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A Cluster-Based Transmit Diversity Scheme for Asynchronous Joint Transmissions in Private Networks

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Index Terms—Private networks, distributed cyclic delay diversity, joint transmission, spectral efficiency.

I. INTRODUCTION

A private network is a promising new connectivity model offering previously unavailable wireless network performance to businesses and individuals. The owners can optimize services at their specific areas by planning and installing their own networks, and ensure reliable communications by an exclusive use of available resources. Since they have complete control over every aspect of the network, they can determine how resources are utilized, how traffic is prioritized, how a specific security standard is deployed, and so on. Potential applications to industries, businesses, utilities, and public sectors have gravitated towards 5G wireless networks with increasingly stringent performance requirements, in terms of availability, reliability, latency, device density, and throughput [1]. The deployment of private networks can be feasible in the shared spectrum or unlicensed spectrum. Furthermore, to increase transmission speeds and capacity, reduce latency, and make the signal closer to the users, a dense deployment of small cells or clusters is expected [2].

To increase the spectral efficiency and coverage, a distributed antenna system (DAS) [3], [4], in which antennas are installed in a distributed manner over a coverage area of the base station (BS), is a promising approach for private networks. When each antenna operates as a BS, the DAS can be recognized as coordinated multiple point (CoMP) [5], [6]. Its core concept is to provide simultaneous communications by a plurality of BSs to a single or multiple users to improve the rate over a whole communication region. As major approaches of CoMP, coordinated beamforming and joint processing that includes joint transmissions (JT) are available. However, since we do not assume full channel state information at the transmitter (CSIT), we will focus on JT in this paper. Geographically placed BSs make the system properly counters path loss and shadowing [7]. However, it is challenging to collect full CSIT in the distributed system. Although a very reliable channel estimate can be obtained by the user, the feedback overhead will be overwhelming for large number of BSs. A conventional codebook based feeding back may not be working for CoMP due to significant differences in received signal strength [8].

In addition, a tight clock synchronization among BSs is required. Its mismatch will cause interference at the user due to the difference in signal arrival times from all the BSs. When Global Navigation Satellite System (GNSS) signals are not available in the private area, it is possible to achieve a desired clock synchronization by the precision time protocol (PTP) [9]. When a plurality of BSs transmit simultaneously, the existence of interference is an intrinsic problem [3] as well. We are investigating the following four problems in this paper.

1) When a DAS is installed in the private environments, it will be affected by multipath-rich propagation.
2) Since the distance between each of the remote radio units (RRUs) varies with respect to the receiver (RX), a received symbol timing cannot be aligned at the RX due to a path dependent propagation delay [10]. Note that RRU has only a single antenna and fixed power for simple processing, so that a system comprising a plurality of RRRUs, called the distributed remote radio unit system (dRRUS), is recognized as the DAS [11].
3) CSIT-dependent precoders are usually employed to minimize interference caused by simultaneous multiple transmissions. Thus, it is necessary to apply an interference-free transmission scheme to achieve a full transmit diversity.

4) Feeding back overhead from the RX increases in proportion to the number of RRUs.

Taking into four mentioned problems, we can summarize the following two key contributions comparing with existing work.

1) A new multi-cluster-based distributed remote radio unit system (MC-dRRUS): To provide a greater throughput for the private network, we propose a new MC-dRRUS, in which the private network server (PNS) provides transmission signals and synchronization to the respective cluster masters (CMs). Within non-overlapping clusters, each CM forms an individual dRRUS.

2) Distributed asynchronous cyclic delay diversity-based JT (dACDD-JT) scheme: It is desired to increase the number of RRUs to cover larger territory and to increase channel diversities. However, such an increase would result in additional interference, difficulty in time synchronization, and undesirable feedback overhead. With an available distribution for propagation delays over the whole paths, the CM is able to consider its variant in assigning the CDD delay at each of its RRUs, which is necessary to remove intersymbol interference (ISI) caused by asynchronous signal reception at the RX [12].

Notation: $\mathbf{I}_N$ denotes an $N \times N$ identity matrix; 0 denotes an all-zero matrix of an appropriate size; and $\mathcal{CN} (\mu, \sigma^2)$ denotes a complex Gaussian distribution with mean $\mu$ and variance $\sigma^2$. The binomial coefficient is denoted by $\binom{n}{k} = \frac{n!}{(n-k)!k!}$. For a vector $\mathbf{a}$, $\mathbb{L}(\mathbf{a})$ denotes the cardinality; and its $i$th element is denoted by $a(i)$. For another vector $\mathbf{a}_{i,N}$ with the second subscript defining its cardinality, $\sum_{i} (\mathbf{a}_{i,N}) = c$ denotes the sum for all set of positive indices of $\{a_{i,1}, \ldots, a_{i,N}\}$ satisfying $\sum_{i=1}^{N} a_{i,j} = c$, and the binomial coefficient becomes the multinomial coefficient as follows: $(c \choose \mathbf{a}_{i,N}) = \frac{(c)!}{\prod_{j=1}^{N} (a_{i,j})!}$.\[
\sum_{\mathbf{a}} \prod_{j=1}^{N} a_{i,j} \triangleq \sum_{n_1=1}^{a_{i,1}} \sum_{n_2=1}^{a_{i,2}} \cdots \sum_{n_N=1}^{a_{i,N}} = \prod_{j=1}^{N} \binom{c}{a_{i,j}} \frac{c!}{\prod_{j=1}^{N} (a_{i,j})!}.
\]

For a set of continuous random variables, $\{x_1, x_2, \ldots, x_N\}$, $x(i)$ denotes the $i$th smallest random variable, so that it becomes the $i$th order statistic. For these order statistics, the spacing statistics, $\{y_1, \ldots, y_N\}$, are obtained by changing the variables as $y_i = x(i) - x(i-1)$ with $y_1 = x(1)$.

II. SYSTEM AND CHANNEL MODELS

Fig. 1 illustrates the considered MC-dRRUS with two non-overlapping and co-located clusters. Each cluster is recognized as an individual dRRUS. The PNS works as the grand master clock by PTP, so that it can compute propagation delay to the RX passing over a particular CM and RRU. In contrast, the CM and RRUs work as the boundary clock and transparent clocks, which have multiple PTP ports to interact with other clocks. The RX is represented as the ordinary clock. Very reliable main backhaul links, $\{b_1, b_2\}$, are configured to provide backhaul access to the clusters via the coordinator that resides at the PNS. Other very reliable secondary backhaul links, $\{b_{i,j}, i = 1, j = 1, \ldots, K\}$, provide backhaul access to RRUs via the CM. The CM controls all RRUs and is responsible for transmitting the signals. Every node in the cluster is assumed to be equipped with a single antenna.

A frequency selective fading channel from the $k$th RRU, deployed in the $i$th cluster, to the RX is denoted by $h_{i,k}$ with $\mathbb{L}(h_{i,k}) = N_{i,k}$. A distance-dependent large scaling fading is denoted by $\alpha_{i,k}$. For a distance $d_{i,k}$ from RRU $i,k$ to the RX, $\alpha_{i,k}$ is defined by $\alpha_{i,k} = (d_{i,k})^{-\epsilon}$, where $\epsilon$ is the path loss exponent. The RX is placed at a specific location with respect to the RRUs, and, thus, independent but non-identically distributed (i.i.d.) frequency selective fading channels from the RRUs to RX are assumed. The RX is assumed to have knowledge of the number of multipath components of the channels connected to itself by either sending a training sequence or adding a pilot as the suffix to each symbol block. To reduce the feedback overhead, the RX first computes $N_{\text{max}} = \max \{N_{i,k}, \forall i, k\}$. After then, it feeds back $N_{\text{max}}$ to the PNS, so that it is not necessary for the CMs to use X2 interface to exchange their channel relevant parameters.

To estimate the clock offset, $\theta$, and propagation delay, $d$, PTP [9] specifies four event messages, such as Sync, Delay-Req, Pdelay-Req, and Pdelay-Resp, within which an accurate hardware timestamp is generated and recorded at transmission and reception of its respective messages. Thus, by

$\sum$\[Access point can be work as the CM in IEEE 802.11be.\]

$\sum$\[Interested reader refer to [13] that investigates unreliable backhaul in the similar system setup. Thus, this paper does not consider unreliable backhaul.\]
after exchanging two-way packets between $D_1$ and $D_2$, four hardware timestamps $(t_1, t_2, t_3, t_4)$, are available at $D_1$ and $D_2$. Based on four timestamps, $d$ and $\theta$ are respectively computed as: $d \approx \frac{t_{3} - t_{2} - (t_{4} - t_{1})}{2}$ and $\theta \approx \frac{(t_{4} - t_{1}) - (t_{2} - t_{3})}{2}$, where we assume that the forward propagation delay, $d_f$, is almost equal to the backward propagation delay, $d_r$, i.e., $d_f \approx d_r$, and clocks are perfectly synchronized in frequency and phase. Applying the same procedure, $D_1$ can estimate the propagation delay to another node, $D_3$, which supports PTP, so that it can be synchronized to $D_2$. This clock synchronization is accomplished via main and secondary backhaul links.

Referring to Figs. 1 and 2, the PNS has a set of propagation delay estimates $\{d_{i,k}\}_{k=1,...,K}$ over the first cluster, $C_1$. For other clusters, the PNS can estimate propagation delay as well. Thus, we can assume that a complete set of propagation delays, $\{d_{i,k}\}_{i=1,...,2,k=1,...,K}$, is available at the PNS by employing PTP. According to this set, the PNS computes the propagation delay for the signal that arrives first at the RX as follows:

$$\hat{d}_{ref} = \min \{\{d_{i,k}\}_{i=1,...,2,k=1,...,K}\}$$

(1)

after then a relative propagation delay with respect to $\hat{d}_{ref}$.

$$\hat{\delta}_{d,k} = d_{i,k} - \hat{d}_{ref}, \text{ for } i = 1, \ldots, 2, k = 1, \ldots, K.$$  

(2)

The distributed CDD (dCDD) scheme was proposed by [11], [14] for distributed cyclic-prefixed single carrier (CP-SC) transmissions to achieve transmit diversity without full CSIT. Depending on the block size, $Q$, of the transmission symbol, $s \in \mathbb{C}^{Q \times 1}$, and the cyclic-prefix (CP) length, $N_{CP}$, which is set to $N_{max}$, the maximum number of RRU s, that achieves ISI-free reception at the RX is determined by $M = \lceil Q/N_{CP} \rceil$, where $\lceil \cdot \rceil$ denotes the floor function. When the $i$th dRRUS is overpopulated with the RRRUs, i.e., $K_i > M$, the CMi needs to select only $M$ RRRUs for dCDD operation. Thus, the RX needs to feedback necessary information to the PNS. Based on available channel estimates, the RX rearranges them according to their strength, from smallest to largest, as follows:

$$\alpha_{i,\{1\}} ||H_{i,\{1\}}||^2 \leq \ldots \leq \alpha_{i,\{M\}} ||H_{i,\{M\}}||^2.$$  

(3)

According to (3), the RX forms a list specifying the strength order, that is, $D_i \hat{\Delta}_{\{1\}}(\{1\}, \ldots (M))$, and then feedbacks $D_i$ to the PNS. Furthermore, CMi can have $D_i$ via the main backhaul communications over $b_i$, from which CMi selects $M$ RRRUs indexed by the last $M$ elements of $D_i$, that is, $RRU_{i,(K-M+1)}, \ldots, RRU_{i,(K)}$. The remaining $K-M$ RRRUs are controlled by CMi to be idle from communications. For the chosen $M$ RRRUs, CMi assigns the CDD delay to $RRU_{i,(K-M+1)}$ as follows:

$$\Delta_m = (m-1)N_{CP}, \text{ } m = 1, \ldots, M.$$  

(4)

Thus, for an overpopulated dRRUS, the PNS can achieve the same objective as distributed MRT (dMRT) with using only partial CSIT. In summary, for dCDD operation, CMi needs to know $M$, $N_{CP}$, and $D_i$, which are available at each of the CMs by backhaul communications made by the PNS.

III. dACDD-JT FOR CP-SC TRANSMISSIONS

Without loss of generality, we assume that $RRU_{1,1}$’s signal arrives first at the RX in the considered private networks. Since the PNS has propagation delay estimates for its whole network, it can compute the distribution for relative propagation delays with respect to $RRU_{1,1}$’s signal. As an initial interactive process between the PNS and RX, the PNS transmits $d_{ref}$ to the RX via clusters.

After the removal of the CP signal and applying post-processing by $d_{1,1}$, the RX receives a composite signal from two clusters as follows:

$$r = \sum_{m=1}^{M} \left[ [\Pi_1,(K-M+m)H_1,(K-M+m)P_1,(K-M+m)s]_1 + [\Pi_2,(K-M+m)H_2,(K-M+m)P_2,(K-M+m)s]_2 \right] + z(5)$$

where $[,]_1$ and $[,]_2$ respectively represent signals transmitted from $C_1$ and $C_2$. In addition, $H_i,(K-M+m)$ is right circulant matrix determined by $\sqrt{P_f} \ast h_i,(K-M+m)$ with $P_f$ denoting the transmission power for single carrier transmissions. Note that $\Pi_i,(K-M+m)$ is right circulant and orthogonal permutation matrix determined by a relative propagation delay, $\delta d_{i,k}(K-M+m)$. Since full CSIT is not available in the considered system, the same $P_f$ is assigned to all the RRRUs.

By shifting down $I_Q$ by $\delta d_{i,k}(K-M+m)$ rows, $\Pi_i,(K-M+m)$ can be obtained. An additional set of permutation matrices, $\{P_i,(K-M+m),\forall i,m\}$, will be defined later. The additive vector noise is denoted by $z \sim \mathcal{CN}(0,\sigma_I^2I_Q)$. For proper operation, we assume that $0 \leq d_{i,k}(K-M+m) \leq N_{CP}$, so that we have $0 \leq \delta d_{i,k}(K-M+m) \leq N_{CP}$.

A. dACDD for JT

Using the properties of the right circulant matrix, (5) can be rewritten as:

$$r = \sum_{m=1}^{M} \left[ H_{1,\hat{m}}\Pi_{1,\hat{m}}[P_{1,\hat{m}}s]_1 + H_{2,\hat{m}}\Pi_{2,\hat{m}}[P_{2,\hat{m}}s]_1 \right] + z$$

(6)

where $\hat{m} \triangleq (K-M+m)$. Furthermore, $[,]_1$ and $[,]_4$ correspond to local operations respectively performed at $RRU_{1,\hat{m}}$ and $RRU_{2,\hat{m}}$. To make ISI-free reception at the RX, it is required that $\Pi_1,\hat{m}P_{1,\hat{m}}$ and $\Pi_2,\hat{m}P_{2,\hat{m}}$ are orthogonal and right circulant matrices, and meet the CDD delay assignment for $RRU_{1,\hat{m}}$. Accordingly, we can readily obtain $\delta T_{1,\hat{m}}$ that meets the condition: $\Delta_{\hat{m}} = \delta d_{i,\hat{m}} + \delta T_{1,\hat{m}}$. For operation $[,]_4$, $RRU_{1,\hat{m}}$ assigns $\delta T_{1,\hat{m}}$ as its CDD delay rather than $\Delta_{\hat{m}}$. By circularly shifting down the transmission symbol $s$ by $\delta T_{1,\hat{m}}$, operation $[,]_1$ can be accomplished. Similar operation is conducted for $[,]_4$. Thus, $P_{1,\hat{m}}$ and $P_{2,\hat{m}}$ can be obtained from $I_Q$ by circularly shifting down respectively by $\delta T_{1,\hat{m}}$ and $\delta T_{2,\hat{m}}$.

ISI caused by a variant propagation delay and multiple transmissions can be removed by a series of circular shifting operations that are respectively performed by the RRRUs.
and caused by propagation. Thus, dACDD is an extensive version of dCDD allowing the distribution of propagation delays over the private network. For proper dACDD operation, the PNS is required to know \(\{d_{i,n}\}_{i=1,2; m=1,\ldots,M}\) and \(\{\delta d_{i,n}\}_{i=1,2; m=1,\ldots,M}\). However, due to the use of PTP, an additional feedback is not necessary from the RX, which is the key difference from [12].

IV. SPECTRAL EFFICIENCY OF JT BY ASYNCHRONOUS MC-dACDD

Using the properties of the right circulant matrix, the achievable signal-to-noise ratio (SNR) realized by MC-dACDD based JT can be derived by the following Theorem 1.

**Theorem 1:** Even for asynchronous signal reception at the RX, ISI-free reception can be achieved via MC-dACDD. Thus, the achievable SNR realized by JT is given by

\[
\gamma_{JT} = \gamma_{JT,1} + \gamma_{JT,2} = \frac{\rho_s}{\sigma^2}
\]

where \(\rho_s = P_T \left( \sum_{m=1}^{M} \alpha_{1,m} \left\| h_{1,m} \right\|^2 + \sum_{m=1}^{M} \alpha_{2,m} \left\| h_{2,m} \right\|^2 \right) \)

with \(\rho \triangleq P_T / \sigma^2 \) and \(\gamma_{JT,1} = \rho \sum_{m=1}^{M} \left\| h_{1,m} \right\|^2 \).

**Proof:** When \(\{h_{1,m}, \forall m\}\) and \(\{h_{2,m}, \forall m\}\) are independent of each other, \(\rho_s\), realized at the RX, is determined by the summation of their squared Euclidean norms.

For overpopulated dRRUS, the CM selects only \(M\) RRUs by referring to the channel strength. Thus, the order statistics are employed in the expression for the achievable SNR. **Theorem 1** proves that by compensating different signal arrival times at the RX, the MC-dACDD makes JT provide the same benefit as dMRT without full CSIT at the PNS and CMs.

**Theorem 2:** Due to the use of JT, the proposed MC-dACDD results in the SNR, \(\gamma_{JT}\) realized at the RX, whose approximation of the moment generating function (MGF) is given by

\[
M_{\gamma_{JT}}(s) = \sum_{n_1, \ldots, n_M} \sum_{a_1, \ldots, a_M} \prod_{k=1}^{M} (M + 1 - k)^{-e_k} \Gamma(e_k) \sum_{l=0}^{N_1} (\delta_l(b_l) - 1) \frac{1}{(b_l + s)^{-G_d(l)}}
\]

where \(G_d \triangleq \sum_{k=1}^{M} G_k\), \(b_l \triangleq \min(1/Q_{1}, \ldots, 1/Q_{2M})\) with \(Q_k\) and \(G_k\), respectively the \(k\)th elements of \(Q = [q_1, \ldots, q_M, \bar{q}_1, \ldots, \bar{q}_M]^T\) and \(E = [e_1, \ldots, e_M, \bar{e}_1, \ldots, \bar{e}_M]^T\). Furthermore, \(N_1\) denotes an upper limit summation, and \(\delta_l \triangleq \sum_{i=1}^{l} r_i \delta_{l-i}\) with \(\delta_0 = 1\) and \(r_i = \sum_{j=1}^{M} E_j (1 - b_j Q_j)^{-1}\). Additional terms specified in (8) are defined in Appendix A.

**Proof:** See Appendix A.

Theorem 2 provides the MGF expressed by the weighted sum of \(N_1 + 1\) terms, proportional to \((1/b_l + s)^{-G_d(l)}\).

**Corollary 1:** The CDF of \(\gamma_{JT}\) can be expressed by a finite number of gamma distributions.

\[
F_{\gamma_{JT}}(x) = 1 - \sum_{n_1, \ldots, n_M} \sum_{a_1, \ldots, a_M} \prod_{k=1}^{M} (M + 1 - k)^{-e_k} \Gamma(e_k) \prod_{l=0}^{N_1} (\delta_l(b_l) - 1) \frac{1}{(b_l + s)^{-G_d(l)}}
\]

where \(\Gamma(\cdot)\) and \(\Gamma_U(\cdot, \cdot)\) respectively denote complete gamma and incomplete upper-gamma functions.

Based on (9), the spectral efficiency (SE) of the proposed MC-dACDD is given by the following theorem.

**Theorem 3:** The achievable SE of the proposed MC-dACDD is given by

\[
SE = \frac{1}{\log(2)} \sum_{n_1, \ldots, n_M} \sum_{a_1, \ldots, a_M} \prod_{k=1}^{M} (1 + 1 - k)^{-e_k} \Gamma(e_k) \left[ \sum_{l=0}^{N_1} \delta_l \frac{1}{(b_l + s)^{-G_d(l)}} \right]
\]

where \(G_{M,n}(t) \triangleq \sum_{a_1, \ldots, a_{n+1}, \ldots, a_M} b_1, \ldots, b_{n+1}, \ldots, b_q\) denotes the Meijer G-function [15, Eq. (9.301)].

**Proof:** We first express the functions of \(x\) in terms of Meijer G-functions, i.e., \((1 + x)^{-1} = G_{1,1}^{2,0}(x|x^{-1})\) and \(\Gamma_u(j, ax) = G_{1,2}^{2,0}(\alpha x^{-1} | x^{-1})\). After this, applying [16, eq. (2.24.1.2)], we can derive (10).

V. SIMULATION RESULTS

We assume the following simulation setup.

1. \(C_1\): Six RRUs are placed at \((-1.2, 4.7), (0.7, 4.0), (3.0, 3.0), (-2.5, 2.7), (-3.3, 0.4),\) and \((-3.0, 3.5)\). The first cluster master, \(CM_1\), is placed at \((0, 2)\) in a 2-D plane.

2. \(C_2\): Four RRUs are placed at \((12.8, 3.3), (7.4, 2.5), (10.0, 4.6),\) and \((9.0, 1.7)\). The second cluster master, \(CM_2\), is placed at \((10.0, 3.0)\) in a 2-D plane.

3. For CP-SC transmissions, we assume that \(Q = 32\) and \(N_{CP} = 8\). Thus, the CMs can support up to four RRUs for dACDD operation, i.e., \(M = 4\).

4. RX is placed at \((3, -3)\).

In all scenarios, we fix \(P_T = 1\). A fixed path-loss exponent is assumed to be \(\epsilon = 2.09\).

6. The relative time difference, \(\delta T_{i,m}\), between the arrival time of the signal transmitted from RRU \(_{i,m}\) with respect to RRU \(_{1,1}\) is represented as an integer value uniformly generated between 0 and \(N_{CP}\).

We consider several frequency selective fading channel parameters for two clusters depending on the respective number of RRUs, \(K_1\) and \(K_2\). For notation purpose, we use \(\mathcal{H}_1 = \{N_{1,j}, j = 1, \ldots, K_1\}\) for \(C_1\) and \(\mathcal{H}_2 = \{N_{2,j}, j = 1, \ldots, K_2\}\) for \(C_2\).

1. \(\mathcal{H}_1\): \(\mathcal{H}_1 = \{2, 3, 4, 2.3\}\) and \(\mathcal{H}_2 = \{3, 2, 3.3\}\).

2. \(\mathcal{H}_2\): \(\mathcal{H}_1 = \{3, 4, 2, 3.2\}\) and \(\mathcal{H}_2 = \{3, 2, 3.3\}\).

3. \(\mathcal{H}_3\): \(\mathcal{H}_1 = \{2, 3, 4, 2, 3.4\}\) and \(\mathcal{H}_2 = \{3, 2, 3, 3.4\}\).

4. \(\mathcal{H}_4\): \(\mathcal{H}_1 = \{2, 3.4\}\) and \(\mathcal{H}_2 = \{3.2, 3.3\}\).

5. \(\mathcal{H}_5\): \(\mathcal{H}_1 = \{3, 4.5, 3, 4.5\}\) and \(\mathcal{H}_2 = \{5, 4.5, 5, 5.5\}\).
We denote the analytically derived SE by $A_n$, whereas we denote the exact performance metric obtained by the link-level simulations by $E_x$ in the sequel. Since there is no existing similar setup, i.e., CP-SC based MC-dACDD with JT, we mainly focus on the proposed scheme in this paper.

![Fig. 3. SE for various system and channel parameters.](image)

We first verify the analytically derived SEs for two overpopulated systems. The first system with $X_1$ assumes that dACDD supports only two RRUs, while five and four RRUs exist in $C_1$ and $C_2$, respectively. For the second system with $X_2$, dACDD supports only four RRUs, while five and four RRUs exist in $C_1$ and $C_2$, respectively. Fig. 3 shows an accuracy of the analytically derived SEs comparing with the exact SEs.

This figure also shows that if $N_1$ is not sufficiently large, an approximation, which is used in Theorem 2, does not provide an accurate SE. Thus, in the sequel, we use a sufficiently large value for $N_1$ without a specific description for it. In general, as $M$ increases, a larger value for $N_1$ is required to obtain very reliable and accurate analytic SEs.

![Fig. 4. SE for various over-popularity of dRRUSs with $X_3$.](image)

In generating Fig. 4, we mainly use $X_3$ with various over-popularity of dRRUSs and assume that $M = 4$. From Fig. 4 we can extract the following facts:

- As the dRRUS is populated with more RRUs, a greater SE can be achieved.
- As the number of clusters increases, a greater SE can be achieved. However, a more tight restriction on the number

![Fig. 5. SE for various values of $M$ and different numbers of multipath components.](image)

At a fixed 18 dB SNR, Fig. 5 shows the SE for various system and channel parameters. For underpopulated and overpopulated dRRUSs, the impact of $M$ on the SE is investigated.

- For a given $K_1$ and $K_2$, as $M$ increases, the dRRUS is populated with less RRUs. Although the SE increases in proportion to $M$, the growth rate of the SE decreases.
- As $K_1$ or $K_2$ greater, the growth rate of the SE increases. For example, $(K_1 = 6, K_2 = 5)$ vs. $(K_1 = 5, K_2 = 4)$.
- As the number of multipath components increases, a greater SE is obtained. For example, $X_3$ vs. $X_5$.

VI. Conclusions

In this paper, we have proposed a multiple cluster-based transmit diversity scheme for asynchronous joint transmissions. To relax the requirement of full channel state information at the private network server and deal with different propagation over the paths of the distributed systems composed of remote radio units, a dACDD scheme has been developed to the private network. The multi-level hierarchical PTP allows to break the dependency of different dRRUS clusters from a common PNS allowing each dRRUS cluster to use dACDD independently from other clusters. For i.i.d. frequency selective fading channels, a new closed-form expression for the spectral efficiency has been derived. Its accuracy has been also verified comparing with the link-level simulations. By integrating a transmission scheme, propagation delay estimation, and operation at the RRUs effectively, we have seen that the proposed multiple cluster-based asynchronous joint transmissions can achieve the desired spectral efficiency for various simulations scenarios.

APPENDIX A: PROOF OF THEOREM 2

To simplify the notation, let us define $x_m$ as $x_m = \rho^{0,1, (K_1 - M + m)} \| h_{1, (K_1 - M + m)} \|^2$. Note that the order statistics are implicitly involved in this definition. We mainly
focus on the derivation of the distribution for $\gamma_{J1}$ in the sequel. The MGF of $\gamma_{J1}$ can be defined as

$$M_{\gamma_{J1}}(s) = \mathbb{E}\left[e^{s \gamma_{J1}}\right] = \int_{0}^{\infty} f_{\gamma_{J1}}(x) e^{sx} dx,$$

where $f_{\gamma_{J1}}(x)$ is the probability density function of $\gamma_{J1}$. Then, the MGF of $\gamma_{J2}$, which is defined as $\sum_{n=1}^{\infty} n\gamma_{J2}^{n-1}$, can be derived as $\gamma_{J2}$ with $\sum_{n=1}^{\infty} n\gamma_{J2}^{n-1}$ similarly.

### REFERENCES


