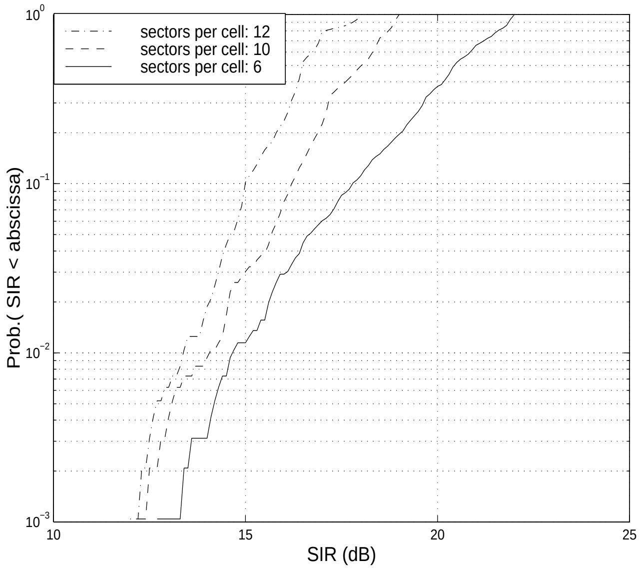


Fig. 6. SIR distribution for different number of sectors per cell

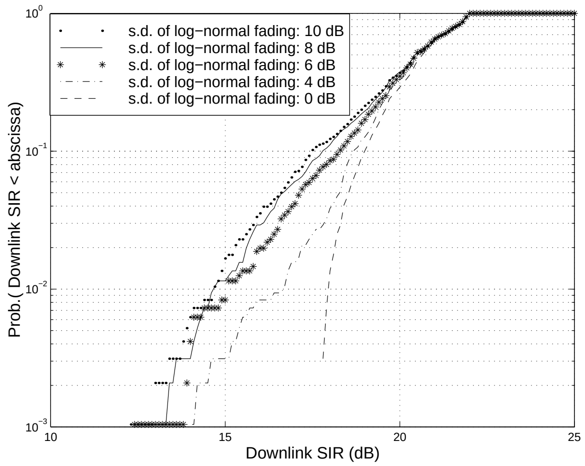


Fig. 7. SIR distribution for different values of standard deviation for lognormal shadow fading

For 0 dB (no fading), 4 dB and 8 dB as the standard deviation, the 99%-coverage SIR is 18 dB, 16.5 dB, and 14.5 dB respectively. A confidence analysis for 5 different seeds for lognormal fading shows a variation of up to 0.5 dB for the 99% coverage SIR value for the reference case.

VI. CONCLUSION

We have shown that sector-based resource allocation is a robust scheme that uses the combination of directional antennas and time re-use to effectively combat co-channel interference in fixed wireless systems. For reasonable choices of system parameters and SIR of about 12 to 14 dB, the scheme delivers high throughput (with an effective reuse factor of one), while permitting a given band of frequencies to be re-used in every sector of every cell. This scheme has very attractive features such as flexible sector planning and flexible re-use patterns for irregular cell layout, non-uniform traffic density, and easy capacity growth.

REFERENCES

1. T. K. Fong, P. S. Henry, K. K. Leung, X. Qiu and N. K. Shankaranarayanan, “Bandwidth Allocation in Fixed Broadband Wireless Networks,” *Proc. of the 6th WINLAB Workshop on Third Generation Wireless Networks*, New Brunswick, NJ, March 20-21, 1997, pp.89-121; a revised version accepted for publication in *IEEE Trans. on Communication*.

2. X. Qiu and K. Chawla, “Resource Assignment in a Fixed Wireless System,” *IEEE Commun. Letters*, Vol. 1, No. 4, pp. 108-110, July 1997.

3. K. K. Leung and A. Srivastava, “Dynamic Resource Allocation for Broadband Services in Fixed Wireless Networks,” *Multiaccess, Mobility, and Teletraffic for Personal Communications*, D. Everitt and M. Rumsewicz (Editors), Kluwer Academic Publishers, 1997, pp. 301-314.

4. I. Katzela and M. Naghshineh, ‘‘Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey,’’ *IEEE Personal Communications*, pp. 10-31, June 1996.

5. W. C. Y. Lee, *Mobile Cellular Telecommunications Systems*, McGraw-Hill, New York, 1989.

SBRA scheme can provide additional flexibility to use the limited bandwidth efficiently.

V. DOWNLINK PERFORMANCE RESULTS

We used our OPNET packet wireless simulator to numerically evaluate the interference characteristics of the SBRA scheme. The system studied had three tiers of interferers for the center cell. Re-use patterns of three and four were studied. Numerical results were generated for the following reference set (and some variations as well) of parameters: a regular hexagonal grid layout, 6 sectors/cell, base antenna FTB ratio = 25 dB, base antenna beamwidth = 60^o, terminal antenna FTB ratio = 15 dB, terminal antenna beamwidth = 30^o, standard deviation of lognormal fading = 8 dB, path loss exponent = 4, and practical (overlapping) antenna pattern.

We studied the downlink and uplink performance, although we present only the downlink results here. In the downlink, we calculated performance under the maximum co-channel interference (CCI) when all sectors were transmitting in their corresponding subframes. Terminal were first assigned to sectors in the following manner. Each terminal antenna was pointed to all bases and then assigned to the base which resulted in the highest SIR. Since lognormal fading to different bases was independent, the above procedure tended to minimize deep fade cases. The primary figure-of-merit is the cdf of the SIR, and the fraction *p* which represents the terminals that do not meet a required threshold. The fraction *p* (target 1 to 5%) represents the outage, i.e. the vulnerable terminals that cannot be accommodated and must be removed from the system. Since the interference conditions are almost static, retransmissions are not useful except for very light load. We do not consider power control on the downlink.

Figure 4 illustrates the value of directional antennas by showing the downlink system performance with omni-directional terminal antennas and directional terminal antennas with beamwidths of 10^o, 30^o, and 40^o. For an SIR outage of 1% (99% coverage), the SIR achieved is 14.5 dB for the reference case of 30^o and 3 dB for the omni case. It is clear that directional terminal antennas are required, and also that terminal antenna beamwidth is not very critical in the range from 10^o to 40^o; this implies a wide tolerance to antenna beamwidths and pointing errors. Figure 4 also shows the performance for a reuse of 4 for the reference case. The 99%-coverage SIR value increases from 14.5 dB to about 16.5 dB and provides a good margin for variation in cell sizes that could bring the co-channel cells slightly closer. Figure 5 illustrates the critical importance of the terminal FTB ratio. The SIR curves are shown for FTB ratios of 10 dB, 15 dB, and 20 dB. The curves do not exceed 22 dB due to the fact that the base antenna FTB has been chosen as 25 dB. For 99% coverage, the achieved SIR is 12 dB, 14.5 dB, and 17 dB. For each 5 dB drop in FTB ratio, the SIR drops by about 2.5 dB. This information is useful since a terminal antenna with a free-space FTB ratio of 20 dB has an effectively-lower interference suppression of 15 dB to 10 dB in the presence of strong local scatterers. Figure 6 shows the SIR results for different numbers of sectors. The 1% SIR outage for 6, 10, and 12 sectors are 14.5 dB, 14 dB, and 13.3 dB respectively. Again, the SIR penalty is small for a larger number of sectors, thus establishing the feasibility of sector growth. Fig. 7 shows the effect of lognormal shadow fading. Besides varying the signal and interference conditions at the terminal, certain fading conditions can also cause a terminal to change sectors. Thus, extreme cases of adverse fading (low signal, high interference) are avoided by the macrodiversity offered by sector selection.

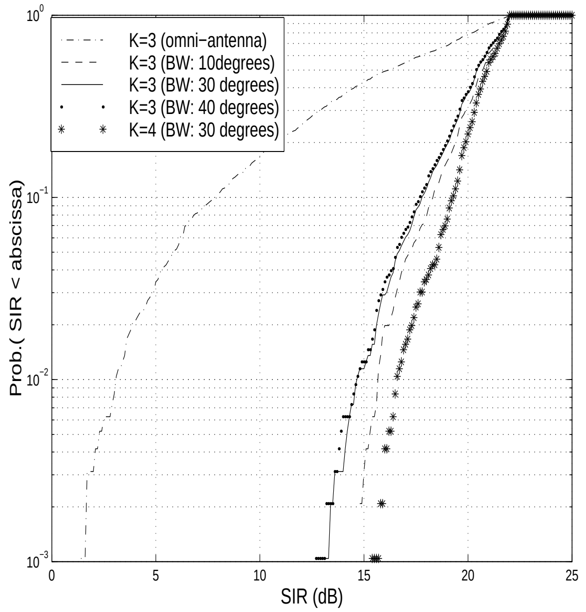


Fig 4. Reduction of interference using a directional antenna at the terminal

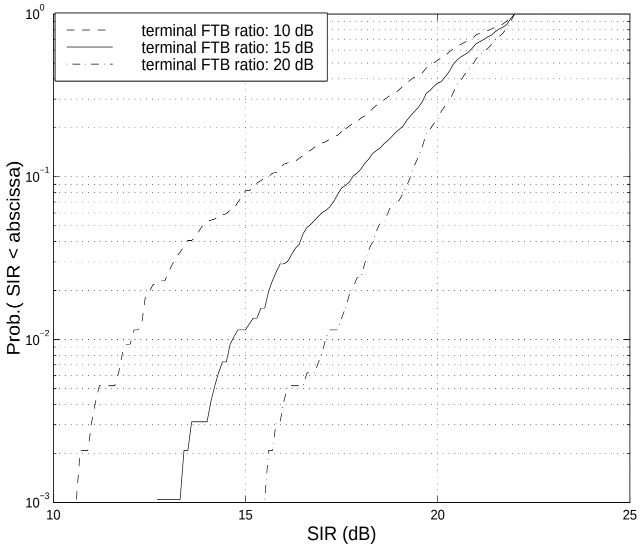


Fig. 5. SIR distribution for different terminal FTB ratios

difficulty in system growth for schemes such as SRA [1], where sector splitting may upset the careful labeling sequence necessary to manage interference. With sector splitting, the operations of the SBRA method remains unchanged. This is a major advantage compared to cell splitting which requires new bases and re-pointing of terminal antennas. If directional antennas are used at the base, sector splitting would require changing of sector antennas, whereas if multi-beam smart antennas are used at the base, it may be possible to reconfigure the antennas at the time of sector splitting without need for replacement.

Consider a system with bases installed in an irregular fashion, as might be the case due to constraints of available locations and non-uniform traffic density. This could give rise to irregular cell sizes and shapes. The SBRA scheme can be implemented with sufficient performance margin to accommodate this in a straightforward manner. In general, the number of adjacent cells and the amount of common boundary with each could vary. We now show how capacity can be enhanced in other parts of an irregular system if reuse requirements vary across the system. We use an example system layout shown in Figure 2 in which K=4 (the maximum number of reuse patterns) is required. Cells are labeled with one of the four cell types (labeling patterns) a, b, c and d. A subscript is added purely to identify each cell, i.e. b_2 and b_3 use the same labeling patterns. Note that cells a_1,b_1,c_1,d_1 are the only group of cells in which each cell is very close to all others in the group; thus the cells almost meet at one point and require the four different labels. In other cases, it is 3 rather than 4 cells that meet at a boundary. As a result, cells have neighbors which use a total of either two or three different patterns; cells with neighbors using only two labels are either edge-cells or would have an even number of neighboring cells. As an illustration, the neighbors of cell c_2 use type a or b, while the neighbors of cell c_1 use a, b, or d. As discussed above, sectors in cell a, b, c and d would be labeled by 1 and 2, 3 and 4, 5 and 6, and 7 and 8, respectively, which are not shown in the figure.

Figure 3a depicts time slots which are grouped into eight subframes and sector with label *i* could use only time slots of subframe i. However, this straight-forward approach may result in a waste of bandwidth in some cells. We now explore the non-uniform labeling to improve the bandwidth usage and system throughput as follows. To illustrate the idea, let us consider a couple of examples. First, assume that a cell (e.g., cell c_2 does not have a neighboring cell with d labeling pattern. In this case, time subframe 7 and 8 normally used by cell d can be divided into six mini-frames, indexed by 1 to 6 as shown in Figure 3b. Thus, in addition to subframe 5 and 6, cell c_2 can also use time slots of mini-frame 5 and 6. (It is understood that sectors with label 5 and 6 in cell c_2 transmit only in time slots of subframe or mini-frame 5 and 6, respectively.) This is feasible because transmission in the mini-frames in cell c_2 is not interfered by any first-tier neighboring cells. Further, cell b_3 can use slots in subframe 3 and 4 as well as those in mini-frame 3 and 4. Similarly, as shown in Figure 3c to 3e, the corresponding subframe can be divided into mini-frames and used by cells with no neighbors having the associated labeling pattern. In an extreme situation, if a cell has only one neighbor, it can use slots in two sets of two mini-frames, derived from four subframes that could have been used by the missing neighbors.

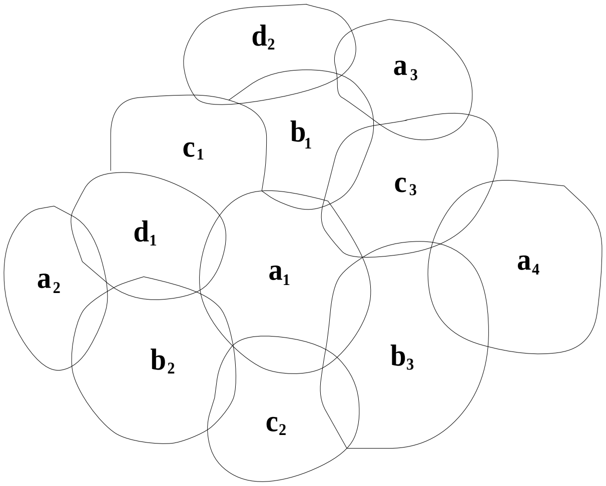


Fig. 2. Non-uniform labeling for irregular cell layouts

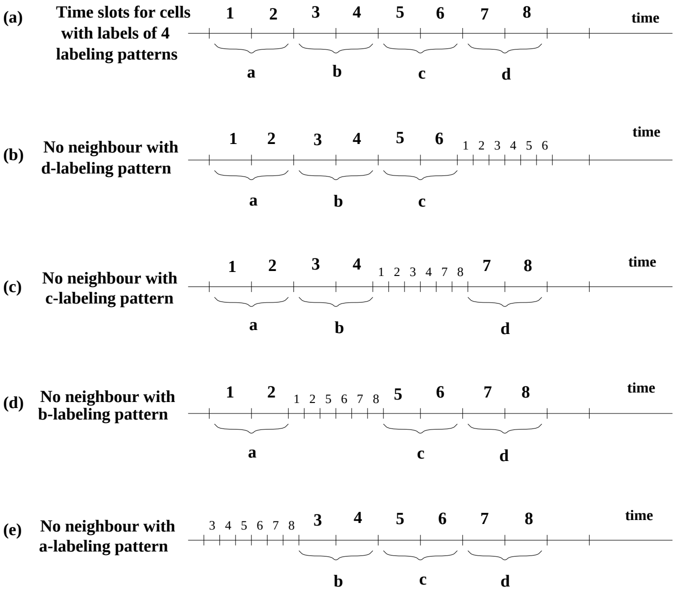


Fig. 3. Frame structures for enhanced capacity
for irregular cell layout shown in Fig. 2

Note that this non-uniform reuse concept is different from time slot reuse in TSRP [2] although the two concepts can certainly be merged in a hybrid scheme. Specifically, the TSRP scheme allows different reuse patterns for different terminals, depending on their reception quality. However, the division of the total bandwidth for different reuse patterns is performed by considering all terminals reception in the system. In contrast, our localized reuse takes a cell-by-cell approach. Thus, the

4. Sector labeling plans and time re-use patterns should be robust enough to allow for the inevitable deviations from a regular cell layout. Also, the number and size of sectors may not always be the same in each cell.

III. THE SECTOR-BASED RESOURCE ALLOCATION (SBRA) SCHEME

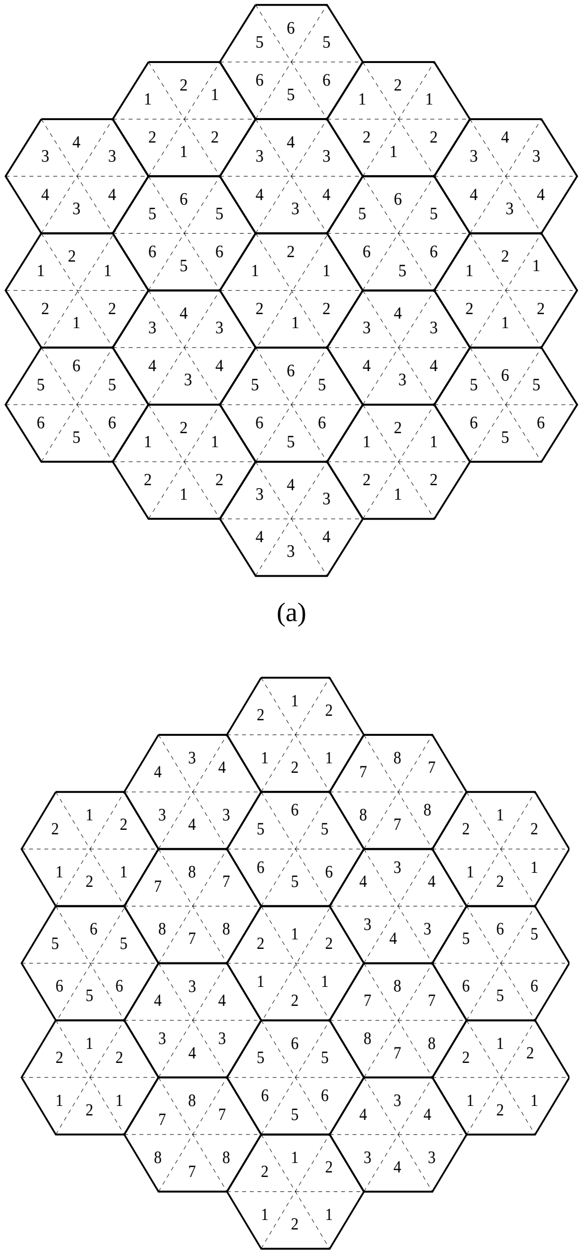
In the sector-based resource allocation (SBRA) scheme, each cell has an even number of sectors with alternate labeling (every other sector in a cell has the same label.) The scheme is presented in the context of time-domain re-use but also applies to frequency channel reuse. The scheme ensures that co-channel sectors in other cells are kept at a sufficient distance. In particular, co-channel sectors are not allowed in the first tier of neighboring cells. There is flexibility in the layout options as explained in the next section.

To illustrate our ideas, Figure 1(a) shows the SBRA scheme labeling for a hexagonal cell system with six sectors *(S = 6)* per cell and a reuse pattern with three (*K = 3*) types of cells. The three cell types use sector labels 1 and 2, 3 and 4, and 5 and 6, respectively. All cells depict an essential characteristic of the SBRA scheme; every other sector of a cell has the same label. This reuse pattern of three ensures that no two adjacent cells are the same type (labeling pattern), and the co-channel interference is reduced to acceptable levels (as co-channel interferers are in the second tier of cells). For a hexagonal layout, three cell types are sufficient to cover all cells in the system in a self-consistent manner.

In the time-domain SBRA scheme, time is divided into slots. Each time frame consists of *2K=6* sub-frames indexed by 1 to 6 for the layout in Figure 1(a), each of which contains multiple time slots. Sectors with label *l* can schedule packet transmission in time slots of subframe *l*. As a result, each sector can transmit on a 16.7% duty cycle, consuming at most one-sixth of the total bandwidth. The total network capacity is increased by the fact that 3 sectors with identical label in each cell can transmit simultaneously. In this example *(K = 3, S = 6)*, the effective overall re-use factor is 1 since, if there are *N* packets (slots) per frame, each cell processes *(N/K) x (S/2) = N* packets per frame. Note that such a high degree of concurrent packet transmission can be supported by the SBRA method because of the high directivity of the antennas. The SBRA scheme can support different re-use patterns and different number of sectors. Figure 1(b) shows an example layout for *K = 4* which offers lower co-channel interference, which may be needed for higher SIR threshold requirements. We now highlight other advantages of the SBRA scheme.

IV. IRREGULAR SECTOR AND CELL LAYOUT & NON-UNIFORM REUSE PATTERNS

The SBRA method is applicable to irregular sector plans where the number of sectors and their corresponding beamwidths vary from cell to cell. The primary constraint is that each cell should have an even number of sectors. There may also be design constraints for practical antennas which constrain the difference in angular sizes of adjacent sectors. Thus, the sector setting for each cell can be chosen to maximize the utilization of equipment while meeting the anticipated traffic demand. Such flexible sector planning is possible because the SBRA scheme does not rely on the alignment of the sectors in other cells.



(a)

(b)

Fig. 1. SBRA method for reuse pattern of (a) 3 and (b) 4.

The SBRA scheme allows sector splitting, which allows for easy growth in network capacity in an existing system. When the traffic load for sectors exceeds capacity, sectors can be further split into smaller sectors, each of which have roughly the same capacity as the original sector. This is in contrast to the

SECTOR-BASED RESOURCE ALLOCATION FOR BROADBAND FIXED WIRELESS NETWORKS

Arty Srivastava, N. K. Shankaranarayanan, and Kin K. Leung
{arty, shankar, kkleung} @ research.att.com

AT&T Laboratories - Research
100 Schulz Drive, Red Bank, NJ 07701-7033, USA

Abstract - We present a sector-based resource allocation scheme for broadband fixed wireless networks. For SIR requirements of about 12 to 14 dB, the scheme can deliver an effective reuse factor of one, while permitting a given spectrum to be re-used in every sector of every cell. The scheme also offers flexible sector planning, easy capacity growth, and addresses irregular cell layout and non-uniform traffic density.

I. INTRODUCTION

As telecommuting and Internet access become increasingly popular, the demand for broadband packet services will grow tremendously. Previous work [1-3] has shown that fixed broadband wireless networks that use directional antennas at both bases and terminals are an attractive and feasible solution for providing such packet services to homes and small businesses. The present work is motivated by pragmatic issues such as realistic antenna patterns, industry trends, non-uniform traffic density, capacity growth methods, and irregular cell layout. We present a simple Sector-Based Resource Allocation (SBRA) scheme that addresses these issues in broadband fixed wireless networks.

II. BROADBAND FIXED WIRELESS NETWORKS WITH DIRECTIONAL ANTENNAS

Consider a broadband fixed wireless network where each cell is divided into multiple sectors, each of which is served by a sector antenna co-located with a base station at the center of the cell. Terminals use directional antennas (typical beamwidths of 30^{o}) mounted on the roof top and pointed to their respective base antennas. The ratios of front-to-back-lobe gain (FTB ratio) for the base and terminal antennas may be different, and are assumed to be finite. For reasons outlined in [1], we pick a TDMA system with a shared downlink channel of 10 to 30 Mb/s that is suitable for broadband wireless systems. Time is slotted such that a packet can be transmitted in each slot.

Due to high data rate and limited spectrum availability, traditional methods for frequency reuse [4, 5] are not applicable in broadband systems. This has been a strong motivation for solutions that can use the same frequency in every sector of every cell in broadband wireless networks. Feasible solutions with high throughput are enabled by the use of directional antennas and time domain reuse [1, 2] in which time frames are divided into sub-frames and used in sectors in a manner analogous to frequency reuse. The Staggered Resource Allocation (SRA) scheme [1] uses a dynamic resource allocation algorithm where the same spectrum is used by every sector and cell on a dynamic time basis. There is a specific sequence in which sectors are labeled, and a specific schedule in which sub-frames are used in each sector with the result that concurrent packet transmissions cause little interference to each other. In fixed wireless systems with aggressive re-use, for a potentially-unacceptable fraction of terminals that are typically near a cell boundary, unfavorable shadow-fading conditions and local-scattering effects can create high interference that cannot be sufficiently suppressed by the directivity of the terminal/base antennas [2]. We refer to these terminals as vulnerable terminals. Techniques are available to increase the service coverage to accommodate such terminals with acceptable QoS [2, 3]. The Time Slot Reuse Partitioning scheme [2] uses multiple time-domain re-use patterns which provide different signal-to-interference ratio (SIR) characteristics. Terminals are categorized based on SIR requirement and assigned to different time-domain re-use patterns, i.e., they use time slots allocated to the respective patterns. Vulnerable terminals thus use patterns with higher re-use factors. The Enhanced SRA scheme [3] modifies the sector labeling scheme and the transmission schedule in the original SRA scheme [1] to accommodate the vulnerable terminals.

In our scheme, we use higher (K = 3 and above for typical cases) re-use factors to accommodate the vulnerable terminals. The resultant capacity drop is made up by concurrent transmissions from alternate sectors in the same cell. Our focus is on the dependence of SIR performance on various parameters, criteria for sector assignment, and pragmatic issues such as flexibility and upgrades. We make the following observations that have motivated our new sector-based resource allocation scheme.

1. For a typical system with a SIR requirement of 10 to 15 dB, any co-channel interferer in the first-tier of neighboring cells would contribute the most significant interference. For coverage targets greater than 80%, it is necessary to remove co-channel sectors to the second tier of cells.
2. Practical sector antenna patterns overlap with those of adjacent sectors of the same cell. Thus, no two adjacent sectors should use the same channel.
3. The common practice of cell splitting for capacity growth in cellular networks is not a good option for fixed wireless networks since the existing directional terminal antennas in the new cell will need to be re-oriented to a new base - a huge and undesirable task! A better solution is to increase the number of concurrent transmissions per cell.