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Performance Evaluation of Spectrum Efficiency of a Cellular Wireless Network in Nigeria (Apapa Lagos, as a Case Study)

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Abstract Ever increasing demand for communication services has led to serious challenges to network operators to ensure acceptable Quality of Service (QoS) at minimum cost. The increasing number of subscribers and demand for greater variety of services make it difficult for network operators to provide the service varieties subscribers want while maintaining acceptable levels of quality of service. Spectrum is a precious commodity, knowing how efficiently different technologies and applications use it allows users and operators to make the best decisions on what wireless technology to deploy and in what configuration. Spectrum efficiency is an important parameter for accessing the frequency requirements of cellular mobile radio systems; radio channel capacity is a measure of the spectrum efficiency of a wireless system. The effect of cluster size, carrier to interference ratio and carried traffic in the spectrum efficiency are discussed. The fundamental figure of merit is the spectral efficiency was found to be 1.3698 fall within the regulator and defined items of Erlangs/MHz/Km^2 proved to be adequate, comprehensive, and appropriate for cellular system. It is also observed that the smallest value of C/I ratio provides largest spectrum efficiency. Comparatively, the study of the 120° sectored and 60° sectored cells can be done in relation to non-sectored (omnidirectional, 360°) cells when a number of interfering base stations are considered. The performance of improvement of the 60° sectored provides better coverage performance than 120° sectored and Omni. Low C/I ratio will cause coverage issue including dropped calls, block calls, and other handset reception problem.

Keywords: *spectrum efficiency, sectorization, C/I Ratio, quality of service, cellular systems, cluster size and Traffic*

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1. Introduction

The objective of early land to mobile radio systems was to achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower [1]. This was done by selecting several channels from a specific frequency allocation for use in autonomous geographic zones. The communications coverage area of each zone was usually planned to be as large as possible. The number of channels that could be obtained from the allocated spectrum was limited. There was generally no in system interference as the same frequencies were reused in the next service area which used to be several hundred miles away. Some of the drawbacks of the early land to mobile systems were limited service capability, high blocking probabilities, inefficient frequency spectrum utilization. If there were two contiguous service areas, then call had to be terminated and reinitiated in the next service area. There was no concept of handoff. In addition to this, the regulatory agencies could not make spectrum allocations in proportion to the increasing demand for mobile services, thus making it imperative to restructure the mobile radio system to achieve high capacity with limited radio spectrum, while at the same time covering very large areas. Large scale integrated circuit technology reduced the size of mobile transceivers to one that could easily fit into the standard automobile. Another factor was the reduction in price of the mobile telephone unit. Technology, feasibility and service affordability caused the transition from early land to mobile systems to the cellular systems.

Mobile communication is currently at its fastest growth period in history; due to enabling technologies which permit wide spread deployment. Historically, growth in the mobile communications field has come slowly, and has been linked to technological advancements. The ability to provide wireless communications to an entire population was first conceived when Bell Laboratories developed the cellular concept in the 1960s and 1970s. The tremendous growth in the mobile communications is primarily due to development of highly reliable, miniature solid-state devices and the development of the cellular concept. The future growth of consumer-based mobile and portable communication systems will depend on radio spectrum allocations, regulatory decisions, adoption of common standards, consumer needs and technology advances in the signal processing, access, and integration of voice and data networks.

2. Spectrum Efficiency for Cellular Networks

The evolution of data services is characterized by an increasing number of users with ever-higher bandwidth demands. As the wireless data market grows, deploying wireless technologies with high spectral efficiency is of paramount importance. Keeping all other things equal, including frequency band, amount of spectrum, and cell site spacing, an increase in spectral efficiency translates to a proportional increase in the number of users supported at the same load per user—or, for the same number of users, an increase in throughput available to each user. Increased spectral efficiency, however, comes at a price because it generally involves greater complexity for both user and base station equipment. Complexity can arise from the increased number of calculations performed to process signals or from additional radio components. Hence, operators and vendors must balance market needs against network and equipment costs. Figure 1 shows the performance characterization, in terms of load and quality, of two different networks, or a single network with a different set of functionalities. Network B is more spectral efficient than Network A because, for a certain benchmarked quality, Network B can carry more traffic, and for a certain traffic load, Network B has a better performance. If certain functionality that increases the spectral efficiency is introduced in Network A, the quality will immediately improve and considering the previous quality as the benchmarking quality level, there will be additional traffic load that can be carried by the network. The relative value of this additional traffic load is the capacity increase provided by the introduced functionality.

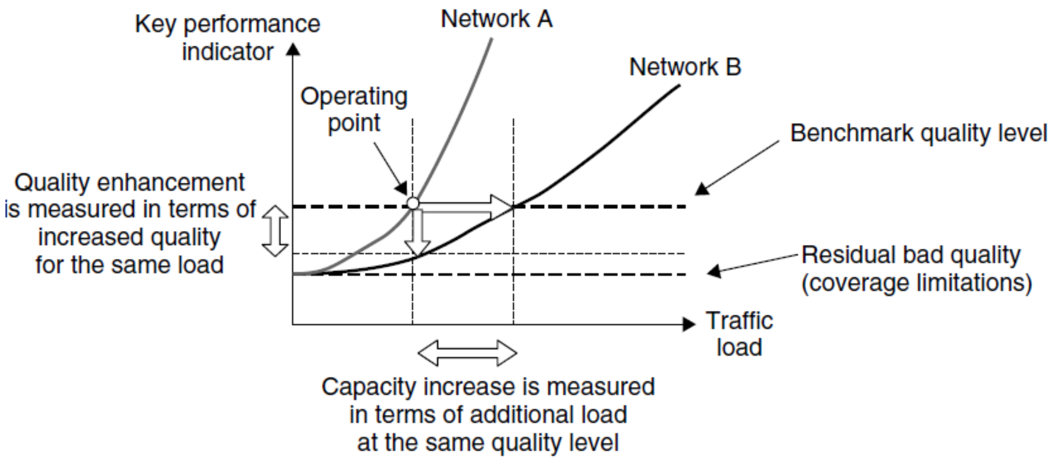

Figure 1. Spectral Efficiency Concept

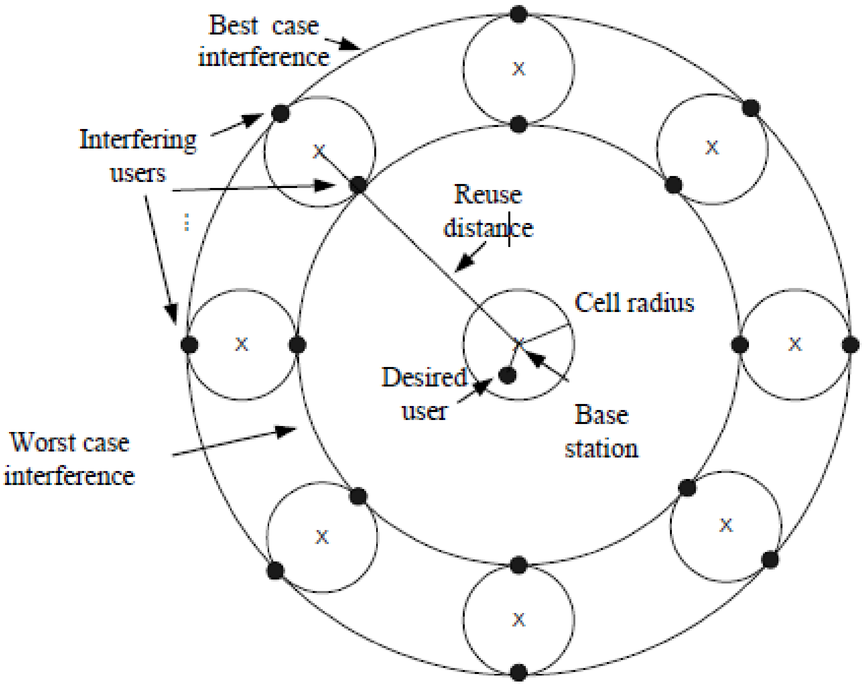

Figure 2. System model for spectral efficiency

Spectral efficiency is one of the significant metrics to be considered in design of wireless communication networks. The cellular concept was a major breakthrough in solving the problem of spectral congestion [2]. It offered high system capacity with a limited spectrum allocation. The spectrum of the wireless channel is interference limited because of the severe channel impairments. In a mobile communication system, the spectral utilization can be enhanced by using various techniques such as choice of multiple access method, channel assignment, bandwidth reduction, and data compression to reduce the transmission rate. The overall spectral efficiency of a cellular communication system can be estimated based on the spectral efficiency component, expressed as channel/MHz/ Km^2, due to the system parameters such as cell area in Km^2, frequency reuse factor, channel spacing in KHz, and type of modulation scheme used, as well as the spectral efficiency component expressed as Erlangs/MHz/Km^2, due to the multiple access method used. Spectral efficiency may be defined as channel/MHz/Km^2 or Erlangs/MHz/Km^2, where Erlang is a measure of the traffic load, in order to capture the frequency reuse in the service coverage area of the system [3]. The Figure 2 obtained in practice depend on factors that are not easily determined and contains a great deal of uncertainty and hence can be sometimes inflated, thus the number of users served per MHz/ km^2 is considered in this study as a more appropriate definition of spectrum efficiency [4].

In a cellular system, the frequency reuse scheme is implemented for the purpose of increasing spectrum efficiency. The system capacity is directly related to spectrum efficiency but not to channel efficiency. In a frequency reuses system, however co-channel separation is more critical to the system than adjacent co-channel interference because adjacent co-channel interference may be eliminated by the use of sharp filter. Some of the key assumptions that affect resulting spectral efficiency is the exact mix of stationary versus mobile users and the distance between base station. Various factors affect how efficiently spectrum is used [5] and [6] including the type of modulation used, error correction methods, reuse of frequencies across geography, the number of users served, radio performance, and the percentage of time a service is active.

2.1. Number of Frequency Reuse Cells K

The formula determining the number of frequency reuse cells in a standard cellular configuration is obtained with γ=4 based on 40dB/dec propagation path loss [7].

$$\frac{C}{I}=\frac{(D/R)^4}{6}=\frac{\left(\sqrt{3K}\right)^4}{6}=\frac{3K^2}{2} \tag{1}$$

or

$$K=\sqrt{2/3\,C/I}. \tag{2}$$

Different clusters lead to different re-use distances: a small cluster means that the distance between the users and the interfering cells is smaller. Therefore, the higher the re-use distance the higher the *C/I* ratio but less frequencies will be available per cell and the capacity will be smaller. Another way to increase *C/I* ratio is by reducing the number of interferers on the network, which can be done by using sectored cells.

The number of frequency reuse cells is a function of the required C/I ratio in a hexagonal cellular radio system that uses omnidirectional antennas**.** As soon as the C/I ratio decreases, the signal strength start deterioration, thereby reducing the cluster. Equation (2) confirms that smaller frequency reuse pattern is required to enhance spectrum efficiency performance.

2.2. Radio Capacity in Cellular Systems

A parameter named radio capacity by Lee [8] is derived and used to measure the spectrum efficiency of a wireless system. The radio capacity of the Omni cellular system is defined as:

$$m=\frac{B_t}{B_c K} \tag{3}$$

Where m is the radio capacity, B_t is the total allocated spectrum for the system, B_c is the channel bandwidth, and K is the number of cells in a frequency reuse pattern. The factor Q is related with cluster size K in a hexagonal-shaped cellular system by

$$Q=\sqrt{3K}. \tag{4}$$

From equation (1), the co-channel interference reduction factor Q is obtained by;

$$Q=\left(\frac{D}{R}\right)=\left[6\left(\frac{C}{I}\right)\right]^{\frac{1}{\gamma}}. \tag{5}$$

The value of C/I ratio is based on the required system performance and the specified value of γ is based on the terrain environment.

From equations (3), (4), and (5), the radio capacity is given as;

$$m=\frac{B_t}{B_C\frac{Q^2}{3}}=\frac{B_t}{B_C\left[\frac{6}{3^{\gamma/2}}\left(\frac{C}{I}\right)_S\right]^{\frac{2}{\gamma}}}. \tag{6}$$

As shown by Lee [8], in mobile radio environment, assume a fourth power rule, $\gamma=4$, the radio capacity is given as;

$$m=\frac{B_t}{B_c\sqrt{\frac{2}{3}(C/I)_s}}=\frac{M}{\sqrt{\frac{2}{3}(C/I)_S}}=\frac{M}{K}(\text{Frequency channel per cell}) \tag{7}$$

Where $(C/I)_S$ ratio is the minimum required carrier to interference ratio. M is the total number of available voice channels. Equation (7) implies that the maximum radio capacity occurs when $(C/I)_S$ and B_c are minimized.

The total number of traffic channels M depends on the multiple access method. In GSM system which uses

TDMA, Mt must be multiplied by the number of TDMA slots per carrier. In the case of GSM, the result would be $Mt = 8M$ traffic channels. The number of traffic channels is the same as the number of possible users since only one traffic channel is allocated per each user. With this extension to the traffic channels, equation (7) can be represented as

$$mt = \frac{Mt}{K}(\text{Traffic channels per cell}). \tag{8}$$

The capacities of uplink and downlink are same but are not comparable because uplink capacity is mainly related to number of users, and downlink capacity is related to transmitted power of BS. When the specified $(C/I)_s$ ratio is reduced, the radio capacity is increased. When the measured (C/I), is less than the specified $(C/I)_s$ ratio both poor voice quality and dropped call can occur. The above equation is obtained based on six co-channel interferers which occur in busy-hour (worst case) and describe the relationship between capacity, voice quality and dropped call rate. Radio capacity depends on issues such as service area, call duration, number of cells and total bandwidth. Equation (8) gives the relationship between the protection ratio and the number of cells per cluster needed for a satisfactory signal reception.

2.3. Cellular Deployments and Cell Size of Cellular Network

In addition to spectral efficiency, an analysis of the capacity of an actual network across a coverage area must also include the number of cell sites. The calculation for network capacity is the capacity of each cell multiplied by the number of cells in a coverage area. The discussion above already explained that the capacity of a cell is the spectral efficiency value times the amount of spectrum used. In most cellular deployments, each base station is divided into three cell sectors. Thus, the capacity of a cellular coverage area is: (Spectral efficiency) × (amount of spectrum) × (number of cell sites) × (number of cell sectors/cell site, usually 3). The growth in cellular network capacity since the 1980s is much more a function of the growth in the number of cell sites than improvements in the spectral efficiency of the technologies involved. In the U.S., there were 913 cell sites in 1985—at the end of 2012 there were 301,779 [9].

Clearly, the smaller the cell, the greater the bandwidth density, as exhibited by both Wi-Fi and cellular small cells. It could be argued that the best use of cellular spectrum would be to deploy small cells everywhere, but the cost of doing so becomes extremely high, since each small cell needs a physical location with mounting, power, and most significantly, backhaul to the core network. Small cells thus use spectrum efficiently by delivering a large amount of bandwidth, but they are not necessarily economically efficient, which explains why cellular operators are only deploying them selectively in areas of high user concentrations—airports for example.

The cell size evaluation of the cellular network can be expressed as,

$$\text{The traffic carried per site} = \nu \times t_o \times A \tag{9}$$

Where ν = number of mobiles per km^2, t_o = traffic in Erlangs per mobile and.

$$\text{A = area of hexagonal cell } \left(i.e.\ 2.6\,R^2\right).$$

During the last census in 2006, Lagos state was shown to have a population of 17,552,942; of this population, metropolitan Lagos has over 85% of the state population. In the built-up areas of metropolitan Lagos, the average density is over 20,000 persons per square kilometer (km^2). According to the National Population Commission (NPC, 2006), the annual increment is 2.282%. The total available bandwidth in each direction is 14MHz, the traffic assumed to be uniform with the average call holding time of 120 seconds, and the call blocking during the system busy hour is 2%. Developed MATLAB codes are used to arrive at the number of mobiles per Km^2 (V) = 958.8605

$$\begin{aligned} &\textit{The carried per cell site}\\ &= 958.8605\ x\ 0.02\ x\ 2.6\ R^2\\ &= 49.860746 R^2\ Erlangs \end{aligned} \tag{10}$$

$$\text{The Spectral Efficiency } (\eta_s) = \frac{\text{Traffic per cell} \times N_c}{B_t \times A}\ Erlangs / Km^2 / MHz \tag{11}$$

Where;
B_t = Bandwidth of the network service
N_c = number of cell in the service (i.e. A/2.6R^2) and
A = Area of service in km^2.

$$\text{The Spectral Efficiency } (\eta_s) = \frac{\text{Traffic per cell}}{2.6R^2 \times B_t}\ Erlangs / Km^2 / MHz \tag{12}$$

and

$$\text{Radius (R)} = \sqrt{\frac{\text{carried traffic}}{49.860746}}. \tag{13}$$

Equation (12) gives a practical representation of the improvement in capacity achieved relative to cell sizes (and reused distance) with available resources. If the reuse distance based on available resource per unit area becomes less, the resource utilization efficiency reduces. However, it reduces interference and improves system capacity. This is one of the significant performance indicators to compare different frequency planning schemes which certainly impacts cellular system design [10].

2.4. Sector Traffic

Most of the mobile base station antennas used in systems today have Omni directional or sectorized static radiation patterns. This approach benefits from the facts that the base station doesn’t have to know the exact position of the mobile users located in a cell. The technique of sectorization is well known, and consists in dividing the cell into several equal angular sectors, and are deployed for enhancing the network capacity and quality of service which have been deteriorating as the number of mobile users continue to increase on daily bases. Since the capacity and QoS in cellular network depend on the number of users, the coverage of a sector is ensured by a directional antenna, which radiates mostly to the area of that sector and not to the others. By doing this, the number of interfering base stations (BSs), is reduced and the co-channel interference decreases. Most of the recent existing base stations (cells) in use in South Western region of Nigeria have three sectors per cell.

The recent cellular mobile systems use three (tri-sectoral) 120^0 antennas to cover one cell, while a six- sectored (hexa-sectoral) cellular system using six 60^0 antennas at a cell site is proposed in this work.

According to Stjernvall [11], one benefit of this approach is that it is economical. Fewer base stations are required over a certain geographic area. The number of interferers (i_o) depends on the beam width angle of each cell sector. For a sector of 360°, $i_o = 6$; for 180°, $i_o =3$; for 120°, $i_o =2$; and for angles smaller than 90°, $i_o =1$. So, m α $1/S$ being S the number of sectors per BS. Figure 3 shown the sector A with 120° receiving interference from two cells and the sector B of 60° receiving interference from one cell.

The bandwidth needed for a deployment is calculated by multiplying the number of sectors of a cluster by the bandwidth of each sector, BW_{sector}. The number of sectors is computed by multiplying the number of cells in a cluster, K, by the number of sectors per cell, S.

$$BW_{total} = K.S.BW_{sector}. \tag{14}$$

Therefore, when the constellation is denser, the distance between the symbols is smaller, so a larger C/I ratio and total bandwidth are needed for a deployment [12].

The strategy to increase the bandwidth of the channel, BW_{sector}, produces an increment of the total bandwidth needed. Nevertheless, this strategy does not increase the spectral efficiency, but allow the processing of more traffic per user and per sector. One disadvantage is the increase of the interference because it depends linearly with the bandwidth.

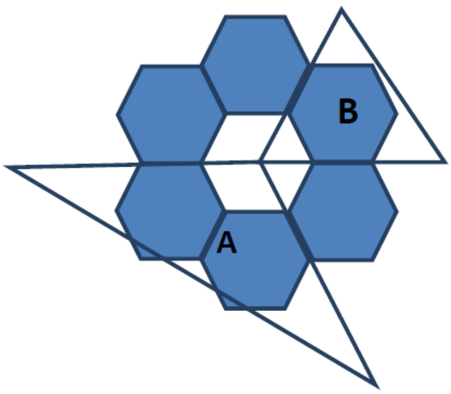

Figure 3. Two Sectors with different Angles, A:120° and B:60° showing the Interferers in each case [12]

3. Analysis of Carrier to Interference Ratio

A parameter of interest to assess the system performance in this case is the carrier-to-interference (C/I) ratio. The ultimate objective of estimating this ratio in wireless systems is because it reflects user's throughput and quality of service. Therefore, computing the signal to interference ratio is important for determining coverage, capacity, and quality of service in a cellular system. The C/I ratio at the mobile is a random variable, affected by random phenomena as mobile location, fading, cell site location, traffic distribution, and others. The Wideband Signal to Interference (SIR) Ratio is also called as Carrier to Interference (C/I) Ratio. The Carrier to Interference ratio is very important in Cellular systems in order to determine the maximum allowed interference level for which the system will work. The more the C/I ratio is, the less co-channel interference we have and there is a room for applying a tighter reuse figure without loss of quality. The C/I ratio value should not be less than a certain threshold for more than 10% of the service area [13] and given as;

$$\text{The mean } \frac{C}{I} = \gamma \log \sqrt{3K} - 10 \log I_o. \tag{15}$$

For the conventional cellular network systems other tier CCI are neglected, which holds because frequencies are less than 2GHz, and cell size radius are 1.6Km (1mile), and above [14]. However, for emerging cellular communication system frequencies are greater than 2GHz, and cell size radius are less than 1km [15]. The C/I ratio is expressed by

$$C/I = 10 \log \left[\frac{1}{I_o} \times \left(\frac{D}{R} \right)^{\gamma} \right] \tag{16}$$

Where, I_o is number of co-channel interferer ($I_o = 6$ in Omni directorial antenna, 2 and 1 in sectoring cell (1st tier), γ is the propagation constant ($\gamma = 4$ in a cellular mobile environment), D is the frequency reuse distance which depends on many factors such as; The number of co-channel cells in the vicinity of the center cell, the geographical of the terrain, the antenna height, the transmitter power within each cell and R is the radius of the cell

According to KiTae and Keunch [16] the equation (16) may be written as

$$C/I = 10 \log \left[\frac{\left(\sqrt{3K}\right)^{\gamma}}{I_o} \right] \tag{17}$$

K = frequency reuse factor (Number of times a frequency can be reused in a network of cells).

A high C/I ratio yields quality communication. A good C/I ratio is achieved in cellular systems by using optimum power levels through the power control of most links. When carrier power, is too high, excessive interference is created, degrading C/I ratio for other traffic and reducing the traffic capacity of radio system. When carrier power is too low, C/I ratio is too low and QoS targets are not met. A simple but very effective formula for evaluating the spectrum efficiency has been derived in this work called radio capacity. Evaluation of any communication system is based on its voice quality resulting in the results in Table 2.

Table 1. Omni Directional Verses Sectorized Cellular System Performance

System	Frf	Total number of channels	Channels per sectors	Offered load/cell (E) 2%	Carried load/cell (E)	Trunking Efficiency GoS=2%	Calls/hour/ cell (cell capacity)	Required cell radius $R(km)$	Spectral efficiency E/km^2 MHz	C/I in dB
Omni	1	125	125	112.3	110.1	88.08	3303	1.0780	1.3698	1.8
	3	125	42	32.3	32.1	76.43	966	0.5567	1.3698	11.3
	4	125	31	22.8	22.3	71.94	684	0.4752	1.3698	13.8
	7	125	18	11.5	11.3	62.78	339	0.3161	1.3698	18.7
	12	125	10	5.5	5.4	51.00	180	0.2216	1.3698	23.3
120^o sector	4	125	10	5.1	5.0	50.00	450	0.3664	1.3698	18.6
	7	125	8	3.6	3.5	43.75	207	0.1886	1.3698	23.4
	12	125	3	0.6	0.6	20.00	87	0.1147	1.3698	28.1
60^o sector	3	125	7	2.9	2.8	40.00	513	0.3589	1.3698	19.1
	4	125	5	1.7	1.7	34.00	306	0.2667	1.3698	21.6
	7	125	3	0.6	0.6	20.00	105	0.1622	1.3698	26.4

Table 2. Simulated values for relations Re-Use factor (Q), Carrier to Interference Ratio (C/I), Cluster size (K), and Spectrum Efficiency for Omni and Sectors Cell

System	Cluster Size (K)	Carrier to interference ratio(C/I) dB	Re-Use Factor (Q)	Channel Bandwidth (KHz)	Spectrum Efficiency Channels/MHz/Km^2
Omni	1	1.8	1.73	200	69.686
	3	11.3	3	200	23.342
	4	13.8	3.46	200	17.504
	7	18.7	4.56	200	9.957
	12	23.3	6	200	6.579
120^0 sectors	4	18.6	3.46	200	10.073
	7	23.4	4.56	200	5.796
	12	28.1	6	200	3.374
60^{0}sectors	3	19.1	3	200	9.509
	4	21.6	3.46	200	7.131
	7	26.4	4.50	200	4.104
	12	31.1	6	200	2.389

4. Results

It can be inferred from Figure 4 that the cluster size and co-chemical reuse factor forms some factors for a more efficient cellular network system which translates to a proportional increase in the number of users supported at the same load per user. It can be seen that co-channel reuse factor varies proportionally with cluster size while at the same time it is inversely proportional to spectrum efficiency. The point of intersection at the two curves thus provides the point of optimum performance. However, MTN uses 3 and 4 as the co-channel factors throughout its Apapa network. It can be seen that the optimum point occurs at 3.4 which implies Apapa is not operating far from the optimum point.

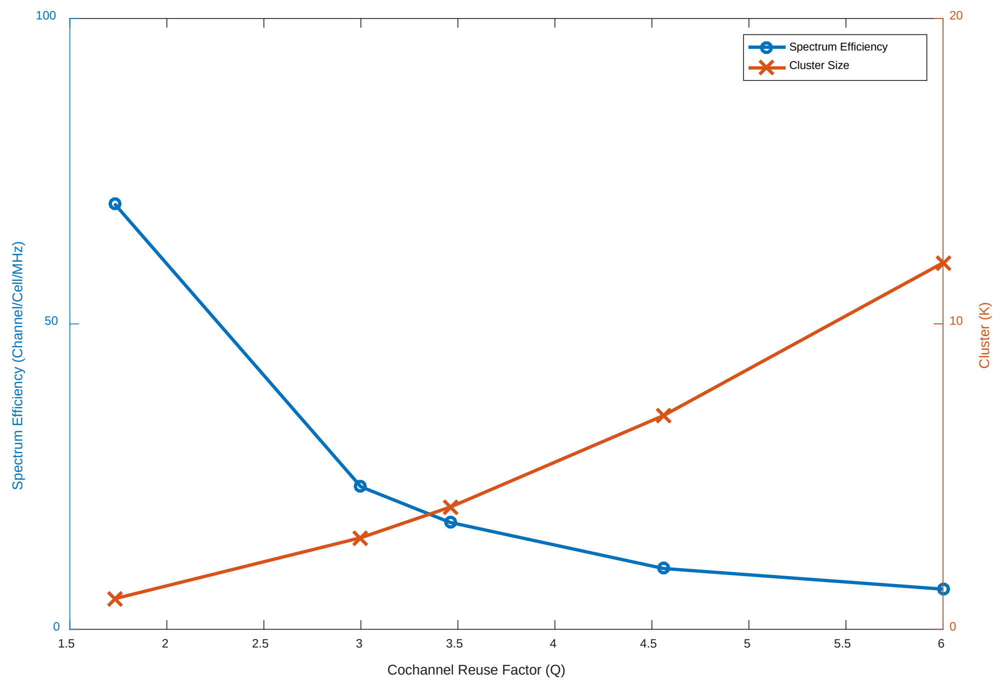

Figure 4. Variation of Co-Channel Reuse Factor with Spectrum Efficiency and Cluster Size for Omni and sectors cell

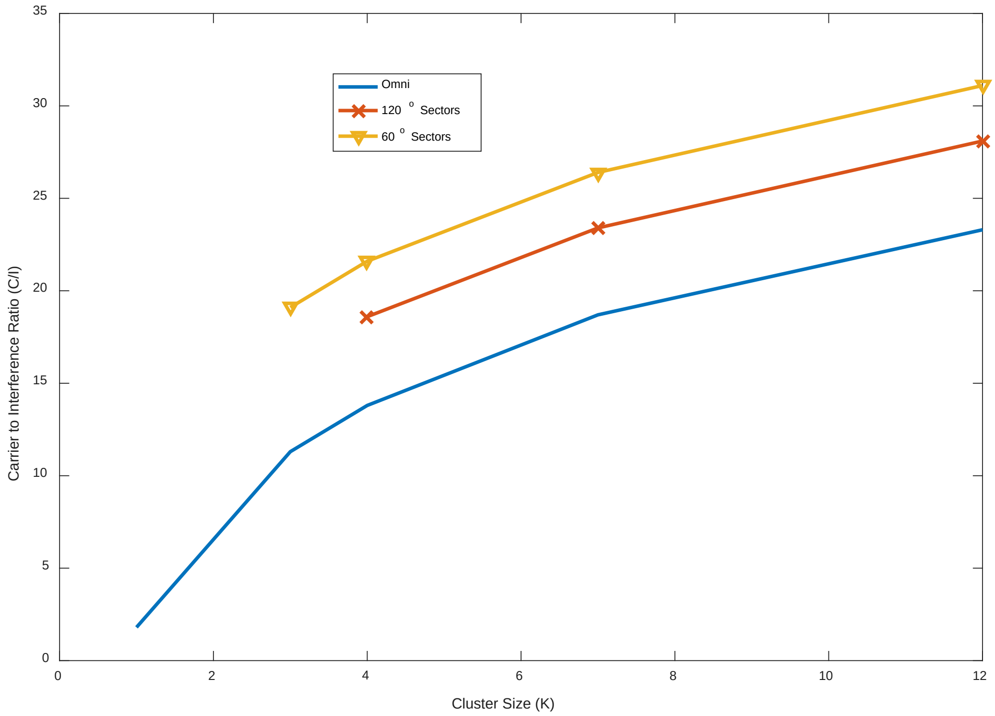

Figure 5. Variation of Cluster Size (K) with Carrier to Interference Ratio(C/I) for Omni, 120^0 Sectors and 60^0Sectors

The graph of Figure 5 gives a clear analysis of the comparison between the effects of interfering signals on the mobile users in wireless network (i.e., the effect of the frequency reuse factor over the C/I ratio). It can therefore be inferred that sectoring reduces co-channel interference, gives access to more mobile users which enhances the capacity of the cellular wireless system. It is also observed that for the same values of cluster sizes (K), 120° sectored and 60^0 sectored cells gives better carrier to interference ratio than non-sectored (omnidirectional, 360°) cells - the performance of improvement of the 60° sectored provides better coverage performance than 120° sectored and Omni. Considering the Apapa area network which uses 120° sectoring, it can be inferred that the network is performing well, though not optimally as it should at 60°. However, it is not recommended to use omnidirectional in the area because of the high interference that would be encountered.

5. Conclusion

Quality of service also relates to signal quality. A network with fewer cell sites might appear economically more efficient than one with more sites, but if users experience dropped calls or cannot connect at all, then the efficiency advantages are of dubious value. If the value of an application could be factored in, then the ultimate spectrum efficiency measure would combine the application value with spectral efficiency of the technology used, degree of frequency reuse, and economic efficiency. Among the alternatives that aim to increase the network capacity, higher order sectorization, and in particular a six sectorized configuration, is nowadays attracting a lot of attention for cellular cell-deployments since a higher number of sectors per site results in improved site capacity and coverage. A six sectorized configuration is attractive for both roll-out phase and growth phase of the network. In the roll-out phase, the radio access network is planned with 6-sector sites instead of 3-sector sites with the advantages that less sites are needed for the same capacity and coverage requirements and to combat the problem of network congestion and instability. In the growth phase, the six sectorized configuration can be used to upgrade existing 3-sector sites where the traffic grows beyond the current sites' capabilities. Hence, a six sectorized configuration is able to enhance the performance of congested hotspots at the cost of a slight performance degradation in the surrounding sites.

Therefore, we recommend that with the parameters and the assumptions that were considered in the study, the adoption of 6-sector sites along with 3-sector sites in cellular cell -deployments allows service operator to reduce capital expenditures compared to the only adoption of 3-sector sites.

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