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Performance Evaluation of Switched Beam Antenna with Different Configurations at 28 GHz

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Abstract—The main target of this paper is to evaluate the performance of a switched beam antenna in a macro-cellular environment at 28 GHz frequency. Another objective of this study is to compare the performance of a cellular system equipped with 7-beams switched beam antenna with conventional system implemented with wide 65° horizontal HPBW antenna. A campaign of 3D ray tracing simulations was carried out by using realistic 3D building data. Performance metrics considered for this study are RX level, SINR, system spectral efficiency, and the relative gain. Different configurations of 7-beams antenna is studied and the advantages and the disadvantages of considered configurations are highlighted in this paper. It is learned from the acquired results that an optimal configuration of 7-beams antenna can provide upto only 209.72 % of relative gain with respect to a traditional 3-sector site deployment. However, the relative performance gain of a 7-beam antenna can be negative under certain circumstances.

Index Terms—Switched beam antenna; performance analysis; 3D ray tracing; macro cellular; 5G.

I. INTRODUCTION

Data traffic has overloaded cellular frequencies under 6 GHz bands. In order to significantly enhance the system capacity and to substantially increase the data rate, the use of higher frequency has become essential as fairly large spectrum is available at higher frequencies. For 5G NR interface one planned frequency band is 28 GHz. In this band the rain attenuation and atmospheric absorption are relatively low as compared with 60 GHz frequency. High pathloss and penetration loss makes the usage of higher frequencies for cellular system challenging. However, these additional losses can be compensated by antenna with high gain and directivity [1].

Smart antennas can be categorized into two main categories: fully adaptive antenna with beam steering capability, and the other one is multiple switched beam antenna [2]. Simple narrow beam antennas with high directivity gain improve the received signal strength for the users located in the main beam direction, and can also help in improving the Signal to Interference plus Noise Ratio (SINR) [3]. However, simple narrow beam antennas are not suitable for the cellular networks where a sector is covering large spatial domain due to the property of high spatial directivity of narrow beam antenna. The main target of the smart antennas is to increase the gain in the desired direction i.e. in the direction of serving user, and to reduce the gain by placing a null in the direction of other users. Antenna is characterized by its energy radiation pattern, Front

to Back Ratio (FBR), and Side Lobe Level (SLL). In case of switched beam antenna, multiple narrow beams overlapping over each other cover a wide sector. As all the signal energy is not directed towards main lobe of the antenna, some of the energy is spread through the side lobes and hence causes an increase in interference level [4].

The aim of this article is to evaluate the performance of a multiple switched beam antenna in a realistic environment using a practical antenna radiation pattern. The target is to evaluate different configurations of switched beam antenna, and analyze their impact on system spectral efficiency i.e. system capacity. A traditional three sector case is used for reference, and later a single beam antenna in a sector is replaced with multiple switched beam antenna having 7-beams. The simulations are performed using a sophisticated 3D ray tracing tool that provides a detailed channel characteristics i.e. Angle of Arrival (AoA), Angle of Departure (AoD), Direction of Arrival (DoA), and Direction of Departure (DoD) of the propagation path. This information about the directional characteristics of the channel is then used in simulations for evaluating the performance of the switched beam antenna.

II. BACKGROUND THEORY

A. Switched Beam Antenna (SBA)

Switched beam antenna belongs to the class of smart antennas. In case of SBA, a single sector is being covered with multiple narrow beams overlapping over each other. Switched beam antenna provides higher directional gain with narrow beams by concentrating power in a narrow spatial domain, and hence helps in achieving a better received signal strength [5]. On the other hand, a switched beam antenna can also help in minimizing the interference in the system, and that in turn increases the capacity. A switched beam antenna can be considered as the simplest smart antenna technology suitable for the initial deployment of massive MIMO antenna [6]. Switched beam antenna with a butler matrix network is a cost effective approach to create an adaptive antenna. Butler matrix can be used as a beam forming network to provide multiple beams with equal power at different progressive phases [5]. Fully adaptive antenna with beam steering requires complex signal processing and computation. Whereas, the SBA is easy to implement, less complex and less expensive compared with full adaptive antenna [3], [7].

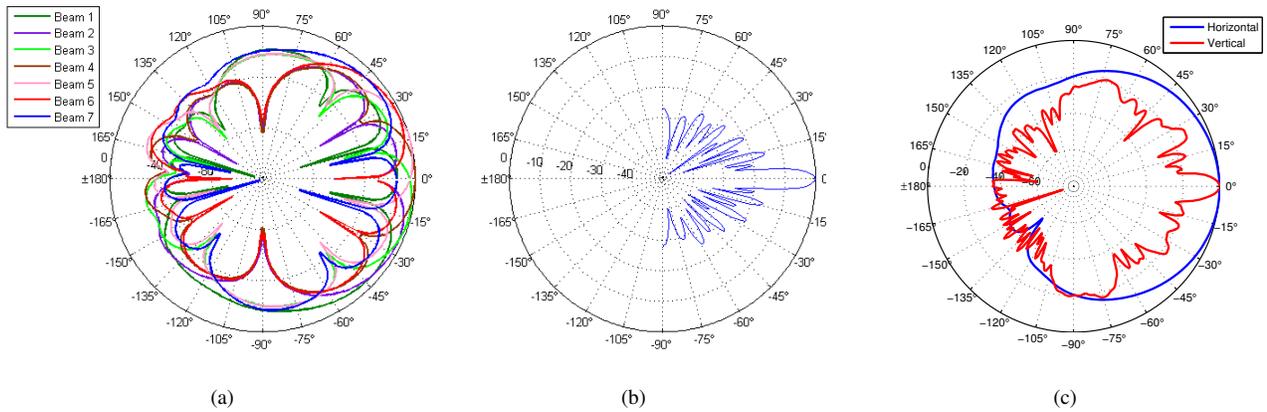


Fig. 1. Radiation patterns, (a) 7-beams antenna horizontal pattern, (b) 7-beams antenna vertical pattern, and (c) Single 65° HPBW antenna.

Fig. 1(a) shows the antenna radiation pattern of a 7-beam SBA in an azimuth plane. There are seven beams pointing in the direction of $+45^\circ$, $+30^\circ$, 15° , 0° , -15° , -30° , and -45° , where the beam with a maximum gain at 0° has a Half Power Beamwidth (HPBW) of 26° in an horizontal plane. The vertical pattern of all seven beams is shown in Fig. 1(b). It can be seen that the antenna has a significantly narrow beam i.e. about 6° HPBW in an elevation plane compared with a horizontal plane. Finally, the horizontal and vertical radiation pattern of a conventional wide 65° HPBW antenna domain is shown in Fig. 1(c). Later, these radiation patterns are used in simulations for the study of this paper.

B. Efficiency Metrics

The spectral efficiency of a cell (η_{cell}) is defined as the maximum aggregate bit rate that a cell can support and is expressed as bps/Hz . The ppectral efficiency of a cell is directly coming from the famous Shannon's capacity formula and is given as:

$$\eta_{cell} = \log_2(1 + SINR) \quad (1)$$

where in Eq. 1, the SINR is the average signal to interference plus noise ratio of a cell. The spectral efficiency of a system (η_{sys}) is defined as the product of the cell spectral efficiency and the number of the cells (ρ_{cell}) in the network as shown in Eq. 2 [4].

$$\eta_{sys} = \eta_{cell} \cdot \rho_{cell} \quad (2)$$

The spectral efficiency of a system can be enhanced by improving the SINR, and it can also be improved by adding more number of cells in a system, given a healthy SINR is maintained after adding more cells. For comparing the relative system capacity (spectral efficiency) gain with respect to the reference case, the relative gain (G_{Rel}) of system spectral efficiency in percentage is computed as follows [4]:

$$G_{Rel} = \left(\frac{G_U - G_{Ref}}{G_{Ref}} \right) * 100 \quad (3)$$

where in Eq. 3, G_U is the system spectral efficiency of the case under consideration, and G_{Ref} is the spectral efficiency of the reference case.

III. SIMULATION ENVIRONMENT AND SIMULATION CASES

This section provides a detail about the simulation platform, environment, and simulation cases considered in this study. The general simulation parameters and assumptions considered for the study of this paper are also provided in this section.

A. Simulation Platform and Environment

A MATLAB based 3D ray tracing tool "sAGA" developed by the authors is utilized for finding the propagation paths between the transmitter and the receiver points. An "image theory" is used in locally developed tool for finding the reflected and diffracted paths with the given number of reflections and diffractions. A small part of Kruunuhaka region from city of Helsinki is selected as a region of interest as shown in Fig. 2. Unlike a regular grid tessellation, ten macro-site locations were picked after careful consideration. Each site is mounted with 3-sector antenna at 30 m height. All together 884 indoor and outdoor users are randomly distributed in an area under consideration. Indoor users are distributed at four different floors i.e. ground, second, fifth and seventh floor depending upon the height of the building. An open space without any wall partition is assumed for indoor plan of the building.

B. Simulation Cases

The following cases are considered in this paper:

1) *Reference 3-sector*: It represents a traditional deployment of the site with three sectors. In this case each sector represents a single cell, and is mounted with wide 65° HPBW antenna in horizontal domain and 7° HPBW in vertical domain. The antenna radiation pattern used for this case is shown in Fig. 1(c).

2) *Random 'N' beams*: In this case, each site has 3-sectors where every sector has 7 beams and each beam represents a single independent cell. N is the number of active beams randomly selected in the serving sector and in the other sectors, and N can have values $N = 1, 2, 3, \dots, 6$. The beams are randomly chosen. The total transmission power is equally divided among the active number of beams in the sector.

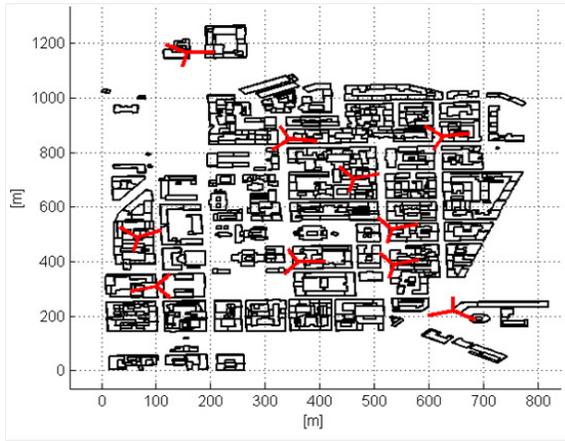


Fig. 2. Area under consideration with site locations.

3) *Worst case*: It also consider a 7-beams switched beam antenna, where all the beams are active at the serving and at the interfering sectors. In this case, a UE will experience a maximum interference from the neighbouring and as well as from the serving site.

4) *Fixed 'M' beams gap*: It is an extended case of switched beam antenna, where a fixed separation of M inactive beams exist in between the two active beams in a serving and interfering sectors. For example $M = 1$, that means only alternate beams can be active in the sector. Only even or odd number of beams can be active with $M = 1$. Similarly, for $M = 2$ a gap of 2 inactive beams exists between two consecutive active beams. Again, the total transmission power is equally divided among the active number of beams in the serving sector.

A Monte Carlo type of simulation is required for 2nd and 4th case, as it involves the random selection of beams in the serving and in the interfering sectors. Therefore, the results presented for 2nd and 4th case in this paper are averaged over 200 snapshots. The general simulation parameters are provided in Table. I.

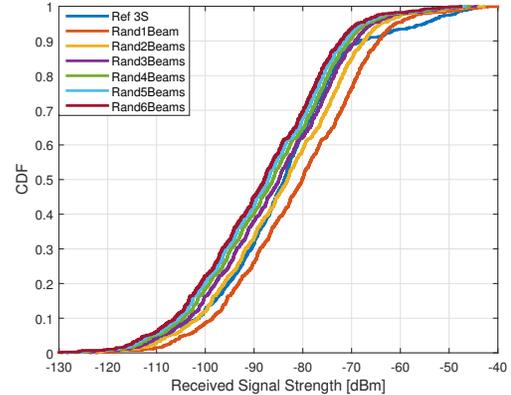
TABLE I
GENERAL SIMULATION PARAMETERS

Parameters	Unit	Value
Frequency	GHz	28
System bandwidth	MHz	20
TX power	dBm	43
Number of Sites	No.	10
Number of Sector at site	No.	3
Antenna height	m	30
Building penetration loss	dB	26.5
UE noise figure	dB	8

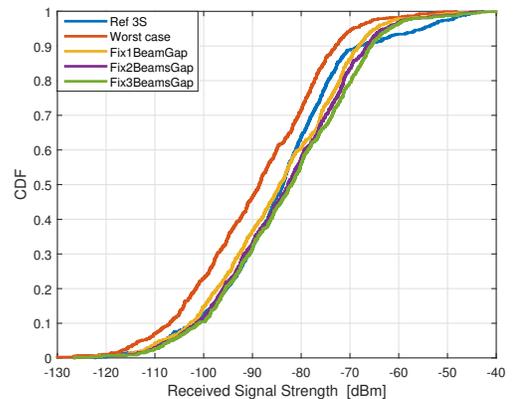
IV. SIMULATION RESULTS AND DISCUSSION

There are four main configurations considered in this study for simulations as discussed in previous section. Again, there are six sub-cases under the case of random selection of N beams i.e. for $N = 1, 2, 3, \dots, 6$. Similarly, there are 3

more sub-cases of the last discussed configuration in which $M = 1, 2$, and 3 inactive beams are assumed between two active beams. Therefore, in order to clearly display the results in figures, each performance metric's results are provided in two separate figures, one for random beam selection cases and other with fixed beams gap cases.



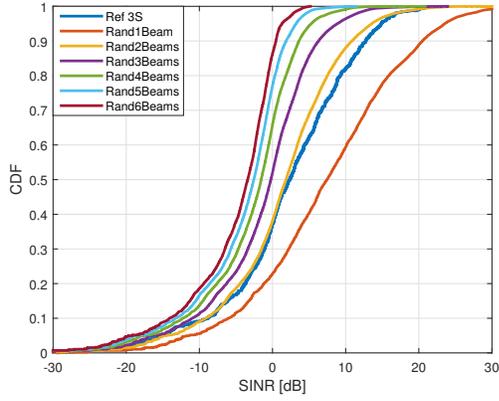
(a)



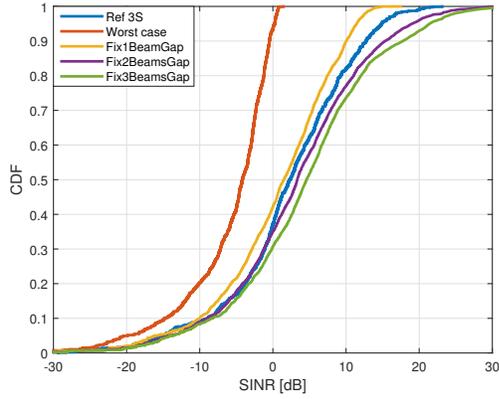
(b)

Fig. 3. CDF of received signal level, (a) Random beam selection cases and reference case, and (b) Fixed beam gap cases and reference case.

Fig. 3 shows the CDF plots of the received signal level for different considered cases. The x-axis shows the received signal level [dBm], and the y-axis shows the CDF value. It is important to mention here that total transmission power per sector was fixed i.e. 43 dBm, and it was equally divided among the active number of beams in the cell. Therefore, higher the number of active beams, the lesser will be the transmission power available in the cell. It can be seen in Fig. 3(a), that the best received signal levels are achieved with single beam selection as full available power can be used in a single beam. Same power is also available in case of traditional 3-sector site, however, narrow antennas have higher directional gain. Therefore, mean RX level of -80.84 dBm and -84.05 dBm is achieved single random beam selection and reference case, respectively. Due to higher propagation losses at 28 GHz frequency, the RX level is pretty low in macro-



(a)



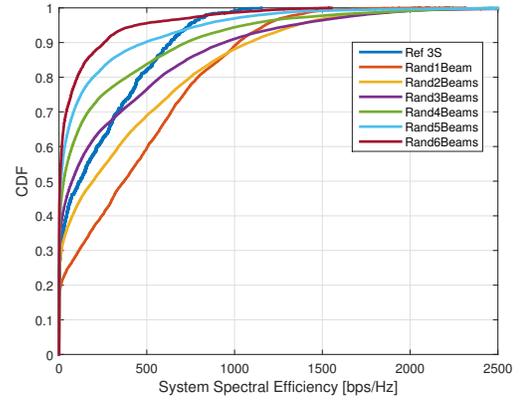
(b)

Fig. 4. CDF of SINR, (a) Random beam selection cases and reference case, and (b) Fixed beam gap cases and reference case.

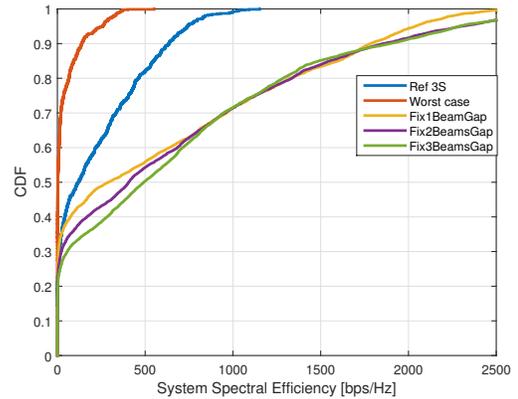
cellular environment. Fig. 3(b) shows the CDF plots of the RX level for different fixed beam gap cases and of the 3-sector reference case. Similar trends are observed in Fig. 3(a), that the RX level decreases with the increase in active number of beams. It is more interesting to see the results of SINR as that directly tells about the quality of the network, and mostly networks are quality i.e. capacity limited.

Fig. 4 shows the CDF plots of the signal to interference plus noise ratio for different considered cases. It is interesting to see in Fig. 4(a) that the SINR of all the random beam selection cases except the single random beam selection is lower than the SINR of reference 3-sector case. It means that even with just two randomly selected active beams the mean SINR of the cell gets poor than the reference case because of the severe beams overlapping. It also shows the limitation of using a multiple number of active beams in the sector. The more number of active beams in the sector the lower will be the SINR of the cell. However, the results presented in Fig. 4(b) show that a better SINR can be achieved in a sector while using multiple beams by placing a fixed number of inactive beams between the two active beams. Thus, at a certain level of spatial isolation is maintained between the two active beams

and it reduces the overlapping between the beams. In worst case scenario, all the beams are active in serving and as well as in the interfering sectors, and therefore the lowest SINR is acquired in this case.



(a)



(b)

Fig. 5. CDF of system spectral efficiency, (a) Random beam selection cases and reference case, and (b) Fixed beam gap cases and reference case.

Fig. 5 shows the CDF plots of system spectral efficiency for different considered cases. It is an already established fact that the SINR goes down by adding more cells (beams) in a sector. However, it is interesting to see the impact of lower cell SINR over whole system capacity (spectral efficiency) as there are more number of cells in a system in the case of multiple beams. It is fascinating to learn that in case of random beam selection as shown in Fig. 5(a), the maximum system spectral efficiency is achieved with single beam only. Although, by adding more beams the number of cells are increased in a system, however due to lower cell SINR the combined spectral efficiency of a system with additional cells (beams) is still less than the one achieved with single narrow beam. The reference 3-sector site case has a mean system spectral efficiency of 227.53 bps/Hz, whereas the mean system spectral efficiency of 439.83 bps/Hz, 384.46 bps/Hz, and 305.01 bps/Hz is attained by randomly selecting one, two, and three beams, respectively. In case of four active beams per sector in a system, the

TABLE II
STATISTICAL ANALYSIS

	Mean RX level [dBm]	Mean SINR [dB]	Average active beams [No.]	Mean system spectral eff. [bps/Hz]	Relative gain [%]
Ref 3S	-84.05	1.98	1	227.5	0
Fix1BeamGap	-84.80	0.46	3.57	625.5	174.92
Fix2BeamGap	-83.41	3.17	2.43	683.7	200.49
Fix3BeamGap	-82.64	4.38	2.14	704.7	209.72
Rand1Beam	-80.84	7.21	1	439.8	93.30
Rand2Beams	-83.85	1.26	2	384.4	68.97
Rand3Beams	-85.61	-1.40	3	305.0	34.05
Rand4Beams	-86.86	-3.1	4	219.9	-3.35
Rand5Beams	-87.83	-4.35	5	144.5	-36.47
Rand6Beams	-88.62	-5.31	6	85.5	-62.41
Worst case	-89.29	-6.09	7	40.6	-82.14

achieved mean system efficiency is 219.9 bps/Hz and is less than that of reference 3-sector case. Therefore, it can be said about a considered SBA that it is not recommended to activate more than three beams, as the relative capacity gain becomes negative with reference to the single 65° HPBW antenna.

Fig. 5(b) shows that the overall best system spectral efficiency of 704.7 bps/Hz is achieved with fixed 3-beams gap, and that means a 209.72 % of additional capacity with respect to the reference 3-sector case. Similarly, the system spectral efficiency of 683.7 bps/Hz and 625.5 bps/Hz is obtained with two and one beam gap, respectively. Now, here it is important to mention that although fixed three beam gap configuration provides the best capacity, but it is only favorable when the sector is highly loaded, and the scheduler has a freedom of choosing the users in selected beams at different Transmission Time Intervals (TTIs). However, if the sector is not loaded then activating the beams without any user with data to transmit would not provide any advantage. Its mean that a smart scheduler is required, and the information about the active users with data transmission should be available at the scheduler for making a decision that which combination of active beams should be used in any TTI. Whereas, on the other hand a basic scheduler is required in case of randomly selecting single beam, and still it can provide a relative capacity gain of 93.3 % with respect to a reference case. Hence, it can be said that the usage of fixed beam gap configuration provides extra gain at the cost of complex computation, and is suitable for high loading scenario. Statistical analysis of the other acquired results is presented in Table. II.

V. CONCLUSION

In this paper the performance of a cellular network utilizing a switched beam antenna and a traditional wide beam antenna is evaluated by using 3D ray tracing simulations in a realistic urban environment. It is learned that due to the presence of antenna side lobes and beams overlapping, randomly activating multiple beams in a sector substantially increase the interference level in a system. As a result of increased interference, the average SINR of the cell is reduced. More number of users can be served in a sector by activating multiple beams, however, the maximum relative capacity gain of 93.3 % is achieved with only single active beam with respect to wide beam antenna.

Next, the gain starts to reduce as the number of active beams is increased, and it becomes even negative when more than three beams are activated simultaneously.

One promising strategy for enhancing the system capacity is to avoid transmissions in neighbouring beams. By ensuring that there exist one in-active beam between two neighbouring active beams, the system spectral efficiency relative gain can be increased to 174.92 %. Similarly, if every third beam is active the relative gain is increased to 200.5 %. Finally, a maximum relative gain of 209.72 % was achieved with three beams gap. However this strategy is only favourable in case of highly loaded network where the scheduler can select multiple users in preferred beams at different transmission time interval. Therefore, a nice balance between complexity and achievable gain is to simply activating one beam at a time, as it is the easiest step to start working with switched beam antenna.

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