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Frequency re-use distance calculation in cellular systems based on Monte-Carlo simulation

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Abstract

Radio spectrum's sharing guideline is an essential component of spectrum utilization process. Since there is no insightful interference avoidance method in a radio system, the careful selection of sharing conditions is the only means for achieving successful co-existence and optimal spectrum usage in the radio system. Spectrum sharing rule can be obtained by an analytical method or statistical method. The analytical method considers the worst case scenario to calculate sharing rules. Nonetheless, this doesn't represent the lasting phenomenon amid ordinary task; moreover sharing rules may be unnecessarily rigid. Henceforth, the Monte Carlo Simulation (MCS) strategy has been utilized to establish a probability of interference based on a random distribution of victim link receiver in time and space with respect to victim link transmitters.

The study has been done for cluster number N with values of 1, 3, 4, and 7 in a cellular system. Monte Carlo Simulation analysis showed the percentages of interference are 24.94%, 9.36%, 3.33%, and 0.4% for N = 1, N = 3, N = 4, and N = 7 respectively. In terms of throughput per total bandwidth per a single site, N = 7 offers a spectrum utilization of 1/7 and N = 4 offers a spectrum

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utilization of 1/4. Therefore, a relative enhancement in capacity of 7/4 has been achieved with 3.3% probability of interference which is below the threshold value of 5%.

Keyword: Electrical engineering

1. Introduction

Usable radio frequencies are an extremely constrained asset in nature. There is just 25 MHz and 75 MHz transmission capacity accessible in GSM 900 and 1800 MHz respectively [1, 2]. Hence, expanding interest for the current radio application and the presentation of another applications have made a major test in radio frequency asset management [1, 3, 4]. The cellular idea was a landmark in taking care of the issue of spectrum congestion and client capacity [1, 4, 5]. This framework offered high capacity with no major technological changes by dividing these limited resource over some predefined distance over and over again [1, 4, 5].

Dividing radio application in topography assumes a basic job when versatile system administrator structures to utilize a similar channel over again to build frequencies use [1]. The dispersing of a similar radio recurrence over some separation is called re-use distance [1, 4, 6]. At the point when same radio frequencies are utilized over again in the range of short separation, it expands frequencies usage factor yet will introduce interference as well [1, 4]. This specific sort of interference is called Co-channel interference and it is a predominant feature/aspect of a wide range of interference in a cellular system [1].

The trade-off between the radio frequencies utilization and re-use distance is done by conventional rigid-techniques that specify sharing rules such as maximum transmitter power, re-use distance, and guard-bands to the existing radio system [1, 2, 4]. This analysis is done for the most pessimistic scenario that specifies minimum separation distance required to avoid interference between the Co-channel frequencies. Thus, the analytical method looks for the corresponding separation distance that would give minimum Carrier to Interference ratio (C/I). However, such most pessimistic scenario suspicion won't be perpetual amid typical activity (i.e. since versatile clients are randomly and consistently appropriated in the inclusion territory of the Base station) and for this reason sharing rules may be pointlessly inflexible [7]. Therefore, spectrum utilization is not ideal and may prompt underutilization of these limited resources.

While statistical analysis based on MCS would give ideal spectrum usage than analytical method since MCS uses a given realistic deployment scenario to establish a probability of interference between victim link and interfering link in the same band or adjacent band [7]. MCS uses a repeated random generation of victim link,

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interfering link and their parameters [3, 8, 9]. After numerous trials (i.e. it is user-defined), not only unfavorable but also favorable case will be accounted and the resulting rules will be fairer than the analytical method. Therefore, spectrum utilization using the MCS is ideal than the analytical method [3, 7, 10, 11].

The MCS has also been used to study interference in [3, 8, 9, 11, 12]. The interference causes degradation of the performance on the victim link receiver system causing a reduction in the data transmission rate, especially for victim link receiver near the edge of the victim link transmitter coverage area [1, 4, 8, 13]. Interference has been recognized as a major bottleneck in increasing the capacity of a radio system and is often responsible for dropped calls [1, 2, 3, 4, 5, 11, 12]. Therefore, this problem cannot be ignored.

There are a number of studies on interference and its mitigation methods to maintain a strategic distance from common Co-channel interference source in the radio system. MCS is one of such studies and has been used in the literature to study the co-existence between LTE and Digital broadcast in [3, 8, 9, 11, 12]. The authors in [3, 8, 9, 11, 12], presumed that the MCS offers the best performance in terms of examining complex interference than the analytical method. From the simulation results in [3, 8, 9, 11, 12], spectrum sharing rule in terms of maximum interfering transmitter power, guard band between the LTE and Digital television frequencies, and least physical partition between the LTE and Digital television had been proposed to avoid the mutual interference between the LTE and Digital television.

However, MCS to calculate a re-use distance (D) between co-channel cells in the cellular system has not been given much consideration. In this paper, therefore, we propose MCS method to study co-channel interference in cellular system and demonstrate via simulation an improvement in terms of spectrum sharing rules with added flexibility unlike the rigid analytical method.

The remainder of this paper is structured as follows: The analytical study on the interference and design of MCS are presented in section 2. Section 3 analyzes the results of the simulation. Conclusions of the whole paper are presented in Section 4.

2. Materials and methods

The Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT) uses four basic elements [3, 7, 8, 9]: These are the Victim Link Transmitter (VLT), the Victim Link Receiver (VLR), Interfering Link Transmitter (ILT), and Interfering Link Receiver (ILR). The VLR receives the desired Received Signal Strength (dRSS), while the ILT generates interfering Received Signal Strength (iRSS), as shown in Fig. 1. Harmful interference occurs when Carrier to Interference ratio (dRSS/iRSS or C/I) at the victim receiver is less than the allowable threshold [7].

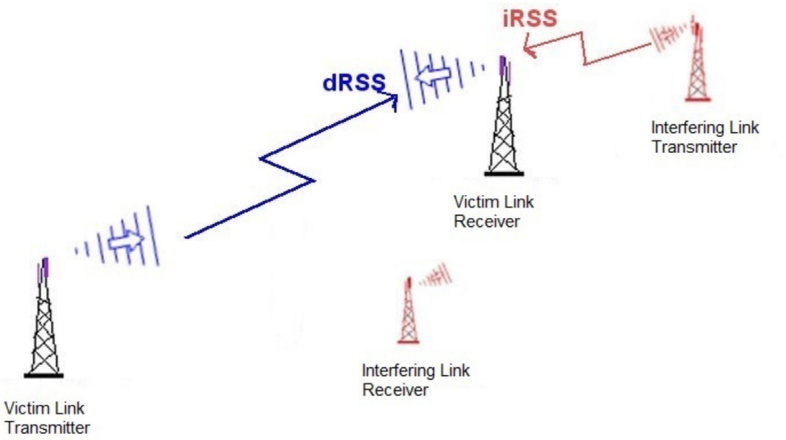

Fig. 1. Typical scenario of victim and interfering link.

SEAMCAT produces random spatial and temporal distributions of VLT, ILT, VLR and their parameters to find whether the interference has happened at the unfortunate VLR or not [7]. The user can set in the software interface the parameters of the VLT and ILT (the number relies upon nature of wireless environment, higher in urban situations) and of the spatial position of VLT and ILT with respect to each other [3].

Victim link consists of VLT, radio path, and VLR as shown in Table 1 [3, 8, 9]. Interfering links consists of one or more ILT, radio path and ILR as shown in Table 2 [3, 8, 9].

2.1. Interference calculation method

Interference occurs when the VLR has a carrier to interference ratio that is less than the minimum allowed protection ratio. The minimum protection ratio may vary from 9 dB (e,g for QPSK) to 26 dB or higher (e.g. for 64QAM…) [7]. Hence, it is very

Table 1. Parameters of interfering link [3, 8, 9].

Parameters	Values
Power	33 dBm
Emission mask	−36 dBm per 100 kHz for GSM 900 MHz [14]
Frequency	Absolute radio frequency channel number 10 (937 MHz)
Bandwidth	200 kHz
Antenna height	33 m
Gain	14.5 dbi
Distance	Distance to VLR depends on the random position of victim
Propagation model	Free space
Cell size	3 km

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Table 2. Parameters of victim link.

Parameters	Values
Power	33 dBm
Frequency	Absolute radio frequency channel number 10 (937 MHz)
Bandwidth	200 kHz
Antenna height	33 m
Gain	14.5 dBi
Pattern	Three sector
Distance	Distance between VLT and VLR varies according to random position of VLR in the coverage area of VLT
Cell size	3 km
Propagation model	Free space model
Sensitivity	−101.5 [9]
Blocking mask	First adjacent channel = −9 dB, Second adjacent channel = −41 dB, Third adjacent channel = −49 dB [15].
Bandwidth	200 kHz
Antenna height	1.5 m
Noise floor	9 dB [9]
Gain	2 dB

important to calculate dRSS and iRSS at the front end of the VLR to determine the value of interference to decide whether interference has happened.

The MCS procedure works by considering numerous autonomous occasions in time and space. For each instance, a scenario is built up using a number of different random variables (i.e. where the interferer is located with respect to the victim) [3, 7, 8, 9]. From these different scenarios, dRSSS is calculated between VLR and VLT, and iRSS is calculated between VLR and ILT. In the event that an adequate number of simulation trials are considered, at that point the likelihood of interference occurring can be calculated with a high level of accuracy [7]. To acquire dependable outcomes, it is prescribed to utilize a substantial number of occasions in the order of 20,000) [7].

Four interference criteria are considered within SEAMCAT [3, 7, 8, 9].

C/I	Carrier to interference ratio;
C/(I + N)	Carrier to interference plus noise ratio;
(N + I)/N	Desensitisation;
I/N	Interference to noise ratio

The SEAMCAT considers the impact of co-channel and adjacent channel interference, including unwanted emissions, intermodulation products, and receiver blocking [3, 7, 8, 9].

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2.1.1. Interfering modes

The level of unwanted emissions consists of the spurious emissions and out-of-band emissions of ILT falling within the VLR'S bandwidth. This phenomenon of picking an electromagnetic field on an adjacent channel is referred to as the Adjacent Channel Leakage Ratio [8]. Unwanted emission is determined using the ILT mask as illustrated in Fig. 2, the selectivity of the VLR, VLT frequency separation, antenna gains, and propagation loss as given in Eq. (1) [7].

$$\textbf{unwanted emissions}(\textbf{dB}) = \textbf{Pt} + \textbf{Gt} + \textbf{Gr} - \textbf{L} + \ +\textbf{Attenuation}\left(\frac{\textbf{dBc}}{\textbf{Bref}}\right) \tag{1}$$

where Pt is transmitter power, Gt is transmitter antenna gain, Gr is receiver antenna gain, and L is free space propagation loss. Attenuation (dBc/Bref) can be calculated as −36 dBm per 100 kHz for GSM 900 MHz [14].

The receiver blocking power is the power captured from the transmission of the interferer due to selectivity imperfections of the victim's link receiver as shown in Fig. 3. The receiver blocking power is determined using the interferer's transmit

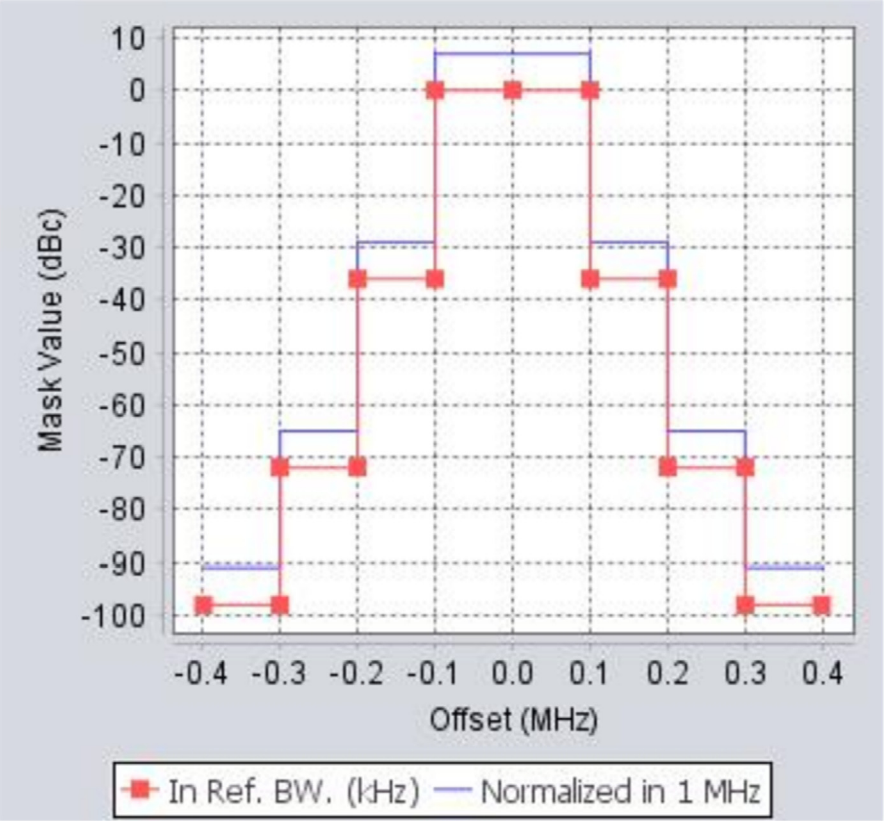

Fig. 2. The unwanted emissions of ILT falling in the VLR bandwidth.

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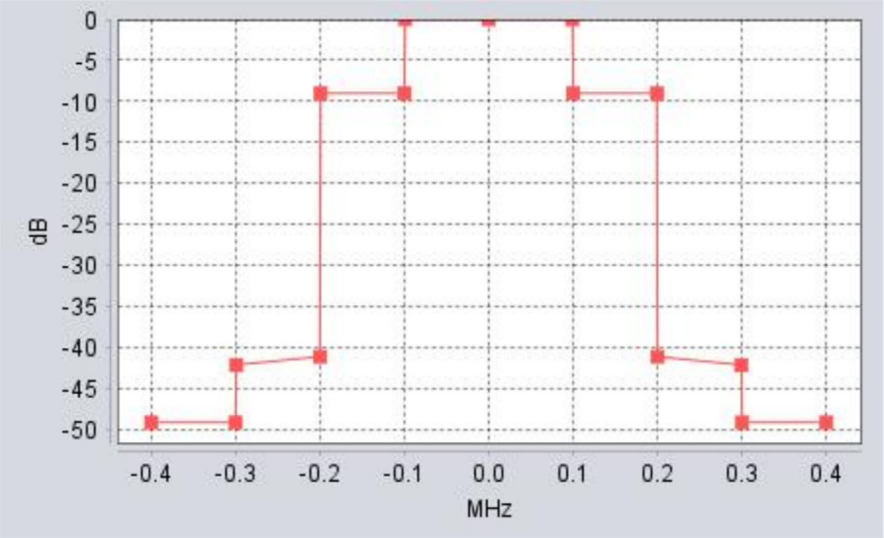

Fig. 3. Blocking of the victim link receiver.

power, VLR blocking performance, interferer/victim link frequency separation, antenna gains and propagation loss as shown in Eq. (2).

$$\textbf{iRSS blocking} = \textbf{Pt} + \textbf{Gt} + \textbf{Gr} - \textbf{L} - \textbf{Attenuation}\,(\textbf{fit}) \tag{2}$$

where Pt is transmitter power, Gt is transmitter antenna gain, Gr is receiver antenna gain, and L is free space propagation loss. Attenuation (fit) in the first adjacent channel = −9 dB, second adjacent channel = −41 dB, and third adjacent channel = −49 dB [15].

If the VLT and ILT operate at the same frequency in the same area as shown in Fig. 4, the VLR will receive interference in the band of the VLR. This particular interference is known as co-channel interference and it is the dominant of all types of interference.

$$\text{iRSS} = \text{Pt} + \text{Gt} + \text{Gr} - \text{L} \tag{3}$$

Where Pt is transmitter power, Gt is transmitter antenna gain, Gr is receiver antenna gain, and L is free space propagation loss.

2.1.2. Analytical study on co-channel interference

In the fully hexagon-shaped cellular system, there are 6*m co-channel cells in the m$^{\text{th}}$ tier, regardless of the number of cell per cluster. VLR in the center cell can be interfered by six Co-channel cells on the first tier, 12 Co-channel cells on the second tier, and 18 Co-channel cells on the third tier and so on as shown in Fig. 5 [4, 6].

At the VLR, which is being served by VLT on the center of the cluster, we used Eq. (4) [4, 6], to calculate the dRSS.

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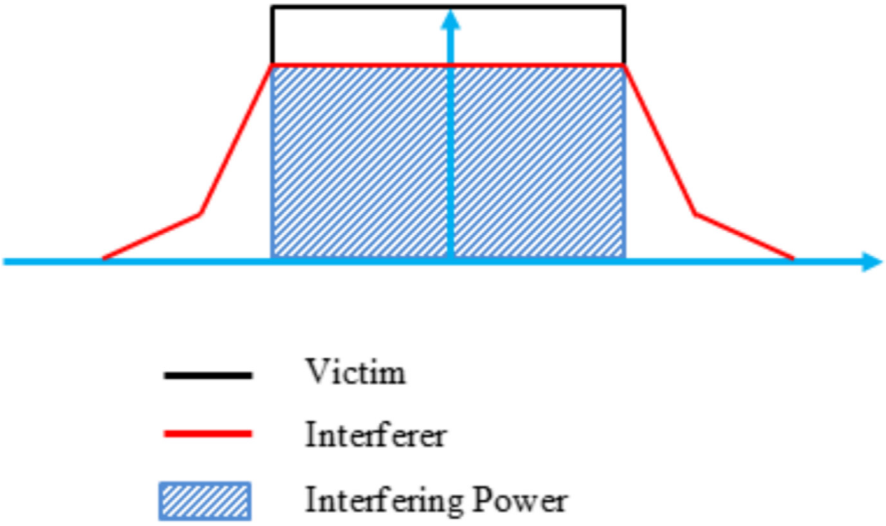

Fig. 4. Co-channel interference.

$$dRSS \propto \frac{1}{R^{\alpha}} \tag{4}$$

where R is a distance between VLR and VLT in meters and α a path-loss constant.

We used Eq. (5) [4, 6], to calculate total iRSS from all the co-channel ILT.

$$iRSS \ \propto \left[\frac{6x1}{D^{\alpha}} + \frac{6x2}{(2D)^{\alpha}} + \frac{6x3}{(3D)^{\alpha}} + \frac{6x4}{(4D)^{\alpha}} + \ldots\right] \tag{5}$$

where D is the re-use distance and α path-loss constant

$$\frac{dRSS}{IRSS} = \left(\frac{D}{R}\right)^{\alpha} \frac{1}{6\sum_{m=1}^{T} \frac{1}{m^{\alpha-1}}} \tag{6}$$

where T is the number of tier and α is path-loss constant.

For the first tier co-channel cell Eq. (6) will reduce to Eq. (7) [4, 6].

$$C/I = \frac{iRSS}{iRSS} = \frac{\left(\frac{D}{R}\right)^{\alpha}}{6}, \tag{7}$$

In dB the same equation will be reduced to:

$$C/I = \frac{dRSS}{iRSS} = 10\log_{10}(D) - 10\log_{10}R - 10\log_{10}6 \tag{8}$$

where R is a distance between a victim link receiver, victim link transmitter in meters, and α a path-loss constant.

When the size of each cell is approximately the same and the base stations transmit the same power, the co-channel interference ratio is independent of the transmitted

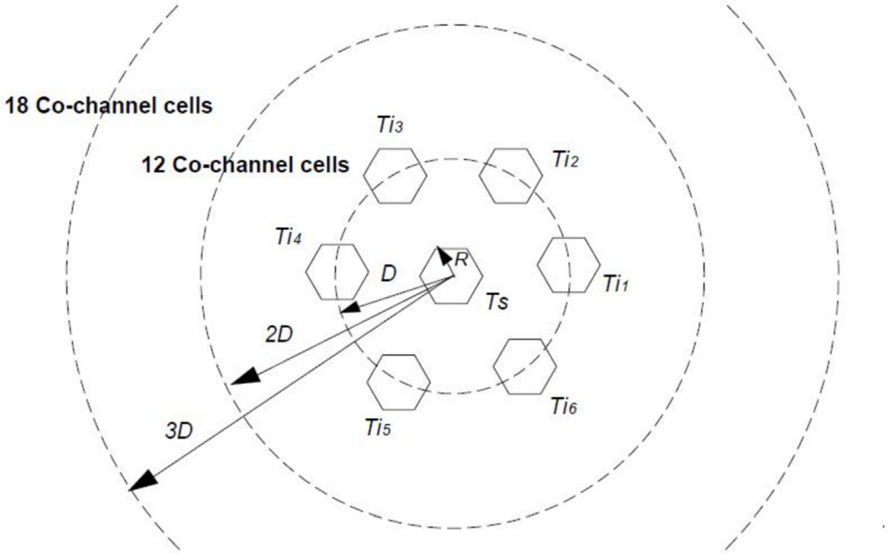

Fig. 5. Co-channel cells [4, 6, 13].

power and becomes a function of the path loss exponent (α), radius of the cell (R), and re-uses distance (D).

2.1.3. Monte Carlo analysis on co-channel interference

Interference from the first tier of co-channel cells on VLR is presented by the help of MCS. In MCS, all co-channel cells are using the same frequency as the cell serving a mobile station as in Fig. 6.

When the total interference from Co-channel cells to VLR is evaluated, the most severe interference comes from the first. To find the nearest co-channel neighbors of a particular cell, one must do the following: (1) move i cells along any chain of hexagons and then (2) turn 60° counter-clockwise and move j cells [1]. This is illustrated in Fig. 6 for i = 3 and j = 2 [1, 2, 4, 16].

$$D = \sqrt{(i^2 + ij + j^2)}\left(R\sqrt{3}\right) \tag{9}$$

where (i, j) are non-negative integers, D is the re-use distance, and R is the coverage area of the cell in the middle of the hexagons.

After the location of all co-channel cells was identified in the cluster, the SEAMCAT tool was used to analyze the co-channel interference.

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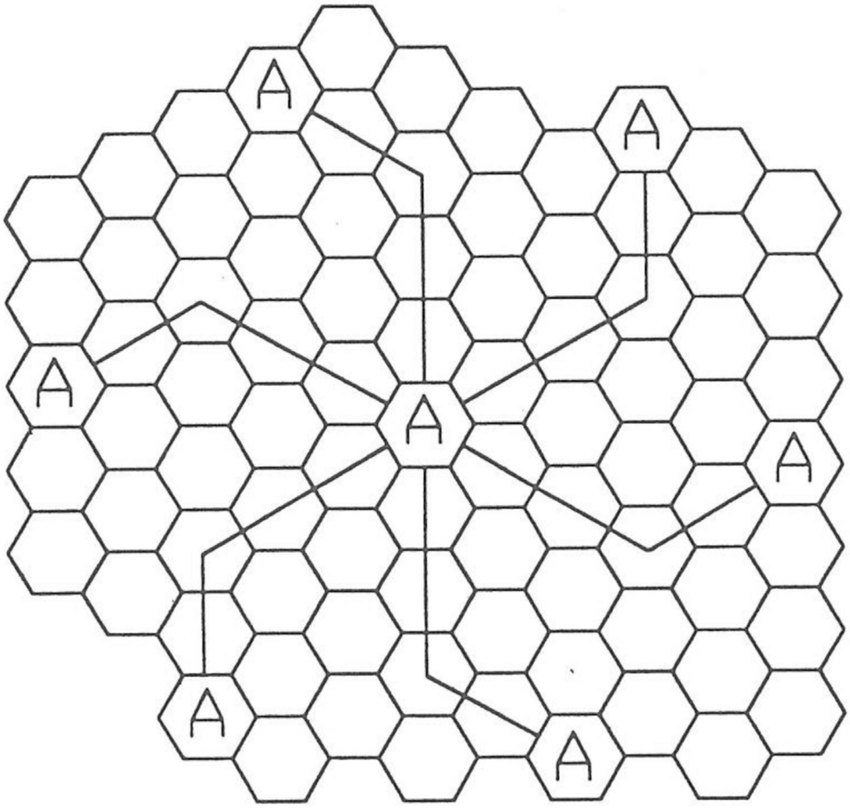

Fig. 6. Method of locating co-channel cells in a cellular system [1].

The simulation methodology for one snapshot is summarized as follows:

i. Decide the location of the center cells and all the surrounding co-channel cells in the cluster according to the re-use distance (1,0), (1,1), (2,0), and (2,1)) for N = 1, 3, 4, and 7 were used respectively to locate all the co-channel cells in the cluster.

ii. Drop victim link receiver into the coverage of the center cell in cluster randomly and uniformly.

iii. Calculate the path loss between center cell to victim link receiver and all co-channel cells to victim link receiver.

iv. Calculate the wanted signal from the center cell at the victim link receiver (dRSS) and unwanted signal (iRSS) at the victim link receiver from all the co-channel. Then record carrier to interference plus noise ratio. After sufficient (in this case, it is 20,000 times) snapshots [8].

MCS was performed to calculate a percentage of events in which carrier to interference and record regardless of whether interference is happening. In this strategy, the MCS tool helps to quantify the probability of interference between radio systems and determines appropriate spectrum sharing rules for possible coexistence between radio systems [7].

The aggregate level of interference (percentage of coverage area loss) can be calculated as the ratio of time interference occurred to the total number of snapshots. The probability of interference of 5% was considered in [8, 9, 12], as the maximum acceptable limit. Along these lines, 5% has been adopted to determine a minimum necessary transmitter powers and re-use distance to avoid the interference from Co-channel cells into Mobile station.

3. Results and discussions

A small value of D/R provides a larger capacity since the cluster size N is small but it introduces a big interference whereas the large value of *D/R* limits the capacity of the cellular system and corresponds to lower interference [1, 4].

A trade-off must be made between these two conflicting interest in actual cellular design. The signal to interference ought to be greater than the minimum acceptable C/I to sustain sufficient voice or data quality. For practical implementation, D/R value of 4.58 is required to maintain the minimum threshold based on worst case situation using the analytical method [1, 5].

3.1. Monte Carlo simulation and analytical study on relative position of ILT to VLT and VLR

In this study, a range of a cell was thought to be 3 km. VLR are uniformly distributed in the coverage area of VLT [1, 4, 5, 13], but the analytical study only considers the worst case scenario that VLRs are on the edge of the cell (R = 3 km). In this regard, the corresponding values of D with respect to VLT can be calculated from Eq. (9). D values are 5.19 km, 9 km, 10.38 km, and 13.74 km for N = 1, N = 3, N = 4, and N = 7 respectively.

In any case, the pessimistic scenario doesn't represent the permanent phenomenon since it seldom happens. In addition, D is fixed with respect to VLT, not to VLR. This gave a little more room for MCS method study to exploit the gap. Fig. 7 shows a random distribution of VLR in time and space with respect to VLT in the MCS.

Since MCS considered not only an unfavorable but also a favorable case, unlike the analytical analysis where a distance between ILT and VLR is D, the MCS shows the distances between ILT and VLR are not necessarily D. As it is shown, the distance between ILT and VLR varies between 5 km to 7 km, 9 km−11 km, 10.5 km−12.2 km and 13.8 km−15.8 km for N = 1, N = 3, N = 4, and N = 7 respectively. This has happened because a VLR is not always at the VLT as indicated in Fig. 8.

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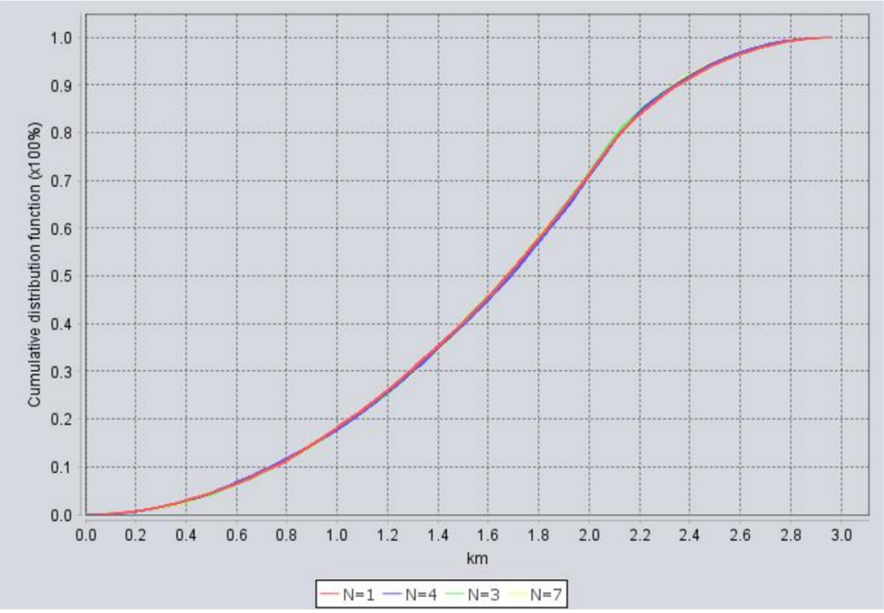

Fig. 7. Distance between the VLT to VLR in Km.

3.2. Monte Carlo simulation and analytical study on co-channel interference

In the case of the analytical method, using the link budget in Eq. (3) the values of iRSS are −48.84 dBm, −53.62 dBm, −54.86 dBm, and −57.33 dBm for N = 1, N = 3, N = 4, and N = 7 respectively. In similar analysis, from the same link budget

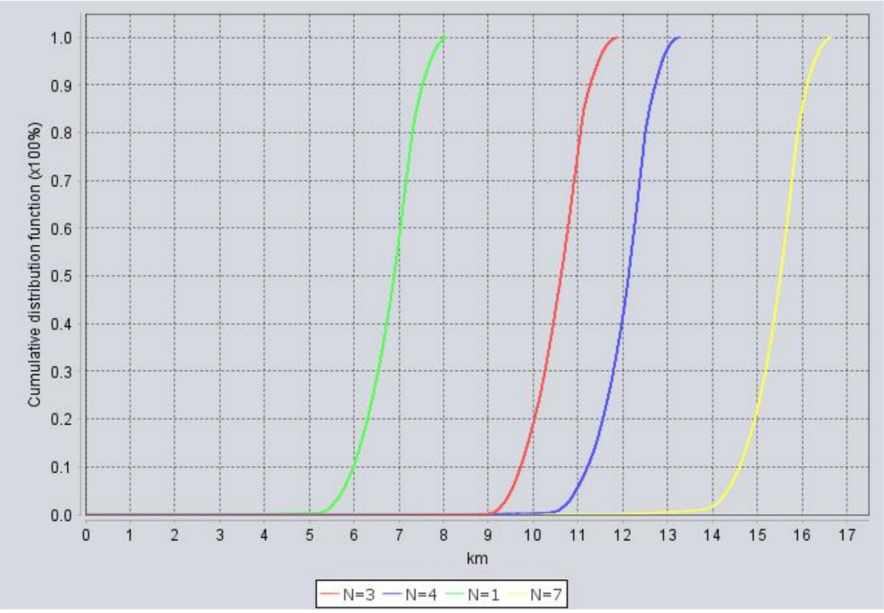

Fig. 8. Distance between ILT to VLR in Km.

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Table 3. Relationship between the D, R, C/I, and path loss exponent.

i	j	N	D/R	C/I (when $\alpha = 2$) in dB	C/I (when $\alpha = 4$) in dB
1	0	1	1.73	−3.17	1.43
1	1	3	3	1.76	11.3
2	0	4	3.46	3.34	14.47
2	1	7	4.58	5.47	18.87

in Eq. (3) the worst case dRSS is −51.87 dBm. The corresponding values of C/I are −3 dB, 1.73 dB, 3.34 dB, and 5.47 dB for N = 1, N = 3, N = 4 and N = 7 respectively. These C/I values are the same as what reported on Table 3 for the case of path loss exponents $\alpha = 2$. However, such analysis is short of realistic VLR's mobility behavior inside the coverage area of VLT.

MCS considered a random position of VLR in time and space, the values of dRSS is not a fixed value as in the case of the Analytical method. As shown in Fig. 9, the dRSS are almost similar for N = 1, N = 3, N = 4 and N = 7 as the dRSS is independent of the co-channel cell separation.

Unlike the analytical method, the variations of distance between the ILT and VLR determine the amount of iRSS from the ITL cells. Fig. 10 indicates the variation of iRSS for N = 1, N = 3, N = 4 and N = 7. It is clearly seen the iRSS is stronger for N = 1 due to the shorter distance between VLR and ILT sites and iRSS is weaker for N = 7 due to the larger isolation distance between VLR and ILT.

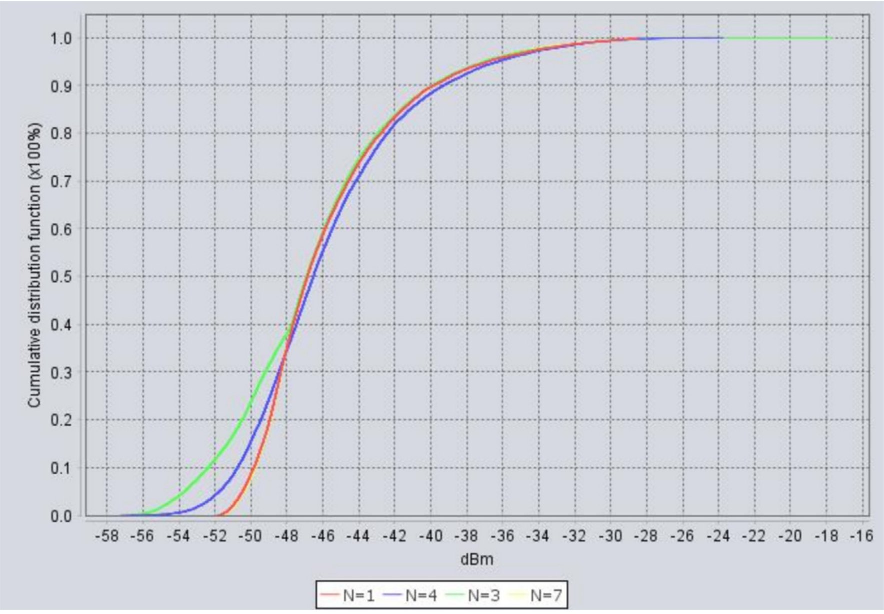

Fig. 9. dRSS from the VLT to VLR in dBm.

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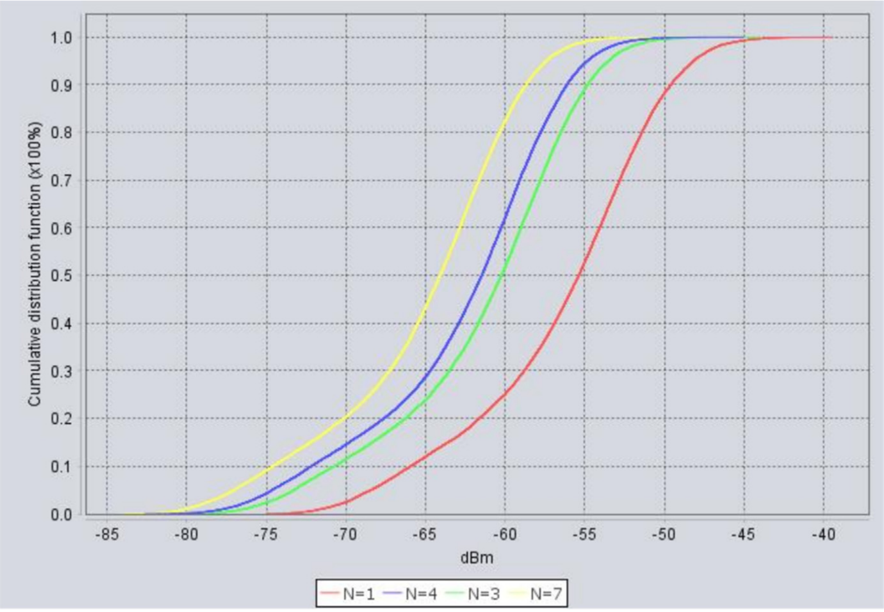

Fig. 10. iRSS from the first tier of co-channel cells in dBm.

Once, dRSS and iRSS are calculated using the MCS, the next step it to calculate the percentage of interference. As indicated in Table 3, D/R = 4.58 was considered to be a minimum threshold to avoid interference in [1, 5], and if we assumed again the path loss exponent is $\alpha = 2$ (i.e. Value used in this simulation), the corresponding values of C/I is 5.47 dB.

From the MCS, as shown in Fig. 11 the percentages of interferences are 24.94%, 9.36%, 3.33% and 0.4% for N = 1. N = 3, N = 4, and N = 7 respectively. As shown

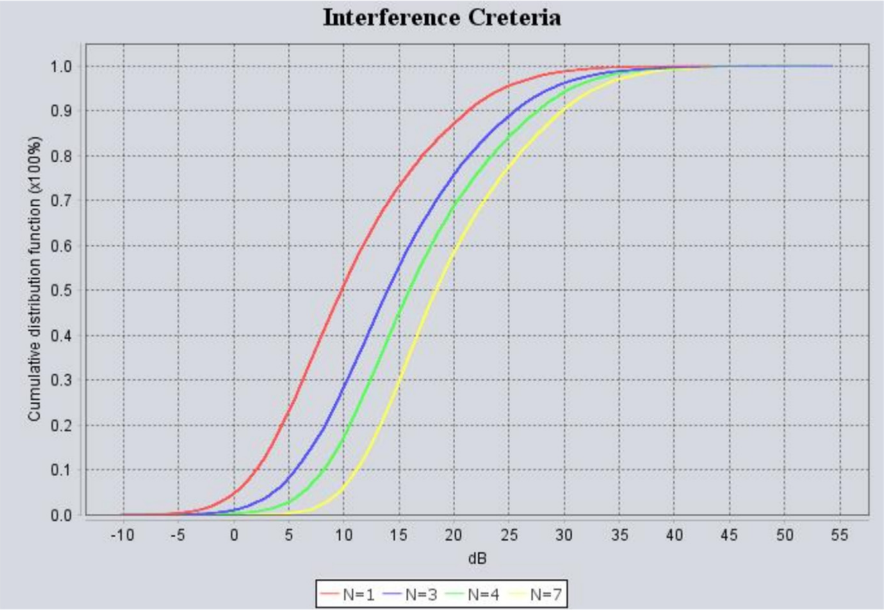

Fig. 11. Interference criteria.

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in Figs. 11 and 12, N = 7 gives the best C/I performance because the co-channel cells are the furthest. N = 1 has a least C/I performance due to the short distance between the co-channel cells. However, in terms of capacity N = 7 offers a spectrum utilization of 1/7 compared to N = 1, in practice a capacity reduction of 1/7 would not be tolerable since the percentage of interference is 24.94% for N = 1.

The probability of interference of 5% was considered as the maximum acceptable limit in many literature [8, 9, 12]. In this regard, the result from simulations indicates N = 4 has 3.33% and N = 7 has 0.4% probability of interference each less the acceptable 5%. In terms of throughput per total bandwidth per a single site, N = 7 offers a spectrum utilization of 1/7 and N = 4 offers a spectrum utilization of 1/4. Therefore, a relative enhancement in capacity of 7/4 has been achieved with 3.3% probability of interference.

3.3. Monte Carlo simulation study on effect of increasing ILT power

Unlike thermal noise which can be solved by increasing the VLT power, co-channel interference cannot be combated by increasing the VLT power [1, 4]. This is because an increase victim link transmitter power increases the interference to neighboring co-channel cells. Fig. 13 shows how co-channel interference is affected by an increase ILT power. The co-channel interference is significant when N = 1 due to the shorter distance between the co-channel cells and relatively small when N = 7 due to the larger distance between the co-channel cells. However, for very high power ($P_r >$ 75 dBm) the effect of interference is the same for N = 1, N = 3, N = 4, and N = 7.

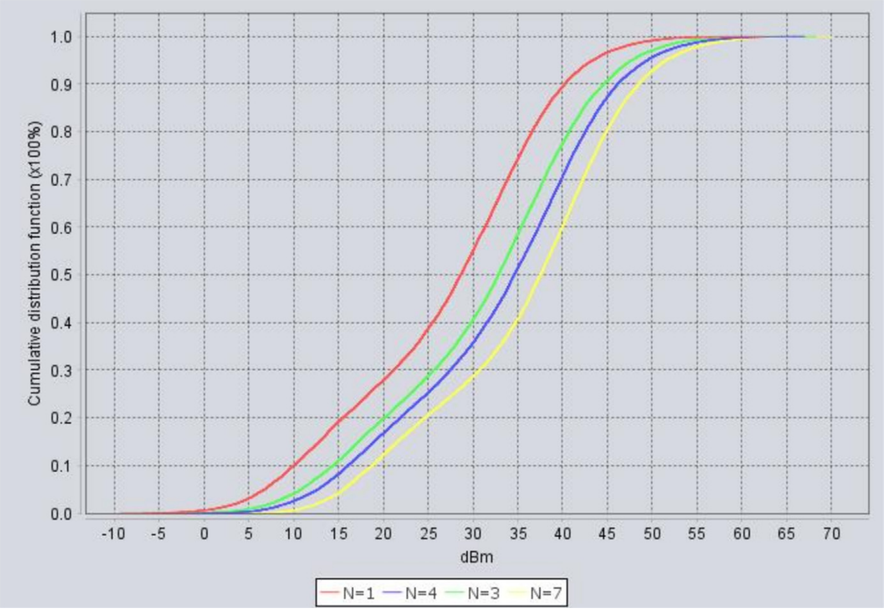

Fig. 12. C/I in dB from the first tier co-channel cell.

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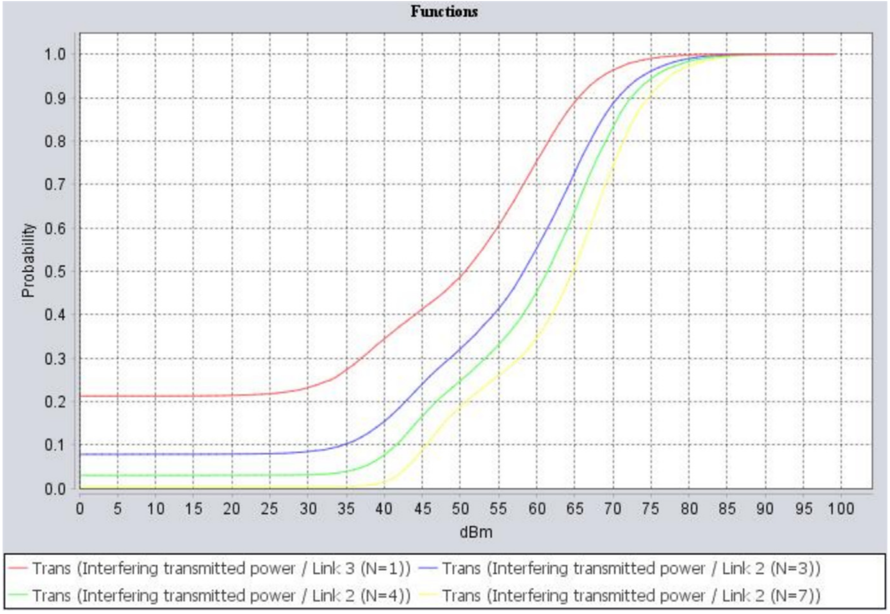

Fig. 13. Effect of ILT power.

4. Conclusion

In this work, the MCA has been undertaken to study co-channel interference in a cellular system. We report a number of MCS results of the CDF as a function of distance, dRSS, iRSS, C/I, and ILT power for cluster number N with values of 1, 3, 4, and 7. The MCS results are compared against the minimum interference threshold. From the MCS, the percentages of interferences are 24.94%, 9.36%, 3.33% and 0.4% for N = 1. N = 3, N = 4, and N = 7 respectively. In terms of throughput per total bandwidth per a single site, N = 7 offers a spectrum utilization of 1/7 and N = 4 offers a spectrum utilization of 1/4. Therefore, a relative enhancement in capacity of 7/4 has been achieved with 3.3% probability of the interference which is well below the threshold value of 5%. The MCS has shown an optimum spectrum sharing rule compared to the Analytical study whose sharing rules are unnecessarily rigid.

Declarations

Author contribution statement

Solomon T. Girma: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Dominic B. O. Konditi: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed analysis tools and data; Wrote the paper.

Ciira Maina: Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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