Integration Femtocells Based on Hybrid Beamforming with Existing LTE Macro-cell for Improving Throughput Towards 5G Networks

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Abstract. In recent years, the mobile data traffic levels have been expected to be 1000-fold per geographical area. Unfortunately, existing communication systems suffer from the Shannon limit. Integration of the key 5G technologies such as millimeter waves (mmWave), massive multiple-input multiple-output (Massive MIMO), and Small-Cells (SC) systems is to achieve the increase in the network throughput and capacity, as well as the enhancement of the spectral efficiency, and energy efficiency. Our objective develops a new hybrid beamforming algorithm for indoor environments working in the 5G networks to achieve the desired goals. The contribution of this study designs and simulates the hybrid beamforming (HBF) that included the analog precoding and combining based on MMSE criteria and the digital precoding based on the Kalman precoding with the mathematical model in detail compared with other algorithms in the literature. Also, it proposes the heterogeneous network that included femto-cells, based on a real channel model to analyze our algorithm and calculate the throughput in all aspects of the 5G network. The proposed HBF achieves spectral efficiency closer to fully digital precoding, meaning that our solution is in the best state under different conditions. The proposed 5G HetNets enhance the macro-cell throughput under different scenarios, such as 2301.6 times compared with the LTE macro-cell.

Keywords: Massive MIMO · Millimeter-Wave · Small-Cells · Heterogeneous Networks

1 Introduction

Recent years have seen an exponential increase in connected devices and data traffic for mobile wireless networks [1]. Some technologies such as smart cities, smart homes, and the Internet of Things (IoT) are becoming a reality. Simultaneously, the Cisco Visual Networking Index (VNI) has estimated the Traffic Forecast 2017–2022. The video traffic was 59% in 2017, and it will be 79% of the total traffic in 2022 [2]. The mobile data traffic levels are expected to be 1000-fold per geographical area [3]. Unfortunately, existing communication systems suffer from the Shannon limit. It means that a modulation and coding scheme, long with the limited bandwidth of the microwave spectrum, cannot

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meet these challenges [4, 5], and [6]. It is because that the research community turns attention into the fifth generation (5G) networks, which enable applications in various fields [6]. Recent studies have confirmed a need to fundamentally modify a mobile system architecture and radio technology for achieving 5G goals. Therefore, an integration of the key technologies such as millimeter waves (mmWave), Massive multiple-input multiple-output (Massive MIMO), and Small -Cells (SC) systems is to achieve the increase in the network throughput and capacity, as well as the enhancement of the spectral efficiency, and energy efficiency [7–11], and [12].

The wavelength of mmWave bands is very small, which causes a propagation loss compared to the microwave bands. However, The Massive MIMO makes mmWave bands suitable by deploying more antennas in a small physical area to achieve high-gain antennas. Furthermore, the Massive MIMO system plays a vital role exploited both the spatial freedom and array gain in enhancing beamforming gain and array gain (spectral efficiency and energy efficiency). Also, the beamforming technique adds up the signals in desired directions and nulls in different directions (constructive and destructive). Thus, the narrow and directional beams are a crucial factor to eliminate interference, and then it focuses antennas energy on the desired direction [13–16], and [17].

Beamforming architecture can be classified into three main categories: Digital Beamforming (DBF), Analog Beamforming (ABF), and Hybrid Beamforming (HBF). In more detail, the DBF requires a dedicated radio chain (RF) equips with a single antenna that leads to more cost and consumed energy. It is because that the DBF is unpractical. On the contrary, the ABF is an energy-efficient solution based on inexpensive phase shifters, facilitating beam steering. However, it is limited to one data stream, leading to severe performance limitations in a multi-user scenario. Thus, it is not easy to cancel interfering signals. As a result, the HBF is a promising approach that exploits the small matrix digital beamforming and the high matrix analog beamforming to meet these challenges [18–31], and [32].

The remainder of the paper is organized as follows: Sect. 2 surveys related research articles, Sect. 3 describes the system model and analyses problem formulation**,** and Sect. 4 discusses the simulation results. Finally, the conclusion is reported in Sect. 5.

Notations: This paper considers A and **a** as a matrix and a vector. On the other hand, A^{H}, A^{-1}, A^{T}, $|\mathrm{A}|$, and $\|\mathrm{A}\|_{\mathrm{F}}$ represent $\mathbb{C}$ the Hermitian, inverse, transpose, determinant, and Frobenius norm of a matrix, respectively. $\mathbb{C}$ is the field of complex numbers. Finally, I and $[\cdot]$ denote the identity matrix and the expectation operator.

2 Related Works

Existing research efforts have been conducted to investigate the performance of ultra-dense small-cells integrated with The LTE macro-cells, known as a Heterogeneous Network (HetNet). In [33], the authors proposed integrating ultra-dense small-cells with the LTE macro-cells to maximize the throughput system. However, the authors did not indicate the details of the study, mainly used hybrid beamforming. The authors in [34] showed a significant compromise between the coverage and link rate in mm-wave HetNets, where there are small-cells within macro-cells as multiple tiers. In [7], the authors presented a survey that facilitates understanding research problems in ultra-dense small-cells with massive MIMO. The authors in [11] presented the survey that focuses on mm-wave HetNets and discussed the system architecture and key technologies extensively to meet the 5G goals. Also, the authors indicated the significant research challenges and open issues. In [35], the authors showed the benefits and challenges that resulted in the wireless backhaul architecture based on mm-wave massive MIMO. Another approach to evaluate the effect of the small cell user density on power consumption was demonstrated in [36]. The authors in [37] discussed and compared many wireless backhaul architectures, in which macro-cells and small-cells are considerable. The authors in [38] presented small-cell planning to enhance energy efficiency within the existing LTE macro-cell. According to the beamforming, there are some studies focused on beamforming as the Zero Forcing hybrid precoding as the digital part, and the codebook as analog part as in [39], the MMSE hybrid precoding as the digital part, and the codebook as analog part as in [40], and also the Kalman hybrid precoding as the digital part and the codebook as analog as in [41].

Our objective proposes a new hybrid beamforming algorithm working in the 5G networks to achieve the desired goals. The contribution of this study designs and simulates the hybrid beamforming that included the analog precoding and combining based on MMSE criteria and the digital precoding based on the Kalman precoding with the mathematical model in detail compared with other algorithms in the literature. Also, it proposes the heterogeneous network that included femto-cells, based on a real channel model to analyze our algorithm and calculate the throughput in all aspects of the 5G network.

3 System Model

The proposed heterogeneous network model is shown in Fig. 1. It is based on the existing LTE macro-cells that serve mobile macro stations (MSs) at the sub-6 GHz band. On the other hand, femto-cells with the mm-wave band help the MSs within the limited area. The LTE macro-cell works as a helper that provides all coverage areas when the femto-cells fail or do not exist.

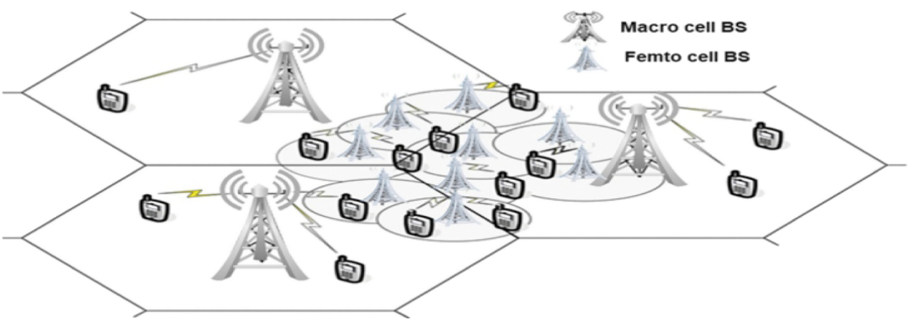

Fig. 1. The proposed HetNet.

LTE macro-cells works with femto-cells to split the large coverage areas into small ones supplied with high bandwidth of millimeter-wave. Femto-cells BS equips with a large number of antennas to maximize throughput underutilized the proposed hybrid beamforming.

The LTE macro uses the DBF and depends on the frequency-division duplex (FDD) system, in which each user estimates the channel state information (CSI) from the received downlink training sequences. After that, it feeds them back to the BS over the uplink control channel since the characteristics of the uplink (UL), and downlink (DL) channels are highly uncorrelated.

The femto-cells BS uses the time-division duplex (TDD) system based on the reciprocity of the UL and DL channels to overcome the problem of the resource-consuming feedback channel. The femto-cells BS exploits it to estimate the UL and DL channel due to the same frequency in forward and reverse links.

The femto-cells BS is given in Fig. 2, in which multi-users Massive MIMO systems incorporate with the hybrid precoding solution, and the mm-Wave channel is considered. The femto-cells BS equips with the number of antenna N_{BS} supplied from $\mathrm{Nt_{RF}}$ RF chains at the BS, known as fully-connected architecture. It maps Ns data streams on the N_{BS} and simultaneously serves K MSs. On the other hand, the MS equips with the number of antenna $\mathrm{N_{MS}}$ and single RF chains to receive the Ns at the receive side.

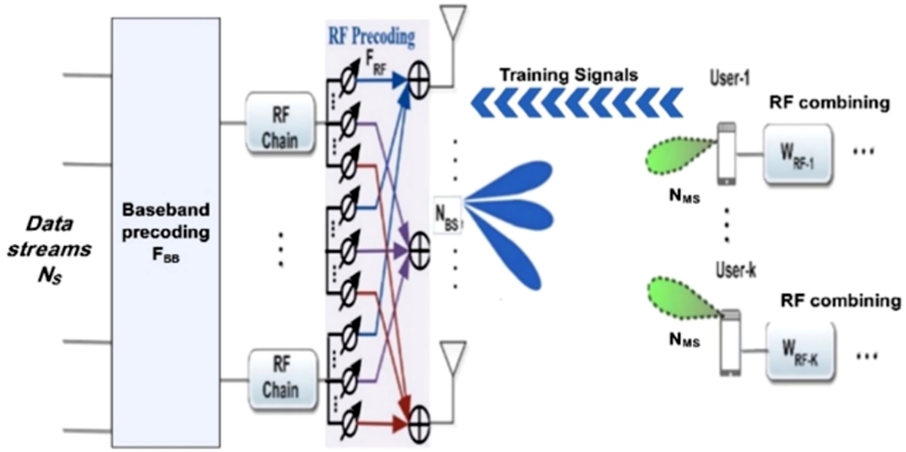

Fig. 2. The proposed hybrid beamforming for femto-cells.

An analog combining $W_k \in \mathbb{C}^{N_{MS}\,x\,k}$ is applied to the training/pilot vector $S_k \in \mathbb{C}^{k\,x\,l}$ at the mobile station before transmitting on the UL. The sampled transmitted signal can be expressed as:

$$x_k = W_k S_k \tag{1}$$

The femtocells BS consists of $F_{BB} \in \mathbb{C}^{N_{RF}\,x\,K}$ digital precoding and $F_{RF} \in \mathbb{C}^{N_{BS}\,x\,K}$ analog precoding applied to the received signal. Thus, the estimated signal after decoding processes can be expressed as:

$$s_{\hat{k}} = \underbrace{H_k^H F_{RF}^H F_{BBk}^H W_k S_k}_{Desired\ signal} + \underbrace{\sum\nolimits_{j \neq k}^{K} H_k^H F_{RF}^H F_{BBj}^H W_K S_j}_{Interference\ signal} + \underbrace{F_{RF}^H F_{BBk}^H n_k}_{Noise} \tag{2}$$

Where $n_k \in \mathbb{C}^K$ is the Gaussian noise vector and H_k is the channel matrix between the BS and the *kth* user. The generated channel model is a realistic radio channel known as QUAsi Deterministic RadIo channel GenerAtor (QuaDRiGa). The Fraunhofer Heinrich Hertz Institute has developed the QuaDriGa for heterogeneous configurations and deployment conditions [42].

The sum achievable rate of the system related to *Kth* user is given as:

$$R_k = \sum\nolimits_{k=1}^{K} \log_2 \left[1 + \frac{\left| H_k^H F_{RF}^H F_{BBk}^H W_k S_k \right|^2}{\left| \sum_{j \neq k}^{K} H_k^H F_{RF}^H F_{BBj}^H W_K S_j \right|^2 + \sigma_k^2} \right] \tag{3}$$

Where σ_k^2 and $|S_k|^2$ are the average noise power and the average total signal power.

3.1 Problem Statement and Proposed Hybrid Beamforming

The hybrid precoding and combining can be designed based on optimizing the sum rate of the proposed system. Also, it can be described through equations as following:

$$\begin{gathered} \underbrace{max}_{F_{RF}, F_{BB}, W} = \sum_{k=1}^{K} R_K \\ \textbf{s.t.} \\ \begin{cases} |(F_{RF})i,j| = \frac{1}{\sqrt{N_{BS}}} \\ |(W_K)i,j| = \frac{1}{\sqrt{N_{MS}}} \\ \|F_{BB}\|_F^2 = K \end{cases} \end{gathered} \tag{4}$$

The above Eq. (4) is not easy to solve since it is a non-convex optimization problem. Therefore, it is decomposed into two sub-problems as the analog and digital stage at the precoding/combining design. In the analog stage, the sub-problem can be reformulated based on maximizing the antenna array gain, which can be represented as the effective channel written as:

$$Heff = H_k^H F_{RF}^H W_k \tag{5}$$

As explained above, the data rate will be increased gradually if the antenna array gain is increased. Therefore, the effective channel can be reformulated as follow:

$$\underbrace{max}_{F_{RF},W} = \sum_{k=1}^{K} \left\| H_k^H F_{RF}^H W_k \right\|_F^2$$
$$\text{s.t.}$$
$$\begin{cases} |(F_{RF})i,j| = \frac{1}{\sqrt{N_{BS}}} \\ |(W_k)i,j| = \frac{1}{\sqrt{N_{MS}}} \end{cases} \tag{6}$$

The proposed solution attempts to apply the MMSE criterion on the uplink channels for obtaining the analog precoding and combining as shown in the following equations:

$$AP_{xx} = \left(H_k^H H_k + \frac{K\sigma^2}{P} I \right)^1 H_k^H \tag{7}$$

Here, the angle $\phi_{i,j}$ of the matrix AP_{xx} is considered the basis for determining the analog combining for the kth MS when the amplitudes are constant, as shown in Eq. (7). Therefore, the analog combining can be calculated as follow:

$$W_k = \frac{1}{\sqrt{N_{MS}}} e^{i(\text{angle } \phi \text{ i,j})} \tag{8}$$

Next, the MMSE criterion is applied to the analog combining and the channel as written:

$$b_k = W_k H_k^H \tag{9}$$

$$AC_{XX} = \left(b_k^H b_k + \frac{K\sigma^2}{P} I \right)^1 b_k^H \tag{10}$$

Similarly, the analog precoder based on the angle $\Omega_{i,j}$ of the matrix AC_{xx} can be formulated as follow:

$$F_{RF} = \frac{1}{\sqrt{N_{BS}}} e^{i(\text{angle } \Omega \text{ i,j})} \tag{11}$$

On the other hand, the digital part can manage the interferences among the MSs if the effective channel is available. In other words, the analog precoding and combining are determined in the analog part above, and then the effective channel is calculated. In this step, we select a Kalman filter as the digital part since it optimally estimates a current value depends on past measurements. The Kalman precoding uses a dynamic model of a system to estimate the desired values. The proposed precoding centralizes on update equations to compute F_{BB} and considers the error estimate as follows:

$$\text{Kalman Gain } G(k) = C(k|k-1) H_{eff}^H \left[H_{eff} C(k|k-1) H_{eff}^H + Lk \right]^{-1} \tag{12}$$

$$\text{Error Estimate} \quad e(k) = \frac{I - H_{eff} F_{BB}(k|k-1)}{\left\| I - H_{eff} F_{BB}(k|k-1) \right\|_F^2} \tag{13}$$

$$\text{Update Estimate} \quad F_{BB}(k|k) = F_{BB}(k|k-1) + e(k)G(k) \tag{14}$$

$$\text{Update Covariance Matrix} \quad C(k|k) = \left[I - G(k)H_{eff} \right] C(k|k-1) \tag{15}$$

$$\text{Normalize} \quad F_{BB} = \sqrt{p} \frac{F_{BB}}{\| F_{BB} F_{RF} \|_F} \tag{16}$$

Where Lk is the covariance matrix of the noise that sets (1/ SNR)*I, and p the transmitted power.

Figure 3 summarizes the processes followed in the Kalman algorithm.

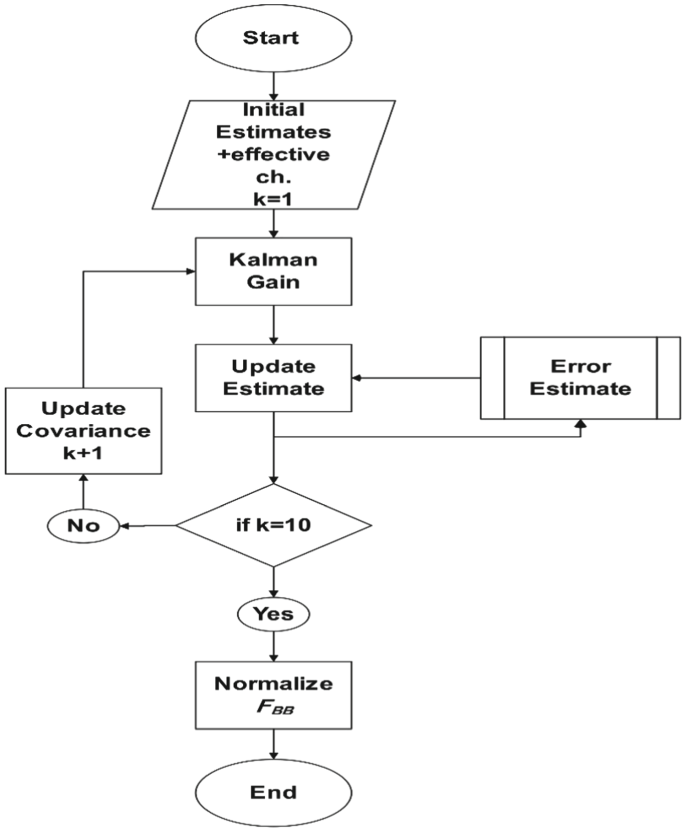

Fig. 3. The flowchart of the proposed digital part.

4 Simulation Results

In this section, the femto-cell is operated at 60 GHZ with 2 GHZ bandwidth. The average achievable rate is used to evaluate the performance. The simulation and comparison are presented between the proposed HBF and analog beamforming, fully digital beamforming, and single-user without interference along with [39, 40], and [41]. The results are more than 1000 random channel implementations on average. MATLAB 2019a software is a simulation tool and environment for the proposed method.

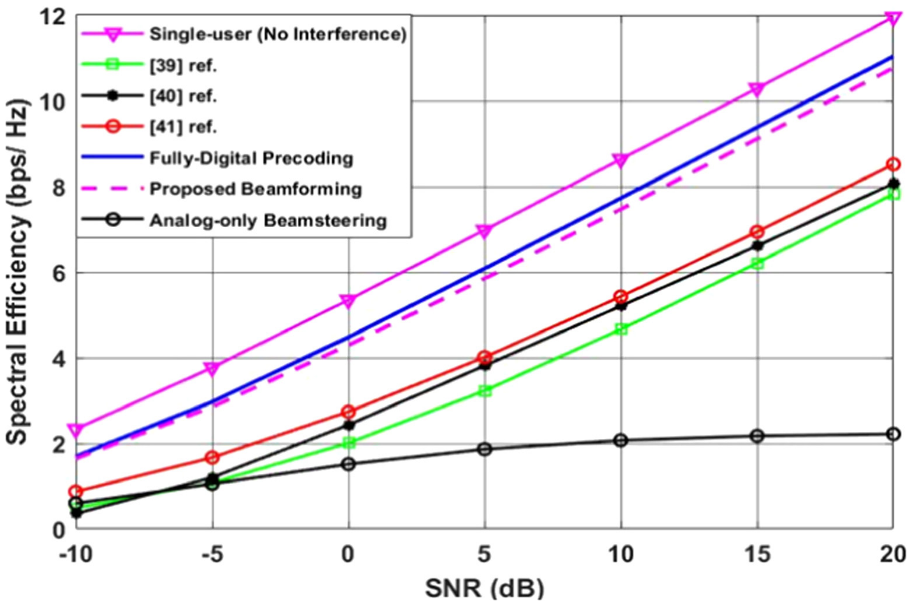

Fig. 4. Spectral efficiency versus the SNR.

Figure 4 illustrates the average achievable rates against the SNR. The simulation parameters are five multi-path channels, four users, 64 BS antennas, and four MS antennas. The proposed HBF is very close to the fully digital beamforming due to the cancellation of multi-user interference based on the digital stage. Also, the analog stage does not depend on the codebook. With the increase of SNR, the proposed HBF and analog beamforming performance gap become larger. It is because that the proposed HBF is preferred to use in low noise scenarios. Finally, the result indicates that the proposed hybrid beamforming outperforms all solutions presented as [39–41], and analog beamforming. However, fully digital beamforming outperforms the proposed hybrid beamforming since it requires the dedicated radio chain equips with a single antenna that leads to more cost and consumed energy.

Figure 5 considers the same settings described in the above figure but sets SNR 10 dB. The figure shows that the proposed HBF is decreased slightly by increasing the number of users than other solutions. Our solution uses the Kalman filter with limited iteration

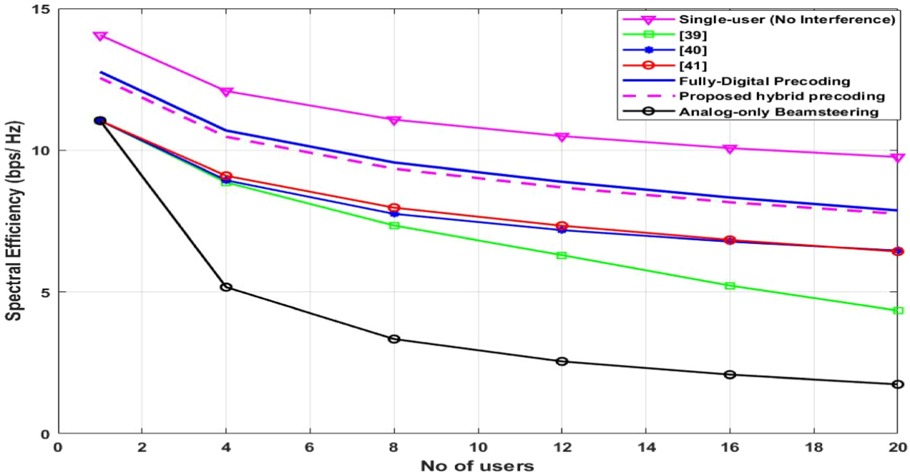

Fig. 5. Spectral efficiency versus the number of users.

to cancel interference between users and increase the array gain based on extracting the angles from MMSE criteria.

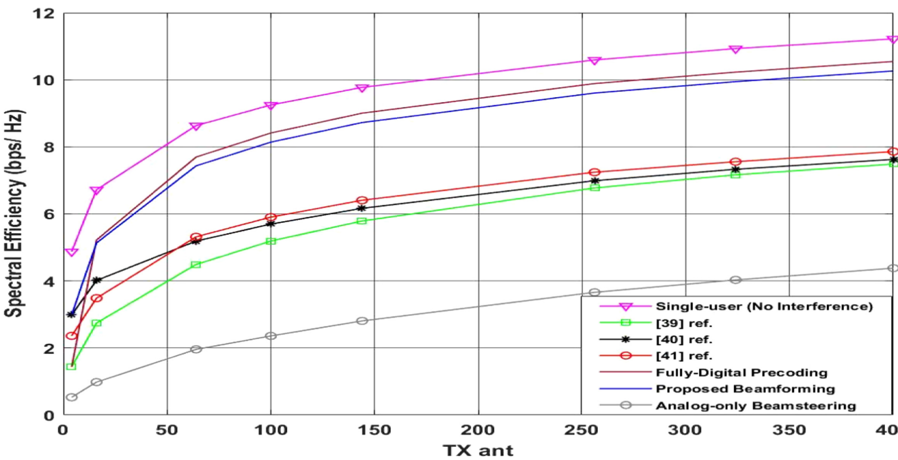

Fig. 6. Spectral efficiency against the BS antennas

Figure 6 considers the same configuration described above but sets the number of users four and confirms that the number of antennas benefits in growing the desired data rate. The BS antennas are increased to grow the desired data rate. The results indicate that the proposed HBF outperforms other solutions. The performance gap between fully digital beamforming and our method is approximately constant with the increasing number of antennas.

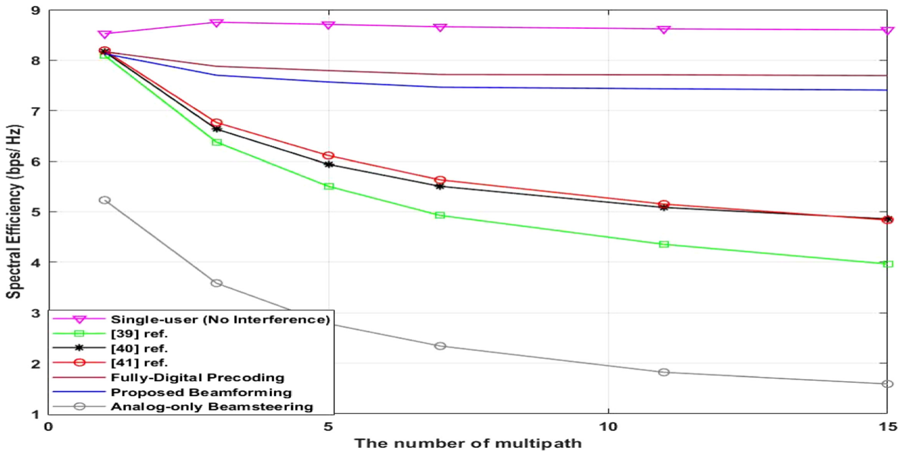

Fig. 7. Spectral efficiency against the number of multi-path.

Figure 7 considers the same configuration described above but sets 64 BS antennas. In the multi-path scenario, the proposed HBF illustrates the best performance than other solutions. Hence, the proposed solution is better in facing the multi-path since the digital stage of the proposed solution can eliminate interferences between signals. The performance of the proposed HBF exceeds the analog beamforming by approximately 21%. It is possible because the randomness of the channel will increase with more multi-path components.

After that, the proposed heterogeneous network model is a backbone of 5G networks, as shown in Fig. 8, based on the existing LTE macro-cells represented as blue dots that serve macro MSs (green dots). On the other hand, femto-cells are represented as red dots with circles, which help femtocells MSs (black dots) in the mm-wave band for near Line Of Sight propagation (LOS) propagation.

In this part, the overall throughput of the LTE-based HetNet with femto-cells is estimated under various system parameters. Table 1 illustrates the list of simulation parameters.

The LTE macro-cell works as a helper that provides all coverage areas when the small-cells fail or do not exist. Femtocells BS equips with a large number of antennas to maximize throughput underutilized the proposed hybrid beamforming. The threshold value is an indicator to associate with the LTE macro-cell or femto-cells based on the only SNR due to the variation in the interference level within one frame. In this work, the MSs with the (8 dB or more) SNR are associated with femtocells, while other users are associate with the LTE macro-cell.

Results illustrated in Table 2 shows that throughput of the macro-cell area is approximately enhanced up to 1162 times compared with the LTE macro-cell. Simulation results show that femtocells serve closed UEs with a package of advantages; as shown above, 88% of MSs are supplied from these femto-cells, resulting in this increase.

Results are presented in Table 3 that the throughput enhancement for the macro-cell area is up to 2301.6 times compared with the LTE macro-cell. The reasons are also the

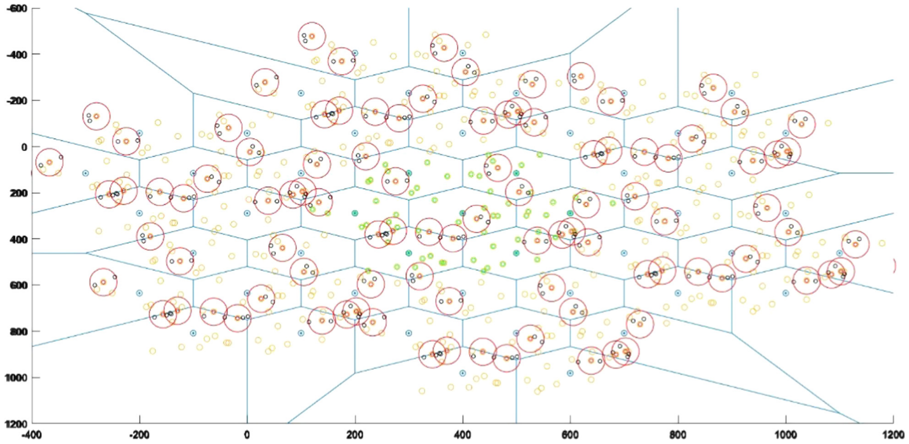

Fig. 8. The proposed HetNet layout.

Table 1. List of simulation parameter

Model parameter	Macro-cells	Femto-cells
Multiple access	OFDM, with normal cyclic prefix	OFDM, with normal cyclic prefix
System bandwidth	20 MHz FDD	2 GHz TDD
Carrier frequency	2.6 GHz	60 GHz
Number of cells	Seven heterogeneous hexagonal	3, 9 per macro-cell area
Number of users	50, 100 per macro-cell area	
Tx powers	47 dBm	20 dBm
Tx antenna elements	6	128 arrays
BS heights	25 m	10 m
UE heights	1.5 m	1.5 m
Propagation model	3GPP 38.901 UMa NLOS	3GPP 38.901 UMi LOS
Inter-site distance	200 m	

Table 2. Three femto-cells and 50 UEs per macro-cell area.

	Assigned UEs	Average UEs throughput (Mbps)	Average BSs throughput (Mbps)
LTE macro-cell	12%	6.7166	40.3
Femto-cells	88%	1063.641	15600
LTE macro-cell + femto-cells macrocell area	100%	936.81	46840

Table 3. Nine femto-cells and 100 UEs per macro-cell area.

	Assigned UEs	Average UEs throughput (Mbps)	Average BSs throughput (Mbps)
LTE macro-cell	10%	3.992	39.92
Femto-cells	90%	1019.999	10200
LTE macro-cell + femto-cells macrocell area	100%	918.3983	91879.84

deployment of femtocells. The LTE macro-cell coverage is decreased, and the throughput of femtocells is decreased slightly due to the increased number of femtocells within LTE macro-cells. Here, it is due to mutual interference between femtocells.

5 Conclusions

Overall, this work offers a successful approach towards 5G networks. The outcome of various experimentations concludes that femtocells serve closed UEs with a package of advantages. However, it is mandatory to solve issues related to the integration of 5G technologies. The design of hybrid beamforming is the main challenge. The proposed HBF passes all simulation scenarios with better spectral efficiency under different parameters than other solutions. It uses the Kalman filter with limited iteration to cancel interference between users and increase the array gain based on extracting MMSE angles. The proposed HBF achieves spectral efficiency closer to fully digital precoding, meaning that our solution is in the best state under different conditions. The proposed 5G HetNets enhance the macro-cell throughput under different scenarios, such as 2301.6 times compared with the LTE macro-cell. The realistic channel usage in this simulation undoubtedly fulfills the fact that the proposed method is a more practical solution.

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