Concept Design of Three-Dimensional Modulation Using Beam Hopping for 5G Networks

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***Abstract*—In this paper, a novel transmission scheme which is called three-dimensional modulation using beam hopping (3DModBH) and a new receiver algorithm are suggested. The new concepts improve the spectral efficiency and the reliability of the transmit signals of 5G networks by using the spatial domain of multiple small cells. The main distinguishing feature of 3DModBH transmission scheme is that it maps additional information bits by exploiting the spatial domain of multiple small cells or base stations (BSs). More specifically, the suggested 3DModBH uses the conventional two-dimensional (2-D) modulation techniques plus the spatial domain of multiple small cells or BSs to transmit the information bits, whereas the state-of-the-art transmission scheme (SoAT) uses only the conventional 2-D modulation techniques to transmit the data. We demonstrate the advantages of the novel scheme in small cell scenario under strong interference in 5G networks. We propose a new receiver algorithm to detect the transmitted information bits in practical interference limited scenario. The performance of 3DModBH scheme and the suggested receiver are compared with the SoAT in term of average bit error rate, receiver complexity, and average bits per channel use in practical 5G scenario.**

***Index Terms*—Transmission Scheme, Small Cells, Interference, 5G networks, long term evolution advanced (LTE-A)**

I. Introduction

The design and standardization of 5G systems aim to increase the user throughput and reliability of the transmit signals [1]. In order to reach the mentioned objectives of 5G wireless systems, researchers have conceived physical layer (PHY) concepts such as massive multiple-input and multiple-output (MIMO) and non-orthogonal multiple access [1].

Massive MIMO is a technology that boosts the number of used antennas on the transmitter and/or receiver side. Massive MIMO system can also significantly enhance both spectral efficiency and transmit signals reliability [2]. Applying a huge number of antennas in massive MIMO leads to lager antennas correlation than the state-of-the-art (SoA) MIMO systems [2]. Therefore, more complicated signal processing algorithms compared to the SoA MIMO systems should be used to separate spatially correlated users [2]. Non-orthogonal multiple access strategy depends on channel gain and difference between different user equipments (UEs), this difference is translated into multiplexing gains by superposing in the power domain of the transmitted signal of multiple UEs with different channel gains [3]. In addition, advance receiver processing is applied, the successive interference cancellation (SIC) receiver is used to deal with intra-cell interference [3]. The last mentioned concept can increase the overall throughput [3]. spatial modulation (SM) is a low-complexity MIMO transmit scheme, which is suggested recently to employ the active transmit co-located antenna indices and signal constellation to convey the information [4]. The main difference between the new suggested three-dimensional modulation using beam hopping (3DModBH) and SM in [4] is that the data in 3DModBH is transmitted using multiple small cells or base stations (BSs), i.e., distributed antenna systems, rather than multiple co-located antennas as in SM. Distributed antennas always yield more capacity than co-located antennas [5]. The presented state-of-the-art transmission scheme (SoAT) PHY concepts apply two-dimensional (2-D) modulation techniques such as quadrature amplitude modulation (QAM) to transmit the information bits.

In this paper, we suggest a new transmission concept which is called 3DModBH and a new receiver algorithm. The novel suggested concept is in contrast to the SoAT PHY concepts where only the conventional 2-D modulation techniques are used to transmit the data. In 3DModBH the conventional 2-D modulation techniques plus the spatial domain of multiple small cells or BSs are used to transmit the information bits. The suggested concept increases the spectral efficiency and the reliability of the transmit signals of 5G networks compared to SoAT transmission scheme. The novel contributions of this paper are as follows:

(1) A complete new transmission concept which is called 3DModBH, is suggested to transmit the information bits using the conventional 2-D modulation techniques plus the spatial domain of multiple small cells or BSs.
(2) 3DModBH is investigated in practical interference-limited 5G scenario.
(3) A new receiver algorithm for 3DModBH is proposed to detect the transmit information bits in practical 5G interference-limited environment.
(4) The computational complexity imposed by the proposed receiver is presented.
(5) The performance of 3DModBH using the new receiver in interference-limited 5G scenario is compared with the

performance of the SoAT using the joint optimal receiver using the key performance indicator (KPI) of 5G systems [1].

The remainder of this paper is organized as follows. The system model of practical 5G scenario is introduced in Section II. The SoAT is presented in Section III. The 3DModBH in interference-free, in practical 5G interference-limited scenario and the new suggested receiver are proposed in Section IV. The computational complexity of the new receiver is conceived in Section V. Our performance results are provided in Section VI, while our conclusions are offered in Section VII.

II. System Model

The 5G cellular architecture is heterogeneous, it includes macrocells, microcells and small cells [6]. we focus on small cell deployment in LTE-A frequency division duplex (FDD) systems [7]. Small cell deployment has four scenarios which are 1, 2a, 2b and 3 [8]. In each scenario, all small cells in the cluster are connected to control unit. This control unit is called a central unit which is responsible for forwarding the information bits to the UE's serving small cell. In the following, the outdoor scenario 2a which is illustrated in figure 4.2-1 in [7], is taken into account. One of the reason for this is that inter-cell interference in the outdoor scenario is stronger than inter-cell interference in the indoor scenarios [8]. The other reasons that motivate us to consider scenario 2a are listed in [8]. In our investigation, we consider one cluster in a macro enhanced node B (eNodeB) area since intra-cluster interference is more limiting than inter-cluster interference [8].

We consider that 30 UEs are dropped per macro-cell area [9]. Moreover, the number of outdoor/indoor clusters per macro-cell geographical area is 4 [7]. It is fair to assume that each macro-cell has 2 outdoor and 2 indoor clusters. It is given in [7] that 2/3 UEs uniformly dropped within the clusters and 1/3 UEs uniformly dropped throughout the macro-cell geographical area. Furthermore, it is given in [7] that 20 percent of UEs are outdoor and 80 percent of UEs are indoor. Considering the given information, the number of UEs which are transmitting data on the same time-frequency resources per outdoor cluster can be calculated as nUE = $30\times2/3\times0.2\times1/2$ = 2. In this case each UE in the cluster has one active serving and one active interfering small cells in each time-frequency resource.

Finally, we required the interference profile for our link-level studies. It has been agreed in [10] that different interference profiles for UEs with different geometries (cell-edge and cell-centre) can be used. In our investigations, we use cell-edge interference profile since the interference power of this scenario is stronger than the interference power of cell-centre scenario. In cell-edge scenario, the power of interfering signal is equal to the power of useful signal since the UE is on the edges of different cells and the distance between the serving small cell and the UE is equal to the distance between the interfering small cell and the UE. Due to the mentioned reason, the small cells have been selected in a way so that the distances between them and the UE are equal.

III. The State-of-The-Art Transmission Scheme

In this investigation, the subcarrier MIMO system is applied. The small cell downlink (DL) scenario with $N_{\mathrm{cell,cluster}}$ small cells in the cluster and with single layer transmission is taken into account. In this transmission, one small cell out of $N_{\mathrm{cell,cluster}}$ small cells serves only one UE out of nUE. Inter-cell interference happens between different UEs which are served by different small cells in the cluster and use the same time-frequency resources [11]. The representation of the received signal at the z-th UE in the cluster can be represented by

$$\underline{\boldsymbol{r}}_z\left[k\right] = \underbrace{\left[\underline{\boldsymbol{g}}_{z,1}\left[k\right],\ldots,\underline{\boldsymbol{g}}_{z,m}\left[k\right],\ldots,\underline{\boldsymbol{g}}_{z,N_{\mathrm{cell,cluster}}}\left[k\right]\right]}_{\underline{\boldsymbol{G}}_{z,1,\ldots,N_{\mathrm{cell,cluster}}}\left[k\right]} \underbrace{\begin{pmatrix} \underline{d}_{q,1}\left[k\right] \\ \vdots \\ \underline{d}_{q,m}\left[k\right] \\ \vdots \\ \underline{d}_{q,N_{\mathrm{cell,cluster}}}\left[k\right] \end{pmatrix}}_{\underline{\boldsymbol{d}}\left[k\right]} + \underline{\boldsymbol{n}}\left[k\right], \tag{1}$$

where $\underline{\boldsymbol{r}}_z\left[k\right]$ is the received signal vector with $\underline{\boldsymbol{r}}_z\left[k\right] \in \mathbb{C}^{N_{\mathrm{R}}\times1}$ at the z-th UE in the cluster and in the k-th subcarrier, where $z \in \{1,\ldots,n\mathrm{UE}\}$. The z-th UE is equipped with N_{R} receive antennas. $\underline{\boldsymbol{g}}_{z,m}\left[k\right] \in \mathbb{C}^{N_{\mathrm{R}}\times1}$ is the effective channel vector between the m-th small cell and the z-th UE. Where $\underline{\boldsymbol{g}}_{z,m}\left[k\right] = \underline{\boldsymbol{H}}_{z,m}\left[k\right]\underline{\boldsymbol{p}}_m$, $\underline{\boldsymbol{H}}_{z,m}\left[k\right] \in \mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{T},m}}$ is the channel matrix from the m-th small cell to the z-th UE, $\underline{\boldsymbol{p}}_m \in \mathbb{C}^{N_{\mathrm{T},m}\times1}$ is the applied precoding vector at the m-th small cell. The m-th small cell has $N_{\mathrm{T},m}$ transmit antennas. Moreover, $\underline{\boldsymbol{G}}_{z,1,\ldots,\mathrm{cell,cluster}}\left[k\right]$ is the effective channel matrix between the first,..., $N_{\mathrm{cell,cluster}}$-th active small cells and the z-th UE in the k-th subcarrier. Furthermore, $\underline{d}_{q,m}\left[k\right]$ is the transmit symbol which is selected from M-ary constellation at the m-th small cell with $\mathrm{E}\left(\underline{d}^*_{q,m}\left[k\right]\underline{d}_{q,m}\left[k\right]\right) = E_{\mathrm{d_{q,m}}}$, where $E_{\mathrm{d_{q,m}}}$ is the average power of the transmitted symbols. Additionally, $\underline{\boldsymbol{n}}\left[k\right] \in \mathbb{C}^{N_{\mathrm{R}}\times1}$ is the additive white Gaussian noise (AWGN) vector with $\underline{\boldsymbol{n}}\left[k\right] \sim \mathcal{CN}\left(\underline{\mathbf{0}}, \sigma_n^2\underline{\mathbf{I}}_{N_{\mathrm{R}}}\right)$. Where σ_n^2 is the AWGN variance on the UE side and $\underline{\mathbf{I}}_{N_{\mathrm{R}}}$ is an identity matrix with $\underline{\mathbf{I}}_{N_{\mathrm{R}}} \in \mathbb{C}^{N_{\mathrm{R}}\times N_{\mathrm{R}}}$. In the SoAT, $N_{\mathrm{cell,cluster}}$ is equal to nUE since there is just one serving small cell per UE [7]. Furthermore, in (1), m represents the small cell index which transmits the $\underline{d}_{q,m}$ symbol from the M-ary constellation to the m-th UE. Where M is the modulation order. Additionally, in (1), $\underline{\boldsymbol{g}}_{z,m}\left[k\right]$ is the effective channel of the serving small cell between the m-th small cell and the m-th UE if $m = z$. Otherwise $\underline{\boldsymbol{g}}_{z,m}\left[k\right]$ represents the effective channel of the interfering small cell.

To explain this transmission scheme, let us assume that there is some information bits in the central unit which should be transmitted to UE1. In this case the central unit forwards the information bits to UE1's serving small cell which is the first small cell. Let us assume that the information bits which should be transmitted to UE1 are $\boldsymbol{b}_1 = [b_{1,1}, b_{1,2}, b_{1,3}, b_{1,4}, b_{1,5}, b_{1,6}] = [0, 0, 1, 1, 0, 1]$. In this example, the first small cell have to use 64-ary constellation to transmit $\boldsymbol{b}_1$ to UE1. Therefore, the first small cell selects $\underline{d}_{q,1}[k]$ from 64-ary constellation.

IV. The Suggested Three-Dimensional Modulation Using Beam Hopping Transmission Scheme

A. Interference-free Three-Dimensional Modulation Using Beam Hopping Transmission Scheme

The new transmission concept in this subsection which is called 3DModBH improves the spectral efficiency and the reliability of the transmit signals of 5G networks by using the spatial domain of different small cells. The main difference between 3DModBH and the PHY concepts presented in Section I is that 3DModBH maps additional information bits onto a set of $N_{\text{cell,3DUE}}$ small cells which serve one UE in the cluster. The overall power of these small cells which serve one UE is equal to the power of one serving small cell in Section III so that the comparison between the two concepts is fair. Additionally, in 3D modulation using beam hopping, there is only one small cell out of $N_{\text{cell,3DUE}}$ small cells in the k-th subcarrier is active to send the information bits to its UE while all other small cells are kept silent. Doing so and detecting the active small cell out of $N_{\text{cell,3DUE}}$ small cells in the k-th subcarrier is used to increase the spectral efficiency and the reliability of the transmit signals. In other words, in 3DModBH, UE exploits the unique characteristics introduced by wireless channels (effective channel vectors) to detect additional information bits and to increase spectral efficiency and the reliability of 5G networks. Then, the received signal in interference-free scenario at the first UE and the k-th subcarrier in the cluster is expressed as

$$\underline{\boldsymbol{r}}_1[k] = \underline{\boldsymbol{g}}_{1,i}[k]\,\underline{d}_{q,1}[k] + \underline{\boldsymbol{n}}[k], \tag{2}$$

where $\underline{\boldsymbol{r}}_1[k]$ is the received signal vector with $\underline{\boldsymbol{r}}_1[k] \in \mathbb{C}^{N_\text{R}\times 1}$ at UE1 in the cluster and in the k-th subcarrier. UE1 is equipped with N_R receive antennas. $\underline{\boldsymbol{g}}_{1,i}[k] \in \mathbb{C}^{N_\text{R}\times 1}$ is the effective channel vector between the i-th small cell and UE1. Where $\underline{\boldsymbol{g}}_{1,i}[k] = \underline{\boldsymbol{H}}_{1,i}[k]\,\underline{\boldsymbol{p}}_i$, $\underline{\boldsymbol{H}}_{1,i}[k] \in \mathbb{C}^{N_\text{R}\times N_{\text{T},i}}$ is the channel matrix from the i-th small cell to UE1, $\underline{\boldsymbol{p}}_i \in \mathbb{C}^{N_{\text{T},i}\times 1}$ is the applied precoding vector at the i-th small cell. The i-th small cell has $N_{\text{T},i}$ transmit antennas. Furthermore, in (2) $i \in \{1, \ldots, N_{\text{cell,3DUE}}\}$ represents the index of the active serving small cell out of $N_{\text{cell,3DUE}}$ small cells which transmits the $\underline{d}_{q,1}[k]$ symbol in the k-th subcarrier to UE1.

To explain the new suggested transmission concept, let us assume that there are some information bits in the central unit which should be transmitted to UE1. In this case the central unit forwards the information bits to one of UE1s' serving small cells out of $N_{\text{cell,3DUE}}$ small cells. Let us recall the used example in Section III and assume that the information bits which should be transmitted to UE1 are $\boldsymbol{b}_1 = [b_{1,1}, b_{1,2}, b_{1,3}, b_{1,4}, b_{1,5}, b_{1,6}] = [0, 0, 1, 1, 0, 1]$. Moreover, let us assume that $N_{\text{cell,3DUE}} = 4$. In this example, the central unit has to decide to which small cell out of $N_{\text{cell,3DUE}}$ small cells, the information bits have to be forwarded. The decision of the central unit depends in this example on $b_{1,1}, b_{1,2}$ since there are 4 small cells which serve UE1. After deciding to which small cell that the the information bits have to be forwarded, the central unit forwards $b_{1,3}, b_{1,4}, b_{1,5}, b_{1,6}$ to the selected small cell. In other words, in the given example,the central unit forwards the last 4 information bits $[1, 1, 0, 1]$ depending on the first two information bits $[0, 0]$. Therefore, in the given example, the central unit forwards the last 4 information bits $[1, 1, 0, 1]$ to the first small cell as shown in Table I. Furthermore, The first small cell have to use 16-ary constellation to transmit $[1, 1, 0, 1]$. Therefore, the first small cell selects $\underline{d}_{q,1}[k]$ from 16-ary constellation. Instead of using 64-ary to transmit $\boldsymbol{b}$ as shown in Section III, in 3DModBH, 4 small cells and 16-ary has been used as depicted in Table I to transmit the same amount of information bits which have been transmitted in Section III using 64-ary. Therefore, the spatial dimension of $N_{\text{cell,3DUE}}$ small cells can be used to decrease the required modulation order or to increase the spectral efficiency.

Table I
MAPPING OF THE INFORMATION BITS IN THE NEW CONCEPT, $N_{\text{cell,3DUE}} = 4$

$b_{1,1}, b_{1,2}$	Selected small cell index	Transmit symbol
$0, 0$	1	$\underline{d}_{q,1}[k]$
$0, 1$	2	$\underline{d}_{q,1}[k]$
$1, 0$	3	$\underline{d}_{q,1}[k]$
$1, 1$	4	$\underline{d}_{q,1}[k]$

B. Interference-limited Three-Dimensional Modulation Using Beam Hopping Transmission Scheme

This subsection present the received signal of 3DModBH in practical interference-limited 5G scenario Section II. In the suggested transmission scheme, a set of $N_{\text{cell,3DUE}}$ small cells out of $n\text{UE} \times N_{\text{cell,3DUE}}$ small cells in the cluster serve only one UE out of nUE in the cluster. Inter-cell interference happens between different UEs which are served by different active small cells. Furthermore, the active serving small cells belong to nUE different sets and use the same time-frequency resources in the DL. The representation of the received signal at the z-th UE in the cluster can be depicted by

$$\underline{\boldsymbol{r}}_z[k] = \underbrace{\left[\underline{\boldsymbol{g}}_{z,i}[k], \ldots, \underline{\boldsymbol{g}}_{z,j}[k]\right]}_{\underline{\boldsymbol{G}}_{z,i,\ldots,j}[k]} \underbrace{\begin{pmatrix} \underline{d}_{q,1}[k] \\ \vdots \\ \underline{d}_{q,n\text{UE}}[k] \end{pmatrix}}_{\underline{\boldsymbol{d}}[k]} + \underline{\boldsymbol{n}}[k], \tag{3}$$

where $\underline{\boldsymbol{g}}_{z,i}[k] \in \mathbb{C}^{N_\text{R}\times 1}$ is the effective channel vector between the i-th small cell and the z-th UE. Where $\underline{\boldsymbol{g}}_{z,i}[k] = \underline{\boldsymbol{H}}_{z,i}[k]\,\underline{\boldsymbol{p}}_i$, $\underline{\boldsymbol{H}}_{z,i}[k] \in \mathbb{C}^{N_\text{R}\times N_{\text{T},i}}$ is the channel matrix from the i-th small cell to the z-th UE, $\underline{\boldsymbol{p}}_i \in \mathbb{C}^{N_{\text{T},i}\times 1}$ is the applied precoding vector at the i-th small cell. The i-th small cell has $N_{\mathrm{T},i}$ transmit antennas. Moreover, in (3) $i \in \{1, \ldots, N_{\mathrm{cell,3DUE}}\}$ represents the index of the active serving small cell which transmits the $\underline{d}_{q,1}[k]$ symbol in the k-th subcarrier to UE1. Moreover, $\underline{\boldsymbol{g}}_{z,j}[k] \in \mathbb{C}^{N_\mathrm{R}\times 1}$ is the effective channel vector between the j-th small cell and the z-th UE. Where $j \in \{(n\mathrm{UE}-1)\times N_{\mathrm{cell,3DUE}}, \ldots, n\mathrm{UE}\times N_{\mathrm{cell,3DUE}}\}$ is the index of the active serving small cell that transmits the $\underline{d}_{q,n\mathrm{UE}}[k]$ symbol in the k-th subcarrier to the $\mathrm{UE}_{n\mathrm{UE}}$. Furthermore, $\underline{\boldsymbol{G}}_{z,i,\ldots,j}[k] \in \mathbb{C}^{N_\mathrm{R}\times n\mathrm{UE}}$ is the effective channel matrix between the i-th,. . ., j-th active small cells and the z-th UE in the k-th subcarrier. Moreover, $\underline{\boldsymbol{d}}[k]$ is the transmitted symbols vector from i-th,. . ., j-th active small cells to the first ,. . ., nUE-th UEs respectively in the k-th subcarrier in the cluster.

C. Suggested Receiver Algorithm for Three-Dimensional Modulation Using Beam Hopping

In this subsection, we present the new suggested receiver algorithms for 3DModBH to retrieve the information bits in practical 5G interference-limited environment which we present in Section II. For the sake of simplicity, we explain in this subsection the proposed receiver for $n\mathrm{UE} = 2$, which means $z \in \{1, 2\}$. Furthermore, i and j are the serving small cell indices for UE1 and UE2, respectively. it would be straightforward to use successive interference cancellation with maximum likelihood receiver (SIC-ML) for $n\mathrm{UE} > 2$. Therefore, the effective channel matrix in this subsection is $\underline{\boldsymbol{G}}_{z,i,j}[k]$ instead of $\underline{\boldsymbol{G}}_{z,i,\ldots,j}[k]$. The information bits can be detected by identifying the effective channel matrix $\underline{\boldsymbol{G}}_{z,i,j}[k]$ of the active small cells out of $\left(N_{\mathrm{cell,3DUE}}\right)^{n\mathrm{UE}}$ effective channel matrices possibilities and $\underline{\boldsymbol{d}}[k]$ out of $(M)^{n\mathrm{UE}}$ transmitted symbols possibilities in the k-th subcarrier. We propose SIC-ML receiver algorithm to detect $\underline{\boldsymbol{G}}_{z,i,j}[k]$ and $\underline{\boldsymbol{d}}[k]$.

To retrieve the information bits $\widehat{\boldsymbol{b}}_z$, which are transmitted in the DL to the z-th UE in the k-th subcarrier, the transmitted symbol from M-ary constellation and the active small cell index out of $N_{\mathrm{cell,3DUE}}$ small cells have to be detected. The proposed receiver in this subsection can be used in practical interference-limited 5G scenario Section II by considering the interference effect on 3DModBH. We present the SIC-ML to detect the transmitted symbols and the active small cell indices for serving and interfering small cells. The suggested receiver consists of two stages: In the first stage, the SIC receiver is used to detect the transmitted symbols $\underline{d}_{q,1}[k], \ldots, \underline{d}_{q,n\mathrm{UE}}[k]$ for each possible effective channel matrix in successive way depending on a specific criterion. The successive detection of the transmitted symbols prevent error propagation on the receiver side. The post processing signal to noise ratio (SNR) criterion [8] is used in this receiver. In the second stage, the maximum likelihood (ML) receiver is applied to detect the right combination of $\underline{d}_{q,1}[k], \ldots, \underline{d}_{q,n\mathrm{UE}}[k]$ and $\underline{\boldsymbol{G}}_{z,i,j}[k]$ out of $\left(N_{\mathrm{cell,3DUE}}\right)^{n\mathrm{UE}}$ possible combinations, where, $i \in \{1, \ldots, N_{\mathrm{cell,3DUE}}\}$ and $j \in \{(n\mathrm{UE}-1)\times N_{\mathrm{cell,3DUE}}, \ldots, n\mathrm{UE}\times N_{\mathrm{cell,3DUE}}\}$.

SIC-ML algorithm

Input: $\underline{\boldsymbol{r}}_z[k]$, all effective channel matrix possibilities which are $\underline{\boldsymbol{G}}_{z,1,(n\mathrm{UE}-1)\times N_{\mathrm{cell,3DUE}}}[k], \ldots,$ $\underline{\boldsymbol{G}}_{z,N_{\mathrm{cell,3DUE}},n\mathrm{UE}\times N_{\mathrm{cell,3DUE}}}[k]$ and M-ary modulation order.

Output: $\widehat{\boldsymbol{b}}_z$ are the detected information bits which are received by the z-th UE.

Initialization: the Euclidean distance threshold $\delta_{\mathrm{ML,threshold}} >> \sigma_n^2$

for i= 1 to $N_{\mathrm{cell,3DUE}}$
  for j= $(n\mathrm{UE}-1)\times N_{\mathrm{cell,3DUE}}$ to $n\mathrm{UE}\times N_{\mathrm{cell,3DUE}}$
    Applying SIC
    (1) Compute $\gamma_{z,i,j}$ using equation (12) in [8].
    (2) $\widetilde{\gamma}_{z,i,j} = \mathrm{Sort}(\gamma_{z,i,j})$.
    (3) $\widetilde{\underline{\boldsymbol{r}}}_z[k] = \underline{\boldsymbol{r}}_z[k]$.
    (4) Compute $\widehat{\underline{\boldsymbol{R}}}^{-1}_{z,i,j}[k]$ using equation (10) in [8].
    for n= 1 to nUE
      (5) $m = \widetilde{\gamma}_{z,i,j}(n)$.
      (6) $x = \mathrm{ceil}(\frac{m}{N_{\mathrm{cell,3DUE}}})$.
      (7) $\widehat{\underline{d}}_{q,x} = \widehat{\underline{\boldsymbol{g}}}^{\mathrm{H}}_{z,m}[k]\,\widehat{\underline{\boldsymbol{R}}}^{-1}_{z,i,j}[k]\,\widetilde{\underline{\boldsymbol{r}}}_z[k]$.
      (8) $\widetilde{\underline{\boldsymbol{d}}}(x)[k] = \widehat{\underline{d}}_{q,x}$.
      (9) $\widetilde{\underline{\boldsymbol{r}}}_z[k] = \widetilde{\underline{\boldsymbol{r}}}_z[k] - \widehat{\underline{\boldsymbol{g}}}_{z,m}[k]\,\widehat{\underline{d}}_{q,x}$.
      (10) $\widehat{\underline{\boldsymbol{R}}}^{-1}_{z,i,j}[k] = \widehat{\underline{\boldsymbol{R}}}^{-1}_{z,i,j}[k] - \widehat{\underline{\boldsymbol{g}}}_{z,m}[k]\,\widehat{\underline{\boldsymbol{g}}}^{\mathrm{H}}_{z,m}[k]$
    end for n
    Applying ML
    $\delta_{\mathrm{ML}} = \| \underline{\boldsymbol{r}}_z[k] - \underline{\boldsymbol{G}}_{z,i,j}[k]\,\widetilde{\underline{\boldsymbol{d}}}[k] \|^2$
    if $\delta_{\mathrm{ML}} < \delta_{\mathrm{ML,threshold}}$
      $\delta_{\mathrm{ML,threshold}} = \delta_{\mathrm{ML}}$.
      $ind_1 = i$.
      $ind_2 = j$.
      $\widehat{\underline{\boldsymbol{d}}}[k] = \widetilde{\underline{\boldsymbol{d}}}[k]$.
    end if
  end for j
end for i

$[b_{z,1}, \ldots, b_{z,y}] = \mathrm{mapInd}(ind_z)$.
$[b_{z,y+1}, \ldots, b_{z,y+s}] = \mathrm{mapSym}(\widehat{\underline{\boldsymbol{d}}}(\mathrm{z})\,[\mathrm{k}])$.
$\widehat{\boldsymbol{b}}_z = [b_{z,1}, \ldots, b_{z,y}, b_{z,y+1}, \ldots, b_{z,y+s}]$.

Notations

- $\gamma_{z,i,j}$: is the post processing SNR vector, which is nUE real values, for all active small cells with the indices i, j in the k-th subcarrier in one cluster.
- Sort: sorts the post processing SNR values at the z-th UE in $\gamma_{z,i,j}$ descendingly.
- $\widehat{\underline{\boldsymbol{R}}}^{-1}_{z,i,j}[k]$: is the covariance matrix for effective channel vectors $\underline{\boldsymbol{g}}_{z,i}[k]$ and $\underline{\boldsymbol{g}}_{z,j}[k]$ in the k-th subcarrier in one cluster.
- ceil: rounds the value of $(\frac{m}{N_{\mathrm{cell,3DUE}}})$ to the nearest integer greater than or equal to that value.
- x: is the index of the UE to which the m-th small cell is the serving small cell.
- ind_1: is the index of the serving small cell for UE1.
- ind_2: is the index of the serving small cell for UE2.
- $y = \log_2(N_{\mathrm{cell,3DUE}})$, $s = \log_2(M)$.
- mapInd(.): maps the small cell index to bits.
- mapSym(.): maps the estimated symbol to bits.

V. Complexity Comparison

In this section, we compare the computational complexity imposed by the suggested receiver in Section IV-C with the computational complexity of the joint ML (JML) receiver presented in [8] to detect the information bits for the SoAT explained in Section III. We quantified the complexity as the number of real-valued multiplications.

The computational complexity per bit for JML receiver may be presented as

$$C_{\mathrm{JML}} = \frac{(4N_{\mathrm{R}} \times n\mathrm{UE} + 2N_{\mathrm{R}}) \times M^{n\mathrm{UE}}}{\log_2(M)}, \tag{4}$$

the term written in equation (13) of the JML receiver mentioned in [8] over one symbol from M-ary constellation can be rewritten as $\parallel \underline{\boldsymbol{r}}_z\,[k] - \underline{\boldsymbol{G}}_{z,1,\ldots,N_{\mathrm{cell,cluster}}}\,[k]\,\underline{\boldsymbol{d}}\,[k] \parallel^2$. This term imposes the complexity of $(4N_{\mathrm{R}} \times n\mathrm{UE} + 2N_{\mathrm{R}})$. In [8], this term is computed for M-ary constellation points and for nUE. Therefore, the numerator in 4 is multiplied with $(M)^{n\mathrm{UE}}$. Since the complexity in 4 is per bits, the numerator is divided by $\log_2(M)$.

The computational complexity per bit for the proposed SIC-ML receiver may be expressed as

$$C_{\mathrm{SIC-ML}} = \frac{(N_{\mathrm{Mul}} - 2N_{\mathrm{R}} + 3n\mathrm{UE}) \times (N_{\mathrm{cell,3DUE}})^{n\mathrm{UE}}}{\log_2(MN_{\mathrm{cell,3DUE}})}, \tag{5}$$

where $N_{\mathrm{Mul}} = 4N_{\mathrm{R}}^3 \times n\mathrm{UE} + 20N_{\mathrm{R}}^2 \times n\mathrm{UE} + 4N_{\mathrm{R}}^2 \times n\mathrm{UE}^2 + 12N_{\mathrm{R}} \times n\mathrm{UE} - 4N_{\mathrm{R}}^2$. The associated complexity for expression (4) and for computing $\gamma_{z,i,j}$ in expression (1) in SIC-ML algorithm is given by $(8N_{\mathrm{R}}^2 \times n\mathrm{UE} + 4N_{\mathrm{R}}^3 + 4N_{\mathrm{R}}^2 \times n\mathrm{UE}^2 + 2N_{\mathrm{R}} \times n\mathrm{UE} + 3n\mathrm{UE})$. Moreover, the complexity for calculating expressions (7), (9) and (10) in SIC-ML algorithm is expressed as $(12N_{\mathrm{R}}^2 \times n\mathrm{UE} + 4N_{\mathrm{R}}^3 \times n\mathrm{UE} - 4N_{\mathrm{R}}^3 + 6N_{\mathrm{R}} \times n\mathrm{UE} - 4N_{\mathrm{R}} - 4N_{\mathrm{R}}^2)$. Furthermore, the computed complexity of $\parallel \underline{\boldsymbol{r}}_z\,[k] - \underline{\boldsymbol{G}}_{z,i,j}\,[k]\,\widetilde{\underline{\boldsymbol{d}}}[k] \parallel^2$ is given by $(4N_{\mathrm{R}} \times n\mathrm{UE} + 2N_{\mathrm{R}})$. Summing up the computational complexity of expressions (1), (4), (7), (9), (10) and $\parallel \underline{\boldsymbol{r}}_z\,[k] - \underline{\boldsymbol{G}}_{z,i,j}\,[k]\,\widetilde{\underline{\boldsymbol{d}}}[k] \parallel^2$ in SIC-ML algorithm and then multiply it by the number of iterations needed which is $(N_{\mathrm{cell,3DUE}})^{n\mathrm{UE}}$. Finally, we can obtain 5 by dividing the results by $\log_2(MN_{\mathrm{cell,3DUE}})$ to get the computational complexity per bit.

VI. Simulation Results

In this section, we present the performance of the suggested 3DModBH transmission scheme in Section IV with the proposed SIC-ML in Section IV-C receiver. The performance of 3DModBH with SIC-ML is compared with the performance of SoAT in Section III with the joint optimal receiver JML in [8]. The performance comparison is carried out in term of KPI of 5G systems. The KPI, which are considered in this section for performance evaluation, are the average bit error rate (BER), the average bits per channel use (bpcu) and receiver complexity. The BER is evaluated in the DL on the UE side. The average BER is calculating by averaging the BER of nUE in the cluster. The average bpcu is the average number of transmitted bits in each time-frequency resource over nUE in the cluster. The simulations are performed for nUE = 2 as described in Section II MIMO system with $N_{\mathrm{T},m} = N_{\mathrm{T},i} = 2$ and $N_{\mathrm{R}} = 8$ [12]. The channel model used in our simulations is the EPA [7]. A practical channel estimation over demodulation reference signals (DMRS) [7] on the UE side is used to estimate the effective channel vectors for all small cells in the cluster. The interference profile which is used in our simulations is explained in Section II. Finally, we use long term evolution (LTE) 10MHz with sampling rate equal to 15.36MHz in our investigations. The DL performance is evaluated at $\mathrm{BER} = 10^{-2}$.

Figure 1 and Figure 2 compare the average BER with SNR curves for the suggested 3DModBH using the proposed SIC-ML receiver with the SoAT using JML receiver. For this comparison, we choose an average bpcu = 6 and 8. The simulation results show, the proposed 3DModBH with $32-\mathrm{QAM}$ in Figure 1 and $128-\mathrm{QAM}$ in Figure 2 for $N_{\mathrm{cell,3DUE}} = 2$ outperform the SoAT by around $1.5\,\mathrm{dB}$ and $2.25\,\mathrm{dB}$, respectively. Furthermore, the simulation results show, the suggested 3DModBH with $16-\mathrm{QAM}$ in Figure 1 and $64-\mathrm{QAM}$ in Figure 2 for $N_{\mathrm{cell,3DUE}} = 4$ significantly outperform the SoAT by around $4.75\,\mathrm{dB}$ and $5.5\,\mathrm{dB}$, respectively. It is observed from these results that decreasing the QAM order and increasing the bits, which are carried out on the spatial dimension of $N_{\mathrm{cell,3DUE}}$ different small cells, results in increasing the gain compared to the SoAT. This stems from the fact that low QAM order is more robust against noise and interference effects and requires lower SNR to achieve a specific performance than high QAM order. Moreover, by comparing Figure 2 and Figure 1, it can be seen that increasing the average bpcu leads to increase the obtained gain by the suggested 3DModBH compared to the SoAT by around $0.75\,\mathrm{dB}$. This is due to the reason is that increasing the average bpcu leads to increase the QAM order, when the $N_{\mathrm{cell,3DUE}}$ is constant as in Figure 2. Increasing the QAM order requires higher SNR to achieve a specific performance as can be seen in Figure 2. Increasing the SNR results in more reliable small cell index detection. Due to this reason, applying the proposed approach in an average bpcu = 8 results in higher gain than applying it in an average bpcu = 6.

Figure 3 compares between the achievable throughput using the suggested idea with the achievable throughput using the SoAT. We quantify the system throughput in term of the average bpcu. It can be observed from Figure 3 that 3DModBH achieves around one bpcu and two bpcu higher than the SoAT at a specific SNR value for $N_{\mathrm{cell,3DUE}} = 2$ and 4, respectively. This is due to the use of the spatial domain of $N_{\mathrm{cell,3DUE}}$ different small cells to transmit the information bits.

Finally, the simulation parameters, which are used to obtain the results in Figure 1, are used here as an example to compare between the complexity of SIC-ML and JML. By substituting the simulation parameters in 5 and in 4, the number of real-valued multiplications for $C_{\mathrm{SIC-ML}} = 5070$ and 20283 for $N_{\mathrm{cell,3DUE}} = 2$ and 4 respectively. Where the number of real-valued multiplications for $C_{\mathrm{JML}} = 54613$. It

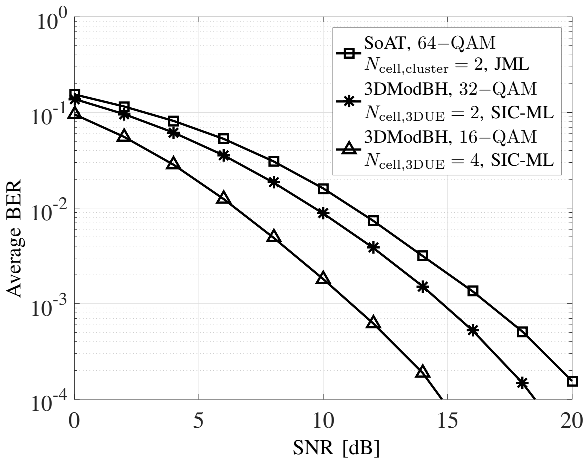

Figure 1. Average BER comparison between 3DModBH using SIC-ML receiver and SoAT using JML receiver, where the average bpcu = 6

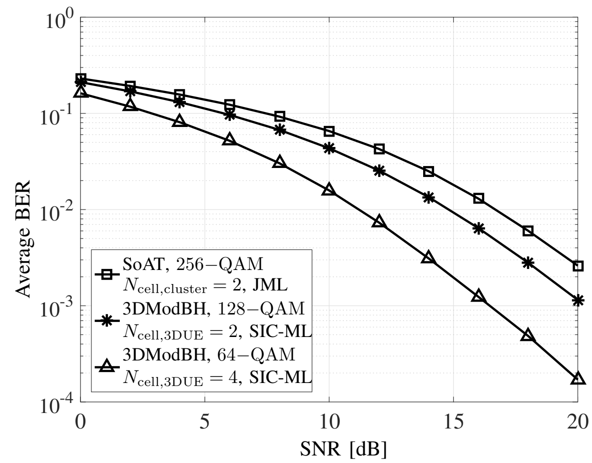

Figure 2. Average BER comparison between 3DModBH using SIC-ML receiver and SoAT using JML receiver, where the average bpcu = 8

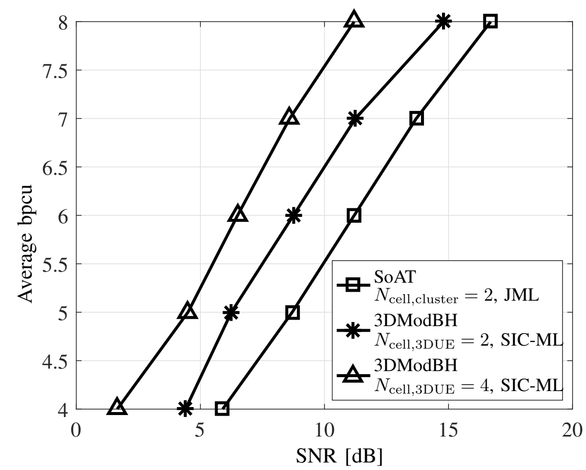

Figure 3. Average bpcu comparison between 3DModBH using SIC-ML receiver and SoAT using JML receiver for different QAM order

can be observed that the complexity of the suggested SIC-ML receiver used with the proposed 3DModBH is much lower than the complexity of JML receiver used with SoAT in spite of the performance enhancement obtained by the suggested concepts.

VII. Conclusion

In this paper, we suggested 3DModBH, which is a new transmission concept for higher performance and spectral-efficient wireless communication systems to be applied in 5G networks. The main idea of the proposed concept is to use the spatial domain of multiple small cells to transmit additional information bits. We investigated 3DModBH in practical interference-limited 5G scenario. We proposed the SIC-ML receiver to detect the transmitted information bits for 3DModBH in interference-limited scenario. We conclude from our investigation that 3DModBH using SIC-ML achieves better performance, higher spectral-efficiency and lower receiver complexity than the SoAT using JML receiver. Considering the mentioned reasons, we argue that our suggested transmission scheme and the proposed receiver can be regarded as possible candidate for 5G wireless systems.

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