Distributed Asynchronous Cyclic Delay Diversity-Based Cooperative Systems with a Passive Eavesdropper

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TR2019-136  December 07, 2019

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IEEE Global Communications Conference (GLOBECOM)
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Index Terms—Physical layer security, distributed asynchronous cyclic delay diversity, secrecy outage probability.

I. INTRODUCTION

Physical layer security (PLS) is emerging as a promising approach that enhances the secrecy level of wireless communications by utilizing physical characteristics of wireless channels, and has attracted considerable recent attention [1]–[6]. As one PLS approach, the transmitting side jams an eavesdropping user (EU) by transmitting artificial noise (AN) [1], [7]–[10] to degrade the reception quality at the EU while maximizing the reception quality at a legitimate user (LU).

When exact channel state information (CSI) of the entire system is available at the transmitting side, the joint data and jamming signal transmissions can be made either at the same transmitter [7] or separate transmitters [9]–[11]. Similarly, multiple transmitters can be jointly used for the data and jamming transmissions without utilizing secrecy beamforming [12].

Without specific descriptions, it has been assumed that exact CSI for the legitimate channels is available by explicit feedback from the LU for processing of beamforming/precoding and jamming signal transmissions. However, the EU can intercept this type of feedback to lessen the benefit of PLS. Thus, it is desirable to avoid this feedback from the PLS perspective. For this reason, an original distributed cyclic delay diversity (dCDD) scheme [13] has been adapted to the PLS system in the presence of a single active EU [12]. In contrast to other works [9], [10], transmit diversity and intersymbol interference (ISI)-free single carrier transmissions are jointly used in [13] to degrade the reception quality, namely the signal-to-interference-plus-noise ratio (SINR), at the EU, while maximizing it, namely the signal-to-noise ratio (SNR) at the LU.

A. Problem statement and contribution

1) Tight time synchronization among remote radio heads (RRHs): RRHs are connected to the central control unit (CU) via wireless backhaul and implemented by only simple hardware, and thus tight synchronization among them is not achievable. For this reason, synchronous signal reception may not be achievable, which influences the objective of dCDD, namely removing ISI caused by frequency selective fading and multiple transmissions. Thus, one of the objectives of this paper is to propose a distributed asynchronous CDD (dACDD) that supports asynchronous single carrier transmissions.

2) Joint selection scheme: The EU is working usually in a passive mode, so that neither the exact CSI of the legitimate channels nor that of the eavesdropper channels is available at the transmitting side [2], [11]. Thus, the joint selection scheme for the data and interfering RRHs proposed by [12] is inappropriate for this new practical setting due to the requirement of partial CSI. To degrade the reception quality at the EU, it is preferable to use as many RRHs as interfering RRHs without causing ISI at the LU. Thus, we introduce a systematic procedure for selecting the data RRH and interfering RRHs under the framework of dACDD in the presence of one passive EU. The single data RRH transmits an intended data signal to the LU, whereas the interfering RRHs are mainly jamming the EU by transmitting the AN as the jamming signal.

Notation: \( \mathbb{N}_0 \) denotes the set of non-negative integers; \( \mathbb{C} \) denotes the set of complex numbers; \( I_N \) denotes an \( N \times N \) identity matrix; \( 0 \) denotes an all-zero matrix of an appropriate size; \( \mathcal{CN}(\mu, \sigma^2) \) denotes a complex Gaussian distribution with mean \( \mu \) and variance \( \sigma^2 \); \( F_{\phi}(\cdot) \) denotes the cumulative distri-
bution function (CDF) of the random variable (RV) $\varphi$, whereas its probability density function (PDF) is denoted by $f_\varphi(\cdot)$; and the binomial coefficient is denoted by $\binom{n}{k}$. The $l$th element of a vector $a$ is denoted by $a(l)$; $\mathbb{L}(a)$ denotes the cardinality of a vector $a$; for a set $\mathbb{S}_M$, composed of $M$ positive integers, $\mathbb{L}(\mathbb{S}_M)$ denotes $\mathbb{S}_M$ with excluding $j$; and $\mathbb{S}_M$ is another set that is obtained after randomizing a list of $\mathbb{S}_M$.

II. SYSTEM AND CHANNEL MODELS

Fig. 1 illustrates the considered distributed communication system. In this example, one RRH highlighted in a different color is assigned as the data RRH, whereas the remaining $(M - 1)$ RRHs are assigned as interfering RRHs.

Fig. 1. Illustration of the considered cooperative system. In this example, one RRH highlighted in a different color is assigned as the data RRH, whereas the remaining $(M - 1)$ RRHs are assigned as interfering RRHs.

A. Asynchronous signal reception

Without loss of generality, we assume that RRH$_1$’s signal arrives at the LU first. The relative time difference between the arrival time of the signal transmitted from RRH$_m$ and that of the signal transmitted from RRH$_1$ is denoted by $T_m \in \mathbb{N}_0$. Due to the use of single carrier transmissions, a transmission symbol block, $s \in \mathbb{C}^{B \times 1}$, comprises $B$ modulated symbols. Also, to eliminate ISI caused by frequency selective fading, $N_{CP}$-length CP is appended to the front of $s$. One example of asynchronous signal reception at the LU is illustrated in Fig. 2. This paper assumes that the relative arrival time differences are all less than $N_{CP}$, so that $T_2 < N_{CP}$ and $T_3 < N_{CP}$.

Due to the frequency selective fading channels from RRHs to the LU, we have $N_{CP} = \max\{N_{h,m}\}_{m=1}^M$. To apply the correct circular shifting at each of the RRHs, $N_{CP}$ must be fed back by the LU. The index of the data RRH is determined in terms of the channel quality measured and then fed back by the LU. Additionally, independent of the LU and EU channels, the CU forms $\mathbb{S}_M$ and $\mathbb{S}_M$, a randomized set of $\mathbb{S}_M$, and share both of them with only RRHs and LU.

Without considering interference, noise, and dACDD operation, the ideally received signal at the LU is given by

$$r_l = \sqrt{P_T \alpha_{h_1}} H_1 s + \sqrt{P_T \alpha_{h_2}} H_2 s + \cdots + \sqrt{P_T \alpha_{h_M} H_M s}$$

(1)

where $P_T$ is the transmission power at the RRHs and $H_m$ is a right circulant matrix determined by $h_m$. Additionally, $\alpha_{h,m}$ accounts for the distance-dependent large scale fading over the channel $h_m$. For a distance $d_{m,m}$, the nth RRH to LU, $\alpha_{h,m}$ is given by $\alpha_{h,m} = d_{m,m}^{-\epsilon}$, where $\epsilon$ denotes the path loss exponent. Furthermore, $\Pi_M$ denotes the $B \times B$ orthogonal permutation matrix obtained by circularly shifting $I_B$ down by $T_m$ rows. Based on (1), the following theorem provides a condition under which dACDD makes asynchronous transmissions without causing ISI at the LU.

Theorem 1: Let $T_m \in \mathbb{N}_0$, with $m \in \mathbb{S}_M$, be the relative arrival time difference of RRH$_m$ with respect to RRH$_1$, and $\Delta_{m} = (m - 1)N_{CP}$, with $\tilde{m} \in \mathbb{S}_M$, be the CDD delay of RRH$_m$, which assures ISI-free reception at the LU. Then, for ISI-free transmission to the LU, RRH$_m$ needs to apply circular shifting by $\delta_{m} \triangleq \Delta_{m} - T_m$. This can be implemented by multiplying the input symbol $s$ by the permutation matrix,
\( P_{B,m,\delta_m} \in \mathbb{N}^{B \times B} \), which can be obtained by circularly shifting \( I_B \) down by \( \delta_m \) rows.

**Proof:** From (1), we can first verify that \( \Pi_m H_m \) is a right circulant matrix, whose first column vector, \( h_m \), is shifted down by \( T_m \) from asynchronous reception at the LU. To move down by \( \Delta_m \geq T_m \) in total, another circular shift by \( \delta_m \) is required at RRH\(_m\) with respect to the input transmission symbol block, \( s \). This operation can be expressed mathematically as multiplication by the permutation matrix, \( P_{B,m,\delta_m} \).

Based on Theorem 1, we can specify a condition for dACDD as follows:

\[
\Delta_m = (\tilde{m} - 1)N_{CP} \text{ with cyclic delay } \delta_m. \quad (2)
\]

Furthermore, \( N_{CP} \) and \( B \) jointly determine the maximum allowable number of RRHs for dACDD operation as follows:

\[
K = \left\lfloor \frac{B}{N_{CP}} \right\rfloor \quad (3)
\]

where \( \lfloor \cdot \rfloor \) denotes the floor function.

For dACDD processing, the set of relative arrival time differences, \( \{T_m\}_{m=2}^{M} \), is required at the CU. Thus, the LU first needs to know \( \{T_m\}_{m=2}^{M} \) via [16], and then feed them back to the CU. Note that due to an additional random relative arrival time difference over the LU channels, independent of the EU channels, asynchronous reception can prevent the ANS from being decoded by the EU.

According to Fig. 1, wherein the \( d \)th RRH is assigned as the data RRH, the symbol block is formed as \( \tilde{s}_d = \left[ s_d(B - N_{CP} + 1 : B, 1) \right] \in \mathbb{C}^{(B+N_{CP}) \times 1} \), and then transmitted via \( h_d \). The corresponding CDD delay is applied to \( s \); that is, \( s_d = P_{B,d,\delta_d} s \), with \( d \in \mathbb{S}_M \). Then, the other RRHs are assigned as interfering RRHs. When the \( m \)th RRH is assigned as an interfering RRH, the resulting ANS is generated as \( j_m = P_{B,m,\delta_m} j \), where \( m \in \mathbb{S}_M \) and \( j \) is the original AN sequence. For \( j_m \), a CP of \( N_{CP} \) symbols is appended to the front of \( j_m \); that is, we have \( \tilde{j}_m = \left[ j_m(B - N_{CP} + 1 : B, 1) \right] \in \mathbb{C}^{(B+N_{CP}) \times 1} \). After that \( \tilde{j}_m \) is transmitted sequentially to the LU via \( h_m \). The EU receives \( \tilde{j}_m \) via \( g_m \).

**B. Received signals**

After the removal of the CP signal, the received signal at the LU is given by

\[
\tilde{r}_L = \sqrt{P_T \alpha_{h,d}} \Pi_d H_d P_{B,d,\delta_d} s + \sum_{m \in \mathbb{S}_M \setminus \{d\}} \sqrt{P_T \alpha_{h,m}} \Pi_m H_m \tilde{j}_m + z_L \quad (4)
\]

where \( P_T \) is the transmission power for ANS transmissions. The additive vector noise over the LU channels is denoted by \( z_L \sim \mathcal{CN}(0, \sigma_z^2 I_B) \).

As for the ANS, \( j \), we assume that \( E\{j\} = 0 \), and \( E\{jj^H\} = I_B \), so that we have \( E\{\tilde{j}_m\} = 0 \), and \( E\{\tilde{j}_m j_m^H\} = I_B \). Note that in the generation of \( \tilde{j}_m \), \( P_{B,m,\delta_m} \) is mainly determined by the LU channels, independent of the EU channels. We can summarize several benefits of dACDD from the PLS perspective as follows:

1) The randomized set \( \mathbb{S}_M \) is not available at the EU. Thus, a set of ANSs, \( \{\tilde{j}_m\}_{m \in \mathbb{S}_M} \), is known only to the CU, RRHs, and LU. That is, the EU cannot decode ANSs. Thus, the dACDD scheme can provide a deliberate set of ANSs to the EU.

2) Since different relative arrival time differences \( \{T_m\}_{m=2}^{M} \) are independent of those of the asynchronous transmissions from RRHs to the EU, \( \{T_m\}_{m=2}^{M} \) appears as the set of random variables to the EU, which means the asynchronous transmissions improve protecting of the ANS from decoding by the EU. This significantly enhances the secrecy level. However, to achieve these benefits, ISI-free reception is required at the LU.

Utilizing ISI-free reception and known ANSs at the LU, we can rewrite (4) as follows:

\[
\tilde{r}_L = \sqrt{P_T \alpha_{h,d}} \Pi_d H_d P_{B,d,\delta_d} s + z_L. \quad (5)
\]

In contrast, the received signal at the EU is given by

\[
\tilde{r}_E = \sqrt{P_T \alpha_{h,d}} \Pi_d G_d P_{B,d,\delta_d} s + \sum_{m \in \mathbb{S}_M \setminus \{d\}} \sqrt{P_T \alpha_{h,m}} \Pi_m G_m P_{B,m,\delta_m} j + z_E \quad (6)
\]

where \( G_d \) and \( G_m \) are right circulant matrices specified by the equivalent channel vectors \( g_d \) and \( g_m \), respectively. Additionally, \( \alpha_{h,m} \) is used to model the distance-dependent large scale fading from the \( m \)th RRH to the EU. The set of relative arrival differences from RRHs to the EU, \( \{T_m\}_{m=1}^{M} \), specifies \( \Pi_m \). We also assume that \( z_E \sim \mathcal{CN}(0, \sigma_z^2 I_B) \). Note that the relative arrival time difference \( T_m \) is independent of the channels from RRHs to the EU, that is, \( T_m \neq T_m \). Most importantly, \( \mathbb{S}_M \) and \( \mathbb{S}_M \setminus \{d\} \) are shared only by by CU, RRHs, and LU.

**III. PERFORMANCE ANALYSIS**

**A. Receive SNR at the LU over i.n.i.d. frequency selective fading channels**

In the sequel, the \( m \)th receive SNR at the LU, achievable by the \( m \)th LU channel, is denoted by \( \gamma_{L,m} = \frac{\alpha_{h,m} P_T}{\sigma_z^2} \| h_m \|^2 \) since \( \Pi_m H_m P_{B,m,\delta_m} \) is right circulant.

For i.n.i.d. frequency selective fading channels, the probability that \( R_RH \) is selected as the data RRH is given by (7), shown at the top of the next page. In (7), we have defined

\[
\alpha_{h,m} \triangleq \frac{P_T \alpha_{h,m}}{\sigma_z^2}, \quad \beta_d \triangleq \sum_{t=1}^{m} 1/\beta_{h,q_t'}, \quad \ell_d \triangleq \sum_{t=1}^{m} \ell_t', \quad \text{and}
\]

\[
\gamma_d \triangleq \sum_{q_1=1}^{M-m} \cdots \sum_{q_{m-1}=1}^{M-1} N_{h,q_1} \cdots N_{h,q_{m-1}} - 1 \sum_{t=0}^{\ell_1} \cdots \sum_{t_m=0}^{\ell_m} (8)
\]

For a set of the channel magnitudes over the LU channels, \( P_{h,j',\lambda d} \) denotes the \( j \)th \( \alpha_{h,s} \) indexed by \( j \in \mathbb{S}_M \).
According to (5), the conditional receive SNR at the LU, given by the channel \( h_d \), which was chosen for data transmissions, is given by

\[
\gamma_{L,d} = \tilde{\alpha}_{h,d} \sum_{l=1}^{N_{h,d}} |h_d(l)|^2.
\]  

(9)

The CDF of \( \gamma_{L,d} \), over an i.n.i.d frequency selective fading channel, is given by (10), shown at the top of the next page.

In (10), we have defined

\[
\begin{align*}
\mathcal{X}_{L_1} & \triangleq \sum_{l=0}^{N_{h,d}-1} 1/\Gamma(l + 1), \\
\mathcal{X}_{L_2} & \triangleq (\tilde{\beta}_d + \frac{1}{\tilde{\alpha}_{h,d}})^{-\sum_{l=0}^{N_{h,d}+l_d} \Gamma(\tilde{\alpha}_{h,d} + l_d)} \frac{\Gamma(\tilde{\alpha}_{h,d} + l_d)}{\Gamma(\tilde{\alpha}_{h,d})} \prod_{l=1}^{M-1} (-1)^{m_l} \prod_{l=1}^{m_l} (\tilde{\gamma}_l(\tilde{\beta}_{q,l}, l_d)^{l_t}),
\end{align*}
\]

and \( \gamma_l(\cdot, \cdot) \) denotes the lower incomplete gamma function [17, Eq. (8.350.1)]. Due to space limitations, we omit the derivation of (10).

B. Receive SINR at the EU over i.n.i.d. frequency selective fading channels

From (6), the received signal at the EU consists of the desired signal being intercepted by the EU, non-decodable interference by the use of ANS, and noise. Thus, the receive signal power, \( S_{E,d} \), and noise-power-plus-interference power due to the interfering signal, \( N_{E,d} \), at the EU are respectively given by

\[
S_{E,d} = P_T \alpha_{g,d} \sum_{l=1}^{N_{g,d}} |g_d(l)|^2 \text{ and } N_{E,d} = P_J \sum_{m \in S_{M,d} \backslash \{d\}} \alpha_{g,m} \sum_{l=1}^{N_{g,m}} |g_m(l)|^2 + \sigma_z^2
\]  

(11)

where \( S_{E,d} \) is the signal power provided by the \( d \)th RRH. Note that \( \tilde{\Pi}_m G_m P_{B,m,\hat{\delta}_n} \) is also right circular. In addition, the remaining \( (M - 1) \) RRHSs are assigned as the set of interfering RRHSs. Thus, \( S_{E,d}/N_{E,d} \) decreases in general as the number of RRHSs increases, which is beneficial for increasing the security of the proposed cooperative system. Note that the EU channels are independent of the LU channels, so that the conditional SINR at the EU is given by

\[
\gamma_{E,d} = \frac{S_{E,d}}{N_{E,d}} = \frac{\tilde{\alpha}_{g,d} \sum_{l=1}^{N_{g,d}} |g_d(l)|^2}{\sum_{m \in S_{M,d} \backslash \{d\}} \tilde{\alpha}_{g,m} \sum_{l=1}^{N_{g,m}} |g_m(l)|^2 + 1}
\]  

(12)

where \( \tilde{\alpha}_{g,d} = \frac{P_T}{\sigma_P^2} \) and \( \tilde{\alpha}_{g,m} = \frac{P_T \alpha_{g,m}}{\sigma_P^2} \). Note that \( \tilde{\alpha}_{g,d} \) is multiplied by \( P_T \), whereas \( \{\tilde{\alpha}_{g,m}\}_{m \in S_{M,d} \backslash \{d\}} \) are multiplied by \( P_J \).

Over i.n.i.d. frequency selective fading EU channels, the PDF of the SINR at the EU is given by

\[
f_{\gamma_{E,d}}(x) = \mathcal{X}_E \mathcal{X}_{L_1} e^{-\frac{1}{\tilde{\alpha}_{g,d}} \sum_{l=0}^{l_d} \Gamma(l + 1)} \frac{1}{\Gamma(l + 1)} \prod_{l=1}^{M-1} (-1)^{m_l} \prod_{l=1}^{m_l} (\tilde{\gamma}_l(\tilde{\beta}_{q,l}, l_d)^{l_t}),
\]

(13)

and the \( \tilde{\beta}_{g,m,\hat{\delta}_n} \) is defined in Appendix A. In addition, \( \tilde{\beta}_{g,m,\hat{\delta}_n} \) denotes the \( m_3 \)th \( \hat{\delta}_{g,\tilde{\delta}} \) indexed by \( m_3 \in S_{M,d} \backslash \{d\} \). Due to space limitations, we omit the derivation of (13). The SINR and SNIR expressed by Eqs. (9) and (12) can be empirically derived when we use a maximum-likelihood detector [18], [19] for CP-SC transmissions.

C. Secrecy outage probability

At a given secrecy rate \( R_s \), the conditional secrecy outage probability is defined by [2]

\[
P_{d,\text{out}}(R_s) = P_R(C_s,d < R_s) = \int_0^{\infty} F_{\gamma_{E,d}}(x) e^{-\frac{1}{\tilde{\alpha}_{g,d}} \sum_{l=0}^{l_d} \Gamma(l + 1)} \prod_{l=1}^{M-1} (-1)^{m_l} \prod_{l=1}^{m_l} (\tilde{\gamma}_l(\tilde{\beta}_{q,l}, l_d)^{l_t})
\]

(14)

where \( J_R \triangleq 2R_c \). A closed form expression for \( P_{d,\text{out}}(R_s) \), can be derived in the next theorem.

Theorem 2: For i.n.i.d. frequency selective fading over the entire legitimate and eavesdropper channels, the proposed single carrier system improves PLS by employing dCDD that supports simultaneous data and jamming transmissions. The achievable conditional secrecy outage probability at secrecy rate \( R_s \) is given by (15), shown at the top of the next page.

In (15), we have defined

\[
\Delta J_R \triangleq J_R(\tilde{\beta}_d + 1/\tilde{\alpha}_{h,d}) + 1/\tilde{\alpha}_{g,d},
\]

\[
\mathcal{X}_{P_{d_1}} = \mathcal{X}_{L_1} e^{-\frac{1}{\tilde{\alpha}_{h,d}} \sum_{j_2=0}^{l_1} \left( \frac{1}{j_2} \right) \mathcal{X}_E \left( \frac{1}{\tilde{\beta}_{g,m,\hat{\delta}_n}} \right)^{l_2-j_2}} \frac{(J_R - 1)^{l_1-j_2} J_R^{l_2-j_2}}{(\tilde{\alpha}_{h,d} + 1/\tilde{\alpha}_{g,d})^{l_2-j_2}} - \mathcal{X}_{P_{d_2}},
\]

and

\[
\mathcal{X}_{P_{d_2}} = e^{-\frac{1}{\tilde{\alpha}_{h,d}} \sum_{j_2=0}^{l_1} \sum_{j_3=0}^{l_3} \left( \frac{m_2}{j_3} \right) \mathcal{X}_E \left( \frac{1}{\tilde{\beta}_{g,m,\hat{\delta}_n}} \right)^{l_2-j_2}} \frac{1}{\Gamma(m_2 + 1)} \left( \tilde{\beta}_d + 1/\tilde{\alpha}_{h,d} \right)^{m_2} \sum_{j_3=0}^{l_3} \left( \frac{m_2}{j_3} \right) (J_R - 1)^{m_2-j_3} J_R^{j_3}.
\]
In (15), \( G_{p,q}^{m,n} \left( \left\{ a_1, \ldots, a_n, a_{n+1}, \ldots, a_p \right\} \right) \) denotes the Meijer G-function [17, Eq. (9.301)].

Proof: Due to space limitations, we omit the derivation.

Again, at each of the transmissions, only one RRH is selected as the data RRH, so that the selections of the data RRH are mutually exclusive and independent of each other. Thus, the marginal secrecy outage probability achieved by the proposed dACDD based PLS system is given by

\[
P_{\text{out}}(R_s) = \sum_{d=1}^{M} P_{d,\text{out}}(R_s) P_r(d). \tag{16}
\]

IV. Simulation Results

In this section, we first verify the derived closed form expression for the secrecy outage probability. To this end, we compare the analytically derived performance metric (denoted by An) with the exact performance metric (denoted by Ex) for various scenarios. The corresponding marginal (unconditional) metrics are denoted by man and mex. Note that man is derived by (16).

We assume that the LU and EU are respectively placed at \((x = 0.5, y = R/2)\) and \((x = 1, y = 3)\). The transmission block size is made of 64 symbols \((B = 64)\). The CP length is given by 16 symbols \((N_{\text{CP}} = 16)\). Thus, four RRHs can be used for dACDD. In all scenarios, we fix \(P_r = 1\) and \(R_s = 1\). Unless otherwise noted, we assume \(P_j/\sigma_j^2 = 2\) dB. A fixed path-loss exponent is assumed to be \(\epsilon = 2.09\) [20]. \(T_m\) and \(T_{m'}\) are uniformly generated in the range \((0, N_{\text{CP}})\). Based on \(\{T_m\}_{m=1}^{M} \), \(\bar{S}_M\) is generated from \(S_M\) with the condition \(\Delta_{\bar{m}} = (m - 1)N_{\text{CP}} \geq T_m, m = 1, \ldots, M\).

To verify the analytically derived performance metrics, such as the secrecy outage probability and probability of non-zero achievable secrecy rate, we consider two geometric scenarios depending on the locations of the RRHs as follows:

1. \( \mathbb{X}_1: M = 3 \) with three RRHs placed at \( \{Re^{j\pi/6}, Re^{3j\pi/6}, Re^{5j\pi/6}\} \).
2. \( \mathbb{X}_2: M = 4 \) with four RRHs placed at \( \{Re^{j\pi/4}, Re^{3j\pi/4}, Re^{j\pi/2}, Re^{3j\pi/2}\} \).

To verify the derived secrecy outage probability over three different locations for a set of RRHs, the following parameters are assumed:

- \( \mathbb{X}_1: R = 5, N_{h,s} = \{1, 2, 3\}, N_{g,s} = \{3, 3, 3\} \) with \( \mathbb{X}_1 \).
- \( \mathbb{X}_2: R = 5, N_{h,s} = \{1, 2, 3\}, N_{g,s} = \{3, 3, 3\} \) with \( \mathbb{X}_1 \).
- \( \mathbb{X}_{21}: R = 5, N_{h,s} = \{1, 2, 3, 1\}, N_{g,s} = 2 \) with \( \mathbb{X}_2 \).
- \( \mathbb{X}_{22}: R = 5, N_{h,s} = \{1, 2, 3, 2\}, N_{g,s} = 2 \) with \( \mathbb{X}_2 \).

For scenarios \( \mathbb{X}_{11} \) and \( \mathbb{X}_{12} \), (7) provides the selection probability as follows:

\[
P_r(d = 1) = 0.56782, P_r(d = 2) = 0.28957, P_r(d = 3) = 0.14261.
\]

For scenario \( \mathbb{X}_{21} \), we have \( P_r(d = 1) = 0.40475, P_r(d = 2) = 0.27162, P_r(d = 3) = 0.11599, \) and \( P_r(d = 4) = 0.20764, \) whereas we have \( P_r(d = 1) = 0.302866, P_r(d = 2) = 0.169747, P_r(d = 3) = 0.0583573, \) and \( P_r(d = 4) = 0.4692097 \) for scenario \( \mathbb{X}_{22} \).

From Fig. 3, we can verify the accuracy of the analytically derived marginal secrecy outage probability for various simulation scenarios.

In generating Fig. 4, we assume that \( \sum N_{h} = 4 \) and \( N_{g,s} = 3 \) for scenarios \( \mathbb{X}_1 \) and \( \mathbb{X}_2 \). The primary interest of this simulation is to investigate the effect of the sum of the multipath components over the LU channels on the slope of the performance curve of the marginal secrecy outage probability.

We can summarize the following facts:

- When \( \sum N_{h} \) is the same, almost the same slope can be obtained in the high SNR region. For example, for differ-
independent of the index of the RRH that specifies the data has been shown to be determined mainly by the sum of the probability have been derived. Their accuracy have also been while minimizing the SINR at the EU. For i.n.i.d. frequency to achieve the maximum achievable diversity gain at the LU, exact CSI of the LU and EU channels at the transmitting side.

Fig. 4. Secrecy outage probability for various scenarios with the constraint of $N_{b,k}=3$, $\sum N_j = 4$, and $R = 5$.

ent combinations for $N_{h,m}$, $\{1, 2, 1\}$, $\{1, 1, 2\}$, $\{2, 1, 1\}$ with three RRHs, and $\{1, 1, 1, 1\}$ with four RRHs have the same slope. When there are fewer multipath components over the EU channels, a lower marginal secrecy outage probability is achieved.

- Due to the i.n.i.d frequency selective fading for the LU and EU channels, a different secrecy outage probability is obtained depending on which RRH is selected as the data RRH, while maintaining the same slope in the high SNR region.

- We can see that the slopes for $P_{d_{out}}(R_s)$ and $P_{out}(R_s)$ will be the same as $1/\sigma_z^2$ increases. Note that since the data RRH is selected based on the instantaneous LU channel that has the greatest channel magnitude, the proposed selection scheme can guarantee that $P_{d_{out}}(R_s)$ and $P_{out}(R_s)$ achieve the same diversity gain from i.n.i.d. frequency selective fading channels.

V. CONCLUSIONS

In this paper, we have proposed a new joint selection scheme for the data RRH and interfering RRHs for a new proposed dACDD based single carrier transmission scheme without exact CSI of the LU and EU channels at the transmitting side to achieve the maximum achievable diversity gain at the LU, while minimizing the SINR at the EU. For i.n.i.d. frequency selective fading channels, new closed-form expressions for the selection probability of the data RRH and secrecy outage probability have been derived. Their accuracy have also been verified. In the high SNR region, the achievable diversity gain has been shown to be determined mainly by the sum of the number of multipath components over the LU channels, and independent of the index of the RRH that specifies the data RRH.

REFERENCES


APPENDIX A

$$\begin{aligned}
\theta_{m,j}\Delta&=\frac{(-1)^{N_{g,m}}}{\beta_{g,m,d}}\sum_{(\delta_{g,k},q_{k})\in S(m,j)}\prod_{k=1, k\neq m}^{M-1} \left(N_{g,k} + q_{k} - 1\right)
(1-\beta_{g,k,d}^{q_{k}})^{N_{g,k}+q_{k}}
\end{aligned}
$$

(A.1)

with $S(m,j)$, the $m$th component of $S(i,j)$, which is defined as a set of $(M-1)$-tuples satisfying the following condition: $S(i,j)\triangleq\{q_1, \ldots, q_{M-1}\} : \sum_{k=1}^{M-1} q_k = N_{g,i} - j$ with $q_i = 0$.\]