In Preparation Towards Future Cellular Networks: The Detailed Analysis of Macro and Micro Site Densification and Sector Densification

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***Abstract*— The next generation of cellular networks is expected to provide huge capacity, and site densification is one of the possible solution to increase the network capacity. The target of this paper is to show the impact of macro/micro site densification and higher order sectorization on signal strength, signal quality and throughput in LTE network. It also highlights the impact of site and sector densification on the cell overlapping and cell border areas. A detailed techno-economical analysis along with area power consumption and area spectral efficiency is also provided in this paper. In site densification, the Intersite Distance (ISD) between the Base Station (BS) sites is decreased, which results in strong Inter Cell Interference (ICI). The results presented in this paper show that the spectral efficiency of the cell decreases with the site densification. However, the average area spectral efficiency increases due to a larger number of cells in the densified network. At the same time the number of cell border users overlapped by multiple servers also increases with the site and sector densification. It is shown that in one square kilometer, increasing the number of cells from 14 (3-sector site with 500 m ISD) to 693 (6-sector site with 100 m ISD) relatively improves the area spectral efficiency by 24.5 times at the cost of 49.5 times more number of cells. Almost identical power efficiency is provided with 3-, and 6-sector site. However, a higher order sectored site was found to be more cost efficient.**

Keywords—Macro cell; densification; cell edge; overlapping areas; ISD; LTE; 5G

I. INTRODUCTION

It is expected that in less than a decade the Fifth Generation (5G) of mobile networks will take over the communications market [1–2]. As with the case of previous generations of mobile networks, the next generation is also expected to be evolved in a number of ways. One of the main targets for the future network is the massive growth in network capacity i.e. up to 1000 times the capacity of the current networks [2–3]. It is expected to have huge user throughput requirement due to new and evolved services e.g. ultra-high quality video streams, high definition videos, cloud computing etc. A gigantic increase in the number of devices coming along with the concept of the internet of things (IoT) [3–5] will also add its share. These requirements and expectation bring many challenges to the developers, researchers and to the operators.

The basic umbrella coverage for mobile networks is generally provided with macro cells. Macrocellular networks provide good coverage and are still able to meet certain capacity demand. However, an increase in capacity demand is witnessed around the globe, therefore novel solutions are needed to meet these new capacity demands. Site densification not only improves the coverage rather it also enhances the capacity of the network. In a densified network, the scarce spectrum resources are being reused more often in a same geographical area than before by having more Base Station (BS) sites in a same area. At times, the micro cells are added in the network with lower antenna height and base station power. However, as the BS sites are placed closer to each other, the problem of cell border area gets even more severe, i.e. the interference coming from the nearby cells is increased due to more number of neighboring cells, and it may degrade the performance of the users at the cell edge.

The topic of network densification and its effects on the capacity and energy-efficiency has been studied widely in the academic world. In [6] the authors have studied the densification of homogeneous and heterogeneous deployments. They have presented the effects of different Intersite Distances (ISDs) with only macro or micro cells and with the combination of these. A similar kind of study has been performed in [7] for the homogeneous network deployment of micro and pico type BSs. The authors in [8] have made an extensive study on this topic while taking into account the energy and cost efficiency in a dense urban environment. Although the network densification is a way to enhance the area spectrum efficiency, more network equipment also means more costs. For Long Term Evolution (LTE) deployment, the total energy consumption analysis of different network densification alternatives has also been studied in [9]. In [10], the authors are even stating that the network densification is the dominant theme when migrating from 4G networks to 5G. It is only logical if one is interested in increasing the network capacity by utilizing the current spectrum allocation only.

In general, the densification of a cellular network also refers to adding micro/femto cells or in general the small cells in between the macro cells. However, in this paper for study purpose only homogeneous macro and homogeneous micro networks are considered. The aim of this paper is to highlight the effects of macro/micro site densification and higher order sectorization on RSRP, SINR, throughput, dominance area, spectral efficiency, power efficiency, and cost efficiency. A comprehensive study is carried out to analyze these effects in a LTE network, and a static simulator implemented in MATLAB was used for this purpose. The results obtain from these LTE network densification simulations can then be used to evaluate the similar effects in other future cellular networks as well.

II. THEORY

A. LTE system

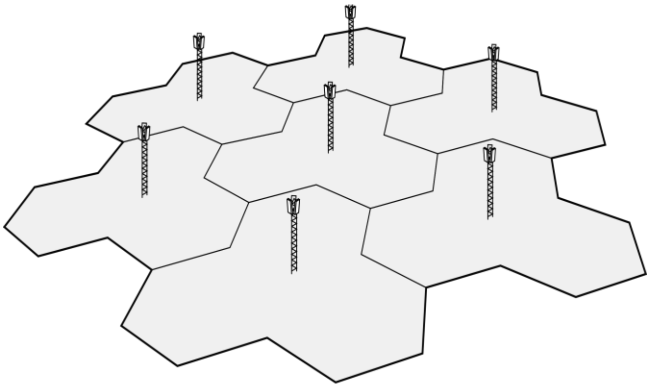
LTE system was designed to bring major improvements to the previous Third Generation (3G) Universal Mobile Telecommunications System (UMTS) cellular networks. These include among others, higher and more flexible throughputs in downlink and uplink directions and lower end-to-end system latency, mostly because of simpler flat architecture working purely on internet protocol (IP), which minimizes the number of network elements [11].

LTE system uses Orthogonal Frequency Division Multiple Access (OFDMA) as the downlink access scheme and Single Carrier Frequency Division Multiple Access (SC-FDMA) as the uplink access scheme [12]. In both directions, it is possible to assign a varying number of Resource Blocks (RBs) to different users, thus enabling a very flexible allocation of spectrum resources. One RB contains 12 subcarriers, each with 15 kHz bandwidth, i.e. in total 180 kHz, and lasts 0.5 ms in the time domain. Furthermore, the allocation of these resource blocks occurs every 1 ms, thus the Transmission Time Interval (TTI) takes two RB in the time domain. One of the most important techniques in maximizing the spectral efficiency is to use higher order modulation and coding scheme techniques to every narrow subcarrier adaptively.

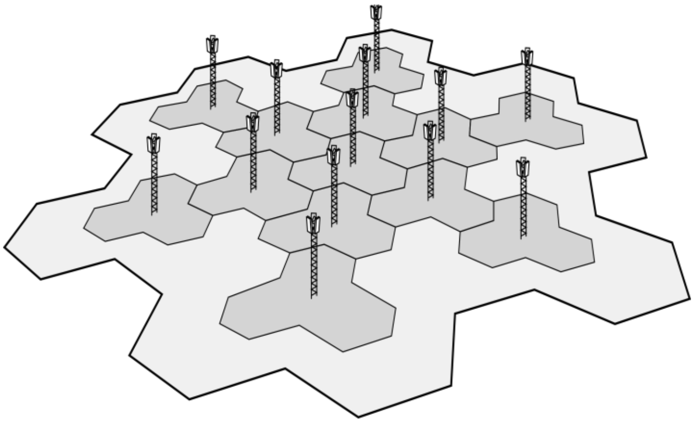
In order to evaluate the useful average signal strength of LTE user, a parameter called Reference Signal Received Power (RSRP) is used. RSRP is similar to Received Signal Code Power (RSCP) used in UMTS networks. The parameter of RSRP is generally used, e.g., to determine the range of a LTE cell.

B. Site densification

Every passing day the mobile network capacity requirements are increasing. There are number of ways by which the network capacity can be enhanced. However, the most intuitive solution to increase the system capacity is to reuse the existing spectrum resources i.e. adding more cells, which means more BSs when using conventional 3-sector site. By increasing the number of BS sites in the same geographical area, the network becomes densified. In other words by reducing the ISD, i.e. bringing the BS sites close to each other results in a densified network, as can be seen from Fig. 1 (a) and Fig. 1 (b).



(a)



(b)

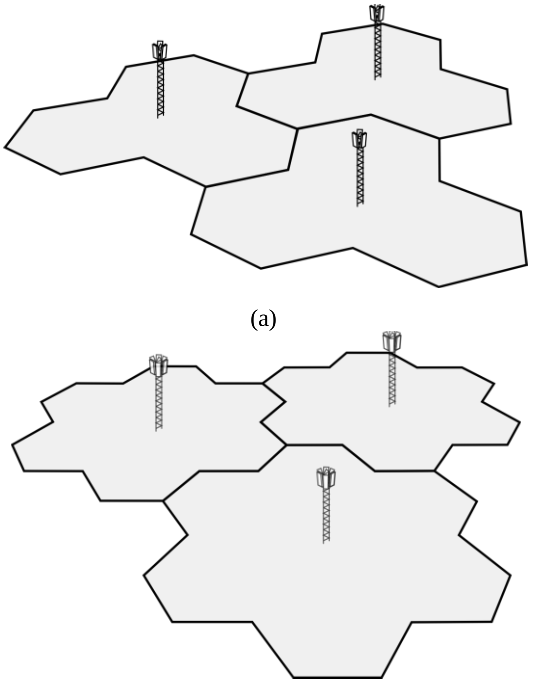
Fig. 1.(a) Macrocellular network topology, (b) Densified macrocellular network topology.

Unnecessary inter cell interference from the neighboring sites can be reduced e.g., by lowering the effective antenna height of the BS site antennas, by electrically or mechanically tilting the antennas more towards the ground, by adopting antennas with narrow beams, by adopting optimized network layout, or by reducing the transmission power.

Nowadays, the cellular market is highly competitive and the cellular service providers are extra conscious about the cost per hertz. Although the site densification is an easy method to increase the network capacity, but it is an expensive solution in terms of expenditure, and is not always feasible for operators due to non-availability of site location. In general, the cost of deploying a cellular network can be divided roughly into two categories: Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). In general the CAPEX forms up a large portion of the Total Cost of Ownership (TCO) for the early years of the BS site deployment. Intuitively, every new added BS site increases the TCO thus yielding to a situation where the addition of new BS sites is not considered as a preferred solution. Another concern related to the site densification is the acquisition of place for new sites, as it is not necessarily always available. Especially in the cities where the property owners are often not interested in renting out their places for the mobile operators, or the local laws and regulations do not allow the operators to place the new sites at certain locations.

C. Higher order sectorization

Another method of increasing the system capacity is to have additional cells (sectors) at the existing BS site, instead of having new BS sites. This means that e.g. the conventional 3-sector site with three 65° to 70° Half power Beamwidth (HPBW) antennas is replaced by a high capacity 6-sector site with six 35° HPBW antennas [14]. Traditional 3-sector site with cloverleaf layout and 6-sector site with snowflake tessellation is shown in Fig. 2 (a) and Fig. 2 (b), respectively. Snowflake tessellation is an optimized network layout for 6-sector sites, presented in [13]. The adoption of narrower beam antennas with relatively higher gain compared with traditional 65° beamwidth antenna helps in providing better coverage, and in minimizing the interference to the neighbor cells [13][15].


(a)

(b)

Fig. 2. (a) 3-sector site network layout, (b) 6-sector site network layout.

The impact of higher order sectorization on macro cells is studied extensively in [13] and indicates that the higher order sectorization can increase the available capacity. However, in [13] it is also stated that higher order sectorization suits better for large ISDs, and higher order sectorization gain gets low for dense networks.

D. Cell border and overlapping areas

In the cellular network, the most problematic areas from both the radio network planning and the user's experience point of view are the cell border areas. Cell borders are normally overlapped with multiple servers as can be seen from Fig. 3. In an overlapping area the interference coming from the other cells is usually causing degradation in the signal quality. This degradation of signal quality results in lower user data rates at the cell edges. In urban environments and in the densified networks these cell border areas or more precisely the overlapping cell areas are more crucial, since the interfering neighbor cells are quite closer to each other.

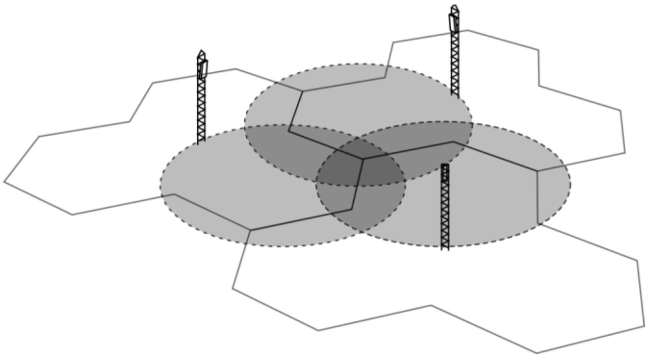


Fig. 3. Cell edge and overlapping area example.

LTE system was designed for a frequency reuse factor of one to maximize the spectrum efficiency from the link level point of view [12]. Thus, the neighboring cells are using the same frequency resources and there are no means to avoid the inter cell interference from the radio network planning point of view, unless some spectrum wasting techniques like hard frequency reuse, fractional frequency reuse, or soft frequency reuse are adopted [12]. Hence, some other means and techniques are needed in order to suppress inter cell interference.

There are different ways to handle the interference coming from the neighboring cells to a certain limit. One of these is called the Inter Cell Interference Coordination (ICIC) as defined by the 3GPP in Release 8 [16]. The idea of ICIC is to control the allocation of LTE RBs to the users especially near the cell border areas in such a way that the neighboring cells would avoid direct interference. However, it results in the waste of some of the spectral efficiency, if a certain amount of RBs cannot be allocated at one instant and that ICIC can only be adopted in the frequency domain to traffic channels. Also, this requires more complex coordination between the evolved NodeBs (eNodeBs). The Enhanced ICIC (eICIC) extended the ICIC to work in the time domain in LTE Advanced (LTE-A) in 3GPP Release 10 and added control channels in the ICIC scheme [17]. The downsides of these features are the increased complexity and stricter synchronization requirement between the neighboring cells. A stochastic geometry analysis studied in [18] also suggests that the gain achieved with the ICIC methods is critically dependent on the spatial dependences between the transmitters and the interferers.

Another method presented by the 3GPP for LTE-A to help the border cell users is the coordinated multipoint (CoMP) as defined by [19]. It has slightly different approach than the ICIC as it can be considered as working like the soft handover used in WCDMA systems as presented in [20]. In CoMP the signals from two or more neighboring cells are processed together, requiring even more complexity from the eNodeBs. Also the user equipment (UE) needs more complex receivers.

E. SINR and spectral efficiency

In this article, the signal quality metric used for the analysis is the Signal to Interference plus Noise Ratio (SINR). The SINR denoted with $\mathit{\Gamma}$, can also be used to define the maximum achievable capacity C in bits/s of a given channel bandwidth W, with the famous Shannon's capacity formula as defined in [21]

$$C = W\langle \log_2 \langle 1 + \mathit{\Gamma} \rangle \rangle, \tag{1}$$

where $\langle \cdot \rangle$ denotes averaging. Thus, the SINR values can be used directly to calculate the available bit rates.

The overall spectral efficiency of a cellular network can be studied with the help of the spectral efficiency parameter η. Spectral efficiency can be obtained from Eq. (1) by dividing the capacity with the used bandwidth W. Spectral efficiency (η) is expressed in bits per second over hertz [bps/Hz]. The spectral efficiency is the indicator of utilization of spectrum. It shows that how well the spectrum is utilized in transmitting the data. In this article the average area spectral efficiency is denoted by η_{Area} and is defined as given in Eq. (2) [22].

$$\eta_{\text{Area}} = \eta_{\text{Cell}} * \text{N}_{\text{Cell}} \tag{2}$$

In Eq. (2), the area spectral efficiency η_{Area} is expressed in [bps/Hz/km^2], η_{Cell} is the average cell efficiency expressed in [bps/Hz], and N_{Cell} is the number of cells covering that area. We found area spectral efficiency as a sophisticated and fair way to study the effects of network densification and higher order sectorization in the macro cellular network, and to compare the performance of site densification with sector densification. When the network is densified either by site densification or higher order sectorization, it is expected that the area spectral efficiency will increase since the spectrum is utilized more frequently in the considered area. However, it will be interesting to see the relative area spectral efficiency gain coming from site and sector densification, and the impact on cell border areas as additional sectors will also increase the interference in the system.

F. *Power efficiency*

Power efficiency is one of the Key Parameter Indicators (KPI) for mobile operators to track the power consumption of their cellular network. This translates directly to lower costs as higher energy efficiency reduces the required power to achieve the target service level. The unit for energy efficiency is [bps/Hz/kW] and is defined as:

$$P_{eff} = \frac{\eta_{\text{Area}}}{P_{\text{km}^2}}, \tag{3}$$

where the area power consumption, P_{km^2} [kW/km^2] is given as [23]:

$$P_{\text{km}^2} = \frac{P_{\text{BS}}}{A_{\text{site}}}, \tag{4}$$

In equation (4), P_{BS} is the power consumption of the BS site [kW] and A_{site} is the area covered by one site [km^2]. In order to compute correct area power consumption, a power consumption model is presented at [23], and it needs to be modelled accurately [23]:

$$P_{\text{BS}} = P_{\text{const}} + P_{\text{load}} * F, \tag{5}$$

where P_{const} is the load-independent power consumption factor, P_{load} is the load-dependent power consumption factor and F is the load factor. It is assumed that the BS sites operate at full load, thus $F = 1$. The load-independent variable P_{const} includes the following power consuming sources: a rectifier, a fiber optic link (for backhaul connection) and an air conditioning unit. However, it is assumed that the air conditioning unit can be left out since new pole-mounted BS sites are already available in the markets. The load-dependent variable P_{load} includes the following power consuming components: a Power Amplifier (PA), transceiver and Digital Signal Processing unit (DSP). It is assumed that the efficiency of the PA is 45 % in this analysis to match the values utilized in [23]. Parameters related to power consumption model are listed in Table 1. Considering the transmission power of macro and micro base station reported in [23] and [24], the transmit power for micro and macro BS in this paper is set to 37 dBm and 43 dBm, respectively.

Table 1. Power consumption model parameters. [23]

Parameter	Unit	Value
Transmit power at antenna	dBm	37/43
Power consumption of DSP unit	W	100
Power Amplifier efficiency	%	45
Power consumption of tranceiver	W	100
Power consumption of rectifier	W	100
Power consumption of fiber optic unit	W	7.5
Load factor (F)	%	100

G. *Cost efficiency*

In order to evaluate the feasibility of implementing any technology, it is important to analyze the cost structure before investments. CAPEX and OPEX provide the total costs the network requires for implementation and maintenance, but in order to normalize the costs between different technologies, a more general metric is required for the cost analysis. Thus, the metric chosen for this study is the total cost per spectral efficiency c_{eff} [bps/Hz/k€] defined as [23]:

$$c_{\text{eff}} = \frac{\eta_{\text{Area}}}{T_{\text{cost/km}^2}}, \tag{6}$$

where $T_{\text{cost/km}^2}$ is the total cost per km^2, which is achieved by normalizing the total cost of BS sites over one square kilometer. The Table 2 and Table 3 shows the approximated CAPEX and OPEX cost for micro and macro base stations, respectively. In [23], omni micro cells were assumed, therefore the cost parameters for micro cell BS were modified with respect to 3-, and 6-sector site. Similarly, cost items for 6-sector macro BS were adjusted. The cost related parameters shown in Table 2 and Table 3 are later used in this paper for calculating the cost efficiency of different deployment configurations.

Table 2. CAPEX costs. [23]

CAPEX	Macro cell BS	Micro cell BS
BS equipment 3-sector site	10 k€	7.5 k€
BS equipment 6-sector site	20 k€	15 k€
Site deployment cost 3-sector	5 k€	1.5 k€
Site deployment cost 6-sector	7 k€	2.5 k€
Total CAPEX 3-sector	**15 k€**	**9 k€**
Total CAPEX 6-sector	**27 k€**	**17.5 k€**

Table 3. OPEX costs. [23]

OPEX	Macro cell BS	Micro cell BS
Site rent (lease)	5 k€/year	3 k€/year
Leased line rent (backhaul)	2.25 k€/year	2 k€/year
O&M for 3-sector site	5 k€/year	4.5 k€/year
O&M for 6-sector site	7 k€/year	6 k€/year
Total OPEX 3-sector	**12.25 k€/year**	**9.5 k€/year**
Total OPEX 6-sector	**14.25 k€/year**	**11 k€/year**

III. SIMULATION ENVIRONMENT, CASES AND SIMULATION PARAMETERS

A. *Simulation Environment, Cases and Parameters*

The impact of site densification (different intersite distance) with different antenna configurations on the coverage and quality of the network is simulated using a static MATLAB simulator. For the system level analysis, a network with a green field plan which consists of 19 sites is configured, using a regular network tessellation. The sectoring schemes used in the simulations are 3-sector and 6-sector sites. Cloverleaf layout and snowflake tessellation is adopted for the cases of 3-sector and 6-sector sites, as shown in Fig. 4 (a) and Fig. 4 (b), respectively.

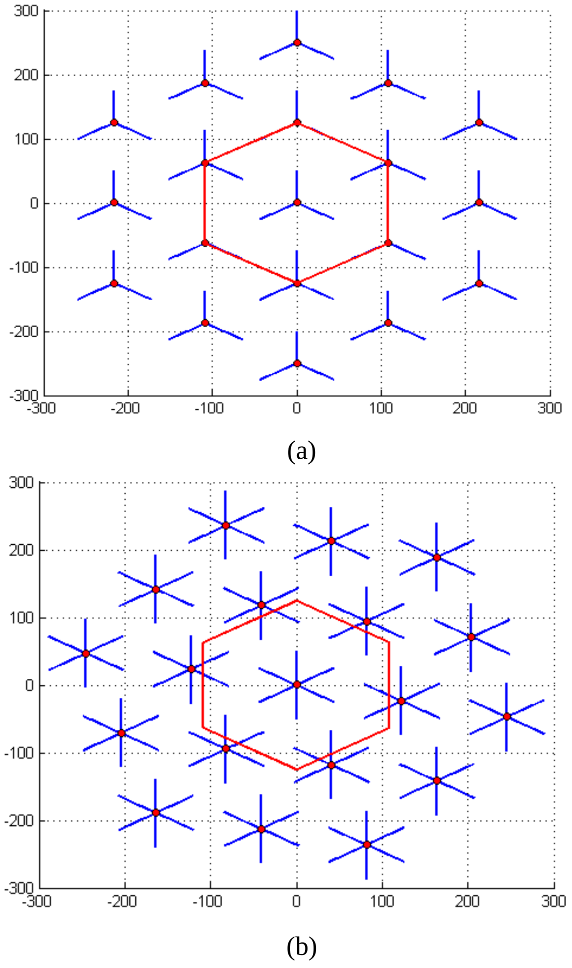


Fig. 4. (a) 3-sector clover layout with 125 m ISD, (b) 6-sector snowflake layout with 125 m ISD.

For all the considered cases, the antennas of different sectors are assumed to be co-located at the same site location. Moreover, there is an equal separation in an azimuth plane between the antennas of the different sectors of the same site. For the case of 3-sector sites, the horizontal Half Power Beamwidth (HPBW) of the antenna is 65°, and the vertical HPBW is 7°, and has an antenna gain of 15.39 dBi. Whereas, for the case of 6-sector sites, the horizontal HPBW of the antenna is 32° and the vertical HPBW is 7°, and the antenna gain is 18.20 dBi.

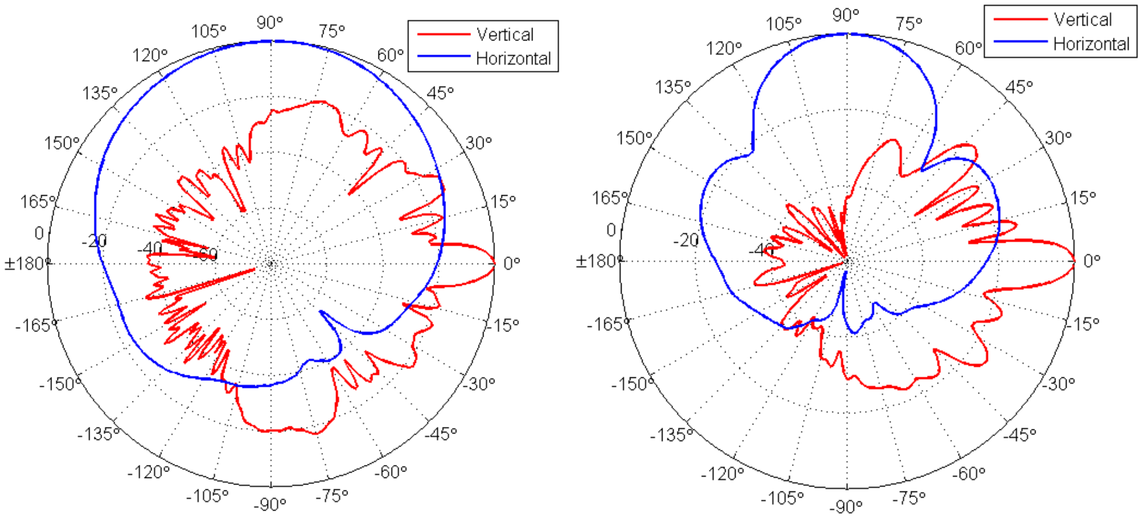
Simulations are done with flat terrain and no building data. In this paper the focus is an urban environment, therefore a COST231-Hata Model for an urban environment was used for making the coverage prediction, and for calculating the received signal strength. For the analysis purpose, the data is extracted only from the hexagon shaped "Focus Zone", which is highlighted as a red polygon in Fig. 4 (a) and Fig. 4 (b). The size of the focus zone is proportional to the intersite distance, i.e. the size of the focus zone increases with the same ratio as the intersite distance increases. Other general parameters used for the simulation purpose are shown in Table 4**.**

Table 4. General simulation parameters.

Parameter	Unit	Value
Frequency band	MHz	2600
LTE bandwidth	MHz	20
UE noise figure	dB	8
eNB power	dBm	37/43
TX height	m	10/20
RX height	m	1.5
LTE orthogonality		1
Slow fading margin	dB	8
Antenna downtilt	degree	2
Own/Other cell loading	%	100

A fully loaded network i.e. 100% own cell and other cell loading is used to model the worst case scenario. A LTE network with perfect orthogonality between the subcarriers, and a flat power spectral density was assumed i.e. equal distribution of power over all subcarriers. To cope with the impact of shadowing a slow fading margin is given, and it is 8 dB for outdoor environment. System bandwidth is 20 MHz, which is the maximum allowed bandwidth for LTE (without carrier aggregation). The RX points were homogeneously spread over the area under consideration i.e. focus zone. At each RX point, the cell with the strongest received signal strength becomes the serving cell, and all other received signals coming from other cells in the network act as interferer. The signal to interference plus noise ratio is then computed with the help of above given information. Later, the received SINR is mapped to throughput using Eq. (1) and assuming only one user per TTI, thus occupying all resource blocks. The post processing of simulation data was done to yield the results for overlapping zone and other performance metrics in refined form.

In this paper simulations are done with five different ISDs i.e. 100 m, 125 m, 250 m, 375 m and 500 m. For small intersite distance of 100 m and 125 m, lower antenna height of 10 m is used with 37 dBm of maximum transmission power, and it represents a "Microcellular" case. Whereas to have better signal propagation at large intersite distances, the antenna height is set at 20 m with 43 dBm of maximum transmission power and it represents a "Macrocellular" case. Antenna radiation patterns in horizontal plane and vertical plane used for 3-sector and 6-sector sites are shown in Fig. 5 (a) and Fig. 5 (b), respectively**.**



(a) (b)

Fig. 5. (a) 65° HPBW antenna pattern for 3-sector site, (b) 32° HPBW antenna pattern for 6-sector site.

IV. SIMULATION RESULTS AND ANALYSIS

First we are presenting the results obtained from 3-sector sites. Fig .6 shows the CDF plot of RSRP for cases of 3-sector sites with different ISDs. The best RSRP samples are found with the lowest ISD of 100 m. The RSRP samples start to deteriorate by increasing the intersite distance and the lowest RSRP samples are acquired with 500 m ISD. It shows that when sites are located close to each other then high RSRP can be achieved, and when the sites are located far apart from each other, then even by increasing the antenna height and transmission power the RSRP results are inferior compared with small ISDs (small cells). Still, in most cases the required SINR is the bottleneck in the practical networks, not the required RSRP. Therefore, only RSRP does not tell much about radio condition and achievable throughput.

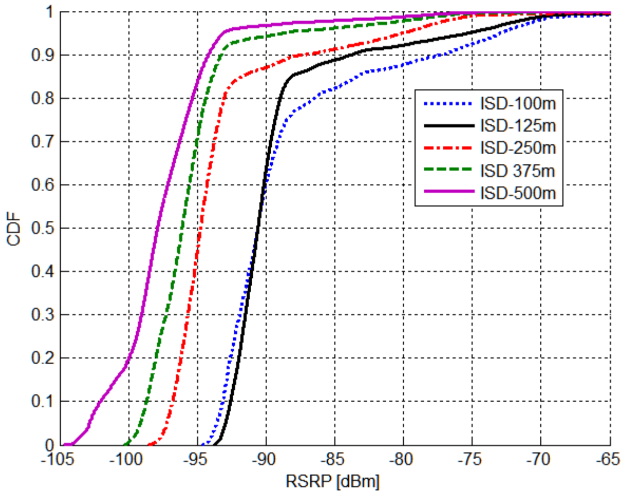


Fig .6. RSRP for 3-sector site case with different ISD

Fig. 7 shows the CDF plots of SINR for the cases of 3-sector sites with different ISDs. The results shown in Fig. 7 are opposite to the ones which are shown in Fig .6, but have direct relation to each other. The results presented in Fig. 7 show, that the achieved SINR is inversely proportional to the intersite distance. However, it is interesting to see that due to low antenna height (10 m) and low transmission power (37 dBm), better SINR is achieved with small ISD of 125 m compared with ISD of 250 m where antennas were mounted at 20 m height and had the larger transmission power of 43dBm.

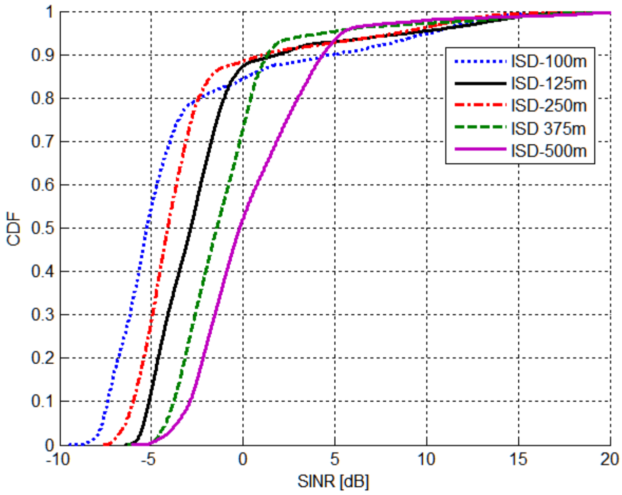


Fig. 7. SINR for 3-sector site case with different ISD.

For the cases with the same transmission power, large intersite distances give better SINR compared with small intersite distances, which means better cell throughput can be provided with large ISD compared with small ISD, and better cell efficiency can be achieved. By bringing the sites close to each other, the interference coming from the neighbor sites gets stronger and has more impact on the serving cell. On the other hand, there are more cells per km^2 with small ISD, which in turn improves the area spectral efficiency. Hence, we can say that by site densification the area spectral efficiency of the network improves, but it does not improve linearly by bringing the sites close to each other.

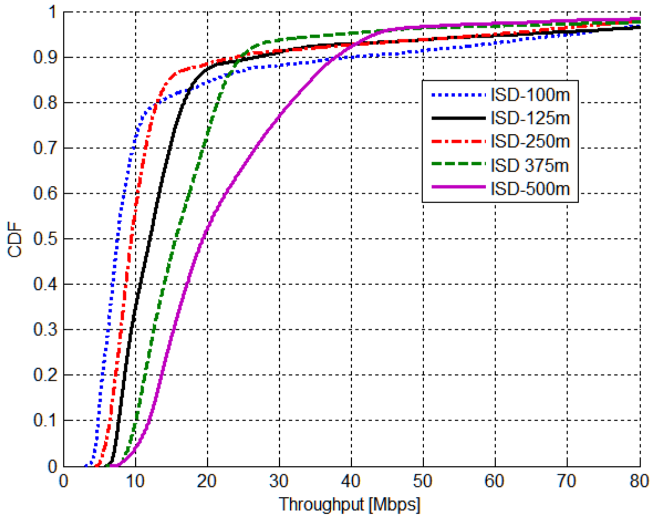


Fig. 8. Cell throughput for 3-sector site case with different ISD.

Fig. 8 shows the CDF plots of cell throughput for the different cases of 3-sector sites. The throughput values shown in Fig. 8 were obtained by using Shannon capacity formula, earlier presented in Eq. (1). As throughput is the function of SINR, and is directly proportional to the achieved signal to interference plus noise ratio, therefore the cell throughput curves shown in Fig. 8 follow the same trend as SINR curves shown in Fig. 7. It means that the high SINR values are directly translated into high throughput values, and vice versa. It is also worth mentioning here that the lowest throughput samples (cell edge) get worst with increasing density of base stations i.e. lower intersite distance, due to more interference coming from the close by interfering sites. It is also found that the high throughput samples i.e. base station nearby area (clear dominance area) are increased with the site densification, however on the other hand cell edge area also gets broader with site densification.

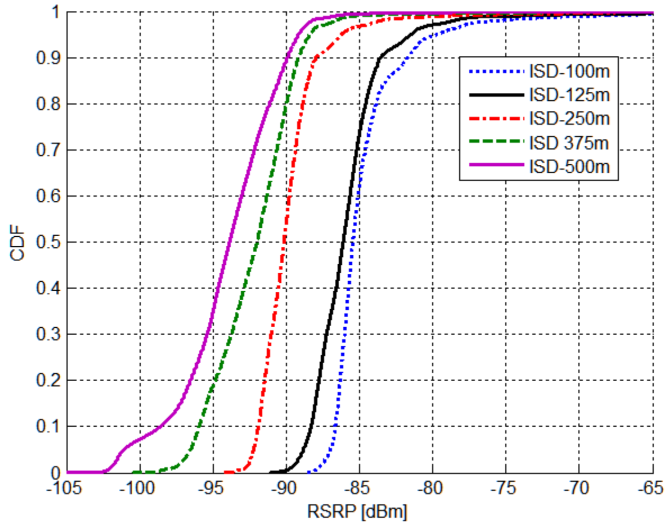


Fig. 9. RSRP for 6-sector site case with different ISD.

In Fig. 9, the RSRP results for 6-sector sites with different ISD are shown. By comparing the results presented in Fig .6 and Fig. 9, the impact of higher order sectorization can be seen. The CDF curves of RSRP for different ISD in Fig. 9 are shifted to the right compared with the ones presented in Fig .6.

It is clearly evident that irrespective of the ISD, the RSRP has improved by adding more sectors to the site. As it was mentioned earlier that from the radio network planning point of view, the SINR is of more concern for the operators than RSRP, therefore it would be more interesting to see the impact of higher order sectorization with cell densification on cell SINR.

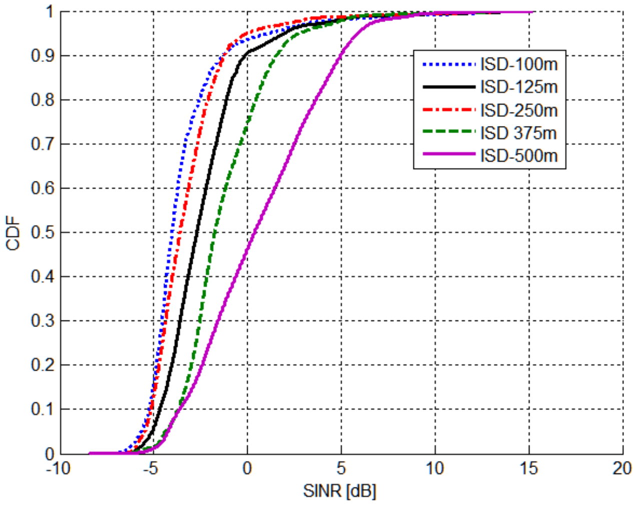


Fig. 10. SINR for 6-sector site case with different ISD.

Fig. 10 shows the CDF plots of SINR for the cases of 6-sector sites with different ISD. Similar trends are observed in Fig. 10 as were seen in Fig. 7, that the SINR declines with the decrease in intersite distance. However, again in case of 125m ISD, due to lower transmission parameters i.e. power and antenna height, the interference was avoided to the neighbor cells which results in better SINR compared with 250 m ISD. By analyzing the results shown in Fig. 7 and Fig. 10, it was found that more samples with higher SINR were obtained with 3-sector sites compared with 6-sector sites. The statistical analysis of RSRP and SINR results for three and six sector sites with different ISD is presented in Table 5.

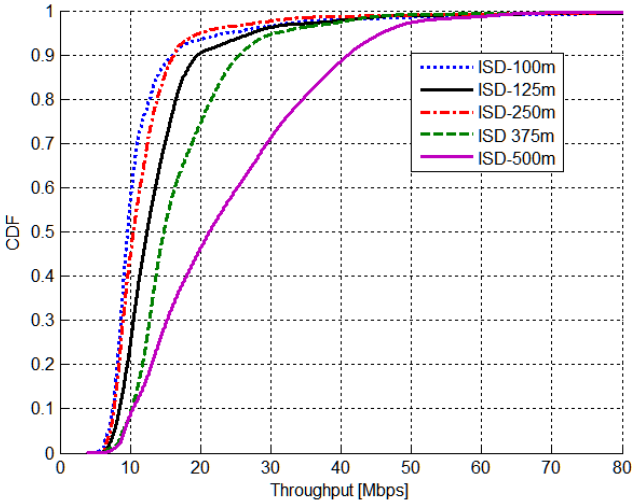


Fig. 11. Cell throughput for 6-sector site case with different ISD.

Fig. 11 shows the CDF plots of cell throughput for the different cases of 6-sector sites. As the average SINR achieved with 6-sector site has degraded compared to 3-sector site case, therefore the cell throughput bears the same affect. It was found that the cell nearby area (good SINR area) is more affected by sector densification, as the number of interfering sectors gets doubled while making a transition from 3-sector site to 6-sector site.

The statistical analysis of RSRP and SINR for different configuration is presented in Table 5, and the detailed statistical analysis of SINR and cell throughput is given in Table 6.

Table 5. Statistical analysis of RSRP and SINR for different configurations.

Case	***RSRP 10%*** (dBm)	***RSRP 90%*** (dBm)	***RSRP median*** (dBm)	***RSRP mean*** (dBm)	***SINR 10%*** (dB)	***SINR 90%*** (dB)	***SINR median*** (dB)	***SINR mean*** (dB)
3-sector ISD-100	-93.13	-77.21	-90.60	**-88.33**	-7.38	4.82	-5.24	**-3.43**
3-sector ISD-125	-92.56	-83.68	-90.58	**-89.07**	-5.12	1.95	-2.85	**-1.87**
3-sector ISD-250	-96.78	-87.07	-94.76	**-93.23**	-5.98	1.20	-4.10	**-2.94**
3-sector ISD-375	-98.68	-93.24	-96.09	**-95.42**	-3.77	1.35	-1.43	**-0.85**
3-sector ISD-500	-102.01	-94.16	-97.87	**-97.43**	-2.89	4.37	-0.17	**0.56**
6-sector ISD-100	-84.61	-85.45	-86.66	**-81.65**	-5.23	-1.26	-4.02	**-3.40**
6-sector ISD-125	-88.28	-83.51	-86.10	**-85.77**	-4.67	-0.07	-2.69	**-2.30**
6-sector ISD-250	-91.90	-87.90	-90.15	**-89.78**	-5.13	-1.23	-3.60	**-3.18**
6-sector ISD-375	-95.91	-89.14	-91.98	**-92.17**	-3.71	1.57	-1.74	**-1.23**
6-sector ISD-500	-98.53	-89.90	-93.85	**-93.97**	-3.62	5.00	0.39	**0.63**

Results presented in Table 5 reveal that the additional sectors with narrow antenna pattern at an existing site have not only improved the RSRP level, rather they have also maintained the cell SINR. It was found that mean RSRP is improved by minimum of 3.26 dB to a maximum of 6.68 dB, whereas the mean cell SINR deteriorate by maximum of almost 0.45 dB by shifting from 3-sector to 6-sector sites. However, the mean RSRP can also be improved upto 9.1 dB and 12.32 dB, and the mean cell SINR can be dropped by 3.99 dB and 4.03 dB by making the ISD smaller from 500 meters to 100 meters for three and six sector sites, respectively.

Table 6 provides better and insight understanding of relation between the cell SINR and cell throughput. Interestingly, it was found that the mean SINR is almost identical in case of 100 m ISD for 3-, and 6-sector site; however the mean cell throughput was degraded by 3.34 Mbps while making a transition from 3-sector site to 6-sector site. It is clearly due to the difference of high throughput samples i.e. 90 percentile cell throughput is 40.26 Mbps and 16.11 Mbps for 3-sector site and 6-sector site, respectively. Similarly, the decline in cell throughput due to site densification can be seen in Table 6.

Table 6. Statistical analysis of SINR and cell throughput for different configurations.

Case	***SINR 10%*** (dB)	***SINR 90%*** (dB)	***SINR median*** (dB)	***SINR mean*** (dB)	***Cell throughput 10%*** (Mbps)	***Cell throughput 90%*** (Mbps)	***Cell throughput median*** (Mbps)	***Cell throughput mean*** (Mbps)
3-sector ISD-100	-7.38	4.82	-5.24	**-3.43**	4.85	40.26	7.56	**15.28**
3-sector ISD-125	-5.12	1.95	-2.85	**-1.87**	7.74	27.20	12.07	**17.38**
3-sector ISD-250	-5.98	1.20	-4.10	**-2.94**	6.49	24.26	9.48	**14.79**
3-sector ISD-375	-3.77	1.35	-1.43	**-0.85**	10.11	24.85	15.65	**19.18**
3-sector ISD-500	-2.89	4.37	-0.17	**0.56**	11.97	38.05	19.44	**23.92**
6-sector ISD-100	-5.23	-1.26	-4.02	**-3.40**	7.57	16.11	9.63	**11.94**
6-sector ISD-125	-4.67	-0.07	-2.69	**-2.30**	8.47	19.75	12.42	**14.41**
6-sector ISD-250	-5.13	-1.23	-3.60	**-3.18**	7.72	16.20	10.46	**12.16**
6-sector ISD-375	-3.71	1.57	-1.74	**-1.23**	10.23	25.69	14.81	**17.24**
6-sector ISD-500	-3.62	5.00	0.39	**0.63**	10.41	41.14	21.31	**24.11**

Table 7. Results of overlapping zone with 3 dB and 5 dB window.

Case	***Single server 3dB*** *(%)*	***Two servers 3dB*** *(%)*	***Three servers 3dB*** *(%)*	***≥Four servers 3dB*** *(%)*	***Single server 5dB*** *(%)*	***Two servers 5dB*** *(%)*	***Three servers 5dB*** *(%)*	***Four > servers 5dB*** *(%)*
3-sector ISD-100	26.62	27.21	12.97	33.21	15.92	5.45	15.85	62.78
3-sector ISD-125	56.17	26.25	16.76	0.83	28.73	25.59	25.13	20.55
3-sector ISD-250	44.29	36.80	12.06	6.85	16.81	11.60	25.21	46.38
3-sector ISD-375	63.20	25.74	11.00	0.06	40.48	24.23	28.95	6.34
3-sector ISD-500	66.11	26.55	7.22	0.12	44.48	34.95	16.22	4.35
6-sector ISD-100	30.58	45.84	19.40	4.18	7.12	16.59	36.56	39.73
6-sector ISD-125	41.05	42.84	12.88	3.24	16.41	35.40	32.24	15.95
6-sector ISD-250	37.40	39.78	21.80	1.02	9.15	24.44	34.34	32.07
6-sector ISD-375	53.79	35.14	10.50	0.57	21.85	42.21	27.82	8.11
6-sector ISD-500	66.83	25.29	6.98	0.91	50.29	24.82	19.63	5.26

Table 7 shows cell overlapping results for different cases. Signal quality is normally a better metric of cell performance than signal strength and is of more importance from operators' point of view. The number of servers within 3 dB and 5 dB window is commonly used by operators to check the quality of radio network planning and is often used as Key Performance Indicator (KPI) by radio planners. Signal quality (SINR) is directly related to coverage overlapping. Single server (dominance) area is normally located near the site location, and cell border area is overlapped by multiple servers.

Table 7 shows the percentage of samples with single and multiple servers within 3 dB and 5 dB window for different cases. It can be seen that single server dominance area reduces by densifying the network, which means by bringing the sites close to each other the impact of interference coming from neighbor cells becomes stronger, and it widens the overlapping zone. Single cell dominance area is almost 66% at 500 m ISD for both 3- and 6-sector sites, which gradually reduces to 26.62% and 30.58% at 100 m ISD for 3- and 6-sector sites, respectively.

It is also important to note that replacing a 3-sector site with 6-sector site case did not change the percentage of dominance area at large intersite distance of 500 m, however for other small ISDs the single server dominance area is affected by the transition of 3-sector to 6-sector site. It also shows that the adoption of narrow antenna pattern for six sector sites has avoided the interference caused to the neighbor cells. Now, if we look at two server column specifically for six sector sites, we found that percentage of samples increases with the site densification, which causes reduction in achieved SINR. The Table 7 provides the basis for the SINR results presented in Table 5, and both the results support each other.

Table 8. Area throughput, area spectral efficiency and relative gains.

Case	***SINR Mean*** (dB)	***Mean Cell Eff*** (bps/Hz)	***Mean Cell Throughput*** (Mbps)	***Number of Cells per km***^{2}	***Mean Area Spectral Eff.*** (bps/Hz/km^2)	***Mean Area Throughput*** (Mbps/ km^2)	***Relative Eff. Gain*** (Times)	***Relative Thr. Gain*** (Times)	***Relative Cell density*** (Times)
3-sector ISD-100	-3.43	0.54	15.28	347	187.27	5302.02	**12.20**	**15.83**	24.79
3-sector ISD-125	-1.87	0.72	17.38	222	160.54	3858.98	**10.46**	**11.52**	15.86
3-sector ISD-250	-2.94	0.59	14.79	56	33.18	828.24	**2.16**	**2.47**	4.00
3-sector ISD-375	-0.85	0.87	19.18	25	21.63	479.45	**1.41**	**1.43**	1.79
3-sector ISD-500	0.56	1.10	23.92	14	15.35	334.87	**1.00**	**1.00**	1.00
6-sector ISD-100	-3.40	0.54	11.94	693	376.23	8273.45	**24.51**	**24.71**	49.50
6-sector ISD-125	-2.30	0.67	14.41	444	296.71	6397.37	**19.33**	**19.10**	31.71
6-sector ISD-250	-3.18	0.57	12.16	111	62.82	1350.17	**4.09**	**4.03**	7.93
6-sector ISD-375	-1.23	0.81	17.24	50	40.50	861.76	**2.64**	**2.57**	3.57
6-sector ISD-500	0.63	1.11	24.11	28	31.05	675.14	**2.02**	**2.02**	2.00

After analyzing the RSRP, SINR and throughput results shown in Table 5 and Table 6, it is interesting to find the spectral efficiency gain, relative efficiency gain and relative throughput gain achieved by minimizing the intersite distance and by adding the sectors at the existing site. Table 8 presents the spectral efficiency results at cell and area level, and shows the relative gain with respect to the reference case of 3-sector sites with 500 m ISD. As we are analyzing the gain of a dense network and the higher order sectorization, therefore a 3-sector with largest ISD of 500 m was selected as a reference case for comparing with others. Mean cell SINR is used to compute the mean cell spectral efficiency. The number of cells per square kilometer shows the number of cells required to cover one square kilometer of area. Due to the large number of cells in a dense network, the high area spectral efficiency and high area capacity (throughput) is achieved with small cells (small intersite distance). Similarly, higher order sectorization also doubles the number of cells which in turn almost doubles the area spectral efficiency which in turn almost doubles the area throughput. It is interesting to see and analyze the relative spectral efficiency gain and relative throughput gain achieved at the cost of extra cells.

Considering the 3-sector sites with 500 m ISD as a reference case, relative 12.2 times more spectral efficiency can be achieved by deploying 24.79 times extra cells. Similarly, 10.46 and 2.16 times relative extra capacity can be added to the network by adding relatively 15.86 and 4 times extra cells. These values show that the relative area efficiency gain does not increase linearly by increasing the number of cells or in other words by densifying the network. Area efficiency gain starts to saturate at smaller intersite distances. In case of higher order sectorization, a similar trend about area spectral efficiency is seen that relative gain saturates at smaller ISDs. However, the higher order sectorization seems to perform better than site densification as 3-sector site case with 250 m ISD gives 2.16 times relative gain with relatively 4 times cells, whereas 6-sector site case at 375 m ISD gives 2.64 times relative gain with relatively 3.57 times cells. Similarly, the detail about the relative throughput gain can be seen in Table 8.

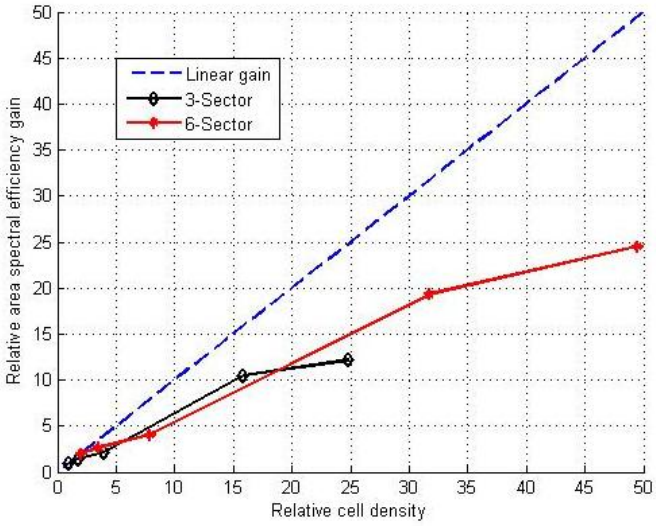


Fig. 12. Relative area spectral efficiency against relative cell density.

To have a better visualization and understanding about the site densification gain, in Fig. 12 the relative area spectral efficiency gain is plotted against relative cell density for 3-, and 6-sector sites. The blue dashed line shows linear densification gain, whereas black and blue lines show cell densification gain for 3-, and 6-sector sites respectively. It can be seen from the curves that relative area spectral efficiency gain starts to saturate for both cases, and the efficiency gain does not increase linearly with the increase in relative cell density. At the same intersite distances due to more number of cells, 6-sector sites have been able to provide fairly large relative gain compared with 3-sector sites.

Table 9. Power efficiency analysis

Case	***Number of Cells per km^2***	***Cell area*** (m^{2}x10^3)	***Load independent power per cell*** (W)	***Load dependent power per cell*** (W)	***Power consumption per cell*** (W)	***Power consumption per*** km^2 (kW)	***Mean Area Spectral Eff.*** (bps/Hz/km^2)	***Power Efficiency*** (bps/Hz/kW)
3-sector ISD-100	347	2.886	108	211	319	110.6	187.27	**1.69**
3-sector ISD-125	222	4.510	108	211	319	70.7	160.54	**2.27**
3-sector ISD-250	56	18.042	108	244	352	19.7	33.18	**1.68**
3-sector ISD-375	25	40.594	108	244	352	8.8	21.63	**2.46**
3-sector ISD-500	14	72.168	108	244	352	4.9	15.35	**3.12**
6-sector ISD-100	693	1.464	108	211	319	220.8	376.23	**1.70**
6-sector ISD-125	444	2.287	108	211	319	141.5	296.71	**2.10**
6-sector ISD-250	111	9.151	108	244	352	39.1	62.82	**1.61**
6-sector ISD-375	50	20.591	108	244	352	17.6	40.50	**2.30**
6-sector ISD-500	28	36.606	108	244	352	9.9	31.05	**3.15**

Table 9 gathers power efficiencies for 3-sector, and 6-sector sites with different ISDs. The results presented in Table 9 were obtained by assuming the power consumption model parameters presented earlier in Table 1. The cell area was assumed to have cloverleaf tessellation for 3-sector site, and snowflake geometry for 6-sector site. The main difference between micro and macro cell power consumption comes from load dependent power consumption parameters. Earlier in this paper, a high area spectral efficiency has been reported by dense and ultra dense network, and now on the other hand higher area power consumption per square kilometer is also coming from the dense networks due to increased number of cells per square kilometer. Power consumption per square kilometer gets doubled with transition from 3-sector to 6-sector site. It is interesting to found that the macro cell with large intersite distance is more power efficient compared to macro cell with small ISD or dense microcellular network. However, a micro cellular network with 125 m ISD was found to be more power efficient compared to macro cellular network with 250 m ISD. Whereas, in terms of power efficiency the higher order sector site reports almost identical results as 3-sector site.

The economical aspect of network deployment is of high importance from operators' point of view. Therefore, it is of extreme importance to carry out techno-economical analysis of network rollout or deployment. Table 10 provides the cost efficiency analysis for the different considered cases. Cost analysis was done at site level, and again the site area for 3-, and 6-sector site was computed with respect to the geometry shown in Fig. 2(a) and Fig. 2(b), respectively. For particular ISD, the number of sites considered for 3-, and 6-sector sites per square kilometer was same; therefore the site area is almost identical despite of considering different geometry for 3-, and 6-sector site. The CAPEX and OPEX costs per site were computed by assuming a cost related parameters presented in Table 2 and Table 3, respectively. Antennas are mounted at high mast in macro base station, whereas antennas in microcellular environment are either wall or pole mounted. Therefore, the micro base station has comparatively smaller CAPEX cost. It is obvious and clearly evident that the cost per km^2 increases with site and sector densification. Cost per square kilometer linearly increases with the increase in site density. However, it was shown in Table 10 that the transition from 3-sector site to 6-sector site doubles the cells (sectors) in the area but the total cost per square kilometer is increased by a factor of around 1.5. In terms of cost efficiency, similar results are obtained here as in case of power efficiency. However, the higher order sectorization was found more cost efficient solution for increasing the area spectral efficiency compared to site densification.

Table 10. Cost efficiency analysis

Case	***Number of sites per km²***	***Site area*** (m²x10³)	***CAPEX per site*** (k€)	***OPEX per site*** (k€)	***Total cost per site*** (k€)	***Cost per*** km² (k€)	***Mean Area Spectral Eff.*** (bps/Hz/km²)	***Cost Efficiency*** (bps/Hz/k€)
3-sector ISD-100	116	8.660	9	9.5	18.5	2146	187.27	**0.087**
3-sector ISD-125	74	13.531	9	9.5	18.5	1369	160.54	**0.117**
3-sector ISD-250	19	54.126	15	12.25	27.25	517.25	33.18	**0.064**
3-sector ISD-375	9	121.784	15	12.25	27.25	245.25	21.63	**0.088**
3-sector ISD-500	5	216.506	15	12.25	27.25	136.25	15.35	**0.113**
6-sector ISD-100	116	8.785	17.5	11	28.5	3306	376.23	**0.114**
6-sector ISD-125	74	13.727	17.5	11	28.5	2109	296.71	**0.141**
6-sector ISD-250	19	54.910	27	14.25	41.25	783.75	62.82	**0.080**
6-sector ISD-375	9	123.547	27	14.25	41.25	371.25	40.50	**0.109**
6-sector ISD-500	5	219.640	27	14.25	41.25	206.25	31.05	**0.151**

V. CONCLUSIONS

In this article, the impact of macro/micro site and sector densification on system capacity using LTE technology has been investigated. A comprehensive campaign of simulations was conducted, and careful post simulation analysis was carried for the research work of this paper. As expected, better signal strength (RSRP) results were achieved with the densified network. However, the signal quality metrics i.e. SINR, user throughput and spectral efficiency results cannot be neglected while evaluating the network performance. Simulation results revealed that although the cell spectral efficiency reduces with the site and sector densification, but the overall area spectral efficiency and area throughput is improved by employing these techniques. It was also found that the relative spectral efficiency gain and relative throughput efficiency gain does not increase linearly with the increase in number of sites, rather it starts to saturate and the site densification becomes less efficient at higher level.

Similarly, higher order sectorization was found to give better relative area spectral efficiency gain in large macro cells compared to the densified network. It is also interesting to found that due to the use of narrow antenna pattern at the higher order sectored site the cell SINR (cell spectral efficiency) is not damaged or deteriorated in comparison with 3-sector site. Simulation results showed that the combination of site and sector densification i.e. 6-sector sites with 100 m ISD can yield area spectral efficiency of around 376 bps/Hz/km^2, which is 24.5 times more than the reference case of the conventional macro 3-sector site with 500 m ISD. On the other hand, it requires almost 50 times the relative number of cells to achieve the area spectral efficiency of 376 bps/Hz/km^2 compared with the reference case.

It was also shown that single server dominance area shrinks, and area with multiple servers broadens with site densification. Single cell dominance area is almost 66% at 500 m ISD for both 3- and 6-sector sites, which is reduced to 26.62% and 30.58% at 100 m ISD for 3- and 6-sector sites, respectively.

The power efficiency analysis showed irrespective of the number of sectors per site, the macro cells with large ISD are more power efficient compared to dense macro/micro cellular network. 3-sector and 6-sector site shows almost identical power efficiency at different ISD. Similar trend is also observed for cost efficiency analysis of 3-, and 6-sector site and found that macro cells with large ISDs are more cost efficient then densified network. However, the higher order sectorization was found clearly more cost efficient solution for increasing the area spectral efficiency compared to site densification.

In awake of 5G network, this combination of site and sector densification can be considered as one good solution to meet the capacity demand of future networks. In this article the LTE technology was adopted for the analysis purpose so that the results can be presented in the form of parameters/indicators like RSRP, and SINR. However, the obtained results should be valid for future network operating in same frequency bands as used in this study, and have reuse factor of one. For the future work, it would be interesting to investigate the impact of site densification with two dimension sectorization (horizontal and vertical).

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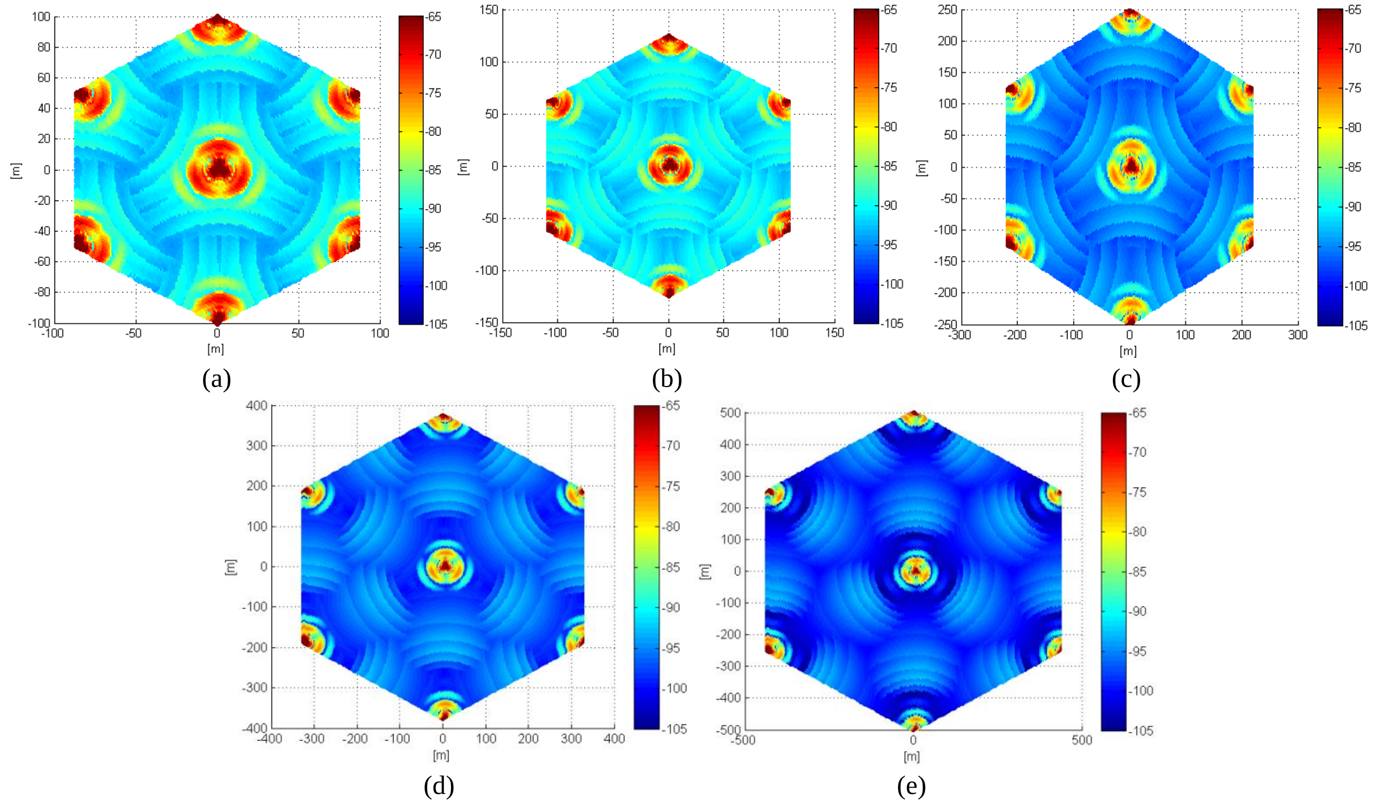
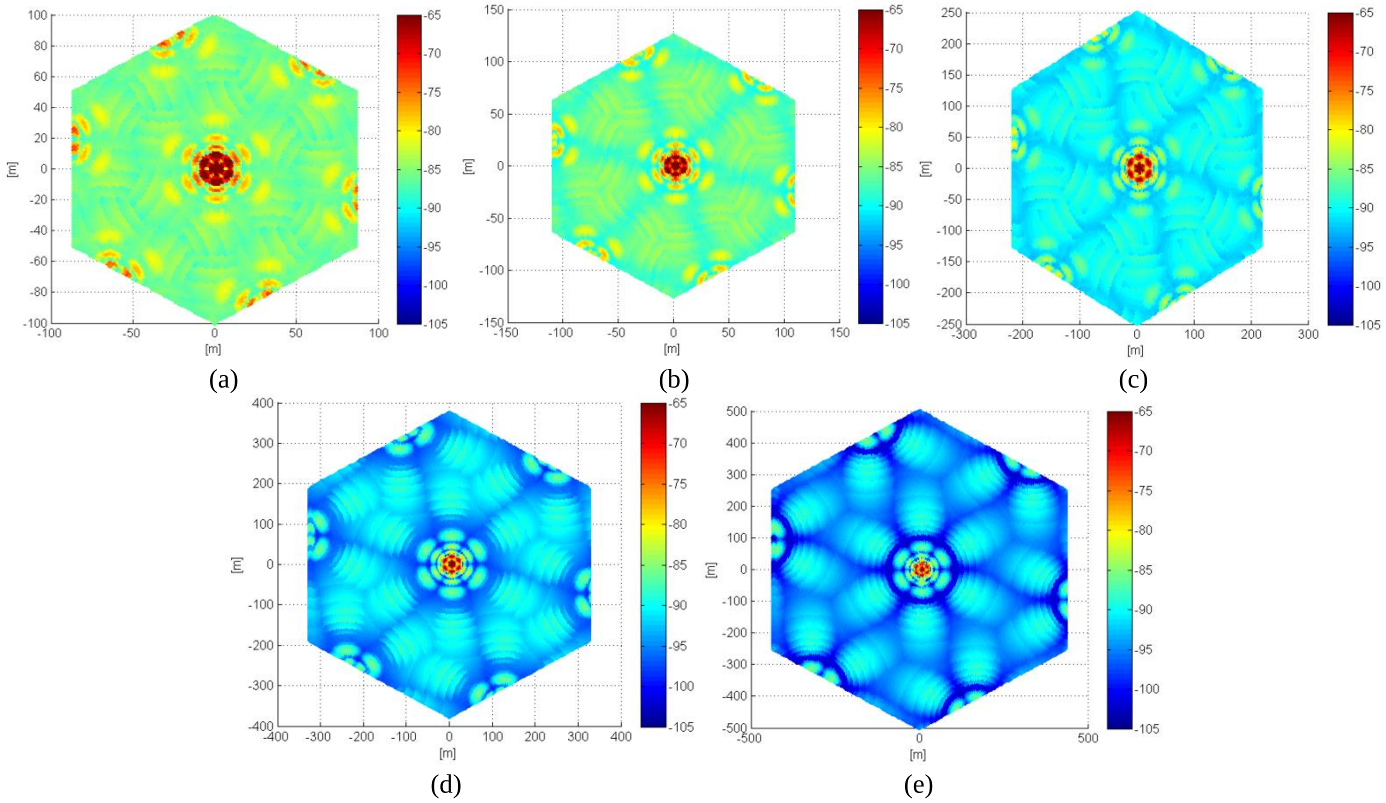


(a) (b) (c)

(d) (e)

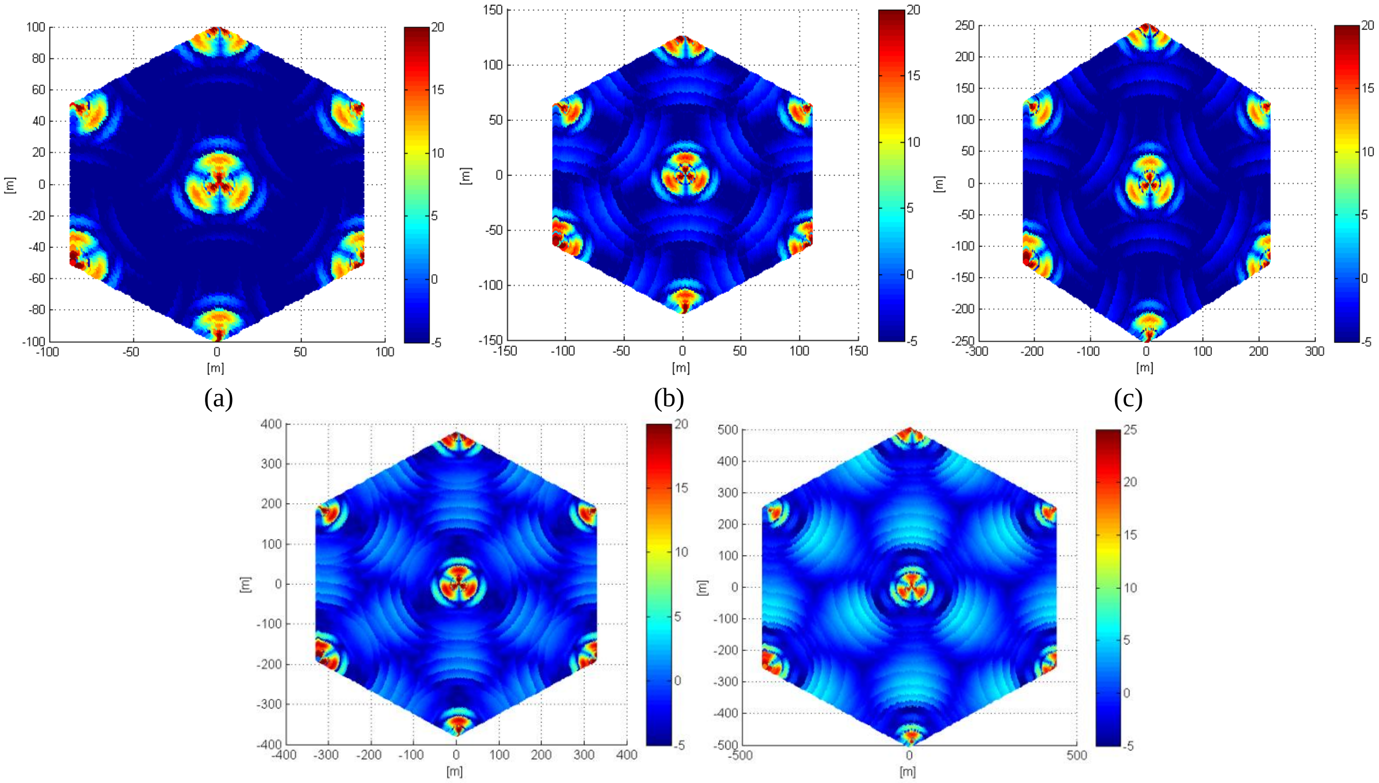
Fig. 13. RSRP coverage plot for 3-sector site case, (a) 100 m ISD, (b) 125 m ISD, (c) 250 m ISD, (d) 375 m ISD, (e) 500 m ISD.



(a) (b) (c)

(d) (e)

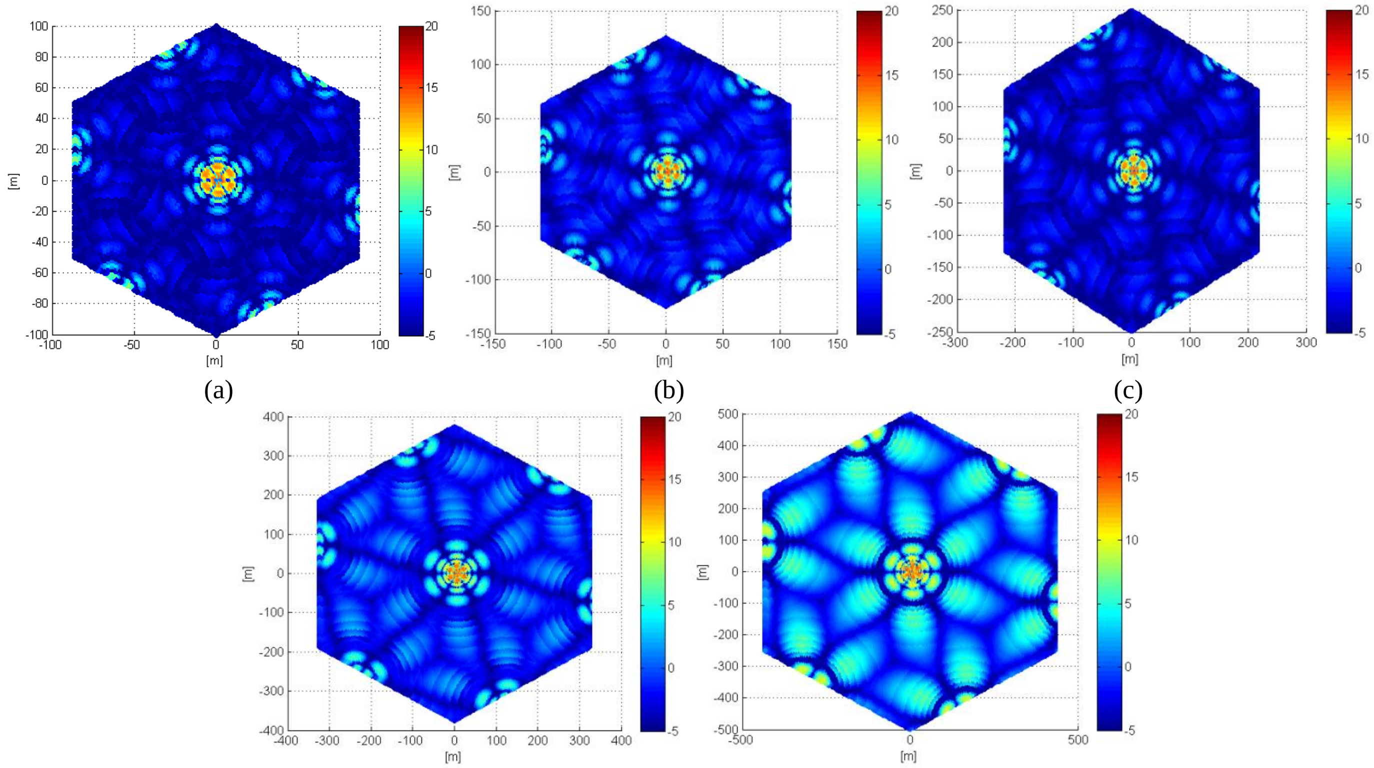
Fig. 14. RSRP coverage plot for 6-sector site case, (a) 100 m ISD, (b) 125 m ISD, (c) 250 m ISD, (d) 375 m ISD, (e) 500 m ISD.



(a) (b) (c)

(d) (e)

Fig.15. SINR plot for 3-sector site case, (a) 100 m ISD, (b) 125 m ISD, (c) 250 m ISD, (d) 375 m ISD, (e) 500 m ISD.



(a) (b) (c)

(d) (e)

Fig.16. SINR plot for 6-sector site case, (a) 100 m ISD, (b) 125 m ISD, (c) 250 m ISD, (d) 375 m ISD, (e) 500 m ISD.