Alamouti-Like Transmission Schemes in Distributed MIMO Networks

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***Abstract*—In this study, we investigate the potential benefits of using Alamouti-like orthogonal space-time-frequency block codes (STFBC) in distributed multiple-input multiple-output (D-MIMO) systems. We derive a closed-form ergodic spectral efficiency (SE) formula, numerically calculate outage SEs, and propose a centralized method for clustering radio units and user equipment so that a suitable STFBC is applied within each cluster. The results show that STFBCs together with an optimized clustering significantly outperform baseline techniques in terms of both ergodic and outage SE when there is no instantaneous channel state information at the time of transmission.**

***Index Terms*—Distributed MIMO, cell-free massive MIMO, Alamouti codes, robust transmission, clustering.**

I. INTRODUCTION

DISTRIBUTED massive multiple-input multiple-output (D-MIMO, also known as cell-free massive MIMO) is a promising network type that can help achieve extreme performance in dense urban scenarios for use cases requiring high data rates. By enabling several geographically distributed radio units (RUs) to cooperate and serve the user equipment (UE), D-MIMO networks provide a more uniform spectral efficiency (SE) and a better coverage probability than conventional cellular systems [1].

To increase the bandwidth and data rate, the mmWave frequency band has been standardized in 5G. In this band, due to high path loss and shadowing, reliable communication becomes a primary concern. Due to a dynamic environment with rapidly changing channels, it might be tricky to obtain up-to-date and accurate channel state information (CSI). As phase noise is also high at the local oscillators of each RU, it may not be possible to make an accurate phase calibration between different RUs. Therefore, D-MIMO at mmWave can make use of non-coherent joint transmission (NCJT) where the information symbols can be transmitted from different RUs without any phase calibration. 3GPP defines three NCJT schemes: transmitting different layers from different RUs (Case 1), space-time-frequency block codes (STFBC) over different RUs (Case 2a), single frequency network (SFN) transmission where each RU transmits the same symbol (Case 2b) [2]. All these techniques are designed for a small number of RUs, and it is not clear how to use them with many more distributed antennas. In traditional collocated MIMO, where all antennas have similar path loss and shadowing, STFBC is an efficient technique to increase diversity under fast fading. When the antennas are distributed, one can also enhance the robustness under slow fading by optimizing outage rates. In D-MIMO networks, STFBCs have the potential to provide high data rates and reliability in dynamic channel environments.

Alamouti codes [3] as the simplest STFBC, reduce the effect of fading at the UE side by providing the same diversity order as the maximal ratio combining with a two-branch transmit diversity scheme. Generalizations to more than two antennas are given in [4]. The authors in [5], [6] exploit the distributed space-time coded protocols that were devised for multi-antenna systems to utilize cooperative diversity in the problems of wireless relay networks. [7] proposes to use STFBCs to enhance the coverage and reliability of system information broadcast for inactive UEs in a D-MIMO network where RUs don't have CSI. There are also other works that investigate STFBCs for collocated massive MIMO [8] and reconfigurable intelligent surfaces [9]. To the best of our knowledge, there is no prior work analyzing user-specific data transmission using STFBCs in D-MIMO networks.

Contributions: In this study, we consider a D-MIMO network covered by disjoint clusters of RUs and UEs where each cluster adopts a possibly different Alamouti-like orthogonal STFBC. We derive a closed-form formula for ergodic SEs, numerically evaluate outage SEs, and propose a clustering method relying on the ergodic SE formulas. The numerical results reveal that STFBCs together with the proposed clustering have various benefits over baseline techniques in terms of both ergodic and outage SEs.

Outline: The organization of the paper is as follows. Section II describes the system model for STFBCs in D-MIMO, Section III involves the proposed clustering method to effectively use STFBCs in D-MIMO, Section IV presents detailed simulation results, and finally, Section V concludes the paper.

II. SYSTEM MODEL

We consider a D-MIMO network with M RUs which are all connected to a central processor (CP) via fronthaul links, and K UEs. Each RU has L antennas and each UE has N antennas. We focus on downlink transmission without CSI at the RU side, where all RUs jointly serve K UEs that are co-scheduled in the same time-frequency resource block. We assume that RUs apply STFBCs to serve UEs with unknown channel coefficients. An RU-UE clustering is performed to form disjoint clusters in which a suitable STFBC is applied

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within each of these clusters. Fig. 1 shows an example D-MIMO network.

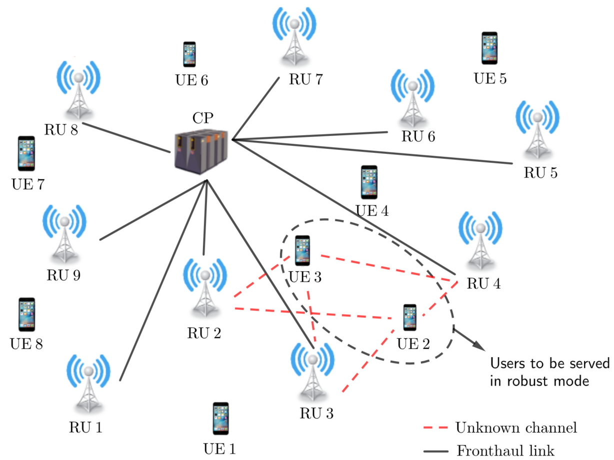


Fig. 1: An example D-MIMO network where some of the UEs are served in robust mode.

STFBCs are characterized by three parameters: the number of transmit antennas, the number of symbols transmitted, and the code period. In [4], for a given number of transmit antennas, the highest rate perfectly orthogonal codes are derived. We know that to effectively use the orthogonal codes, the channel should stay constant during the code period. As indicated in [4], as the code period increases, the code rate becomes lower. Therefore, it is not feasible to use a single cluster with a large STFBC. To limit the fronthaul traffic and make the code period small enough, we only consider the three smallest perfectly orthogonal codes whose code matrices are

$$\underbrace{\begin{pmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{pmatrix}}_{\mathbf{C}_{2,2,2}}, \underbrace{\begin{pmatrix} s_1 & s_2 & s_3 \\ -s_2^* & s_1^* & 0 \\ -s_3^* & 0 & s_1^* \\ 0 & -s_3^* & s_2^* \end{pmatrix}}_{\mathbf{C}_{3,3,4}}, \underbrace{\begin{pmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_4^* \\ -s_3^* & 0 & s_1^* & s_5^* \\ 0 & -s_3^* & s_2^* & s_6^* \\ 0 & -s_4 & -s_5 & s_1 \\ s_4 & 0 & -s_6 & s_2 \\ s_5 & s_6 & 0 & s_3 \\ -s_6^* & s_5^* & -s_4^* & 0 \end{pmatrix}}_{\mathbf{C}_{4,6,8}}, \tag{1}$$

where s_i's are symbols to be transmitted, rows show the time/frequency instants and columns denote the signals transmitted from the related transmit antennas. These three orthogonal codes have $2, 4$, and 8 code periods and we also take the direct transmission case into account without any STFBC whose code period can be considered as 1.

To apply STBFCs in D-MIMO, we form disjoint RU-UE clusters and use a suitable code within each cluster by sharing symbols between UEs in that cluster. Notice that in the original STFBC framework, it is focused on a single user to transmit multiple symbols; however, we can use the same transmission idea by sharing symbols between multiple UEs where each UE independently decodes its intended symbols. In multi-user case, as the symbols are shared between UEs, the SE of each UE is reduced by some factor. Similarly, the diversity gain will be less compared to the single-user case. On the other hand, if the inter-user interference is high, especially for closely located UEs, multi-user clustering might be beneficial.

We assume that in a cluster, symbols are distributed between UEs one by one according to the UE ordering in the cluster. For instance, in the case of 5 single antenna RUs and 3 UEs, assuming that we have two clusters $\{\mathrm{RU1}, \mathrm{RU2}, \mathrm{RU3}, \mathrm{UE1}, \mathrm{UE2}\}$ with symbols s_1, s_2, s_3 and $\{\mathrm{RU4}, \mathrm{RU5}, \mathrm{UE3}\}$ with symbols s_4, s_5, the intended symbol sets for UE 1, 2, 3 become $\{s_1, s_3\}, \{s_2\}, \{s_4, s_5\}$, respectively. Notice that the first cluster uses the code $\mathbf{C}_{3,3,4}$ and the second one uses the code $\mathbf{C}_{2,2,2}$.

As there is no CSI on the RU side, we assume that RUs do not apply any beamforming. According to the STFBC chosen and the time/frequency index, they simply transmit one of $s, -s, s^*, -s^*, 0$ where s is a complex data symbol which is intended for a UE in the related cluster. We also assume that some downlink pilot signals are transmitted from RUs and the channel coefficients are perfectly estimated at the UE side. In a D-MIMO network with a given RU-UE clustering, the received signal at the k-th UE can be written as

$$\mathbf{r}_{k,n} = \sum_{i \in S_k} \mathbf{h}_{k,n,i} s_i + \sum_{i \in C_k \setminus S_k} \mathbf{h}_{k,n,i} s_i + \sum_{i \notin C_k} \mathbf{h}_{k,n,i} s_i + \mathbf{z}_{k,n}, \tag{2}$$

where $\mathbf{r}_{k,n}$ is the received signal vector by the n-th antenna of the k-th UE, S_k is the index set of symbols intended for UE k, C_k is the index set of symbols transmitted in the cluster of UE k, $\mathbf{h}_{k,n,i}$ is the channel vector for the i-th symbol and n-th antenna of UE k, $\mathbf{z}_{k,n} \sim \mathcal{CN}(\mathbf{0}, \sigma_k^2 \mathbf{I})$ is the noise vector at n-th antenna of UE k. Here the column vector $\mathbf{r}_{k,n}$ has dimension $T_0 = 8$ which is the least common multiple of all possible code periods. We consider T_0 time/frequency samples and consider all symbols transmitted within this interval. Elements of $\mathbf{r}_{k,n}$ show the received signal at the corresponding time/frequency sample. In (2), we transform the channel vectors by applying conjugation and/or multiplication with -1 or 0 to their elements to write the received signal in terms of the original s_i symbols. It is known that once the code is perfectly orthogonal, the transformed channel vectors become also orthogonal, i.e., $\mathbf{h}_{k,n,i}^H \mathbf{h}_{k,n,j} = 0$ for all $i \neq j$ and $i, j \in C_k$.

Thanks to the orthogonality of the code and the disjoint nature of clusters, the symbols in $C_k \setminus S_k$ can be eliminated by the k-th UE whereas the symbols outside the cluster C_k cannot be eliminated. Therefore, we can define a signal-to-interference-plus-noise ratio (SINR) for the symbol s_i for any $i \in S_k$ as

$$\mathrm{SINR}_{k,i} = \frac{d_{k,i} P_t}{\sum\limits_{j \notin C_k} \mathbb{E}[d_{k,j}] P_t + \sigma_k^2}, \tag{3}$$

where $d_{k,i} = \sum\limits_{n=1}^{N} \mathbf{h}_{k,n,i}^H \mathbf{h}_{k,n,i}$ for all k, i and P_t is the transmit power for each RU antenna. In this study, we assume that there is a separate power amplifier for each transmit antenna at the RU side, and hence a transmit power limit per antenna is assumed. We treat the interference $d_{k,j}$ for $j \notin C_k$ and noise terms as unknowns with known statistics. On the other hand,

Theorem 1.

$$\mathrm{SE}_{\text{ergodic},k} = \frac{1}{T_0} \sum_{i \in S_k} \left(\prod_{r=1}^{a} \lambda_{r,i}^{u_r} \right) \sum_{r=1}^{a} \sum_{\ell=1}^{u_r} \frac{\Phi_{r,\ell,i}(-\lambda_{r,i}) \log_2(e)}{\lambda_{r,i}^{u_r-\ell+1}(\ell-1)!} \left[(-1)^{u_r-\ell+1} e^{\lambda_{r,i}} P_{u_r-\ell+1}(\lambda_{r,i}) \mathrm{Ei}(-\lambda_{r,i}) + Q_{u_r-\ell+1}(\lambda_{r,i}) \right], \tag{4}$$

where $\lambda_{1,i}, \lambda_{2,i}, \ldots, \lambda_{a,i}$ are distinct eigenvalues of the matrix $P_t \left(\sum_{j \notin C_k} \mathbb{E}[d_{k,j}] P_t + \sigma_k^2 \right)^{-1} \mathbf{R}_k^{-1}$ with multiplicities $u_1, u_2, \ldots, u_r$, respectively, $\Phi_{r,\ell,i}(-\lambda_{r,i}) = (-1)^{\ell-1}(\ell-1)! \sum_{\Omega_{r,\ell}} \prod_{j=1,\, j \neq r}^{a} \binom{u_j + i_j - 1}{u_j - 1} (\lambda_{j,i} - \lambda_{r,i})^{-u_j - i_j}$, and $\Omega_{r,\ell} = \left\{ \{i_j\}_{j=1,\, j\neq r}^{a} : \sum_{j=1,\, j \neq r}^{a} i_j = \ell - 1, i_j \geq 0, \forall j \neq r \right\}$.

the term $\mathbf{h}_{k,n,i}$ and hence $d_{k,i}$ for each $i \in S_k$ is assumed to be known by the k-th UE.

Throughout the study, we assume that the correlation matrix $\mathbf{R}_k$ of channel vectors $\mathbf{h}_{k,n,i}$ for all n, i is known by CP. $\mathbf{R}_k$ includes large-scale fading coefficients ($\beta_{m,k}$'s) on its diagonal and correlations on its off-diagonal. The channels corresponding to different RUs and different UEs are independent, but the channels of the antennas of the same RU and similarly the channels of the antennas of the same UE are correlated. Finally, the small-scale fading is assumed to be Rayleigh distributed.

A. Achievable User SEs

As the instantaneous channel is not known on the RU side, we can follow different approaches to find achievable user SEs. Under fast fading assumption where the channel coding period includes all possible channel states, we can evaluate the ergodic SEs by

$$\mathrm{SE}_{\text{ergodic},k,i} = \mathbb{E}[\log_2(1 + \mathrm{SINR}_{k,i})]. \tag{5}$$

Another approach is to consider outage SE where we assume a constant transmission rate and the signal can be decoded without any error only if the instantaneous SINR is larger than some threshold $\mathrm{SINR}_{\text{min},k,i}$. In this case, we can calculate the outage SE as

$$\mathrm{SE}_{\text{outage},k,i} = (1 - p_{\text{out}}) \log_2(1 + \mathrm{SINR}_{\text{min},k,i}), \tag{6}$$

where $\Pr(\mathrm{SINR}_{k,i} < \mathrm{SINR}_{\text{min},k,i}) = p_{\text{out}}$. In general, the outage SE is used when there is no instantaneous CSI at the transmitter side. In this study, we consider both these SE expressions in performance comparison.

Using the assumptions about channel coefficients, we can evaluate the pdf of $\mathrm{SINR}_{k,i}$ and find a closed-form formula for ergodic SEs. On the other hand, it is hard to find a closed-form formula for outage SEs and the Monte-Carlo method can be applied to evaluate it numerically.

B. Ergodic SE Calculation

Using the SINR formula given in (3), we can evaluate the ergodic SEs as

$$\mathrm{SE}_{\text{ergodic},k} = \frac{1}{T_0} \sum_{i \in S_k} \mathbb{E}[\log_2(1 + \mathrm{SINR}_{k,i})]. \tag{7}$$

Notice that we extend all codes to T_0 time/frequency samples by considering multiple code periods if necessary. Therefore, we use the factor $\frac{1}{T_0}$ since each symbol s_i is transmitted within T_0 time/frequency samples. The term $\mathbb{E}\big[d_{k,j}\big]$ in the denominator of (3) can be calculated as

$$\mathbb{E}\big[d_{k,j}\big] = \sum_{m \in U_k} \beta_{m,k}, \tag{8}$$

where U_k is the set of RUs in the cluster of the k-th UE. The result in (8) is obtained using the fact that each element of the vector $\mathbf{h}_{k,n,j}$ has distribution $\mathcal{CN}(0, \beta_{m,k})$ for some $m \in U_k$ and by the symmetry of the orthogonal codes used, each RU in a cluster transmits a specific symbol exactly once within a single code period.

To evaluate $\mathrm{SE}_{\text{ergodic},k,i}$, we need the pdf of $d_{k,i}$ which is a sum of correlated exponential random variables with different mean values. To make the necessary calculations, we use Theorem 1. Due to the page limit, we only present the theorem statement, the full proof is given in [10].

To prove Theorem 1, we first prove that $d_{k,i}$ is a hypo-exponential random variable and its pdf can be evaluated using the channel correlation matrix of channel vectors $\mathbf{h}_{k,n,i}$ for related k, n, i values. The proof includes applying a whitening transformation and using the findings of [11]. We can also consider $d_{k,i}$ as the unique eigenvalue of the rank-1 matrix $\mathbf{x}_{k,i}\mathbf{x}_{k,i}^H$ where $\mathbf{x}_{k,i} = [\mathbf{h}_{k,1,i}^T \; \mathbf{h}_{k,2,i}^T \; \cdots \; \mathbf{h}_{k,N,i}^T]^T$ and use the findings of [12]. Secondly, to calculate the mean in (5) we use the pdf of the hypo-exponential random variable derived and evaluate the expectation using induction and integration by parts as done in [10]. We can also consider the exact MIMO capacity equation given in [13] to reach the same result. Finally, using the two observations described, Theorem 1 in (7) that finds user ergodic SEs can be proved as in [10]. It can be seen that for small-cells where each UE is served by a single RU, the formula in Theorem 1 turns into the classical SE formula used in the literature [14].

C. Outage SE Calculation

To evaluate outage SEs, we use the SINR equations obtained in (3). It is hard to find a closed-form formula as it is required to find the inverse image of the cumulative distribution function (CDF) of SINRs. To find a solution, we use the Monte-Carlo method by generating independent channel coefficients and approximate the terms $\mathrm{SINR}_{\text{min},k,i}$, $\mathrm{SE}_{\text{outage},k,i}$ in (6). The user outage SEs can be calculated as

$$\mathrm{SE}_{\text{outage},k} = (1 - p_{\text{out}}) \sum_{i \in S_k} \log_2(1 + \mathrm{SINR}_{\text{min},k,i}). \tag{9}$$

III. Cluster Formation

The main task of this study is to determine RU-UE clusters to optimize overall system performance. In this section, we present a heuristic clustering method relying on closed-form ergodic SEs where clusters are formed in 3 stages. The algorithm uses large-scale fading and correlation parameters and can be implemented at CP. The steps of the algorithm are given in Algorithm 1.

Algorithm 1: Proposed Cluster Formation

Input: $\beta_{m,k}$ for all m, k and $\mathbf{R}_k$ for all k.
Output: All RU-UE clustering.

1. **(One-to-one matching):** Associate UEs and RU antennas in one-to-one manner. Each UE is matched with one antenna of an RU with the largest possible $\beta_{m,k}$ to form K disjoint clusters.
2. **(Cluster merging):** Prioritize clusters according to the minimum ergodic SE in each cluster. The most prior one has minimal SE. Starting from the most prior cluster pair, check whether merging the two clusters increases the worst $K/4$ ergodic SEs of UEs. After each merging, perform prioritization of the remaining clusters again and continue the same process.
3. **(Add remaining antennas):** According to the final prioritization of clusters obtained in Step 2, check whether any of the unused RU antennas can be added to the most prior cluster to increase the worst $K/4$ ergodic SEs of users. If any RU antenna is added to a cluster, then re-calculate the prioritization of clusters and continue this process until all unused RU antennas are checked.
4. **return** All RU-UE clustering.

Under the assumption $ML \gg K$, it can be shown that the asymptotic complexity of this algorithm is $\mathcal{O}(MLK^2)$. The proof is given in [10].

IV. Numerical Results

To see the benefits of STFBCs, we perform various numerical simulations in an indoor factory area. We define some grid points from which we select RU and UE positions randomly. The simulation parameters are given in Table I. We choose the carrier frequency, area, UE noise figure, and path loss and shadowing models considering the scenario given by Table 7.8-7 and P_t according to Table 7.8-2 in [15]. We assume that there are many mobile blockers/scatterers in the factory blocking the LOS path and creating many random paths between RUs and UEs, and hence we consider an NLOS-only scenario with Rayleigh small-scale fading. In this respect, the factory scenario differs from common mmWave deployments with sparse channels and frequent LOS availability. We choose the outage probability (p_{out}) as a relatively low value to make the retransmissions infrequent.

For comparison purposes, we consider small-cells, SFN, and maximal-ratio-transmission (MRT) precoding techniques. In the small-cell approach, each UE is served by a single RU, and for SFN each UE is served by some set of RUs. For SFN, we follow the 95% rule to select RUs with the largest $\beta_{m,k}$ values whose sum is 95% of the sum of all $\beta_{m,k}$'s for each UE. Both these two methods assume no CSI at the RU side and transmit the UE symbols without any beamforming. The same symbol is transmitted from all antennas of the selected RUs. As another baseline method, we consider MRT which makes use of instantaneous CSI at the RU side. For MRT we consider different variants in terms of the number of selected RUs (single or 95% rule) and the level of channel information at the UE side (perfect or statistical where only the mean of the effective channels is known). For MRT, we assume perfect CSI at the RU side to see the performance upper bound. Statistical channel knowledge at the UE side is analyzed in the literature [14], where there are no downlink pilots. Detailed formulations and achievable SEs of all these methods are given in [10] where we follow the principles proposed in [16].

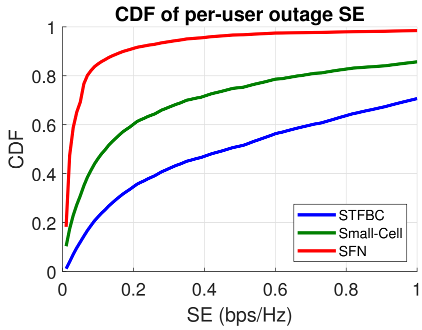
TABLE I: Simulation parameters

Parameter	Value/Model
Carrier freq. and bandwidth	28 GHz, 200 MHz
Area	120×60 meters
RU grid	16×8 grid with spacing 7.5 meters
UE grid	120×60 grid with spacing 1 meter
Path loss and shadowing model	3GPP InF-SL [15]
Small-scale channel model	Rayleigh
P_t, UE noise figure	0.2 W, 9 dB
Outage probability, p_{out}	0.01

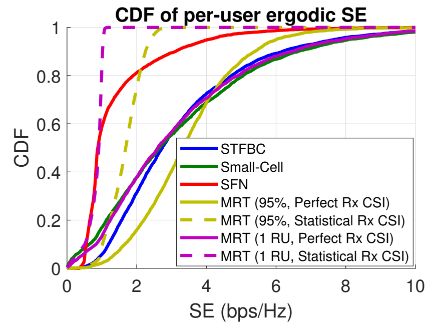
In Fig. 2a and 2b, we see the per-user CDFs for outage and ergodic SEs. We observe that STFBC significantly outperforms small-cell and SFN in terms of outage SEs. It has much better 5th percentile ergodic SEs compared to small-cell, SFN, and MRT (1 RU), and better than SFN and MRT with statistical receiver CSI in terms of median ergodic SEs. We conclude that, for a single antenna case, with the help of clustering, STFBC can achieve even better performance than some methods with transmit CSI. Another observation is about the comparison of ergodic SEs of STFBC and small-cells. Notice that in Step 1 of the clustering algorithm, we match RUs and UEs as in small-cell approach. Step 2 and 3 tries to maximize the worst-case user ergodic SEs and hence we observe a significant enhancement on 5th percentile user ergodic SEs. On the other hand, the median values are similar for STFBC and small-cell, and this shows that the clustering can optimize the worst-case SEs of users by maintaining a similar performance for all users on average.

In Fig. 2c and 2d, we present the results considering all simulations performed. We consider the overall results for different parameters. We select (M, K, L, N) so that $4 \leq M \leq 32$, $1 \leq K \leq 8$, $1 \leq L \leq 8$, $1 \leq N \leq 6$, and $ML \geq K$. We conclude that STFBC provides 3.5 times better median and 10 times better 5th percentile outage SEs than small-cell. Furthermore, by optimizing clustering, we obtain better 5th percentile ergodic SEs than MRT (1 RU), small-cell, and SFN. In terms of median ergodic rates, which can be dramatically enhanced by beamforming and multi-layer transmission effects obtained by transmit CSI, MRT with perfect receiver CSI outperforms STFBC. On the other hand, MRT with statistical receiver CSI has lower median ergodic rates than STFBC due to insufficient CSI at UEs.

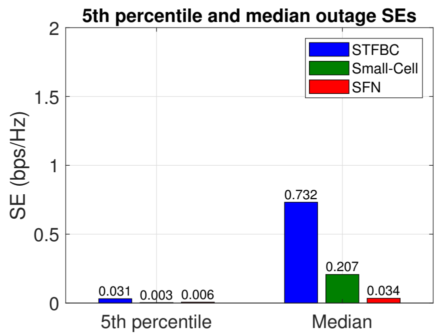
As a final remark, we observe that ergodic SEs are always



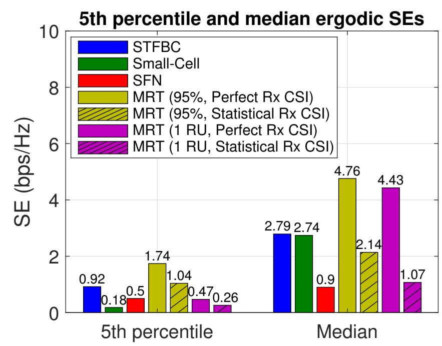
(a) CDF of per-user outage SEs



(b) CDF of per-user ergodic SEs



(c) 5th percentile and median outage SEs



(d) 5th percentile and median ergodic SEs

Fig. 2: CDF of per-user outage (a) and ergodic (b) SEs for $M = 16, K = 4, N = L = 1$, and 5th percentile and median outage (c) and ergodic (d) SEs for all simulations with various (M, K, N, L) quadruples.

higher than outage SEs for all methods. This is because outage SEs are obtained under the constant transmission rate assumption where no bits can be decoded when the corresponding instantaneous SINR is less than the predefined threshold. Ergodic SEs are computed assuming that all channel states can be observed within a single channel coding period and hence they provide an upper bound on the performance.

V. Conclusion

In this study, we have investigated the potential benefits of STFBCs in D-MIMO networks. We know that there may be several reasons why accurate channel estimation for downlink channels may not be performed at the RU side. In such cases, as a robust transmission scheme, the network can switch to STFBC to increase diversity at the UE side without requiring instantaneous channel estimates. The results show that the proposed scheme has important advantages in D-MIMO networks. STFBC together with an optimized clustering significantly outperforms baseline methods, i.e., small-cell approach and SFN transmission, in terms of both outage and ergodic SE.

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