

**HUGHES**  
NETWORK SYSTEMS



# **System Analysis for Point-to-Multipoint Networks Part 1: Frequency Reuse Planning**

January 2003

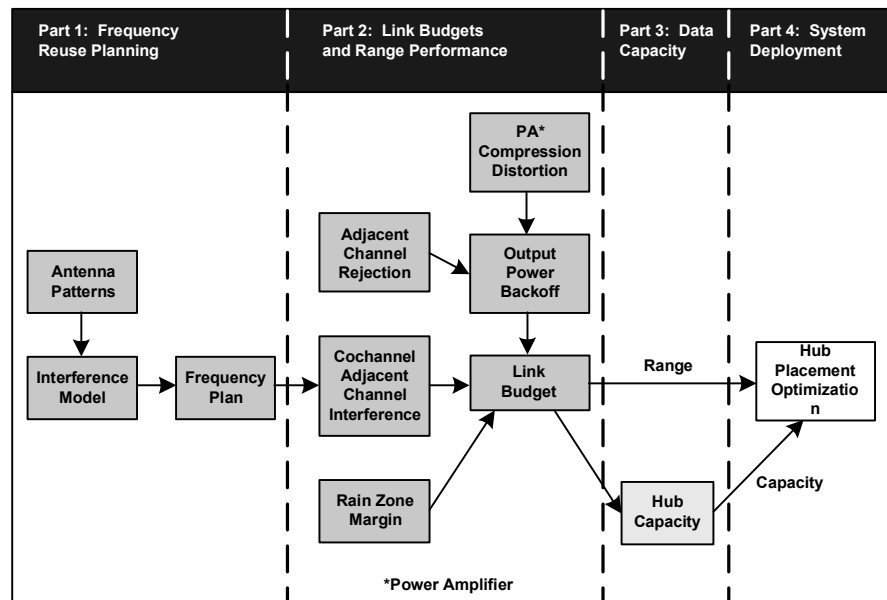
## A White Paper for Telecommunications Service Providers Using the AIReach® 9000 System

This AIReach® Broadband white paper affords service providers the rationale, analyses, and guidelines for developing and deploying point-to-multipoint (PMP) millimeter-wave communication systems for broadband wireless access (BWA). The intended audience of this paper is the technical staffs of telecommunications service providers who are taking advantage of the AIReach® 9000 system for BWA networks.

Drawing on Hughes' unparalleled experience and capabilities in highly-complex radio transmission systems, this paper analyzes system performances including hub range, coverage capabilities, and data hub capacity. Typical link budgets are presented and parameter rationale is discussed. Analysis and recommendations for hub deployments are also addressed, and derivations supporting these analyses are presented. Deployment issues are discussed resulting in installation procedure recommendations.

### 1.0 Background

*System Analysis for Point-to-Multipoint Networks* is organized into four parts, of which this white paper is the first. As shown in **Figure 1-1**, these four parts are: Frequency Reuse Planning, Link Budgets and Range Performance, Data Capacity, and System Deployment.



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**Figure 1-1. Organization of System Analysis for Point-to-Multipoint Networks**

### 2.0 Frequency Reuse Planning

In a spectrum-limited environment, the available frequency channels must be reused. Therefore, the goal of the frequency planning exercise is to produce a plan optimized for the

available frequencies, desired capacity, and the environmental or physical conditions of the service area. This paper deals with such planning and optimization to minimize the cochannel interference and maximize frequency reuse. It also compares theoretically expected results with Hughes' own simulations of the PMP environment.

To obtain an optimized frequency plan, the antenna patterns of both the hub terminal (HT) and the remote terminal (RT) must be known. Only when these patterns are known can the potential interference areas be established and the extent of the interference impact be determined.

### 3.0 Antenna Patterns

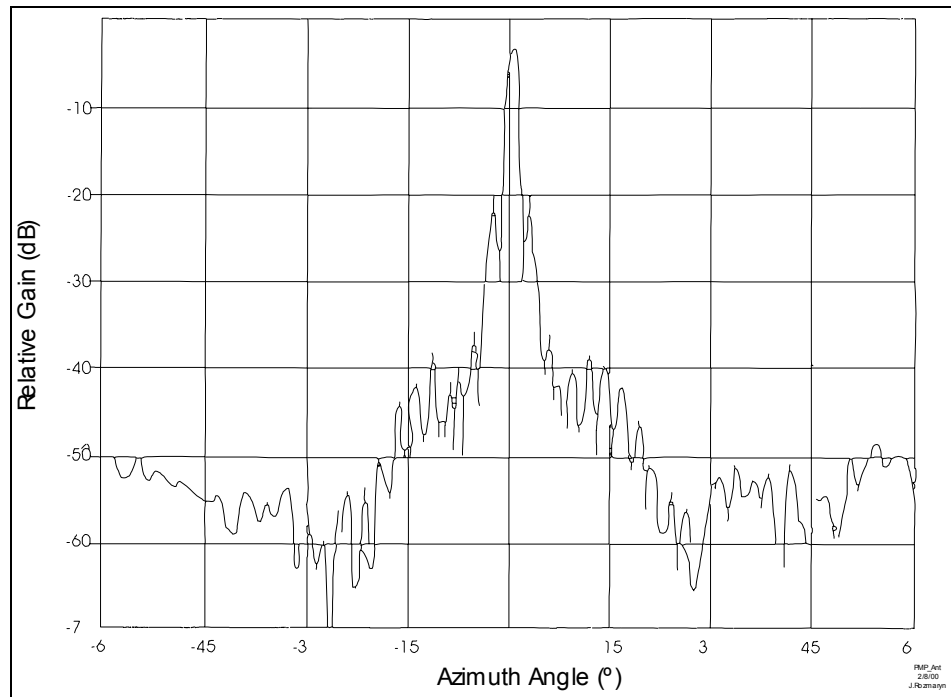
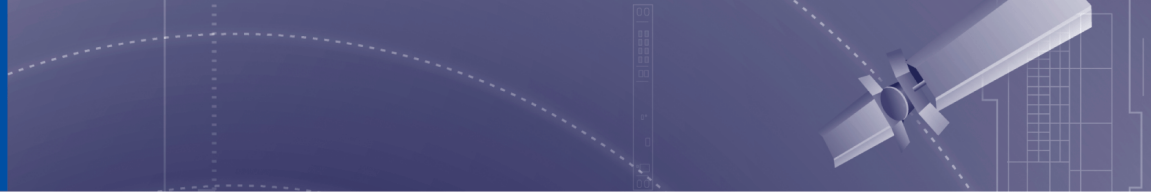
The key to understanding cochannel interference in the millimeter wave PMP systems is the performance and patterns of the HT and RT antennas. The individual patterns will determine the amount of cochannel interference. The RT antenna interference is more critical as it determines the locations of potentially affected subscribers. The backlobe and sidelobe performance dominates the interference magnitude.

### 4.0 Remote Terminal Antenna Pattern

A typical millimeter wave PMP RT antenna has a nominal beamwidth of less than 2° and a gain in excess of 35 dBi. It is typically specified with a pattern mask as shown in **Table 4-1**.

<b>Table 4-1. Minimum Sample Pattern Mask for Remote Terminal Antenna (Values are dB below the peak)</b>	
<b>Nominal Beamwidth</b>	<b>Antenna Gain</b>
5°–10°	25 dB
10°–15°	29 dB
15°–20°	33 dB
20°–30°	36 dB
30°–100°	42 dB
100°–180°	55 dB

The measured antenna pattern for the vertical beam of a typical AIReach RT antenna is shown in **Figure 4-1**. As can be noted, the measured patterns have at least 10 dB more suppression than required, thus providing additional cochannel interference protection.



**Figure 4-1. Remote Terminal Vertical Antenna Pattern**

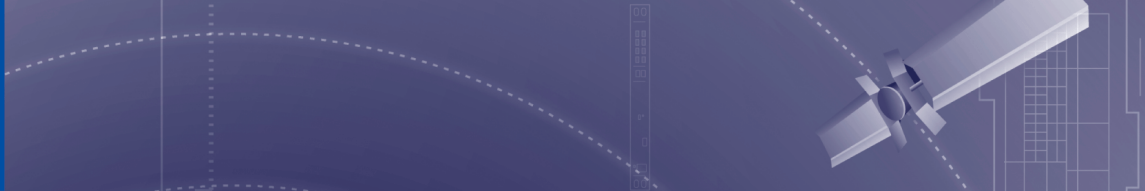
## 5.0 Hub Antenna Pattern

PMP HT antennas come in a variety of beamwidths. Without loss of generality, the HUGHES AIReach 9000 makes 90°, 45°, and 22.5° beamwidth antennas available for the hub. These correspond to hubs of 4, 8, and 16 sectors, respectively.

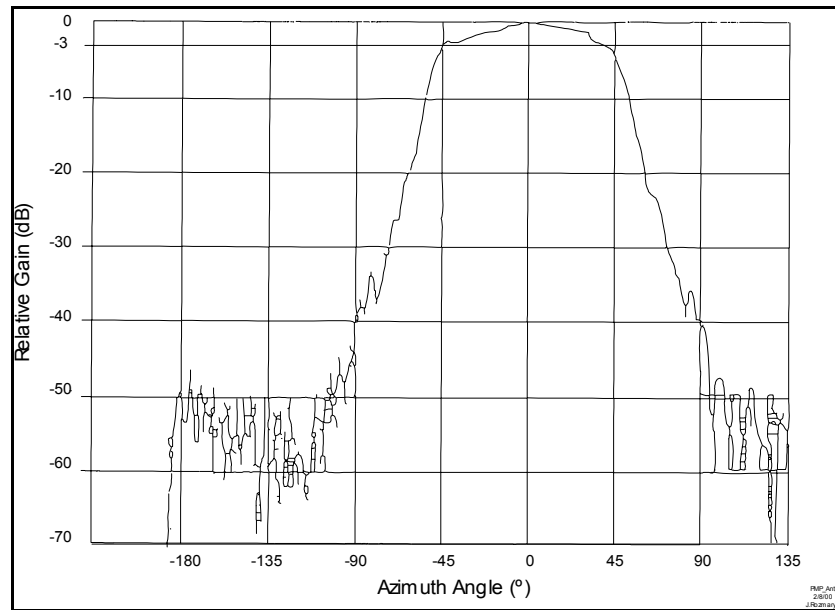
The nominal gain for a 90° antenna is 16 dBi, and a minimum sample pattern mask is specified as follows (values are dB below the peak):

+135°	+180°	35 dB
-135°	-180°	35 dB

The measured vertical antenna pattern of a typical AIReach HT is shown in **Figure 5-1**. Again, the AIReach antenna significantly outperforms the minimum required values, this time by at least 15 dB.



Hub Terminal Vertical Antenna Pattern - 90°



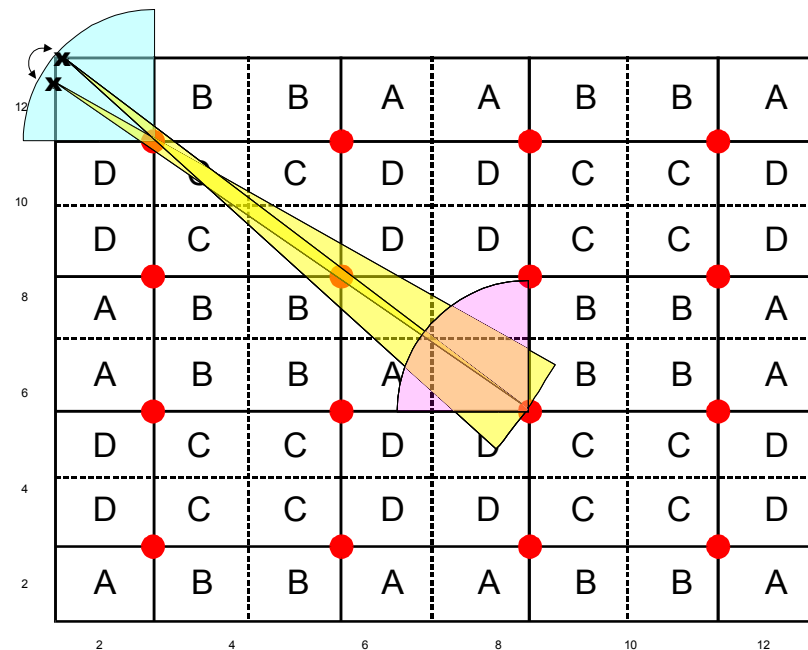
**Figure 5-1. Hub Terminal Vertical Antenna Pattern with Four 90° Sectors**

## 6.0 Cochannel Interference Overview

The predominate source of downlink cochannel interference stems from the RT antenna pattern. If the RT antenna and its serving hub antenna align with the interfering RT antenna at the same frequency, cochannel interference will be present.

**Figure 6-1** illustrates the interference concept. The large dots in the figure represent hub placements. “A” represents the assigned frequency channel. The quarter-circle antenna patterns are shown for two cochannel-aligned hubs with a 90° beamwidth. Two RTs are shown (marked as X) in the upper left corner, and their antenna patterns are shown in alignment with the cochannel hubs. These two RT sites will experience cochannel interference from the remote hub.

## Frequency Plan 90° Sectors with 4 Frequencies



**Figure 6-1. PMP Interference Source for Reuse with Four 90° Sectors**

The amount of interference is a function of distance to the serving hub and to the interfering hubs. In this illustration there is a five-sector separation between the RT(s) and the interfering hub. At the edge of coverage the distance ratio of the desired hub to the undesired hub is 5 to 1. In an environment where the propagation model attenuation falls off as the distance<sup>2</sup>, a distance ratio of 5 yields a 14 dB path loss attenuation; therefore, yielding a 14 dB carrier-to-interference ratio (CIR). This may be sufficient for QPSK demodulation but is not sufficient for either 16-QAM or 64-QAM demodulation. These areas are known as “potential zones of limited modulation.” It is only “potential” since any building or natural blockage to the interfering hub will eliminate the area as a limited modulation RT site. RTs closer to the serving hub experience an improved C/I because of the increase in the distance *ratio* with the interfering hub.

If the alignment falls out of the RT beamwidth either horizontally or vertically, or if the transmission angle lies beyond the nominal beamwidth of the interfering HT antenna, no interference will be generated. This is true since the antenna attenuation pattern suppresses the undesired transmission signal.

The only area that will be a potential zone of limited modulation capacity is the triangular area bounded by the two RTs and their HT, as shown in **Figure 6-2**. RT locations beyond these two points do not align within the beamwidth of the RT antenna and cause no interference. What is apparent is that the area of limited modulation decreases with a narrower subscriber antenna pattern.

In addition to this interference zone, there are two other areas with the same limitations, as seen in **Figure 6-2**. *Note that these areas are exaggerated to show the interference concept.*

## Frequency Plan 90° Sectors with 4 Frequencies

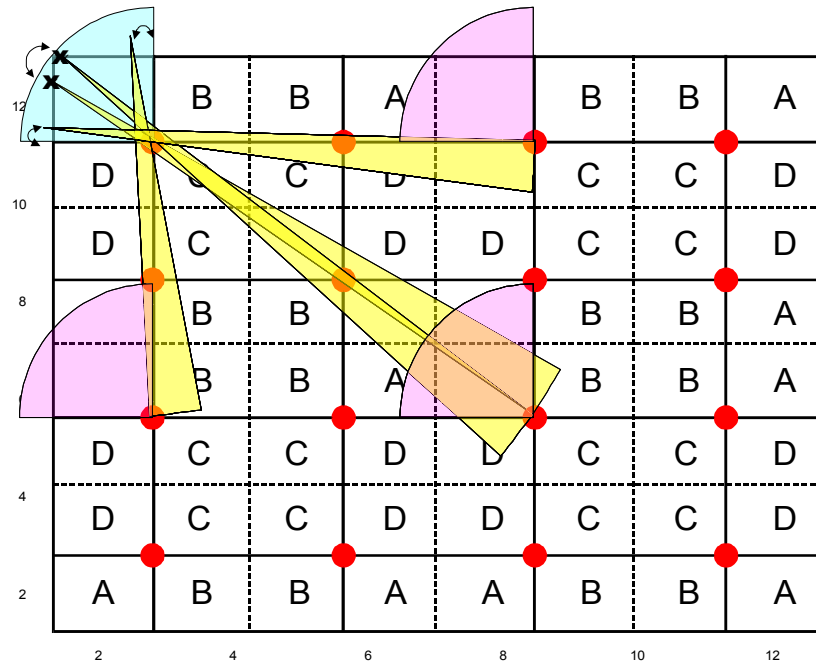


Figure 6-2. PMP All Interference Sources for Reuse with Four 90° Sectors

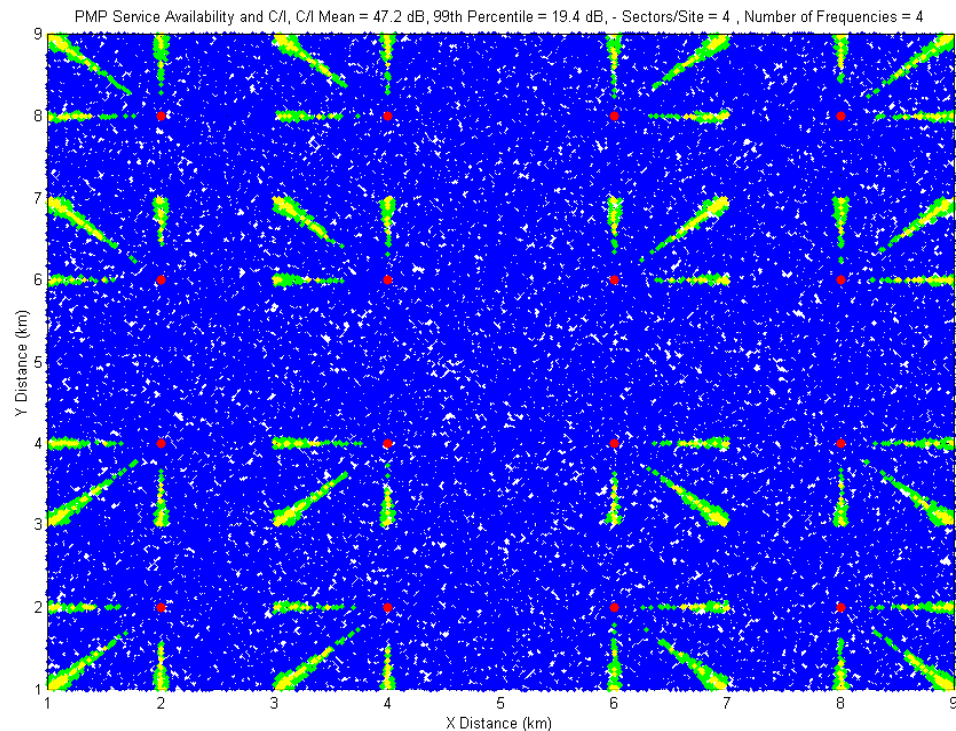
### 7.0 Regular 90° Sector Frequency Plan

There are only three dominant cochannel interferers in the underlying frequency reuse plan of **Figure 6-2**. All other cochannel transmitters are either in the sidelobes or backlobes of the HT antenna or RT antenna. Therefore, they are “invisible” to the RTs under discussion since, based on the AIReach antenna patterns shown, the sidelobes are attenuated at least 40 dB.

This reuse pattern is optimal as it places the cochannel interferers at a maximum distance before the pattern repeats.

**Figure 7-1** shows the result of simulation when using this frequency reuse plan and the minimum “required” hub and subscriber antenna patterns. It is important to note that simulated as well as practical results would be greatly improved using the actual “measured” antenna patterns.

## PMP Simulation 90° Sector, 4 Channel Performance



**Figure 7-1. PMP Simulation with 90° Sector, Four-Channel Reuse**

The X and Y coordinates in this figure are in kilometers. The red dots represent the HT locations. It is noted that these dots are on the grid pattern shown previously. Using Hughes' powerful simulation capabilities, this figure represents 100,000 simulation points, each of which yields a colored dot. The white areas represent unexercised simulation points. The assumed C/I required to support the three modulation modes — QPSK, 16-QAM, and 64-QAM — are 12 dB, 19.2 dB, and 25.8 dB, respectively.

What appears to be a solid blue background is actually made up of individual blue dots, which represent points with a high enough C/I to accommodate all modulation modes (i.e., at least 25.8 dB). The green dots represent locations with enough C/I to accommodate QPSK and 16-QAM modulations only. The yellow dots represent locations with enough C/I to accommodate QPSK only.

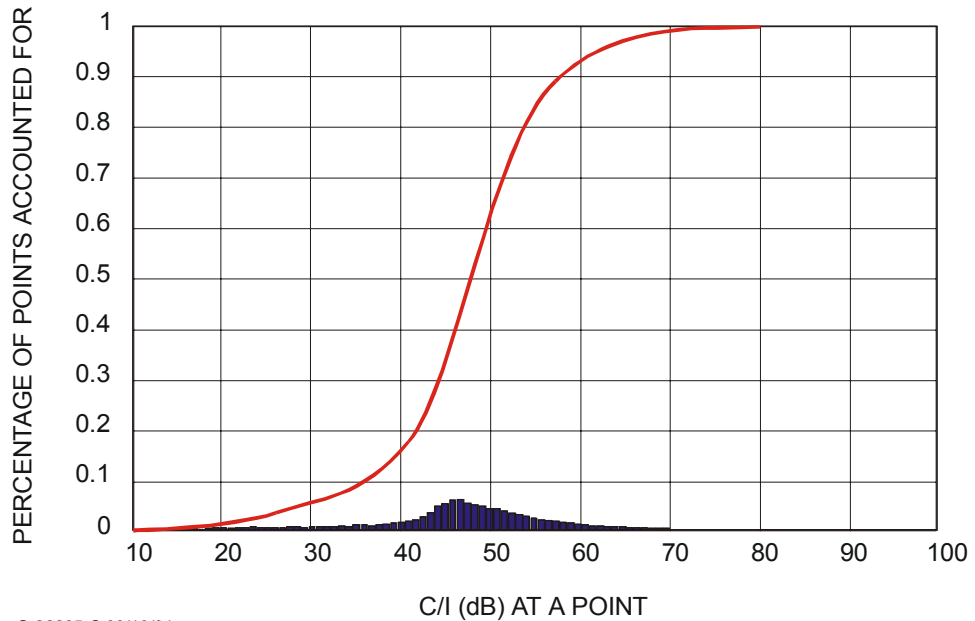
By observing the figure, the following conclusions may be drawn:

The shapes and locations of zones of limited capacity are consistent with the predicted pattern discussed above.

The total area of zones of limited capacity is insignificant compared with the total area. All areas can at least support QPSK.

**Figure 7-2** shows the histogram and cumulative histogram for the C/I of all simulation points. The mean C/I for this network is 47.2 dB. The 99th percentile C/I is 19.4 dB. Using this histogram to determine the coverage percentage of the network area for each modulation reveals that:

- 64-QAM (C/I=25.8 dB) covers 96% of the area
- 16-QAM (C/I=19.2 dB) covers 99% of the area
- QPSK (C/I=12 dB) covers 100% of the area.



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**Figure 7-2. PMP Simulation with 90° Sector, Four-Channel Reuse**

## 8.0 Capacity Doubling Strategies

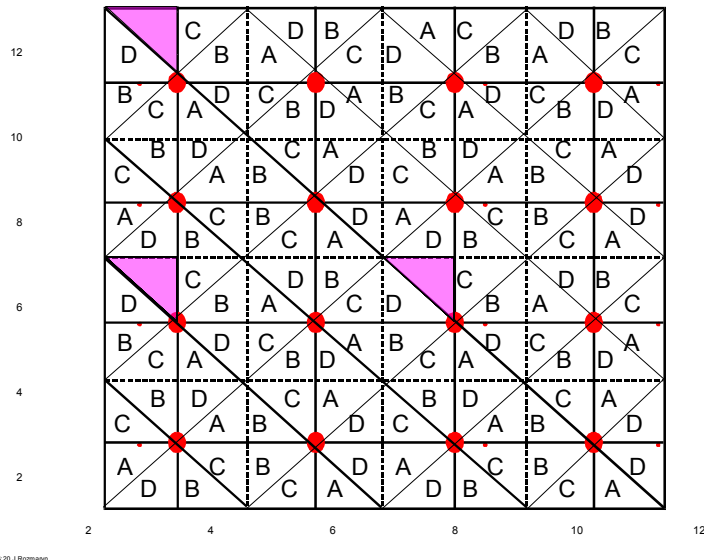
When additional capacity is required, there are several methods for designing the network. This discussion assumes that there are four channels available for reuse. The first method involves using two frequencies per sector without changing the beamwidth per sector (i.e., the coverage overlaps). This results in two frequency sets: frequencies A and C are in one set; frequencies B and D are in the other. The optimal reuse pattern for this approach is shown in **Figure 8-1**.



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**Figure 8-1. Frequency Plan with 90° Sector, Two-Channel Reuse**

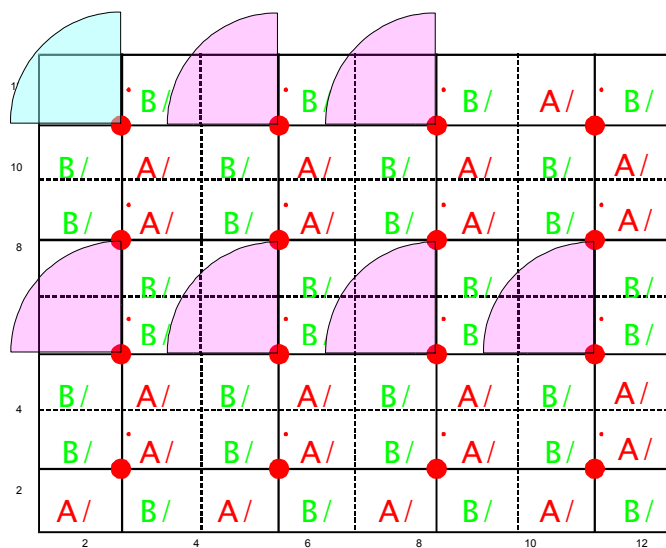
The second approach would be to keep the frequencies separate and increase the number of sectors to eight by using 45° sectors. This approach is shown in **Figure 8-2**. It has the benefit of providing more channels per cell than the four-frequency reuse approach. The performance difference is shown to be quite significant.



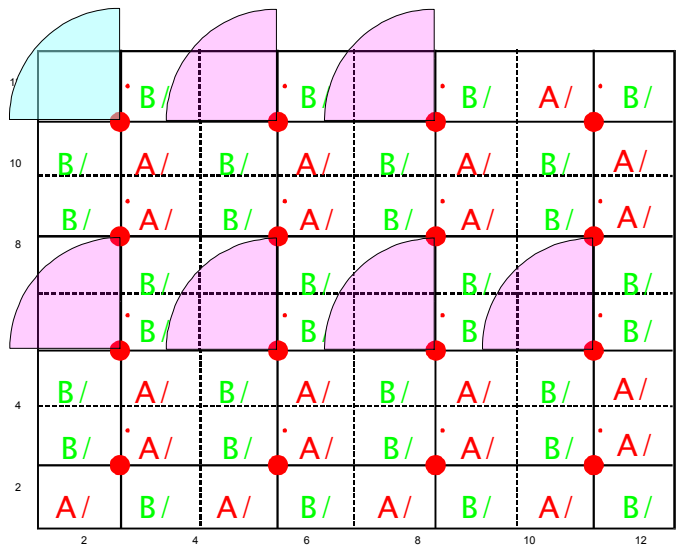
**Figure 8-2. Frequency Plan with 45° Sector, Four-Channel Reuse**

## 9.0 Double Frequency Approach

For the two-frequency set approach, the dominant cochannel interference sources are shown in **Figure 9-1**. There are many more interferers than in the four-frequency set case. The simulation for this reuse configuration is shown in **Figure 9-2**.



**Figure 9-1. Interference Sources with 90° Sector, Two-Channel Reuse**

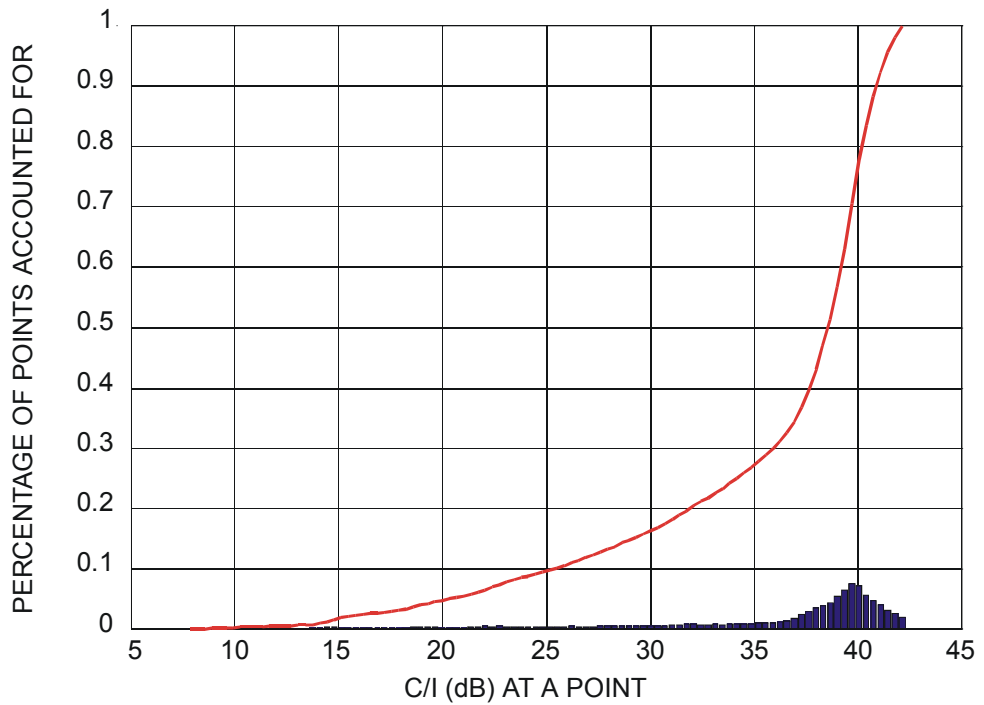


**Figure 9-2. PMP Simulation with 90° Sector, Two-Channel Reuse**

Here the results of the many interference sources are noted. Small red dots represent points where the C/I is insufficient to support any modulation, and such areas are now visible. The histogram of this simulation is shown in **Figure 9-3**.

The mean C/I for this network is 35.9 dB. The 99<sup>th</sup> percentile C/I is 14.3 dB. Using this histogram to determine the coverage percentage of the network area for each modulation reveals that:

- 64-QAM (C/I=25.8 dB) covers 89% of the area
- 16-QAM (C/I=19.2 dB) covers 96% of the area
- QPSK (C/I=12 dB) covers 99.5% of the area.



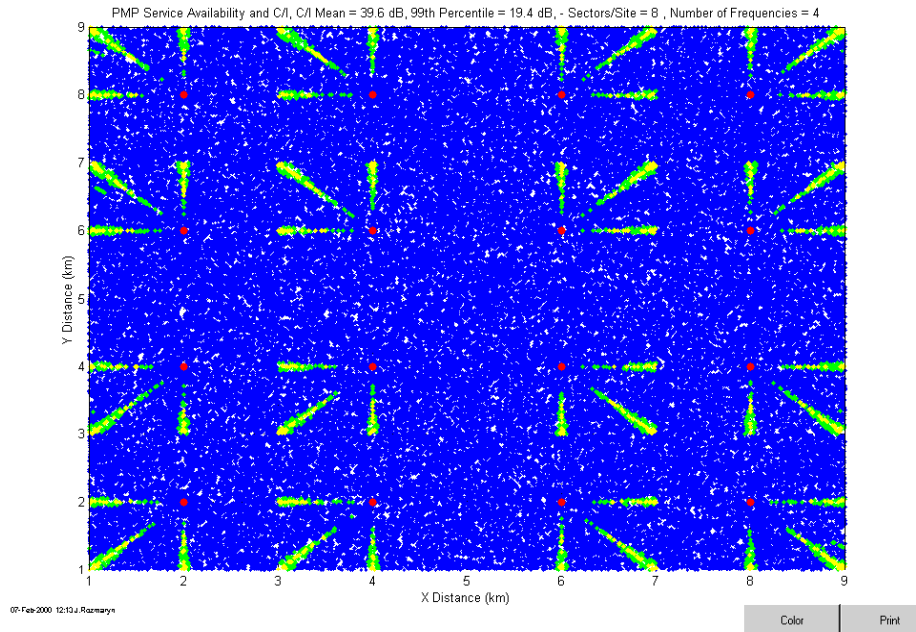
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**Figure 9-3. PMP Histogram Simulation with 90° Sector, Two-Channel Reuse**

## 10.0 Eight-Sector Approach

The dominant interference sources for the eight-sector approach are presented in **Figure 8-2**. This figure represents an optimal reuse pattern. For every sector there are only two interference sources. The interference pattern will be the same as in the four-sector/four-frequency case. The resulting simulation is shown in **Figure 10-1**. The pattern indeed does have the same form as the four-sector/four-frequency case.

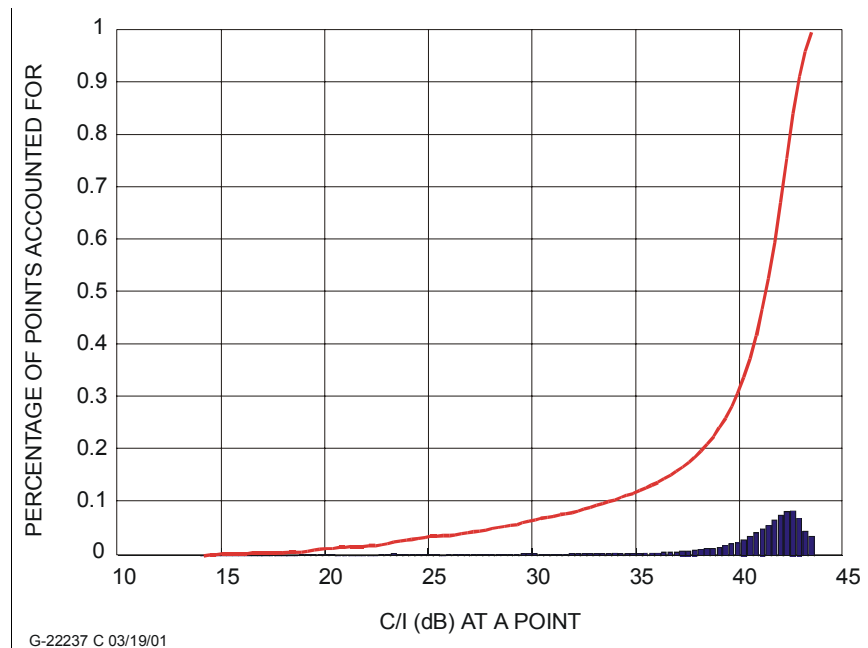
## PMP Simulation 45° Sector, 4 Channel Performance



**Figure 10-1. PMP Simulation with 45° Sector, Four-Channel Reuse**

The histogram for the eight-sector approach is shown in **Figure 10-2**. The mean C/I for this network is 39.6 dB. The 99<sup>th</sup> percentile C/I is 19.4 dB. Using this histogram to determine the coverage percentage of the network area for each modulation reveals that:

- 64-QAM (C/I=25.8 dB) covers 97% of the area
- 16-QAM (C/I=19.2 dB) covers 99% of the area
- QPSK (C/I=12 dB) covers 100% of the area.



**Figure 10-2. PMP Simulation with 45° Sector, Four-Channel Reuse**

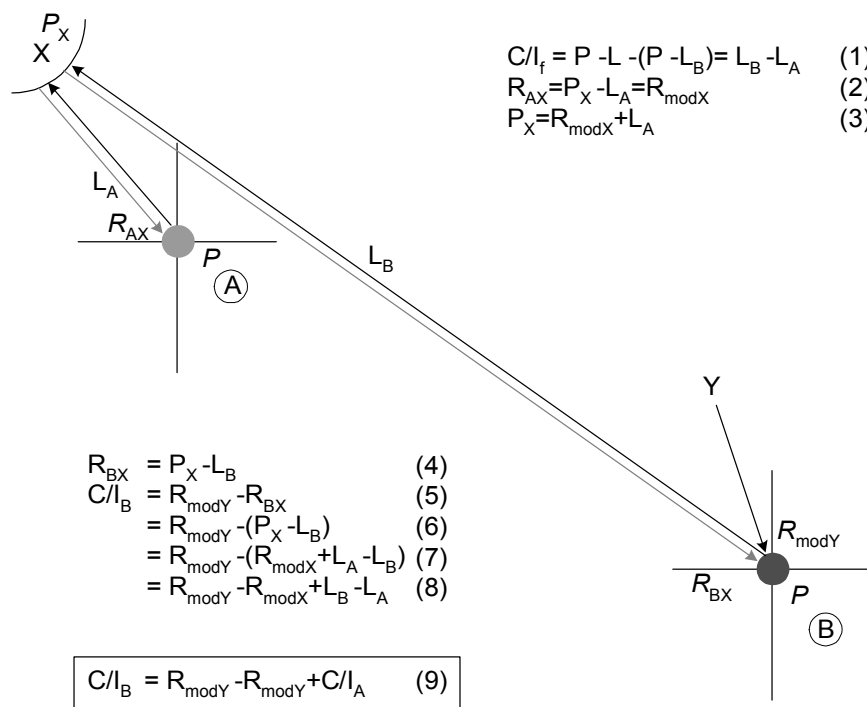
An important conclusion is that the four-channel, eight-sector hub configuration outperformed the two-channel, four-sector hub configuration. For example, the 64-QAM performance increased from 89% coverage to 97% coverage. The implementation costs for both configurations are the same since, in both cases, the implementation requires two radios and two antennas. The only difference is the beamwidth of the HT antenna.

## 11.0 Uplink Interference

All previous analyses have focused on the downlink interference. The uplink interference analysis is presented here.

In the cochannel uplink case, the received interference from an interfering RT must be derived.

**Figure 11-1** shows the derivation of the uplink cochannel interference. In this illustration there are two cochannel HTs labeled A and B. Each HT transmits at a power level of P dBm with arbitrary modulations. RT X is served by HT A, and RT Y is served by HT B.



$R_{modY}$	$R_{modX}$	$R_{modY} - R_{modX}$	
-84/QPSK	-84/QPSK	0	$C/I_B = C/I_f$
-70/64QAM	-70/64QAM	0	$C/I_B = C/I_f$
-70/64QAM	-84QPSK	14	$C/I_B = C/I_f + 14$
-84QPSK	-70/64QAM	-14	$C/I_B = C/I_f - 14$
90° Sector, BER=1e-8			

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**Figure 11-1. Uplink Cochannel Interference Analysis**

The C/I detected by RT X in the forward link is defined as  $C/I_f$ .  $C/I_f$  is just the path loss difference between the two HTs,  $L_B - L_A$ .

To compute the C/I due to RT X at HT B in the reverse link, the signal levels of both RT X and RT Y must be extracted. RT Y is served by HT B and is interfered by RT X. The output power of X = the target modulation power level plus the path loss to HT A from X. This is true since the power level on the reverse link is controlled to a designated received power level.

The C/I seen by HT B is the difference between the signal generated by wanted RT Y minus the signal generated by RT X. Following the derivation in **Figure 11-1**, the resulting C/I at HT B is shown in Equation 9. Put simply, the C/I generated by RT X is equal to the C/I that RT X experiences in the forward direction, plus the difference of the modulation target receive signal levels.

For a 90° sector with a bit error rate (BER) of 1e-8, the derived target signal levels are -84 dBm for QPSK and -70 dBm for 64-QAM. The table in **Figure 11-1** tabulates the resulting C/I at HT B for all combinations of modulation types.

When the modulations are the same at both HTs, the generated output C/I equals the forward link C/I. When the local subscriber is operating in 64-QAM and the interferer is operating in QPSK, there is a C/I increase of 14 dB. However, when the local subscriber is operating in QPSK mode and the interferer is operating in 64-QAM mode, there is a 14 dB decrease from the interferer's forward C/I. This decrease is of no consequence since 14 dB less C/I is required for the demodulation of QPSK modulation.

In fact, it seems that if subscribers are not permitted to register when the forward C/I is less than the minimum C/I for the QPSK modulation, and if the subscribers are power controlled to the target RSL (Receive Signal Level), then the uplink interference will have no impact on the uplink demodulation performance.

This can be shown mathematically as follows:

From Equation 1,

$$C/I_B = R_{\text{mody}} - R_{\text{modx}} + C/I_f \quad [1]$$

If the receive levels  $R_{\text{mody}}$  and  $R_{\text{modx}}$  are determined by the noise floor and the required C/I, then

$$R_{\text{mody}} = \text{Noise Floor} + C/I_{\text{mody}} \quad [2]$$

and

$$R_{\text{modx}} = \text{Noise Floor} + C/I_{\text{modx}}, \quad [3]$$

then

$$C/I_B = C/I_{\text{mody}} - C/I_{\text{modx}} + C/I_f. \quad [4]$$

If  $C/I_f$  is the forward  $C/I$  that the interferer sees, then the worst-case  $C/I_f$  is the minimum  $C/I$  for that modulation or  $C/I_{\text{mod}x}$ . Therefore,

$$C/I_{\text{Bmin}} = C/I_{\text{mod}y} - C/I_{\text{mod}x} + C/I_{\text{mod}x} \quad [5]$$

or

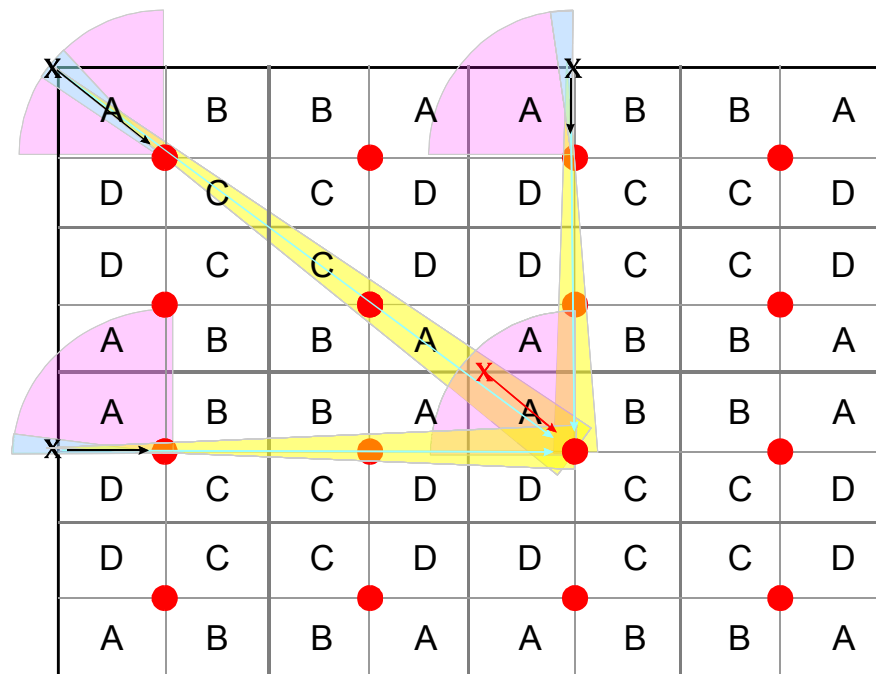
$$C/I_{\text{Bmin}} = C/I_{\text{mod}y} \quad [6]$$

This means that the  $C/I$  experienced by the local subscriber is never less than the  $C/I$  required for this modulation, independent of the modulation of the interferer, provided that:

- Subscribers are power-controlled to their target modulation RSL
- An installed subscriber must meet the minimum forward (downlink)  $C/I$  to support its modulation
- The RSL measurements used for power control are accurate.

Therefore, there is more to the uplink interference picture than initially is apparent. There is a basic difference between the uplink and the downlink interference.

**Figure 11-2** shows the uplink interference version of the frequency plan in **Figure 6-2**.



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**Figure 11-2. Uplink Interference with 90° Sector, Four-Channel Reuse**

HT 1 in **Figure 11-2** is a 90° sector. It will see potential interferers from not one but three different sectors of the same frequency as illustrated. The above analysis is valid for one interferer but not for three. The equations must be modified to account for the three interferers. It might seem that in the worst case the three interferers would be additive and consequently increase the interference by 5 dB. However, since they are power controlled to their target RSL values, the probability is low that all three will be at maximum power.

To quantify the impact on the performance, use Equation 1,  $C/I_B = R_{\text{mody}} - R_{\text{modx}} + C/I_f$  where  $R_{\text{mody}}$  is the desired RSL and  $R_{\text{modx}} + C/I_f$  is the interference RSL.

Therefore,

$$C/I_B = R_{\text{mody}} - \text{Linear Sum}(R_{\text{modxi}} - C/I_{fi}) \quad (1 \leq i \leq 3) \quad [7]$$

Using Equations 2 and 3,

$$C/I_B = \text{Noise Floor} + C/I_{\text{mody}} - \text{Linear Sum}(\text{Noise Floor} + C/I_{\text{modxi}} - C/I_{fi}) \quad [8]$$

Extracting the Noise Floor from inside the Linear Sum yields:

$$C/I_B = \text{Noise Floor} + C/I_{\text{mody}} - \text{Noise Floor} - \text{Linear Sum}(C/I_{\text{modxi}} - C/I_{fi}) \quad [9]$$

or

$$C/I_B = C/I_{\text{mody}} - \text{Linear Sum}(C/I_{\text{modxi}} - C/I_{fi}) \quad [10]$$

$$\text{Let } C/I_{fi} = C/I_{\text{modxi}} + \Delta C/I_{xi} \quad [11]$$

where  $\Delta C/I_{xi}$  is the excess C/I above the C/I required for demodulation,

Equation 10 becomes

$$C/I_B = C/I_{\text{mody}} - \text{Linear Sum}(-\Delta C/I_{xi}) \quad [12]$$

or

$$C/I_B = C/I_{\text{mody}} + \text{Linear Sum}(\Delta C/I_{xi}) \quad [13]$$

$$\text{Let } \epsilon_{\Delta C/I} = \text{Linear Sum}(\Delta C/I_{xi}) \quad [14]$$

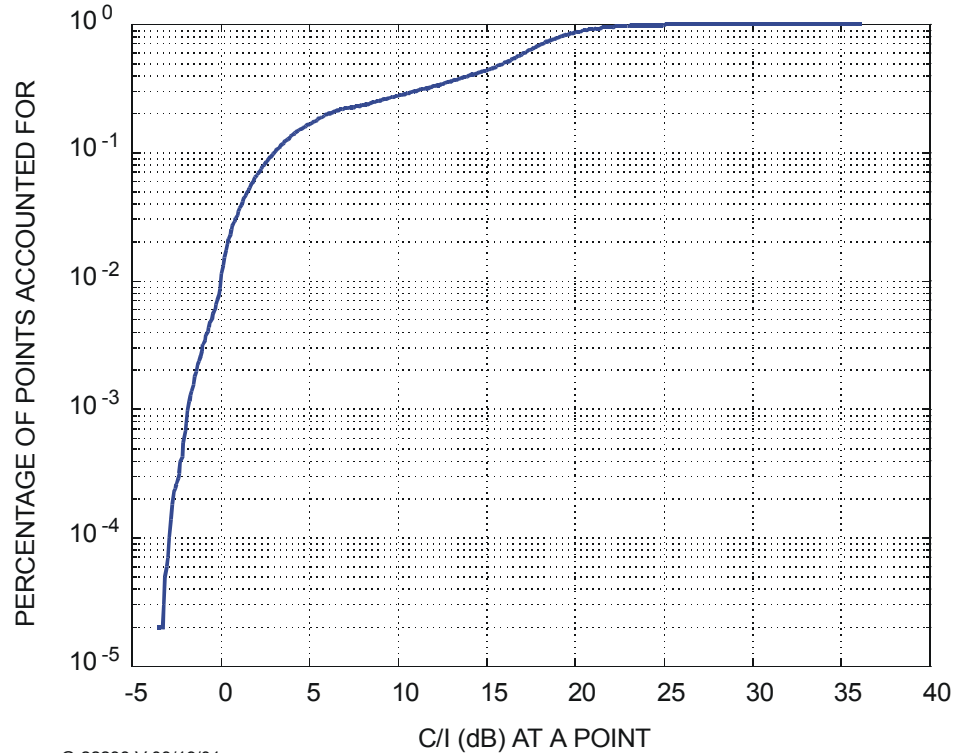
and finally,

$$C/I_B = C/I_{\text{mody}} + \epsilon_{\Delta C/I} \quad [15]$$

$f_{\epsilon}$  (C/I) is the probability distribution of  $\epsilon_{\Delta C/I}$  with respect to C/I. Once its distribution is generated from C/I simulations, the amount that  $C/I_B$  misses its target modulation C/I can be determined by Equation 15.

Performing the simulation using the configuration shown in **Figure 11-2** and computing the resulting C/I produces the histogram shown in **Figure 11-3**. From this histogram, we

observe that only 1% of the subscriber deployments would yield negative values for  $\epsilon_{\Delta C/I}$ ; therefore, the uplink  $C/I$  would not meet its required value. The worst case is  $C/I_B = C/I_{\text{mody}} - 3.7$  dB, which would occur in only about 0.001% of the installations.



**Figure 11-3. Uplink Interference with Joint Three Simultaneous Interferers,  $f_{\Delta}(C/I)$**

Even for the 1% of deployments that might be affected, the only time that a subscriber would be impacted is if uplink bursts for all three interferers occurred simultaneously. Hughes AIReach<sup>®</sup> Broadband supports an airlink of up to 45 Mbps. For the sake of discussion, if this were simply divided into 28 fixed North American T1 terminations (1.544 Mbps each), each assigned to one subscriber, then the probability that all three interferers are transmitting simultaneously would be  $(1/28)^3$  or an equivalent availability of 0.99995.

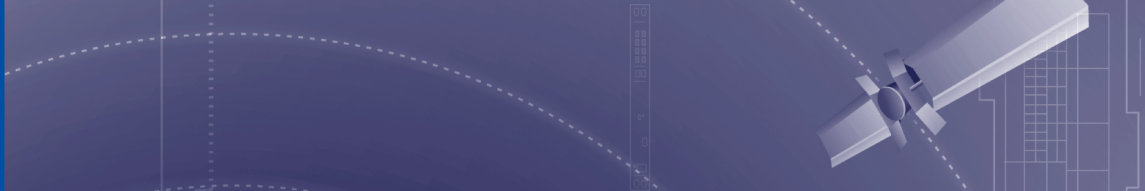
In summary, uplink interference can be worse than downlink interference but has very little statistical impact on subscriber performance; therefore, downlink interference performance should determine the cochannel interference of the PMP network.

Deploying a scanning narrowbeam antenna, the probability of the three interferers overlapping is further reduced, and the resulting interference impact would be negligible.

### Other Methods

The above frequency reuse planning assumed that the hubs are deployed on a perfect grid and that no building blockages occur. While perfect alignment does not occur in practice – and building blockages do occur – the principles discussed are largely valid.

A more robust approach is to optimize the frequency reuse based on realistic deployments and either theoretical or measured path loss values. Two frequency reuse optimization techniques used by Hughes in the design of PMP networks are called simulated annealing



and genetic algorithms. These techniques select near-optimal frequency reuse plans that maximize a specific-quality metric to rapidly find a near-optimal configuration. This selection is achieved by utilizing blockages to the best network advantage. Hughes has deployed both techniques with comparable results.

In simulated annealing, using the initial arbitrary frequency configuration, the quality metric is computed. Each sector tries all of the available frequencies and selects the one that most increases the quality metric. This process continues until all the sectors have completed frequency reselection. The process is iterated until there are no more improvements to the metric. The selected configuration is now randomized to avoid finding a local metric peak. This process is repeated until the best configuration is generated.

The advantage of this procedure is that it does not require perfectly placed hubs, and can use either theoretical path loss values or measured path loss values.

### **Summary**

*Frequency Reuse Planning*, Part 1 of *System Analysis for Point-to-Multipoint Networks*, has concentrated on the issues associated with various types of intrasystem interference and how to mitigate them. It has addressed antenna patterns and planning considerations for cochannel interference on both uplink and downlink.

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