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Channel Alternation and Rotation for Trisectorized Cellular Systems

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Abstract. Conventional trisectored cellular systems have not taken full advantages of antenna directivities to enhance frequency reuse efficiency. A novel Channel Alternation and Rotation (CAR) scheme is proposed to coordinate channel assignments with antenna directivities. CAR employs a multi-interval cell-reuse layout. Each cell type is allocated extra channel set(s) to provide network designers the flexibility to assign channels avoiding nearest front lobe interference to enhance the carrier to interference ratio (C/I). CAR allows deployment of smaller and non-integer reuse factors based on C/I requirements, thus increasing channel capacity. Since current base station equipment is utilized, no additional costs are introduced.

Keywords: channel alternation and rotation, channel allocation, channel assignment, frequency reuse, frequency planning

Introduction

Due to the limited available radio spectrum, system capacity in a cellular system is determined by frequency reuse. In a typical frequency reuse plan, the entire available spectrum is partitioned into frequency channels, grouped into channel sets, and allocated to each cluster of N contiguous cells. Each *cell*, a radio coverage within a certain geographical area by a base station, is then allocated a unique group of channel sets to form a pattern. The pattern formed is reused uniformly in adjacent clusters to provide regular separation intervals and to allow reusing frequency channels simultaneously in all co-channel cells (cells having the same channel sets). Thus, N is a rhombic number restricted within a finite set of values, e.g., 3, 4, 7. With those fixed constraints, conventional approaches in trisectorized cellular systems to date have not taken full advantage of antenna directivities to maximize frequency reuse efficiency.

We propose a channel allocation scheme, called CAR, to coordinate channel assignments with antenna directivities. CAR employs a multi-interval cell-reuse layout where each cell type is allocated extra channel set(s) to provide network designers the flexibility to rotate and alternate (or substitute) channels avoiding nearest front lobe interference to enhance C/I. This scheme, seemingly locally poor since additional channel sets are allocated to each cell type, is globally good since it allows deployment of tighter and non-integer reuse factors based on C/I requirements to increase frequency reuse ef-

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ficiency. Performance analyses show that CAR increases channel capacity up to 31%. Since existing base stations are used, CAR deployment schemes do not introduce additional manufacturing costs.

With the fast growing demand in mobile services, further exacerbated by infrastructure build-outs that have yet to pay off leaving cellular carriers with battered balance sheets, cellular network designers must strive to achieve highest possible frequency reuse efficiency with minimal costs. Rebuilds of existing system infrastructure are expensive and therefore undesirable, a simple and economical approach, such as CAR, is needed to maximally exploit the scarce and expensive radio spectrum and existing infrastructures.

Several possible technologies can be adopted to improve system capacity, namely sophisticated dynamic channel allocation, multi-beam and adaptive antenna array, cell splitting, frequency hopping, etc. [Katzela and Naghshineh, 4; Rappaport, 10; Steele et al., 12]. However, these approaches are costly since base stations, network equipment, or user terminals must be modified, if not completely replaced. The more economical and simpler approach is through the use of innovative channel allocation methodologies.

The remainder of this paper is organized as follows. In section 1, we further describe frequency reuse planning in trisectorized cellular systems. In section 2, we describe how directional antenna systems are exploited in CAR, and presents the CAR scheme. We demonstrate the performance advantages of the CAR approach over conventional reuse plans and other channel rotation schemes based on system capacity and C/I margins in section 3. Our conclusions are drawn in section 4.

1. Trisectorized cellular systems

In a typical frequency reuse plan, the allocation of channel sets is organized to form a pattern that is reused uniformly in clusters of N contiguous cells. To provide regular and equal reuse separation intervals that allow the reuse of frequency simultaneously in all co-channel cells, each cell is allocated a unique group of channel sets equaling the number of sectors in a cell and N is a rhombic number determined by the two shift parameters i and j as expressed in,

$$N = i^2 + ij + j^2, \tag{1}$$

where i and j are nonnegative integers. Hence, N is restricted within a finite set of numbers, $N = \{1, 3, 4, 7, \ldots\}$.

Typically, a co-channel cell can be located by: (a) moving along i hexagonal cells, (b) turning 60° counter-clockwise, and (c) moving j cells. Thus, the separation interval between co-channel cells, or reuse distance Q, is determined by $Q = R\sqrt{3N}$, where R is the radius of the cell.

Smaller N or shorter separation interval between co-channel cells increases frequency reuse efficiency but decreases C/I and quality of services. Conversely, while the cell size is kept constant, larger N or longer reuse distance enhances C/I, but reduces system capacity since co-channel cells are located much farther apart. Due to fast growing demand in mobile services and further exacerbated by infrastructure build-outs that have

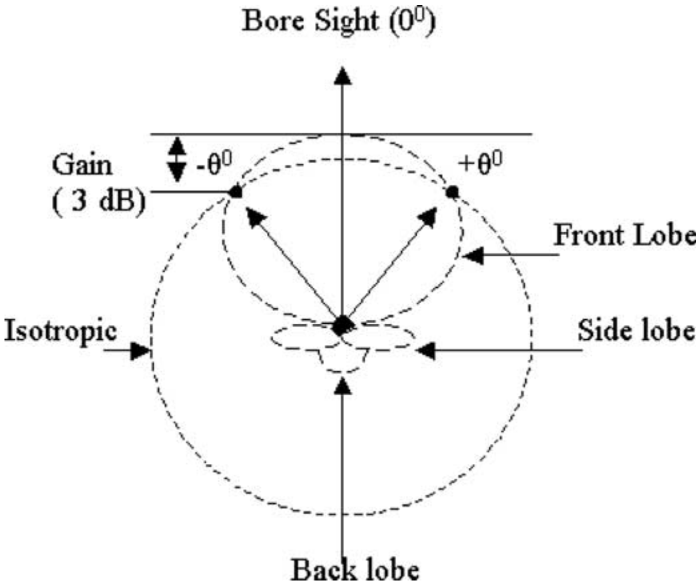

Figure 1. Directional antenna radiation pattern and antenna gain relative to omni-directional system.

yet to pay off, cellular network designers must strive to achieve tightest possible frequency reuse to maximally exploit the scarce and expensive radio spectrum and existing infrastructures.

Different cellular systems require different C/I thresholds. As general guidance, 18 dB, 14 dB, and 9 dB are required as the minimum acceptable C/I protection margins in Advanced Mobile Phone System (AMPS), digital Time Division Multiple Access (TDMA) such as IS-136, and Global System for Mobile Communication (GSM), respectively [Kinoshita and Asano, 5; Rappaport, 10]. Normally, 18 dB can be maintained with a 7-cell reuse in an omni-directional antenna system.

Unlike in omni-directional antenna, where power radiates equally in all directions, directional antennae concentrate the power in the direction of the bore sight (at 0°). This translates into power gain that is expressed relative to isotropic gain. As shown in figure 1, a typical antenna pattern is associated with a front lobe, two side lobes, and a back lobe. Based on the received signal strength at the cell boundary and with respect to antenna bore-sight, the region spanning within $\pm\theta$, where power voltage has reduced by about one half (-3 dB) of its maximal strength, determines the antenna's beam-width. Due to antenna directivities, power voltage is reduced significantly in other directions, therefore interference from the side and back lobe is minimal. To increase C/I protection and frequency reuse efficiency, conventional cellular systems typically employ three directional antennae at each base station in clusters of 3, 4, and 7 cells [Kinoshita and Asano, 5; Steele et al., 12; Wang, 14]. This directional system will be denoted $N * k$ reuse plan, where k is the number of sectors in a cell.

While most conventional cellular systems employ three 100° to 120° directional antennae at each base station, some also use three 60° to 70° directional antennae in

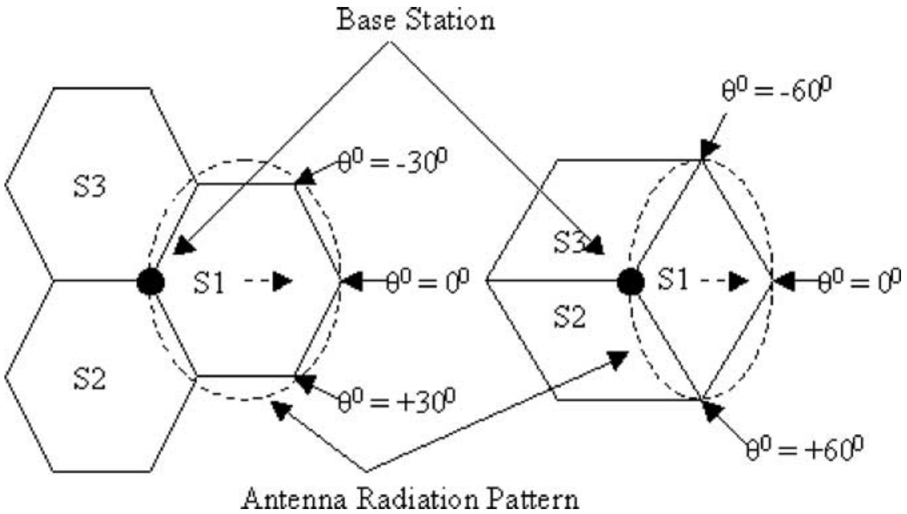

Figure 2. Cell layouts: Sector S1 is served by a directional antenna. Left: 60-degree narrow-beam trisectorized cell. Right: 120-degree wide-beam trisectorized cell.

a clover-leave cell structure [Rappaport, 10; Wang, 14]. Since antenna with narrower beam-width concentrates energy power into a smaller region that further reduces interference in other directions, the clover-leave cell structure provides additional C/I protection, allowing tighter frequency reuse to improve channel capacity. To differentiate the two architectures, 60° cell layout has been referred to as Narrow-Beam Trisector Cellular (NBTC) while 120° cellular system is called Wide-Beam Trisector Cellular (WBTC) [Wang, 14].

In figure 2, we depict the cell layouts of two systems where sectors S1, S2, and S3 represent the coverage areas of the three directional antennae from each base station. Since actual cell size and coverage vary depending on number of factors, e.g., terrain, the ideal tessellating hexagonal WBTC cell and NBTC sector are commonly used for studying purpose.

In a typical conventional $7 * 3$ reuse plan depicted in figure 3, seven WBTC cells, labeled A, B, C, D, E, F, and G, are grouped into a cluster. Each cell is partitioned into 3 sectors and each sector, covered by a directional antenna, is assigned a unique channel set. Thus, a total of 21 channel sets are used in the system. With respect to adjacent channel separation, a possible channel assignment is as follows: $A = \{1, 8, 15\}$, $B = \{3, 9, 16\}$, $C = \{4, 10, 7\}$, $D = \{6, 11, 18\}$, $E = \{7, 12, 19\}$, $F = \{2, 13, 20\}$, and $G = \{5, 14, 21\}$. This channel assignment pattern is replicated in adjacent clusters to provide equal separation intervals among six co-channel cells. For simplicity, only these six nearest co-channel A-type cells, $CI_1, \ldots, CI_6$, are labeled. Among them, only CI_4 and CI_5 are front lobe interferers while CI_1, CI_2, CI_3, and CI_6 are side and back lobe interferers, respectively. Figure 3 also depicts the worst interference scenario, that is, when MS is at the edge of a serving sector, e.g., sector 1 (or channel 1) in the centered A-cell, where desired signal is weakest (-3 dB) and co-channel interference is strongest.

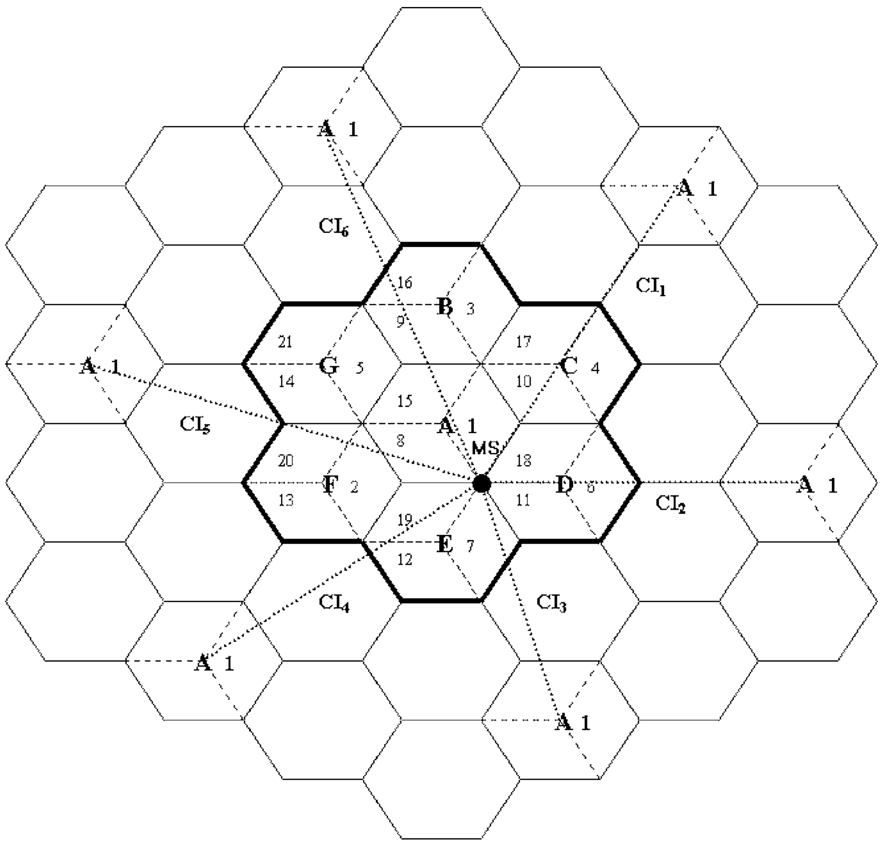

Figure 3. Conventional 7 ∗ 3 reuse plan and worst co-channel interference scenario.

In comparison with an omni-directional system, the 7 ∗ 3 reuse plan increases C/I to 20.7 dB from 17.8 dB. This improvement is due mainly to the reduction of interference from the two side lobe interferers and the negligible interference from the two back lobe co-channel interferers.

The reuse plans 4 ∗ 3 and 3 ∗ 3 are also widely deployed in IS-136 and GSM systems, particularly in Japan and Europe, respectively [Kinoshita and Asano, 5]. Conventional reuse plan tighter than 3 ∗ 3 is not practical in trisectorized cellular systems since 1 and 2-cell reuse require allocating the same channels to neighboring sectors without any separation that, in turns, reduces C/I protection below acceptable level [Steele et al., 12; Xiang, 17]. Thus, 3 ∗ 3 is the tightest reuse plan for systems that require at least one buffer cell between co-channel cells.

Antenna rotation schemes for trisectorized cellular systems called directional frequency reuse (or group reuse) and Interleaved Channel Assignment (ICA) were studied and reported in [Faruque, 2] and [Wang, 14], respectively. Generally, in directional frequency reuse, frequency channels are grouped into three sets. Each set is then carefully allocated to sectors that point in a particular direction. This technique shows some improvements in C/I; however, repeat patterns have become too complex to expand and manage. In ICA, each unique channel pair is assigned to two rotating sectors in each cell type and rotated in each subsequent adjacent co-channel cell on the same row. The remaining channel sets are used as common channels and assigned sequentially to the third sectors that point in the same direction. To minimize interference of the common channels in non-rotating (third) sectors, an Interleaved NBTC (INBTC) cell layout in which antennae point in six different directions is employed. Thus, existing cellular structure may require modifications, e.g., relocating cell sites. Such modification is costly, particularly from a WBTC system. Such approaches, therefore, may be deployed in some newer systems, more than to upgrade existing trisectorized cellular systems.

2. Channel alternation and rotation

2.1. Conceptual design

Since interference from antenna back lobe is negligible and interference from side lobe is significantly reduced, CAR scheme is proposed to take full advantages of antenna directivities by systematically alternating and rotating channels to avoid front lobe interference with the nearest co-channel cells where interference is strongest. If nearest front lobe interference is avoided, C/I is improved which, in turns, allows deployment of tighter frequency reuse to improve frequency efficiency. To achieve these objectives, we propose:

(i) cell layout planning: *Multi-interval cell-reuse separations*.

(ii) frequency planning: *Channel alternation and rotation to avoid nearest front lobe interference.*

In cell layout planning (i), multi-interval cell-reuse allows the grouping of cells into clusters of any (integer) size; thereby allowing deployment of reuse plans based on the C/I requirement, rather than being restricted to within reuse clusters of 3, 4, and 7 cells as determined by equation (1).

In frequency planning (ii), if the main beam power (front lobe) radiates towards the nearest co-channel cell partially, the interfering channel is *rotated*. Thus, the interference is reduced since it becomes a side lobe interferer instead of a front lobe interferer. When the antenna main beam power radiates towards the nearest co-channel cell completely, the interfering channel is *alternated*. Thus, nearest front lobe interference is avoided. Using CAR schemes, the interference is reduced since it is the result of only side and back lobe co-channel interference and interference from antenna front lobes from remote co-channels. The CAR concept is generalized as follows:

- If any set of channels can be rotated to avoid front lobe interference with its *nearest* co-channels, rotate the set.
- If rotation cannot be accomplished, alternate the set.

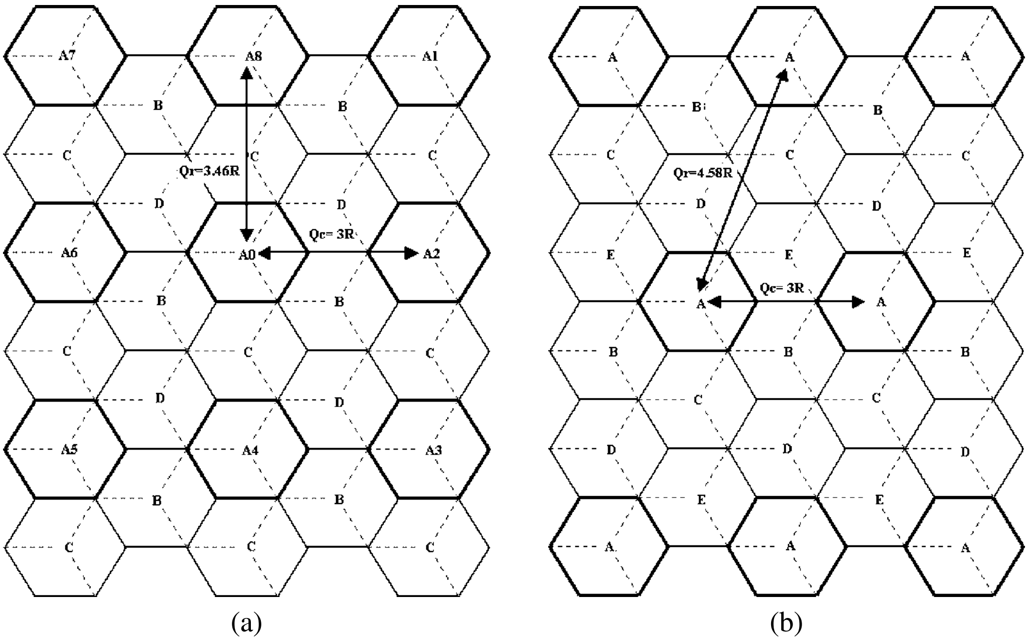

Figure 4. CAR cell reuse layouts and reuse distances for 4 and 5-cell reuse: (a) $N = 4$; (b) $N = 5$.

2.2. *Cell layout*

In CAR, we label cells by assigning an ordinal to each cell in the clusters of the N cell types as $A, B, \ldots, N$-type sequentially in zigzag order along each pair of tessellating columns and repeat likewise for all other tessellating column pairs. This arrangement allows cells to be grouped into reuse clusters of any integer size since all cells in a row are co-channel cells having the same ordinal (the same cell type). Thus, the reuse distance between adjacent co-channel cells is determined by:

$$Q_c = 3R$$

and

$$Q_r = \begin{cases} NR\dfrac{\sqrt{3}}{2} & \text{for } N = \{2, 4, 6, \ldots\}, \\ \sqrt{(1.5R)^2 + \left(NR\dfrac{\sqrt{3}}{2}\right)^2} & \text{for } N = \{1, 3, 5, \ldots\}, \end{cases}$$

where Q_c, Q_r represent the reuse distance between column and row-adjacent co-channel cells, respectively.

In figure 4, we illustrate cell layouts for $N = \{4, 5\}$ as described above. Including $N = \{1, 3\}$ (not shown) where cell layouts are identical to conventional counterparts as $Q_c = Q_r$, each cell in a 5-cell cluster also has six co-channel cells on the first ring as in a conventional system. Two are at distance $Q_c = 3R$, but the other four are at distance

$Q_r = 4.58R$ which is equal to the conventional 7-cell reuse. Each cell in a cluster with even number of cells, $N = \{2, 4\}$, has eight co-channel cells on the first ring with three different reuse distances. For $N = 4$, the two shortest reuse intervals, Q_c remains at $3R$ and Q_r equals the conventional 4-cell reuse; the other is at reuse distance $Q_r = 4.58R$, which is again equivalent to conventional 7-cell reuse.

Consider the 4-cell layout depicted in figure 4(a). Assume A_0 is the center cell and, in clockwise direction, A_1–A_8 are co-channel cells starting from the top right. Among them, A_2, A_4, A_6, and A_8 are nearest co-channel cells while A_1, A_3, A_5, and A_7 are farther away. Assume that S1, S2, S3 are the three sectors as denoted in figure 2. Sector S1 in cell A_0 radiates toward nearest cell A_2 completely. Thus, if the co-channel used in sector S2 of cell A_2 is alternated (or substituted), nearest front lobe interference from A_0 to co-channel A_2 is avoided. Interference from A_0 to A_1 and A_3 is less significant due mainly to the longer reuse distance in comparison to cell A_2. Also consider sectors S2 and S3 in A_0, if sector S3 and S2 in A_6 are rotated, S2 and S3 of cellA_0 become side lobe interferers instead; hence, interference is reduced. Sectors S2 and S3 also completely radiate toward cells A_4 and A_8, respectively. Thus, if the interfered co-channels are alternated, then nearest front lobe interference is also avoided.

2.3. Channel assignment

To allow frequency alternation among nearest co-channel cells, in CAR, each cell type is allocated x additional channel set(s) that results in $k + x$ unique channel sets per cell type and $N * (k + x)$ channel sets system-wide. Thus, CAR can be generalized as an $N * (k + x)$ reuse scheme.

In trisectorized cellular system, where $k = 3$ and for $x = 1$, the available frequency channels are grouped into $N * (3 + 1)$ channel sets. Each cell is assigned only 3 out of 4 allocated channel sets; hence, there are $\binom{4}{3} = 4$ unique patterns per cell type. For example, in a $4 * (3 + 1)$ reuse plan, the channels allocated to A-type cells are 1, 5, 9, and 13. Thus, A-type cells consist of four patterns: $A_{p1} = \{1, 5, 9\}$, $A_{p2} = \{1, 5, 13\}$, $A_{p3} = \{1, 9, 13\}$, and $A_{p4} = \{5, 9, 13\}$, where pi indexes the pattern number. Consequently, the reuse pattern in CAR comprises of $N * 4$ cells. With respect to N, $k = 3$, and $x = 1$, the possible channel allocations for CAR reuse plans are illustrated in table 1. The CAR algorithm then can be generalized as follows:

1. Tile labeling:
   (a) Based on C/I requirement, determine cell reuse cluster N.
   (b) Select a tile comprising of $N*4$ contiguous cells spanning across four tessellating columns and $N * 2$ tessellating rows.
   (c) Assign ordinals $(A, B, \ldots, N\text{-type}\}$ to every cell in the first two tessellating columns sequentially in zigzag order. Assign ordinals to the remaining cells in the next two columns likewise (see figure 4).

Table 1
Possible channel assignment in CAR reuse plans for trisectorized cellular systems using one alternate channel set.

	Reuse plan				
Cell type	$N = 5$ $5 * (3 + 1)$	$N = 4$ $4 * (3 + 1)$	$N = 3$ $3 * (3 + 1)$	$N = 2$ $2 * (3 + 1)$	$N = 1$ $1 * (3 + 1)$
A	1, 6, 11, 16	1, 5, 9, 13	1, 4, 7, 10	1, 3, 5, 7	1, 2, 3, 4
Pattern A_{p1}	1, 6, 11	1, 5, 9	1, 4, 7	1, 3, 5	1, 2, 3
A_{p2}	1, 6, 16	1, 5, 13	1, 4, 10	1, 3, 7	1, 2, 4
A_{p3}	1, 11, 16	1, 9, 13	1, 7, 10	1, 5, 7	1, 3, 4
A_{p4}	6, 11, 16	5, 9, 13	4, 7, 10	3, 5, 7	2, 3, 4
B	2, 7, 12, 17	2, 6, 10, 14	2, 5, 8, 11	2, 4, 6, 8	
B_{p1}	2, 7, 12	2, 6, 10	2, 5, 8	2, 4, 6	
B_{p2}	2, 7, 17	2, 6, 14	2, 5, 11	2, 4, 8	
B_{p3}	2, 12, 17	2, 10, 14	2, 8, 11	2, 6, 8	
B_{p4}	7, 12, 17	6, 10, 14	5, 8, 11	4, 6, 8	
C	3, 8, 13, 18	3, 7, 11, 15	3, 6, 9, 12		
C_{p1}	3, 8, 13	3, 7, 11	3, 6, 9		
C_{p2}	3, 8, 18	3, 7, 15	3, 6, 12		
C_{p3}	3, 13, 18	3, 11, 15	3, 9, 12		
C_{p4}	8, 13, 18	7, 11, 15	6, 9, 12		
D	4, 9, 14, 19	4, 8, 12, 16			
D_{p1}	4, 9, 14	4, 8, 12			
D_{p2}	4, 9, 19	4, 8, 16			
D_{p3}	4, 14, 19	4, 12, 16			
D_{p4}	9, 14, 19	8, 12, 16			
E	5, 10, 15, 20				
E_{p1}	5, 10, 15				
E_{p2}	5, 10, 20				
E_{p3}	5, 15, 20				
E_{p4}	10, 15, 20				

2. Channel assignment:
   (a) For each cell type, determine the $k + x$ channel sets (see table 1).
   (b) For each cell, allocate k channel sets from within its particular type, subject to:
      (i) If any set of channels can be rotated to avoid front lobe interference with its nearest co-channels, rotate the set.
      (ii) If rotation cannot be accomplished, alternate the set.

An illustration for the $N = 4$, $k = 3$, and $x = 1$ (or CAR $4 * (3 + 1)$) is depicted in figure 5. In this typical example, there are four cell types, namely A, B, C, and D. Each cell type is allocated 4 channel sets, shown in table 1, as follows: Type $A = \{1, 5, 9, 13\}$, $B = \{2, 6, 10, 14\}$, $C = \{3, 7, 11, 15\}$, and $D = \{4, 8, 12, 16\}$. A possible channel assignment is as follows:

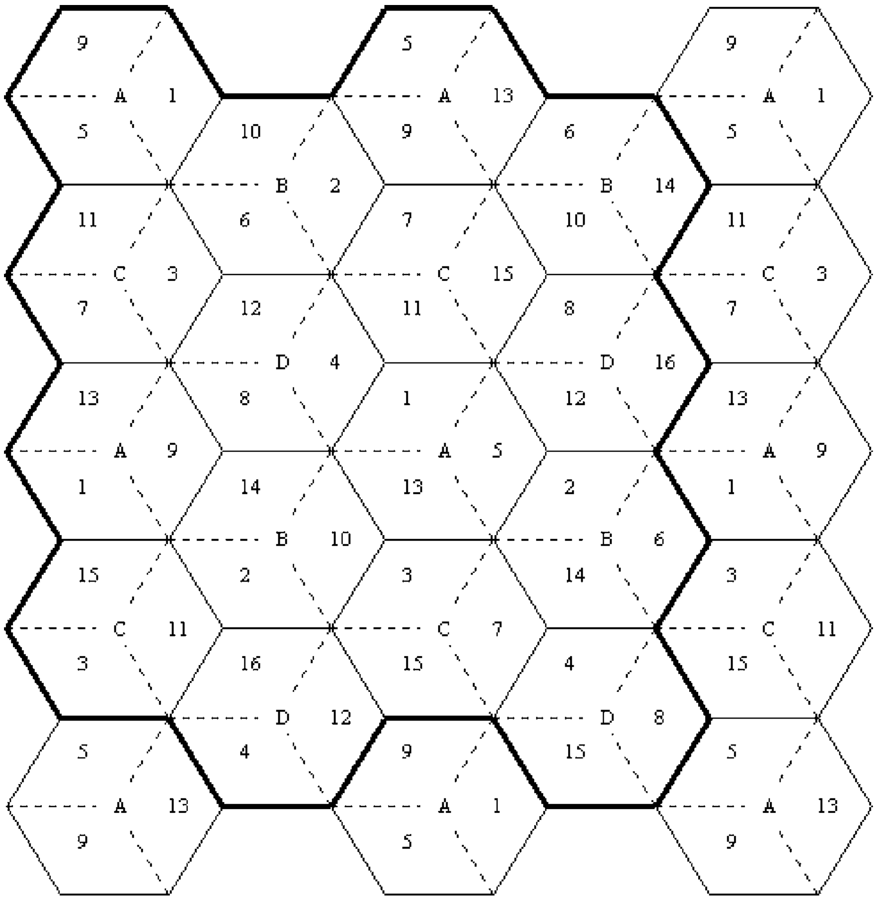

Figure 5. Repeat pattern for CAR $4 * (3 + 1)$ reuse plan utilizing 120-degree wide-beam trisectorized cell.

1. Select a tile comprising of $4 * 4$ contiguous cells containing within 4×2 rows and 4 columns. Assign ordinals to each cell as A, B, C, and D-type as described above.

2. Start with the first A-type cell, use two of the four allocated channel sets for A-type cells, e.g., 5 and 9, as the Rotating channel Pair (RP) and other two sets, 1 and 13, as the Alternating channel Pair (AP). Assign RP channels to the two rotating sectors S2 and S3. Assign one of the two AP channels, e.g., channel 1, to the alternating sector S1.

3. Move to the next A-type cell in the same row. Rotate channels 5 and 9 in rotating sectors. Alternate (or substitute) channels 1 with 13 in the alternating sector. Thus, channel 13 is assigned to the alternating sector instead.

4. Advance to the first A-cell on the next row. Reverse the AP channels with the RP channels. Thus, 5 and 9 become AP channels while 1 and 13 become RP channels.

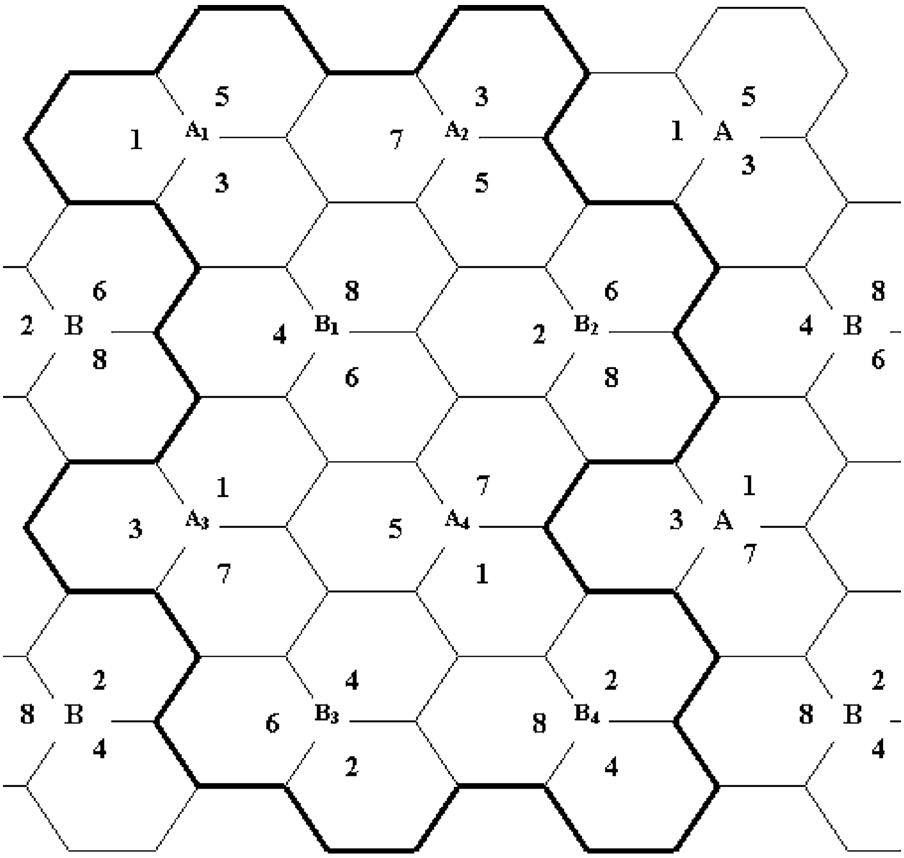

Figure 6. Repeat pattern for CAR $2 * (3 + 1)$ reuse plan utilizing 60-degree narrow-beam trisectorized cell.

5. Assign channels avoiding nearest front lobe interference with co-channel directly above. Thus, RP channel 13 is assigned to the rotating sector S3 and RP channel 1 to S2. Assign AP channel 9 to sector S1, as channel 5 would have stronger front lobe interference from sector S2 above.

6. Move to the next A-type cell in the same row. Rotate RP channels 1 and 13 in rotating sectors. Alternate AP channels 5 with channel 9 in the alternating sector.

7. Repeat from step 2 for B, C, and D cell types using their allocated channels to complete the tile.

Applying the above algorithm, for $N = \{2, 3, 5\}$, we obtain reuse plans for $2 * (3 + 1)$, $3 * (3 + 1)$, and $5 * (3 + 1)$. In an NBTC architecture, reuse plans $1 * (3 + 1)$ and $2 * (3 + 1)$ are derived. In figure 6, we depict the NBTC $2 * (3 + 1)$ reuse plan. Note that to provide at least a buffer cell among co-channel cells, conventional systems must use $N = 3$. With $N = \{1, 2\}$, CAR's $1 * (3 + 1)$ using NBTC and $2 * (3 + 1)$ still allow at least a buffer cell between co-channel mobile users.

3. Performance evaluation

3.1. Reuse factor

In conventional systems, each channel set is used once in the cluster of N cells, therefore, N (or $1/N$) is also the reuse factor. In CAR, each channel set is reused three times in a repeating pattern of $N * (3 + 1)$ cells. Thus, the reuse factor for CAR, labeled N_{CAR} (or $1/N_{\mathrm{CAR}}$), can be generalized as

$$N_{\mathrm{CAR}} = \frac{N * (k + x)}{j}, \tag{2}$$

where j is the number of times the same channel set is repeated in the pattern. Hence, the reuse factors for the CAR reuse plans $1 * (3+1)$, $2 * (3+1)$, $3 * (3+1)$, $4 * (3+1)$, and $5 * (3+1)$ are 1.3, 2.7, 4.0, 5.3, and 6.7, respectively. In conventional systems, only integer reuse factors of 1, 3, 4, and 7 are considered; however, reuse factor of 1 does not provide the necessary one buffer cell needed to separate co-channel mobile users. Thus, $N = 3$ is the tightest possible reuse plan that satisfies this constraint. CAR allows tighter reuse factors of 1.3 and 2.7 in reuse plans $1 * (3 + 1)$ and $2 * (3 + 1)$ that still provide at least a buffer cell separating co-channel mobile users.

3.2. C/I and system capacity

To evaluate the performance of CAR against conventional reuse plans, a worst-case interference scenario is assumed. That is, we assume that a mobile user is at the edge of a serving sector, where the desired signal is weakest and the co-channel interference is strongest. We adopt the static formula commonly used to evaluate worst C/I, which is expressed as

$$\frac{C}{I} = 10 \log \left[\frac{G(\theta_0) d_0^{-\lambda}}{\sum_{i=1}^{n} G(\theta_i) d_i^{-\lambda}} \right], \tag{3}$$

where cell radius is normalized to 1 and d_i (or D_i/R) represents the normalized distance from the mobile user to the ith co-channel base station. n is the number of co-channel interferers. λ is the path loss exponent, set equal 4. $G(\theta_0)$ is the power received by the mobile user from the serving base station, and $G(\theta_i)$ is antenna gain from the ith co-channel base station at angle θ_i, with respect to the antenna bore-sight; both are expressed in decibels as

$$G(\theta_i) = 10^{G(\theta_i)_{\mathrm{dB}}/10}. \tag{4}$$

For comparison purposes, in this study we assume all hexagonal cell sites are theoretically equal and transmit at the same power. We use a commercial 3 dB, 120-degree beam-width directional antenna with 13.45 dBd gain and front-to-back ratio of 25 dB for WBTC systems. Instead of a 60-degree directional antenna, we use a 3 dB, 65 degree direction antenna with 15 dBd gain and front-to-back ratio greater than 25 dB in NBTC system as it provides better coverage that, in turn, slightly improves C/I as compared

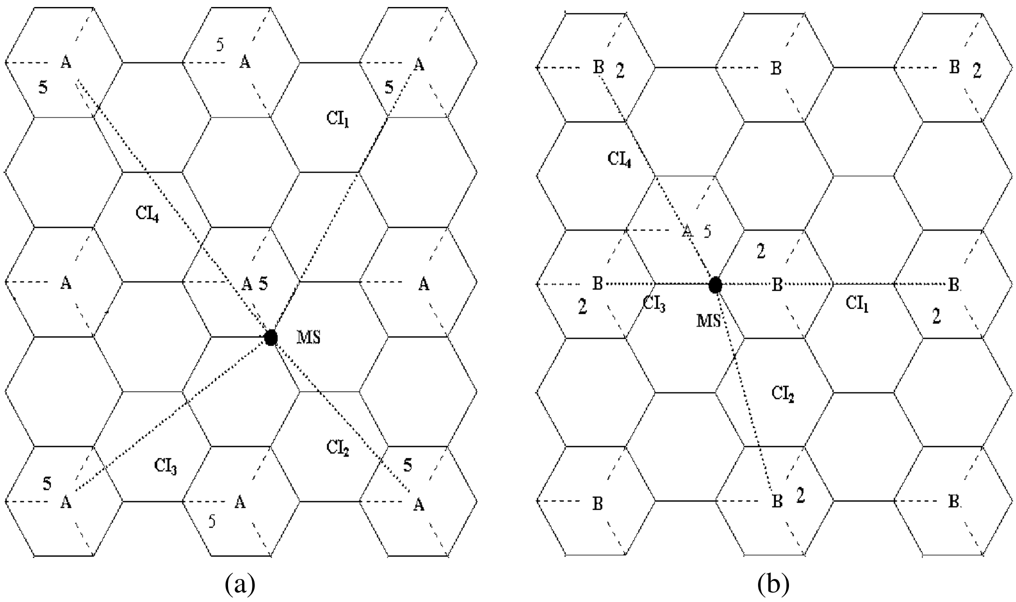

Figure 7. Worst interference location in $4 * (3 + 1)$ reuse plan utilizing 120-degree wide-beam trisectorized cell. (a) Interference on sector S1 (channel 5). (b) Interference on sector S3 (channel 2).

with previous studies [Nguyen et al., 9]. Antenna down tilting, shadowing factor, and other interference suppression techniques are neglected in all compared plans for simplification. We assume the system is fully loaded, that is, all significant interferers, including some front and side lobe co-channel interferers from the second ring farther away, are included. The C/I for all reuse plans, therefore, will be somewhat pessimistic as compared to other studies as only front lobe interferers on the first ring are considered [Rappaport, 10; Steele et al., 12, and others].

As an illustration, we depict the worst scenario in WBTC $4 * (3 + 1)$ reuse plan in figure 7(a), where the mobile user is operating at the edge of the serving sector on channel 5 and CI_i represents the significant ith co-channel interferer. Among all co-channel A-cells, the four nearest ones either do not contain channel 5 or have back lobes pointing toward the mobile user. Thus, possible strongest interference from nearest co-channels is avoided. The two front lobe interferers, CI_1 and CI_2 are from reuse distance $Q = 4.6R$, which is equal to the conventional 7-cell reuse. However, due to head-to-head front lobe interference, they are the two dominant co-channel interferers. CI_3 and CI_4 are side lobe interferers, thus interference is minimal. In base station diversity, the mobile user monitors the strongest signals from neighboring channels for possible handoffs. Thus, it also detects signals from channels 13 from the adjacent sector in the same base station, and channels 2, 14, 7, and 3 from neighboring base stations. In figure 7(b), we show the interference for channel 2 from which the mobile user can also operate. In this case, CI_1 and CI_4 are dominant but side lobe interferers; thus, worst C/I is expected to improve when base diversity is considered.

Table 2
Performance comparisons between CAR and conventional reuse plans employing Wide-Beam Trisectorized Cells utilizing 3 dB, 13.5 dBd gain, 120-degree directional antenna.

Reuse plan	Cell reuse factor	Worst C/I (dB)		Cell capacity (%)	Capacity increment (%)
		Worst scenario	Base diversity		
$7 * 3$	7	20.7	–	14.29	–
$5 * (3 + 1)$	6.7	19.3	20.0	15.00	5.00
$4 * (3 + 1)$	5.3	17.9	18.9	18.75	31.25
$4 * 3$	4	15.4	–	25.00	–
$3 * (3 + 1)$	4	15.6	16.4	25.00	0
$3 * 3$	3	12.3	–	33.33	–
$2 * (3 + 1)$	2.7	11.7	12.6	37.50	12.50

In table 2, we illustrate the performance of the $2 * (3 + 1)$, $3 * (3 + 1)$, $4 * (3 + 1)$, and $5 * (3 + 1)$ reuse plans in comparison with conventional reuse plans. Both employ WBTC architecture. Due to symmetrical channel allocation in conventional systems, the reuse distances from all possible neighboring channel candidates are the same. Thus, worst C/I of the channel candidates for the same mobile user located at the edge of the serving sector is typically similar. The difference, if any, is mainly due to antenna radiation pattern and is therefore neglected. However, in the CAR scheme, worst C/I in the alternating sector S1 is different from the rotating sectors S2 and S3; thus base diversity is considered.

To provide 18 dB, conventional $N * 3$ systems must employ a 7-cell reuse cluster, which provides a C/I of 20.7 dB. In CAR, reuse plans $4 * (3 + 1)$ and $5 * (3 + 1)$ provide C/I margins of 18.9 dB and 20 dB or 17.9 dB and 19.3 dB in worst cases, respectively, which are still at and above the minimum acceptable threshold required in various systems such as AMPS or dual AMPS/TDMA. Note that if a conventional $4 * 3$ reuse plan does not support the required C/I, e.g., 18 dB, a $7 * 3$ reuse plan must be deployed since 5 and 6-cell reuse clusters are not used. Thus, at smaller and fractional reuse factors of 5.3 and 6.7, CAR $4 * (3 + 1)$ and $5 * (3 + 1)$ increase channel capacity by 31.25% and 5% over the conventional $7 * 3$ plan, respectively.

Both reuse plans $3 * (3 + 1)$ and $4 * 3$ require the same number of channel sets, 12, and each cell is also allocated three channel sets, channel capacities remain the same as expected. Although the difference in worst case C/I is negligible, 15.6 dB vs. 15.4 dB, CAR's $3 * (3 + 1)$ reuse plan provides some improvement over a conventional $4 * 3$ counterpart when base diversity is considered. It increases C/I by about 1 dB. Also in CAR, each cell only uses 3 out of 4 available allocated channel sets, the unassigned channel is still available that can be deployed within certain constraints, e.g., in a multi-tiered cell system or channel borrowing, to further improve frequency reuse efficiency as needed.

Table 3
Performance comparisons between CAR and conventional reuse plans employing Narrow-Beam Trisectorized Cells utilizing 3 dB, 15 dBd gain, 65-degree directional antenna.

Reuse plan	Cell reuse factor	Worst C/I (dB)		Cell capacity (%)	Capacity increment (%)
		Worst scenario	Base diversity		
$3*3$	3	17.8	19.0	33.33	–
$2*(3+1)$	2.7	15.2	22.8	37.50	12.50
$1*(3+1)$	1.3	7.6	14.5	75.00	125.00

The performance of the $2*(3+1)$ reuse plan is compared with a conventional $3*3$ system. Both also employ WBTC architecture. The results indicate that the worst C/I in $2*(3+1)$ is reduced by a margin of 0.6 dB, to 11.7 dB from 12.3 dB; however, with base diversity, it actually improves C/I over the $3*3$ reuse plan by 0.3 dB to 12.6 dB. Although nearest co-channels in $2*(3+1)$ are back lobe interferers, due to short reuse distance of $Q_r = R\sqrt{3}$, they also cause considerable interference. If back lobe interference is further suppressed, e.g., directional antennae with front-to-back ratio greater than 25 dB are deployed, a gain of up to 1 dB is also possible. Thus, for systems employing a $3*3$ reuse plan, the $2*(3+1)$ reuse plan can be deployed that increases channel capacity by 12.50% as it only requires 8 channel sets while a $3*3$ system uses 9 channel sets.

In table 3, the performances of $1*(3+1)$ and $2*(3+1)$ reuse plans employing NBTC are shown in comparison with conventional $3*3$ counterpart. In an NBTC system, a user at the edge of a sector also receives two neighboring signals. At least, one comes from an adjacent base station with different reuse distance and angle, thus C/I is different. Therefore, base station diversity is considered for all reuse plans compared.

In comparison with a conventional NBTC $3*3$ system, the $2*(3+1)$ reuse plan also increases channel capacity by 12.50% while worst C/I is reduced by 2.6 dB to 15.2 dB from 17.8 dB, which is still over the 14 dB and 9 dB requirements for TDMA and GSM systems, respectively. Using base diversity, $2*(3+1)$ actually improves C/I performance over $3*3$ reuse plan by a significant margin of 3.8 dB, from 19 dB to 22.8 dB. In NBTC $2*(3+1)$ reuse plan, we had learned that the alternating sector S1 experiences the worst interference as compared to the two rotating sectors S2 and S3, thus antenna down-tilting or reduction of power can be used to balance and improve signal quality, if needed.

Due to very tight frequency reuse, worst case C/I in a $1*(3+1)$ reuse plan varies significantly within the same sector. It provides up to 14.5 dB for mobile users at the near left and right edges ($\theta = \pm 60$ degrees) of the sector, 9.9 dB at the two edges of the beam-width ($\theta = \pm 30$ degrees), but only 7.6 dB at the edge in the bore-sight direction. Note that a user at the edge in bore-sight direction also detects two quality signals (at 14.5 dB) from a neighboring base station that it can be handed-over to. Thus, the average worst C/I is still slightly above the 9 dB required in GSM. However, additional C/I margin is needed to compensate other factors such as ground noise and shadowing. Also, the

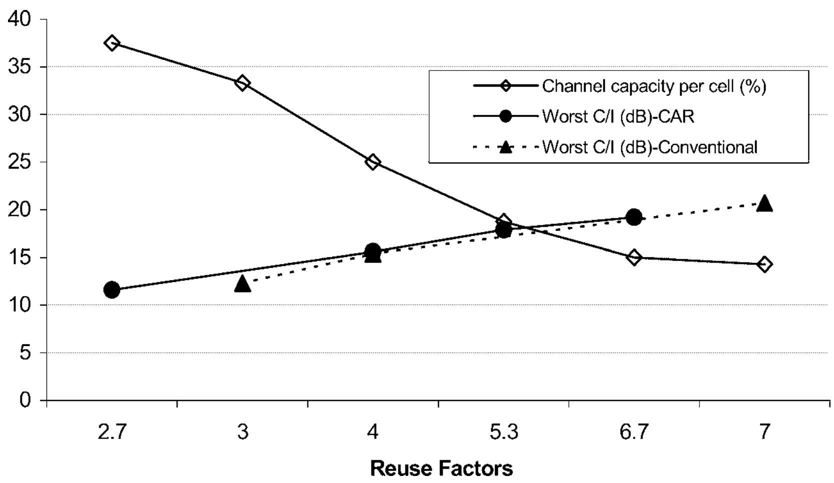

Figure 8. Performance comparisons between CAR $N*(3+1)$ and conventional $N*3$ reuse plans utilizing wide-beam trisectorized cell with 3 dB, 13.5 dBd gain, 120-degree directional antenna.

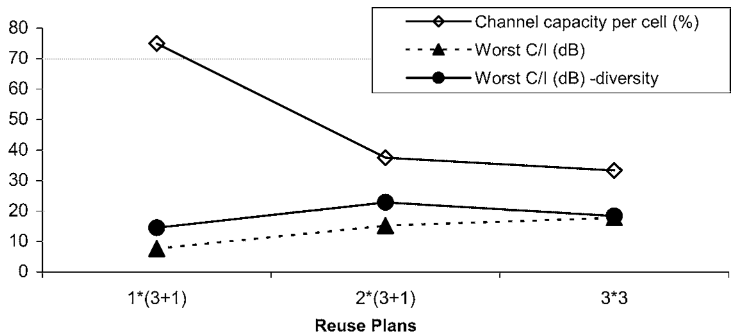

Figure 9. Performance comparisons between CAR $N*(3+1)$ and conventional $N*3$ reuse plans utilizing narrow-beam trisectorized cell with 3 dB, 15 dBd gain, 65-degree directional antenna.

$1*(3+1)$ reuse plan only uses four channel sets; therefore, allocation of adjacent channels within the same base station is unavoidable, which also must be accounted for. Advance techniques such as frequency hopping, reuse partitioning can be deployed to provide the additional protection. If implemented, it can increase channel capacity by up to 125% over $3*3$ reuse plan. CAR $1*(3+1)$ is a possible candidate for micro or pico-cell, or indoor systems where cell size is small and interference is controlled.

In figures 8 and 9, we provide the complete overview of all reuse plans compared for each cell architecture. Other researches suggest that a conventional reuse plan tighter than $3*3$ is not practical in trisectorized cellular systems since reducing the separation between co-channel cells reduces C/I protection level [Steele et al., 12; Xiang, 17]. The $1*(3+1)$ using NBTC and $2*(3+1)$ reuse plans have proven otherwise.

4. Conclusion

Conventional approach typically restricts cell reuse within clusters of 3, 4, or 7 cells. CAR allows the grouping of cells into clusters of any (integer) size with fractional reuse factors; thereby allowing deployment of reuse plans based on the C/I requirement. In a typical environment where a $4*3$ reuse plan does not satisfy the minimum acceptable C/I by a few dB, a $7*3$ reuse plan is deployed. CAR $4*(3+1)$ and $5*(3+1)$ reuse plans can be employed that satisfy the C/I requirement thus improving channel capacity by 31.25% and 5% over a conventional $7*3$ reuse plan, respectively. At the same channel capacity, CAR $3*(3+1)$ reuse plan provides up to one dB improvement in signal quality. With very low reuse factor of 2.6, CAR $2*(3+1)$ provides comparable C/I protection while improves channel capacity by 12.5% over a conventional $3*3$ reuse. At extremely tight reuse, the NBTC $1*(3+1)$ still provides at least a buffer cell between co-channel mobile users; thus, with advance interference suppression techniques, e.g., frequency hopping, it is a possible tightest reuse plan that can significantly improve channel capacity.

With the growing demand in mobile services, cellular network designers must strive to achieve tightest possible frequency reuse without additional costs. Our analytical findings demonstrate that CAR, what is a seemingly locally poor channel assignment scheme, is actually a globally good algorithm that is more efficient in terms of the total number of channels used. It provides wireless network designer the flexibility alternate and rotate co-channels avoiding nearest front lobe interference that results in a shorter reuse distance, less cell types, and the consequent use of a smaller number of frequencies to support the same number of simultaneous users within a geographical area, or conversely, a greater number of simultaneous users within a fixed channel allotment.

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