Proceedings of the Seventh International Conference on Research in Intelligent and Computing in Engineering pp. 63–68
DOI: 10.15439/2022R14
ISSN 2300-5963 ACSIS, Vol. 33

Performance Evaluation Of Multi-Hop Relaying IoTs Networks Using Hop-By-Hop Cooperative Transmission Under Impact of Co-channel Interference

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***Abstract*—The performance of the multi-hop relaying networks applied to Internet of Things (IoT) networks is investigated in the present work. To ameliorate the reliability of the whole network, for each hop, we employ cooperative communications subject to co-channel interference. In particular, several cooperative schemes are applied in the present work namely, incremental relaying, selection combining, and maximal ratio combining. In this context, we derive the exact closed-form expressions of end-to-end (e2e) outage probability (OP) of the whole systems over Rayleigh fading distribution. Numerical results based on the Monte-Carlo method are then employed to not only confirm the accuracy of the proposed mathematical framework but also to illustrate the advantages of the considered schemes compared with the conventional multi-hop relaying without using cooperative communications.**

***Index Terms*—Cooperative communication, multi-hop relaying, co-channel interference, outage probability.**

I. Introduction

Cooperative communication and relaying techniques [1]-[5] are widely used in self-organized networks (such as IoTs networks) to enhance performance. So far, the cooperative relaying has been applied into various developed wireless networks such as secure communication at physical layer [6], wirelessly EH (energy harvesting) [7], NOMA (Non-Orthogonal Multiple Access) [8], IRS (Intelligent Reflecting Surface) [9], underlay spectrum sharing cognitive radio [10], etc. Different with the conventional relaying technique, a destination node using cooperative communication can exploit the direct link for obtaining higher diversity order [11]. In addition, the destination can use MRC combiner [11] or SC combiner [12] to decode the received data. However, disadvantage of cooperative communication is that two orthogonal time slots are used for each data transmission. In [11], [13], the authors proposed an incremental cooperation (IC) approach, where the relay node was only used when the direct transmission was not successful. As a result, IC enhances spectrum usage efficiency, as compared with conventional cooperative communication [11], [13].

For far source-destination distance, multi-hop relaying (MHR) [14]-[18] that uses multiple intermediate relays is often employed. However, performance of the conventional MHR methods in [14]-[18] is severely degraded over multi-path fading and co-channel interference (CCI) channels. In [19]-[21], the authors evaluated and optimized performance of various MHR schemes operating on the CCI environments. In [22]-[28], the authors proposed diversity-aided MHR models to further enhance performance for the MHR networks. Particularly, the authors of [22]-[25] measured e2e outage probability (OP) of cooperative multi-hop relaying schemes, in which the source and relay nodes cooperate together to exploit the spatial diversity. However, it is too difficult to deploy these schemes into the IoTs networks because of a requirement of high synchronization and high storage capacity at the relays. In [26]-[28], the authors introduced path-selection methods to obtain higher diversity order for multi-path MHR networks. In particular, the optimal path in [26]-[28] is the one which provides the highest e2e channel capacity. In addition, it is difficult to implement these path-selection approaches in the IoTs networks because they require perfect channel-coefficient estimation on all the paths.

Different with [19]-[28], this paper considers the MHR networks using hop-by-hop cooperative communication. References [29]-[30] are the most relevant to this paper. Indeed, reference [29] used the cooperative transmission to obtain better e2e OP performance for cognitive MHR networks with hardware imperfection. Different with [29], this paper does not consider the cognitive networks, but investigates impact of CCI on the e2e OP. Published work [30] also applied hop-by-hop cooperative communication for the MRH networks using Fountain codes. Next, we will summarize the main motivation and main contribution of this paper as follows:

- Different with [29]-[30], we consider various cooperative transmission methods: i) in the first one, named MHR-SC, the receiver at each hop uses SC to decode the received data; ii) in the second one, named MHR-MRC, MRC is employed by the receiver at each hop; in the third one, named MHR-IC, the IC technique is applied at each hop.

- For MHR-IC, the receiver at each hop does not use SC and MRC. We also propose a simple time allocation strategy for the hop-by-hop cooperative transmission to improve the OP performance for MHR-IC.

- We provide exact formulas of the e2e OP of MHR-SC, MHR-MRC and MHR-IC over CCI and Rayleigh fading channels, and use computer simulations to verify these derived formulas.

- The obtained results show that the considered schemes obtain much better OP performance than the conventional MHR one (named MHR-WoCC).

In the following, we will present the proposed scheme model in Section II, performance evaluation in Section III, the computer simulations and the theoretical results in Section IV, and conclusion in Section V.

II. SYSTEM MODEL

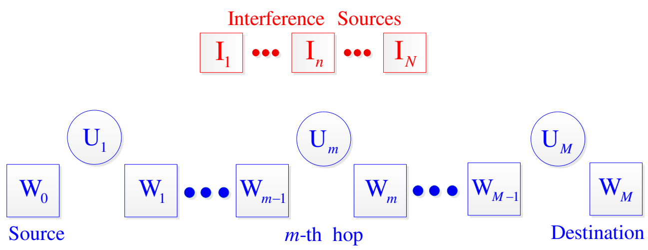

Fig. 1. The proposed MHR IoTs scenarios.

Fig. 1 demonstrates operation principle of MHR-SC, MHR-MRC and MHR-IC, where the source (W_0) transmits its data to the destination (W_M) with assistance of $M-1$ decode-and-forward (DF) relays denoted as W_1, W_2, …, W_{M-1}, where $M \geq 1$. The $W_0 \to W_M$ route is previously established by the network layer [31]-[32], and is used to send the source data to W_M. Considering the $m-$th hop $(m = 1, 2, ..., M)$; W_{m-1} communicates with W_m via assistance of a coopertive node (U_m). Note that U_m is one of the nodes which are in radio range of W_{m-1} and W_m. In addition, considering ultra-dense IoTs networks [33]-[34], and hence there always exists at least one cooperative node at each hop. Assume that N CCI sources (named I_n $(n = 1, 2, ..., N)$) cause co-channel interference on the receivers U_m and W_m.

Assume that all the IoTs nodes have single antenna; the $W_0 \to W_M$ communication has to use M time slots. If the e2e delay is 1 time unit, then time allocated for each time slot is $\tau = 1/M$.

Considering the $m-$th hop in MHR-WoCC; W_{m-1} transmits the data to W_m, without using the help of U_m.

For MHR-SC and MHR-MRC, the transmisson at the $m-$th hop is split into two equal phases with equal duration of $\tau/2$. In particular, in the first one, W_{m-1} sends the data to U_m and W_m. Then, U_m attempts to decode the received data, and it will forward the data to W_m at the second one if the decoding status is successful. If W_m can receive the data from both W_{m-1} and U_m, this node in MHR-SC (MHR-MRC) will use SC (MRC) for the decoding operation.

In MHR-IC, duration of the first and second sub-time slots is allocated by $\alpha\tau$ and $(1-\alpha)\tau$, respectively, where α $(0 < \alpha \leq 1)$ is a pre-designed value. Particularly, in the first sub-time slot, W_{m-1} sends the data to U_m and W_m. At the end of the first sub-time slot, if the decoding status at W_m is successful, it will feedback a ACK message to inform, and then will transmit the data to W_{m+1} $(m+1 \leq M)$. If W_m fails to decode the data, it will send back a NACK message to request the help from U_m. In this case, U_m will retransmit the data to W_m at the second sub-time slot if the decoding status of U_m is correct. As mentioned above, W_m in MHR-IC will not use any the combining technique. Moreover, we can observe that if $\alpha = 1$, MHR-IC becomes MHR-WoCC.

Let $g_{T,R}$ denote channel gain of the $T \to R$ Rayleigh fading channel, where T is a transmitter $(T \in \{W_{m-1}, I_n, U_m\})$ and R is a receiver $(R \in \{W_m, U_m\})$; cumulative distribution function (CDF) and probability density function (PDF) of $g_{T,R}$ are written, respectively as

$$F_{g_{T,R}}(x) = 1 - \exp(-\lambda_{T,R}x), f_{g_{T,R}}(x) = \lambda_{T,R}\exp(-\lambda_{T,R}x), \quad (1)$$

where $\lambda_{T,R} = (d_{T,R})^{\beta}$, with $d_{T,R}$ is distance between T and R, and β is path-loss exponential [11].

Under impact of CCI, the channel capacity between W_{m-1} and W_m in MHR-WoCC can be formulated as

$$C_{W_{m-1},W_m}^{\text{MHR-WoCC}} = \frac{1}{M}\log_2\left(1 + \frac{Pg_{W_{m-1},W_m}}{\sum_{n=1}^{N} Qg_{I_n,W_m} + \sigma_0^2}\right). \quad (2)$$

In (2), we assume that transmit power of the W_{m-1} and U_m transmitters is *P*, and that of the CCI sources is *Q*, for all *m* and *n*. In addition, it is also assumed that variance of Gaussian noises at all the receivers (R) is σ_0^2.

Considering MHR-SC and MHR-MRC; the channel capacity of the $W_{m-1} \to W_m$ and $W_{m-1} \to U_m$ links can be expressed, respectively as

$$C_{W_{m-1},W_m}^{Z} = \frac{1}{2M}\log_2\left(1 + \frac{Pg_{W_{m-1},W_m}}{\sum_{n=1}^{N} Qg_{I_n,W_m} + \sigma_0^2}\right), \quad (3)$$

$$C^{Z}_{W_{m-1},U_m} = \frac{1}{2M}\log_2\left(1+\frac{Pg_{W_{m-1},U_m}}{\sum_{n=1}^{N} Qg_{I_n,U_m}+\sigma_0^2}\right), \quad (4)$$

where $Z \in \{\text{MHR-SC,MHR-MRC}\}$.

When W_m in MHR-SC (MHR-MRC) uses SC (MRC) to decode the received data, the channel capacity obtained at W_m can be formulated, respectively as

$$C^{\text{MHR-SC}}_{W_m,SC} = \frac{1}{2M}\log_2\left(1+\frac{P\max\left(g_{W_{m-1},W_m}, g_{U_m,W_m}\right)}{\sum_{n=1}^{N} Qg_{I_n,W_m}+\sigma_0^2}\right), \quad (5)$$

$$C^{\text{MHR-MRC}}_{W_m,MRC} = \frac{1}{2M}\log_2\left(1+\frac{P\left(g_{W_{m-1},W_m}+g_{U_m,W_m}\right)}{\sum_{n=1}^{N} Qg_{I_n,W_m}+\sigma_0^2}\right). \quad (6)$$

We note that the channel gains g_{I_n,W_m} are the same in the first and second sub-time slots. As a result, as performing SC or MRC, W_m does not need to estimate g_{I_n,W_m}.

In MHR-IC, the channel capacity of the $W_{m-1}\to W_m$, $W_{m-1}\to U_m$ and $U_m \to W_m$ links is given, respectively as

$$C^{\text{MHR-IC}}_{W_{m-1},W_m} = \frac{\alpha}{M}\log_2\left(1+\frac{Pg_{W_{m-1},W_m}}{\sum_{n=1}^{N} Qg_{I_n,W_m}+\sigma_0^2}\right), \quad (7)$$

$$C^{\text{MHR-IC}}_{W_{m-1},U_m} = \frac{\alpha}{M}\log_2\left(1+\frac{Pg_{W_{m-1},U_m}}{\sum_{n=1}^{N} Qg_{I_n,U_m}+\sigma_0^2}\right), \quad (8)$$

$$C^{\text{MHR-IC}}_{U_m,W_m} = \frac{1-\alpha}{M}\log_2\left(1+\frac{Pg_{U_m,W_m}}{\sum_{n=1}^{N} Qg_{I_n,W_m}+\sigma_0^2}\right). \quad (9)$$

III. PERFORMANCE ANALYSIS

This section evaluates the e2e OP of the Z scheme, where $Z \in \{\text{MHR-WoCC,MHR-SC,MHR-MRC,MHR-IC}\}$. At first, we assume that the $T\to R$ link is outage if channel capacity $C^{Z}_{T,R}$ is below a pre-determined threshold (C_{th}). Otherwise, (i.e., $C^{Z}_{T,R} \ge C_{th}$), assume that the receiver R can correctly decode the data received from the transmitter T.

Hence, we can formulate the e2e OP of the Z scheme as

$$\text{OP}^{Z}_{e2e} = 1-\prod_{m=1}^{M}\left(1-\text{OP}^{Z}_{m}\right), \quad (10)$$

where OP^{Z}_{m} is OP at the $m-$th hop of the Z scheme.

A. The MHR-WoCC Scheme

From (2), $\text{OP}^{\text{MHR-WoCC}}_{m}$ can be expressed as

$$\begin{aligned}\text{OP}^{\text{MHR-WoCC}}_{m} &= \Pr\left(C^{\text{MHR-WoCC}}_{W_{m-1},W_m} < C_{th}\right)\\ &= \int_0^{+\infty}\ldots\int_0^{+\infty} F_{g_{W_{m-1},W_m}}\left(\theta_1\sum_{n=1}^{N}x_n+\chi_1\right)\\ &\times f_{g_{I_1,W_m}}(x_1)\ldots f_{g_{I_N,W_m}}(x_N)\,dx_1\ldots dx_N,\end{aligned} \quad (11)$$

where $\rho_1 = 2^{MC_{th}}-1, \theta_1 = \frac{Q\rho_1}{P}, \chi_1 = \frac{\sigma_0^2\rho_1}{P}$.

For ease of presentation and analysis, we can assume that the random variables g_{I_n,U_m} $\left(g_{I_n,W_m}\right)$ are independent and identical, i.e., $\lambda_{I_n,U_m} = \lambda_{I,U_m}$ and $\lambda_{I_n,W_m} = \lambda_{I,W_m}$, $\forall m,n.$

Now, substituting CDF of g_{W_{m-1},W_m} and PDF of g_{I_n,W_m} into (11), after some careful manipulation, we obtain

$$\text{OP}^{\text{MHR-WoCC}}_{m} = 1-\left(\frac{\lambda_{I,W_m}}{\lambda_{I,W_m}+\lambda_{W_{m-1},W_m}\theta_1}\right)^{N}\exp\left(-\lambda_{W_{m-1},W_m}\chi_1\right). \quad (12)$$

B. The MHR-SC Scheme

In this scheme, $\text{OP}^{\text{MHR-SC}}_{m}$ can be formulated as

$$\begin{aligned}\text{OP}^{\text{MHR-SC}}_{m} &= \Pr\left(C^{\text{MHR-SC}}_{W_{m-1},U_m} < C_{th}\right)\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},W_m} < C_{th}\right)\\ &+\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},U_m} \ge C_{th}\right)\Pr\left(C^{\text{MHR-SC}}_{W_m,SC} < C_{th}\right).\end{aligned} \quad (13)$$

Using (3)-(4), similar to (11)-(12), we can compute $\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},W_m} < C_{th}\right)$ and $\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},U_m} < C_{th}\right)$, respectively as

$$\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},W_m} < C_{th}\right) = 1-\left(\frac{\lambda_{I,W_m}}{\lambda_{I,W_m}+\lambda_{W_{m-1},W_m}\theta_2}\right)^{N}\exp\left(-\lambda_{W_{m-1},W_m}\chi_2\right), \quad (14)$$

$$\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},U_m} < C_{th}\right) = 1-\left(\frac{\lambda_{I,U_m}}{\lambda_{I,U_m}+\lambda_{W_{m-1},U_m}\theta_2}\right)^{N}\exp\left(-\lambda_{W_{m-1},U_m}\chi_2\right). \quad (15)$$

where $\rho_2 = 2^{2MC_{th}}-1, \theta_2 = \frac{Q\rho_2}{P}, \chi_2 = \frac{\sigma_0^2\rho_2}{P}$. In addition, we note that $\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},U_m} \ge C_{th}\right) = 1-\Pr\left(C^{\text{MHR-SC}}_{W_{m-1},U_m} < C_{th}\right)$.

For $\Pr\left(C^{\text{MHR-SC}}_{W_m,SC} < C_{th}\right)$, using (5), we can write

$$\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-SC}} < C_{\text{th}}\right) = \int_0^{+\infty}...\int_0^{+\infty} F_{T_{\max}}\left(\theta_2\sum_{n=1}^{N} x_n + \chi_2\right) \times f_{g_{\mathrm{I}_1,\mathrm{W}_m}}\left(x_1\right)...f_{g_{\mathrm{I}_N,\mathrm{W}_m}}\left(x_N\right)dx_1...dx_N, \quad (16)$$

where $T_{\max} = \max\left(g_{\mathrm{U}_m,\mathrm{W}_m}, g_{\mathrm{W}_{m-1},\mathrm{W}_m}\right)$ whose CDF is

$$\begin{aligned} F_{T_{\max}}\left(x\right) &= F_{g_{\mathrm{W}_{m-1},\mathrm{W}_m}}\left(x\right)F_{g_{\mathrm{U}_m,\mathrm{W}_m}}\left(x\right) \\ &= 1 - \exp\left(-\lambda_{\mathrm{U}_m,\mathrm{W}_m}x\right) - \exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}x\right) \\ &\quad + \exp\left(-\left(\lambda_{\mathrm{U}_m,\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\right)x\right). \end{aligned} \quad (17)$$

Combining (1), (16) and (17), and after calculating the integrals, we obtain

$$\begin{aligned} &\Pr\left(C_{\mathrm{W}_m,\mathrm{SC}}^{\text{MHR-SC}} < C_{\text{th}}\right) = \\ &1 - \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{U}_m,\mathrm{W}_m}\theta_2}\right)^N \exp\left(-\lambda_{\mathrm{U}_m,\mathrm{W}_m}\chi_2\right) \\ &- \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\theta_2}\right)^N \exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\chi_2\right) \\ &+ \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \left(\lambda_{\mathrm{U}_m,\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\right)\theta_2}\right)^N \\ &\times \exp\left(-\left(\lambda_{\mathrm{U}_m,\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\right)\chi_2\right). \end{aligned} \quad (18)$$

C. The MHR-MRC Scheme

Similar to MHR-SC, $\mathrm{OP}_m^{\text{MHR-MRC}}$ can be expressed as

$$\begin{aligned} &\mathrm{OP}_m^{\text{MHR-MRC}} = \\ &\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-MRC}} < C_{\text{th}}\right)\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{W}_m}^{\text{MHR-MRC}} < C_{\text{th}}\right) \\ &+ \Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-MRC}} \ge C_{\text{th}}\right)\Pr\left(C_{\mathrm{W}_m,\mathrm{MRC}}^{\text{MHR-MRC}} < C_{\text{th}}\right). \end{aligned} \quad (19)$$

We note that $\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{W}_m}^{\text{MHR-MRC}} < C_{\text{th}}\right) = \Pr\left(C_{\mathrm{W}_{m-1},\mathrm{W}_m}^{\text{MHR-SC}} < C_{\text{th}}\right)$ and $\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-MRC}} < C_{\text{th}}\right) = \Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-SC}} < C_{\text{th}}\right)$. For $\Pr\left(C_{\mathrm{W}_m,\mathrm{MRC}}^{\text{MHR-MRC}} < C_{\text{th}}\right)$, we have

$$\Pr\left(C_{\mathrm{W}_m,\mathrm{MRC}}^{\text{MHR-MRC}} < C_{\text{th}}\right) = \int_0^{+\infty}...\int_0^{+\infty} F_{T_{\text{sum}}}\left(\theta_2\sum_{n=1}^{N} x_n + \chi_2\right) \times f_{g_{\mathrm{I}_1,\mathrm{W}_m}}\left(x_1\right)...f_{g_{\mathrm{I}_N,\mathrm{W}_m}}\left(x_N\right)dx_1...dx_N, \quad (20)$$

where $T_{\text{sum}} = g_{\mathrm{W}_{m-1},\mathrm{W}_m} + g_{\mathrm{U}_m,\mathrm{W}_m}$. To find CDF of T_{sum}, we can use moment generating function (MGF) method proposed in [35].

Moreover, we note that the cooperative relay U_m is selected so that $d_{\mathrm{W}_{m-1},\mathrm{U}_m}$ and $d_{\mathrm{U}_m,\mathrm{W}_m}$ should be shorter than $d_{\mathrm{W}_{m-1},\mathrm{W}_m}$, or $\lambda_{\mathrm{U}_m,\mathrm{W}_m} < \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}$. Hence, we can obtain CDF of T_{sum} as

$$\begin{aligned} F_{T_{\text{sum}}}\left(x\right) = 1 &- \frac{\lambda_{\mathrm{U}_m,\mathrm{W}_m}}{\lambda_{\mathrm{U}_m,\mathrm{W}_m} - \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}}\exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}x\right) \\ &- \frac{\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}}{\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m} - \lambda_{\mathrm{U}_m,\mathrm{W}_m}}\exp\left(-\lambda_{\mathrm{U}_m,\mathrm{W}_m}x\right). \end{aligned} \quad (21)$$

Plugging (1), (20) and (21) together, we have

$$\begin{aligned} &\Pr\left(C_{\mathrm{W}_m,\mathrm{MRC}}^{\text{MHR-MRC}} < C_{\text{th}}\right) = \\ &1 - \frac{\lambda_{\mathrm{U}_m,\mathrm{W}_m}}{\lambda_{\mathrm{U}_m,\mathrm{W}_m} - \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}}\left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\theta_2}\right)^N \\ &\times \exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\chi_2\right) \\ &- \frac{\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}}{\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m} - \lambda_{\mathrm{U}_m,\mathrm{W}_m}}\left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{U}_m,\mathrm{W}_m}\theta_2}\right)^N \\ &\times \exp\left(-\lambda_{\mathrm{U}_m,\mathrm{W}_m}\chi_2\right). \end{aligned} \quad (22)$$

D. The MHR-IC Scheme

In this scheme, $\mathrm{OP}_m^{\text{MHR-IC}}$ can be formulated as

$$\begin{aligned} \mathrm{OP}_m^{\text{MHR-IC}} &= \Pr\left(C_{\mathrm{W}_{m-1},\mathrm{W}_m}^{\text{MHR-IC}} < C_{\text{th}}\right)\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-IC}} < C_{\text{th}}\right) \\ &+ \Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-IC}} \ge C_{\text{th}}\right) \\ &\times \underbrace{\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{W}_m}^{\text{MHR-IC}} < C_{\text{th}}, C_{\mathrm{U}_m,\mathrm{W}_m}^{\text{MHR-IC}} < C_{\text{th}}\right)}_{J}. \end{aligned} \quad (23)$$

Similarly, we can obtain the following results:

$$\begin{aligned} &\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{W}_m}^{\text{MHR-IC}} < C_{\text{th}}\right) = \\ &1 - \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\theta_3}\right)^N \exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\chi_3\right), \end{aligned} \quad (24)$$

$$\begin{aligned} &\Pr\left(C_{\mathrm{W}_{m-1},\mathrm{U}_m}^{\text{MHR-IC}} < C_{\text{th}}\right) = \\ &1 - \left(\frac{\lambda_{\mathrm{I},\mathrm{U}_m}}{\lambda_{\mathrm{I},\mathrm{U}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{U}_m}\theta_3}\right)^N \exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{U}_m}\chi_3\right). \end{aligned} \quad (25)$$

where $\rho_3 = 2^{\frac{MC_{\text{th}}}{\alpha}} - 1, \theta_3 = \frac{Q\rho_3}{P}, \chi_3 = \frac{\sigma_0^2\rho_3}{P}$.

Considering the probability J marked in (23); using (7) and (9), which yields

$$\begin{aligned} J = \int_0^{+\infty}...\int_0^{+\infty} &F_{g_{\mathrm{W}_{m-1},\mathrm{W}_m}}\left(\theta_3\sum_{n=1}^{N} x_n + \chi_3\right) \\ &\times F_{g_{\mathrm{U}_m,\mathrm{W}_m}}\left(\theta_4\sum_{n=1}^{N} x_n + \chi_4\right) \\ &\times f_{g_{\mathrm{I}_1,\mathrm{W}_m}}\left(x_1\right)...f_{g_{\mathrm{I}_N,\mathrm{W}_m}}\left(x_N\right)dx_1...dx_N, \end{aligned} \quad (26)$$

where $\rho_4 = 2^{\frac{MC_{\text{th}}}{1-\alpha}} - 1, \theta_4 = \frac{Q\rho_4}{P}, \chi_4 = \frac{\sigma_0^2\rho_4}{P}$.

Substituting CDFs and PDFs given in (1) into (26), and after some careful calculation, we finally obtain

$$\begin{aligned} J = 1 &- \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\theta_3} \right)^N \exp\left(-\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\chi_3\right) \\ &- \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \lambda_{\mathrm{U}_m,\mathrm{W}_m}\theta_4} \right)^N \exp\left(-\lambda_{\mathrm{U}_m,\mathrm{W}_m}\chi_4\right) \\ &+ \left(\frac{\lambda_{\mathrm{I},\mathrm{W}_m}}{\lambda_{\mathrm{I},\mathrm{W}_m} + \left(\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\theta_3 + \lambda_{\mathrm{U}_m,\mathrm{W}_m}\theta_4\right)} \right)^N \\ &\times \exp\left(-\left(\lambda_{\mathrm{W}_{m-1},\mathrm{W}_m}\chi_3 + \lambda_{\mathrm{U}_m,\mathrm{W}_m}\chi_4\right)\right). \end{aligned} \tag{27}$$

IV. SIMULATION RESULTS

Section IV presents Monte-Carlo simulations to check exactness of the formulas derived in Section III, and to compare the e2e OP performance of the considered schemes. In this section, coordinate of the nodes is fixed as follows : $\mathrm{W}_m\left(\frac{m}{M},0\right)$, $\mathrm{U}_m\left(\frac{2u-1}{2M},0\right)$, $\mathrm{I}_n(0.5,1)$, where $m = 0,1...,M$, $u = 1,2,...,M$, $n = 1,2,...,N$. In addition, we fix the path-loss exponential by $\beta = 3$, the outage threshold by $C_{\mathrm{th}} = 0.25$, the number of CCI sources by $N = 2$. We also assume that transmit power of all the transmitters is the same, i.e., $P = Q$, and we denote $\Psi = P/\sigma_0^2$ as the transmit SNR.

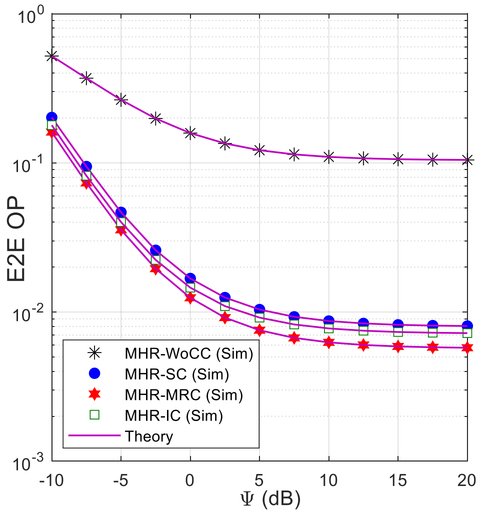

Fig. 2. E2e OP as a function of Ψ (dB) when $M = 4$ and $\alpha = 0.6$.

Fig. 2 presents the e2e OP as a function of Ψ in dB with $M = 4$ and $\alpha = 0.6$. As we can see, the OP performance of all the schemes is better as Ψ increases. However, at high Ψ regimes, all the OP values converge to saturation values due to impact of CCI. Fig. 2 also shows that MHR-SC, MHR-MRC and MHR-IC obtain much better performance than MHR-WoCC. It is due to the fact that MHR-SC, MHR-MRC and MHR-IC use the hop-by-hop cooperative transmission, which significantly enhances reliability of the data transmission. Next, it is seen that MHR-MRC obtains the best performance due to the optimal combiner used, while OP of MHR-IC is between those of MHR-MRC and MHR-SC.

Fig. 3 shows the e2e OP as a function of M with $\Psi = 10$ (dB) and $\alpha = 0.45$. Similar to Fig. 2, OP of MHR-SC, MHR-MRC and MHR-IC is much lower than that of MHR-WoCC, and MHR-MRC obtains the best performance. However, in Fig. 3, MHR-SC outperforms MHR-IC, and this means that the value of α significantly impacts on the OP performance of MHR-IC. Fig. 3 also shows that there exists the optimal values of the number of hops at which the e2e OP of the considered schemes is lowest.

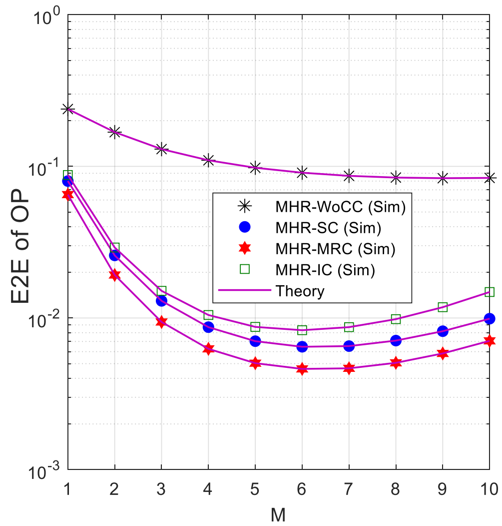

Fig. 3. E2e OP as a function of M when $\Psi = 10$ (dB) and $\alpha = 0.45$.

Fig. 4 investigates impact of α on the e2e OP of MHR-IC when $\Psi = 10$ (dB) and $M = 6$. As observed, there exists an optimal value of α at which the OP performance of MHR-IC is best. In particularthe optimal value of α in this figure is 0.55. It is also seen from Fig. 4 that MHR-MRC still provides the best OP performance, and MHR-IC outperforms MHR-SC when $0.5 \le \alpha < 0.65$.

It is worth noting from Figs. 2-4 that the Monte-Carlo based simulation results match well with the analytical ones, which validate our derived expressions.

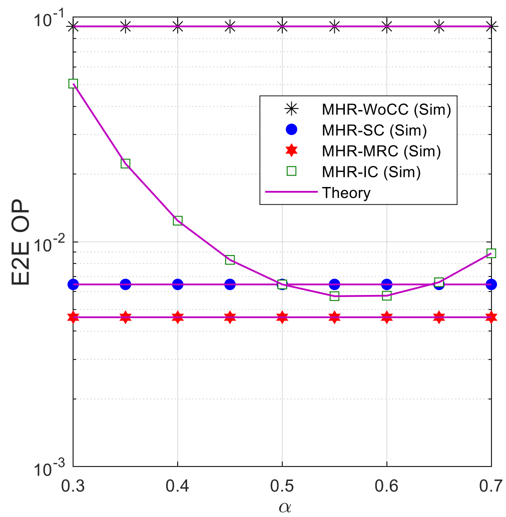

Fig. 4. E2e OP as a function of α when $\Psi = 10$ (dB) and $M = 6$.

V. Conclusion

This paper evaluated the e2e OP of the cooperative transmission aided MHR IoTs networks under impact of CCI via both simulation and analysis. The results presented that using hop-by-hop cooperative communication significantly enhanced the OP performance for the MHR IoTs networks, as compared with the conventional MHR scheme (MHR-WoCC). Moreover, to further enhance the OP performance for the considered schemes, the number of hops of the source-destination route should be designed optimally.

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