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Improving the Spectral Efficiency of a Downlink 5G Heterogeneous Massive MIMO System Using Beamforming Technique

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Abstract— **To meet the demand for an improved quality of experience for user equipment (UE) and improved spectral efficiency offered by mobile network operators, 5G Networks have been designed to employ advanced technologies such as beamforming, Massive MIMO, etc. However, the major issue facing 5G systems is interference due to the implementation of universal frequency reuse for all cells in the 5G Network. This work proposes a coordinated beamforming technique for a two-tier downlink 5G massive MIMO system to tackle inter-cell interference and consequently improve the system spectral efficiency of the 5G system. The choice of coordinated beamforming vectors that optimized the weighted sum spectral efficiency of the system while satisfying the constraints was formulated as a non-convex, non-polynomial hard (NP-Hard) optimization problem and reformulated to a convex problem by fixing the signal-to-interference-and--noise ratio (SINR) to a threshold and solved using CVX. The results showed that the proposed method attained at least the theoretical minimum achievable spectral efficiency for a 5G system which is 30 bit/s/Hz, outperforming other methods based on same parameters: *Kr = 9*, *N = 20*, *SNR = 30dB*, (where *Kr* and *N* are the total number of UEs in the system and the total number of transmit antenna at the base stations). The results also showed that with an increase in *Kr* and *N*, spectral efficiency is improved.**

I. Introduction

The increasing request for high data rates and reliable communication in modern mobile wireless communication systems has continued to grow with the increasing number of user equipment (UEs) and increasing reliance on wireless connectivity, leading to the development of the fifth generation (5G) networks. To meet this demand, 5G networks have been designed to utilize advanced technologies. However, one of the major challenges facing 5G networks is the implementation of the universal frequency re-use, which means that the same frequency band (C-band) is utilized by all cells in the 5G network. This can lead to severe inter-cell interference which negatively impacts the spectral efficiency of the system.

To address this problem, researchers have turned to advanced technologies such as massive MIMO and beamforming. However, the design of coordinated beamforming vectors in a 5G Heterogeneous massive MIMO system is a challenging problem, because it involves finding the optimal trade-off between the beamforming gain, the inter-UE interference, and the multi-cell interference. Traditional methods for beamforming design, such as zero-forcing and regularized zero-forcing often result in suboptimal solutions and do not fully exploit the potential of massive MIMO systems. In this work, we aim to address these issues and contribute to the advancement of this field by proposing a new beamforming design perspective for a 5G Heterogeneous Massive MIMO system based on convex optimization. The selected designed coordinated beamforming vectors which will be the output of the optimization will be able to optimize the aggregate spectral efficiency of the 5G Heterogeneous Massive MIMO system.

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II. Prior Works

We have published similar works in [1] and [2] and this present work is leveraging those works to achieve results peculiar to a 5G Heterogeneous massive MIMO system. In [1] the goal is to design beamformers that are not suboptimal and not convex, which give an optimal solution to the optimization problem which was formulated as: to maximize the weighted sum-rate for a downlink heterogeneous cellular network under four constraints. The technique used in [1] is branch and bound [9]. The notable difference to this present work from [2], is that the utility function considered in the optimization problem in this work is the weighted sum spectral efficiency, while in [2] it is the weighted sum-rate. Also, in this work, the constraints considered in the optimization problem are altogether three against four constraints considered in [2]. This would increase the search space for obtaining the optimal/suboptimal coordinated beamforming vectors which serve as the solution to the optimization problem. Finally, in [1] and [2], the simulation setting and parameters considered are tailored to an LTE-Advanced system whereas in this work it was tailored to a 5G Heterogeneous massive MIMO system.

The Authors in [3] and [4] designed energy-efficient beamforming vectors for multi-user massive MIMO systems using convex optimization. Our work differs from this because our utility function in the optimization problem is focused on maximizing the sum spectral efficiency of the system and not the energy efficiency which is the case in their work.

The authors in [5-7], proposed optimization of the weighted sum spectral efficiency in massive MIMO systems. The objective function considered in their optimization problem is similar to ours but the constraints we considered differ from the one they considered. Hence, the optimal solution to the optimization problem obtained from this work differs from theirs. Furthermore, the authors in [8] also considered the worst-case weighted sum-rate maximization in a multi-cell massive MIMO downlink system. They solve their optimization problem through the iterative method. Our work differs from that approach because we reformulated the non-convex NP-Hard optimization problem to convex by fixing the signal-to-interference-and-noise-ration and the interference to a constant term, making the whole optimization problem convex.

Notations: $(\cdot)^T$ denotes the transpose operation, $(\cdot)^H$ is the transpose-conjugate operation, $|\cdot|$ is the magnitude of a complex variable, $\|\cdot\|_2$ denotes the Euclidean norm of a vector. $\mathbb{E}\{\cdot\}$ is the statistical expectation over a random variable. $\mathbb{C}$ denotes the set of complex numbers. $\mathbb{C}^N$ denotes the set of complex N vectors. For matrices, we utilize uppercase boldface letters; for column vectors, we use lowercase boldface letters; and for scalars, we use either uppercase or lowercase letters without boldface letters.

III. System Model (Methodology)

Let's examine the downlink of a two-tier 5G heterogeneous network (HetNet) that is comprised of a total of Kt cells within the HetNet, which are K_p picocells under-laid in the coverage of a single macro-cell. Since every HetNet cell is assumed to use the same frequency spectrum, inter-cell interference is taken into account. In the HetNet, the base stations (BSs) set is represented by $\mathcal{M} = \{0, \ldots, K_t\}$, where 0 represents the macro base station (MBS). Let BS_j denote the j^{th} BS which can be any of the BSs, that is Pico BS (PBS) or MBS, and is assumed to have N antennas with which it serves K active UEs per cell. UEs are assumed to have a single receive antenna. In this study, a single UE antenna is preferred over multiple UE antennas for practical reasons, including reduced UE hardware complexity and form factor as well as longer battery life. $\mathcal{S}_j \subset \{1, \ldots, K_r\}$ is the set of UEs that BS_j serves, where K_r denotes the total number of UEs served in the HetNet. Furthermore, the kth UE should be denoted as UE k.

The complex-baseband data signal received at UE k is $y_k \in \mathbb{C}$ and is given by the relation:

$$y_k = \sum_{j=1}^{K_t} \sqrt{g_{j,k}}\, \left(\boldsymbol{h}_{j,k}^s\right)^H \boldsymbol{x}_j + n_k. \tag{1}$$

Where $\sqrt{g_{j,k}}$ is the large-scale pathloss from BS_j to UE k. Also $\mathbf{h}_{j,k}^s \in \mathbb{C}^N$ is the small-scale frequency-flat fading channel vector from BS_j to UE k, while $\mathbf{x}_j \in \mathbb{C}^N$ is the data signal vector transmitted at BS_j and intended for it served user equipments. Furthermore, $n_k \in \mathbb{C}$ is the additive noise from the surroundings and is modeled as circularly symmetric complex Gaussian, distributed as $n_k \sim \mathbb{C}\mathcal{N}(0, \sigma^2)$, where σ^2 is the noise power. To have the spatial separation of data symbols s_k from BS_j to UE $k \in \mathcal{S}j$, the transmitted signal vector is denoted as a linear combination of the beamforming vectors in the form:

$$\boldsymbol{x}_j = \sum_{k\in\mathcal{S}_j} \boldsymbol{w}_k s_k \tag{2}$$

Where the transmit beamformers for each symbol intended for the UE k are represented by $\boldsymbol{w}_k \in \mathbb{C}^{N\times1}$. s_k is assumed to be uncorrelated and is modeled as $s_k \sim \mathbb{C}\mathcal{N}(0, p)$, where the symbol p is normalized to unit power in this work. Assuming that the BS_l is the serving base station of UE k, the signal-to-interference-and-noise ratio (SINR) at UE k is given by

$$SINR_k = \frac{\left|\boldsymbol{h}_{l,k}^H \boldsymbol{w}_k\right|^2}{{\sigma_k}^2 + \sum_{m\neq k}\left|\boldsymbol{h}_{l,k}^H \boldsymbol{w}_m\right|^2 + \sum_{j\neq l}^{Kt}\sum_{n=1}\left|\boldsymbol{h}_{j,k}^H \boldsymbol{w}_n\right|^2} \tag{3}$$

Where $\boldsymbol{h}_{l,k} \triangleq \sqrt{g_{j,k}}\boldsymbol{h}_{j,k}^S$, the numerator in (3) represents the desired receive signal power, while the second and third terms of the denominator represent the multi-UE interference and the received inter-cell interference respectively. Note that the multi-UE interference occurs within the cell and can be described as intra-cell interference.

The achievable spectral efficiency for UE k in this HetNet is given by

$$SE_k = \log_2(1 + SINR_k) \tag{4}$$

A. Optimization Problem Formulation and Solution

Finding $\{\boldsymbol{w}_k\}\forall k = 1, \ldots, K_r$, that will maximize the weighted sum SE of the system under consideration, while satisfying certain power and quality of service (QoS) constraints for every UE is one of the goals of this work. Thus the optimization problem is formulated as

$$\underset{\{\boldsymbol{w}_k\}_{k=1}^{K_r}}{maximize} \quad \sum_{k=1}^{K_r} u_k SE_k,$$

$$\text{Subject to} \quad \mathcal{C}_1: SINR_k \geq \gamma_k \quad k = 1, \ldots, K_r,$$

$$\mathcal{C}_2: \textstyle\sum_{k\in\mathcal{S}_j}\|\boldsymbol{w}_k\|_2^2 \leq P_j \quad \forall j \in \mathcal{M}, j \neq 0 \tag{5}$$

$$\mathcal{C}_3: \textstyle\sum_{k\in\mathcal{S}_j}\|\boldsymbol{w}_k\|_2^2 \leq P_j \quad \forall \text{j} = 0.$$

To enable clarity, Table 1 contains the major system parameters and their descriptions.

Table 1. System Parameters

K_p	The total number of PBS in the 5G system.
K_m	The total number of MBS in the 5G system
K_t	The total number of BSs in the 5G system
BS_j	The jth BS.
$\mathcal{S}_j$	The set of UEs served by BS_j
N	The total number of transmit antennas at PBS or MBS
K	The total number of active served UEs in each cell
$\sqrt{g_{j,k}}$	The large-scale pathloss from BS_j to UE k.
$\boldsymbol{h}_{j,k}^s$	The small scale (fading) channel vector from BS_j to UE k.

$\boldsymbol{x}_j$ The data signal vector transmitted at BS_j and intended for its served UEs.	
K_r	The total number of UEs in the 5G system
σ^2	The noise Power.
P_j	The power limit at BS_j
$\mathcal{M}$	The set of base stations in th`e 5G HetNet

The weighted sum spectral efficiency of the system is represented by the utility function in (5), where u_k denotes a non-negative weight allocated to each UE, selected to reflect a distinct amount of the individual channel gain. The constraints ($\mathcal{C}_1$~$\mathcal{C}_3$) represent the desired quality of service constraint upper bounded by a threshold denoted as γ_k for UE k; Pico base station power constraint and Macro base station power constraint respectively.

Power constraints $\mathcal{C}_2$~$\mathcal{C}_3$ are very important because the power resources usable for transmission need to be limited to enable power efficiency. Also, in practical terms, the power constraints help to safeguard the dynamic range of the power amplifiers. Other importance of the power constraints include: they help restrict the radiated power in certain directions, also, they help control interference caused to certain UEs, and finally, they help manage the prolonged cost and revenue of running a base station.

Because no effective techniques are known to produce a solution in polynomial time, maximizing the weighted sum spectral efficiency of a system under certain given constraints as stated in ($\mathcal{C}_1$~$\mathcal{C}_3$) is typically regarded as a non-convex, non-polynomial hard optimization problem. Nevertheless, branch and bound algorithms as demonstrated in [10], can yield global optimal solutions to this kind of problem.

Let's look at each function that makes up the optimization problem in order to determine the true reason for its non-convexity in (5). The optimization of the concave utility function in (5) is contingent upon the system's UEs' signal-to-interference-and-noise ratio. See (3). The power constraints function in $\mathcal{C}_2$~$\mathcal{C}_3$ are all convex functions. The SINR constraint function in $\mathcal{C}_1$ is a non-convex function of beamforming vectors $\{\boldsymbol{w}_k\}_{k=1}^{K_r}$, which cannot be classified as a semi-definite constraint or second-order cone constraint. To get more insight on the reason behind the non-convexity of (5), let us rewrite it as follows:

$$\underset{\{w_k\}_{k=1}^{K_r}}{maximize} \quad \sum_{k=1}^{K_r} u_k SE_k,$$

$$\text{Subject to} \quad \mathcal{C}_1: \left|\boldsymbol{h}_{l,k}^H \boldsymbol{w}_k\right|^2 \geq \gamma_k\,(\Gamma_k) \quad k=1,\ldots,K_r,$$

$$\mathcal{C}_2: \textstyle\sum_{k\in\mathcal{S}_j} \|\boldsymbol{w}_k\|_2^2 \leq P_j \quad \forall j \in \mathcal{M}, j \neq 0 \tag{6}$$

$$\mathcal{C}_3: \textstyle\sum_{k\in\mathcal{S}_j} \|\boldsymbol{w}_k\|_2^2 \leq P_j \quad \forall \text{j} = 0$$

Where $\Gamma_k = {\sigma_k}^2 + \sum_{m\neq k}\left|\boldsymbol{h}_{l,k}^H \boldsymbol{w}_m\right|^2 + \sum_{j\neq l}^{Kt}\sum_{n=1}\left|\boldsymbol{h}_{j,k}^H \boldsymbol{w}_n\right|^2$

In other words, it is the SINR constraint that prevents (6) from being a convex problem. This constraint is non-convex due to the multiplication between γ_k (the SINR threshold at UE k) and Γ_k (inter-cell interference and the multi-UE interference caused to UE k). To resolve the non-convexity, the SINR threshold at each UE will be fixed or the Γ_k will be fixed as well, making it to be a known constant. For example, we can assume $\gamma_k = 0.8$ for all UEs or Γ_k= 0.5 for all UEs. In this work, we decided to fix all the SINR thresholds to the same constant. This will resolve the issue of non-convexity of the optimization problem, and the discipline convex-optimization problem can, now, be solved using CVX, a software package for specifying and solving convex programs in a MatLab environment.

IV. SIMULATION RESULTS

We evaluate the performance of the proposed method of this work by comparing it with the proposed method of another of our works in [2] and other conventional existing resource allocation methods based on the aggregate spectral efficiency, average SNR, and numbers of transmitted antennas.

A. Simulation Settings

We took into consideration the Urban-Macro for 5G New Radio roll-out scenario. The chosen carrier frequency, assuming a 100MHz bandwidth, is in the range of 3.4GHz to 4GHz (C-band). Suppose we have a straightforward simulation scenario where a minimum of five randomly distributed Pico base stations (PBSs) are installed at hotspot locations inside the macro base station (MBS) coverage region. Since there is a 45m minimum seperation between Pico sites and it is expected that PBSs are not geometrically isolated from one another, interference between PBSs is possible and is taken into consideration. There is a minimum of 80m seperating the Macro base station location from the Pico base station location. The 5G heterogeneous network's UEs are thought to be uniformly distributed and situated at the cell range expansion (CRE). Such that each UE will receive significant inter-cell interference. Note, that more focus is on UEs in the CRE area because they suffer both signal attenuation from their serving BS and inter-cell interference from neighboring cells. The uniform distribution of UEs served by PBS falls between 40m and 60m from the PBS. In similar vein, the uniform distribution of UEs served by MBS falls between 215m and 265m from the MBS. Additionally, the distance between the macrocell UEs and the PBS is between 42m and 46m, while the distance between the picocell UEs and the MBS is between 225m and 275m. 5G-ACIA [11] is also the basis for other system parameters. The UE transmit power is 23dBm, while the total BS transmit powers for MBS and PBS are 46dBm and 30dBm respectively. The channel vector between BS_j and UE k is modeled as $\boldsymbol{h}_{j,k} \triangleq \sqrt{g_{j,k}}\,\boldsymbol{h}_{j,k}^s$. Where $\sqrt{g_{j,k}}$ is the large-scale pathloss from BS_j to UE k, also $\boldsymbol{h}_{j,k}^s \in \mathbb{C}^N$ is the small-scale flat fading channel vector BS_j to UE k. The large scale pathloss in a linear scale is given as

$$g_{j,k} = \frac{\psi}{d_{j,k}^n}\,. \tag{7}$$

Where ψ is a constant which accounts for system losses; n is the path-loss exponent, typically $n > 3$, while $d_{j,k}$ is the distance between BS_j and UE k. The large-scale path loss model in dB for the macro and Pico cells are respectively $PL(dB) = 128.1 + 37.6\ \log\left(\frac{d_{j,k}}{10^3}\right)$ and $PL(dB) = 140.7 + 36.7\ \log\left(\frac{d_{j,k}}{10^3}\right)$. This simulation setting will be used except otherwise indicated.

In Fig. 1, the aggregate system spectral efficiency was plotted against the average SNR for different beamforming approaches.

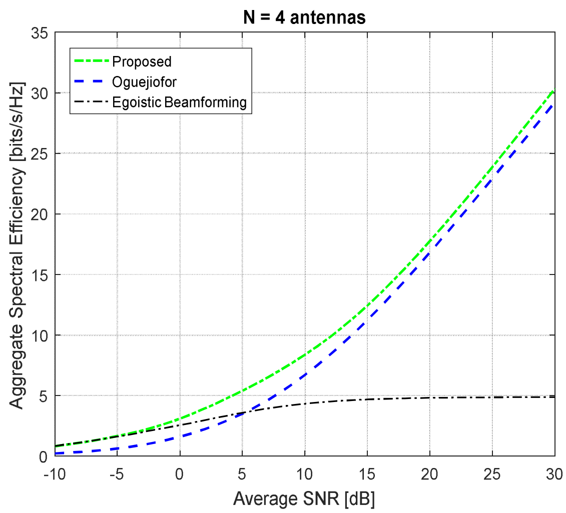

Fig. 1 Aggregate Spectral Efficiency as a function of SNR for different beamformers, and Kr = 4.

The proposed method outperforms methods used by Oguejiofor *et al.* in [2] and the Egoistic beamforming method in [12]. The Egoistic beamforming method is a method whose design doesn't consider interference from other cells. The method is more interested in designing beamformers for UEs in each cell without considering interference from other cells. This method, as can be seen, cannot compete with the proposed method when applied to a 5G heterogeneous network where inter-cell interference is a factor because universal frequency is being utilized.

The theoretical minimum achievable spectral efficiency for a 5G system is assumed to be 30 bits/s/Hz based on 3GPP simulations. If one is using 30 bits/s/Hz as a baseline, then it will take the following parameters (*Kr*=4, *N*=4, *SNR* = 30 dB) for the proposed method to actualize it. The egoistic beamforming method cannot achieve that based on the same parameters, while it will take Oguejiofor's method a higher SNR to achieve it.

In Fig. 2, the proposed method outperforms other considered methods. At *SNR* = 30 dB, the proposed method achieved a spectral efficiency of 43 bit/s/Hz, while Oguejiofor*'s* method also surpassed the 30 bits/s/Hz at *SNR* = 30 dB. However, at *SNR* = 30 dB, comparing Fig. 1 to Fig. 2, one can observe that the proposed method achieved an improved spectral efficiency of 13 bit/s/Hz. This is due to the increase in the number of transmit antenna at each base station in each cell (from *N* = 4 to *N* = 12).

In Fig. 3, the proposed method outperforms other considered methods. At *SNR* = 30 dB, the achievable spectral efficiency of the system by the proposed method is 45 bit/s/Hz. The improved spectral efficiency achieved when compared to Fig. 2 is as a result of the designed coordinated beamforming vectors that improve its performance with an increment in the number of transmit antennas.

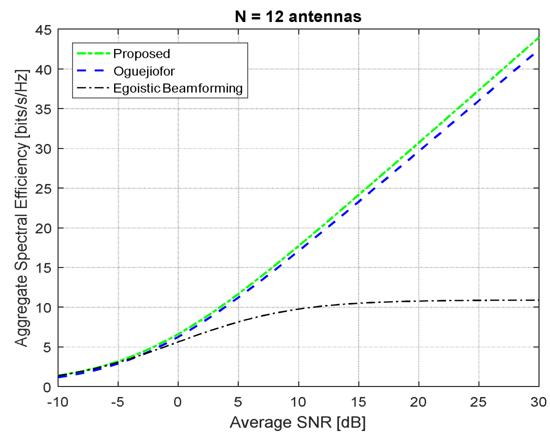

Fig. 2 Aggregate Spectral Efficiencies Achievable at Different SNR for *N* = 12, *Kr* = 4

In Fig. 4, the proposed method outperforms other considered methods. The proposed method at *SNR* = 30 dB was able to achieve a spectral efficiency of 48 bits/s/Hz, while Oguejiofor's method also surpassed the 30 bit/s/Hz at *SNR* = 30 dB. However, the Egoistic method achieves a spectral efficiency of 12 bit/s/Hz. At *SNR* = 30 dB comparing Fig. 1 to Fig. 4, one can see clearly that the proposed method achieved an improved spectral efficiency of 18 bit/s/Hz. This is due to the increase in the number of transmit antennas in each BS in each cell and also, the optimal coordinated beamformers designed by the proposed method which helps the transmit antenna to focus the desired signal energy on the desired UE.

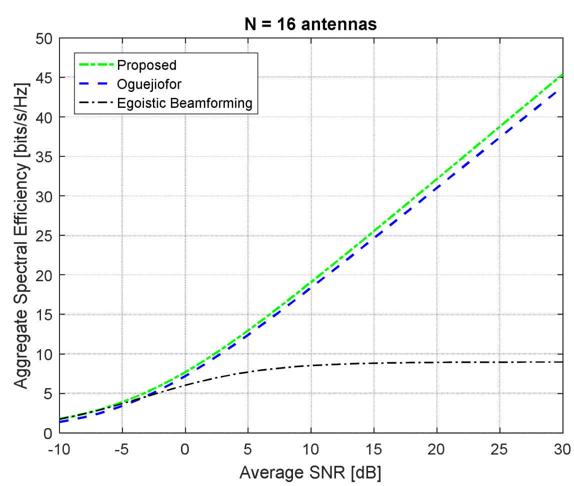

Fig. 3 Aggregate Spectral efficiencies achievable at different *SNR* for *N* =16, *Kr* = 4

In Fig. 5, the proposed method performs better than other compared methods. The aggregate spectral efficiency achievable for the proposed method is 95 bit/s/Hz at *SNR* = 30 dB. When compared to the aggregate spectral efficiency achievable for the proposed method in Fig. 4, which has the following parameters (*N* =20, *Kr* =4), one can see that at *SNR* = 30 dB, the achievable aggregate spectral efficiency is at 48 bits/s/Hz.

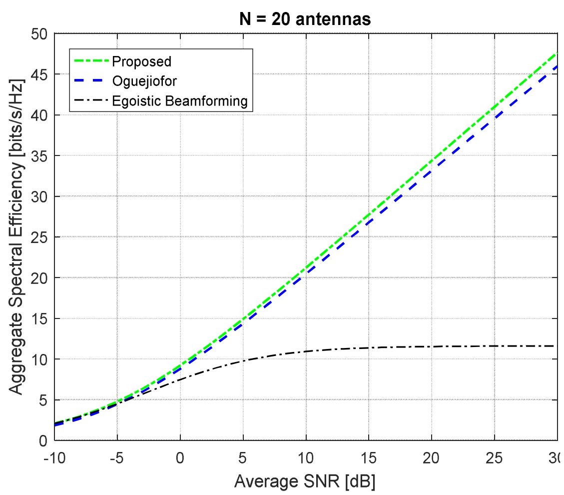

Fig. 4 Aggregate Spectral efficiencies achievable at different *SNR* for *N*=20, *Kr* = 4

Therefore, the aggregate spectral efficiency in Fig. 5 has improved by 47 bit/s/Hz to that achievable in Fig. 4 at *SNR* = 30 dB. What this means is that as the number of UEs increases in the system, together with the transmit antenna at each base station, the aggregate spectral efficiency of that system must increase when coordinated beamforming methods like the one proposed in this work is utilized at the base stations for precoding of signals before downlink transmission.

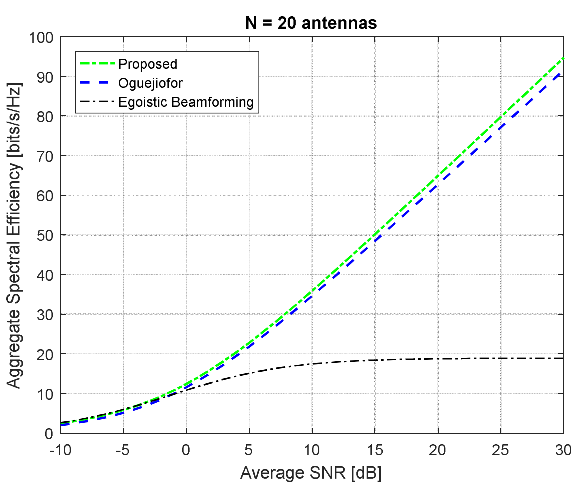

Fig. 5 Aggregate Spectral efficiencies achievable at different *SNR* for *N*=20, *Kr* = 9.

In Fig. 6, the plot of the aggregate spectral efficiencies of the system as a function of the number of transmit antennas on base stations shows that at SNR = 10 dB, for 20 transmit antennas, the spectral efficiency achievable by the proposed method is approximately 37 bit/s/Hz, while that of oguejiofor's method is approximately 36 bit/s/Hz.

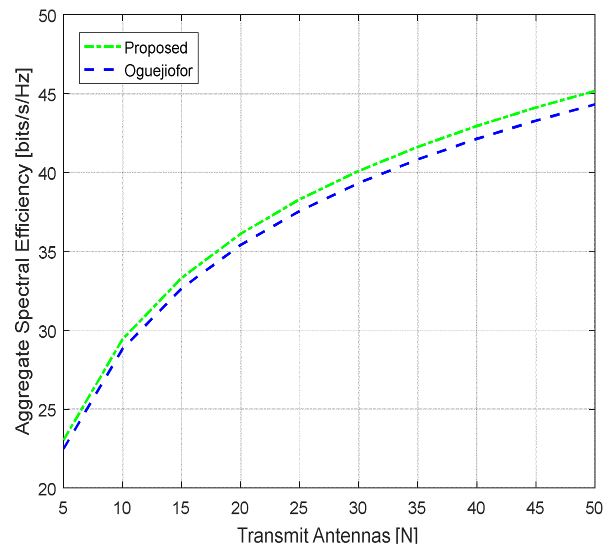

Fig. 6: Aggregate spectral efficiency at different transmit antenna for *SNR* = 10dB

This is quite similar to the figure obtained in Fig. 5 under SNR = 10 dB. However, it was observed that to achieve a minimum spectral efficiency of 30 bit/s/Hz, which is the minimum requirement for a 5G system by 3GPP, for a low SNR =10 dB, the number of transmit antennas needed at the base stations must be greater than 10.

V. Conclusion

In this work, the proposed method helps to mitigate the inter-cell interference problem that occurs in a 5G heterogeneous network deployed under a universal frequency reuse scheme. The proposed method was able to improve the system's spectral efficiency using optimally coordinated beamformers designed to curb inter-cell interference and focus the desired signal energy on the desired UE. We recommend that further work should investigate situations when UEs are very large and equal to or greater than the number of transmit antennas in all the cooperating cells.

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