Data-Driven Based Optimal Placement and Performance Evaluation of FD-MIMO for Enhanced 4G Mobile Networks Under Realistic Environment

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Abstract. To accommodate the increasing mobile user data rate demand, various capacity enhancing technologies have been developed and incorporated in enhanced fourth generation (4G) and fifth generation technology standards. For mobile operators, to achieve user satisfaction and then a successful business, planning and using the advanced antenna techniques in a cost effective manner is important. To that end, the planning work needs to accurately consider spatiotemporal distribution of user demand, propagation characteristics of the planning area and existing network capability and configuration. Although benefits of advanced antenna techniques are researched well, approaches to exploit their benefits in a cost-effective way considering realistic network environment is rarely reported. In this article, we present a practical multi-objective based FD MIMO antenna placement for enhanced 4G mobile network. We use Matlab to implement the proposed method and performance comparisons are performed considering 1800 MHz and C-band. Performance results show that the proposed method that can be applied for gradual deployment can be achieved considering the trade-off between users satisfaction and cost while maximizing aggregate throughput. It is observed that, implementing 3D vertical sectors in all sites with different operating band provides up to 319.93% aggregate system capacity gain compared to the existing macro only horizontal sectorized antenna configuration.

Keywords: 4G · 5G · Vertical beams · Multi-objective · FD MIMO · Antenna planning

1 Introduction

Global mobile data traffic has been increasing and is predicted to increase significantly in the coming years due to rise in penetration of various traffic-intensive applications [1, 2]. For instance, International Telecommunication Union predicts mobile traffic will grow up at an annual rate of around 55% in 2020–2030 and global mobile traffic per month is projected to reach to 607 EB in 2025 and 5016 EB in 2030, see Fig. 1 [2].

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The monthly average consumed traffic per user is also estimated to be 39.4 GB and 257 GB in 2025 and 2030, respectively [2]. Similar to the global trend, mobile traffic is also significantly increasing in emerging market like Ethiopia (especially in cities) mainly due to the increasing penetration of social media services [3, 4].

To successfully accommodate this increasing traffic and guarantee mobile users satisfaction, mobile network operators need to improve their network capacity in a cost effective manner. For that, various capacity enhancing mobile technologies have been developed and incorporated in enhanced fourth generation (4G) and fifth generation (5G) technology standards. Technologies that desnsify base stations, expand operating bandwidth up to 400 MHz and apply advanced antenna techniques with up to tens of antennas are among the most important ones [5–9].

Benefits and challenges of different use cases of 3D beamforming capability of advanced antenna system are investigated and presented in literature, e.g. [10, 13]. Densifying cells not only in the vertical domain but also in the horizontal domain considering spatial distribution of demand is one of the most practical use cases of 3D beamforming to considerably improve network performance, [12]. Traditionally, such approach is called vertical sectorization where macro cells are divided into two or more vertical beams (sectors) with different down tilt and beam width but same frequency resource [14, 15]. Unlike small cell densification, macro cell densification using vertical sectorization does not require additional sites and associated network elements which simplify deployment and reduce network cost.

Authors in [14–20] investigate the capacity impact of macro cell densification using active antenna system (AAS) under synthetic environments. In [21–25], performance of tilt, beam width and transmit power optimization methods for the vertical beams is analyzed. Field trial experiments have also undertaken to understand and characterize actual performance cell densification [26, 27]. These performance investigation, optimization and field trial works show that significant network capacity improvement can be achieved by macro cell densification. However, cell splitting can also limit cell coverage and the data rate of cell edge users due to additional co-channel interference unless different carrier configuration is applied among neighboring cells [21]. Although capacity benefits of macro cell densification using advanced antenna technique are researched well, planning approaches to exploit their benefits in a cost-effective manner considering realistic network environment and C-band is rarely reported. For small cell densification, planning framework and analysis considering realistic network environment including Addis Ababa and different network performance and cost objectives are presented in [29–34].

Inspired by aforementioned small cell planning framework, in this work we present a data-driven antenna planning approach for cost-effective gradual deployment of multiple vertical cells on top of existing macro cells. The planning approach is demonstrated using a practical case study for selected urban area in Addis Ababa. We implement the approach for the case study using Matlab and performance analysis is performed considering 3D buildings and existing network data for the selected area. Network data is collected from network management system (NMS) of Addis Ababa. We make the analysis considering currently used 1800 MHz band and C-band which is the most popular band for 5G deployment. Performance results show that gradual deployment of vertical beams with different antenna configuration is cost-effective. For example, for all macro cells (54 cells) 1800/1800 MHz configuration, a relative gain of about 33.1%, 39.6% and 86.3 at 10%-ile, 50%-ile and 90%-ile are obtained, whereas for 28 macro cells 1800/3600 MHz configuration, a relative gain of about 58.6%, 98.2% and 151.7% at 10%-ile, 50%-ile and 90%-ile are obtained. While being cost-effective, up to 319.93% aggregate network capacity improvement can be achieved compared to existing LTE network.

The rest of the paper is organized as follows. Section 2 discusses and illustrates a multi-objective problem formulations and optimization algorithm for macro cell densification. Section 3 describes the planning study area, spatial user demand distribution and applied simulation assumptions. Section 4 presents performance results and discussion. Finally, Sect. 5 provides concluding remarks and potential future works.

2 System Model and Deployment Scenarios

2.1 Multi-objective Problem Formulation

In this article, to study the data driven antenna planning approach, a downlink LTE network is considered. A 3x1cellular network having K number of macro sites will have 3K numbers of total macro LTE cells. Let, the notation C refer to a macro LTE cell and a cell with conventional cell index i is denoted by c_m^i, where, m indicates, if a cell is replaced with two vertical sectors (inner and outer beams) and i = 1, 2..., 3K. For the conventional cell layout, the value of m will be zero, but if a cell is replaced, m takes a non-zero value of m = 1 and m = 2 to specify the outer and the inner beams respectively [35]. When, cell splitting is applied on M number of macro LTE cells, total numbers of macro cells and vertically divided sectors becomes 3K + M. If M = 0, there are only macro LTE cells and if M = K, all cells are replaced with inner and outer beams.

For macro LTE cell having a coverage area of (*A*) and *L* number of user nodes, *SINR* performance of a user located at *u* is given by [35],

$$\mathrm{SINR} = \frac{p(U,\ c_0^z)}{\sum_{i \neq z} p(U,\ c_o^i) + N} \tag{1}$$

Where, $p(u, c_0^z)$ is the received power of a user from serving cell (c_0^z) at a location of *u*. When a macro LTE cell is replaced with vertical sectors, *SINR* performance of a user located at *u* is given by

$$\mathrm{SINR} = \begin{cases} \dfrac{p(U,\ c_1^z)}{\sum_{i \neq z} \left(\sum_{m=1}^{2} p(U, c_m^i)\right) + N} & \text{when user is associated with outer beam} \\ \dfrac{p(U,\ c_2^z)}{\sum_{i \neq z} \left(\sum_{m=1}^{2} p(U, c_m^i)\right) + N} & \text{when user is associated with inner beam} \end{cases} \tag{2}$$

Where, $p\left(u, c_1^z\right)$and $p\left(u, c_2^z\right)$ are received signal powers of the users from outer and inner sectors respectively and, throughput *(TP)* performance of the user located at *u* from macro LTE cell using Shannon formula is given by [36].

$$\mathrm{TP} = BW_{eff}N_{PRB}B_{PRB}log_2(1 + \frac{SINR}{SINR_{eff}}) \tag{3}$$

When cell is replaced with inner and outer beams, a user located at *u* connects to either inner or outer beam depending on the the received signal strength and consequently will have a different *SINR* performance. As a result, the *TP* performance after cell spliting is given by [35],

$$\mathrm{TP}' = BW_{eff}N_{PRB}B_{PRB}log_2(1 + \frac{SINR'}{SINR_{eff}}) \tag{4}$$

Where, BW_{eff} is bandwidth efficiency, N_{PRB} is number of Phsical Resource Block (PRBs), B_{PRB} is the bandwidth per PRB, and $SINR_{eff}$ is *SINR* efficiency.

$$\Gamma = \frac{\mathrm{TP}' - \mathrm{TP}}{\mathrm{TP}} \tag{5}$$

When *M* numbers of macro LTE cells replaced by inner and outer beams, L_1 number of users are served by *3K-M* macro LTE cells and L_2 numbers of users are served by *2M* numbers of replaced beams. Hence aggregate throughput ($T\mathrm{P}'_{agg}$) of the network is given by

$$\mathrm{TP}'_{agg} = \sum\nolimits_{n=1}^{L1} TP(u_n) + \sum\nolimits_{n=1}^{L2} \mathrm{TP}'(u_n) \tag{6}$$

Where, $\sum_{n=1}^{L_1} TP(u_n)$ is an aggregate user throughput served by macro cells and $\sum_{n=1}^{L_2} TP'(u_n)$ is an aggregate user throughput served by replaced beams. For every *M* number of macro cells selections, there will be *P* number of options given by

$$\mathrm{P} = \frac{3k!}{3k - M!\ * M!} \tag{7}$$

Equation 7 leads to the following question: from those *P* options how optimal sets are identified fulfilling cell edge and average user throughput constraints given by

$$\mathrm{TP}'_{\mathrm{ce}} = \mathrm{T}([0.05\,N_{ut}]) \text{ and } \mathrm{TP}'_{\mathrm{au}} = \mathrm{T}([0.5\ N_{ut}]) \tag{8}$$

Where, *T* is a vector containing user throughputs sorted in ascending order. This is a kind of multi-objective problem having multiple objectives: Minimizing number of splitting cells (f_1) and maximizing aggregate throughput (f_2) which can be formulated as:

$$\mathrm{Min}_{\mathrm{x}}\ f(\mathrm{x}) = [\mathrm{f}_1(\mathrm{x}),\ -\mathrm{f}_2(\mathrm{x})] \tag{9}$$

Where, x shows whether a macro LTE cell is replaced or not. To solve a problem in (9), evolutionary algorithms are effective meta-heuristics as the mathematical structure of the objective functions does not feature convexity or continuity [29]. According to [37] non dominated sorting genetic algorithm II (NSII GA) has less complexity, fast convergence, good scalability and empirically very near optimal compared with other compared algorithms. As a result the popular multi-objective evolutionary algorithm called NSII GA is selected.

2.2 Application of NSII GA on Antenna Planning

Non dominated sorting genetic algorithm II (NSII GA) accepts initial populations, fitness function and stopping condition as an input and gives an individual's that can give best fitness values as an output. To come up with the final results the algorithm performs a number of iteration. While the algorithm performs iterations, it uses reproduction option to bring new generations. Those reproduction options are elite count, cross over and mutation. For our case, the initial populations are denoted by X and given by

$$\mathrm{X} = \begin{bmatrix} x_{1,1} & x_{2,1} & \cdots x_{i,1} & \cdots & x_{3k,1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{1,1} & x_{2,2} & \cdots x_{i,z} & \cdots & x_{3k,z} \\ & & \vdots & & \\ & & \vdots & & \\ & & \vdots & & \\ & & \vdots & & \\ x_{1,z} & x_{2,z} & x_{i,z} & \cdots & x_{3k,z} \end{bmatrix} \tag{10}$$

Where, z = 1,2,……Z., number of population and $x_{i,z}$ are macro LTE cell status whether cell splitting is applied or not at each cell having a cell index *i* and denoted byc^i.

$x_{i,z}$ = 1, If a macro LTE cell is replaced by inner and outer beams.
$x_{i,z}$ = 0, If a cell is not replaced.

Thus, X consists of Z number of randomly selected populations with different combination of 0 and 1 which indicates status of *3k* macro LTE cells. The fitness function is given by Eq. (6).

2.3 FD-MIMO Antenna Model

In general the antenna pattern is determined by element pattern and array factor. Let antenna elements are uniformly spaced in the horizontal direction with a spacing of d_H and in the vertical direction with spacing of d_v as shown in Fig. 1 [12].

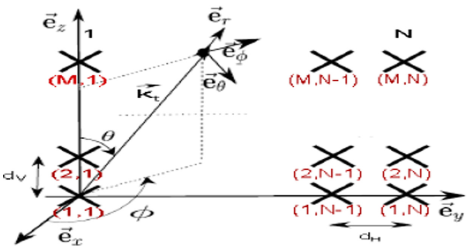

Fig. 1. 2D antenna array system [12].

By defining $u_y = \sin\theta \sin\phi$ and $u_z = \cos\theta$, the beam pattern can be expressed as [10–12].

$$G(u_y, u_z) = \cdots \sum\nolimits_{m=1}^{M} \sum\nolimits_{n=1}^{N} A_E(\theta, \ \phi) w^{*}_{m,n} e^{\frac{j2\pi}{\lambda}(m d_H u_y + n d_V u_z)} \tag{11}$$

A_E (θ, ϕ) + AF (θ, ϕ) (dB).

Where, ϕ and θ are the azimuth and elevation angles respectively. A_E (ϕ, θ) is the 3D element pattern that can be obtained from resulted azimuth and elevation pattern. According to [11, 12], the azimuth and elevation radiation pattern for a single element are formulated as:

$$A\ (\phi) = -\min\ [12,\ \frac{\phi}{\phi_{3dB}},\ A_m], \qquad A_m = 25\ \text{dB} \tag{12}$$

$$A\ (\theta) = -\min\ [12,\ \frac{\phi}{\phi_{3dB}},\ SLA_v], \qquad SLA_v = 20\ \ \text{dB} \tag{13}$$

Then 3D element pattern can be formulated as follows:

$$A_E(\phi,\ \theta) = -\min\ \{\ -[A(\phi) + A(\theta)],\ A_m\} \tag{14}$$

3 Simulation Environments

To study the performance impact of gradual densification of macro cells with vertical sectors with C-band, a realistic network environment in Addis Ababa, Ethiopia with dense hotspots is selected. The studied area is about 5.47 Km^2 and consists of 18 macro sites with real-location of the existing Addis Ababa LTE network. The location of macro sites are shown in Fig. 2 below.

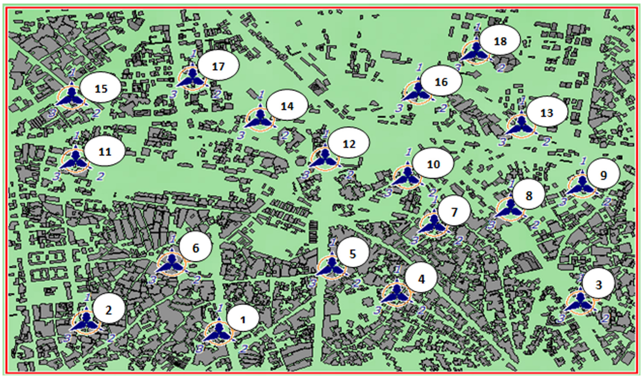

Fig. 2. Performance studied area

3.1 User Distribution

User's locations or demand nodes are one of the important parameters that can have an impact on performance of mobile network. Thus, in cellular network performance analysis, a careful selection of user distributions model is important to be more realistic. In this work, we use a reference [38] to locate demand nodes which uses telecom operator's data as an input parameter.

According to the procedures set in the reference, numbers of demand nodes are found as follows. First the studied area is divided into 8 rows and 11 columns based on pixel wise collected data from Ethio-telecom. The area of each pixels are considered as the same and denoted by a. Then, for each pixel, the corresponding traffic density ($g_{\,(\mathrm{m},\ \mathrm{n})}$) per $K\mathrm{m}^2$ is obtained. Finally, number of demand nodes is obtained by [35].

$$N(\mathrm{m},\ \mathrm{n}) = \cdots \frac{a\,x\,g(m,n)}{r} \tag{15}$$

Where, r is the individual data rate requirements in Kbps which is assumed equal for all individual pixels (less than the minimum traffic density). The subscripts n and m represents longitude and latitude of the studied area respectively. Once the number of demand node obtained according to Eq. (13), users are distributed randomly in their respective pixel.

3.2 Studied Scenarios and Simulation Parameters

Performance of the proposed mulit-objective based planning method is studied using simulation parameters and technology usage option of different inner and outer band configurations stated under Tables 1 and 2 below.

Table 1. Simulation parameters

Parameters	Values/Assumptions
Transmit power	46 dBm
UE-height	1.5 m
UE-number	1337
Noise frigure	9 dB
Band width efficiency	0.5
SINR efficiency	0.85
Fast fading	8 dB
Shadow fading	Rayleigh fading
Cell association	RSRP
Scheduling	Round robin
Resolution	5 m

Table 2. Studied scenarios.

Scenarios	Inner and outer band configuration	Band width (Inner/outer beams)
Case 1	1800/1800 MHz	20/20 MHz
Case 2	3600/3600 MHz	20/20 MHz
Case 3	1800/3600 MHz	20/(20/60) MHz

4 Results and Discussions

This section presents performance impact of gradual densification of macro LTE cells with 3D vertical sectors, for antenna configurations listed in Table 2. For comparisons purpose, aggregate capacity of all macro only (MO) and replaced 3D vertical sectors are used. To come up with the results, the following Matlab based system level simulations are performed. First path loss of each user is obtained using Proman. Next, users are associated with their serving cell based on received signal power level. Then, resource blocks are scheduled using frequency domain round robin. Finally, SINR and throughput performance are calculated using Eqs. (1), (2), (3) and (4). This process is repeated a number of times and the statics are collected. Throughput performance is used as a fitness value to find the Pareto frontier while optimization is performed.

Figure 3 and 4 are plotted to compare UE SINR of the existing MO configuration and studied scenarios indicated in Table 4. Simulation result shows that, configuring VS with different operating bands significantly improve UE SINR at all percentile. For example, UE SINR values of MO, 1800/1800 MHz and 1800/3600 MHz, at 10%-ile are: –3.44 dB, –5.04 dB and –2.76 dB, at 50%-ile: 1.46dB, 0.51dB and 3.24 dB and at 90%-ile: 10.12 dB, 8.96 dB and 11.99 dB respectively (see Figs. 5 and 6).

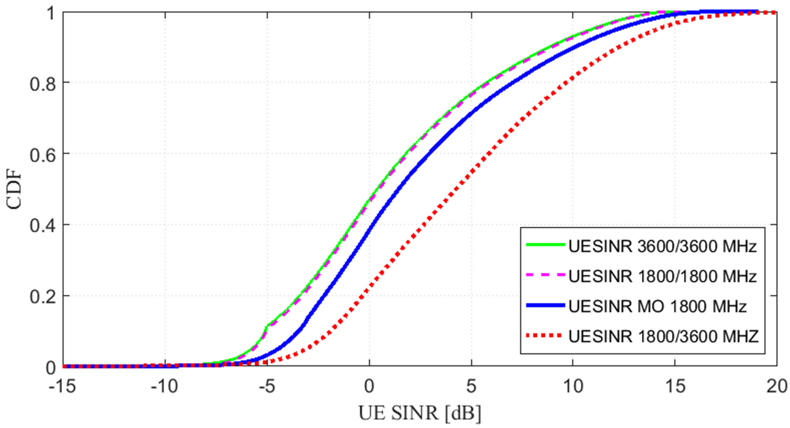

Fig. 3. CDF of UE-SINR for different inner and outer band configurations

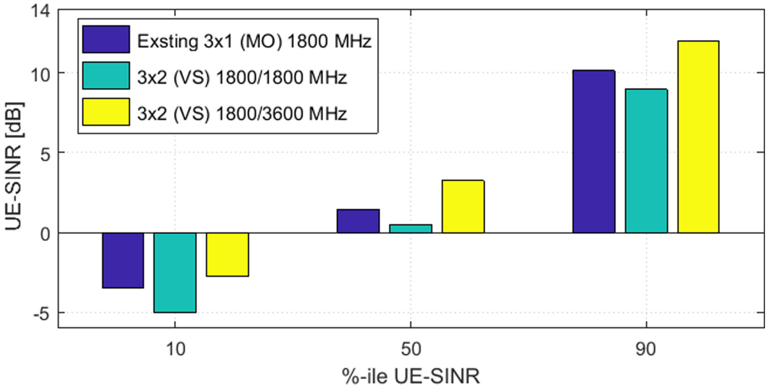

Fig. 4. UE-SINR at 10%-ile, 50%-ile and 90%-ile

The aggregate capacities of the studied scenarios are compared with the existing 3x1 LTE mobile network as shown in Table 3. Result shows that, aggregate capacity of MO, 1800/1800 MHz 1800/3600(20/20) MHz, and 1800/3600(20/100) MHz are 1.6224 Gbps, 2.4058 Gbps, 3.9595 Gbps and 6.813 respectively. Based on these values, the corresponding relative aggregate capacity gains of the studied configurations are 48.3, 144.1 and 319.93 respectively (see Table 3).

Table 3. Aggregate capacity and gain

Configurations	Aggrigate capacity(Gbps)	Gain w.r.t macro configuration (%)
Macro only	1.6224	Reference
1800/1800 MHz	2.4058	48.3
1800/3600 (20/20 MHz)	3.9595	144.1
1800/3600 (20/60 MHz)	6.1830	319.93

Pareto frontiers of 1800/1800 MHz and 1800/3600 MHz with their corresponding aggregate capacity are shown in Fig. 5. Aggregate capacity of MO network, all VS 1800/1800 MHz and all VS 1800/3600 MHz are used as an asymptotic value. This figure also shows how aggregate capacity of pareto frontier behaves while the number of vertical beams is increasing. In general, as numbers of vertical beams increased, aggregate capacity also increased. However as the number progress, the studied scenarios tend to close their respective asymptotic value differently (see Fig. 5).

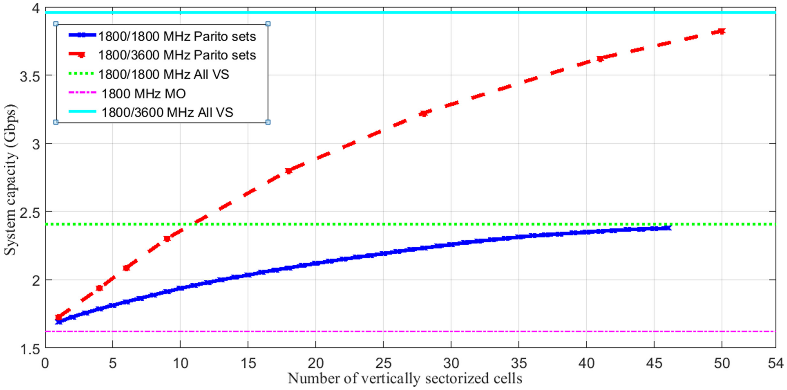

Fig. 5. Aggregate capacity and Pareto points of studied scenarios

UE throughput gain of commonly 28 pareto location of 1800 MHz/1800 MHz and 1800/3600 MHz are compared at different percentiles as depicted in Fig. 6. Both cases provide significant user throughput gain compared to the existing MO configuration. For example, for the case of 1800/1800 MHz, a relative gain of about 33.1%, 39.6% and 86.3 at 10%-ile, 50%-ile and 90%-ile respectively, whereas for the case of 1800/3600 a gain of 58.6%, 98.2% and 151.7% at 10%-ile, 50%-ile and 90%-ile are obtained compared with the existing macro only configuration.

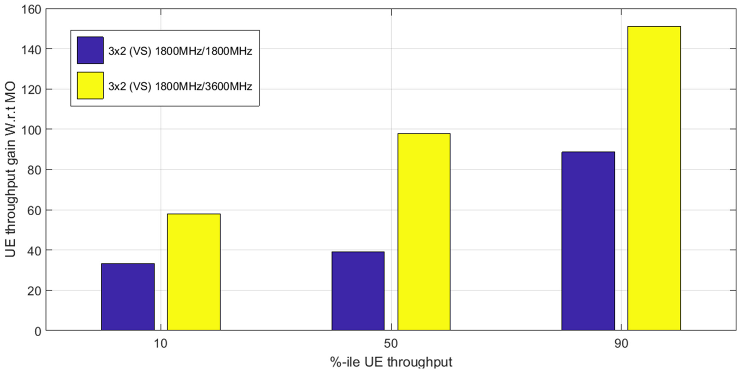

Fig. 6. CDF of UE-SINR for different inner and outer band configurations

5 Conclusion

In this paper, a data driven antenna planning approach for a stepwise deployment of vertical sectors under realistic network environment for selected area of Addis Ababa LTE mobile network have been analyzed. The analysis is accompanied with literatures survey, mutiobjective problem formulation and demand node location using the real data from Ethio-telecom network management system. Simulations are performed to find Pareto frontier that can maximize system capacity and analyze the performance impact of applying vertical sectors on the top of the existing macro LTE network. The result provides different parito frontier that can maximize system capacity. While number of pareto sets increase, system capacity also increase. It is also observed that, 3D vertical sectors with different operating bands significantly improve system performance. For example, for the case of 1800/1800 MHz, a relative gain of about 33.1%, 39.6% and 86.3 at 10%-ile, 50%-ile and 90%-ile respectively whereas, for the case of 1800/3600 a gain of 58.6%, 98.2% and 151.7% at 10%-ile, 50%-ile and 90%-ile are obtained. This is because, co-channel interference between inner and outer beams does not occur in the case of different band configuration, unlike the same operating band configuration. Performance impact of static 3D beams in high rise building and dynamic user centric 3D beams in 5G mobile network from planning and optimization perspective are an important future work.

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