \left(N_a - \frac{B_1 N_b}{B_2}\right)^{(N_a+q)} B_2^{q_a}} \\
&\quad \left. \left\{ \gamma\left[N_a + q, \left(N_a - \frac{B_1 N_b}{B_2}\right) \frac{u_3 - u_1}{B_1}\right] - \gamma\left[N_a + q, \left(N_a - \frac{B_1 N_b}{B_2}\right) \frac{u_1}{B_1}\right] \right\} \right] \\
&\quad \times \left[\sum_{p_a=0}^{N_b-1} \frac{\left(\frac{N_b}{b_1}\right)^{p_a}}{p_a! (1/N_a)^{N_a} \Gamma(N_a)} \sum_{r=0}^{p_a} (-1)^r \binom{p_a}{r} \left(\frac{u_4}{c}\right)^{p_a-r} (a_1)^r \frac{1}{\left(N_a - \frac{a_1 N_b}{b_1}\right)^{N_a+r}} \frac{\Gamma(N_a+r)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \left[2 \left\{ \frac{u_4 N_b}{c b_1 m_k} \right\}^{(m_k-p_a+r)/2} \right. \right. \\
&\quad \left. \left. K_{m_k-p_a+r} \left\{ 2 \sqrt{\frac{u_4 N_b m_k}{c b_1}} \right\} - \sum_{j=0}^{N_a+r-1} \frac{1}{j!} \left[\frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{c a_1} \right]^j 2 \left\{ \frac{u_4 \left(N_a - \frac{a_1 N_b}{b_1}\right)}{c a_1 m_k} + \frac{u_4 N_b}{c b_1 m_k} \right\}^{\frac{(m_k-p_a+r-j)}{2}} \right. \right. \\
&\quad \left. \left. K_{m_k-p_a+r-j} \left\{ 2 \sqrt{\frac{u_4 m_k \left(N_a - \frac{a_1 N_b}{b_1}\right)}{c a_1}} + \frac{u_4 N_b m_k}{c b_1} \right\} \right] + \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{c a_1}\right)^{p_a} (m_k)^{m_k}}{p_a! \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{c a_1 m_k}\right)^{(m_k-p_a)/2} K_{m_k-p_a} \left(2 \sqrt{\frac{u_4 N_a m_k}{c a_1}} \right) \right] \quad (55)
\end{aligned}$$

8) Appendix H: Closed form PU outage expression for AF relaying:

$$\begin{aligned}
\mathcal{P}_{out}^{(PU,AF)} &= 1 - \left[\mathcal{P}\{R_{PU_1}^{(2,AF)} \geq R_{PU}\} \times \mathcal{P}\{R_{PU_2}^{(2,AF)} \geq R_{PU}\} \right] \\
&= 1 - \left[\sum_{q_a=0}^{N_b-1} (N_b u_1)^{q_a} \frac{\exp\left(-\frac{N_b F_1 u_1}{(C_1 - E_1 u_1)}\right) \sum_{q=0}^{q_a} \binom{q_a}{q} \sum_{l=0}^q \binom{q}{l} F_1^{q_a-q} H_1^{q-l}}{q_a! \Gamma(N_a) (1/N_a)^{N_a} (C_1 - E_1 u_1)^{q_a}} \right. \\
&\quad \left. 2 \left(\frac{N_b u_1 / (C_1 - E_1 u_1)}{N_a + \frac{N_b H_1 u_1}{(C_1 - E_1 u_1)}} \right)^{(N_a+q-2l)/2} K_{N_a+q-2l} \left(2 \sqrt{\frac{N_b u_1}{(C_1 - E_1 u_1)} \left(N_a + \frac{N_b H_1 u_1}{C_1 - E_1 u_1}\right)} \right) \right. \\
&\quad \times \sum_{q_a=0}^{N_a-1} (N_a u_1)^{q_a} \frac{\exp\left(-\frac{N_a F_2 u_1}{(C_2 - E_2 u_1)}\right) \sum_{q=0}^{q_a} \binom{q_a}{q} \sum_{l=0}^q \binom{q}{l} F_2^{q_a-q} H_2^{q-l}}{q_a! \Gamma(N_b) (1/N_b)^{N_b} (C_2 - E_2 u_1)^{q_a}} \\
&\quad \left. 2 \left(\frac{N_a u_1 / (C_2 - E_2 u_1)}{N_b + \frac{N_a H_2 u_1}{(C_2 - E_2 u_1)}} \right)^{(N_b+q-2l)/2} K_{N_b+q-2l} \left(2 \sqrt{\frac{N_a u_1}{(C_2 - E_2 u_1)} \left(N_b + \frac{N_a H_2 u_1}{C_2 - E_2 u_1}\right)} \right) \right] \quad (56)
\end{aligned}$$

9) Appendix M: Closed form SU outage expression for AF relaying:

$$\begin{aligned}
\mathcal{P}_{out}^{(SU,AF)} &= 1 - \left[\sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_4 U_2 N_b}{V_1}\right)^{p_a-r} \exp\left(-\frac{u_4 U_2 N_b}{V_1}\right) \frac{\left(\frac{u_4 N_b}{V_1}\right)^{r-l} \left(\frac{U_1 N_b}{V_1}\right)^l \Gamma(N_a+l)}{p_a! \{(1/N_a)^{N_a}\} \left(N_a - \frac{U_1 N_b}{V_1}\right)^{N_a+l} \Gamma(N_a)} \right. \\
&\quad \left[\frac{2 \left(\frac{u_4 N_b}{V_1 m_k}\right)^{\frac{m_k+l-r}{2}} K_{m_k+l-r} \left(2 \sqrt{\frac{u_4 N_b m_k}{V_1}} \right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} - \sum_{j=0}^{N_a+l-1} \exp\left\{ -\left(\frac{u_4 U_2}{U_1}\right) \left(N_a - \frac{U_1 N_b}{V_1}\right) \right\} \frac{\left(N_a - \frac{U_1 N_b}{V_1}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_4 U_2}{U_1}\right)^{j-t_l} \left(\frac{u_4}{U_1}\right)^{t_l}}{j! \{(1/m_k)^{m_k}\} \Gamma(m_k)} 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{\frac{m_k+l-r-t_l}{2}} \right. \\
&\quad \left. \left. K_{m_k+l-r-t_l} \left(2 \sqrt{\frac{u_4 N_a m_k}{U_1}} \right) \right] + \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_4 N_a}{U_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_4 U_2 N_a}{U_1}\right)}{p_a! \Gamma(m_k)} \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r} 2 \left(\frac{u_4 N_a}{U_1 m_k}\right)^{(m_k-r)/2} K_{m_k-r} \left(2 \sqrt{\frac{u_4 N_a m_k}{U_1}} \right) \right. \\
&\quad \times \left[\sum_{p_a=0}^{N_b-1} \sum_{r=0}^{p_a} \binom{p_a}{r} \sum_{l=0}^r (-1)^l \binom{r}{l} \left(\frac{u_s U_2 N_b}{S_2}\right)^{p_a-r} \exp\left(-\frac{u_s U_2 N_b}{S_2}\right) \right. \\
&\quad \frac{\left(\frac{u_s N_b}{S_2}\right)^{r-l} \left(\frac{S_1 N_b}{S_2}\right)^l \Gamma(N_a+l)}{p_a! \{(1/N_a)^{N_a}\} \left(N_a - \frac{S_1 N_b}{S_2}\right)^{N_a+l} \Gamma(N_a)} \left[\frac{2 \left(\frac{u_s N_b}{S_2 m_k}\right)^{\frac{m_k+l-r}{2}} K_{m_k+l-r} \left(2 \sqrt{\frac{u_s N_b m_k}{S_2}} \right)}{\{(1/m_k)^{m_k}\} \Gamma(m_k)} \right. \\
&\quad \left. - \sum_{j=0}^{N_a+l-1} \exp\left\{ -\left(\frac{u_s U_2}{S_1}\right) \left(N_a - \frac{S_1 N_b}{S_2}\right) \right\} 2 \left(\frac{u_s N_a}{S_1 m_k}\right)^{\frac{m_k+l-r-t_l}{2}} \frac{\left(N_a - \frac{S_1 N_b}{S_2}\right)^j \sum_{t_l=0}^j \binom{j}{t_l} \left(\frac{u_s U_2}{S_1}\right)^{j-t_l} \left(\frac{u_s}{S_1}\right)^{t_l}}{j! \{(1/m_k)^{m_k}\} \Gamma(m_k)} K_{m_k+l-r-t_l} \left(2 \sqrt{\frac{u_s N_a m_k}{S_1}} \right) \right] \\
&\quad \left. + \sum_{p_a=0}^{N_a-1} \frac{\left(\frac{u_s N_a}{S_1}\right)^{p_a} (m_k)^{m_k} \exp\left(-\frac{u_s U_2 N_a}{S_1}\right)}{p_a! \Gamma(m_k)} \sum_{r=0}^{p_a} \binom{p_a}{r} (U_2)^{p_a-r} 2 \left(\frac{u_s N_a}{S_1 m_k}\right)^{(m_k-r)/2} K_{m_k-r} \left(2 \sqrt{\frac{u_s N_a m_k}{S_1}} \right) \right] \quad (57)
\end{aligned}$$

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