Spatial Multiplexing based on Distributed Antenna Arrays for Mobile WiMAX Networks

Christos Papathanasiou[1] , Nikos Dimitriou[2] , Leandros Tassiulas[1]

1. Centre for Research & Technology, Hellas, University of Thessaly, Greece
2. Institute of Accelerating Systems & Applications, National & Kapodistrian University of Athens, Greece

Email: cpapa@uth.gr, nikodim@phys.uoa.gr,thsamios@hol.gr, leandros@.uth.gr

***Abstract:* - A novel cell architecture based on Distributed Antenna Arrays for next generation mobile WiMAX systems is proposed. By exploiting Spatial Multiplexing and beamforming techniques, our target is to maximize the throughput of a high speed user by keeping low the deployment costs. Radio over Fiber is one of the best solutions to feed from a central point distributed arrays and share wireless resources with flexibility. The new architecture is compared to the case of using co-located antenna systems. Simulation results evaluate the enhancement in the system performance that is achieved by using the proposed methods at the transmitter and the receiver sides with different complexity.**

I. INTRODUCTION

The IEEE 802.16e standard introduces Multiple Antennas System (MAS) technologies, based on Multiple Input Multiple Output (MIMO) techniques in order to provide high user throughput, [1]. These technologies are classified into two categories: open loop Spatial Multiplexing (SM) and closed loop based on Channel State Information (CSI). Also, Orthogonal Frequency Division Multiplexing (OFDM) is used to enable simple high-performance receiver structures in the presence of frequency selective fading channels. MIMO systems exploit the spatial dimension using antenna arrays at the transmitter and receiver sides. In [2], different transmit antenna configurations are compared for 3 GPP macro-cellular environments. The beamforming configuration of two antennas with $d = \frac{\lambda}{2}$ (d is the distance between antenna elements and λ the wavelength) results in the highest data rate for users with low Signal to Noise Ratio (SNR). The configuration with the two antennas placed far apart ($d = 10\ \lambda$) results in the highest data rates for users with high SNR. While users at low SNR conditions may benefit greatly from a boost in their received power with four antennas the configuration that include two beamformers (in which each beamformer has two antennas) give even higher data rates for all SNR ranges compared to the configuration with four widely-spaced antennas. An overview of interference reduction techniques in a SM multicell system is presented in [3]. A Radio over Fiber (RoF) system involves multiple antennas that are distributed around a cell and connected to a Central Controller(CC) via optical fiber. In such a scheme, the fiber is used to route the broadband modulated optical signals to remote Distributed Antennas. The Radio Frequency (RF) signals are detected and transmitted. The use of RF over fiber allows a significant reduction in the complexity and costs of remote Distributed Antennas. The RF signal is transmitted in analog form via the fiber to the antenna array site. Only simple optical/electrical converters and RF amplifiers are necessary at the reception. In [4], MIMO capacity is studied for independent lognormal macroscopic fading and independent Rayleigh microscopic fading between widely spaced antenna arrays and a mobile user. For the same number of total antennas involved and assuming unknown channel gains at the transmitter, Distributed Antennas always yield more capacity than multiple co-located antennas. In a network including high speed users, the fast radio channel changes may introduce delays that are greater compared to the delays caused by the optical fiber [5]. Additionally, the placement of DAs within a cell is a primary design issue. According to the conventional approach, one DA is placed at the center of cell. The service area is divided into grids. The design process consists of a) choosing the number of DAs and their placement b) maximizing SNR and throughput for each user.

Our approach exploits multi-DA diversity by using SM and beamforming techniques in an optimum way to take account of inter-stream interference. As the propagation conditions between the mobile and DAs are different, one or more received signals (streams) may be weak due to shadow fading, multipath effects, etc. By applying beamforming to all transmitted streams and combining all the streams at the receiver and not only those which correspond to strong links, we could increase significantly spectral efficiency. We assume the availability of a realistic amount of channel feedback to identify the transmitted beams as a function of the channel statistics. It's only necessary to update this information at a rate similar to that of small scale fading. Our proposed solution yields a jointly optimal combination of a number of transmitted beams and receiver filters under the criterion of minimizing the minimum mean square error (MMSE) between the transmitted and the received signals. The performance of such a system is limited by mutual inter-stream interference. Our scheme increases the user throughput due to the high angular spread (spatial selectivity) of the high channel gains which produce large

---

This work is supported by European Commission N-CRAVE STREP (FP7-INFSO-ICT-215252) & WiMAGIC STREP (FP7-ICT-215167)

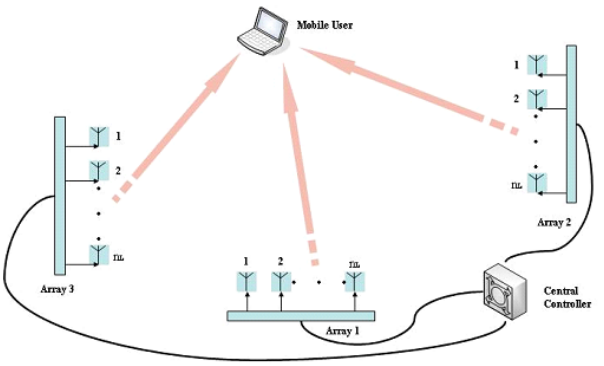

Figure 1. System deployment

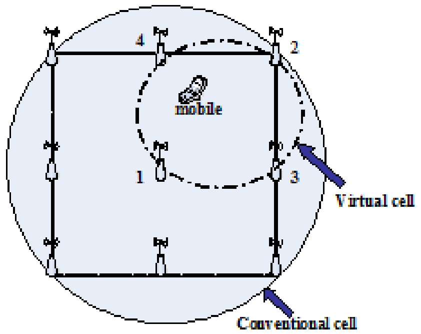

Figure 2. Proposed structure for DAs

and strong number of eigen-modes even under Line Of Sight (LOS) conditions.

The proposed configuration is shown in fig. 1. The paper is organized in the following way: Section II describe the novel architecture based on DAs. The transmitter scheme is presented in section III. The SNR mathematical expression is derived and the receiver techniques are explained in section IV. Simulation results are given in section V. Finally, section VI concludes this paper.

II. CELL ARCHITECTURE

A large number of DAs are assumed to be installed within a cell area and a star-shaped network is assumed among the numerous remote DAs and one central controller. Let's consider N_p antenna arrays distributed around a cell each with having N_t antenna elements. At each slot, a number of DAs are assigned to simultaneously transmit streams of OFDM modulated symbols to the user. The user separates the respective streams by processing the signal vectors received at the user's antenna array equipped with N_r antenna elements. The number of simultaneously transmitted streams is smaller or equal to N_r. The size of mobile terminals limits the number of receiver antenna elements down to two or four. These values are compliant with [1]. The RoF system transports RF wave signals over optical fiber. The data first modulates the RF source which in turn modulates an optical light source (for example a Laser Diode) using an External Optical Modulator. This signal is carried over optical fiber to a DA, where the optical signal is converted into RF with a photodiode and the transmitted over the air. In our proposed configuration, each cell is divided into four rectangular areas forming a square grid. The DAs are assumed to be located at the corner of each rectangular area of each grid [6]. Fig. 2 depicts the cell structure and the location of the DAs. The conventional cell has a BS located at its center while a virtual cell (VC) is assumed to be formed by a set of DAs which are in the reach of a certain mobile. The notion of a VC is introduced in [6]. The number of DAs (cardinality of the VC) is equal to the number of the receiver antenna elements N_r. Each mobile has its own VC according to the best propagation conditions. In the downlink, the information is sent to the mobile user by all DAs of its VC in parallel. Two options are considered: Full Diversity and Selection Diversity schemes. In the former case, the mobile receives signals from all DAs of VC, while in the latter case, the downlink information is always transmitted only from the DAs of the VC with the better radio links. For comparison purposes, we investigate the layout with one Antenna Array located in the center of the conventional cell.

III. ADAPTIVE MIMO TRANSMISSION

In a mobile WiMAX system, the wireless channel changes with time due to the mobility of the user and the scattering environment. The CSI cannot be instantaneously transmitted from the mobile to DAs, therefore it is outdated to some degree. The mean value of the channel gain $h(t)$, $g = \mathcal{E}\{h(t)\}$ averages the fluctuation of channel gain over time. The symbol $\mathcal{E}\{\ \}$ denotes expected value. The channel coefficients are averaged over one frame duration. Transmit beamformers are determined as a function of the statistics of the small scale fading, which reflect the propagation environment. It was found that in a MIMO point to point system with partial CSI available at the transmitter, beamforming has a nearly optimal performance [7].

Let H_l ,$l \in VC = \{1,2,3,4\}$ be the channel matrix between DA l and the mobile user and G_l the corresponding mean value. The feedback information can be represented as $G_l = [g_{ji}^l]$, where $j \in \{1,2,3,4\}$ is the receiver antenna element and $i \in \{1,2,3,4\}$ the transmitting antenna element of the DA l. We compute the singular value decomposition (SVD) of the MIMO channel matrix as $G_l = U_l \Sigma_l V_l^H$ where the matrix Σ_l with non zero diagonal elements in decreasing order represents the power allocation at each eigen-mode. The columns v_{lp} of matrix V_l are the optimum weights of DA l for the p-ith eigen mode. For our spatial multiplexing scheme, each DA l multiplies the transmitted signal by the right singular vector v_{l1}, which corresponds to the strongest eigen mode. Let's consider that the matrix G is composed of the submatrices G_l of equal size

$$G = [G_1 \mid G_2 \mid \cdots \mid G_{N_p}] \quad (1)$$

We define the transmitter matrix V which is composed of the beamforming vectors V_l as

$$V = \left[V_1 \mid V_2 \mid \cdots \mid V_{N_p}\right] =$$

$$\begin{bmatrix} V_1^1 V_2^1 V_3^1 V_4^1 & 0\ 0\ 0\ 0 & \cdots & 0\ 0\ 0\ 0 \\ 0\ 0\ 0\ 0 & V_1^2 V_2^2 V_3^2 V_4^2 & \cdots & 0\ 0\ 0\ 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0\ 0\ 0\ 0 & 0\ 0\ 0\ 0 & \cdots & V_1^{N_p} V_2^{N_p} V_3^{N_p} V_4^{N_p} \end{bmatrix}^T$$

Finally, the transmitted signal is represented with the vector $X_0 = \begin{bmatrix} x_0^1 & x_0^2 & \cdots & x_0^{N_p} \end{bmatrix}$ of size $N_p\mathbf{x}1$. Assuming that x_0^l , $l \in \{1, 2, \cdots N_p\}$ has zero mean, the total radiation power is equal to

$$P_{tx} = \sum_{l=1}^{N_p} \|v_{l1}\|_2^2 \ P_l \quad (2)$$

where P_l denotes the power boost factor and $\|v_{l1}\|_2^2 \, P_l = P_{max}$, P_{max} being maximum transmit power at each DA. The matrix V_l derived from SVD is a unitary matrix so that $V_l^H \ V_l = I_{M_t}$. Therefore

$$P_l = P_{max} \quad \text{and} \quad P_{tx} = N_p \ P_{max} \quad (3)$$

In the abovementioned analysis, we have considered that the channel is flat fading. This is true for one subcarrier n at one frame m and therefore channel matrix H_l mayt be denoted as $H_l(n, m)$. At the receiver, equalization and demodulation operate on subcarrier and frame by frame basis where the channel is approximately constant. We can omit the subcarrier index n and the time index m respectively. We assume a cluster as a structure grouping adjacent subcarriers. If the number of subcarriers within a cluster occupies a bandwidth of the same order of the channel coherence bandwidth, the channel variations over the subcarriers within the same clusters are small. Thus, our study could be extended on a cluster basis.

IV. RECEIVER IMPLEMENTATIONS

If the receiver decodes successfully the different streams, higher throughput can be achieved. Independent blocks are transmitted in parallel from DAs and consequently a superposition of these streams arrives at the receiver. Our goal is to extract co-channel interference between the streams. Linear equalization with MMSE criterion is investigated in order to estimate the transmitted information. By applying Successive Interference Cancellation (SIC) techniques, the streams are detected step-by-step and the estimated interference is successively subtracted from the received signal. Generally, the signal separation can be achieved by estimating the MIMO channel matrix $H = [H_1 \mid H_2 \mid \cdots \mid H_{N_p}]$. In our scheme, we consider that perfect CSI is available at the receiver. Let $Y = [y_1 \ y_2 \ \cdots \ y_{N_r}]$ of size $N_r\mathbf{x}1$ be the received matrix at the antenna port .

$$Y = H \ V \ X_0 + n \quad (4)$$

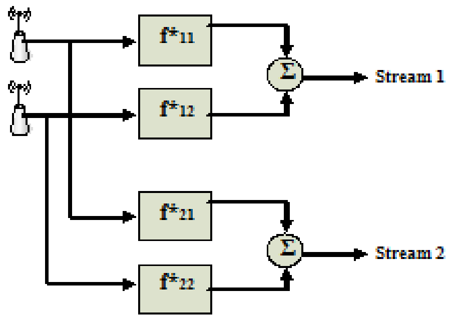

Figure 3. Filters' structure with two antenna elements at the receiver

The vector n size $N_r\mathbf{x}1$ denotes the zero mean Additive Gaussian Noise (AWGN). The estimated vector $\hat{X}_0$ of the transmitted signal X_0 is obtained using the theory for linear optimum discrete-time filters, known as Wiener filters [8].

$$\hat{X}_0 = F_{SDM}^H \ Y \quad (5)$$

where the filter weights are $F_{SDM} = [f_{l,j}]$, $\forall \ l \in \{1, 2, \cdots, N_p\}, \forall \ j \in \{1, 2, \cdots, N_r\}$. The filter coefficients require the knowledge of the correlation matrix of the received signal Y and the desired response X_0.

$$F_{SDM} = \mathcal{E}\{Y \ Y^H\}^{-1} \ \{Y X_0^H\} \quad (6)$$

If the noise power at the receiver is $\sigma_0^2 \ I_{N_r\mathbf{x}N_r}$, taking into account that $\mathcal{E}\{X_0^H \ X_0\} = I_{N_p\mathbf{x}N_p}$ and assuming that the channel matrix $H \ V$ is estimated at the receiver we get:

$$F_{SDM} = HV[HV(HV)^H + \sigma_0^2 I_{N_r\mathbf{x}N_r}]^{-1} \quad (7)$$

The MMSE receiver just considers a bank of separate filters to estimate the data streams as it's shown in fig. 2. The number of transmitted data streams must be chosen to be no more than the number of received antennas e.g. 1 ≤ $N_P \leq N_r$. If f_{SDM}^l is the lth row of the matrix F_{SDM}, the $SINR(l)$ of the transmitted stream l is given by

$$SINR(l) = \frac{\left|(f_{SDM}^l)^H H_l V_{l1}\right|^2}{\sum_{k \neq l} \left|(f_{SDM}^l H_k V_{k1}\right|^2 + \left\|f_{SDM}^l\right\|^2 \sigma_0^2}$$

If there are more available DAs than the dimension of the receiver antenna array, then there should be a procedure to eliminate some DA's in order to match exactly the number of transmitted streams with the number of receiver antenna elements. Based on the SINR calculation, an optimal solution with reduced set of DAs can be found by exhaustive searching. **1)** We start with an initial set that contains all candidate N_p DAs. **2)** The second step considers all the possible ordered subsets with number of subset elements (cardinality) equal to M. This number of ordered M subsets is $\frac{N_p!}{(N_p-M)!}$ **3)** Then the $SINR(1)$ is calculated for all subsets **4)** The M subsets with the higher $SINR(1)$ are chosen. The first element of these subsets corresponds to the selected DA. Although the MMSE receiver applies optimal linear filtering and the streams don't have a highly correlated channel matrix, inter-stream interference may be present. The following SIC algorithm is proposed: **1)** The SINR is calculated for all streams. The stream with the largest SINR is selected as the target stream. To simplify the notation, we assume that streams are in decreasing SINR order from 1 to N_p. **2)** The interference that originates from the stream 1 is subtracted from the initial received signal Y.

$$Y_{step2} = Y_{step1} - H_1 V_1 \hat{X}_0^1 \quad (8)$$

A new estimated $\hat{X}_0$ is obtained by recomputing F_{SDM}^2 inserting zero on channel matrix H_1 , $H = [0 \mid H_2 \mid \cdots \mid H_p]$. We then calculate the new SINR(2) **3)** Step 2 is repeated for $l = 3, 4, \cdots N_p$ until all streams are detected. The SIC algorithm requires the repeated operation of the MMSE algorithm and therefore introduces a relatively high computational effort which increases the complexity.

V. SIMULATION RESULTS

A network deployment is considered with a 800 m x 800 m square cell where nine DAs are dispersed in symmetrical positions as in fig. 2. The main system parameters according to IEEE 802.16e specifications are given in table I. The C2 metropolitan area for urban macro-cell from WINNER II channel model is used [9]. The applied scenario C2 supposes that the DAs are placed above rooftops and the mobiles move outdoors on a street level. We provide simulations in MATLAB environment to show the advantage of the proposed structure in terms of downlink user throughput. At each established link between the user and the DA, the received SINR is calculated. Table II demonstrates which type of modulation and coding rate is used in relation to the received SINR [1]. The user is allowed to be arbitrarily located on the square cell. For each configuration, the physical (PHY) data rate is computed by Monte-Carlo simulations where 100 realizations of channel matrix H are generated using the WINNER II channel model. Finally, a conventional cell with an Antenna Array at the center of cell (CDA) is used for comparison. A first application is proposed for a road vehicular communication system (scenario I). We restrict the layout of fig. 2 to a two-DA (Arrays 1 and 3) configuration in which a user moves on the line that connects DA1 and DA3. The number of receiver antenna elements is assumed to be equal to two. Fig 4 presents the average PHY data rate as a function of the distance between the user and DA1. The results show that the cell with two DAs obviously outperforms that with a single antenna array at the center of the cell (CDA case). In the middle of the line, the minimum average data rate that is achieved is equal to 19 Mbits/s for CDA compared to 31 Mbits/s for the receiver with a bank of two separate MMSE filters and 36 Mbits/s for the receiver using the SIC scheme. In scenario II, four DAs are assumed to be located on the corners of the top right square cell (positions 1,2,3,4) and one Antenna Array is assumed to be again located on point 1 (on the center of the original square cell). The average PHY data rate of a user with two antennas at random positions is given in fig. 5. The cell architecture with the 4 DAs (employing MMSE and SIC) achieve a noticeable improvement over the CDA case employing one Antenna Array. The SIC strategy provides user throughputs from 15 Mbits/s to 62 Mbits/s while the CDA achieves throughputs between 3 Mbits/s and 31 Mbit/s. Finally, we studied scenario III with four receiver antennas and nine DAs distributed over the corners of the simulation grid. The results in fig. 6 show that the maximum throughput of the SIC method may yield a 200% improvement compared to the scenario II. Also, the minimum throughput improvement may be 350%. Fig. 7 compares the full diversity scheme (employing 4 antenna element DAs) to the selection diversity scheme with 2 DAs and one Antenna Array (DA). The scenario III with the SIC strategy at the receiver is used. We conclude that the full diversity scheme outperforms those schemes that are based on exploiting a selected set of streams.

TABLE I. SYSTEM PARAMETERS

Parameter	Value	Parameter	Value
Frequency Band (GHz)	5.25	OFDM Symbol Duration (µs)	102.86
Number DA elements	4	Number of Data Subcarriers	800
Number mobile array antenna elements	4	DA Transmit Power (mW)	250
Mobile Velocity (Km/h)	110	Channel Profile	WINNER II C2 Metropol
Channel Bandwidth (MHz)	10	Mobile Distribution	Uniform, random positioning
Frame Duration (ms)	5	Traffic Model	Full Buffer

TABLE II. TYPE OF MODULATION AND CODING RATE ACCORDING TO SNR

Modulation	Coding	SNR (dB)
BPSK	1/2	3
QPSK	1/2	6
QPSK	3/4	8.5
16 QAM	1/2	11.5
16 QAM	3/4	15
64 QAM	2/3	19
64 QAM	3/4	21

VI. CONCLUSIONS

A new cell architecture with nine DAs compliant with the IEEE 802.16e standard is presented. RoF technology could offer the advantage of distributing Antenna Arrays within a cell and exploit the spatial diversity with a reduced implementation cost. We propose a novel cell layout by exploiting the spatial selectivity of the channel and the interference minimization offered by the beamforming transmission aiming to enhance the spectral efficiency. We compared various DA layouts versus a conventional cell architecture with a BS at the center of cell and showed the benefits of DAs in terms of average PHY data rate for high speed users.

REFERENCES

[1] IEEE standard for Local metropolitan area networks "part 16: Air interface for Fixed and Mobile Broadband Wireless Access Systems; Amendment 2: Physical and Medium Access Control Layers for combined Fixed and Mobile Operation in Licensed Bands and Corrigendum", 28 February 2006.

[2] K. Zangi and L. Krasny, "Impact of Transmit Antenna Array Geometry on Downlink Data Rates in MIMO systems" in Proc. European Wireless 2007, Paris France, April 2007.

[3] J. G. Andrews, Wan Choi and R. W Heath, "Overcoming Interference in Spatial Multiplexing MIMO Cellular Networks", IEEE Wireless Communications, December 2007.

[4] Wonil Roh Paulraj, A. , "MIMO channel capacity for the Distributed Antenna Systems", VTC 2002 fall, Vancouver Canada.

[5] I. Harjula, A. Ramirez, F. Martinez, D. Zorrilla, M. Katz and V. Polo, "Practical Issues in the Combining of MIMO Techniques and RoF in OFDM/A Systems," Proc. EHAC'08 (2008).

[6] Shidong Zhou Ming Zhao Xibin Xu Jing Wang Yan Yao "Distributed wireless communication system: a new architecture for future public wireless access", Communications Magazine, IEEE,Mar 2003

[7] Jafar, S.A. Goldsmith, A. "Transmitter Optimization and Optimality of Beamforming for Multiple Antenna Systems", Wireless Communications, IEEE Transactions on, July 2004

[8] Simon Haukin, "Adaptive filter theory", third edition

[9] IST-4-027756 WINNER II Deliverable 6.13.14 "Winner II system concept Description" v.1.1, 172 pages, January 2008.

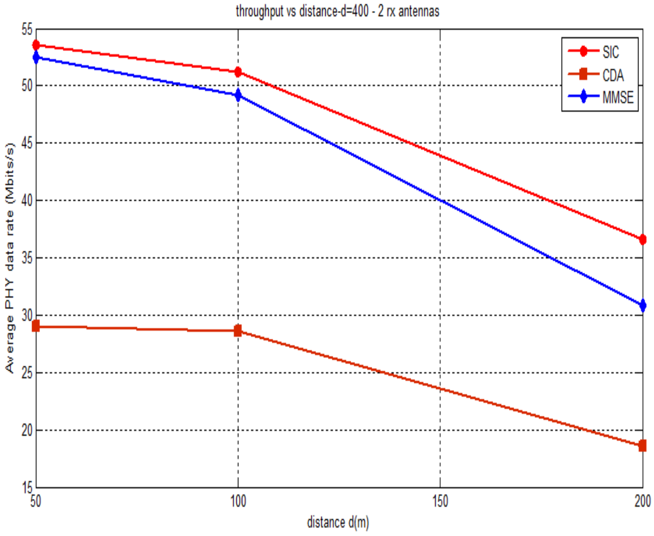

Figure 4. Average PHY data rate versus distance (scenario I)

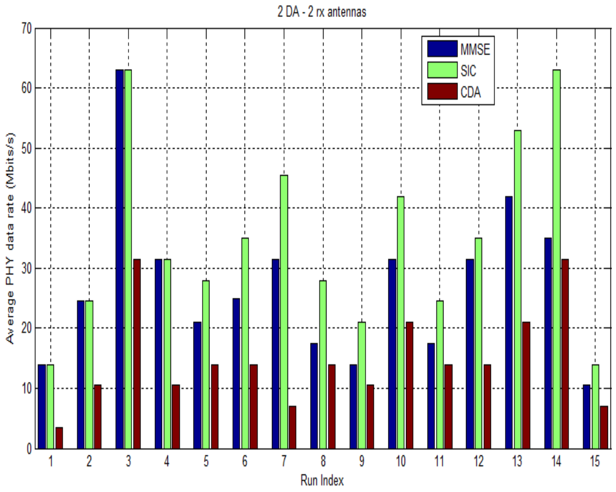

Figure 5. Average PHY data rate for different positions of user (scenario II)

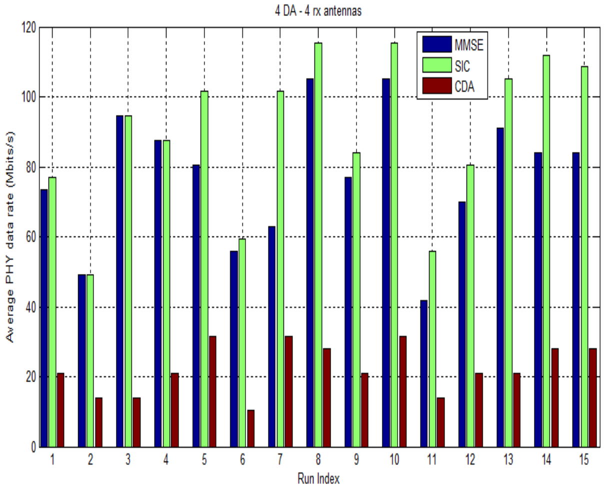

Figure 6. Average PHY data rate for different positions of user (scenario III)

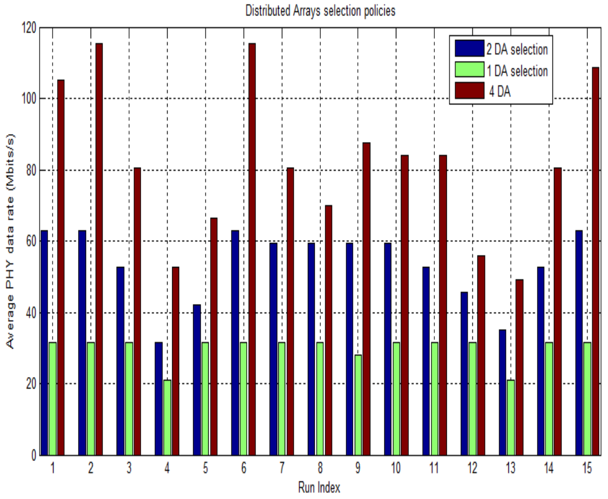

Figure 7. Full and selective diversity scheme at scenario III