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Capacity Limitation of Small Cell Densification

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***Abstract*—Deployment of small cells is considered as an easy approach for adding capacity to the system. However, it is important to realize that in a non-noise limited system, each additional cell increases the interference in the system. The target of this paper is to show the capacity limitation of the cellular network with an increasing number of small cells in a network. Ultra-dense deployment of small cells implies a high probability of line of sight (LOS) transmission between the transmitter (TX) and receiver (RX). The LOS transmission helps in enhancing the received signal strength, whereas, on the other hand, the interference power significantly grows with small cell densification. This paper presents the analytical analysis of bad cell border area for one-, and two-dimensional grid of small cells. The lamp post solution for the small cell deployment along the street is studied through simulations. The acquired results show that the overall interference in the system and the bad signal to interference plus noise ratio (SINR) cell border area grows with cell densification. System capacity saturates and then starts to collapse as the capacity loss due to the additional cell interference becomes dominant over the gain of cell densification after the saturation point.**

***Index Terms*—Small cell, cell densification, ultra dense network, capacity, cell border area.**

I. INTRODUCTION

Cellular systems are generally based on terrestrial networks, and for efficient spectrum usage. The mobile network operator (MNO) utilizes the whole available spectrum in every cell, i.e., adopt a frequency reuse factor of one. However, the utilization of the same frequency spectrum in every cell causes co-channel interference, and it deteriorates the signal to interference plus noise ratio (SINR), and that in turn impacts the system capacity [1]. Moreover, a definite threshold of SINR is set to maintain a certain quality of service (QoS) requirement for the users at the cell border area. The problem of bad SINR happens especially at the cell border area i.e., at the junction of two neighboring cells [2]. In the case of cellular concept, these cell border areas are unavoidable, and the target of MNO is to minimize the geographical size of these cell border areas to minimize the capacity loss due to interference.

Mobile network operators need to provide coverage and services in different types of the environment i.e., rural, urban, dense urban, hotspot areas, etc., for both outdoor and indoor users. Generally, the blanket or umbrella coverage is offered by the macro or micro-cellular base stations (BSs), where each site has multiple cells or sectors [3]. The location and position of the antenna have a significant impact on the signal radio propagation. Traditionally, mobile networks were deployed by using outdoor BSs, where the antennas were mounted at building rooftops or on the tower masts. 3^{rd} generation partnership project (3GPP) provides several path loss models for various types of environments, where the signal attenuation varies in different types of environment [4].

The frequency spectrum is a scarce and limited resource, and thus the same frequency resource is reused in a cellular network. Especially, for the system utilizing the frequency reuse factor of one, the same frequency band is reused in every cell. The easiest approach of adding a capacity in the system is to add new cells in the system, also known as cell densification [5]. Small cells are generally deployed in a high traffic demand or hotspot areas such as city centers, city squares, stadiums, at the location of events or festivals, indoor offices, shopping malls, etc [6]. In case of an ultra-dense network (UDN), there is a high density of cells in a small area [7]. The antennas of the indoor small cells are normally placed on the walls or ceiling of the floor, whereas, the antenna of the small cell in an outdoor environment is typically placed at the height of $8-12$m above the ground. In such cases, there is a high probability of having a line of sight (LOS) link between the transmitter (TX) and receiver (RX) [8]. Small cell deployment using lamp post in cities is a good example where users at outdoor street canyons maintain a LOS with the TX. Different coverage and capacity issues of small cells are studied in various studies [8], [9], however, no concrete strategy or limitation for ultra-dense deployment of small cells is provided. Especially impact of LOS connections on neighbor cell interference, and on the size of the area with bad signal to interference plus noise ratio (SINR) is not highlighted enough. Lamp post implementation for small cells is widely proposed and studied [10]–[13], however, the impact of cell densification on cell border area is not presented.

In this study work, first, the analytical analysis of bad cell border area is presented for one-, and two-dimensional grid of small cells. Moreover, a case study of small cell deployment using a lamp post solution over a street of 1km is considered for simulation. The impact of cell densification on SINR and system capacity is analyzed. The rest of the paper is organized as follows, Sec. II presents the analytical analysis of bad cell border area, Sec. III provides details of the simulation environment, parameters, and models, Sec. IV shows simulation results and discusses the findings of this work. Finally, Sec. V concludes the paper.

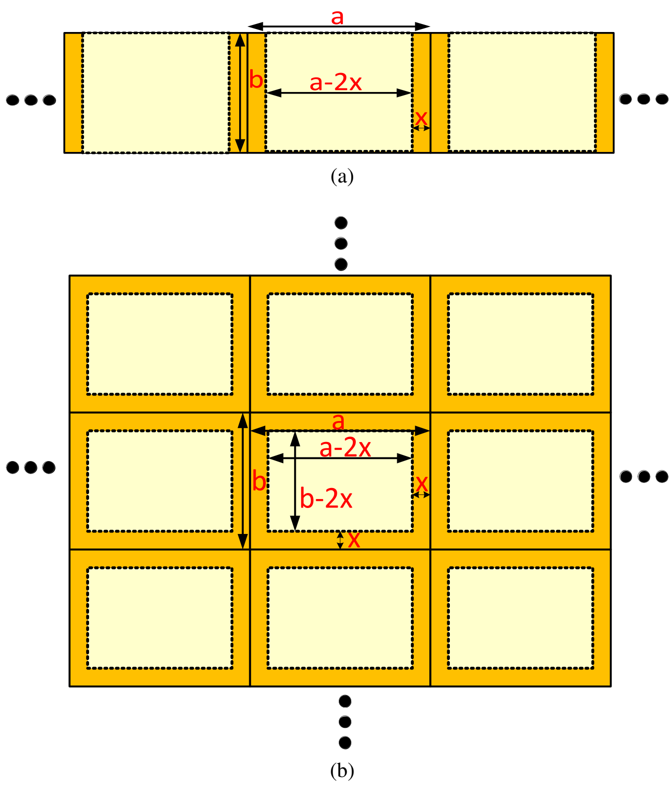


Fig. 1. Illustration of small cell geometry, (a) One dimensional grid of small cells, and (b) Two dimensional grid of small cells.

II. ANALYTICAL ANALYSIS OF BAD CELL BORDER AREA

During the radio network dimensioning process, network planners define the coverage or service area of the cell based on a target SINR threshold. Especially, at the junction of two cells i.e., cell border area, sometimes the SINR is below the target threshold due to the interference coming from the neighboring cell. Here, in this paper, the cell border area which has a SINR value below the target SINR threshold is called a "bad cell border area". Generally, for analytical analysis, sectored-macro cells are represented by hexagons [14], however, no specific shape is defined for small cell deployment. In this work, the small cell is represented by a rectangle, Fig. 1(a) and Fig. 1(b) illustrate the geometry of small cell deployment in one- and two-dimensional domain, respectively. Along the highways, roads, and streets, small cells are deployed in one-dimension as shown in Fig. 1(a), whereas, at hot spot areas, cite centers, festivals, and events, small cells are deployed in two dimension as shown in Fig. 1(b). It can be seen in Fig. 1(a), that small cell has borders at two sides only, whereas in Fig. 1(b) the cell is surrounded by neighboring cells from all four sides. Therefore, in a two-dimensional grid, the bad cell border area is larger compared with a one-dimensional grid.

In Fig. 1, a and b are the length and width of the small cell, respectively, and x is the length of the bad cell border area. Now, considering the geometry of the small cell given in Fig. 1, the total area of the cell (A_C) is ab, and the bad cell border area (A_B) is $2bx$ and $2ax + 2bx - 4x^2$, for one- and two-dimensional grid of small cells, respectively. In a special case of square geometry i.e., $a = b$, bad cell border area for two-dimensional cell grid is given as $4ax - 4x^2$. It shows that the bad area increases linearly in the case of one-dimensional grid, and it follows a second-degree polynomial in the case of two-dimensional grid.

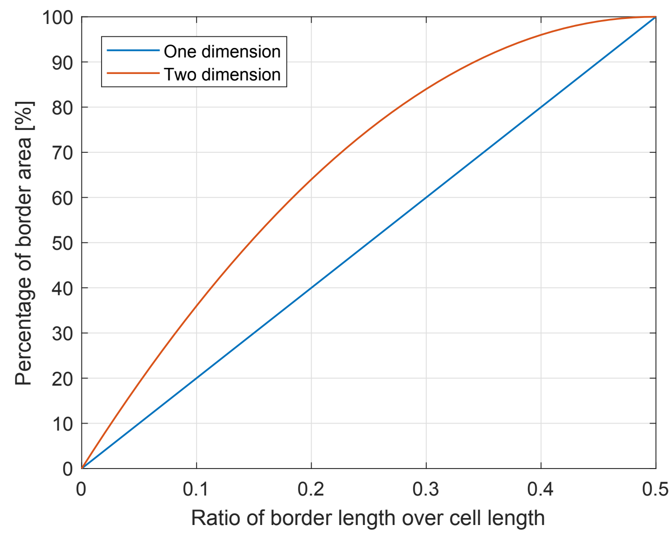


Fig. 2. Percentage of border area for one and two dimensional small cell deployment.

Here, the percentage of the border area over whole cell area (Γ_B) is defined as $(A_B/A_C) \times 100$, whereas the ratio of border length over cell length (β_B) is x/a. While considering a square geometry of the small cell, Fig. 2 shows Γ_B as a function of β_B. It can be noticed in Fig. 2 that for only $\beta_B = 0.1$, 20% and 36% of the total cell area is considered as a bad area for one and two-dimensional small cell grid, respectively. Moreover, as bad area increases linearly for one-dimensional grid, therefore Γ_B is extended to 40% for $\beta_B = 0.2$, and $\Gamma_B = 64\%$ for two dimensional grid at $\beta_B = 0.2$. These results show, that although the increase in border length is small yet the increase in bad cell area is significant. These results arise a research question that whether the ratio of the border length over cell length β_B stays the same, increases, or decreases with cell densification. It would be interesting to know the impact of cell densification on a composite bad area in a cell, as the target of MNO is to keep the bad cell border area at a minimum level. If the ratio β_B stays the same with cell densification, the cell capacity would remain the same, and system capacity would increase linearly. In case the ratio β_B increases, the cell capacity would decrease with cell densification, and finally, in case the ratio β_B decreases, the cell capacity would improve with cell densification. The target of this study work is to address these questions and provide an insight value for the radio network planners about the small cell deployment.

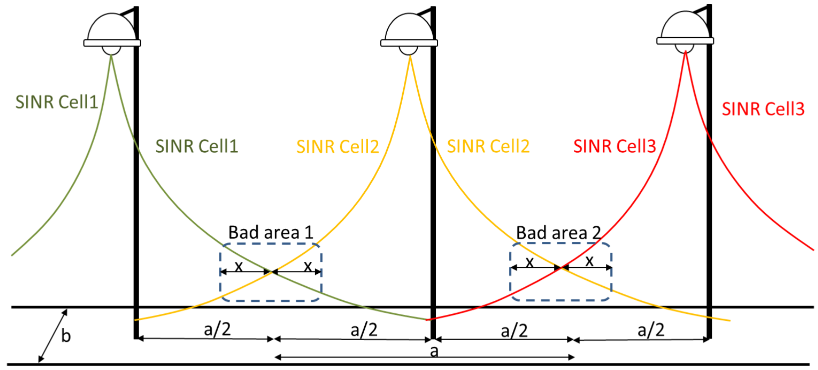
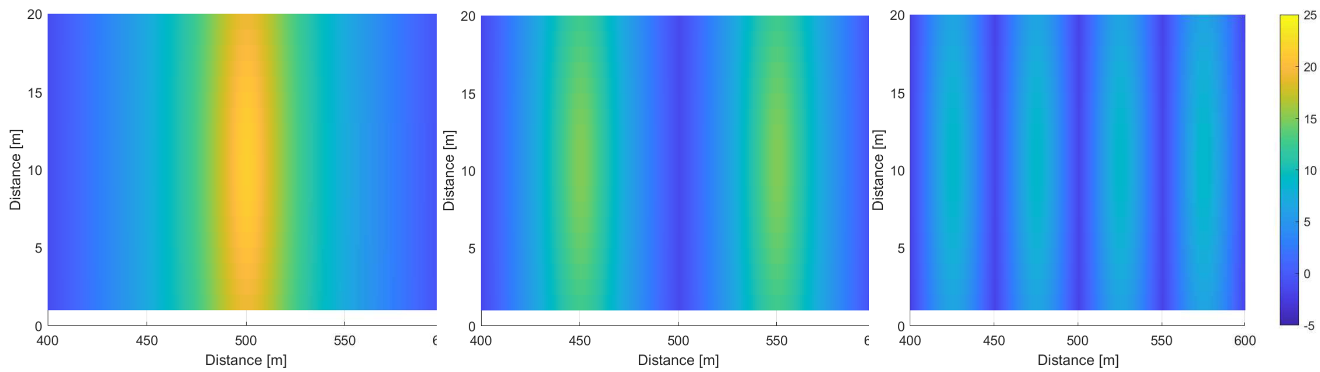


Fig. 3. Small cell deployment at lamp post.



(a) (b) (c)

Fig. 4. Heatmap of SINR for, (a) 5 cells, (b) 10 cells, and (c) 20 cells per kilometer.

III. Simulation environment, parameters, and models

In this paper, the focus is to study the impact of cell densification using lamp post solution. Therefore, we have considered a straight street of 20m width and 1km length for the simulations. The lamp posts are placed in the middle of the street as shown in Fig, 3. The height of the street lamp post is generally between $8-12$m, therefore, at TX, an omnidirectional antenna at 12m height is assumed. In a reference case, 5 cells with an equal inter-cell distance of 200m are considered for providing coverage over a 1km street. In other cases of cell densification, the number of cells is increased to 10, 20, 40, 60, and 80, and that corresponds to the inter-cell spacing of 100m, 50m, 25m, 16.66m, and 12.5m, and the relative cell density with respect to reference case is $2\times$, $4\times$, $8\times$, $12\times$, $16\times$, respectively. A grid of RX points with 1m separation is generated across the considered street, and an omnidirectional antenna at 1.5m is assumed at the RX side. The transmission power of the BS is 33 dBm, and the frequency of operation is between $0.5-100$ GHz. For determining the noise floor level at the RX, the system bandwidth of 20 MHz, and a user equipment (UE) noise figure of 8 dB is assumed. In the case of small cells e.g., lamp post deployment, the BS antenna is at low height, and there exists a high probability of having a LOS link between the TX and RX. In such case, a well-known free space path loss (FSPL) model given in Eq. 1 can be used to estimate a minimum path loss PL_{FSPL} between the TX and RX, wherein Eq. 1, d is the spatial separation between the TX and RX in meters, and f is the centre frequency in MHz.

$$PL_{FSPL} = 20\log_{10}(d) + 20\log_{10}(f) - 27.55 \quad (1)$$

The free space propagation model is independent of TX and RX antenna heights and is valid for the LOS environment. In simulations, it is expected that human bodies, or cars, or any other moving objects (e.g. birds or drones) are not preventing LOS connections. Thus, simulations consider the worst-case scenario, or basic phenomenon when propagation is optimal and constant in a small cell environment. A modified form of Shannon Capacity formula given in Eq. 2 is used to estimate a throughput T at an application layer, where N_B is the number of parallel bit streams, B is the system bandwidth in Hertz, $SINR$ is the signal to interference plus noise ratio in linear scale, α is the control channel overhead. In our simulations, a single bitstream $N_B = 1$, 20% control channel overhead i.e., $\alpha = 0.2$, 20 MHz system bandwidth i.e., the whole spectrum is allocated to the user in DL, is assumed for computing the application layer throughput.

$$T = N_B B Log_2(1 + SINR)(1-\alpha) \quad (2)$$

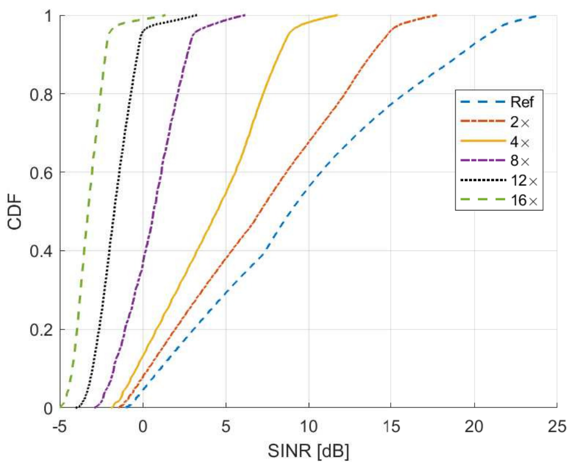


Fig. 5. CDF of SINR.

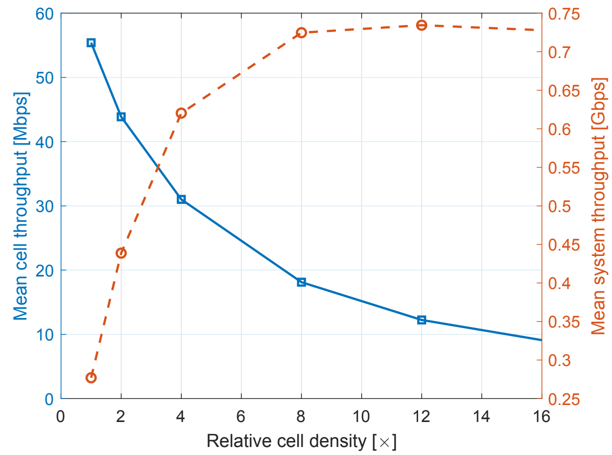


Fig. 6. Mean cell and system throughput.

IV. Simulation Results and Discussion

This section discusses the simulation results and presents the findings of the study. It is a well-known fact that adding more cells in a system improves the received signal power level, however, it is interesting to see the impact of cell densification on SINR, as user quality of service (QoS) and quality of experience (QoE) are directly linked to SINR. With the given system parameters, the noise floor at the RX is at the level of $-92.9\,$dBm, and it is important to mention here, that system is not found noise-limited i.e., the received signal power levels were higher compared with the noise floor at the receiver for frequencies between $0.5 - 100\,$GHz. Fig. 4 shows the heatmap of SINR over the street of 200m length for different cell densities. Fig. 4(a) shows the heatmap of reference case i.e., 5 cells/km. It can be seen in Fig. 4(a) that there is only one cell covering the area of $200m \times 20m$, and the maximum SINR of around $25\,$dB is achieved in the center of the cell. Whereas, in Fig. 4(b) the same area is covered with two cells, and due to more number of cells i.e., more interference in the system, the maximum achieved SINR is limited to around $18\,$dB. Similarly, in Fig. 4(c), the maximum achievable SINR is further reduced and the number of cell border areas is increased with a cell density of 20 cells/km.

Fig. 5 shows the cumulative distribution function (CDF) of SINR for different cell densification cases. It can be seen in Fig. 5 that the SINR over the whole cell area deteriorates with cell densification. As mentioned earlier that network planners set a certain SINR threshold with respect to the required service type for defining a cell border area. In this study, the target SINR of $5\,$dB is considered, and samples below target SINR will be considered as in the bad cell border area. Interestingly, it is found that with the reference cell grid, 29% of the samples are below the target threshold, and that is further extended to 38%, 54%, and 99% while the cell density is increased by $2\times$, $4\times$, $8\times$, respectively. Similarly, it is found that not only the cell border area grows, rather the mean value of SINR is also degraded with cell densification.

Throughput is directly proportional to the SINR as given in Eq. 2. The mean value of CDF of SINR presented in Fig. 5 is used to estimate the mean throughput of the cell. Finally, the mean system capacity is calculated by multiplying the mean throughput of the cell with the total number of cells present in the system. Fig. 6 shows the mean cell and system throughput as a function of cell density. It can be seen that individual cell capacity decreases with cell densification, whereas, the system capacity saturates and hits the maximum value at $12\times$ cell density as compared with the reference scenario. After which the system capacity starts to deteriorate as individual cell throughput is quite low due to excessive interference from neighboring cells. It is interesting to see in Fig. 6 that the system capacity is increased by 58% while the cell density is increased by $2\times$ with respect to the reference case, whereas the increase in system capacity is around 41% while the cell density is changed from $2\times$ to $4\times$, and then the increase in system capacity is only around 17% for the $4\times$ to $8\times$ change in cell density. These results show that capacity improvement starts to get saturated after $4\times$ higher cell count, which means 20 cell/km. These results can be used as a baseline and can be considered as a recommendation for not using omnidirectional small cells with less than 50m inter-cell spacing along the streets and roads. It should be noted that in the case of two-dimensional small cell grid e.g., market squares, stadiums, indoor locations, hotspots, etc., there is more interference as compared with one-dimensional cell grid i.e., lamp post configuration, as shown through analytical results in Sec. II. Therefore, the inter-cell spacing should be higher than 50m as recommended for a one-dimensional small cell grid.

Fig. 7 shows the relative system throughout gain as a function of relative cell density with respect to the reference case of 5 cell/km. Ideally, relative system throughput gain should increase linearly with an increase in relative cell density. However, it can be seen that relative system throughput gain is $1.6\times$, $2.2\times$, $2.6\times$ for the relative cell density of $2\times$, $4\times$, and $8\times$, respectively. It shows the in-efficiency of ultra-dense small cell deployment along the road/street.

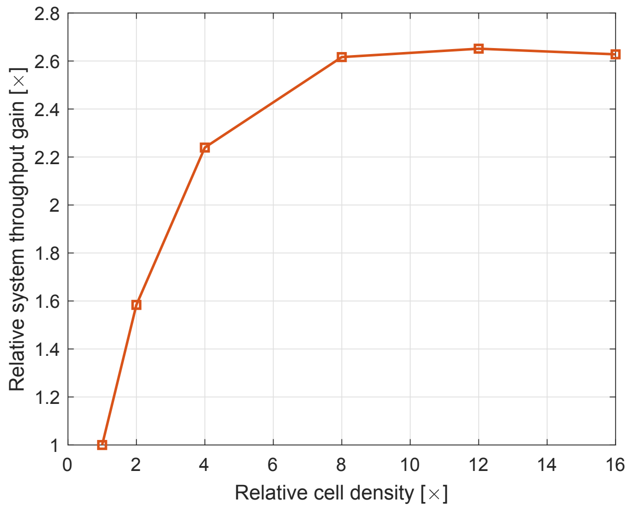


Fig. 7. Relative throughput gain against cell densification.

Finally, it is good to highlight that the SINR results presented here are valid for frequencies between $0.5 - 100$ GHz as noise-limited cases are not considered for the analysis. There is an offset in path loss in case of frequency change which moreover does not change the bad SINR area, as a constant propagation slope is assumed in our simulations. Similarly, different transmit powers, antenna gains, or losses bring no change on bad cell border areas. However, interference to the neighboring cell could be avoided by employing a complex and advanced antenna system (AAS) with beamforming and beam tracking capabilities, and by increasing the coordination between the neighboring cells. In the case of small cells, in terms of management, capital expenditure, and operational expenditure, these solutions are difficult to implement. Whereas, in order to deploy small cells at a large scale, the deployment of small cell solutions should be easy and inexpensive.

V. Conclusions

The cell border area with SINR value below the target SINR threshold is considered as a bad cell border area or area with a service outage. In the first part of this work, the bad cell border area is analytically quantified for one-, and two-dimensional grid of small cells. This work addressed the question of whether the ratio of the bad border length over cell length stays the same, increases, or decreases with cell densification. For the simulation work of this paper, lamp post small cells with omnidirectional antennas were considered to provide continuous and uninterrupted coverage over a street, and the target was to study the impact of interference on cell border area and system capacity in a typical small cell LOS propagation environment. Through acquired simulation results it was found that the mean value of cell SINR deteriorates with increasing cell density. Therefore, the cell capacity decreases by densifying the small cell grid. Moreover, the ratio of the bad border length over cell length increases with cell densification. It was found that a minimum separation of around 50m should be maintained between the lamp post small cells for efficient spectrum utilization, as the gain of adding cells with less than 50m separation was not found significant. However, the minimum inter-cell distance can be further reduced by employing a complex and more advanced antenna system (AAS), and by increasing the coordination between the neighboring cells. It was found that system capacity saturates at one point, and then it started to degrade as the loss in capacity due to the interference of additional cells started to dominate the gain of additional cells in the system. It was also found that the system capacity saturated at the inter-cell spacing of 16.6m, and then started to collapse with additional cells.

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