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Performance Analysis of Joint Transmission CoMP schemes for ABS assisted cellular networks

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***Abstract*—An aerial base station (ABS) assisted cellular network is envisioned as a cheap and quick technology to provide connectivity in developing countries particularly in rural areas. ABSs provide strong line of sight links that cause severe interference in the network. We therefore analyse the performance of three joint transmission coordinated multipoint (JT CoMP) schemes for variable ABS altitude and density. These are fixed number, fixed region and interference aware JT CoMP. We apply CoMP only to the lower power base stations (BSs) that is small BSs and ABSs. Using simulations, we show that the JT CoMP schemes improve the coverage probability, average rate and energy efficiency of the network. Using a modified performance metric we show that interference aware JT CoMP gives the best performance in terms of cost which is determined by the cluster size. In this paper we also present practical considerations for the implementation of these JT CoMP schemes.**

***Index Terms*—Aerial base station, average rate, CoMP, coverage probability, energy efficiency, joint transmission CoMP, rural communications**

I. Introduction

The use of aerial base stations (ABSs) to support terrestrial base stations is envisioned as a promising solution to enhance connectivity [1], [2]. ABSs are unmanned aerial vehicles (UAVs) or drones equipped with telecommunications equipment. Unlike terrestrial BSs, ABSs are anticipated to provide quick and cheap deployment since they do not require the processes of land acquisition and structure setup among other factors [2]. Developing countries are especially daunted by lack of adequate information and communication technology (ICT) infrastructure especially in rural areas and the high cost of access [3]. In sub-Saharan Africa, UAVs are already in use for a variety of applications notably transportation of medical supplies in hard to reach areas in Rwanda and Malawi and for imagery [4].

ABSs are envisioned as a cost effective and quick approach to providing connectivity for rural areas and emergency situations [5]. They provide strong line of sight (LoS) links unlike the terrestrial communications that is dominated by non LoS (NLoS) links. In fact the ABSs create strong interference to the terrestrial BSs which deteriorates their performance in the network [5]. As more BSs are deployed to meet the soaring data demands, interference becomes more severe [6]. There are various interference mitigation techniques including inter-cell-interference-coordination (ICIC), successive interference cancellation, interference alignment and pre-coding techniques for multi-input multi-output (MIMO) [7]. In this paper we investigate coordinated multi point (CoMP) as an interference mitigation technique for an ABS assisted cellular network. CoMP is a novel technique developed by the third generation partnership project (3GPP) [7]. This technique is unique in that it treats interference as a useful signal or blocks the interference signal. It is efficient at eliminating inter cell interference (ICI) [6]– [8].

The three types of CoMP are joint transmission (JT), dynamic cell selection (DCS) and coordinated scheduling/coordinated beamforming (CS/CB) [6], [7]. With JT CoMP a number of BSs forming a cooperating set or cluster simultaneously transmit data to a user. DCS is a simplified version of JT in which only one BS out of the cooperation set transmits data to a user. CS/CB utilizes coordinated scheduling of radio resources and coordinated antenna beamforming of cooperating BSs to mitigate interference [7], [9].

JT CoMP schemes are widely studied for terrestrial BSs [6], [7]. The downlink performance of three JT CoMP schemes is analysed in [6] for a millimeter wave (mmWave) cellular network under low and high BS density deployments. The coverage probability of a heterogeneous network (HetNet) with CoMP is analysed in [10]. [11] presents an analytical framework based on Poisson-Delaunay triangulation for the coverage probability of a cell edge user in a single tier network with JT and DCS CoMP schemes. In [12] the coverage and handoff probabilities for aerial users served by three cooperating terrestrial BSs are derived using the Poisson-Delaunay triangulation.

In this paper we analyse the downlink performance of JT CoMP schemes in an ABS assisted cellular network. Unlike other work, we present a system model for a rural setting or emergency situation where the deployment of ABSs is low (less than 10/km^2). A modified CoMP scheme is presented that minimizes wastage of resources since CoMP is only applied when it gives better performance than the non CoMP scenario. We provide the coverage probability, average rate and energy efficiency and how they are affected by ABS altitude and density.

The rest of this paper is organized as follows: Section II describes the system model. In Section III we present the three JT CoMP schemes and their practical limitations. We discuss our performance metrics in Section IV. Our results are

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presented in Section V. Section VI concludes the paper.

II. System model of ABS assisted cellular network

In this paper, we analyze the downlink performance of JT CoMP schemes for an ABS assisted cellular network. Our network consists of terrestrial macro and small BSs (MBSs and SBSs) and ABSs as shown in Fig. 1. In this work we consider low altitude platform UAVs (LAPs) that are deployed up to a few hundred kms above the ground. We assume that all the BSs in the same tier, i, transmit with the same power, P_i and are deployed at the same altitude, h_i. The BSs are distributed according to a homogeneous PPP (HPPP) ϕ_i with intensity λ_i. Our user is positioned on the ground with coordinates $(0, 0)$. Our model considers low deployment of ABSs while catering for redundancy. This is applicable for low resource environment typical of rural Africa. It can also be applied to emergency communications for coverage in disaster areas. This model is also applicable to low dense deployment of ABSs in security conscious countries that may be wary of the versatility of UAVs. The three use cases identified are similar in that they only require as low a number of UAVs as possible. We next describe the large scale path loss and the small scale fading for the air to ground (A2G) and the ground to ground (G2G) channels. A2G is the channel between the aerial BSs and the ground users while G2G is the channel between the terrestrial BSs and the ground users.

A. Air to Ground channel

Large scale path loss model – We consider both the line of sight (LoS) and non line of sight (NLoS) links from the ABSs. We therefore adopt the probability of the LoS, P_L, between a terrestrial transmitter and user at specified elevations [13] as defined by International Telecommunications Union (ITU) and given in (1). Consequently, the probability of NLoS, $P_N = 1 - P_L$. The average path loss, $L_A = P_L L_L + P_N L_N$ where L_L is the LoS path loss and L_N is the NLoS path loss given by (2).

$$P_L(x) = \frac{1}{1 + aexp(-b(\frac{180}{\pi} tan^{-1}\frac{h}{x} - a))} \tag{1}$$

$$L_j = \varepsilon_j (x^2 + h^2)^{\frac{-\alpha_j}{2}} = \varepsilon_j r^{-\alpha_j} \tag{2}$$

In (1), a and b are parameters that classify the environment i.e. suburban or rural, urban and high rise urban. The angle $tan^{-1}\frac{h}{x}$ is the elevation angle in radians between the ABS height, h, and the Euclidean distance, x, on the ground between the projection of the ABS and a ground user.

In (2), ε_j, is the mean excess path loss over the free space path loss. It accounts for the shadowing and scattering of signals by man-made structures [13]. The Euclidean distance between an ABS and user is r. The parameter, α_j, is the path loss exponent. The NLoS path loss exponent, α_N, is higher because it suffers more obstruction than the LoS (α_L).

Small scale fading model – We adopt the Nakagami-m channel with parameters: shape parameter, m_j and scale parameter $\Omega_j = \frac{1}{m_j}$ [1], [14]. The channel gain between a user and ABS at r_j, g_j is modelled using the Gamma distribution $\mathcal{G}(m_j, \frac{1}{m_j})$ whose probability density function (PDF) is given in (3) in [5]. For the LoS, $m_L = 3$ and for the NLoS $m_N = 2$.

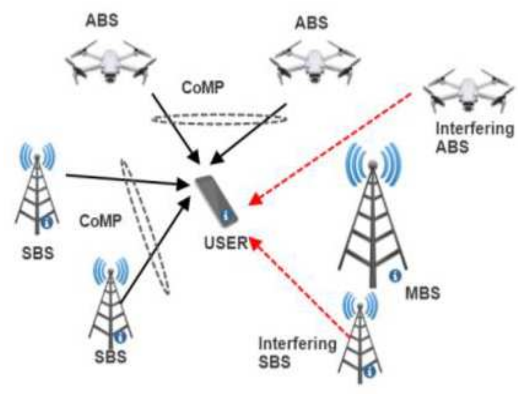

Fig. 1. System model.

B. Ground to Ground channel (G2G)

Large scale path loss model – We used (2) to model the large scale path loss for both terrestrial BSs i.e. the MBSs and SBSs. The path loss exponent $\alpha > 2$ for MBSs and SBSs. Small scale fading model – For the terrestrial BSs NLoS links predominate. We therefore used the Rayleigh fading channel. It follows an exponential distribution with mean of unity (1) such that $g \sim exp(1)$.

C. Other assumptions

We considered an interference limited network since noise is assumed to be negligible. We also assumed universal frequency reuse. Consequently, all BSs are assigned the same frequency and are potential interferers to the serving BS.

III. JT CoMP schemes

In this paper, we analyse the performance of three JT CoMP schemes for an ABS assisted cellular network. These are fixed number (FN), fixed region (FR) and interference aware (IA) schemes. In a HetNet, CoMP is applied either as intra tier or inter tier. For intra tier CoMP, clusters are formed by BSs in the same tier. For inter tier CoMP, clusters are formed across tiers. In our work we adopted intra tier CoMP which will require less complexity in implementation.

A. Fixed Number JT CoMP

A typical user receives signals from more than one BS. The BSs which transmit signals form a cooperating cluster with a fixed size. All other BSs outside the cluster are considered to be interferers. The cooperating cluster consists of the nearest K BSs where K is the cluster size. The larger the cluster size, the better the performance.

B. Fixed Region JT CoMP

The cooperating cluster consists of all BSs within a fixed region. This region is defined by a fixed radius from the user. All BSs outside the fixed region cause interference to the serving BS. The size of the fixed region and density of the BSs determine the performance of this scheme.

C. Interference aware JT CoMP

The cooperating cluster is variable unlike either fixed number or fixed region. Interference aware JT CoMP uses an SIR threshold to determine which BSs form the cooperating cluster. A typical user first chooses the BS with the strongest received power. The BS with the strongest received power is the serving BS_k with power $P_k = P_i q_i {r_k}^{-\alpha_i}$ for $i \in \{A, S\}$ for ABS and SBS respectively. Parameter q_i is the small scale fading for BS_i. Then BSs whose ratio of received power from the serving BS to other BSs is less than the set threshold constitute the cluster. That is if the ratio of BS_j, $(P_k/P_j) \geq \tau_c$ where τ_c is the cooperative threshold then BS_j is a member of the cooperating set. When the threshold is high more BSs participate in the cooperation. A low threshold implies that fewer BSs will participate in the cooperation. Hence the performance of this scheme depends on the cooperation threshold and density of BSs.

D. Enhancement JT CoMP schemes

In our work, we only apply JT CoMP schemes when they provide better SIR than the case without CoMP. In this way, we avoid wasting resources when CoMP does not provide any improvement whilst ensuring that cell edge users who suffer low SIR are served.

We also achieve load balancing in the network by only applying CoMP to the lower power BSs i.e. SBSs and ABSs. Therefore, more users are served by the lower power BSs. The performance is slightly compromised since MBSs do not participate in the cooperation.

E. Practical limitations of JT CoMP schemes

JT CoMP schemes jointly process and exchange user data and channel state information (CSI). They thus require tight time and frequency synchronization and highly reliable backhaul. [16] notes that imperfect or outdated CSI and uncoordinated interference may hinder the performance of JT CoMP schemes.

In our work we propose that CoMP is applied only to the lower power BSs i.e. SBSs and ABSs. Cooperating BSs are choosen from the same tier to reduce on implementation complexity and latency. Strong LoS links exist between ABSs therefore mmWave signals can be used to achieve high capacity wireless backhaul links to enable timely exchange of data and CSI. This ensures synchronization and low latency. Either wired or wireless backhaul links can be used between SBSs. For closely placed SBSs wired backhaul links using optic fiber cables guarantee high capacity and low latency. However, SBSs may be randomly placed making wired backhaul impractical. Moreover SBSs may be privately owned and can be switched off [17]. Wireless backhaul links using mmWave offer a cheaper alternative to either optic fiber or copper cable and flexibility at the cost of reduced capacity and higher latency due to the NLoS conditions that prevail.

F. SIR of JT CoMP

For the three JT CoMP schemes all the BSs in the cluster simultaneously transmit a signal to the user. They therefore do not contribute to the interference. Instead, they provide constructive interference and a stronger received signal at the user. All other BSs outside the cluster cause interference to the serving BS. We therefore define the received signal at the user y in (3).

$$y = \sum_{k \in C} Q_k x_k + \sum_{m \in C'} Q_m x_m + \sum_{i} \sum_{z \in \phi_i} Q_z x_z + n^2 \quad (3)$$

$$y = \sum_{k \in C} Q_k x_k + \sum_{m \in C'} Q_m x_m + \sum_{i} \sum_{z \in \phi_i} Q_z x_z \quad (4)$$

In (3) Q is the channel matrix. It is a product of the path loss and small scale fading. The first term on the right-hand side of (3) is the desired signal from the cooperating cluster C, while the second term is the out of cluster interference from BSs in the same tier, C'. The third term is the interference from BSs in other tiers. The last term is the noise which is neglected. Hence (3) reduces to (4) for an interference limited network. We assume that the transmitted signal x has a statistical expectation $\mathbb{E}[x] = 1$. We therefore present the SIR in (5). The numerator is the received power from all BSs in the cooperating cluster. The denominator consists of interference from the out of cluster BSs in the same tier and other tiers.

$$SIR = \frac{\sum_{k \in C} Q_k x_k}{\sum_{m \in C'} Q_m x_m + \sum_i \sum_{z \in \phi_i} Q_z x_z} \quad (5)$$

IV. Performance metrics

In this section we describe the metrics for performance analysis of a CoMP enabled network. Specifically we define the coverage probability, average rate and energy efficiency. We also present a metric to measure performance against cluster size.

A. Coverage Probability

The downlink coverage probability, P_c, is the probability that a user achieves an SIR larger than a predefined SIR threshold, T. It is given in (6).

$$P_c = \mathbb{E}_r[\mathbb{P}(SIR \geq T)] \quad (6)$$

B. Average rate

We define the average rate, SE, of a typical user as the average number of bits transmitted over a given bandwidth, B. In general, the average rate is obtained using the Shannon capacity formula given in (7).

$$SE = \mathbb{E}_{r,SIR}[In(1 + SIR)] \quad (7)$$

It is shown in [5] that the average rate in (7) is evaluated to give (8) where P_c is the coverage probability and T is the predefined SIR threshold. The units of SE are bps.

$$SE = BP_c \log_2(1 + T) \tag{8}$$

C. Energy Efficiency

The energy efficiency, EE, is the ratio of the average network throughput to the average network power consumption [15]. It is given in (9) with units of bps/J. The transmit powers for the three tiers are P_M, P_S and P_A for the MBSs, SBSs and ABSs respectively. The BS densities for the three tiers are λ_M, λ_S and λ_A for MBSs, SBSs and ABSs respectively.

$$EE = \frac{(\lambda_M + \lambda_S + \lambda_A) P_c \log_2(1 + T)}{(\lambda_M P_M + \lambda_S P_S + \lambda_A P_A)} \tag{9}$$

D. Average rate per cluster size

It is important for us to compare the three techniques to guide implementation decisions by network operators regarding issues such as cost. It is challenging to accurately establish the performance of one scheme relative to the others because each scheme has its own unique defining parameters i.e. cluster size for FN, area for FR and cooperating threshold for IA. We therefore define a new metric which measures performance against the cluster size for instance the ratio of the average rate to the cluster size. Cluster size is a key determinant of the implementation cost [18].

V. Results

In this section we present our simulation results. We consider an ABS assisted cellular network with ABSs, SBSs and MBSs distributed according to PPP in a rural environment with radius of 5 km. For the ABS, LoS and NLoS links are considered while for the SBS and MBS only NLoS links are considered since they are dominant due to obstacles. The simulation parameters for this scenario are given in Table I. We used Monte Carlo method (MC) to obtain the simulation results.

Fig. 2 shows the coverage probability as SIR threshold varies. This result was obtained by using two BSs for fixed number (FN) JT CoMP. The radius for the fixed region (FR) JT CoMP and the SIR threshold for interference aware (IA) JT CoMP are given in Table I. ABSs are deployed at an altitude of 100 m. We observe that the JT CoMP schemes give higher coverage probability than the non CoMP network. The improvement is expected because the user

TABLE I
Simulation Parameters

Parameter	Value
Power(dBm): P_M, P_S, P_A	40, 30, 30
Altitude(m): h_M, h_S	50, 10
Density(/km^2): λ_M, λ_S, λ_A	4, 10, 2
Path loss exponent: α_M, α_S, α_L, α_N	3, 3, 2.5, 3
Mean excess path loss: ε_M, ε_S, ε_L, ε_N	0.7943, 0.7943, 0.7943, 0.01
Environment parameters: a, b	Rural (4.9, 0.43)
IA SIR threshold τ_c	10 dB
Radius of fixed region	500 m

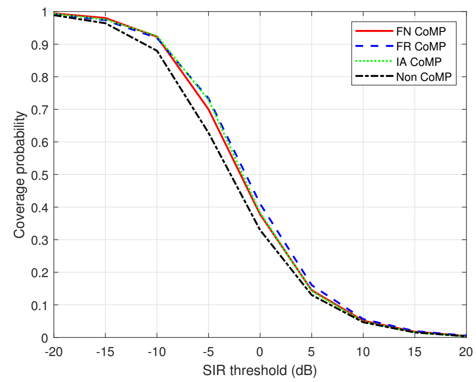

Fig. 2. Variation of coverage probability with SIR threshold.

receives joint transmissions thus a stronger signal from two or more BSs. The improvement is slight because of the set of parameters choosen for the JT CoMP schemes. For instance we chose the least number of 2 cooperating BSs for FN. The average number of cooperating BSs obtained from 10,000 MC simulation runs for FR is 4 and for IA it is 3. However increasing the number of cooperating BSs for FN increases the coverage probability since a stronger signal is achieved with less interference. In the case of FR increasing the cooperation area implies that more BSs participate in the cooperation giving an even stronger signal. Increasing the SIR threshold for IA would also result in an enhanced coverage probability since more BSs are involved in the cooperation.

In Fig. 3 we show the variation of average rate with ABS altitude, a key parameter in ABS assisted cellular networks at two different SIR thresholds. We used a cluster size of 3 for FN. The JT CoMP schemes outperform the non CoMP scenario because they provide a stronger received SIR. Similar to the non CoMP scenario, there is an optimum altitude for the JT CoMP schemes at which the average rate is maximized. The initial increment in average rate as altitude increases is due to the increase in the probability of LoS for ABSs which results into a stronger received signal. As the ABS altitude increases beyond the optimum, the loss in coverage due to the increased path loss exceeds the gains due to the increased probability of LoS. From Fig. 3 we observe optimum altitudes of 100 m and 50 m for the CoMP and non CoMP networks respectively. Therefore by deploying CoMP schemes it is possible to use ABSs at higher altitudes that have fewer obstacles and yet obtain good performance. At the lower SIR threshold of -10 dB FN outperforms the other schemes and IA gives better performance than FR for the rural environment. However at the higher SIR threshold of –5dB, IA outperforms the other two schemes because it effectively identifies those BSs that cause the largest interference without limitations of number or area. Additionally for FN it is possible that the nearest K BSs do not provide the strongest signals because of NLoS hence its poorer performance compared with IA.

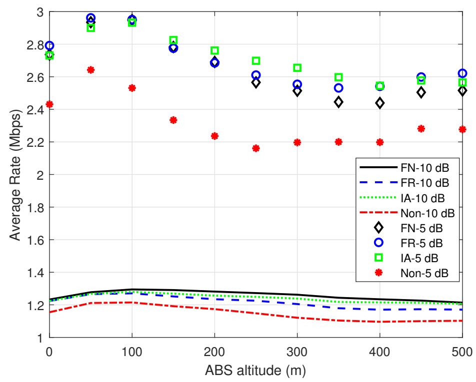

Fig. 3. Variation of average rate with ABS altitude.

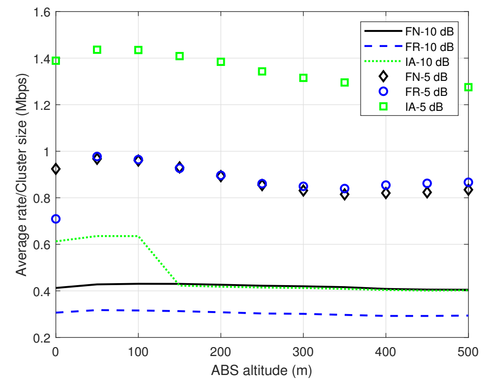

Fig. 5. Average rate/Cluster size with varying ABS altitude.

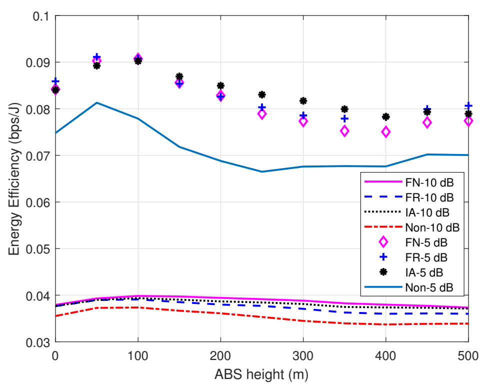

Fig. 4. Variation of energy efficiency with ABS altitude.

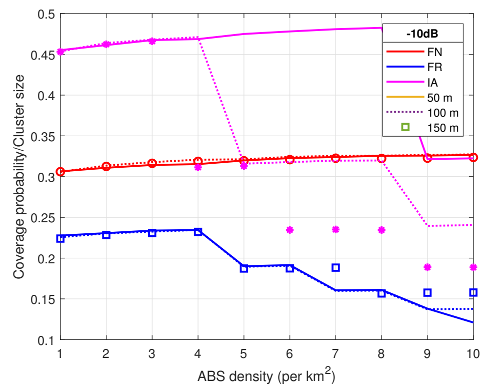

Fig. 6. Ratio of coverage probability to cluster size with varying ABS density. Line, dashed line and markers correspond to 50 m, 100 m and 150 m respectively.

In Fig. 4 we show the variation of energy efficiency with ABS altitude. We observe that the CoMP schemes outperform the non CoMP scenario. This is expected since an aggregate signal which is stronger is received from the cooperating BSs. The variation of the energy efficiency with the ABS height follows the same explanation as for the average rate.

Fig. 5 presents the ratio of average rate to the cluster size for varying ABS altitude. The cluster size is obtained as the average number of cooperating BSs over 10,000 MC simulation runs. The average rate per cluster size enables us to compare the performance of the 3 JT CoMP schemes in terms of implementation cost. Our results show that IA outperforms FN and FR. It uses the smallest cluster size. At -10 dB IA initially uses a cluster size of 2 BSs and beyond 100 m it uses a cluster size of 3 similar to FN. On the other hand, FR uses a cluster size of 4. At – 5 dB IA uses a cluster size of 2 compared with 3 for FN. FR initially uses a cluster size of 4 and beyond 50 m it uses 3 similar to FN. FR uses the largest cluster size since all BSs within a specified area are included. The cluster size for FR reduces because as the altitude increases the ground radius must reduce and therefore fewer ABSs are included in the cluster. Overall, the IA scheme performs better than either FN or FR because it inherently adapts to mitigate the interference. IA effectively identifies those BSs that generate the strongest interference closest or not and includes them in the cooperating cluster. The detriment of using FN or FR is that some of the nearest K BSs may not provide the strongest interference due to for instance the prevailing NLoS conditions.

The effect of ABS density on the coverage probability at three different altitudes is shown in Fig. 6. We use an SIR threshold of – 10 dB. Similar to the case of ABS altitude, we observe that IA outperforms FN and FR as ABS density increases. It achieves the highest coverage probability per cooperating BS. Fig. 6 shows that as the ABS density increases the coverage rate per cluster size for FN increases while that for FR and IA reaches a maximum and then reduces. The coverage probability increases with ABS density since the ABSs are closer to the user and thus give stronger received signals. This implies that the probability of a user being served increases. For FN the coverage probability increases while the cluster size is fixed. The drop observed in Fig. 6 for FR and IA is due to increasing cluster sizes with each additional BS in the cluster giving smaller increment in coverage probability. FR gives the worst performance because inherently the cluster size grows with the ABS density. For IA, we observe that the optimum ABS density that maximises the coverage probability per cluster size reduces as altitude increases from 8 ABSs/km^2 at 50 m to 4 at 100 m and 3 at 150 m. At a higher altitude we expect that the received signals from ABSs deteriorate due to the greater path loss.

VI. Conclusion

In this paper we have analysed the performance of fixed number, fixed region and interference aware JT CoMP schemes for an ABS assisted cellular network. Our network consists of ABSs and terrestrial BSs i.e. MBSs and SBSs. In our work we propose that CoMP is only applied to the lower power BSs i.e. SBSs and ABSs in order to achieve load balancing. Additionally we only apply CoMP when it provides better SIR recieved at the user than when CoMP is not applied i.e. non CoMP scenario. In this way we avoid wastage of resources. Through simulations for a rural environment we established that CoMP schemes give an improvement in coverage probability, average rate and energy efficiency for varying ABS altitude and density. Our results show that the average rate and energy efficiency are maximized at an optimum ABS altitude of 100 m for the presented simulation parameters. They also show that the coverage probability per cluster size is maximised at an optimum ABS density that reduces as the ABS altitude increases. We used the performance against cost metrics of average rate per cluster size and coverage probability per cluster size to show that IA performs better than either FN or FR with varying ABS altitude and density. IA inherently adapts to interference by choosing the strongest interferers to form a cluster unlike FN or FR which are static. Future work should develop an analytical framework for an ABS assisted cellular network with JT CoMP schemes to supplement the simulation results. The practical implementation of JT CoMP schemes requires tight synchronization and reliable backhaul with low latency since data and CSI must be exchanged among all cooperating BSs in a timely manner. The other CoMP schemes including dynamic cell selection (DCS) and coordinated scheduling/coordinated beamforming (CS/CB) utilise one BS to transmit data to a user. They are anticipated to be less complex than JT CoMP schemes and have more relaxed backhaul requirements. It is imperative to investigate DCS and CS/CB in order to establish modifications that may be required when they are applied to an aerial BS assisted cellular network.

References

[1] D. Saluja, R. Singh, K. Choi, and S. Kumar, “Design and analysis of aerial-terrestrial network: A joint solution for coverage and rate,” IEEE Access, vol. 9, pp. 81855–81870, 2021, doi: 10.1109/ACCESS.2021.3086696.

[2] S. Mugala, D. Okello, and J. Serugunda, “Leveraging the technology of unmanned aerial vehicles for developing countries,” SAIEE ARJ, vol. 111, no. 4, pp. 139–148, 2020.

[3] National Planning Authority, “Third National Development Plan (NDPIII) 2020/21-2024/25 ,” Kampala, Jul. 2020.

[4] N. Wang, “‘As It Is Africa, It Is Ok’? Ethical Considerations of Development Use of Drones for Delivery in Malawi,” IEEE Transactions on Technology and Society, vol. 2, no. 1, pp. 20–30, 2021.

[5] S. Mugala, J. Serugunda, L. Zhang, D. Okello, and J. Zhong, “Coverage and Rate of Low Density ABS Assisted Vertical Heterogeneous Network,” in 2022 IEEE 33rd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2022, pp. 945–950.

[6] J. Zhao, L. Yang, M. Xia, and M. Motani, “Unified Analysis of Coordinated Multipoint Transmissions in mmWave Cellular Networks,” IEEE Internet Things J, vol. 9, no. 14, pp. 12166–12180, 2022.

[7] S. Gulia and A. Ahmad, “An Investigation on the Performance of Intra-site and Inter-site Coordinated Multipoint LTE-A Networks,” in 2021 International Conference on Innovative Practices in Technology and Management (ICIPTM), 2021, pp. 221–226. doi: 10.1109/ICIPTM52218.2021.9388336.

[8] Q. Chen, K. Yang, H. Jiang, and M. Qiu, “Joint Beamforming Coordination and User Selection for CoMP-Enabled NR-U Networks,” IEEE Internet Things J, vol. 9, no. 16, pp. 14530–14541, 2022, doi: 10.1109/JIOT.2021.3063733.

[9] R. Macharia, K. Lang’at, and P. Kihato, “Interference Management upon Collaborative Beamforming in a Wireless Sensor Network Monitoring System featuring Multiple Unmanned Aerial Vehicles,” in 2021 IEEE AFRICON, 2021, pp. 1–6. doi: 10.1109/AFRICON51333.2021.9570907.

[10] G. Nigam, P. Minero, and M. Haenggi, “Coordinated multipoint in heterogeneous networks: A stochastic geometry approach,” in 2013 IEEE Globecom Workshops (GC Wkshps), 2013, pp. 145–150. doi: 10.1109/GLOCOMW.2013.6824977.

[11] Y. Li, M. Xia, and S. Aïssa, “Coordinated Multi-Point Transmission: A Poisson-Delaunay Triangulation Based Approach,” IEEE Trans Wirel Commun, vol. 19, no. 5, pp. 2946–2959, 2020, doi: 10.1109/TWC.2020.2969199.

[12] Y. Li and M. Xia, “Ground-to-Air Communications Beyond 5G: Coordinated Multi-Point Transmission Based on Poisson-Delaunay Triangulation.” Mar. 2022. doi: 10.48550/arXiv.2209.05714.

[13] A. Al-Hourani, S. Kandeepan, and A. Jamalipour, “Modeling air-to-ground path loss for low altitude platforms in urban environments,” in Globecom 2014: Symposium on selected areas in communications, 2014, pp. 2898–2904. doi: 10.1109/GLOCOM.2014.7037248.

[14] M. Alzenad and H. Yanikomeroglu, “Coverage and rate analysis for unmanned aerial vehicle base stations with LoS/NLoS propagation,” in 2018 IEEE Globecom Workshops (GC Wkshps), 2018, pp. 1–7. doi: 10.1109/GLOCOMW.2018.8644511.

[15] A. He, D. Liu, Y. Chen, and T. Zhang, “Stochastic geometry analysis of energy efficiency in HetNets with combined CoMP and BS sleeping,” in 2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC), 2014, pp. 1798–1802. doi: 10.1109/PIMRC.2014.7136461.

[16] G. C. Alexandropoulos, P. Ferrand, J. Gorce, and C. B. Papadias, “Advanced coordinated beamforming for the downlink of future LTE cellular networks,” IEEE Communications Magazine, vol. 54, no. 7, pp. 54–60, 2016, doi: 10.1109/MCOM.2016.7509379.

[17] S. Chen, T. Zhao, H.-H. Chen, Z. Lu, and W. Meng, “Performance Analysis of Downlink Coordinated Multipoint Joint Transmission in Ultra-Dense Networks,” IEEE Netw, vol. 31, no. 5, pp. 106–114, 2017, doi: 10.1109/MNET.2017.1600192.

[18] C. Unachukwu, “Improved interference management techniques for multi-cell multi-user MIMO systems,” PhD, The University of Leeds, 2014.