ATG Spectrum Migration

Evolution of the ATG Migration Concept (Part 2)

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1. Executive Summary

When spectrum was originally allocated for air-to-ground communications services[1], the system architecture was designed to support multiple users on multiple networks using a dynamic, demand access scheme. Designed as a narrowband voice-centric FDMA network, the Air-To-Ground (ATG) technology evolved from one using analog modulation to one having a digital format today. Despite its evolution from analog to digital, the ATG technology retained legacy narrowband access protocols with a limited channel capacity of just a few kilobits per second. Thus, the current ATG spectrum utilization is neither efficient nor modern in its conveyance of information, whether voice or data.

In contrast, the advent of wideband high-speed cellular technology yielding data rates in the hundreds and thousands of kilobits per second (up to 2.4 Mbps) offers a striking advantage over legacy ATG wireless technology capacity and spectral efficiency. AirCell has developed and analyzed a novel approach for re-farming the ATG spectrum. This innovative architectural approach integrates state-of-the-art technologies such as CDMA2000 1xEvDO within the ATG 2MHz spectral allocation. It provides enhanced spectral utilization and dramatically increases public benefit.

This technical research paper critically evaluates the deployment of 1.25MHz CDMA systems in the ATG 2 MHz bands. It is seen as a continuation of AirCell's efforts to determine the optimal way for migrating and modernizing the commercial side of ATG communications. In the previous report [1] on this subject AirCell had considered the possibility of ATG spectrum sharing for two carriers using CDMA technology. This report builds upon contributions of previous AirCell work and examines the theoretical and practical aspects of ATG spectrum sharing between *four* CDMA carriers.

Key technical and operational objectives of the ATG spectral migration proposal considered in this report include:

- Enabling the operation of four concurrent CDMA network service providers in the 2x2MHz of paired ATG spectrum band,
- Determining the optimum spectrum sharing plan for four systems,
- Creating an evolutionary path for the incumbent operator to transition from the present narrowband paradigm to broadband CDMA,
- Determining the nature and level of inter-system interference that can be expected in the shared ATG spectrum environment,
- Examining the effectiveness of various known interference mitigation strategies and their applicability to ATG communication,
- Enhancing spectral efficiency and overall public benefit.

[1] The air to ground services are operating in Air to Ground (ATG) band. This band has 4 MHz of spectrum, with 2 MHz for each direction in a full-duplex communication mode.

2. Introduction

This report presents a further study evaluating migration possibilities for the spectrum allocated to Air-to-Ground (ATG) communication services. This study builds upon the previous AirCell proposal [1], in which AirCell evaluated the possibility of ATG spectrum sharing between two co-polarized CDMA systems. Through the use of extensive computer simulations, AirCell demonstrated that an innovative method of spectrum allocation provided enough isolation for virtually interference-free operation of two CDMA systems within the existing 2x2MHz of ATG spectrum.

Encouraged by results of the initial findings, and realizing that there is an interest for deployment of more than two systems in the ATG band, in this report AirCell broadens its proposal so that operation of four systems can be accommodated. The purpose of this report is to examine the methodology and enabling technologies that would allow sharing of the ATG spectrum between four CDMA systems, each having channelization of 1.25 MHz.

2.1. Review of the Previously Proposed ATG Spectrum Migration

ATG communications is allocated a pair of frequency bands in the UHF portion of the radio spectrum. These two bands occupy frequencies from 849-851MHz, and from 894-896MHz. Each band is 2MHz wide and utilizes frequency division duplex (FDD), i.e. one of the bands is used for communication from ground-to-air, while the other one is used in the opposite direction.

The spectrum migration strategy proposed in the original AirCell proposal is outlined in Fig. 2.1. As seen, the proposal advocates deployment of two CDMA 1xEvDO systems sharing the ATG spectrum. The channel bandwidth of each CDMA systems is 1.25MHz and since ATG spectrum is only 2MHz wide, there is at least 500kHz spectrum overlap between the two carriers. To reduce the interference between the systems, the allocation of the ATG bands are swapped for the second system. For ground-to-air communication, one of the systems uses the lower ATG band while the other system uses the higher one. For the air-to-ground communication, the bands are allocated in a reverse manner. For the sake of brevity this type of spectrum allocation will be referred to as cross-duplex operation. In the proposed cross-duplex operation, inter-system interference can occur only on paths between two base stations or between two aircraft of the deployed systems. Other interference paths are not possible. Through proper engineering of base station sites, base-to-base interference can be controlled. Therefore, the dominant type of interference is the one remaining on the paths between aircraft. This type of interference was the primary focus of studies in the previous AirCell report [1]. Its impact was quantified and proven to be very small in all cases of practical interest.

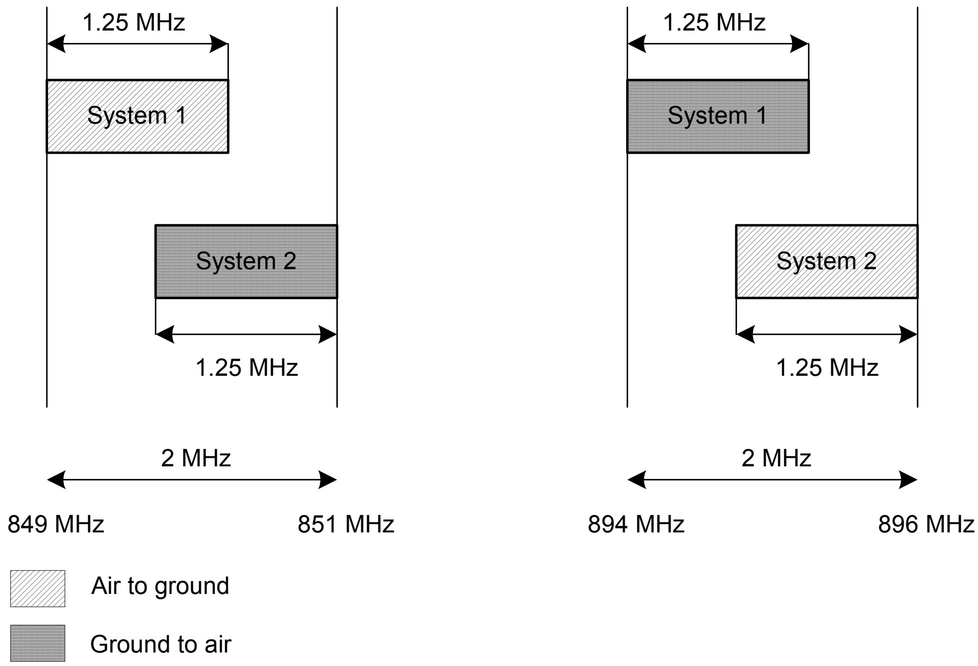

Figure 2.1. The first proposal for ATG spectrum migration

In addition to the scenario of 40% overlap indicated in Fig.2.1, in [1] AirCell has evaluated the spectrum plan shown in Fig. 2.2 as well. This plan allows for co-existence of the legacy narrowband system with newly deployed CDMA systems. Therefore, its importance is in the initial stages of the ATG spectrum migration. In this case, two CDMA carriers overlap over their entire bandwidth. Therefore, scenarios presented in Fig. 2.1 and Fig. 2.2 represent two phases in the wideband ATG rollout: Phase 1 with co-existing legacy providers (100% CDMA carrier overlap, narrowband service still operational, Fig. 2.2) and Phase 2 when narrowband ATG service has terminated (40% CDMA carrier overlap Fig. 2.1).

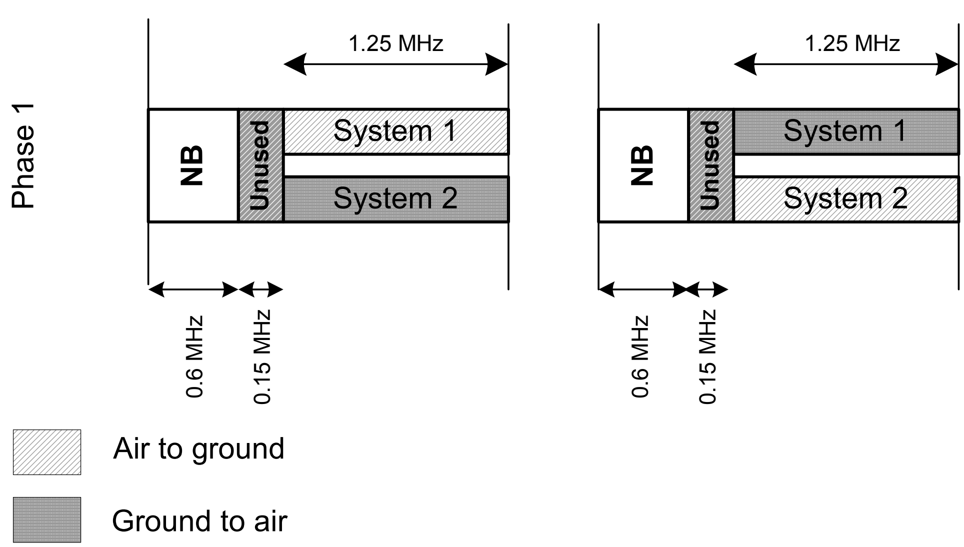

Figure 2.2. The second proposal for ATG spectrum migration

Both transitional and full wideband operation were shown in [1] to suffer only negligible inter-system interference for several cases of system loading and network configurations. This conclusion held even though the two systems were co-polarized. In other words, the additional 12-15dB of cross-polarization isolation available is not required to enable two-system operation if they are operating in the cross-duplex mode. Since wideband operation of two systems brings significant improvements in spectral efficiency, with demonstrated negligible degradation in the inter-system interference, AirCell suggested that the FCC adopt the reallocation proposed in [1], thus supporting the development of competitive services with wideband capabilities in the ATG spectrum.

2.2. Four-system Extension of the Original Spectrum Allocation Proposal

This technical report builds upon the encouraging results presented in [1], extending the ATG spectrum migration proposal from two to four CDMA systems. As mentioned in the previous section, cross-duplex operation enables deployment of two CDMA systems that are operating on the same polarization. This observation is the key to further extension of the AirCell proposal towards deployment of four CDMA systems. By leveraging the 12-15dB of system isolation that stems from operation using cross-polarization, AirCell demonstrates the feasibility of deploying the two additional systems in the same ATG band.

The methodology adopted in this report is similar to the approach used in the previous two-system study. CDMA-based technologies, such as the one proposed here, are not suitable for analytical closed-form performance characterization. Wireless CDMA network performance critically depends on too many parameters that are not subject to simple assumptions. Among them are the counts and locations of mobile users, mobility patterns, data rates, etc. Therefore, CDMA systems are rather analyzed by simulation using the technique commonly known as the *Monte Carlo* method. The Monte Carlo approach derives system performance predictions through generalization of results obtained from many individual realistic scenarios. Such scenarios represent snapshots of the entire system with defined number, initial positions, velocities, traffic and other parameters describing mobile stations, in this case aircraft. By analyzing many realistic snapshots, meaningful conclusions may be drawn regarding the expected network performance.

To evaluate the feasibility of deploying four systems in the ATG spectrum , a Monte Carlo simulator was built using the powerful Matlab™ engineering simulation software. Two distinct operational scenarios were investigated: Airport and Cross-Country. The simulation is dynamic in the sense that snapshots are tracked through time and updated periodically (1 second updating is used). The simulator provides a platform to examine various aspects of the proposed ATG deployment, including:

- Inter-system interference quantification
- Interference mitigation methods
- Possible spectrum allocation strategies
- Compatibility with existing systems

The challenge for deployment of two more carriers in a band that is already shared by two wideband carriers is to identify additional adequate mechanisms for interference suppression. Two such mechanisms are introduced in this study - polarization isolation and beam-switching antenna systems. The Monte Carlo simulator models effects of these interference-mitigation techniques in order to answer the fundamental question of the feasibility of co-existence of four-systems. The main conclusion, drawn from the results presented in this report, is that four CDMA systems, comprised of two cross-duplex systems operating on each of two orthogonal polarizations, can operate in the ATG spectrum. Results leading to this conclusion will be presented in the remaining part of this report. Interference reduction techniques necessary to enable that operation will be explained. Use of advanced (but readily available) hardware, such as switched beam antennas, may be required to maximize system capacity in some situations.

2.3. Outline of the Report

Following this introduction, Section 3 is devoted to description of isolation techniques that can be utilized in the deployment of four ATG systems. Known and well-understood engineering methods are proposed to ensure required isolation, including cross-duplex operation, cross-polarization and smart antenna systems antennas. Section 4 analyzes possible spectrum allocation plans. Three plans are presented, isolation mechanisms of each plan are identified, and an optimal plan for the deployment of four systems is identified. The simulators built to evaluate the dominant interference mechanisms of the four-system deployment scenario are described in Section 5. Section 6 presents quantitative results of the analyses of various deployment scenarios. Finally, section 7 summarizes the most important findings of the report.

Appendices give in-depth derivation and justification of concepts and results that were used in the simulation. Appendix A reports the results from AirCell's tests of path losses between aircraft and Appendix B provides an important statistical summary of aircraft density around major airports. It justifies some of the assumptions adopted throughout the simulation and shows that the loading assumed in the Monte Carlo simulation runs were somewhat conservative, based upon typical loading expected in the vicinity of the ten busiest US airports.

Simulation results presented in this report further strengthen the argument for adoption of the proposed ATG migration concept aimed at bringing broadband communications to the airline passenger market.

3. Isolation Mechanisms in ATG Spectrum Allocation

The main characteristic of wideband CDMA wireless systems is that many communication links are maintained using the same carrier frequency. Multiple users are differentiated by orthogonal spreading codes that widen the spectrum of the information-bearing signal. Spreading codes provide a processing gain defined as the ratio between the spread-spectrum and the baseband information bandwidth. The processing gain enables very low signal to interference plus noise ratios but requires excellent synchronization between the transmitter and the receiver. Synchronization is needed to de-spread the signal at the receiver by multiplying it with the same sequence applied during spreading at the transmitter. Details on the CDMA principles are beyond the scope of this report and are available in many references, such as [3, 4, 5].

The most important difference between AirCell's ATG proposal and classical terrestrial CDMA solutions is the co-existence of multiple systems in the same frequency band. In terrestrial networks, each system operates within a separate portion of the spectrum. The interference between any two systems is eliminated through proper frequency separation and strict enforcement of spectrum licensing. Due to the small size of the ATG band, deployment of multiple CDMA systems where each one of them operates in its own portion of spectrum is not possible. Therefore, to compensate for lack of frequency separation, other techniques for interference isolation between the systems need to be deployed.

In this report, AirCell considers four different methods for providing necessary interference isolation between the ATG systems. They are listed as:

- Cross-duplex operation
- Partial spectrum overlap
- Polarization isolation, and
- Deployment of smart antennas

In previous FCC filings [1], AirCell has demonstrated that use of cross-duplex operation and partial spectrum overlap allows safe, cost effective and almost interference free operation of two CDMA systems. However, to deploy up to four systems, additional isolation mechanisms need to be considered. Within this report, use of orthogonal polarization and switched beam base station antennas are introduced as means for providing additional interference isolation. Other proposals for ATG spectrum sharing examine the possibility of utilizing smart antennas on the aircraft side [10].

Before a detailed discussion of various interference reduction techniques, one needs to consider the principal problem of inter-system interference between CDMA systems sharing the same frequency band. This problem is frequently referred to as the *near-far* problem. To explain the nature of the near-far problem, consider the situation depicted in Fig. 3.1. The aircraft in Fig. 3.1 is subscribed to System 1. It is at a location far from the closest System 1 base station and near a base station of System 2. The aircraft is power controlled by System 1 and since it is far from the closest serving BS, transmitting at a high power level.

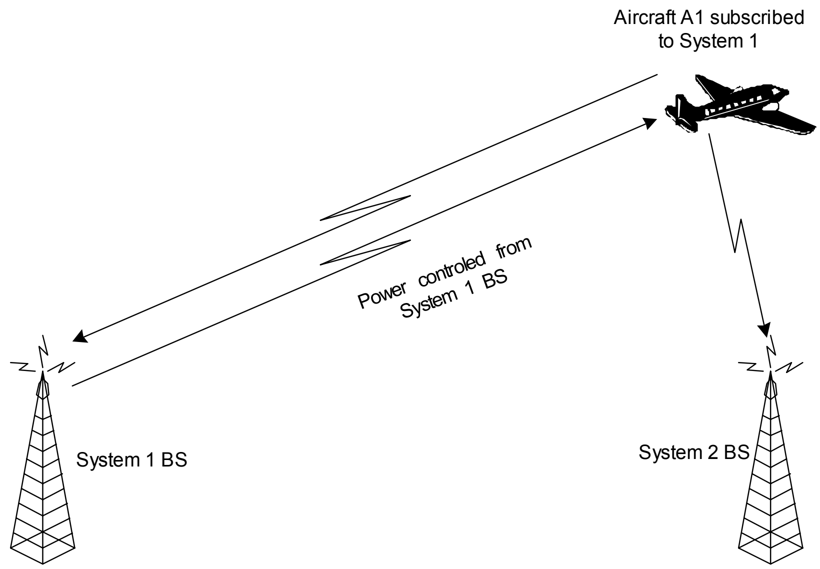

Figure 3.1. Near-far problem in multi-system CDMA operation

Given that the two systems share the same spectrum without additional interference isolation, high power transmission of the aircraft will create substantial interference to the System 2 BS receiver. At the same time, on the forward link a signal from System 2 BS causes a high level of interference to an already weak signal that the aircraft receives from the BS of System 1.

Fig. 3.1 illustrates that in addition to traditional challenges of CDMA, such as synchronization, code orthogonality, power management and noise rise monitoring to prevent overloads, ATG CDMA multi-system deployment must address the issue of additional interference isolation among operating systems. Various techniques that can be used to provide such isolation are discussed below.

3.1. Cross-duplex Operation

Cross-duplex operation has been introduced as an isolation mechanism in the case of a two-system ATG deployment discussed in [1]. Cross-duplex operation establishes swapped air-to-ground and ground-to-air links between two systems operating on the same polarization. The spectrum allocation in the case of cross-duplex operation was already introduced in Fig. 2.1 and Fig. 2.2 (cf. Section 2). The concept is further illustrated in Fig. 3.2. Instead of potentially harmful near-far inter-system interference on forward and reverse links, cross-duplex operation redistributes interference potential among four possible cases. The cases are given as follows.

1. System 1 forward link → System 2 reverse link: In this case, transmission from the System 1 BS may be received at base station receivers belonging to System 2 – Case of *base to base* interference.
2. System 1 reverse link → System 2 forward link: Transmission from an aircraft subscribed to System 1 may reach receivers of an aircraft subscribed to System 2 – Case of *aircraft to aircraft* interference.
3. Same as 1 with roles of systems 1 and 2 swapped.
4. Same as 2 with roles of systems 1 and 2 swapped.

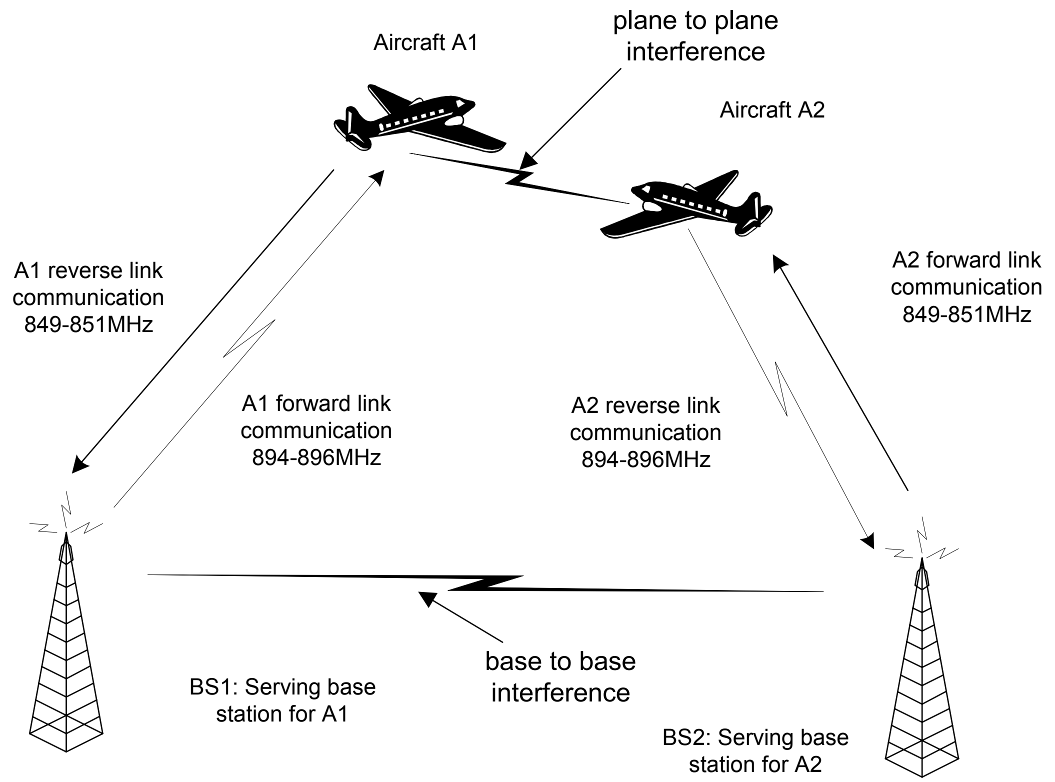

Figure 3.2. Possible cross interference paths

Among the four listed occurrences, cases of base-to-base interference (listed as 1 and 3 above), are most easily managed. As discussed in [1], and as thoroughly analyzed in Appendix C of this report, this type of interference is effectively suppressed by maintaining sufficient distance between base stations (BSs) from different systems and through the proper selection of up-tilted antenna patterns. Up-tilted patterns are helpful in controlling own-network multipath and are frequently used in various ATG systems. Essentially, assuming BS towers of approximately equal heights, choosing antennas with the antenna pattern nulls at a horizon direction effectively eliminates base-to-base inter-system interference.

Since aircraft positions are not fixed, a more complex interference potential (listed as 2 and 4 above) occurs on air-to-air links. This interference was examined and quantified in [1], assuming the worst-case omni-directional aircraft antenna patterns. It was shown that even without aircraft antenna directional selectivity, CDMA networks easily manage the added inter-system interference. The interference suppression in air-to-air links comes from the aircraft's physical separation required by the FAA. Given current FAA rules, negligible residual interference is generated on air-to-air links assuming even conservative (worst case) aircraft distributions.

For all simulations used to support ATG migration concepts, AirCell uses free space propagation on air-to-air links. This is quite a conservative assumption especially in cases of the highest importance, when two aircraft are in close proximity. A good indication of actual aircraft to aircraft path loss isolation can be obtained from field measurements conducted by AirCell and documented in Appendix A in this report. From these measurements, it follows that due to aircraft body shadowing and antenna patterns, aircraft to aircraft path losses routinely exceed that of free space. In some cases the margin can be as high as 30-40dB.

Therefore, spectrum swapping (Fig. 2.1 and Fig. 2.2) introduces isolation for two-system operation by eliminating the potential for interference between aircraft and other-system base stations. In other words, even though two systems share the same spectrum, BSs of System 1 (or 2), receive signals only from aircraft subscribed to System 1 (or 2). Similarly, aircraft of System 1 (or 2), receive forward link signals only from System 1 (or 2) BSs. Signal reception from System 2 BS at System 1 aircraft is not possible due to swapped spectrum regime. Likewise, signals originating at System 1 aircraft cannot be received at System 2 BSs. The impact of the remaining ground-to-ground and air-to-air intersystem links was analyzed in a detailed manner and shown to be very small and causing no service outage. Therefore, spectrum swapping in the cross-duplex system operation provides an effective isolation mechanism enabling co-existence of two co-polarized systems within the ATG band.

3.2. Partial Spectrum Overlap

Another isolation mechanism already proposed in [1] is the partial spectrum overlap. It is based on the excess bandwidth in the ATG 2MHz spectrum compared to the 1.25MHz wide 1xEv-DO carrier. As illustrated in Fig. 2.1, this excess bandwidth allows for reduction of the spectral overlap from 1.25MHz to 500KHz. To support legacy narrowband services in Phase 1 of the CDMA rollout, a full overlap may be necessary as shown in Fig. 2.2. The migration path from full to partial overlap is presented in Fig. 3.3. As mentioned in Section 2, partial overlap will be feasible in later stages of the ATG multi-system rollouts when operation of the legacy narrowband system, still active in an early stage, terminates. At that point, one of the CDMA providers may shift into the band previously occupied by the narrowband provider, thus providing the partial spectrum overlap between two systems.

With a 40% instead of 100% overlap, the air-to-air interference remaining after spectrum swapping described in Section 3.1 will be scaled down to approximately 40% of its initial value. Thus, the partial overlap adds roughly 4dB to the inter-system interference margin when compared to the full spectrum overlap:

$$IM = 10\log\left(\frac{1}{0.4}\right) = 3.98\ \text{dB} \qquad (3.1)$$

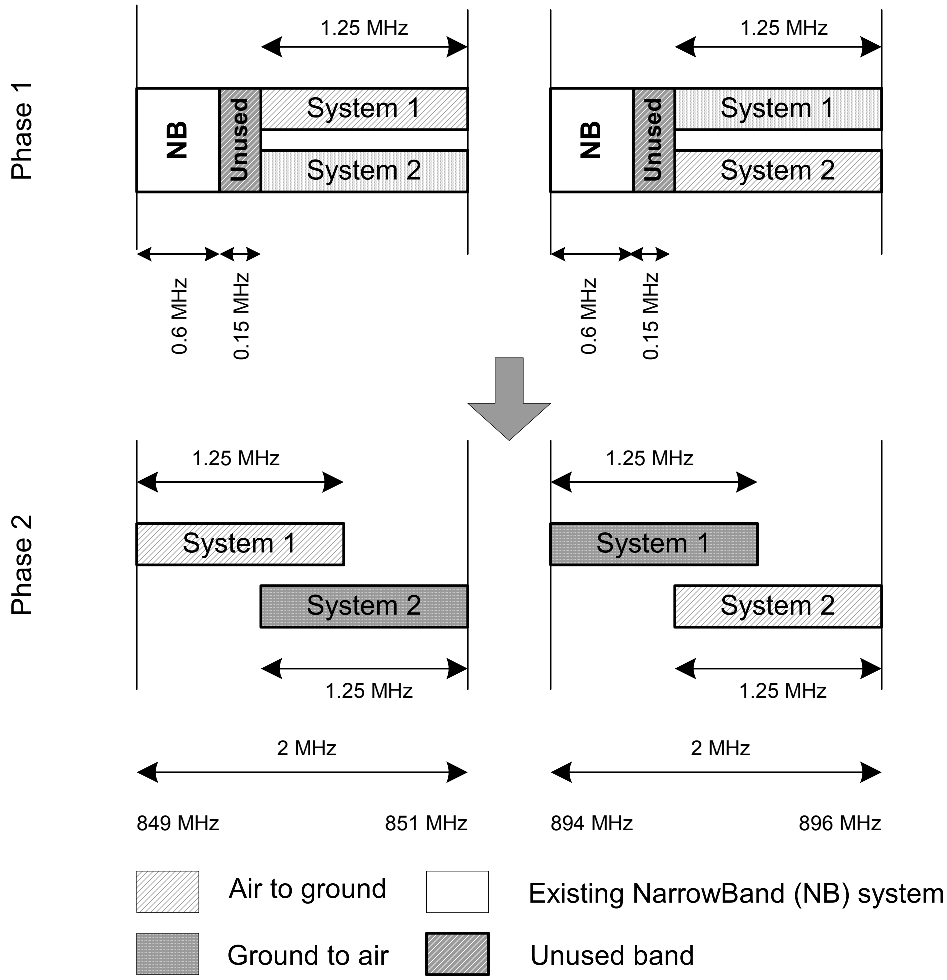

Figure 3.3. Spectral migration plan from

3.3. Polarization Isolation

Isolation mechanisms discussed in sections 3.1 and 3.2 were already included in AirCell's original two-system proposal [1]. To add two more CDMA systems in the ATG band, additional means of isolation need to be introduced. While cross-duplex and partial spectrum overlap were shown to enable two CDMA systems, to enable deployment of four systems use of orthogonal polarization becomes necessary. The polarization of the radiated EM wave is defined by the trajectory of the tip of the electric field vector relative to the ground plane and is determined by the radiating antenna. In most ATG wireless communications, vertical polarization is the dominant, meaning that the electric field harmonically varies perpendicular to the Earth's surface.

Theoretically, mutually orthogonal polarizations are completely isolated. A horizontally polarized signal incident on a vertically polarized antenna would not induce any voltage at the antenna terminals. However, in practice, it is not easy to ensure polarization purity. Signals assumed as vertically polarized usually have a parasitic horizontal component. As a matter of fact, the polarization impurity is added already at the transmitting antenna due to imperfection in antenna manufacturing. Additional depolarization occurs also in the wireless channel during EM wave propagation because of reflections, scattering and diffractions. For that reason the use of polarization diversity in terrestrial channels is difficult since there are many potential depolarization sources. On the other hand, line-of-sight (LOS) ATG radio channels have much less exposure to such influences, and the expected level of depolarization is much lower than what one would find in mostly obstructed terrestrial paths.

In practice, the level of polarization isolation is hard to predict analytically. Measurements are necessary to determine the exact polarization isolation between antennas. Such measurements have shown that isolations on the order of 15dB are realistic in ATG links [6]. In this report, a conservative value for polarization isolation of 12dB is used to investigate the impact of two additional CDMA systems added using orthogonal polarization. The addition will result in two pairs of cross-spectrum systems, each pair operating at one of the linear orthogonal polarizations, horizontal or vertical.

It is important to note that for the last eight years, AirCell has successfully operated a horizontally polarized ATG system sharing spectrum with existing terrestrial cellular technologies. In this case polarization isolation provides sufficient isolation for safe co-existence and virtually interference free operation between AirCell's ATG system and terrestrial narrowband technologies. For a deployment of wideband systems that are initially designed with orthogonal polarization in mind, polarization isolation may prove to be even more effective.

3.4. Isolation Through Beam Shaping

Isolation due to switched-beam antennas and beam shaping was not required to enable two-system ATG service as shown in [1]. Analyses presented there have demonstrated negligible levels of inter-system interference even with the use of very simple antenna systems: omnidirectional aircraft antennas and fixed single-beam BS antennas. With the introduction of two additional systems into the ATG band, *smart* antennas need to be considered for better interference isolation. The smart antennas can be deployed either on the base station or the aircraft side. Additionally, two implementation flavors are possible: beam switching and beam steering. For the work presented in this report AirCell considers switched-beam antennas on the base station side. Implementation of beam steering on the aircraft side is well studied in other ATG migration proposals [10].

Switched-beam antennas have a major impact on the CDMA forward link from a BS to a mobile. The idea behind the beam switching is to transmit only in a narrow direction towards the user instead of broadcasting over the entire horizontal 360^o of space. This concept may be illustrated with the help of Fig. 3.4. The figure shows BS1 serving two aircraft, A1 and A2. Co-system BS2 is serving aircraft A3 while aircraft A4 is served by BS3 belonging to another CDMA system. Aircraft activate appropriate beams on serving BSs such that the forward link transmission is limited to only active beams. In the example given in Fig. 3.4, two beam segments will be active on BS1, one on BS2 and one BS3. The switched beam isolation provides benefits to both the co-system mobiles and the mobiles from other systems. It is seen that aircraft A3 and A4 do not experience interference from BS1 because angular beam segments of BS1 in direction of A3 and A4 are not active.

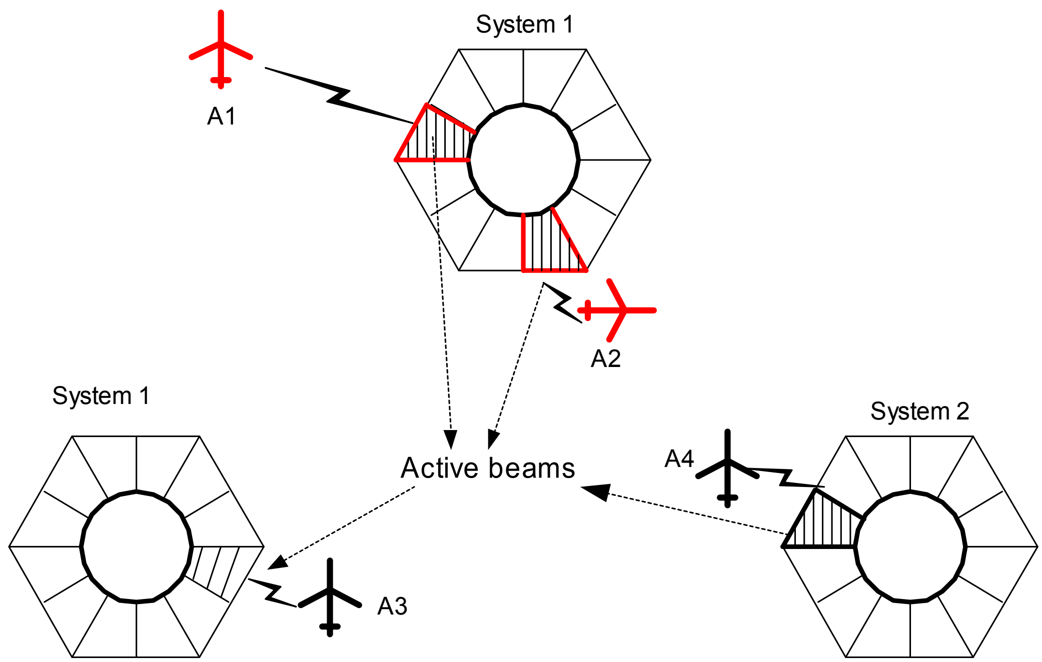

Figure 3.4. Isolation due to beam-switching

The net effect from the power radiation through only a subset of angular ranges is a decrease of total interference in the band. This spatially selective power transmission is the main mechanism behind the interference isolation using switched-beam antennas on the forward link.

Aircell proposes 1xEv-DO-like standard for the ATG band because of its high spectral efficiency [2]. It is a combination of TDM and CDMA where the pilot burst is followed in time by a traffic burst intended for a single user. Pilot bursts are used by mobiles to acquire the system and estimate channel conditions by measuring Signal-to-Interference-plus-Noise-Ratio (*SINR*). The *SINR* is defined as the ratio of the received useful signal and the aggregated interference (transmissions to other users), and thermal noise. *SINR* estimates from all mobiles are fed back into the BS controller and used as inputs to scheduling and data rate allocation algorithms. The pilot burst must be received by all mobiles and therefore requires omnidirectional (all beam segments) transmission. Following processing of all *SINR* reports from aircraft, a scheduler allocates the traffic burst to the most suitable mobile. Scheduling algorithms are beyond the scope of this report and are largely irrelevant to the RF simulations presented. Driven by the scheduler, traffic bursts are transmitted through selected switched-beam segments. This results in lower total interference during traffic bursts compared to omnidirectional transmission. The improvements from switched-beam transmission may be illustrated using the following simple example.

Example 3.1. Consider the scenario presented in Fig. 3.4. Assumptions on received signal levels (*RSL*s in dBm), at each aircraft from each BS in case of omnidirectional BS antennas are given in Table 3.1. Beams are assumed ideal such that the antenna gain is constant within the beamwidth with zero contribution outside of the beam segment. None of the aircraft in Fig. 3.4 is illuminated by beams other than the serving beam, and no beams illuminate more than one aircraft. This is the best possible scenario as all mobiles are isolated from each other on the forward link during traffic bursts. Assuming thermal noise power at each aircraft receiver equal to –105dBm, the *SINR* values during omnidirectional transmission (pilot bursts) are calculated in the last column of Table 1.

Table 3.1. *RSL* and *SINR* during pilot bursts assumed associated with Example 3.1 and Fig. 3.4

Aircraft	*RSL* from BS1	RSL from BS2	RSL from BS3	*SINR*[dB]
A1	-78	-101	-103	19.9
A2	-73	-87	-88	11.4
A3	-93	-73	-99	18.8
A4	-91	-89	-79	7.8

For example, *SINR* for mobile A1 is calculated as:

$$SINR_1 = 10\log\frac{10^{-7.8}}{10^{-10.1} + 10^{-10.3} + 10^{-10.5}} = 19.9\text{dB} \tag{3.2}$$

If switched beam antennas are deployed at all three BSs, there is no other CDMA power during traffic bursts except for the serving signal. Denominators of *SINR* expressions contain only thermal noise (assumed at –105dBm), resulting in *SINR*s of 27dB, 32dB, 32dB and 26dB for aircraft A1 to A4 respectively. This represents an improvement of approximately 7dB, 20.6dB, 13.2dB and 18.2dB respectively.

From Example 3.1 and Fig. 3.4 it should be obvious that the improvement of forward link *SINR* during traffic bursts will depend on the number of illuminated beam segments. Narrower segments and lower overall loading will lead to greater benefits from switched-beam isolation. If the network is heavily loaded and antennas switch among relatively few wide beams, most of the beams will be active and the performance approaches that of an omnidirectional antenna. Note also that switched beam is not equivalent to the sectorization common in terrestrial cellular systems. While each sector is a separate BS with independent link budgets, segments of a switched beam antenna belong to a single sector and are dynamically activated depending on the location of the mobile. Both mechanisms help increase isolation in interference limited CDMA systems.

The beam switching described has a major impact on forward link interference suppression. It helps the reverse link as well because inactive beams do not contribute to the noise rise at BS receivers. Significant isolation mechanism on the reverse link may be provided by shaping the beam of the aircraft ATG antenna. Air-to-air interference was identified as potentially the most challenging element of the swapped spectrum proposal. Simulations in [1] assumed omnidirectional aircraft antennas. This conservative assumption may safely be relaxed by introducing directive aircraft antenna patterns. The goal of the aircraft beam shaping is to focus transmission towards the ATG base stations and place nulls in the direction of other aircraft. Depending on the antenna pattern, beam shaping could increase isolation between aircraft that are subject to mutual interference due to cross-duplex frequencies. Beam-shaping may be implemented adaptively since location information and radar data are already available at the aircraft. Even without adaptability, fixed directive beams with a limited beamwidth around the nadir direction would help isolate forward link reception and reverse link transmission from two aircraft operating in cross-duplex spectrum.

4. Analysis of Spectrum Allocation Plans

This section analyzes different spectrum allocation plans capable of hosting four CDMA systems within an ATG frequency band. The systems use 1.25 MHz channelization consistent with cdma2000 1xEv standards. To accommodate four systems in just 2MHz of paired spectrum, a combination of isolation mechanisms described in Section 3 must be used along with an appropriately chosen spectrum allocation plan. The analysis presented in this section provides a comparison between the different possible spectrum allocation approaches and determines which one provides the most optimal systems operation.

Based on the analyses presented in [1], and isolation techniques discussed in Section 3, three spectrum allocation plans can be identified. Their analyses are provided as follows.

4.1. Spectrum Plan 1

A diagram of Spectrum Plan 1 is schematically represented in Fig. 4.1. It shows deployment of four 1.25MHz wide CDMA carriers. Cross-duplex operation (i.e. spectrum swapping), partial channel overlap and polarization isolation are deployed in combinations presented in Fig. 4.1. More specifically, details of the plan for each of the four systems are provided as follows.

- **System 1**: Reverse link on the lower ATG band (849-851MHz), forward link on the higher ATG band (894-896MHz), no frequency offset[2], and vertical polarization.

- **System 2**: Forward link on the lower ATG band, reverse link on the higher ATG band, 0.75MHz frequency offset, and vertical polarization.

- **System 3**: Reverse link on the lower ATG band, forward link on the higher ATG band, no frequency offset, and horizontal polarization.

- **System 4**: Forward link on the lower ATG band, reverse link on the higher ATG band, 0.75MHZ frequency offset, and horizontal polarization.

As seen, from Fig. 4.1, the plan proposes extensive and innovative methods for spectrum sharing. Since there are large spectral overlaps between different systems, other interference isolation methods are used to support sharing. Isolation mechanisms between the pairs of CDMA systems are as given as follows:

1. Systems 1 and 2 are co-polarized but isolated through spectrum swapping and partial 40% channel overlap.

2. Systems 1 and 3 are isolated through polarization isolation, there is no spectrum swapping and overlap is full.

[2] The frequency offset is defined with respect to the beginning of the ATG frequency band.

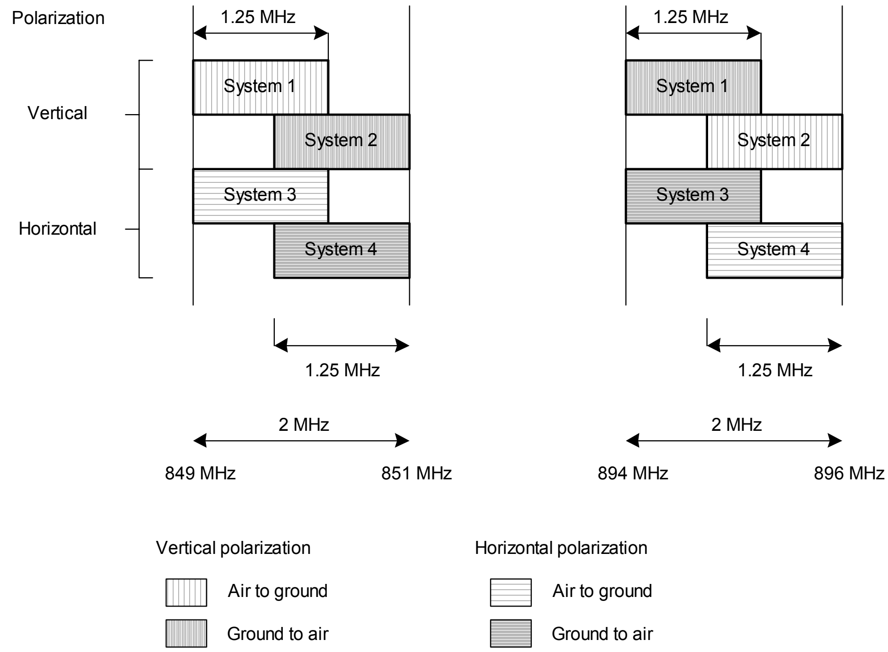

Figure 4.1. Spectrum Plan 1

3. Systems 1 and 4 are cross-polarized with partially overlapped and swapped spectra.

4. Systems 2 and 3 are cross-polarized with partial overlap and swapped spectra (same as systems 1 and 4).

5. Systems 2 and 4 are cross-polarized, but co-spectrum (same as systems 1 and 3).

6. System 3 and 4 are co-polarized and isolated through swapped spectra and partial overlap (same as systems 1 and 2).

The above list of spectrum plan properties is conveniently visualized using the schematic presented in Fig. 4.2. With the help of the schematic, one identifies three possible directions of inter-system interference. For the sake of brevity they will be referred to as the *horizontal*, *vertical* and *diagonal* interference. When the two systems are co-polarized they are on the two horizontal interference lines. For example, systems 1 and 2 and systems 3 and 4 interfere horizontally. The methods that can be used to isolate systems along the horizontal interference direction are spectrum swapping and partial channel overlap. In the case of two-system deployment analyzed in [1], the horizontal direction is the principal direction of inter-system interference. Adding systems 3 and 4 that operate on the orthogonal polarization from systems 1 and 2 significantly increases overall capacity but introduces vertical and diagonal interference directions. To provide interference control in such a scenario, three interference isolation mechanisms are used across the interference directions. The annotations in Fig. 4.2 are short hand indication of the isolation method and are interpreted as follows.

- PL = polarization isolation
- SW = switched spectra (cross-duplex isolation)
- [X%] = overlap percentage, partial (40%) or full (100%)

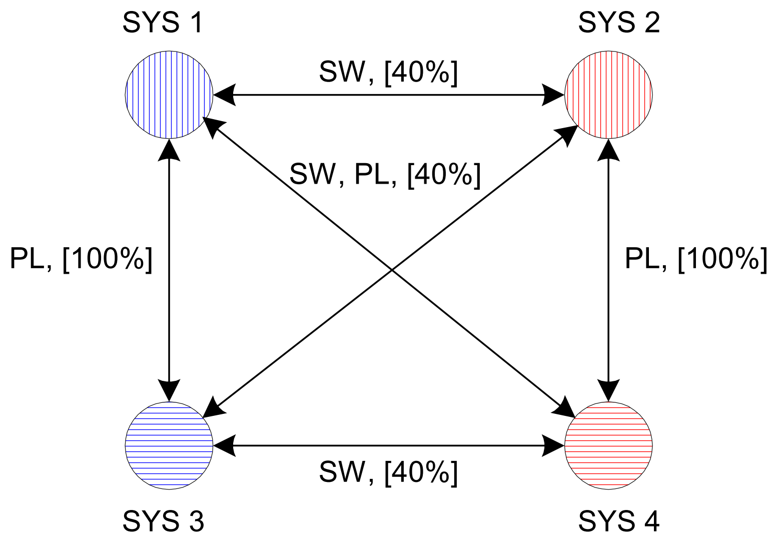

Figure 4.2. Spectrum Plan 1 interference diagram[3]

For the four-system deployment in accordance with Spectral Plan 1, each system is exposed to inter-system interference from all three interference directions: horizontal, vertical and diagonal. However, the interference levels from the different directions are not the same.

- Horizontal interference was thoroughly analyzed in [1]. There, it was shown that spectrum swapping provides sufficient isolation for safe operation of two co-polarized systems.

- Systems separated by the diagonal are isolated through spectrum switching, partial overlap and cross-polarization. Therefore, in the case of Plan 1, this interference direction is unlikely to have any measurable effects.

- Vertically separated systems are exposed the most to inter-system interference. According to spectrum plan 1, in the vertical direction, spectra are fully overlapped and cross-polarization is the only interference suppression mechanism.

Since horizontal and diagonal directions can be largely eliminated as causes of large inter-system interference, the only one that requires further investigation is the vertical direction. For that reason, this direction is the focus of simulations presented in Section 6 of this report.

4.2. Spectrum Plan 2

Spectrum Plan 2 provides another possibility for accommodating four CDMA systems within the 4MHz ATG bands. This plan is illustrated in Fig. 4.3. It is similar to Spectrum Plan 1 given in Fig. 4.1 except for different frequency offsets used by horizontally polarized systems 3 and 4. The interference diagram corresponding to Spectrum Plan 2 is presented in Fig. 4.4.

[3] The same color indicates 100% spectrum overlap. The shading of the circle matches the direction of polarization.

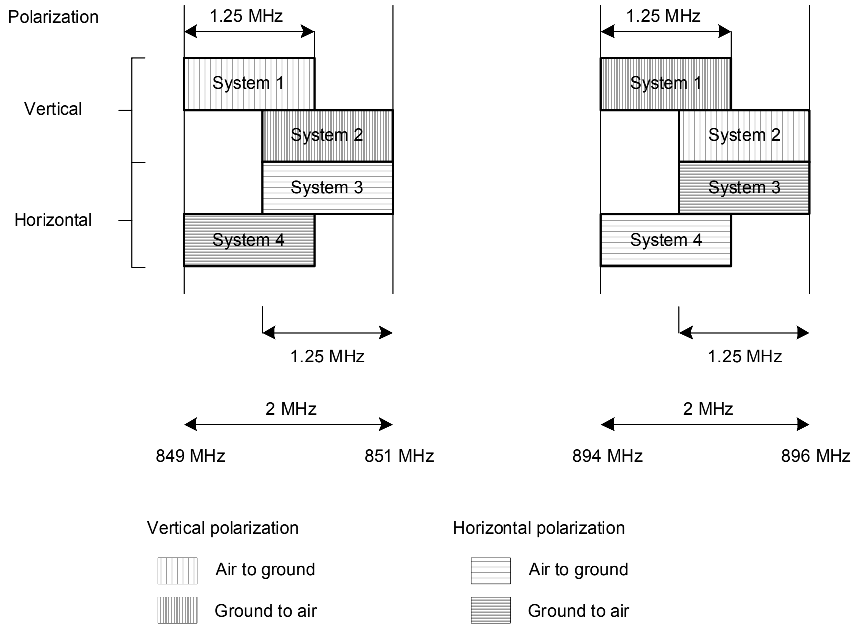

Figure 4.3. Spectrum Plan 2

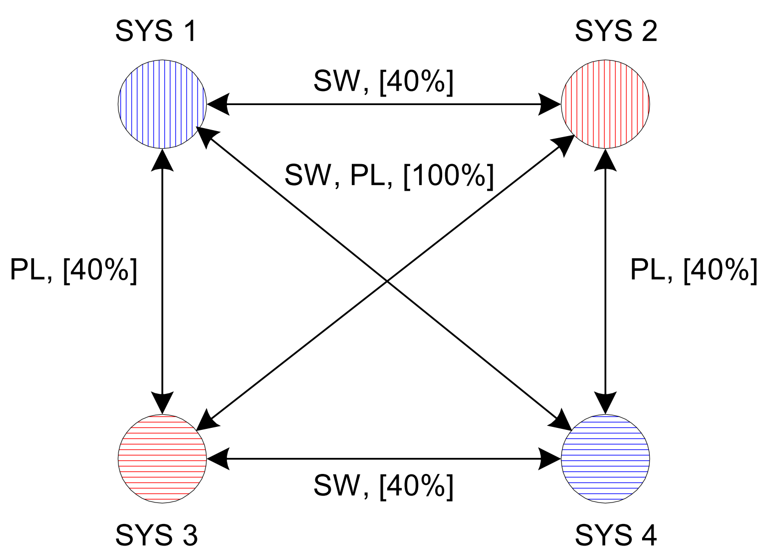

Figure 4.4. Spectrum Plan 2 interference diagram

Comparing interference diagrams in Figs 4.4 and 4.2, one notices that in the case of Plan 2, the cross-polarized vertical interference is enhanced by partial (40%) overlap. In Plan 1, vertically separated systems had fully overlapped spectra. As shown in Section 3, due to partial channel overlap, vertical interference in Plan 2 is expected to have 4dB more isolation than the vertical interference in Plan 1. Repositioning the spectrum allocation for systems 3 and 4 shifts full overlap to the diagonally separated systems as indicated by 100% overlap on the diagonals in Fig. 4.4. Since diagonal systems are still isolated by both swapped spectra and cross-polarization, the effect of this shift is negligible. Therefore, swapping partial/full overlaps between diagonal and vertical system pairs helps suppress potentially harmful vertical interference. As a result, the diagonal interference is slightly increased but this interference was very small to begin with and its slight increase can be safely neglected.

4.3. Spectrum Plan 3

The third spectrum allocation plan is shown in Fig. 4.5. Compared with the previous two plans, one notices the following differences:

- Spectrum plans 1 and 3 differ in horizontal and vertical directions. While Plan 1 has partial overlap between co-polarized systems (horizontal direction), and full overlap between cross-polarized systems (vertical direction), Plan 3 is the opposite: full overlap between co-polarized and partial overlap between cross-polarized systems.

- Spectrum plans 2 and 3 differ in vertical and diagonal directions. Partial/full overlaps are replaced such that the partial overlap between co-polarized systems (horizontal separation) in Plan 2 became full overlap in Plan 3. Diagonal overlaps (cross-polarized and switched spectrum isolation), were replaced the opposite way: from the full 100% overlap in Plan 2 to a partial 40% overlap in Plan 3.

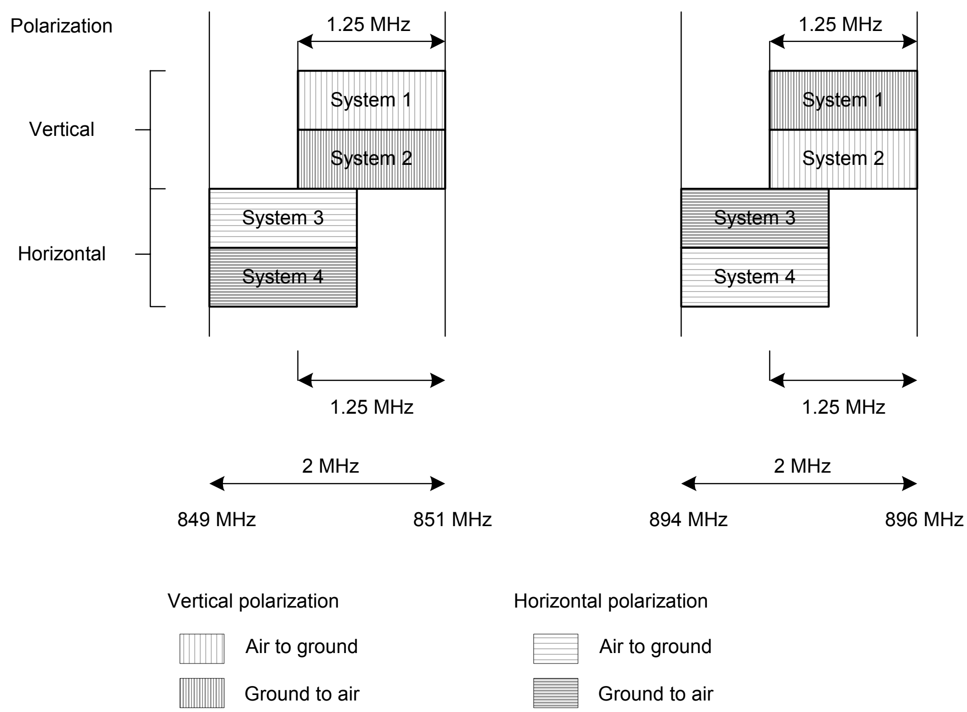

Figure 4.5. Spectrum Plan 3

Co-polarized systems are still cross duplex but now fully overlapping. Systems whose spectra are not swapped are isolated through partial overlap and cross-polarization.

The interference diagram derived from Fig. 4.5 is presented in Fig. 4.6. Compared to Spectrum Plan 1, vertical interference is improved by changing overlap from 100% in Spectrum Plan 1 to

40% in Spectrum Plan 3. However, horizontal isolation is lower in Spectrum Plan 3 because of full overlap between systems 1 and 2 (and 3 and 4 on the other horizontal).

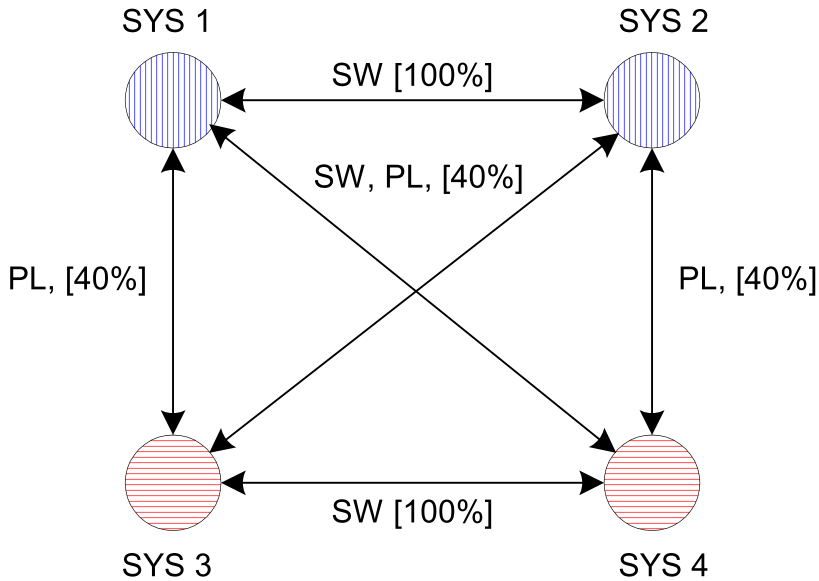

Figure 4.6. Spectrum Plan 3 interference diagram

4.4. Optimum Plan Selection

This section will discuss isolation properties of the three allocation plans introduced in Sections 4.1-4.3. As visualized in interference diagrams in Figs. 4.2, 4.4 and 4.6, three interference directions are recognized: horizontal, vertical and diagonal. Referring to interference diagrams, each spectrum plan has the following characteristics:

- **Horizontal separation**: In all three spectral plans, horizontally separated systems are co-polarized and isolated through swapped spectra. In spectrum plans 1 and 2, the systems have additional isolation from partial overlap. This increases the isolation by approximately 4dB when compared to the fully overlapped Spectrum Plan 3. Therefore, taking into account co-polarized systems, Spectrum Plan 1 and Spectrum Plan 2 provide better isolation than Spectrum Plan 3.

- **Vertical separation**: Vertically separated systems on interference diagrams are co-spectrum (same duplex scheme), and cross-polarized. The difference among plans is in the spectral overlap. Spectrum Plan 1 has full overlap between vertically polarized system 1 (or 2), and horizontally polarized systems 3 (or 4). Due to partial spectrum overlap, Spectrum plans 2 and 3 provide 4dB more isolation along the vertical direction than Spectrum Plan 1. Therefore, taking into account cross-polarized systems, spectrum plans 2 and 3 are recommended. Combined with the discussion above related to the horizontal separation, Spectrum Plan 2 is favored in both categories while other the two plans appear favored in one direction each.

- **Diagonal separation**: Cross-polarization and spectrum swapping isolate systems located on diagonals of the interference diagrams. The difference between the plans is in the amount of spectral overlap. The overlap is partial (40%) in plans 1 and 3 and full (100%) in Spectrum Plan 2. Isolation amongst diagonally separated systems is thus 4dB lower in Spectrum Plan 2 relative to plans 1 and 3. Therefore, based on the consideration of diagonal separation, Spectrum Plan 2 would be less favored than plans 1 and 3.

While Spectrum Plan 2 provides superior isolation between systems separated horizontally (co-polarized and cross-duplex), and vertically (cross-polarized, co-duplex), it has lower isolation in the diagonal (cross-polarization, cross-duplex) direction. However, due to isolation already provided by orthogonal polarization and swapped spectra, adding partial spectrum overlap along a diagonal axis is not required. Vertical and horizontal directions are therefore the dominant considerations, and, since only Spectrum Plan 2 (Section 4.2) contains partial overlap in both directions, it is expected to provide better overall isolation than the other two plans.

Therefore, Spectrum Plan 2 is identified as the optimum plan, expected to result in the lowest overall interference levels among different ATG systems. For that reason, this plan will be the focus of simulations presented in Section 6 of this report.

4.5. Operation in Transitional Period

Spectrum Plan 2 introduced in Section 4.2 and illustrated in Figs. 4.3 and 4.4 has been identified as the optimum four-system plan from the standpoint of inter-system interference. However, Spectrum Plan 2 does not allow for the co-existence of the legacy narrowband FDMA/TDMA services and all four CDMA systems. The legacy narrowband service uses vertical polarization. In spectrum plans 1 and 2, partially overlapped spectra of CDMA systems 1 and 2 are extended throughout the entire 2MHz cross-duplex bands. Therefore, there is no room for the narrowband provider in either Spectrum Plans 1 or 2.

Spectrum Plan 3 is the one that can be deployed in a transitional period when all four CDMA systems have been rolled out in addition to the existing narrowband FDMA/TDMA provider. Thus, in this transitional period, five systems are serving the ATG market as shown in Fig. 4.7. Two CDMA systems and a narrowband system fill the entire 2MHz band on the vertical polarization. The total bandwidth of all individual 6KHz channels in the FDMA/TDMA ATG system is 600KHz, leaving 150KHz of unused “vertically polarized spectrum”. That deployment is quite similar to Phase 1 of the two-system rollout covered in [1] and shown in Fig. 2.2. The only difference is in the overlap between the narrowband system and horizontally polarized CDMA systems 3 and 4.

With two additional CDMA systems, there is interference potential between the spectrally overlapping FDMA/TDMA service and CDMA systems 3 and 4, as seen in Fig. 4.7. CDMA System 4 has a benefit of the cross-duplex operation with respect to the narrowband systems and therefore, the interference between the two is significantly reduced. However, CDMA System 3 and the narrowband system are co-spectrum and with full spectral overlap. For that reason the interference potential existing between the narrowband system and CDMA System 3 is significant. The only isolation mechanism available in this case is cross-polarization: CDMA

System 3 deploys horizontal polarization while the narrowband FDMA/TDMA is vertically polarized.

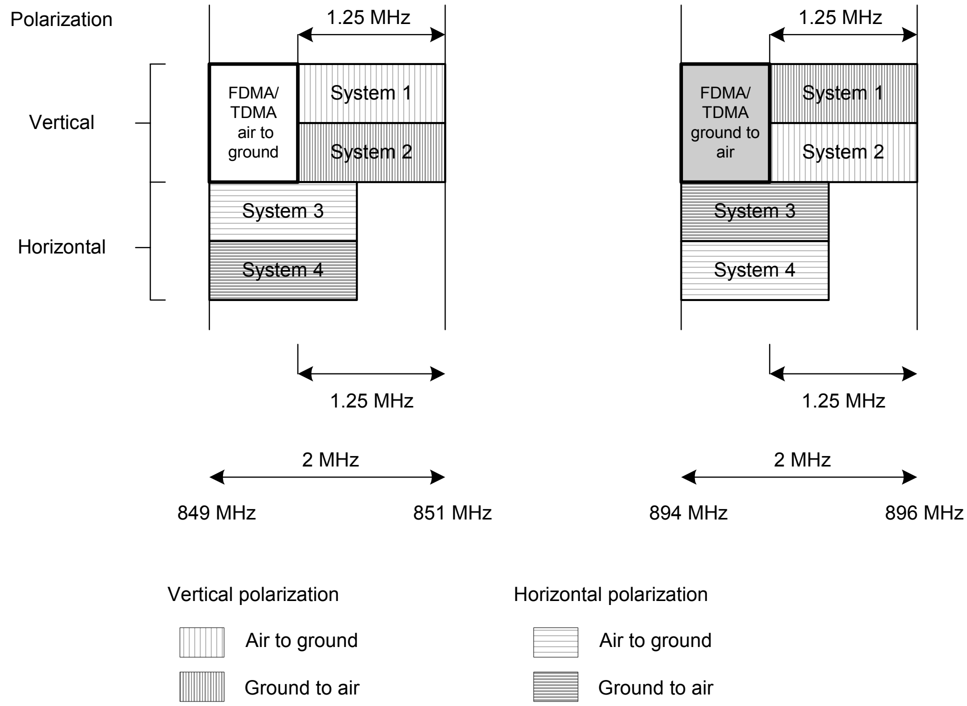

Figure 4.7. Spectrum plan for a transitional rollout period

Full analysis of the interference between narrowband and CDMA system 3 requires better understanding of traffic loading of the two systems. When systems are lightly loaded they can tolerate each other very well. CDMA systems have an inherent immunity towards narrowband jammers. Additionally, due to CDMA energy spreading across the wide channel and the narrowband front-end filters of the FDMA/TDMA systems, the interference from CDMA to FDMA/TDMA becomes small as well. This is especially the case with low CDMA traffic loading. During a transitional period, the assumption of low loading on CDMA networks is reasonable. However, more thorough analysis that takes the actual traffic into account should be performed. Alternatively, deployment of all CDMA systems may be shifted to 1.25MHz on the right hand side of the ATG band. This way, on the CDMA side, there is approximately 4dB isolation loss, which is quite tolerable with low network loading. At the same time, the narrowband system is completely isolated and operates without any inter-system interference to or from the CDMA systems.

5. Simulator Description

Due to the complexity of the proposed ATG spectrum reuse scenario, an analytical approach to the inter-system interference analysis would have to incorporate a significant set of simplifying assumptions. To avoid an introduction of such assumptions, the study presented in this report adopts the approach of *analysis by simulation*. In this approach, the operation of the system is simulated under various realistic operating conditions. During the simulations, parameters that indicate important aspects of the system's performance are recorded. After the simulations are completed, the recorded performance indicators are presented in a meaningful statistical fashion. This type of approach is usually referred to as the Monte Carlo (MC) analysis approach, and it is frequently utilized in the performance evaluation of complex communication systems.

To evaluate the possibility of a four-system operation within ATG band, AirCell has developed two custom 1xEvDO simulators. The first of the two simulators was used to determine feasibility of the cross-duplex deployment. A detailed description of this simulator and analysis of obtained results were presented in a previous AirCell report [1]. This section focuses on the upgraded simulator designed to evaluate deployment of two 1xEv-DO systems operating in co-duplex mode but using different polarizations.

5.1. Description of the Simulation Test Bed

The test bed used for AirCell simulations is presented in Fig. 5.1. Two CDMA systems are analyzed at a time, each having four base stations. The market of interest is assumed to be circular with the cell sites of the two systems placed as indicated in Fig. 5.1. The aircraft are flown in a random fashion over the market area. The number of aircraft is chosen to represent different levels of loading (low, medium and high), relative to a theoretical pole point as calculated in [1]. The general parameters of the simulator are provided in Table 2. For the sake of consistency, these parameters are kept the same for all simulations.

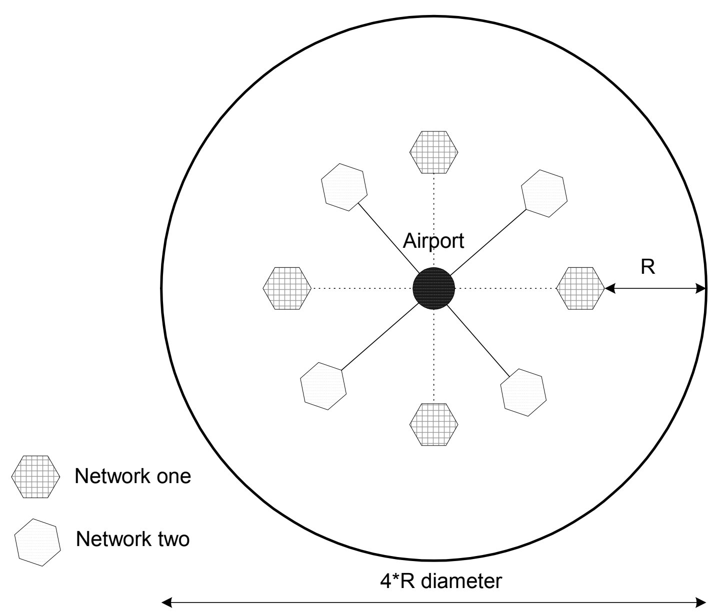

Figure 5.1. Topology of the test bed scenario

Table 5.1. Simulator parameters

Parameter	Value	Unit	Description
SIM_TIME	7200	Seconds	Duration of the simulation time
TIME_STEP	1	Seconds	Increment of the simulation time
f	870	MHz	Average operating frequency
NumCallsAC	10	-	Average number of voice calls per aircraft of the first system
NumCallsAF	10	-	Average number of voice calls per aircraft of the second system
W	1.2288e6	-	Chip rate for 1xEvDO system
Zmin	1000^1, 18000^2	feet	Minimum aircraft altitude
Zmax	40000	feet	Maximum aircraft altitude
Vmin	380^2, 180^1	knots	Minimum velocity of the aircraft
Vmax	450^2, 250^1	knots	Maximum velocity of the aircraft
MinVerSep	1500	feet	Minimum vertical separation between aircraft
MinHorSep	5	miles	Minimum horizontal separation between aircraft
VAF	0.5	-	Average voice activity
FL_IF_Scaling	$0.5/1.25^3$, 1^4	-	Scaling of the interference due to partial overlap
BS.PA_power	20	W	Base station transmit power
BS.NF	4	dB	Base station noise figure
BS.DL_CL	3	dB	Forward link cable losses
BS.UL_CL	3	dB	Reverse link cable losses
MS.PA_power	23	dBm	Mobile station transmit power
MS.NF	8	dB	Noise figure of the mobile
MS.EbNt	4	dB	Required Eb/Nt for the reverse link
R	12.5^1, 100^2	miles	Cell site radius (Fig. 16)
Pol_Izol	12	Db	Cross-polarization isolation
AG	$9^2/12^1$	Db	Antenna gain

[1] – airport scenario; [2]- cross-country scenario
[3] – 40% spectrum overlap; [4] – 100% spectrum overlap

The flight rules governing aircraft separation in flight, are covered in part in the *Aeronautical Information Manual* published by the U.S. Department of Transportation (From Title 14 of the *Code of Federal Regulations*) Paragraph 4-4-10 *IFR Separation Standards* and Paragraph 5-3-7 *Holding* contain specific guidelines. Also, the Federal Air Regulations (FAR) Part 91.179 *IFR cruising altitude or flight level* also describe vertical separation. Since almost all commercial aircraft and general aviation jet aircraft operate under IFR flight rules, these standards are suitable guides for the air-to-ground communication system simulations. Vertical separations range from 1,000 feet in crossing aircraft to 4,000 feet in aircraft above 29,000 feet heading in the same basic direction. AirCell chose 1500 feet for an average separation for the purpose of the simulations. Horizontal separation is 3 to 5 miles minimum, with 5 miles or greater as a typical separation. For the purpose of the simulation, AirCell chose a distance of 5 miles.

For the simulations presented in this study, AirCell has identified two typical operation scenarios. The first scenario is referred to as the *Cross-country* scenario and it is based on a typical systems' operation in the areas along the cross-country airplane flight corridors. This scenario is characterized by the following system parameters:

- Omni directional cell site configurations
- Low traffic requirements (2-3 aircraft within the cell site coverage area)
- Large cell site radii (set to 100 miles)
- High altitudes of serviced planes (from 18,000 to 40,000 feet)
- Large aircraft velocities (from 380 to 450 knots)

The second scenario is referred to as the *Airport scenario*. This scenario models the systems' operation around metropolitan areas and large airports. This scenario is characterized by the following set of properties:

- Sectorized cell site configurations (three sector configurations are assumed)
- High traffic requirements (2-3 aircraft within a sector coverage area. This yields up to 9 aircraft within the cell site coverage area for each of the two systems)
- Small cell site radii (set to 12.5 miles)
- Lower altitudes of serviced planes (from 1,000 to 40,000 feet)
- Lower aircraft velocities (from 180 to 250 knots)

Two scenarios are quite different from the standpoint of typical cell site configurations, airplane velocities, altitudes and the amount of traffic per unit area. For that reason, the results of simulations for both scenarios are included in the reports. In practice, there may be some configurations that are neither cross-country, nor airport like. However, these configurations can be seen as being between the two extremes and their performance is bounded by the results obtained for airport and cross-country scenarios.

5.2. Cross-duplex 1xEvDO Simulator

To evaluate the possibility of cross-duplex operation between two CDMA systems, AirCell uses a cross-duplex 1xEvDO simulator. This is a time domain dynamic simulator. The simulations are performed in accordance with five steps. They are listed as follows.

1. Initial distribution of the aircraft positions and assignment of their velocities
2. Calculation of the RF propagation path losses
3. Evaluation of the systems' performance indicators assuming no inter-system interference
4. Re-evaluation of the performance indicators while taking the cross interference into account
5. Update of the aircraft positions

The above steps are performed in an iterative manner for a specified duration of the simulation time and with a specified time increment (1 second used in all simulations). Typically 2 hours (7200 aircraft position updates), were analyzed to smooth out the randomness introduced in step 1 above. A prime indicator of the iterative process convergence is similar results between two analyzed systems are obtained. The Key Performance Indicator (KPI) used in [1] to evaluate the impact of the inter-system interference is the *forward link* (i.e. base station to aircraft) *pilot quality*. Within the 1xEvDO system, each mobile measures the forward link pilot quality during the full-power pilot burst, which precedes the full-power traffic bursts dedicated to individual users. The quality of the pilot is expressed through a quantity called Signal-to-Interference-and-Noise-Ratio (*SINR*). Formally, the *SINR* is defined as [2]:

$$SINR = \frac{S}{I_1 + I_2 + \cdots + I_N + N_0} \quad (5.1)$$

where *S* is the power of the pilot of the serving base station, I_k, $k = 1,2,\cdots,N$ are powers of the interfering pilots and N_0 is the power of the thermal noise. There is a difference between *SINR* in (5.1) and *Ec/Io* pilot quality measurements used in other IS-95 based CDMA systems. In *Ec/Io* calculations, the pilot power of the serving site is a part of the denominator as well [3]. For that reason, *Ec/Io*, when expressed in dBs, is always negative. On the other hand, the *SINR* ratio given in (5.1) can take both positive and negative values.

On the basis of the *SINR* measurement reports, base stations perform management of the forward link data rates. Depending on the reported *SINR* measurements, a base station determines its forward link traffic data rate, as well as the coding and modulation for the traffic burst immediately following the pilot. One typical mapping between the forward link pilot *SINR* and the corresponding traffic data rates is given in Table 5.2 [2]. Better *SINR* reports from a mobile to a BS will trigger allocation of a higher data rate to that mobile. Since 1xEv-DO systems serve a single user per traffic burst, scheduling algorithms based on fairness and optimized average throughputs are implemented. Such algorithms are not considered here since the simulation stays on the RF level. That makes the simulation only loosely specialized for the 1xEv-DO system and generally applicable to other CDMA-based solutions as well.

Table 5.2. *SINR* for 1% packet error rate

Data rate [kb/sec]	*SINR* [dB]
38.4	-12.5
76.8	-9.5
102.6	-8.5
153.6	-6.5
204.8	-5.7
307.2	-4.0
614.4	-1.0
921.6	1.3
1228.8	3.0
1843.2	7.2
2457.6	9.5

The *SINR* computations without the inter-system interference (baseline) were compared with the cross-duplex operation in [1]. As already mentioned in previous sections, with CDMA systems operating in a cross-duplex mode, the dominant inter-system interference comes from the reverse link (aircraft-to-base) of one system to the forward link (base-to-aircraft) of the other. As a result of such interference, the *SINR* is degraded causing a decrease in the forward link transmission rate. Table 5.2 is then referenced to translate pilot *SINR* degradation into a data rate reduction. Extensive simulations summarized in [1] showed that such degradation is very small, even in the worst- case scenarios for two-systems in cross-duplex operation.

5.3. Cross-polarization 1xEv-DO Simulator

The Matlab™ simulator built to analyze cross-duplex inter-system interference, described in Section 5.2, has been modified to evaluate the possibility of hosting four 1.25 MHz CDMA systems in the ATG band. The modified version allows quantification of the interference suppression benefits derived from orthogonal polarization, beam-shaping and partial spectrum overlap. The focus of the simulator is shifted from the air-to-air interference between the two cross-duplex systems, evaluated in [1], to the forward-forward and reverse-reverse interference occurring between two co-duplex systems. Interference between co-duplex systems is reduced by the cross-polarized transmission. The situation under consideration is illustrated in Fig. 5.2.

If spectrum allocation plans 1 through 3 introduced in Section 4 are considered, two co-duplex system pairs would be systems 1-3 and 2-4 (Figs 4.1 to 4.5). In all plans, the cross-interference between co-duplex systems is reduced through polarization isolation. Additionally, plans 2 and 3 provide interference reduction through partial spectrum overlap as well. Since cross-duplex operation has been shown to provide sufficient isolation, System 1 can safely coexist with systems 3 and 4. Demonstrating that systems 1 and 3 can coexist would thus in effect complete the argument that four CDMA systems in spectrum allocation plans proposed in Section 4 are feasible. Therefore, analyzing inter-system interference between systems 1 and 3 (or equivalently between 2 and 4) is the main contribution of this report.

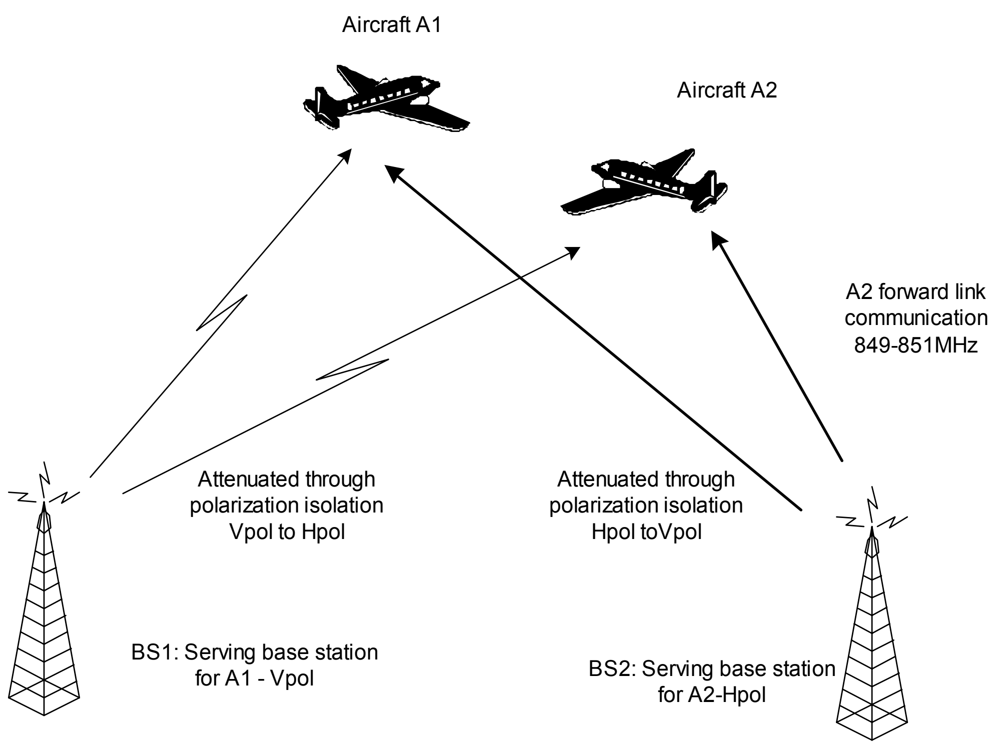

Figure 5.2. Interference between co-duplex systems

Switched-beam antennas are also introduced to the simulator to provide improved co-system and inter-system interference-reduction. The benefits of switched beam antennas affect only traffic bursts on the forward 1xEv-DO link. Pilot bursts are used for system acquisition and therefore, they must be broadcasted through all beams. For that reason, pilot *SINR* does not improve by selective beam activation. The forward link benefits from the fact that if a co-duplex system does not have the segment active in the direction of the mobile, that particular mobile will not suffer inter-system interference during the traffic burst. Beam-switching also helps in minimizing the noise rise on the reverse link. The benefits on both links are inversely proportional to the loading at all systems. For highly loaded systems, due to a large number of aircraft, most beam segments will be active.

Steps performed in the modified cross-polarized simulator are given as follows:

1. Simulation parameter initialization and CDMA system definition, not changed during simulation.
2. Initial distribution of the aircraft positions and assignment of their velocities.
3. Calculation of angles between aircraft and BSs necessary to simulate effects of beam-switching.
4. Calculation of the RF propagation path losses.
5. *SINR* calculation of pilots from each BS received at each mobile and selection of the serving BS. The selection is performed on the basis of best *SINR*.
6. Activation of appropriate beams at each BS and calculation of the forward traffic *SINR*
7. Calculation of aircraft transmitted power and BS noise rise.
8. Update of the aircraft position.
9. Steps 3-9 are repeated until results from a pre-defined number of time-updates have been accumulated.

A more detailed descriptions of steps 1 through 9 is provided as follows

Step 1. Before executing the MC simulation, all simulation parameters are initialized. The parameters are initialized in accordance with default values provided in Table 5.1. Most of the parameters are constant for all simulations. However, few parameters vary depending on the scenario and the spectrum allocation plan. For example, the airport scenario sets radius *R* in Fig. 5.1 equal to 12.5 miles, while the cross-country scenario uses *R*=100 miles. The airport scenario also assumes sectorized sites with three directional antennas with 12dB gain. The cross-country scenario utilizes 9dB omni antennas.

The number of antenna beams and the number of aircraft per system are also specified in this initial step. Three levels of loading (25%, 50% and 75% of the theoretical pole-point) are investigated. These loading percentages translate into a nominal number of aircraft per system as listed in Table 4. Based on the assumed traffic demand, the theoretical pole-point was determined to be approximately four aircraft per BS [1]. For example, in the case of four 3-sector BSs the pole point of the system can be calculated as:

$$4 \text{ (base stations)} \cdot 3 \text{ (sectors)} \cdot 4 \text{ (mobiles per sector)} = 48 \text{ aircraft}$$

This pole point for the system in a cross-country scenario (omni antennas, 1 sector per BS), can be estimated as

$$4 \text{ (base stations)} \cdot 1 \text{ (sectors)} \cdot 4 \text{ (mobiles per sector)} = 16 \text{ aircraft}$$

Table 5.3. Mapping between the percentage loading and the number of aircraft per system

Loading	Aircraft per system, cross-country	Aircraft per system, airport
25%	4	12
50%	8	24
75%	12	36

Step 2. In the second step the simulator randomly distributes the aircraft within the market area. The market is assumed as circular with the cell site placement as indicated by stars in Fig. 5.3. The altitudes of the aircraft are selected in a random fashion within an interval from $Z_{\min}$ to $Z_{\max}$. Each aircraft is assigned a velocity vector. The magnitude of each velocity vector is between $v_{\min}$ and $v_{\max}$, while its direction is chosen in a random fashion. Values of these altitude and velocity ranges are given in Table 5.1. One example of a typical initial scenario is presented in Fig. 5.3. Locations of the aircraft for the two systems are presented as either red or blue dots. Locations of the BSs is represented using stars.

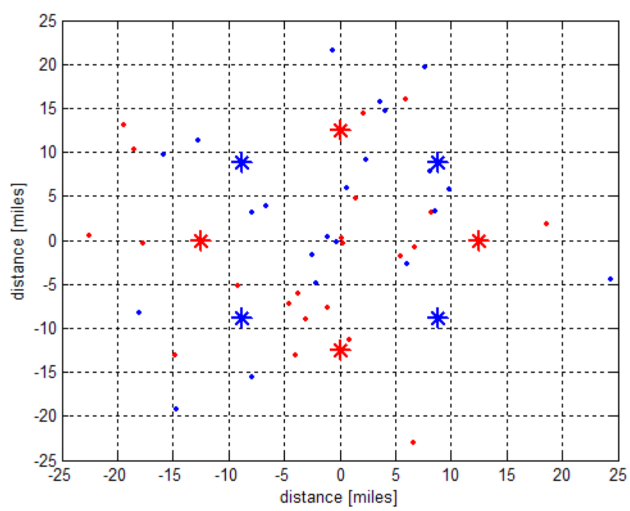

Figure 5.3. Example of an initial scenario; CDMA system 1 – red; CDMA system 3 – blue;

Step 3. Based on the BS and aircraft locations, BS heights, aircraft altitudes and antenna beam configuration, the antenna-pointing geometry is calculated in step 3. It includes calculation of azimuths between all BSs and all aircraft. In the case of 2 systems, 4 BSs per system and 12 aircraft per system, the number of azimuth angles that must be calculated is:

$$8 \text{ (total BSs)} \cdot 24 \text{ (total aircraft)} = 192 \text{ azimuth angles}$$

Calculated azimuth angles are used in path-loss calculations to look-up the BS antenna gain in the direction of the aircraft. From an azimuth angle calculated for a given aircraft, the beam of each BS antenna system illuminating that aircraft is identified.

Step 4. For calculation of propagation path losses between a base station and an aircraft, the simulator uses a formula given by

$$PL = PL_{FS} + CL - AG(\theta,\phi) + Pol\_Izol \quad (5.2)$$

where

PL	- path loss expressed in dB
PL_{FS}	- free space path loss expressed in dB
CL	- losses associated with the RF cabling expressed in dB
$AG(\theta,\phi)$	- antenna gain of the base station expressed in dB
θ,ϕ	- elevation and azimuth angles, respectively
Pol_Izol	- polarization isolation in dB

In (5.2), the free space path loss is calculated in accordance with [7]:

$$PL_{FS} = 36.5 + 20\log(f) + 20\log(d) \quad (5.3)$$

where

f	- operating frequency expressed in MHz
d	- distance between the base station and the aircraft expressed in miles

As indicated in (5.2), the antenna gain is taken into account as a function of the aircraft's azimuth and elevation relative to the base station antenna. The simulator reads horizontal and vertical patterns of the antenna and determines the gain of the base antenna as a function of the aircraft position. Antenna patterns are given in one-degree resolution lookup tables. To simplify the simulations, the aircraft antenna is assumed to be omni-directional in both planes. Additionally, the effects of the aircraft body are neglected. This leads to somewhat conservative predictions (i.e. there is more interference), since there is no consideration for aircraft antenna selectivity.

Polarization isolation is zero between co-system BS/aircraft pairs and set at 12dB between cross-polarized BSs and aircraft. For calculations of the path loss between a BS and an aircraft, the simulator uses the free space formula given in (5.3).

At the end of this step, the simulator has calculated path losses from each BS to each aircraft. The path loss between a BS-aircraft pair where BS belongs to one system and the aircraft belongs to the other one includes the effects of polarization isolation.

Step 5. Next step takes the path loss predictions from step 4 and the BS/aircraft parameter definitions in step 1 and calculates *SINR* during pilot burst. The *SINR* is calculated according to (5.1). At each aircraft, the *SINR* from all BSs of the serving system is calculated to find the best server. The best server is defined as the one with the highest *SINR* value.

Step 6. During pilot burst *SINR* calculation, beam-switching is not utilized because pilots are broadcast in all directions. During the pilot burst interval, all beam segments from all BS antennas must be active. On the other hand, during a traffic burst, only selected beams are active. This decreases the total interference on the forward link because an aircraft may not be illuminated from a beam of a co-duplex system BS if no aircraft served by the co-duplex systems are within the footprint of that beam. The probability of beam a being inactive is obviously inversely proportional to the loading on the system served, so the beam-switching will be more effective in less-loaded environments. If all beams are active, there is no isolation gain from switched beam antennas. This isolation gain for a given BS is expressed as the ratio between the number of aircraft per beam and the total number of aircraft served by the BS.

The difference in beam-switching between cross-country and airport scenario is shown in Fig. 5.4. It compares omni sites deployed in cross-country and sectorized sites used in the airport scenario. Simulations have considered 1, 6 and 12 beams per omni site and 1, 2 and 4 beams per 120^o-sector sites. In other words, twelve beams per omni site and four beams per each of three-sector sites, result in altogether 12 beam segments, each with a 30^o width. The simulation assumed 30dB beam selectivity, meaning that in the direction outside of an active beam, antenna gain is 30dB below the nominal gain anywhere within the active beam. That assumption is illustrated in Fig. 5.5.

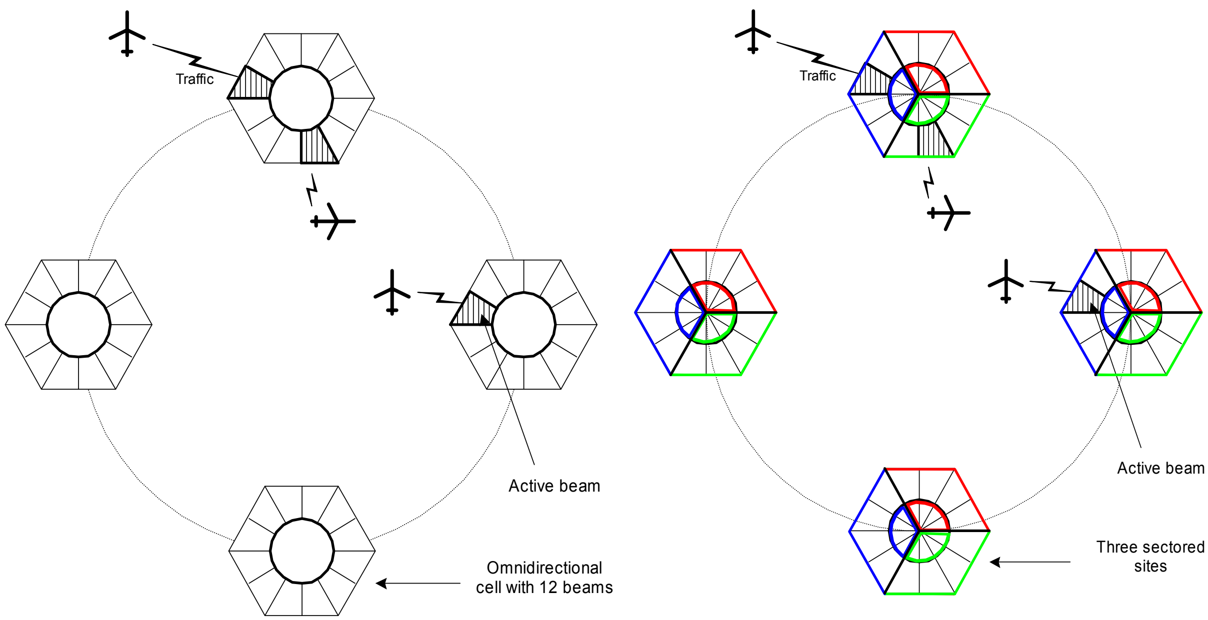

Figure 5.4. Switched beam in cross-country (left) and airport (right) scenarios. Case of twelve beams per site is shown.

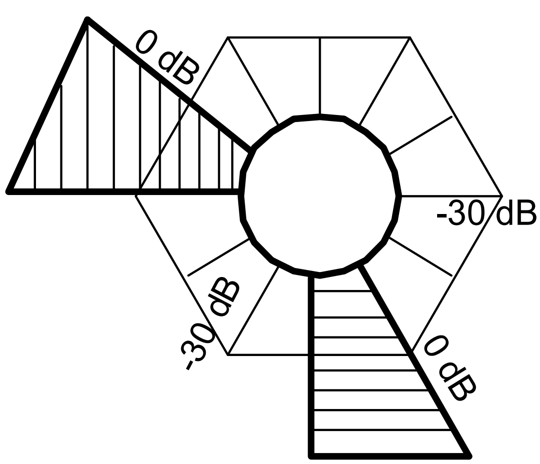

Figure 5.5. Switched-beam selectivity model adopted in the simulation

At the end of step 6, all aircraft have identified serving BSs based on the pilot-burst SINR. In addition, if switched beam antennas are used, all beam segments that are serving mobiles are turned on. Based on the beam activity, SINR during forward traffic bursts is also calculated.

Step 7. Simulations of the reverse link are used to determine the level of the aircraft transmit power as well as the noise rise on the BS receivers. These calculations need to be performed in an iterative manner. First, the noise rise at the base station is set to 0dB. Then assuming zero noise rise, the transmit powers required from each of the aircraft are calculated. Using calculated aircraft powers, the noise rise level on each base station is updated. With updated noise levels, the simulator calculates new aircraft powers and so on. The process is repeated until the convergence of aircraft powers and BS noise rise is reached.

Calculation of the required aircraft TX power requires knowledge of the reverse link data rate. As indicated in Table 5.1 for reported simulations, AirCell assumes a nominal traffic load of ten voice users per aircraft. However, this value is treated as a mean value for a random variable distributed in accordance with a Poisson PDF. Additionally, 1xEvDO provides a fixed set of available reverse link data rates. The actual aircraft data rate is always rounded up to the closest allowed 1xEvDO data rate.

Step 8. In this final step, the positions of the aircraft are recalculated in accordance with

$$\boldsymbol{r}(k+1) = \boldsymbol{r}(k) + \boldsymbol{v} \cdot \Delta t \tag{5.4}$$

where

$\boldsymbol{r}(k+1)$	- vector of the new aircraft position
$\boldsymbol{r}(k)$	- vector of the current aircraft position
$\boldsymbol{v}$	- aircraft velocity vector
Δt	- time increment

Throughout the simulation, time increment was assumed at 1 second and velocity initialized randomly in ranges listed in Table 5.1 for airport and cross-country scenarios. During the simulation, an aircraft may leave the market area. If this happens, a new aircraft will appear at a random position on the market circle with a velocity vector pointing in a random direction towards the circle's inner side. This way, the total number of aircraft within the market area is kept constant during the entire simulation.

Step 9. The last step is not an independent task but rather a loop that repeats steps 3-9. The number of repetitions (time increments), was typically set at 7200. Setting the time increment to 1 second, 7200 repeats extend each simulation to a two-hour period. The two-hour simulation time proves to be sufficient for simulation convergence and statistical validity of system performance indicators [1].

6. Simulation Results

In a deployment of four CDMA systems in the ATG band, there are two dominant types of inter-system interference. The first type is interference between co-polarized systems in cross-duplex operation, while the second type is the interference between co-duplex but cross-polarized systems. To analyze both types of interference, AirCell has developed two specialized 1xEvDO simulators. The first simulator is used to analyze the inter-system interference between two co-polarized systems in a cross-duplex mode. A detailed description of this simulator along with obtained results is documented in [1]. For the sake of completeness of this report, Section 6.1 presents the highlights of these results. The second simulator is used to examine the interference between co-duplex systems operating on orthogonal polarization. The results of this simulator obtained for various simulation cases are presented in Section 6.2. These results represent the main focus of this report.

When the analysis of a communication system is performed using Monte Carlo (MC) simulations, many different performance indicators can be recorded. The simulator used in this study provides the same flexibility and a presentation of all the results would be overwhelming. This report summarizes the results by presenting a small set of representative plots.

Evaluation of the results obtained from both simulators provides a good indication of the feasibility of sharing the ATG band between four CDMA systems.

6.1. Cross-duplex Simulation Results

This section provides a brief review of results characterizing the inter-system interference between two co-polarized ATG systems operating in cross-duplex mode. Referring back to diagrams previously presented in Figs 4.3, 4.5 and 4.7, one notes that this interference occurs between systems positioned across same horizontal direction. Four cases analyzed in [1] are divided in two scenarios and two overlap regimes. The scenarios are:

- Airport scenario
- Cross-country scenario

The Airport scenario model assumes that the high densities of aircraft from both networks are in and around a localized region. The aircraft are flown at various altitudes, velocities and directions consistent with an airport location. On the other hand, the Cross-country scenario simulates aircraft flying between airport destinations typically at relatively constant altitudes. Differences in the network configuration between these two scenarios are listed in Table 5.1.

For each of the two scenarios, two spectral plans are considered:

- Phase 1, (Consistent with Spectral Plan 3 given in Figs. 4.5 and 4.6): *100% CDMA Carrier spectrum overlap*. That regime is necessary during the evolutionary period when narrowband ATG operation co-exists with broadband CDMA operation. This transitional period allows the incumbent ATG operator to gracefully migrate its systems to pure CDMA operation.

- Phase 2, (Consistent with Spectral Plan 2 given in Figs. 4.3 and 4.4): *40% CDMA Carrier spectrum overlap*. This option is possible when the narrowband ATG operation is terminated and only CDMA operation is present. Phase 2 has greater overall capacity relative to Phase 1 since cross-interference is reduced.

Thus, in [1], a total of four specific cases have been simulated and a summary of the results from each case is repeated here. The data for the migration or transition period where the CDMA waveforms of System's 1 and 2 are overlapped 100% is shown in Tables 6.1 and 6.2. Tables 6.1 (a) and (b), show the results for the Airport scenario while Tables 6.2 (a) and (b), are obtained for the Cross-country scenario.

Table 6.1 (a). Probability of experiencing SINR degradation larger than 1dB - Airport scenario with 100% spectrum overlap

Loading [%]	System 1 [%]	System 2 [%]	Average [%]
25	0	0	0
50	1.0	1.0	1.0
75	6.1	6.2	6.15

Table 6.1 (b). Absolute and relative forward link throughput reduction – Airport scenario with 100% spectrum overlap

Loading [%]	Absolute throughput reduction [kb/sec]	Relative throughput reduction [%]
25	0.2	0.02
50	9.15	1.09
75	42.84	5.18

Table 6.2 (a). Probability of experiencing SINR degradation larger than 1dB - Cross country scenario with 100% spectrum overlap

Loading [%]	System 1 [%]	System 2 [%]	Average [%]
25	0	0	0
50	0.02	0.02	0.02
75	0.7	0.45	0.58

Table 6.2 (b). Absolute and relative forward link throughput reduction - Cross country scenario with 100% spectrum overlap

Loading [%]	Absolute throughput reduction [kb/sec]	Relative throughput reduction [%]
25	2.03	0.19
50	6.25	0.55
75	19.84	1.78

This specific case, Airport scenario with 100% spectrum overlap, is the worst-case scenario possible. The aircraft are at their closest operating distance with respect to each other (System 1 aircraft to System 2 aircraft) and there is no spectral isolation (since the overlap is 100%).

However, even for this transitional case, at a nominal CDMA network loading of 50% of the pole point, the relative reduction in forward path throughput is only 1.09% relative to its average value when the inter-system interference is not present. This is clearly not an issue and certainly does not approach the definition of "Harmful Interference".

In the final deployment of the CDMA ATG systems, the legacy narrowband ATG system is retired and CDMA networks operating in cross-duplex mode transition to a spectrum plan with a 40% mutual channel overlap. Referring to Section 4, this is consistent with Spectrum Plan 2, which is identified as optimal from the system isolation standpoint. The results of simulations for this phase of deployment and two typical operating scenarios are provided in Tables 6.3 and 6.4. Tables 6.3(a) and 6.3(b) summarize the results obtained for the Airport scenario. The overlap reduction from 100% to 40% caused the relative forward path data reduction to decrease from 1.09% to 0.2% - virtually negligible level. The improvement in the data rate is the result of reduced inter-system interference. In a Cross-country scenario (Table 6.4), when the system loading is for example 50%, the reduction of the forward link data rate dropped from 0.55 to only 0.21%.

Table 6.3 (a). Probability of experiencing SINR degradation larger than 1dB - Airport scenario with 40% spectrum overlap

Loading [%]	System 1 [%]	System 2 [%]	Average [%]
25	0	0	0
50	0.2	0.2	0.2
75	1.3	1.28	1.29

Table 6.3 (b). Absolute and relative forward link throughput reduction – Airport scenario with 40% spectrum overlap

Loading [%]	Absolute throughput reduction [kb/sec]	Relative throughput reduction [%]
25	0.13	0.02
50	3.96	0.48
75	17.31	2.01

Table 6.4 (a). Probability of experiencing SINR degradation larger than 1dB - Cross country scenario with 40% spectrum overlap

Loading [%]	System 1 [%]	System 2 [%]	Average [%]
25	0	0	0
50	0	0	0
75	0.2	0.15	0.18

Table 6.4 (b). Absolute and relative forward link throughput reduction - Cross country scenario with 40% spectrum overlap

Loading [%]	Absolute throughput reduction [kb/sec]	Relative throughput reduction [%]
25	0.67	0.06
50	2.3	0.21
75	9.44	0.87

Figures 6.1(a) and (b), summarize results for swapped spectrum isolation (horizontal separation in interference diagrams). The percentage of throughput reduction is plotted as a function of loading. It confirms that even at high loading, the practical impact on throughput can be neglected. For example, in the Cross-country scenario at 50% loading, neither 40% nor full overlap degrades the throughput by more than 1% (Fig. 6.1 (a)). In the worst case, the Airport scenario with 75% loading and 100% overlap, throughput reduction only slightly exceeds 5%.

Therefore, from the results obtained by the first AirCell simulator, safe, economic and interference free operation of two co-polarized and cross-duplexed CDMA systems within ATG band is possible and relatively easy to achieve.

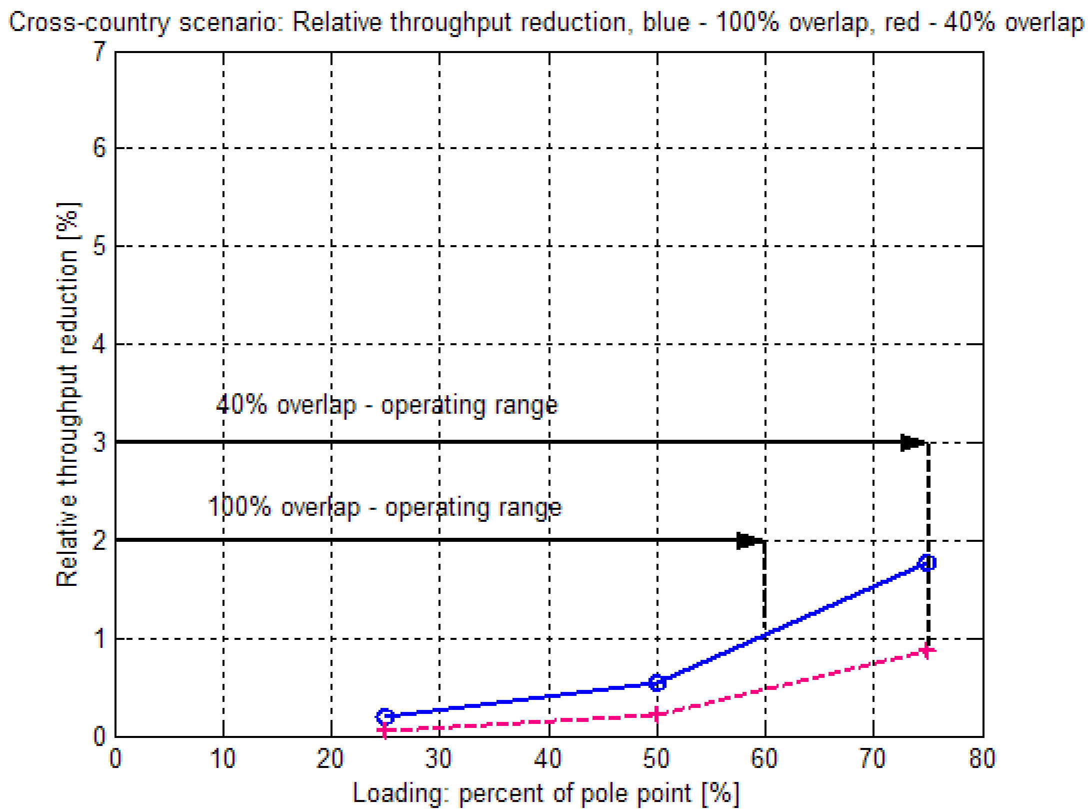

Figure 6.1 (a). Relative throughput reduction in the Cross-country scenario

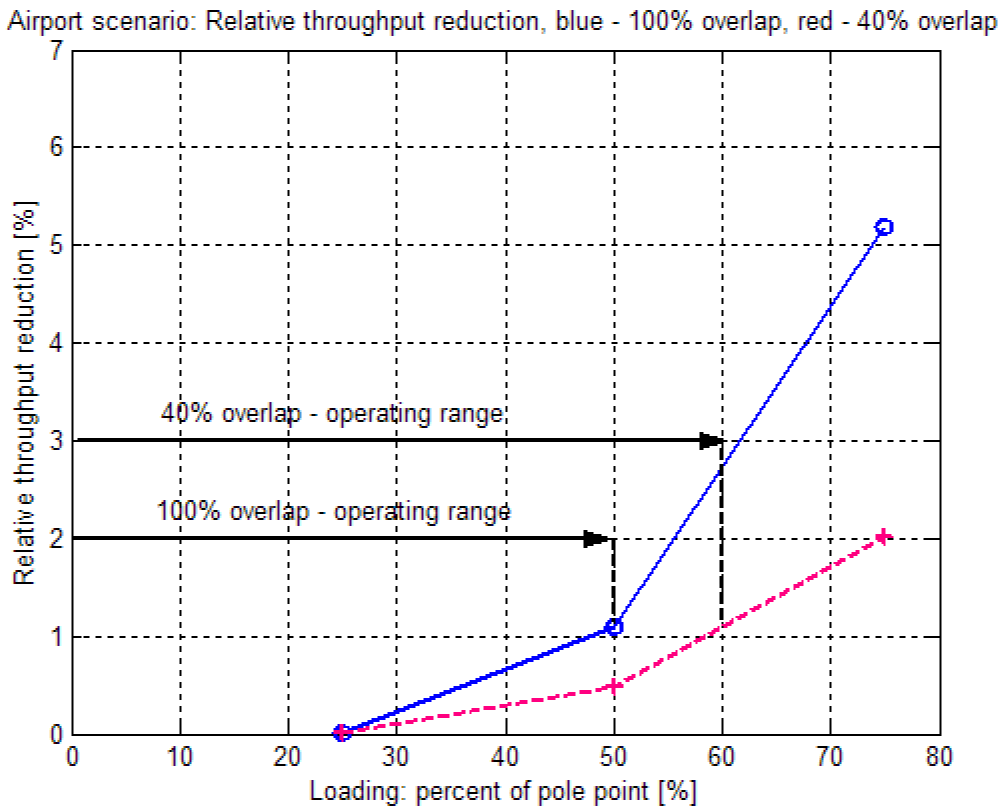

Figure 6.1 (b). Relative throughput reduction in the Airport scenario

6.2. Cross-polarization Results

This section presents the analysis of inter-system interference between two CDMA systems operating in co-duplex but cross-polarized modes. Referring back to diagrams in Section 4 (Figs. 4.3, 4.5 and 4.7) this interference occurs along the vertical direction. The results of the analysis summarized in this section are presented in a form of plots generated as outputs of AirCell's cross-polarization simulator (c.f. Section 5). The plots are in the form Cumulative Distribution Function (CDFs) curves for four Key Performance Indicators (KPI) of 1xEvDO system. The selected KPIs are listed as:

Pilot *SINR*	- indicator of forwrad link performance
Forward link traffic *SINR*	- indicator of forwrad link performance
Reverse link mobile TX power	- indicator of reverse link performance
Reverse link noise rise	- indicator of reverse link performance

As a part of the study, many different simulation scenarios are considered. The ones that were selected for presentation in this report are listed in Fig. 6.2. All simulations were performed with assumed 40% spectral overlap. This is consistent with Spectrum Plan 2 (c.f. Section 4, Figs 4.3 and 4.4.), which has been identified as the most optimal from the interference suppression standpoint. Two different base station antenna types are considered in both omnidirectional and sectorized cases:

- Antennas with –20dB null-fill in vertical patterns

- Antennas with 0dB null-fill in vertical patterns

Vertical antenna patterns corresponding to these two antenna types are plotted in polar coordinates in Fig. 6.3. An antenna with a –20dB null-fill pattern has a very narrow beam close to the horizon direction of the vertical pattern. The vertical pattern of this antenna is a simplified version of the one that AirCell uses on some of their sites operating in the cellular frequency band. The antenna with 0dB null-fill has no discrimination in the vertical pattern above the horizon. This antenna pattern is idealized, and in fact does not show the antenna uptilt that would be used to minimize the multipath impact of ground reflections and to discriminate against signals from cross-duplex base stations. However, its use represents a first order approximation of beam switching in vertical plane and deployment of truly three-dimensional sites. Use of this antenna in the case of the airport scenario provides some important insight in methods for interference reduction in very high network loading scenarios. In the horizontal plane, base station may employ switched beams. Discussion on switch beam implementation was provided in Section 5.

For given antenna pattern types, both the Airport and the Cross-country scenarios were simulated. As indicated in Fig. 6.2 different numbers of switched beams were examined. Considered scenarios are listed as:

- 1, 6 and 12 beams per site in the Cross-country scenario
- 1, 2 and 4 beams per sector in the Airport scenario

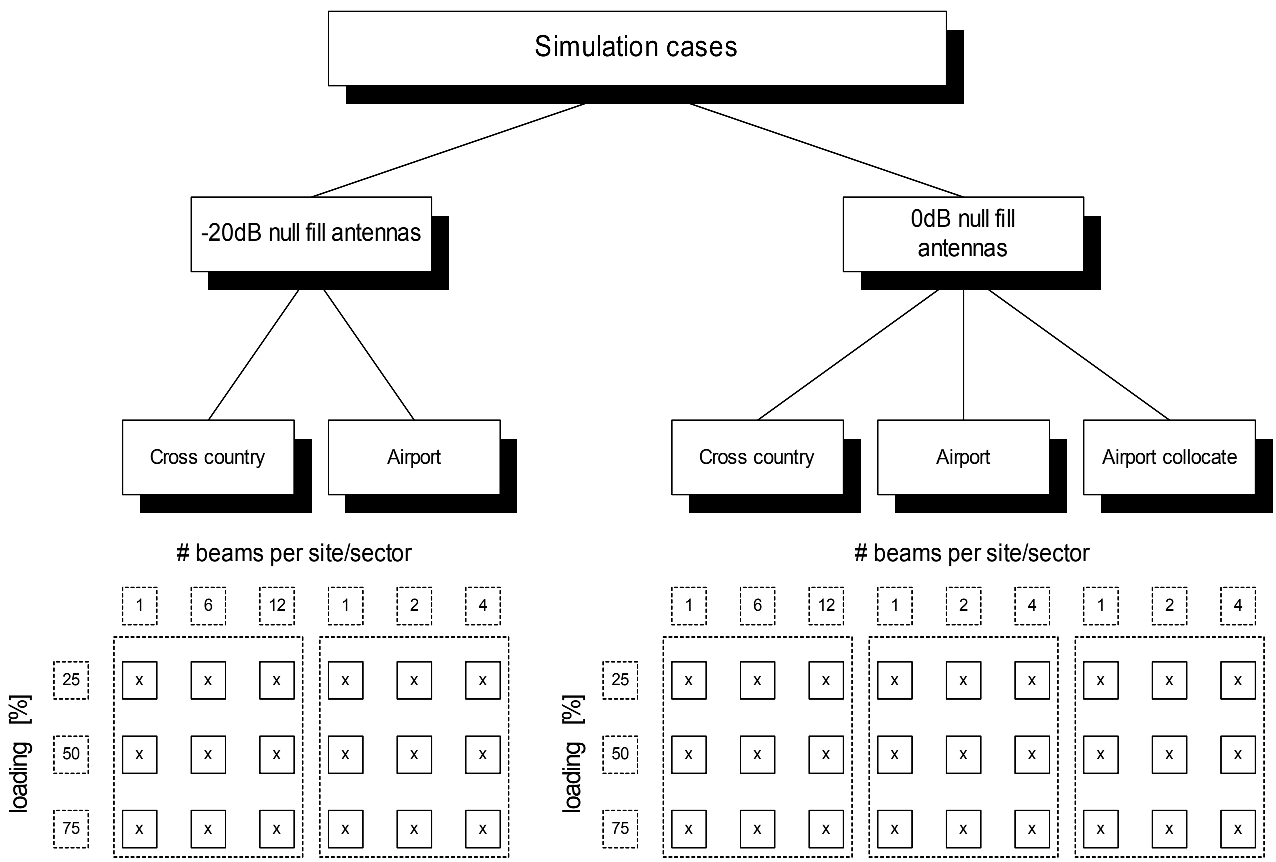

Figure 6.2. Breakdown of simulated cases

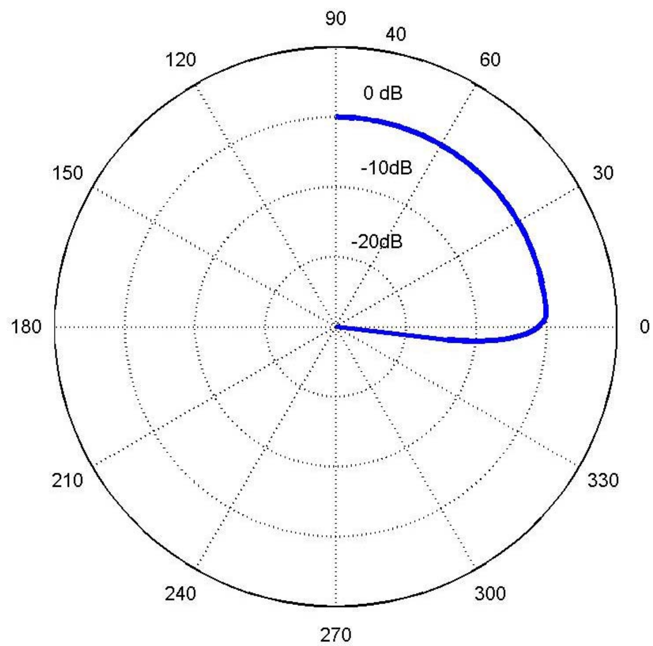

Figure 6.3. 0dB null-fill (left) and –20dB null-fill (right) vertical antenna patterns

With 0dB null-fill antenna patterns, the case of collocated BSs in the Airport scenario was added to the simulation case set. In the base station collocation, BS antennas from both systems are placed on the same tower. The collocation decreases the effect of worst-case near-far problem. In the case when the BSs are collocated, the mobiles are power controlled from the same spatial locations. Therefore, the case described as the source of near far problem in Section 3 never occurs. Due to high antenna selectivity in vertical plane, the near far problem is not as pronounced when –20dB null fill antenna patterns are used. Therefore, the analysis of that case is not included in this report.

As outlined in Fig. 6.2, a total of 45 different simulations have been performed. Cases considered range from lightly loaded (25%), widely separated (Cross-country scenario) aircraft and base stations more heavily loaded (75%) and closely spaced (Airport scenario) aircraft and base stations. The mapping between the percentage loading and nominal number of aircraft per BS was given as in Table 5.3.

The order of result presentation is following the outline suggested by Fig. 6.2. Each subsequent section presents results obtained for cases in "one block" of the simulation matrix presented in Fig. 6.2.

6.3. Cross-Country Scenario with -20dB null-fill antennas

This section presents results obtained from the analysis of the cross-country scenario and antennas with –20dB null fill vertical patterns. The CDF curves for the four considered KPIs (pilot *SINR*, traffic channel *SINR*, mobile TX power and reverse link noise rise), for various simulation cases, are presented in Figs 6.4 through 6.15. Each plot has three traces obtained for the three different loading scenarios. In all figures, the blue trace corresponds to 25% loading, the red trace corresponds to 50% loading and the green trace correspond to 75% loading scenarios. Deployment of the switched beam antennas is examined as well. Figures 6.4 to 6.7 are obtained with one beam per cell, i.e., using regular omnidirectional configuration. Figures 6.8 to 6.11 characterize the systems with 6 beams; while for Figs 6.12 to 6.15 base stations deploy a 12-beam antenna system. The 10^{th}, 50^{th} and 90^{th} percentiles for analyzed KPIs and various simulation cases are provided in Tables 6.5 through 6.7.

The following observations can be made:

- The CDF of pilot *SINR* remains the same for all simulation cases. This is expected since the pilot is transmitted through all the beams. The median pilot *SINR* is around 2dB. According to Table 5.2, this translates to a median forward link throughput of about 1Mb/sec per site. This value is consistent with results obtained in [1].

- The CDF of traffic channel *SINR* changes as a function of two parameters: system loading and the number of beams in an antenna system. At low levels of loading, traffic *SINR* is significantly better than the corresponding pilot *SINR*. As the loading increases, the difference becomes smaller. However, from Figs 6.5, 6.9 and 6.13 one observes that the implementation of switched beams provides consistent and relatively large improvement of the traffic channel *SINR*. The median improvement between 1 and 6 beams is on the order of 11-14dB, depending on the network loading. This significant improvement can be used to increase available data rate throughput on the forward link. Table 5.1 which provides nominal mapping between pilot *SINR* and data rates was derived under assumptions that the pilot *SINR* provides a good estimate of the forward link traffic *SINR*. Comparing entries in Table 6.5, one observes that in the case of no beam-switching, this is indeed the case. For high network loading, two metrics converge in values. However, in the case of switch beam deployment, the constant positive bias between traffic and pilot *SINRs* can be used to offset values in Table 5.1 and achieve higher data throughput on the forward link. By offsetting the value in Table 5.1, one enables the system to leverage interference reduction, obtained through deployment of switch beam antennas.

- The aircraft (i.e. mobile) transmit power remains below 23dBm in all cases. There is a slight improvement of about 2dB that results from deployment of switch beam antennas. However, this improvement alone would not justify deployment of beam switching in cases when obtained forward link data rate is sufficient.

- The noise rise at BS receivers remains within the range of values commonly encountered in terrestrial CDMA systems and it is quite consistent with loading levels. There is a slight noise rise reduction that results from the switch beam antenna deployment which may not be needed since aircraft transmit power never reaches its maximum of 23dBm.

Table 6.5. Percentile values for KPIs – Cross-country scenario, 1 beam

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	3	8	-2	3	8	-2	3	8
Traffic *SINR* [dB]	0	5	11	-1	3	10	-2	3	9
MS TX Power [dBm]	2	10	15	4	11	16	7	14	20
Noise rise [dB]	0	1	2	1	3	4	4	5	8

Table 6.6. Percentile values for KPIs – Cross-country scenario, 6 beams

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	2	6	-2	3	8	-2	3	8
Traffic *SINR* [dB]	9	18	25	7	17	24	6	14	23
MS TX Power [dBm]	5	10	14	4	11	15	5	12	17
Noise rise [dB]	0	1	2	0	2	3	1	3	6

Table 6.7. Percentile values for KPIs – Cross-country scenario, 12 beams

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	2	8	-2	3	8	-2	3	8
Traffic *SINR* [dB]	11	20	28	9	18	27	9	17	25
MS TX Power [dBm]	2	9	14	3	10	15	5	12	18
Noise rise [dB]	0	1	2	0	2	3	1	3	6

Based on the results presented in Figs. 6.4 to 6.15, and the summary given in Tables 6.5 to 6.7, the following conclusions can be drawn:

- For all examined cross-country scenarios, all significant KPIs remain within ranges consistent with normal operation of 1xEvDO system. At no time do systems suffer from inter-system interference that is beyond what can be successfully managed.

- Use of switched beam antennas provides benefits of increased traffic *SINR* and slight reduction of the reverse link noise. However, if in a particular deployment, the forward link obtained without beam switching is sufficient, the systems can safely operate with regular antennas

- In the cross-country scenario, two co-duplex cross-polarized CDMA systems operate without causing significant interference to each other.

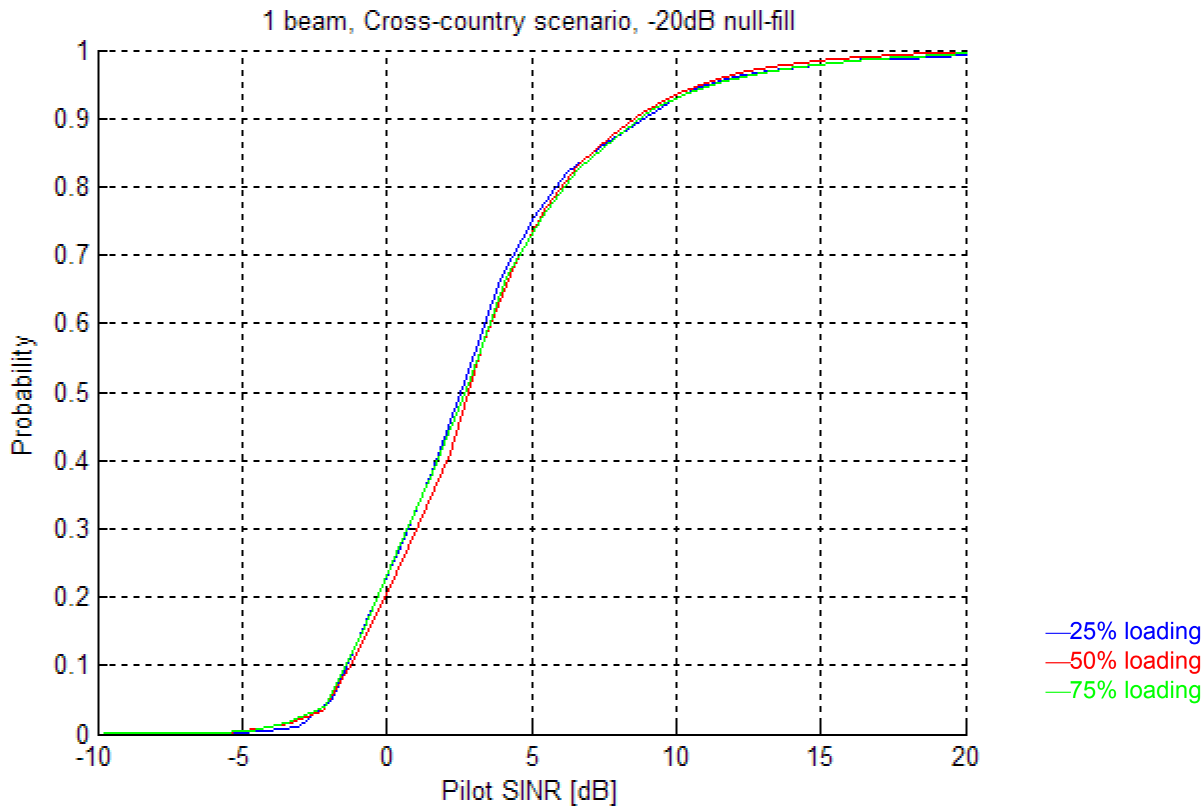

Figure 6.4. Pilot SINR, Cross-country, 1 beam, -20dB null-fill

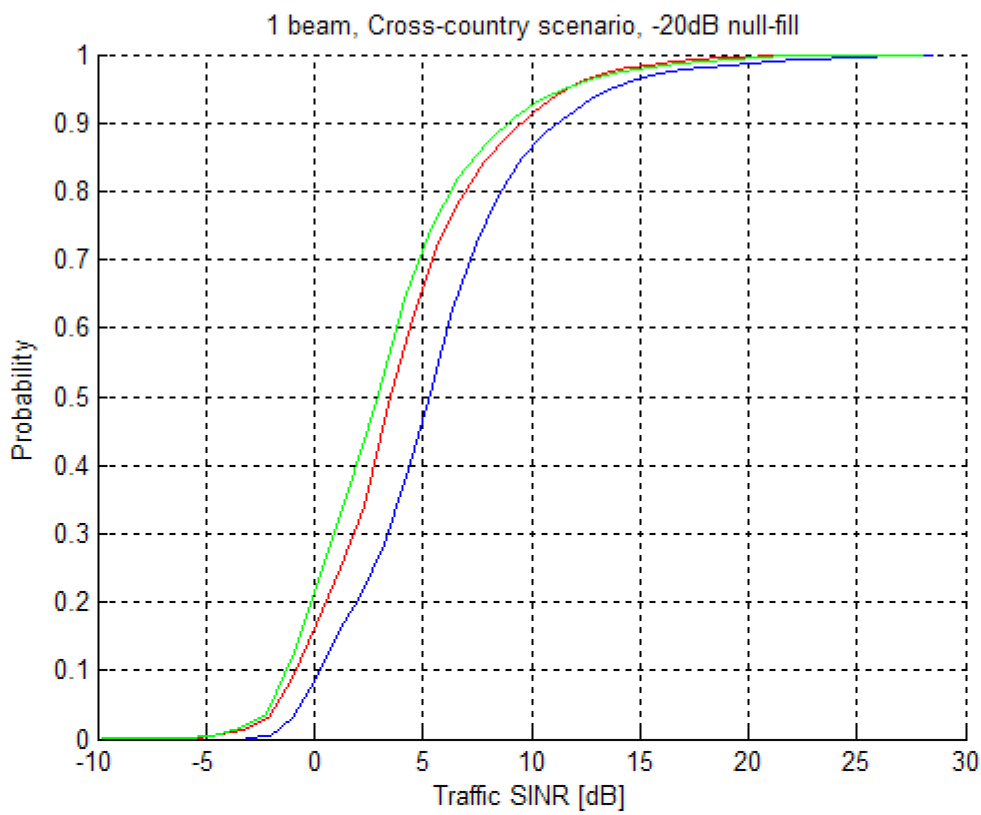

Figure 6.5. Traffic SINR, Cross-country, 1 beam, -20dB null-fill

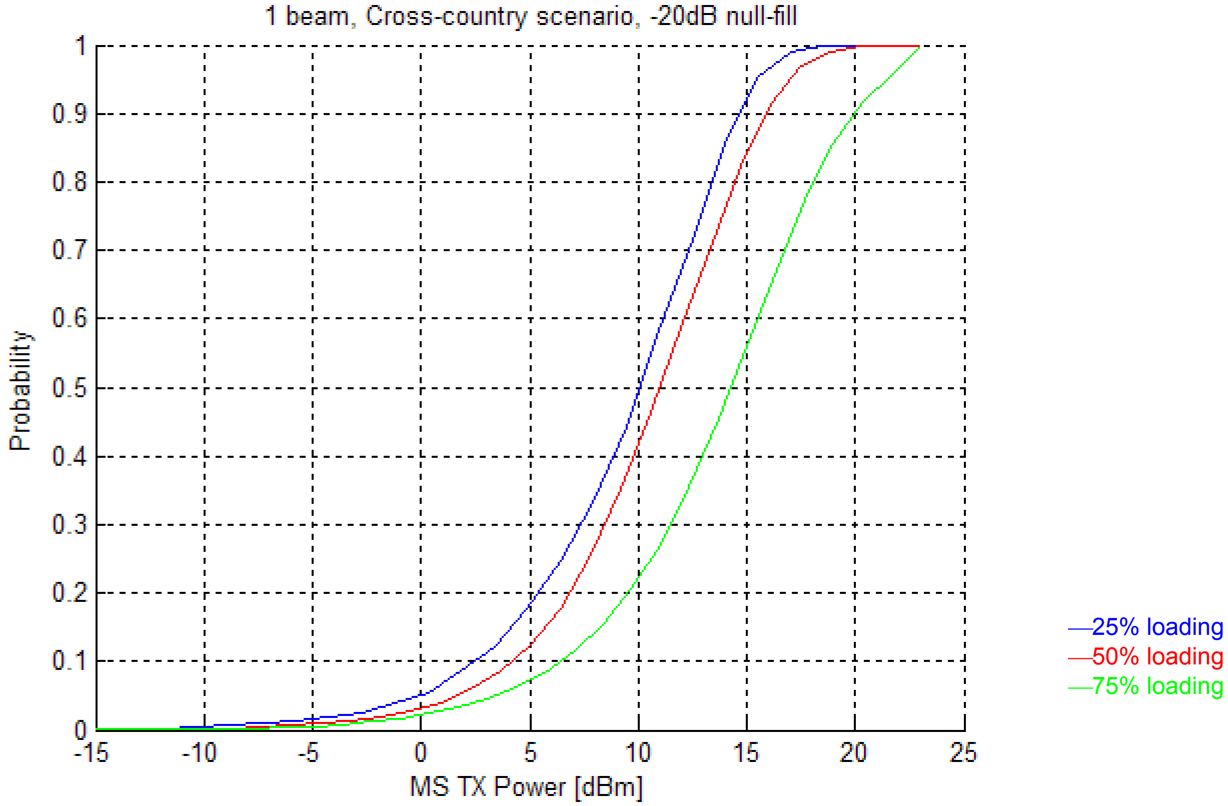

Figure 6.6. Reverse link transmitted power, Cross-country, 1 beam, -20dB null-fill

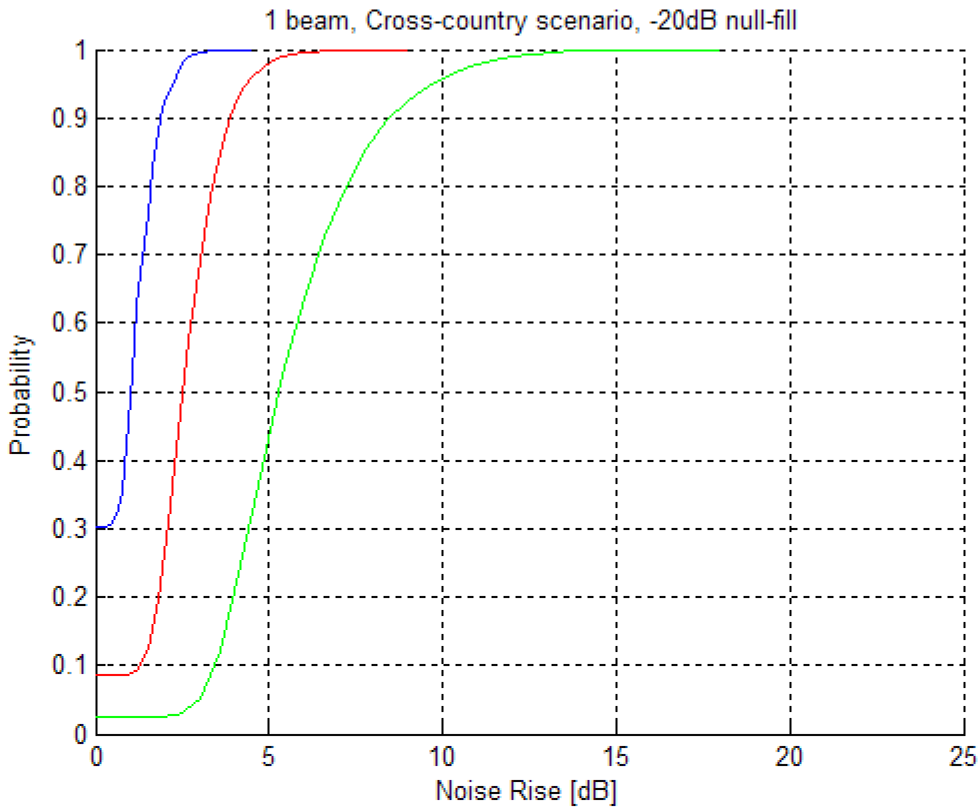

Figure 6.7. Noise rise, Cross-country, 1 beam, -20dB null-fill

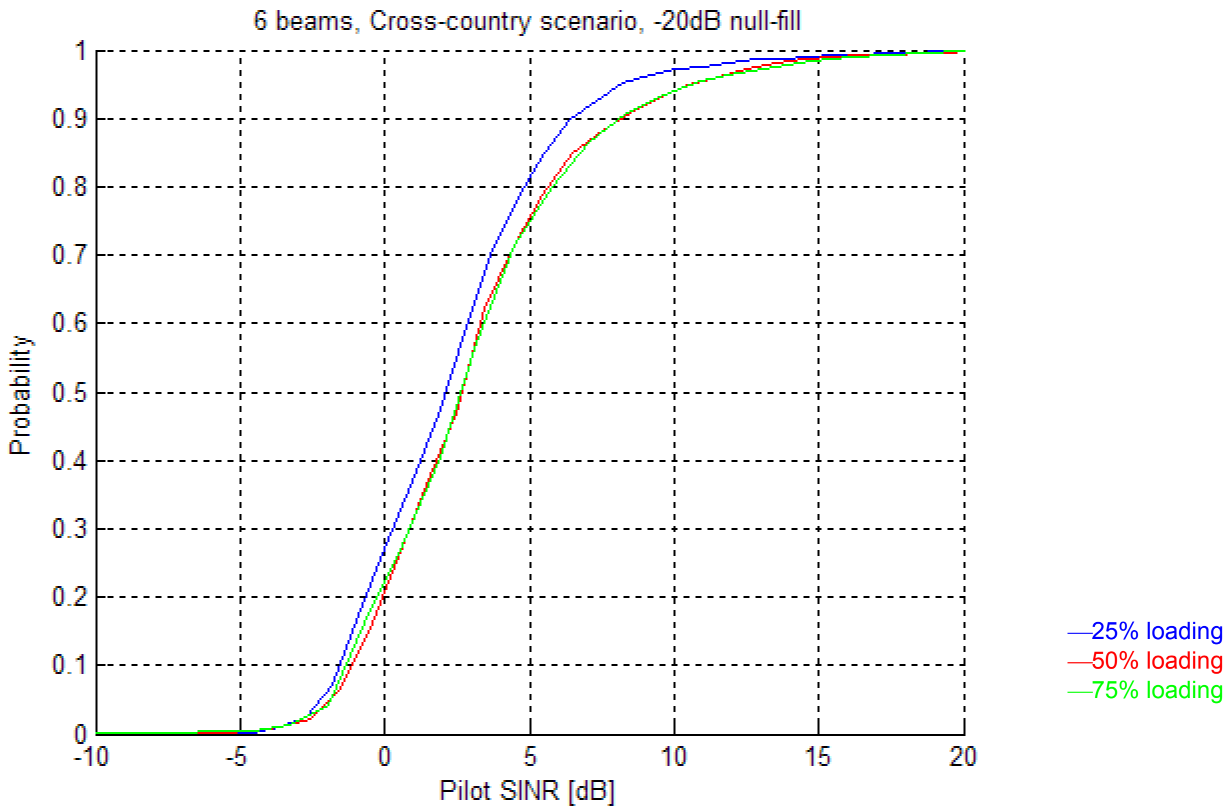

Figure 6.8. Pilot SINR, Cross-country, 6-beams, -20dB null fill

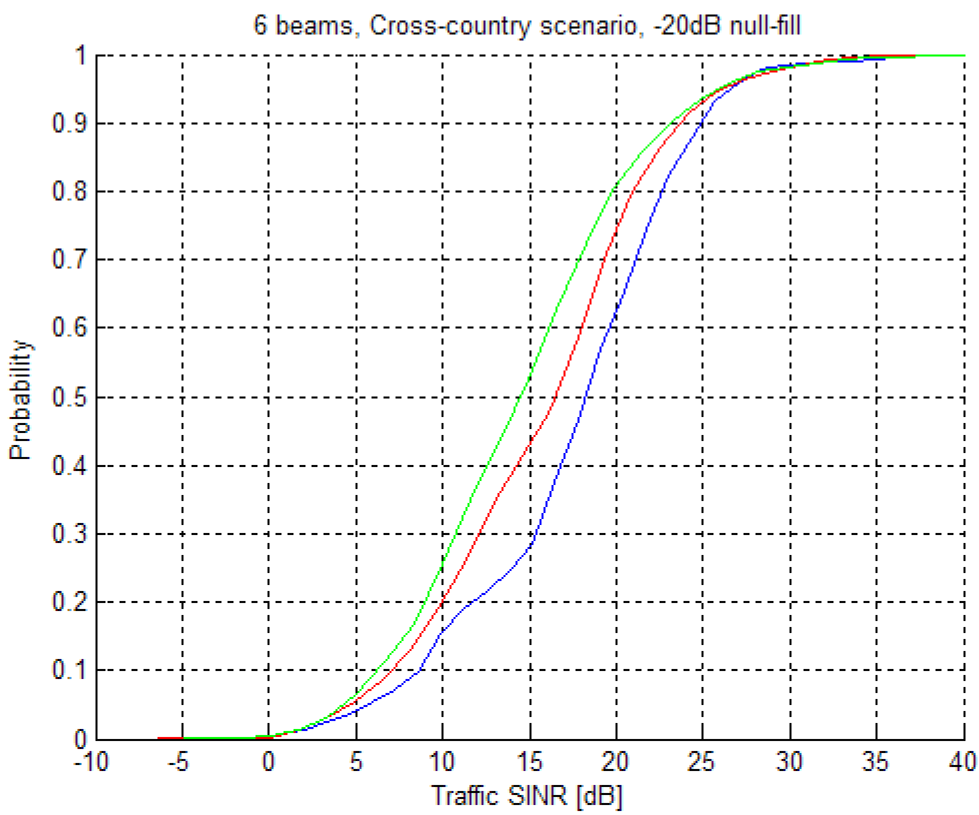

Figure 6.9. Traffic SINR, Cross-country, 6 beams, -20dB null-fill

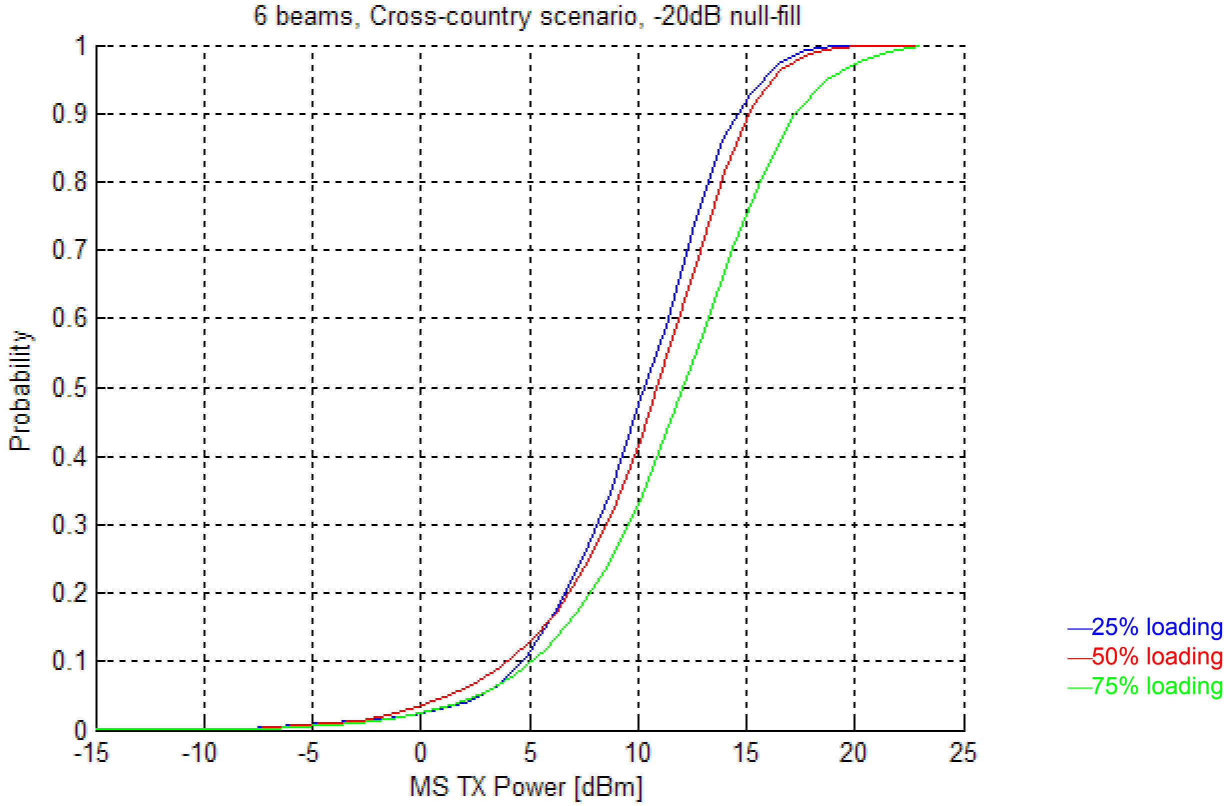

Figure 6.10. Reverse link transmitted power, Cross-country, 6 beams, -20dB null-fill

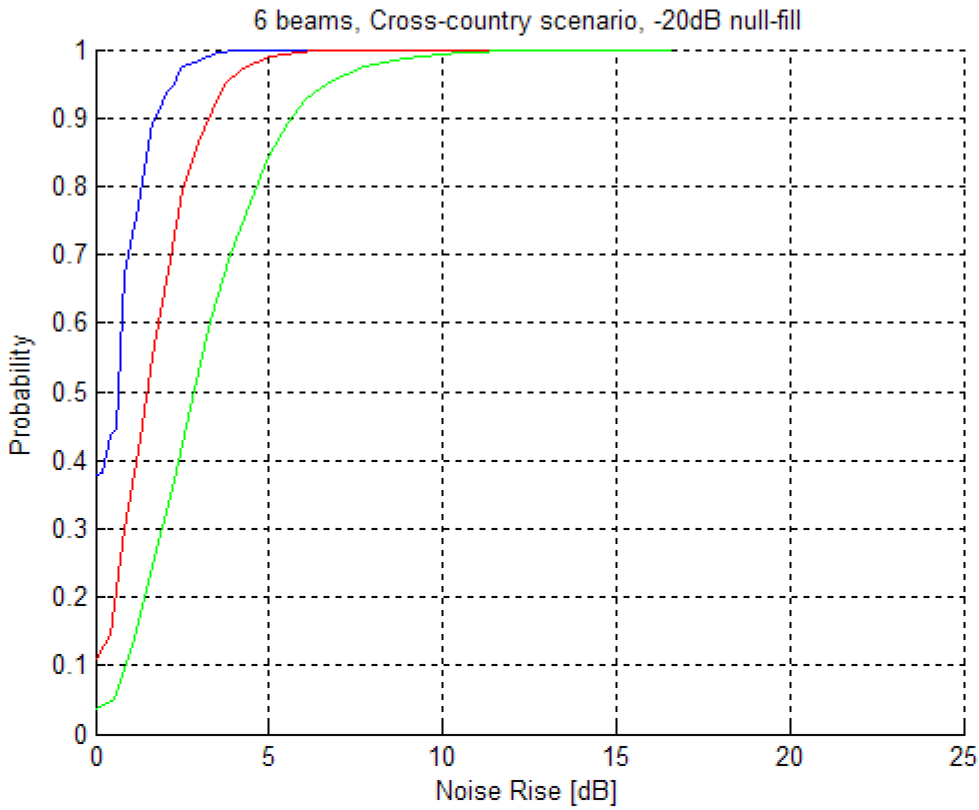

Figure 6.11. Noise rise, Cross-country, 6 beams, -20dB null-fill

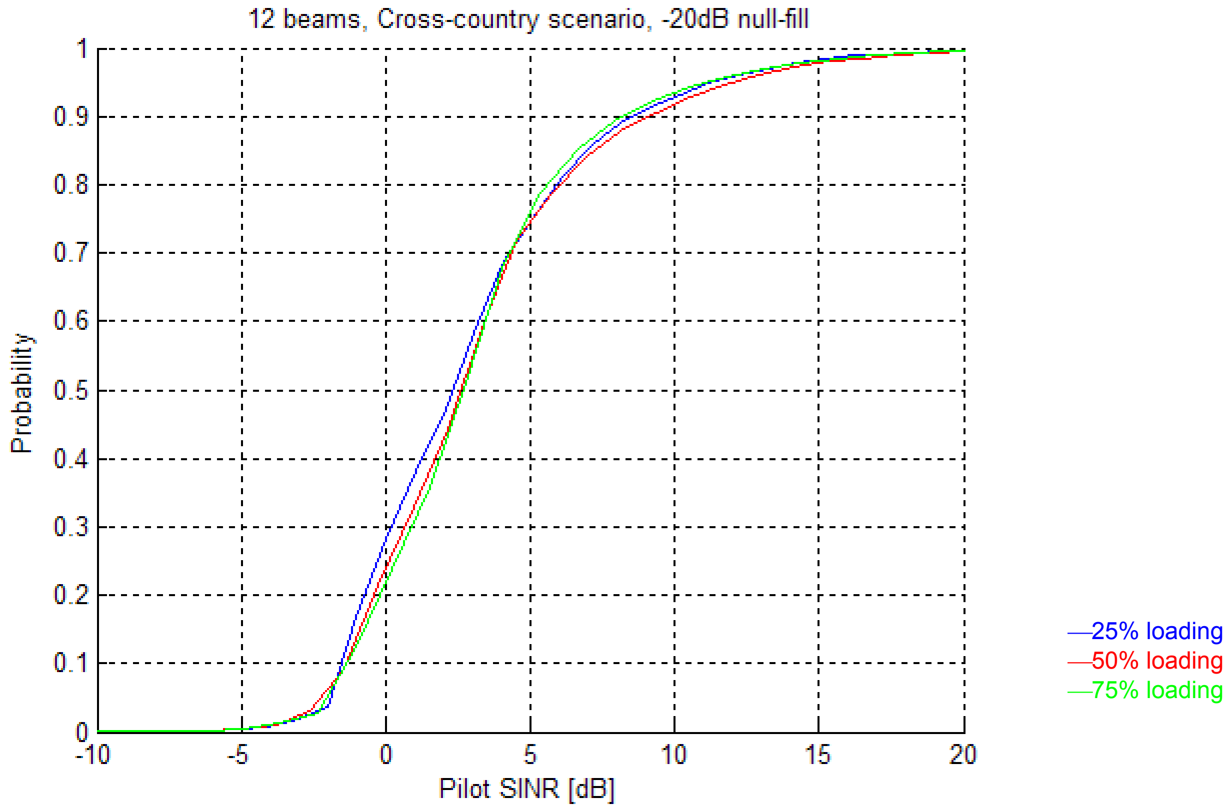

Figure 6.12. Pilot SINR, Cross-country, 12 beams, -20dB null-fill

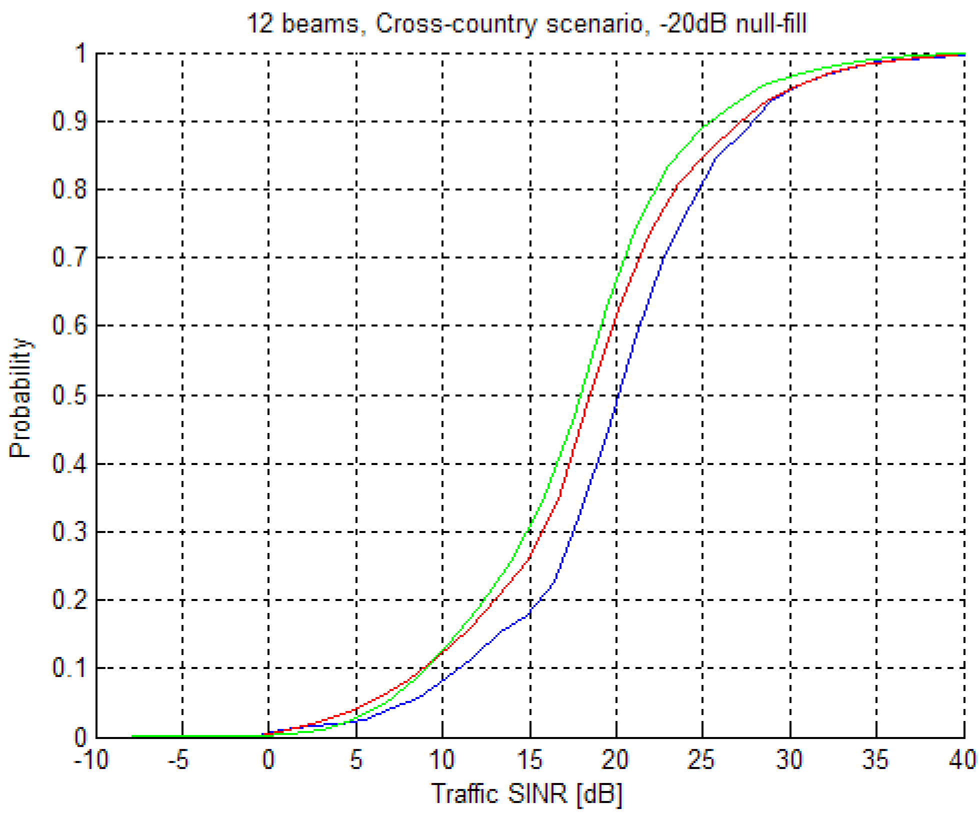

Figure 6.13. Traffic SINR, Cross-country, 12 beams, -20dB null-fill

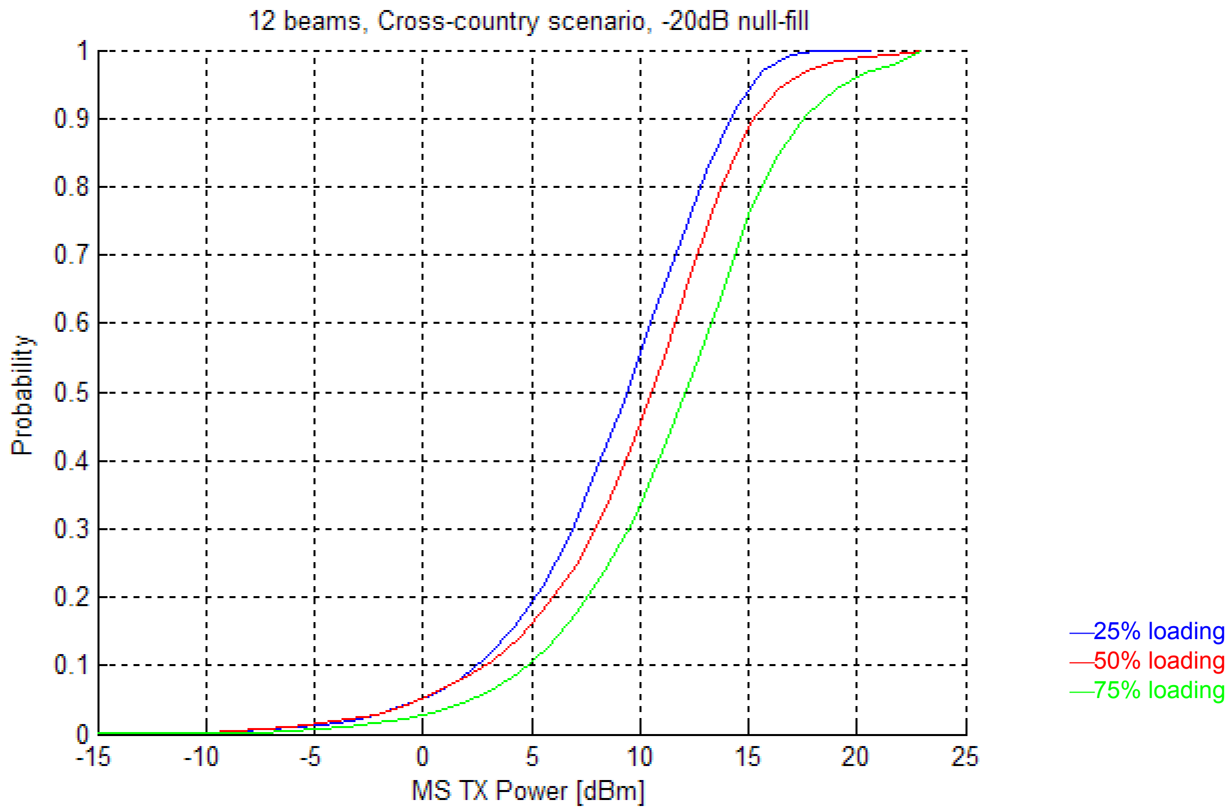

Figure 6.14. Reverse link transmitted power, Cross-country, 12 beams, -20dB null-fill

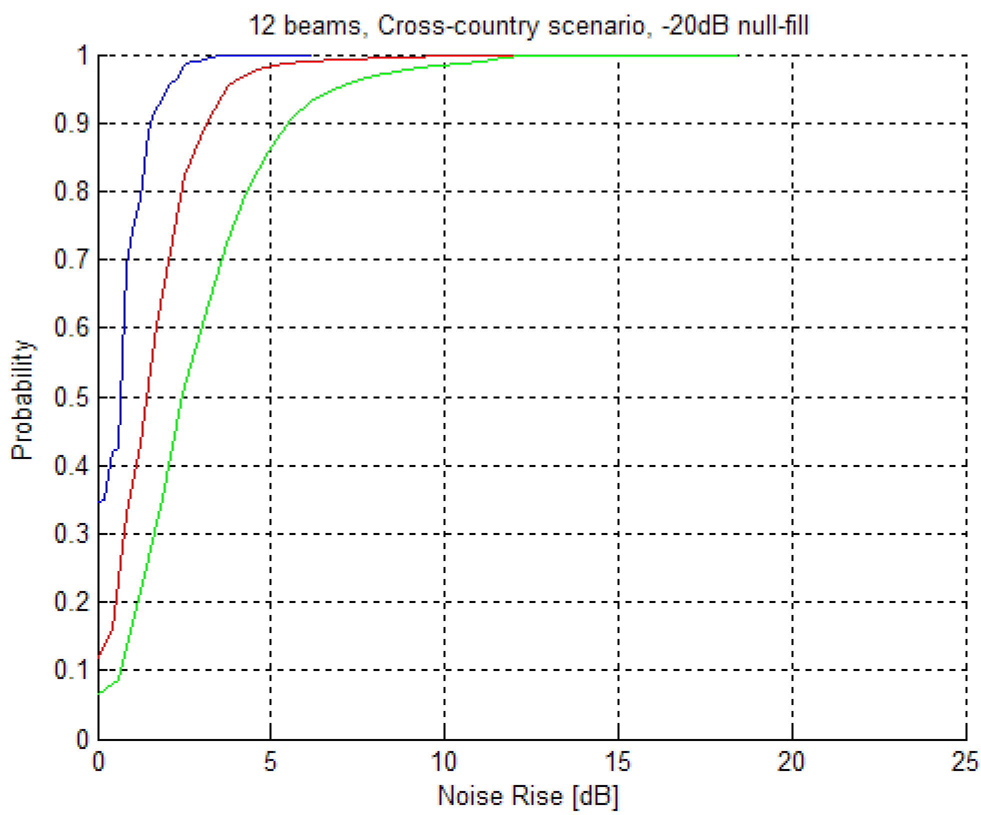

Figure 6.15. Noise rise, Cross-country, 12 beams, -20dB null-fill

6.4. Airport scenario, -20dB null-fill

This section presents results obtained in the analysis of the airport scenario and antennas with –20dB null fill vertical patterns. The CDF curves for the four considered KPIs (pilot *SINR*, traffic channel *SINR*, mobile TX power and reverse link NR), for various simulation cases, are presented in Figs 6.16 through 6.27. Each plot has three traces obtained for three different loading scenarios. The systems deploy switch beam antennas as well. Figures 6.16 to 6.19 are obtained using one beam per sector. This configuration corresponds to a standard three-sector deployment commonly encountered in cellular terrestrial systems. Figures 6.20 to 6.23 characterize a system with two beams per sector (6 beams per cell), while for Figs 6.24 to 6.27 there are four beams per each sector.

The following observations can be made:

- As in the case of cross-country scenario, and for the same reasons, the pilot *SINR* curves remain the same for all simulations. However, comparing the two scenarios one notices an approximately 4dB degradation in median pilot *SINR* for the airport scenario. This degradation can be attributed to closer cell spacing, which increases both co-system and inter-system interference.

- Similar to the case of cross-country scenario, the use of switch beam antennas introduces large improvements to traffic channel *SINR*. Depending on the system loading, the improvements are as high as 6-9dB. Through offsetting values in Table 5.1 by proper amount, the improvements in traffic channel *SINR* can be used to increase forward link data rate.

- In cases of 25% and 50% loading, the aircraft transmit power remains below 23dBm. Therefore, for loading smaller than 50%, the system operates without major reverse link constraints. The noise rise becomes quite high, but due to the small sizes of airport cells, it can be tolerated.

- As loading reaches 75% of the pole point, the noise rise becomes very high (greater than 25dB), and causing aircraft to transmit at the highest possible power level. At such high loading, two approaches may be used. The first approach is the introduction of additional interference management techniques. Some aspects of this approach will be examined in the remaining part of this section. The second approach is similar to traditional cell splitting. To increase the capacity of the system, and improve its ability to deal with higher loads, the operator may reduce the size of the cells. The cell size is reduced through decreasing transmit power and modifying antenna system to restrict coverage. New cells that may be built to cover any resultant gaps in coverage and provide additional capacity. The concept of cell splitting is very well understood and it is a part of daily engineering practice in terrestrial cellular systems.

Table 6.8. Percentile values for KPIs – Airport scenario, 1 beam

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-3	-1	2	-3	-1	2	-3	-1	2
Traffic *SINR* [dB]	-2	0	7	-3	-1	3	-3	-1	2
MS TX Power [dBm]	-8	2	10	-4	12	22	4	21	21
Noise rise [dB]	0	1	4	0	9	19	0	19	25

Table 6.9. Percentile values for KPIs – Airport scenario, 6 beams

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-3	-1	2	-3	-1	2	-1	-1	2
Traffic *SINR* [dB]	-1	3	15	-1	2	8	-1	2	7
MS TX Power [dBm]	-9	1	8	-6	9	22	2	20	23
Noise rise [dB]	0	1	4	0	6	17	0	17	24

Table 6.10. Percentile values for KPIs – Airport scenario, 12 beams

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-3	-2	2	-3	-2	2	-3	-2	2
Traffic *SINR* [dB]	-1	9	24	-1	6	17	-1	5	13
MS TX Power [dBm]	-9	0	8	-7	7	20	-2	18	23
Noise rise [dB]	0	1	3	0	3	14	0	13	23

Base on the results presented in Fig 6.16 and the summary provided in Tables 6.5 and 6.7, the following conclusions can be drawn:

- For system loading below 50% of the pole point, all significant KPIs remain within ranges allowing normal operation of 1xEvDO systems.

- Use of beam switched antennas provides significant benefits to forward link throughput.

- In the airport scenario, for system loading below 50% two co-duplex, co-polarized systems operate without causing harmful interference to each other. Beyond 50% loading, either cell splitting or advance interference management techniques should be used.

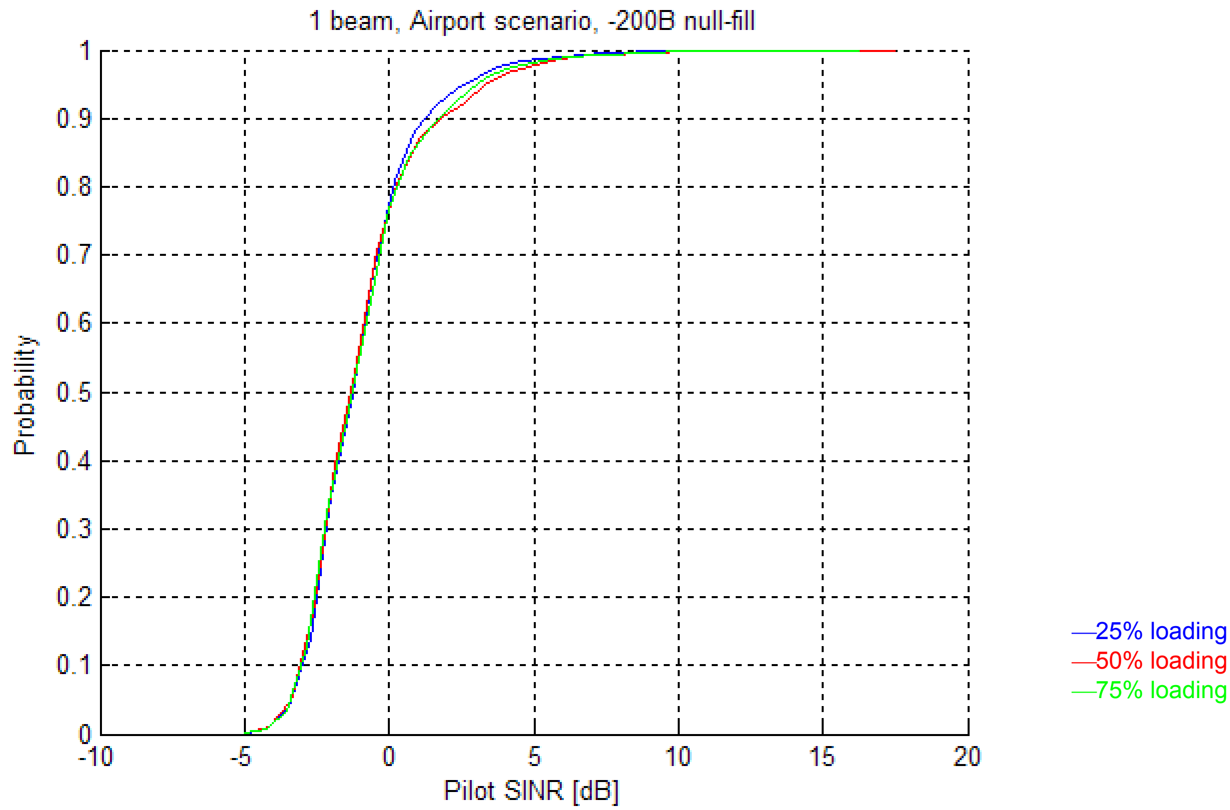

Figure 6.16. Pilot SINR, Airport, 1 beam, -20dB null-fill

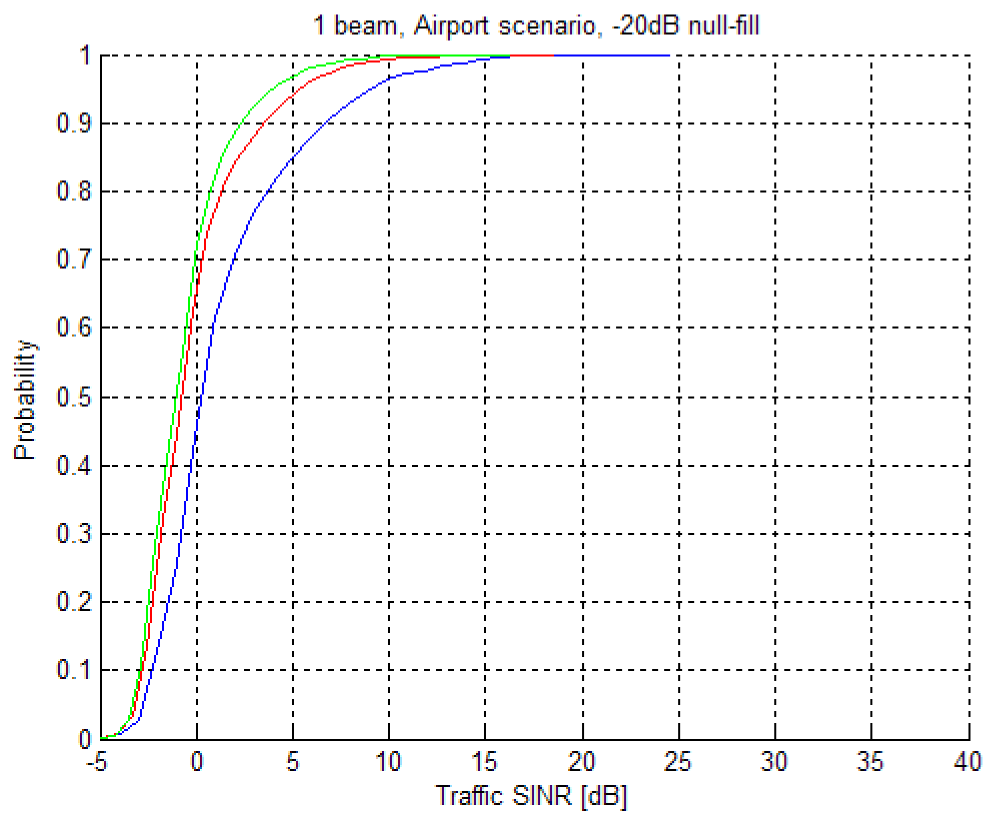

Figure 6.17. Traffic SINR, Airport, 1 beam, -20dB null-fill

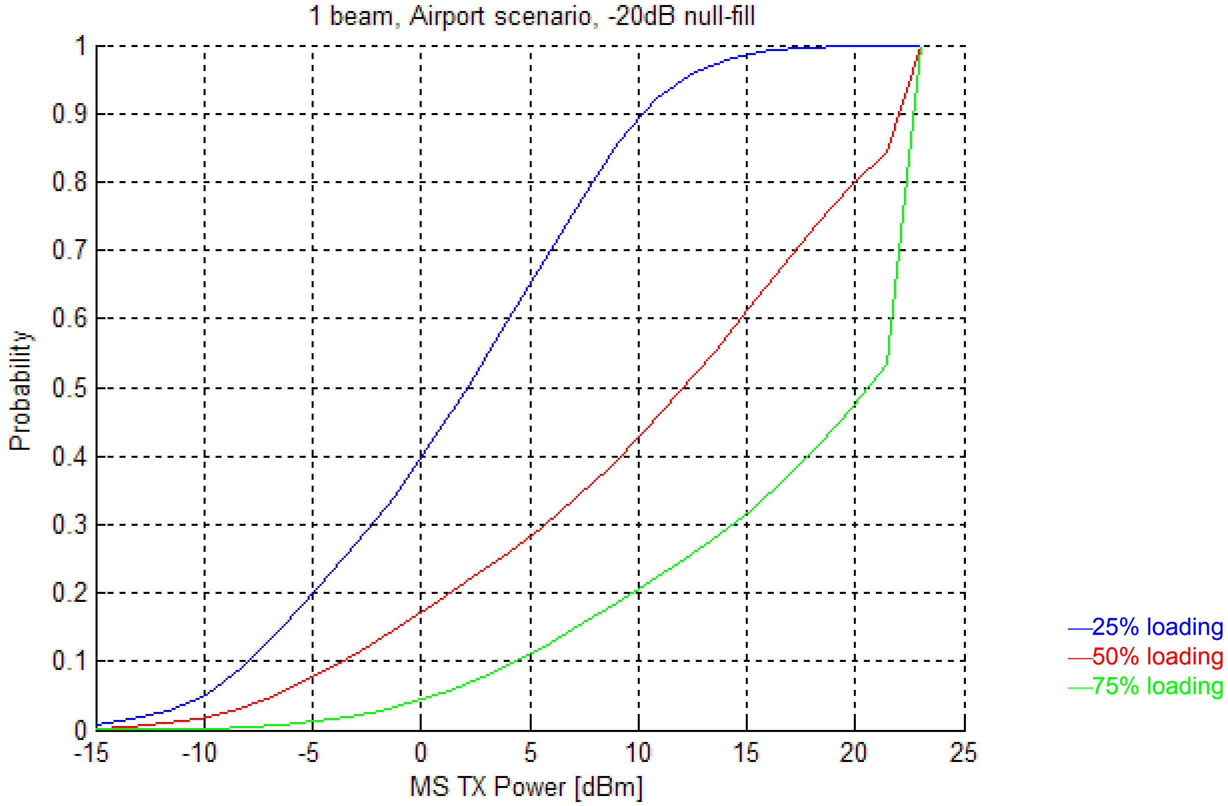

Figure 6.18. Reverse link transmitted power, Airport, 1 beam, -20dB null-fill

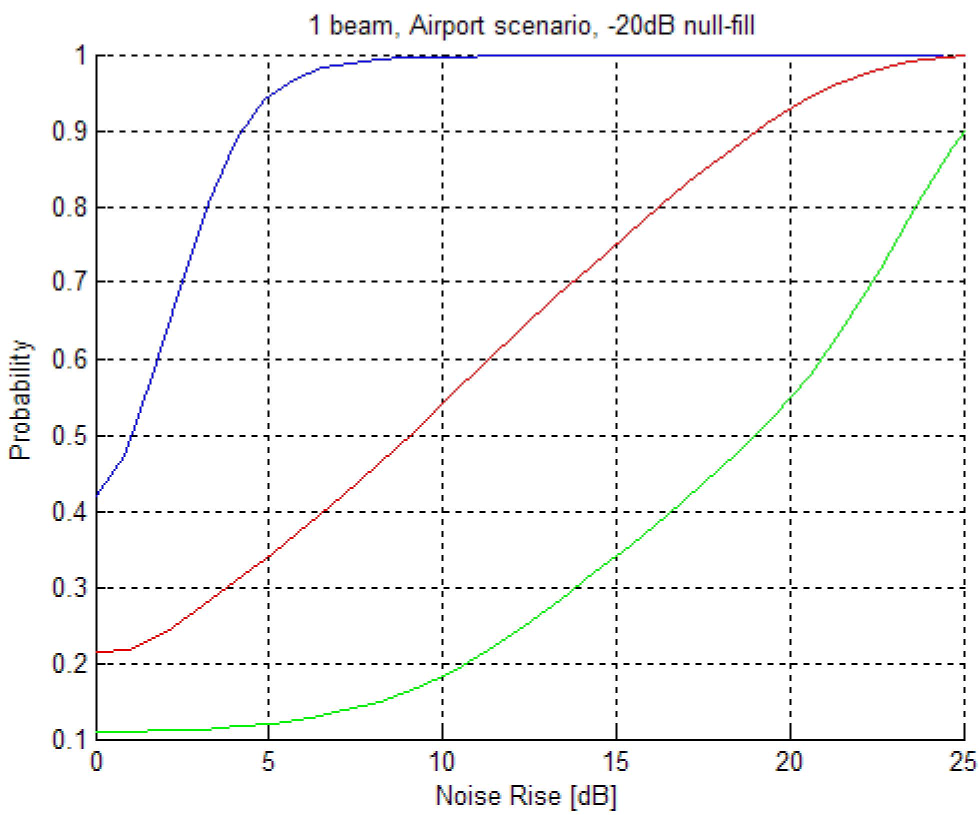

Figure 6.19. Noise rise, Airport, 1 beam, -20dB null-fill

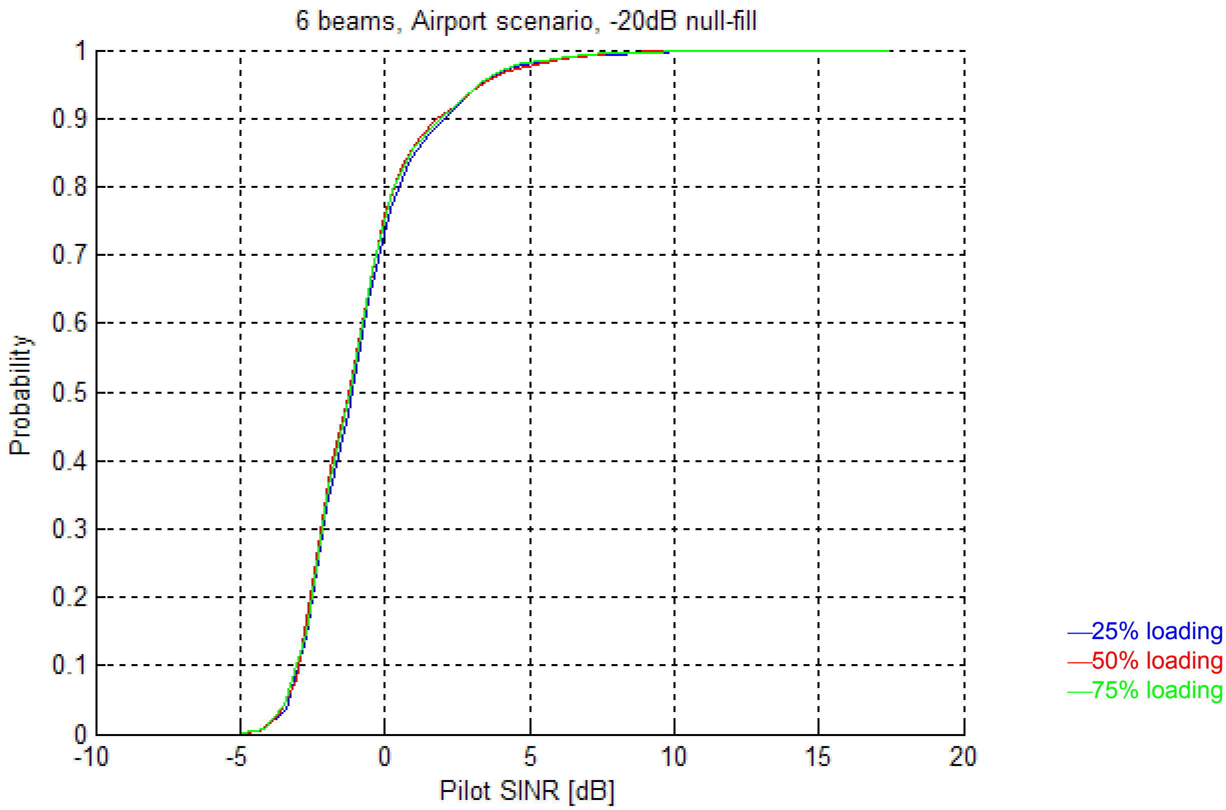

Figure 6.20. Pilot SINR, Airport, 6 beams, -20dB null-fill

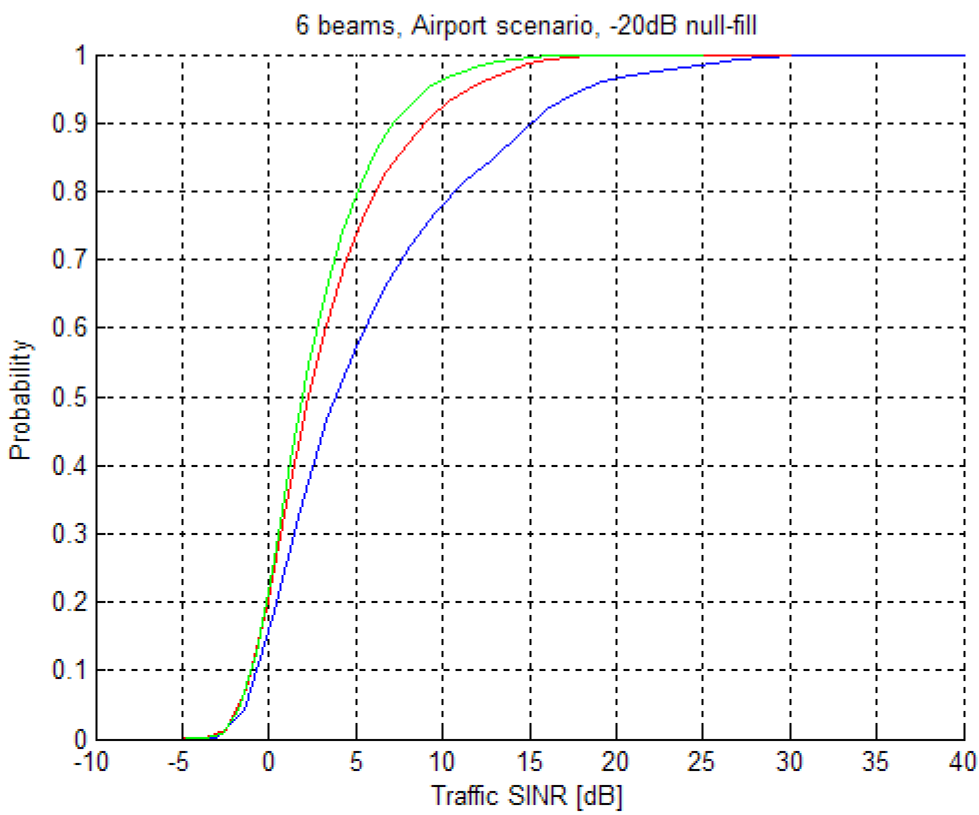

Figure 6.21. Traffic SINR, Airport, 6 beams, -20dB null-fill

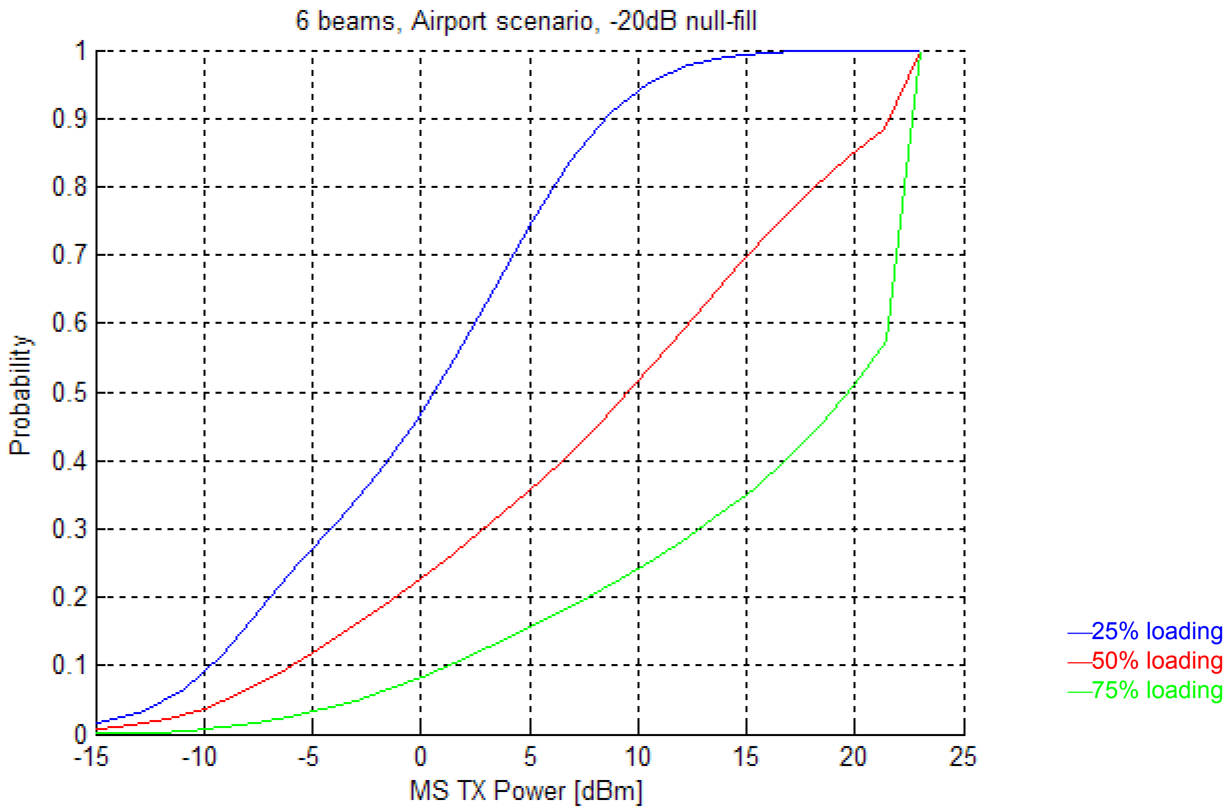

Figure 6.22. Reverse link transmitted power, Airport, 6 beams, -20dB null-fill

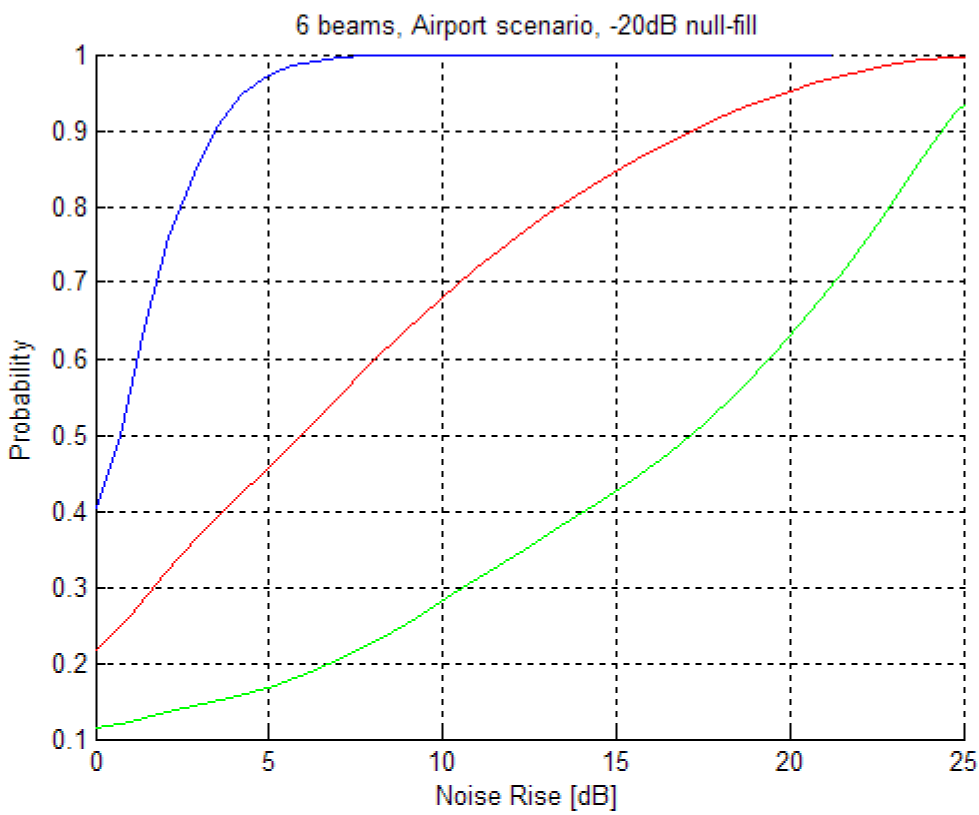

Figure 6.23. Noise rise, Airport, 6 beams, -20dB null-fill

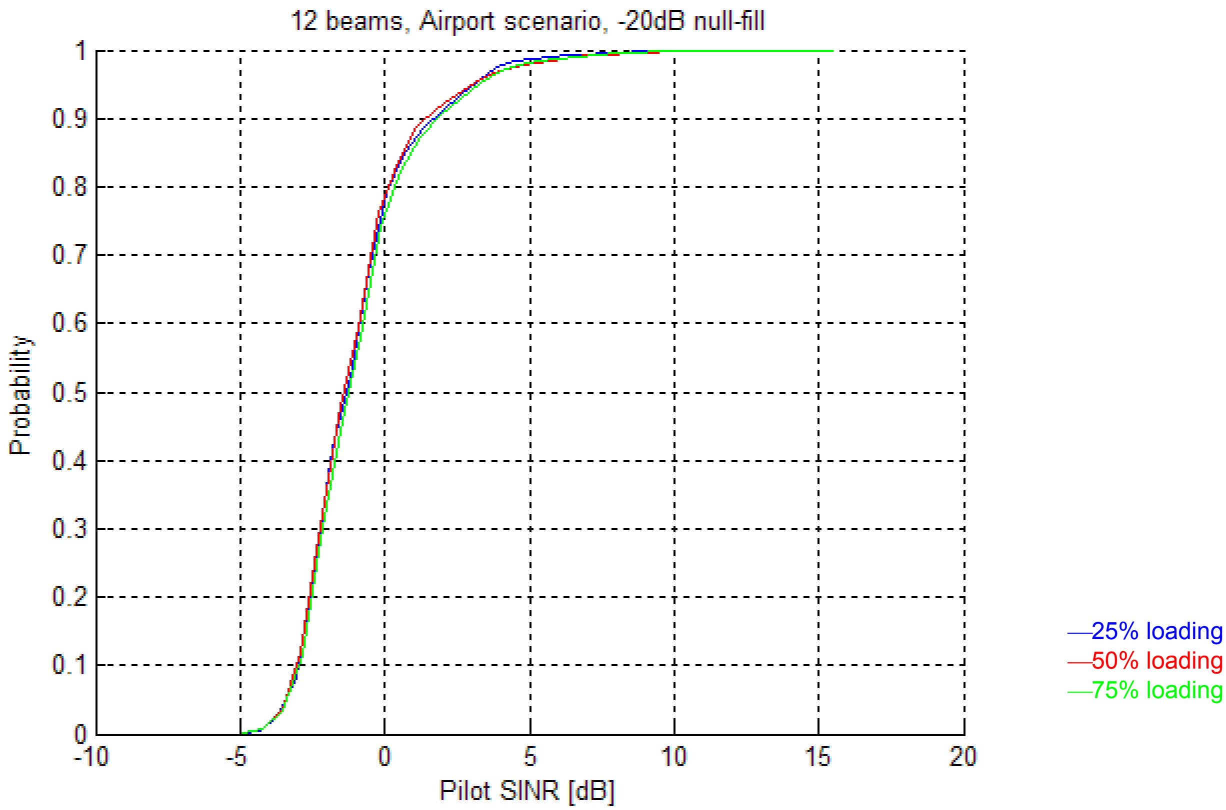

Figure 6.24. Pilot SINR, Airport, 12 beams, -20dB null-fill

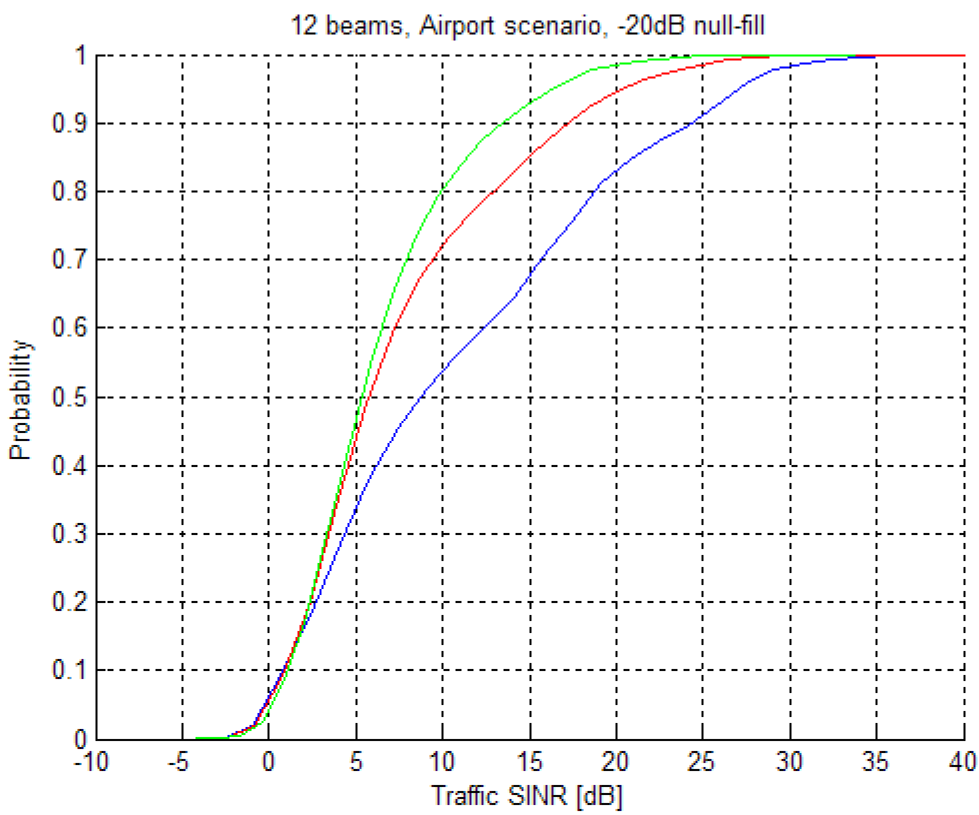

Figure 6.25. Traffic SINR, Airport, 12 beams, -20dB null-fill

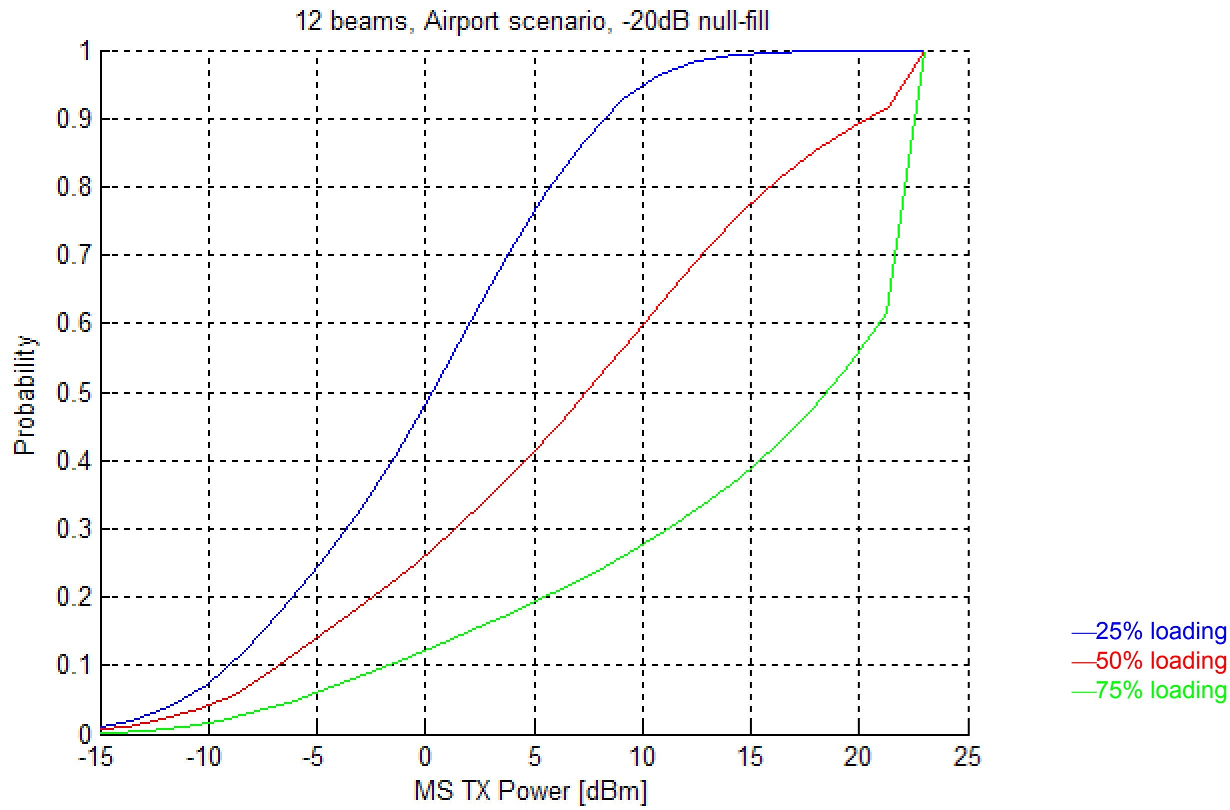

Figure 6.26. Reverse link transmitted power, Airport, 12 beams, -20dB null-fill

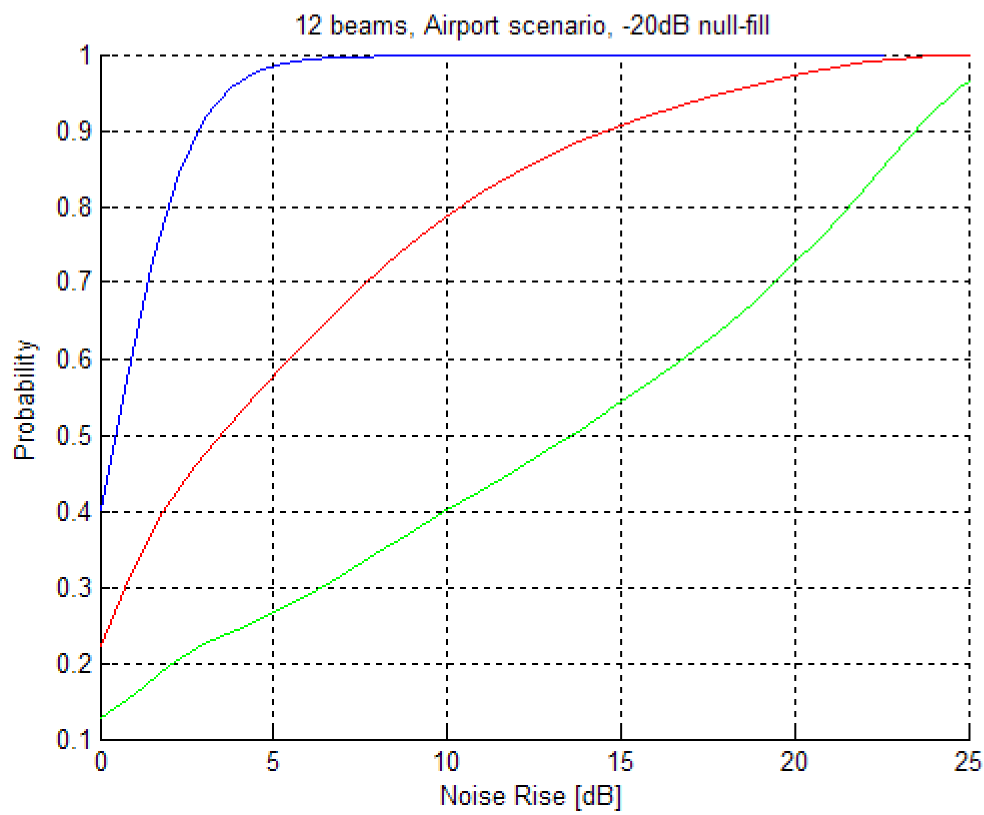

Figure 6.27. Noise rise, Airport, 12 beams, -20dB null-fill

6.5. Airport scenario, 0dB null-fill

The systems analyzed in Sections 6.3 and 6.4 deployed antennas with relatively small gains for high elevation angles. These kind of antennas are commonly found in ATG deployment when the cells are expected to have large radii. In such cells, the vast majority of aircraft are at elevation angles of just a few degrees above the horizon. In such circumstances, shaping the antenna pattern so that the gain at low elevation angles is high provides significant improvements to the link budget, and, is therefore frequently used.

In the airport scenario, due to capacity requirements, cells are bound to be smaller. As a result, larger numbers of aircraft fly in the cell vicinity and are at higher elevation angles. The event, when an aircraft flies right over the serving site, might not be a rare one. In such circumstances, patterns with low level of vertical null fill become sub-optimal.

To determine the extent of a need for antenna patterns with higher relative gains at higher elevation angles, this section provides analysis of an airport scenario where base stations use antennas with 0dB null fill. The vertical pattern of such antenna is presented in Fig. 6.3. It is recognized that an antenna with 0dB null fill pattern is not a very realistic. This is especially the case when no beam switching is used. However, if the benefits of vertical null fill prove to be sufficiently large, the effective antenna pattern can be synthesized using multiple antenna elements in either fixed or switch beam modes. Given that the idealized 0dB null pattern is not realistic, the results presented in this section should be treated in a qualitative rather than a quantitative manner.

The CDF curves for the four considered KPIs and for various simulation cases, are presented in Figs 6.28 through 6.35. Each plot has three traces obtained for three different loading scenarios. The systems consider switched beam antennas as well. However, for the sake of brevity only 1 beam and 4 beams per sector are presented. Figures 6.28 to 6.31 are obtained using one beam per sector and Figs 6.32 to 6.35 characterize a system with four beams per each sector.

The following observations can be made:

- The CDF plots for pilot *SINR* became similar to the ones developed for cross-country scenario. This is obviously an improvement over the airport scenario with –20dB null fill antennas. The improvement can be explained by noting that in the case of 0dB null fill antennas; no aircraft operates in the "antenna sidelobe" of the closest cell site. In that respect, the airport deployment with 0dB null fill antennas becomes very much similar to cross country scenario.

- Use of horizontal beam switching provides a very large benefit to forward link traffic channel *SINR*. As discussed in previous sections, this improvement may be used to provide increased forward link data rate.

- The aircraft transmit power remains below 23dBm in *all* operational scenarios. Even in the case of 75% loading, the combined effects of interference reduction through beam switching and the link budget advantage, from null fill, reduces the aircraft TX power to values below 15dBm (at 90% percentile).

- The noise rise values in the 75% loading case are quite large. However, due to improvement in link budget that results from null fills, they are compensated and as a result, the aircraft never transmits at highest transmit power level.

Table 6.11. Percentile values for KPIs – Airport scenario, 0dB null fills, 1 beam

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	2	6	-2	2	6	-2	2	6
Traffic *SINR* [dB]	0	5	14	-1	3	8	-1	2	7
MS TX Power [dBm]	-15	-9	-6	-13	-7	-2	-9	-2	15
Noise rise [dB]	0	1	3	0	3	7	3	8	24

Table 6.12. Percentile values for KPIs – Airport scenario, 0dB null fills, 12 beams

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	2	5	-2	2	6	-2	2	6
Traffic *SINR* [dB]	6	20	37	4	13	29	4	11	24
MS TX Power [dBm]	-15	-10	-6	-14	-8	-3	-12	-6	8
Noise rise [dB]	0	1	2	0	2	4	1	4	16

Based on results presented in Figs 6.28 to 6.35 and summaries provided in Tables 6.11 and 6.12, the following conclusions can be drawn:

- Null fills improve overall performance of the system in airport scenario with respect to all KPIs.

- Implementation of null fills reduces both the co- and inter-system interference to the point that allows safe operation of both systems, even at the 75% loading.

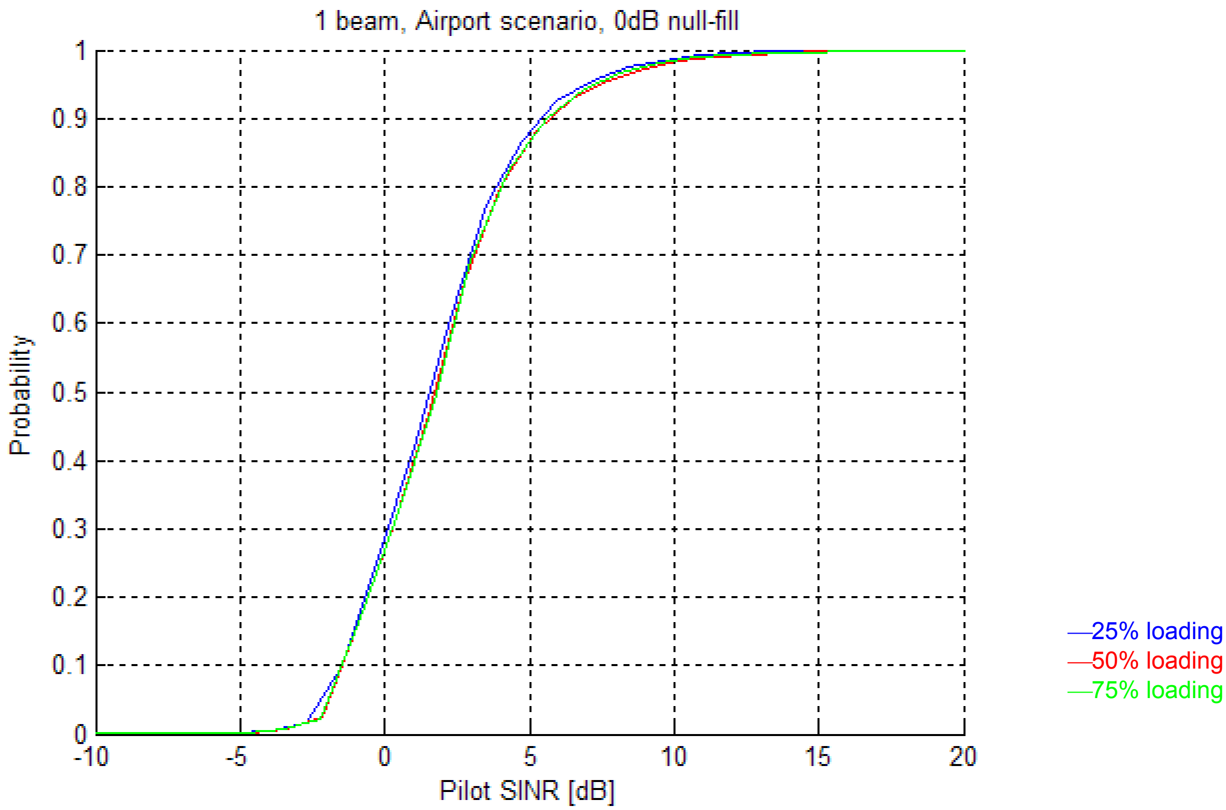

Figure 6.28. Pilot SINR, Airport scenario, 1 beam, 0dB null-fill

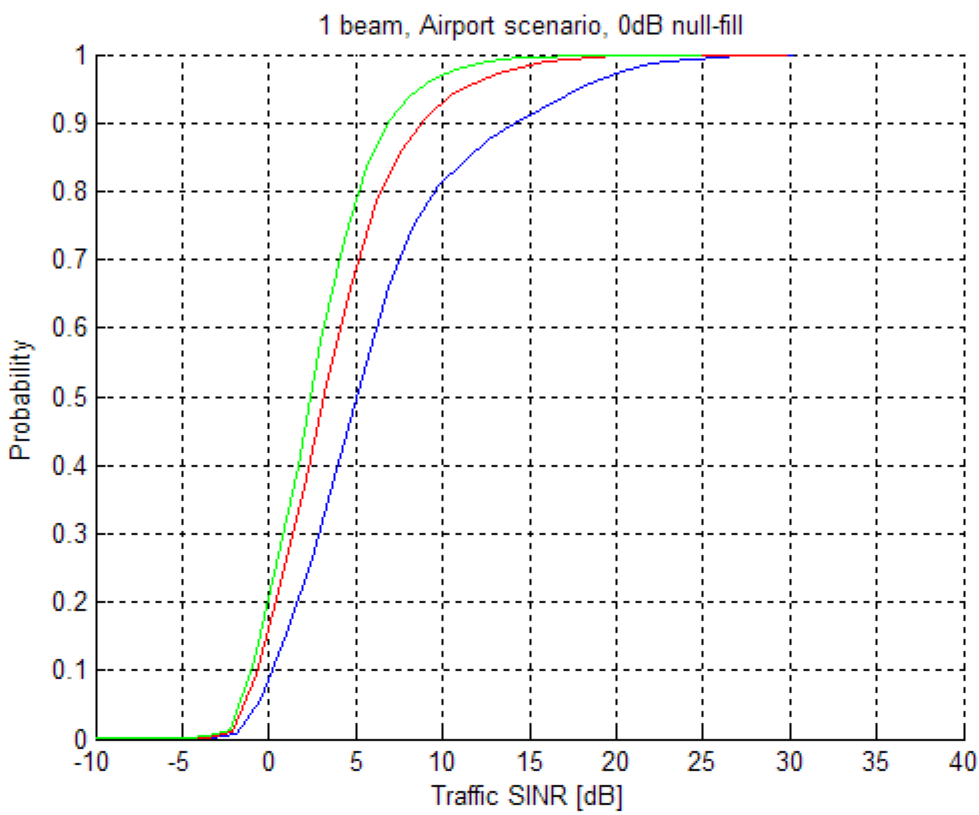

Figure 6.29. Traffic SINR, Airport, 1 beam, 0dB null-fill

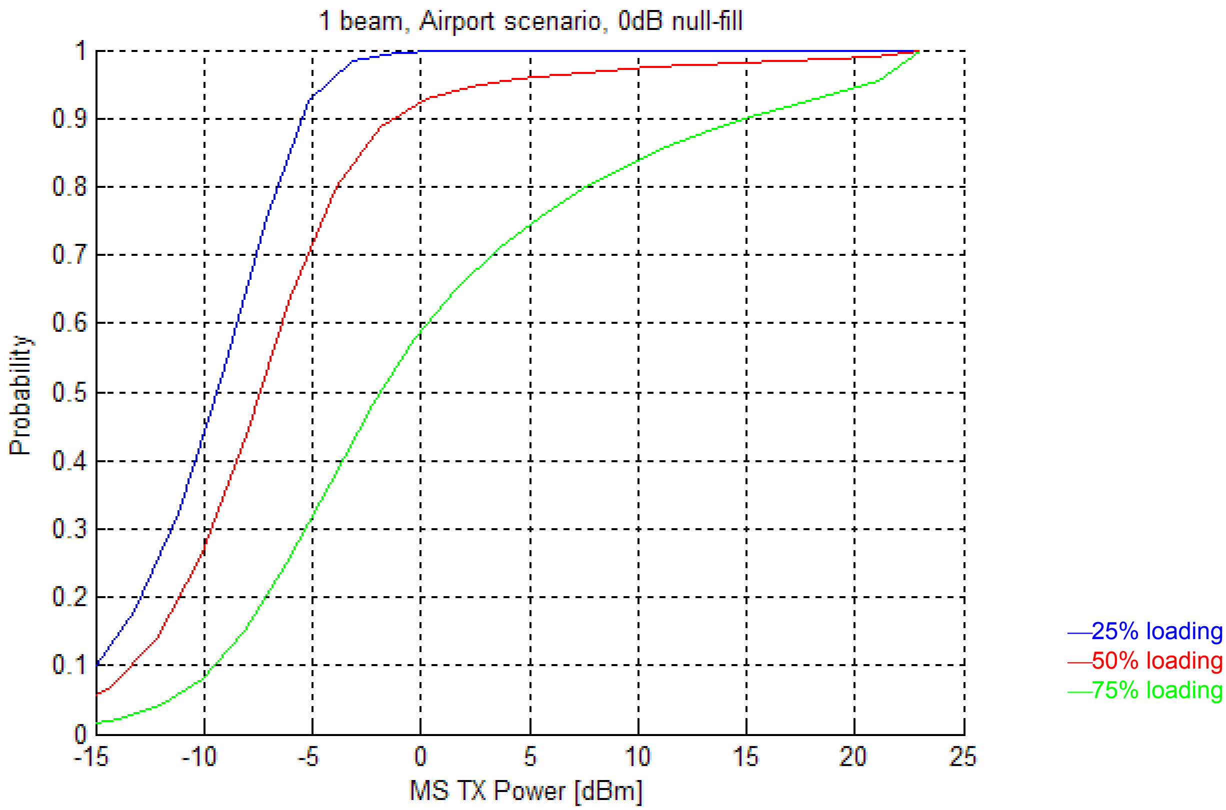

Figure 6.30. Reverse link transmitted power, Airport, 1 beam, 0dB null-fill

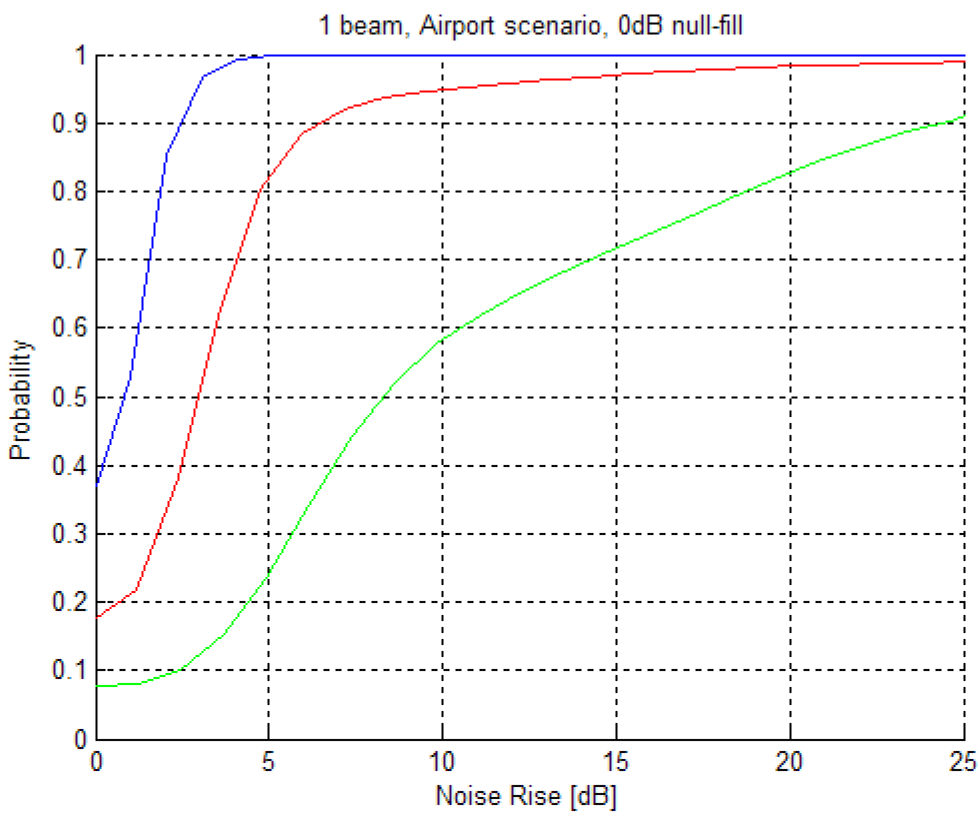

Figure 6.31. Noise rise, Airport, 1 beam, 0dB null-fill

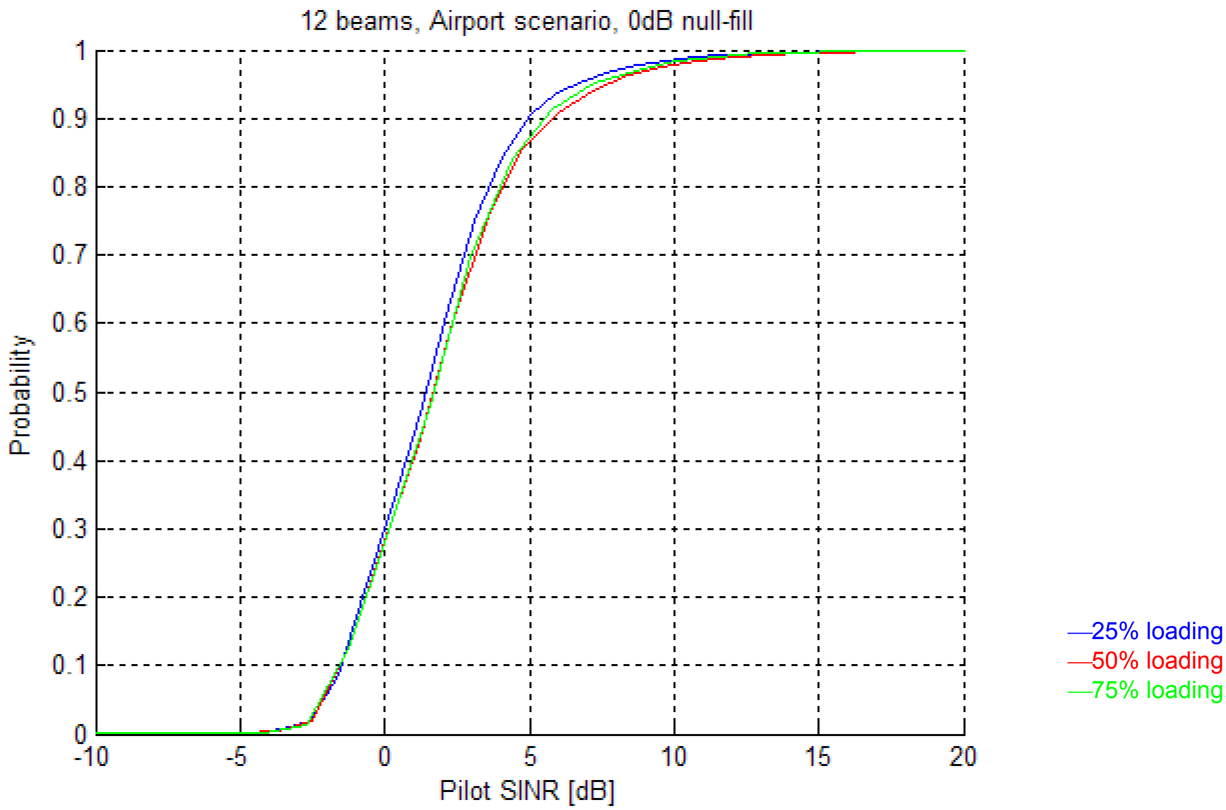

Figure 6.32. Pilot SINR, Airport, 12 beams, 0dB null-fill

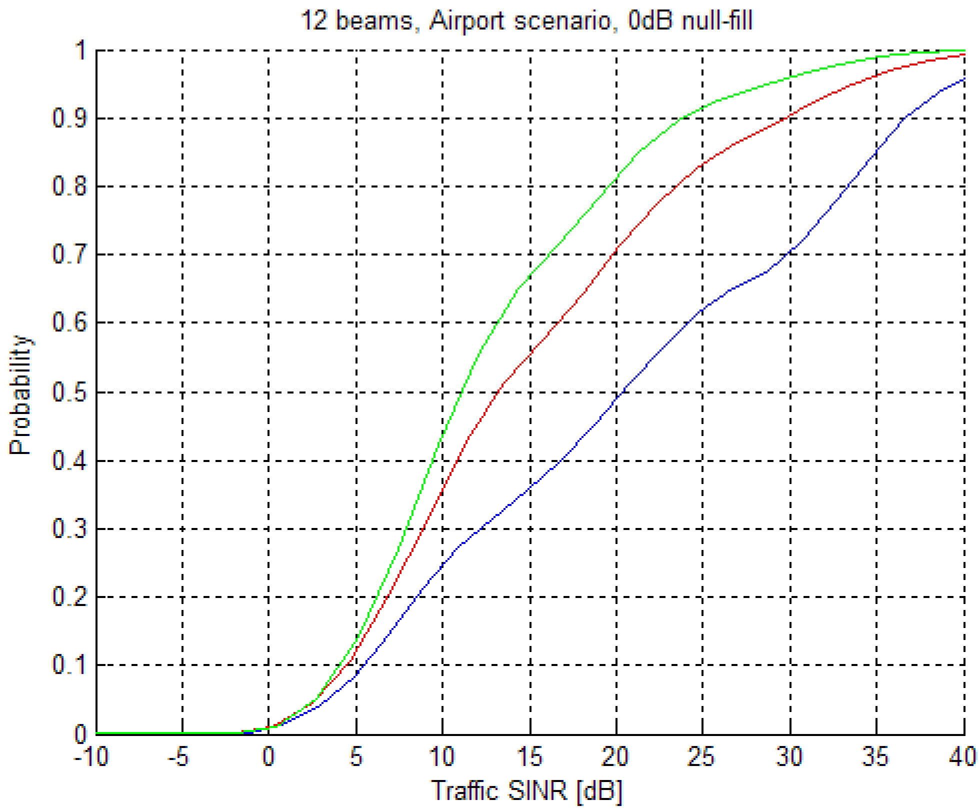

Figure 6.33. Traffic SINR, Airport, 12 beams, 0dB null-fill

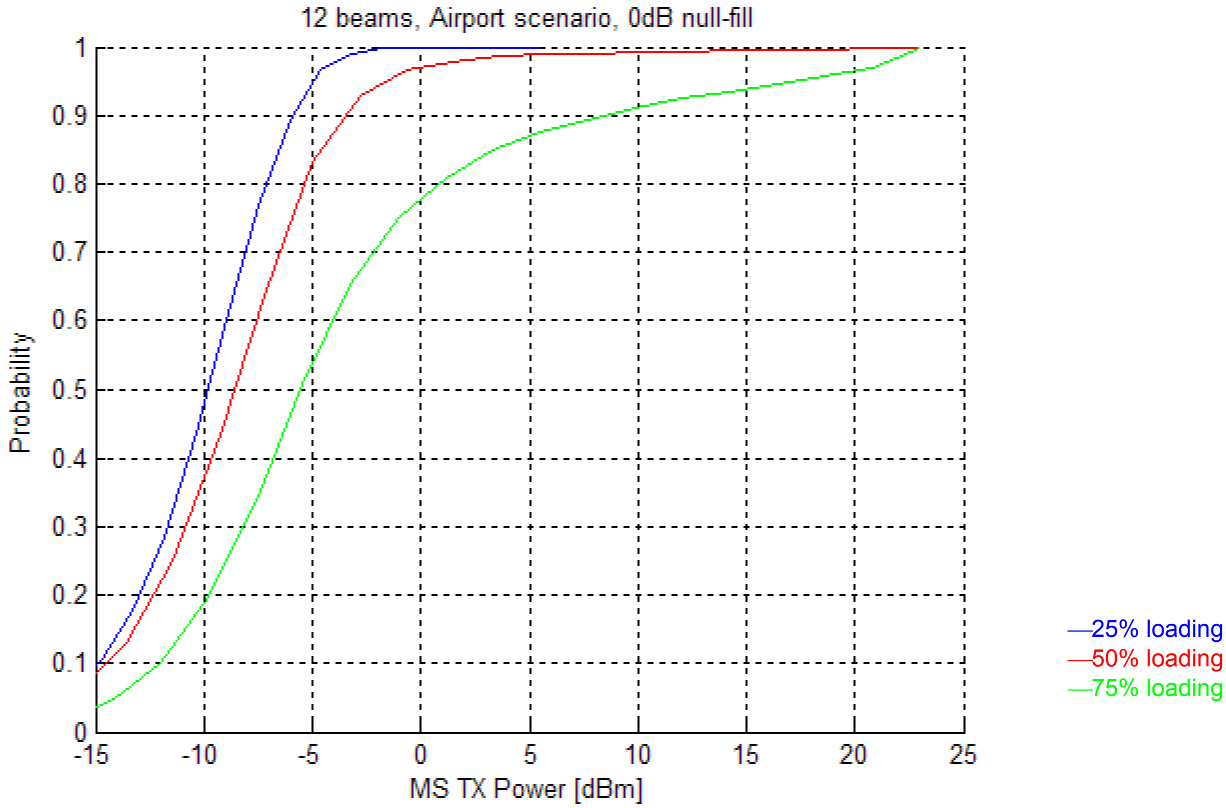

Figure 6.34. Reverse link transmitted power, Airport, 12 beams, 0dB null-fill

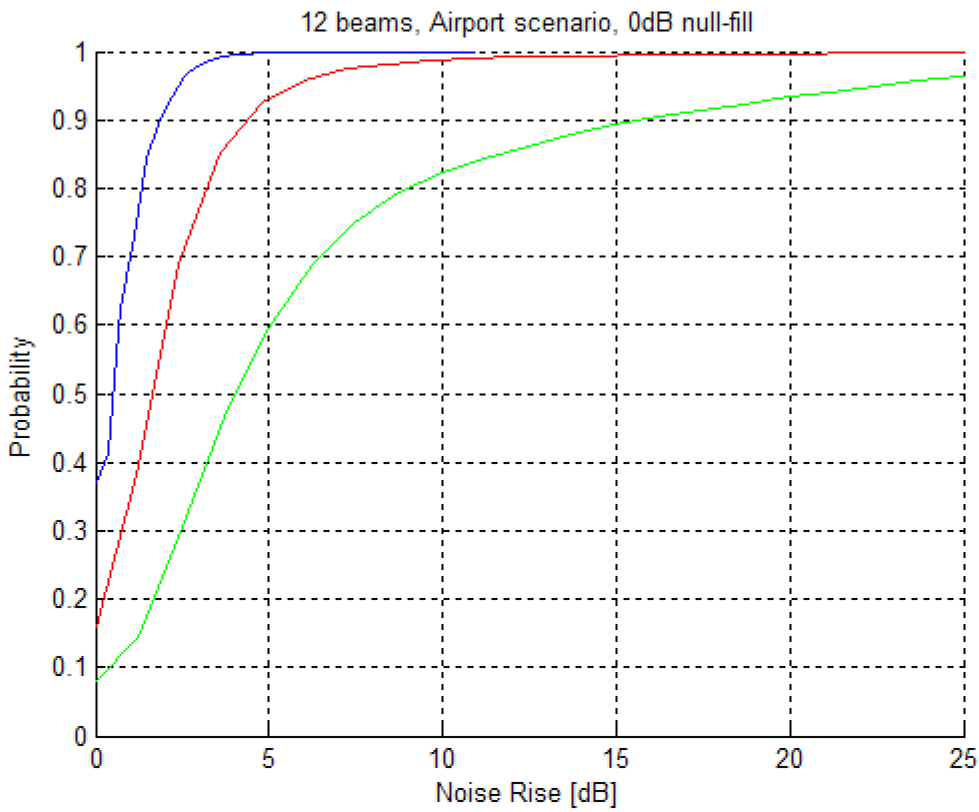

Figure 6.35. Noise rise, Airport, 12 beams, 0dB null-fill

6.6. *Airport scenario, 0dB null-fill, collocated base stations*

To reduce the possibility of the near-far problem the collocation of the sites from different systems is considered in this section. In the case of collocated co-duplex base stations the transmit power of the aircraft that belongs to the different systems are controlled from the same physical location. Therefore, the near-far problem that was described in Section 3 never occurs. For the study presented in this section, the antennas with 0dB null fill are used. The same remarks regarding the antennas made in previous section are valid here as well.

The results of the analyses are presented in Figs 6.38 to 6.43. The figures present four considered KPIs in the same manner as in Sections 6.3 to 6.5. The summary of the results is given in Tables 6.13 and 6.14.

Table 6.13. Percentile values for KPIs – Airport scenario, 0dB null fills, collocated BS, 1 beam

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	2	5	-2	2	6	-2	2	6
Traffic *SINR* [dB]	0	5	14	-1	3	8	-1	2	7
MS TX Power [dBm]	-15	-10	-6	-14	-8	-3	-10	-2	16
Noise rise [dB]	0	1	2	0	3	6	2	8	25

Table 6.14. Percentile values for KPIs – Airport scenario, 0dB null fills, collocated BS, 12 beams

	25% loading			50% loading			75% loading		
Percentile	10	50	90	10	50	90	10	50	90
Pilot *SINR* [dB]	-2	2	6	-2	2	6	-2	2	6
Traffic *SINR* [dB]	6	20	38	4	13	30	4	11	23
MS TX Power [dBm]	-16	-10	-6	-14	-8	-6	-12	-6	10
Noise rise [dB]	0	1	2	0	2	4	0	4	17

Comparing results between collocated and non-collocated airport scenarios, one notices only marginal changes in the noise rise and aircraft transmit power. Therefore, it seems that when the null fill antennas are used, 12dB of polarization isolation provides a significant level of interference reduction to completely suppress the near far problem, and collocation does not provide significant benefit.

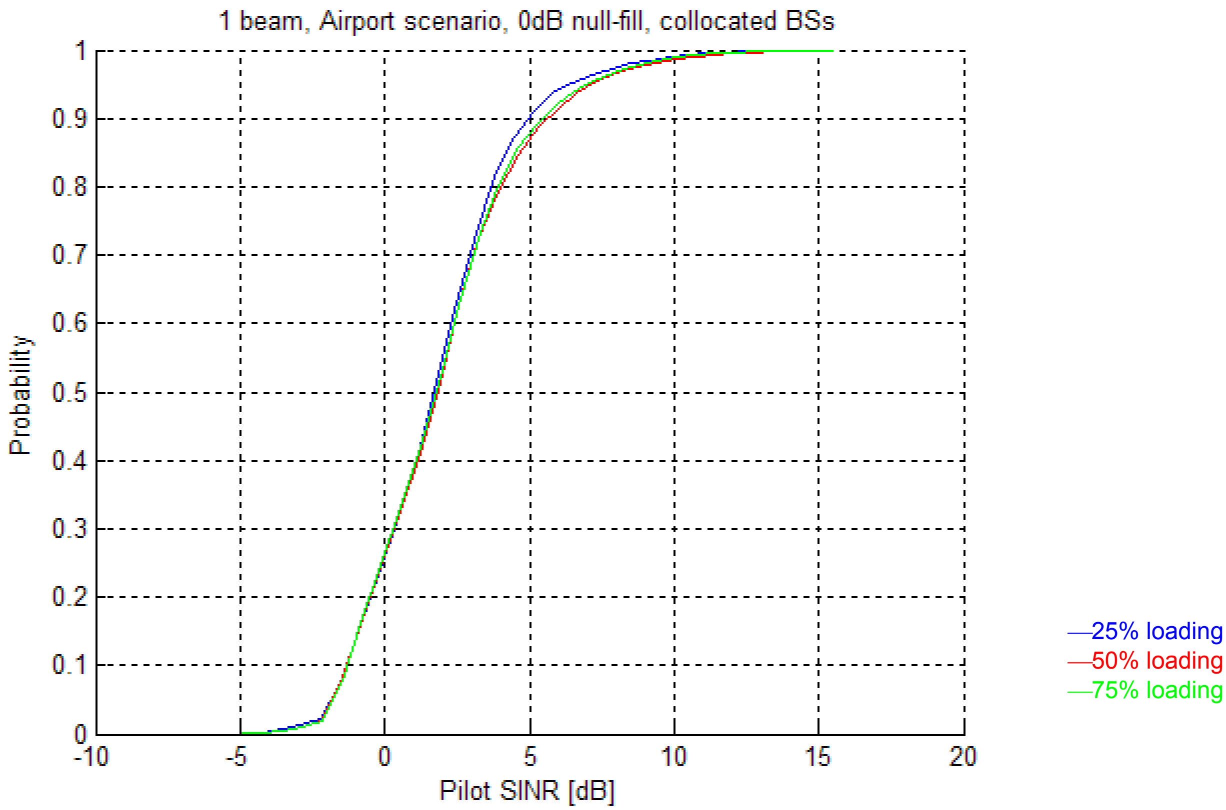

Figure 6.36. Pilot SINR, Airport, 1 beam, 0dB null-fill, collocated BSs

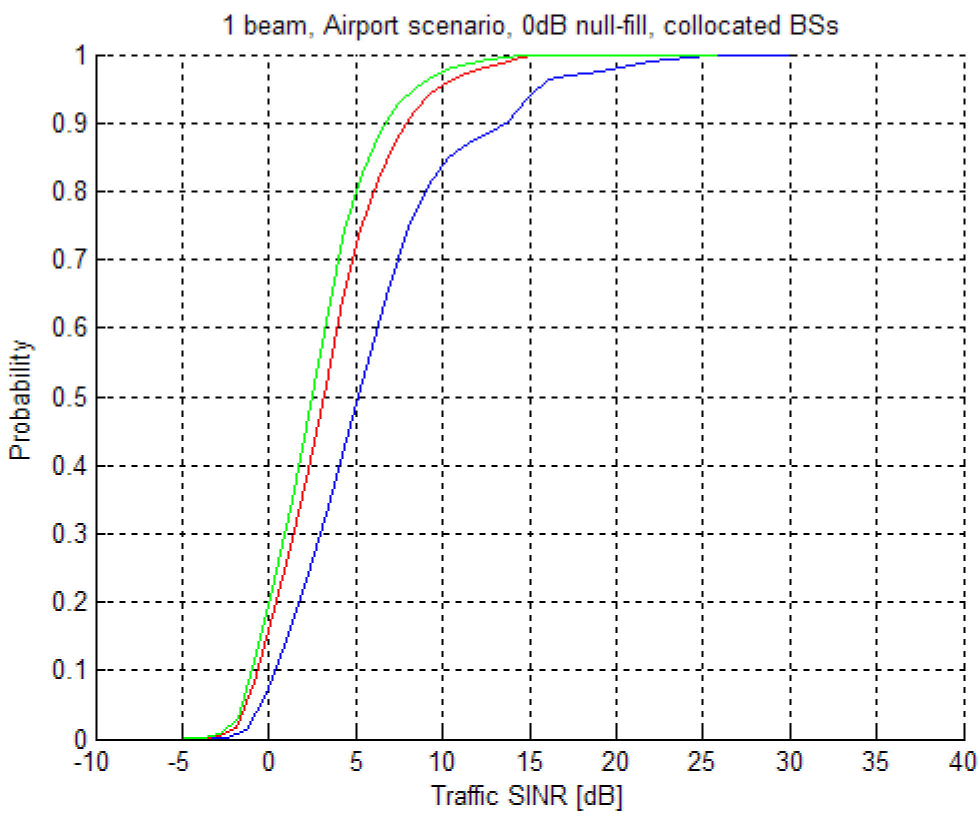

Figure 6.37. Traffic SINR, Airport, 1 beam, 0dB null-fill, collocated BSs

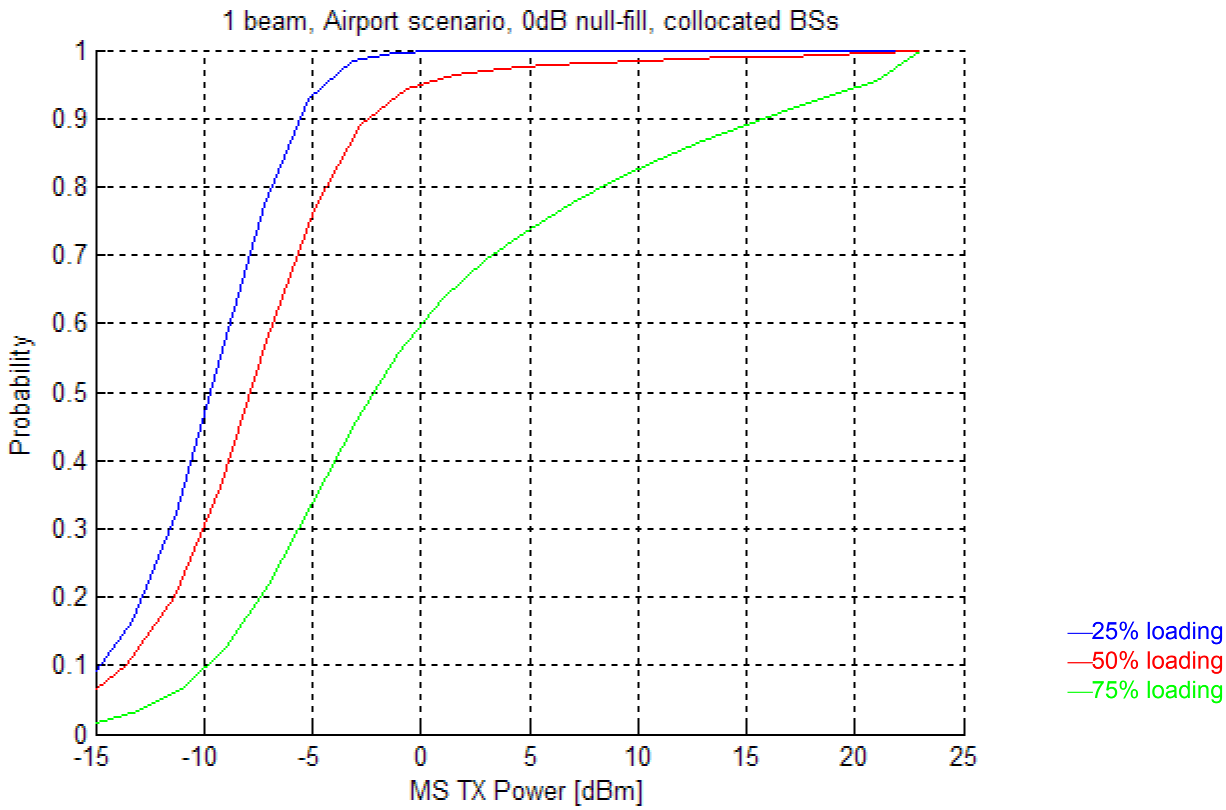

Figure 6.38. Reverse link transmitted power, Airport, 1 beam, 0dB null-fill, collocated BSs

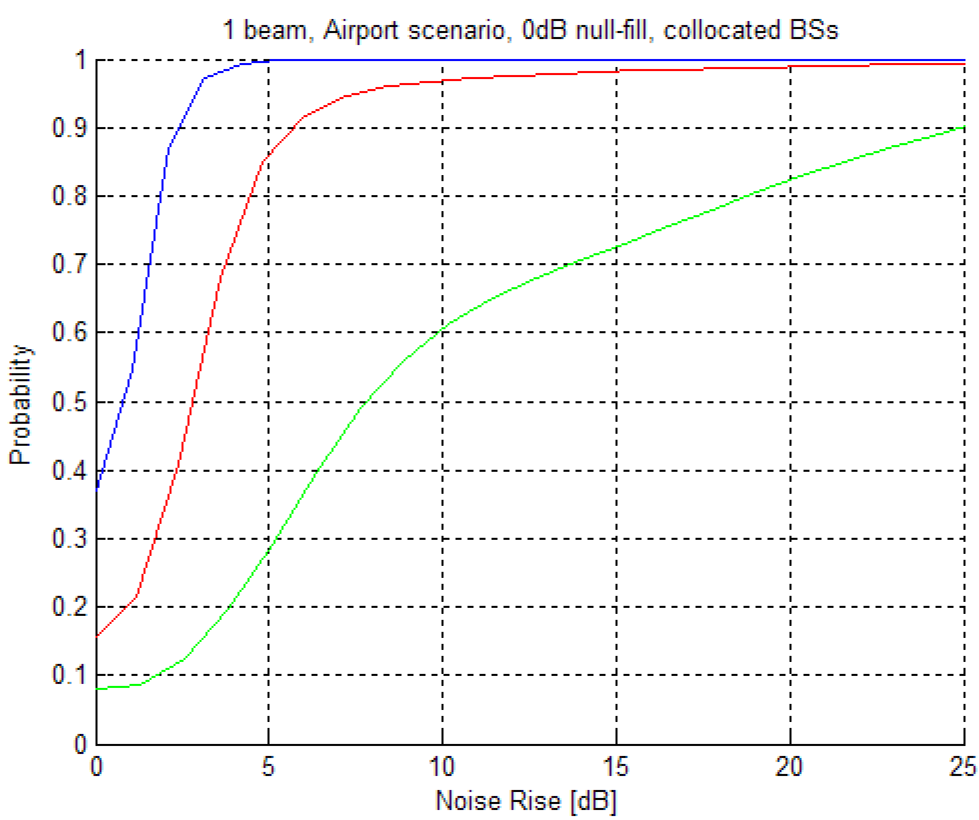

Figure 6.39. Noise rise, Airport, 1 beam, 0dB null-fill, collocated BSs

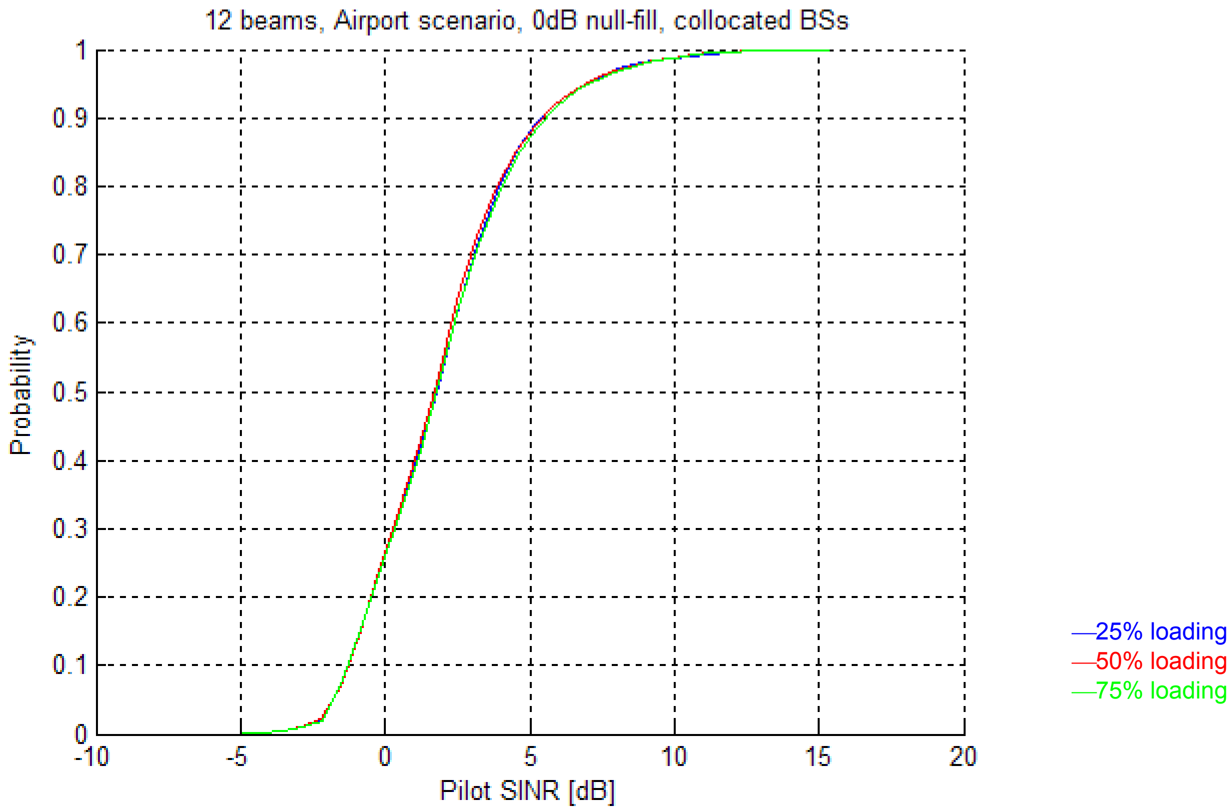

Figure 6.40. Pilot SINR, Airport, 12 beams, 0dB null-fill, collocated BSs

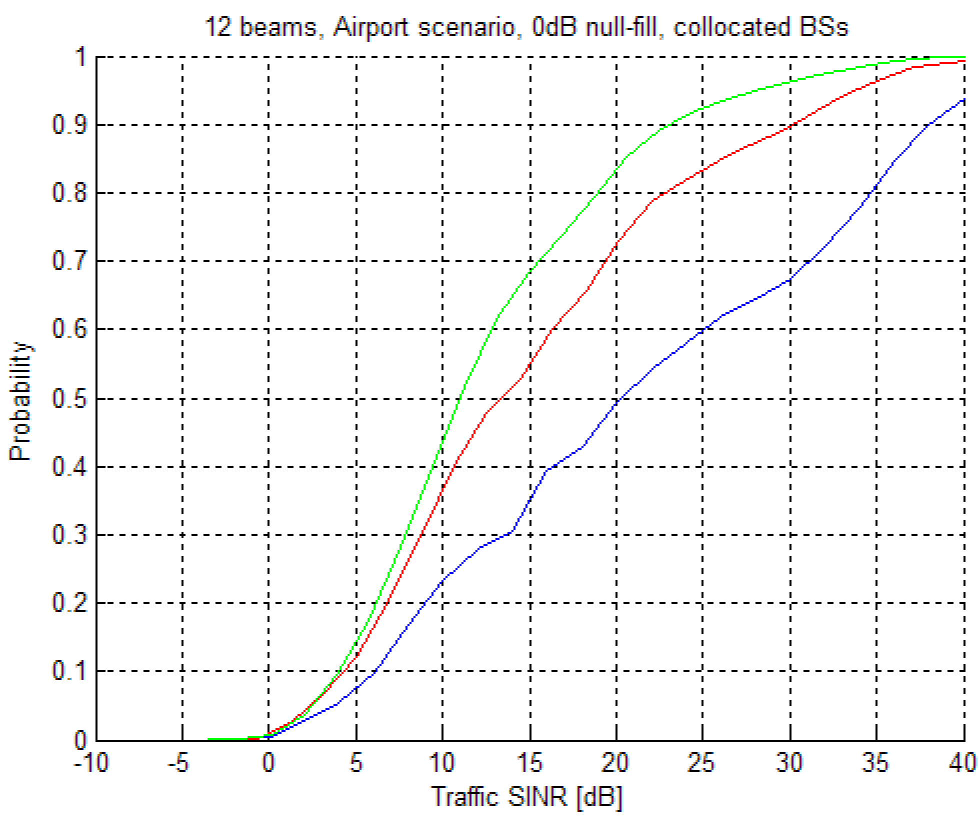

Figure 6.41. Traffic SINR, Airport, 12 beams, 0dB null-fill, collocated BSs

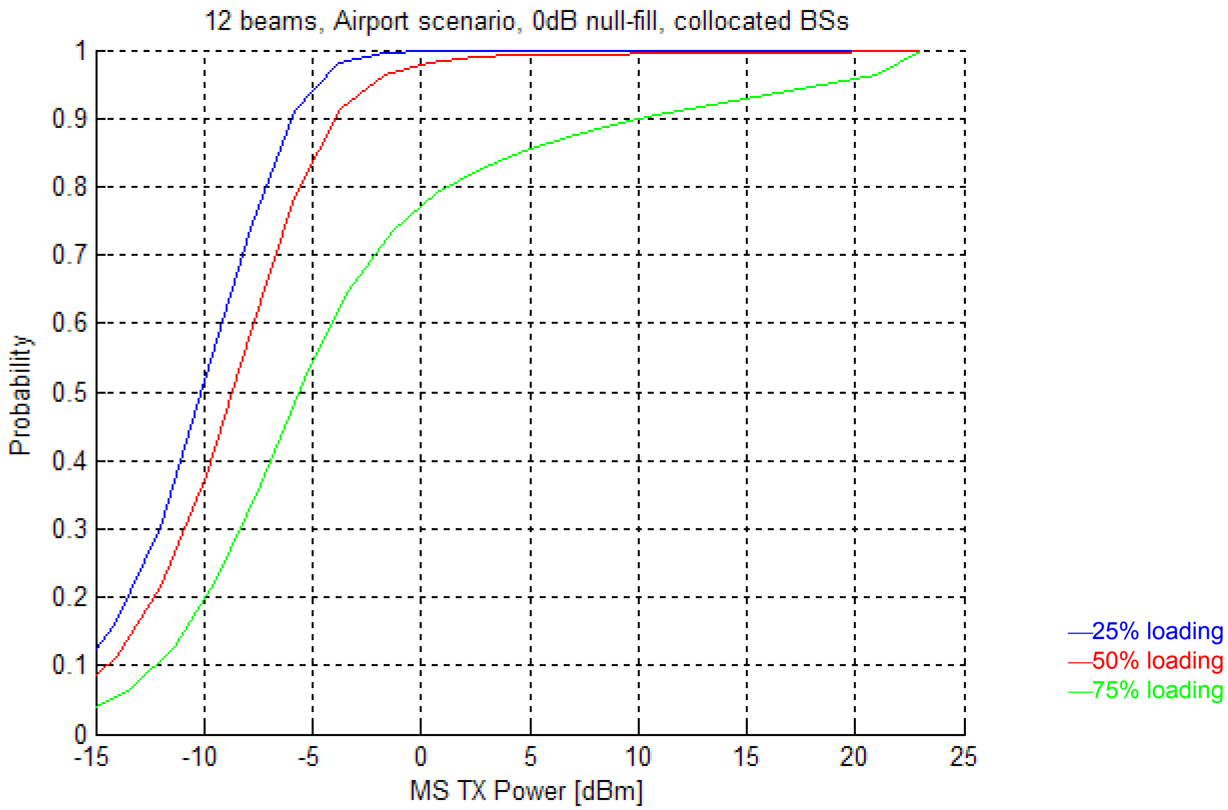

Figure 6.42. Reverse link transmitted power, Airport, 12 beams, 0dB null-fill, collocated BSs

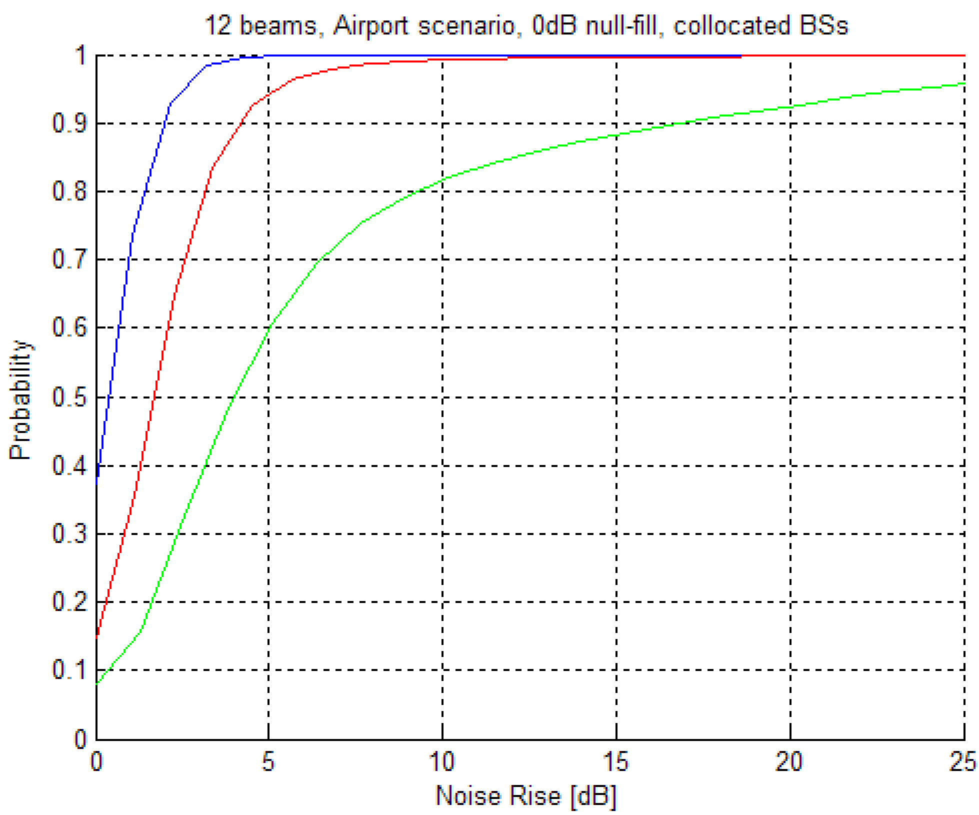

Figure 6.43. Noise rise, Airport, 12 beams, 0dB null-fill, collocated BSs

6.7. Summary

This section reports the analysis of inter-system interference resulting from spectral overlap of four CDMA systems deployed within ATG band. Based on the analysis of spectral plans presented in Section 4, one easily identifies two dominant interference types. They are listed as:

1. Type 1 (horizontal interference) – inter-system interference between co-polarized systems operating in a cross duplex mode.
2. Type 2 (vertical interference) – inter-system interference between co-duplex systems operating in cross-polarized mode.

Type 1 interference was thoroughly analyzed as a part of AirCells previous filing [1]. This analysis demonstrated that cross-duplex operation provides sufficient isolation for safe, cost effective and virtually interference free operation of two co-polarized systems. A minimum amount of interference may occur from the reverse link of one to the forward link of the other system. However, even in the worst-case scenario of systems operating around an airport and loaded up to 75% of the theoretical pole point, the degradation due to inter-system interference is very small. It results in throughput reduction of the forward link that is not larger than a few percent of its average value. The analysis of type 1 interference was not repeated in this report, however. Section 6.1, provides a brief review of the results of the analyses presented in great detail in [1].

Type 2 interference was comprehensively analyzed as a part of this report. To provide adequate analysis results, AirCell has build a custom 1xEvDO simulator using Matlab™ simulation platform. Numerous cases were analyzed and results of the analyses are reported in this section. A high level summary of the findings may be provided as follows:

- In the case of cross-country scenario the inter-system interference between two co-duplex, cross-polarized systems is very small. The performance parameters of both systems are within the range of typical 1xEvDO systems and can support loading of at least 75% of the theoretical pole point (c.f. Section 6.3).

- In the airport scenario, with base station antennas using –20dB null fills, polarization isolation alone is sufficient for interference free operation of cross-polarized system up to the 50% pole point loading (c.f. Section 6.4, Tables 6.8 to 6.10). For operation beyond 50% of the pole point loading either cell splitting or additional interference reduction need to be used.

- Vertical null filling of the base station antenna patterns was evaluated (c.f. Section 6.5). It has been demonstrated that when the nulls of the vertical pattern are reduced, two cross-polarized systems generate less inter-system interference. The case analyzed utilized 0dB null fills and the interference was reduced to the point that allowed safe operation of the cross-polarized systems even at 75% of the pole point loading.

- The use of switched beam antenna systems was evaluated in all cases considered. The use of such antennas has demonstrated benefits to the performance of the forward link traffic channel. Additionally, some improvements of the reverse link were noted as well. However, in cross-country scenario, regardless of loading and for the airport scenario with lighter loading, the use of switch beam antennas is not required.

The results presented in this section demonstrate the feasibility of sharing the ATG spectrum between four CDMA systems. By employing cross-duplexing and cross-polarization, the inter-system interference can be made very small and manageable in all cases of practical interest.

7. Summary and Conclusions

This report examined the viability of ATG spectrum sharing between four CDMA systems. The channel width of the CDMA systems was selected in accordance with cdma2000 1xEv standards as 1.25MHz. Since ATG provides only 2x2MHz of paired spectrum band, the CDMA systems cannot be isolated through frequency band separation, and for that reason alternative isolation methods needed to be considered. As a part of this report the following isolation methods were considered:

- *Cross-duplex system operation* –aircraft spacing and spatial isolation between ground base stations allows spectrum swap between transmit and receive frequency band for systems operating on the same polarization.

- *Using orthogonal polarization* – the systems operating in a co-duplex mode (i.e. transmit bands and receive bands for two systems are the same) are isolated through operation using orthogonally polarized EM waves. The orthogonal polarization provides at least 12dB of isolation between the signals.

- *Partial spectrum overlap* – to enhance isolation between some pairs of CDMA systems they are channelized with partially overlapping spectra.

- *Switched-beam antenna deployment at base stations* – deployment of switch beam antennas increases isolation on the forward link.

- *Null filling of base station antenna patterns* – the use of antenna patterns with significant gain at larger elevation angles helps in the reduction of interference in airport scenarios.

Judicious use of the above listed isolation methods along with proper spectrum partitioning allows deployment of four CDMA systems. The spectrum migration in the four-carrier deployment scenario can be summarized as follows:

- Two carriers using the same polarization are isolated through operation in cross duplex mode. Based on results reported in [1], this allows for virtually interference free operation in all scenarios of practical interest.

- Two carriers that are operating in a co-duplex mode are separated through orthogonal polarization.

- Additional isolation based on the partial spectrum overlap is used for both cross-polarized and cross-duplexed systems. This is accomplished through Spectral Plan 2 described in Section 4.

- In the cross-country deployment and in low loading airport deployment, cross-duplex and cross-polarization operation provides sufficient isolation for safe and interference free operation of the four systems (c.f. Section 6.3 and 6.4).

- In high loading airport deployment addition of null filled antennas allows interference free operation (c.f. Section 6.5)

- Use of the above listed technologies is sufficient to provide interference free operation of deployed CDMA systems up to 75% of their theoretical pole point capacity (c.f. Section 6).

Given the public benefit will be served by adopting this spectrum migration concept, and that this concept is technically viable through engineering means of modest complexity, AirCell strongly recommends that the FCC adopts this proposal in timely fashion.

8. References

[1] I. Kostanic and D. McKenna, *Evaluation of the ATG Spectrum Migration Concept*, Aircell technical report presented to FCC, March 10, 2004.
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[10] Boeing proposal for ATG FNPRM, Presented to WTB, March 2004.

Appendix A: Inter-aircraft Path-loss Isolation Measurements

The path loss isolation between two flying aircraft is an important input parameter for modeling of the inter-system interference in a cross-duplex scenario. In the previous FCC filing [1], AirCell has assumed the worst-case scenario in which the isolation depends only on the separation between the aircraft. In reality, due to the antenna pattern effects and shielding coming from the body of the aircraft, the path loss isolation can be expected to be significantly larger.

To determine the path loss isolation value between flying aircraft, AirCell has performed a series of flight tests. The tests were performed over western Nebraska and they involved a pair of aircraft equipped with standard AirCell ATG communication equipment. The first aircraft was operating a CW transmitter with fixed transmit power of 17.24dBm. The frequency of transmission was set to 844.35MHz (Cellular band channel 645). The second aircraft was equipped with a Grayson CW cellular receiver, which was set to provide raw power measurements on the transmission channel. Knowing the transmit power and measuring the received power, AirCell was able to determine the value of path loss isolation with an accuracy level of approximately 1dB.

Figure A1 presents the flying routes of the two aircraft involved in the test. The first aircraft flew along the blue route while the second aircraft followed the red one. As seen in Fig. A1, the aircraft were flown very close to one another. The vertical separation between aircraft was kept at approximately 1000 feet. While vertical separation was kept the same value, horizontal separation was varied. At about the middle point of the route, two aircraft exchanged leading positions. Therefore during the flight, the aircraft covered wide range of relative distances, viewing angles and mutual positions.

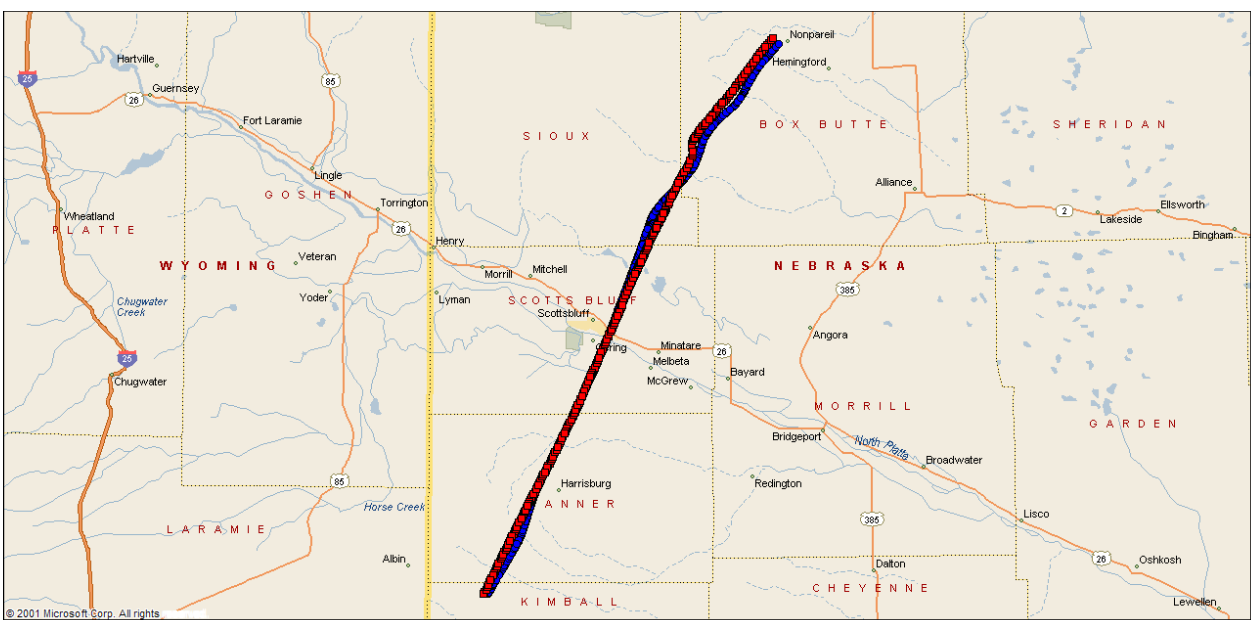

Figure A1. Flight routes for the two planes involved in the aircraft path loss isolation tests

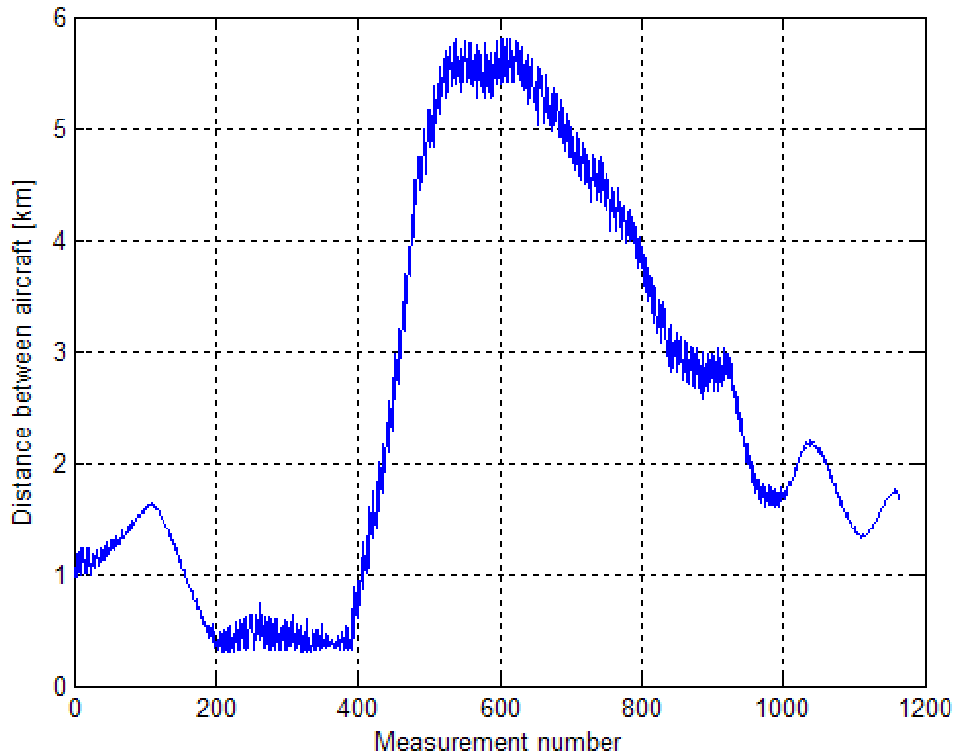

Figure A2. Distance between the aircraft during the flight tests

Approximately 1200 measurements were taken during the experiment. The plot of distance between the aircraft during the measurement time is presented in Fig. A2. It is evident that a large number of measurements were taken at distances smaller than 3 miles (4.82km), which is usually assumed as the closest proximity between aircraft in real world scenarios. The "high frequency" component showing distance variations in Fig. A2 can be attributed to slight inaccuracies in the GPS reading. Due to unbiased and zero mean nature of this component, its effects on the overall measurement accuracy can be neglected.

Results

The scatter plot of the measured aircraft-to-aircraft isolation is presented in Fig. A3. The red line in the plot represents the isolation obtained under assumptions of isotropic aircraft antennas and free space propagation. As seen, the measured path loss is almost always greater than the one predicted by the red line. The only exceptions are several points recorded at distances of approximately 5.5 km. For those points, the path loss between the transmitter-receiver pair is slightly smaller due to gain of the aircraft antennas. At distance of 5.5km, two aircraft are practically at elevation angles of approximately zero with respect to each other. Therefore, the aircraft antenna gains are at their maximum values. This produces a link budget gain of approximately 4dB, which occasionally reduces the overall isolation to a value slightly smaller than that of free space propagation. However, even for distances above 5.5km, vast majority of measurements show path losses that are well above that of free space.

For measurement points where two aircraft are at distances smaller than 4km, one notices that the path loss isolation exceeds free space by a significant margin. The margin is due to combined effects of the aircraft antenna pattern and shielding from an aircraft body. The effect is especially pronounced at the shortest distances.

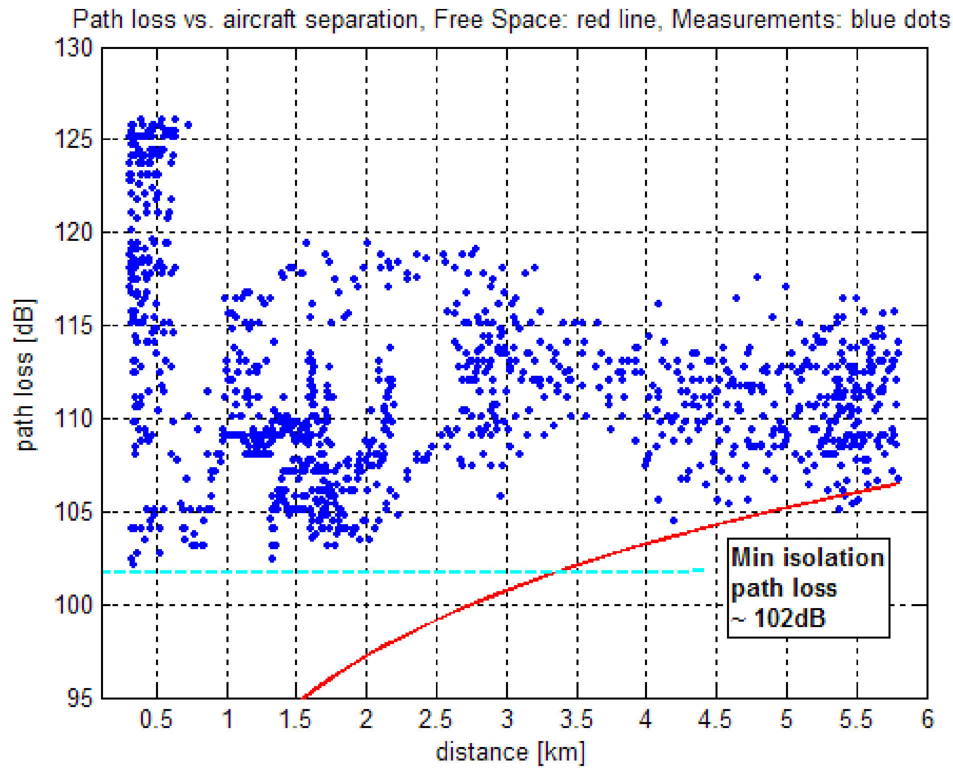

Figure A3. Measurements of the path loss isolation between aircraft

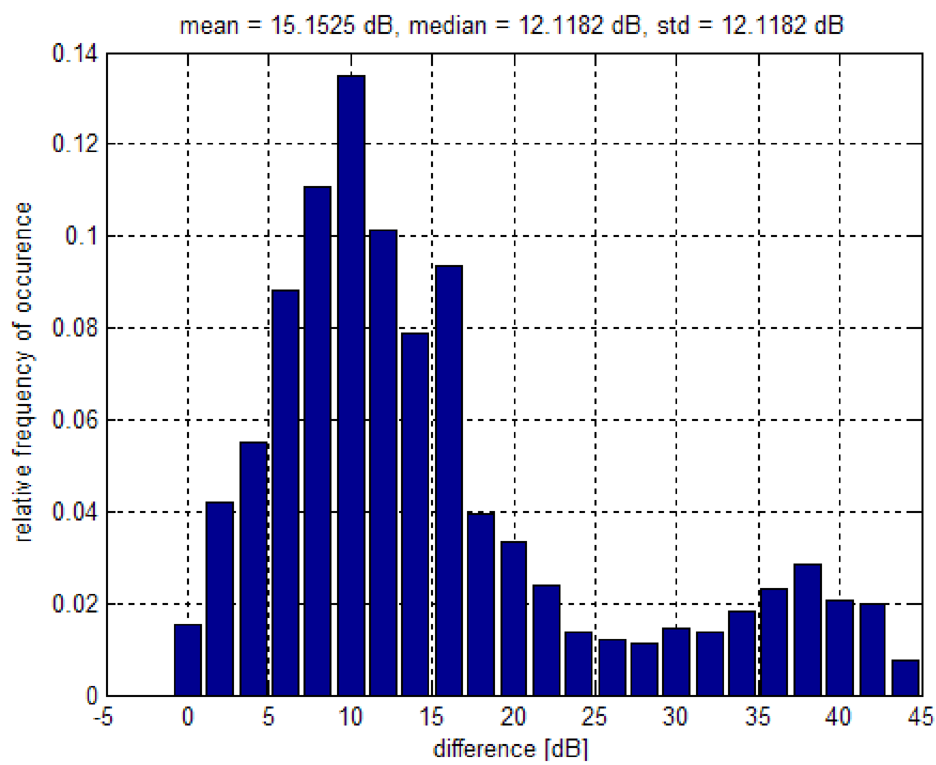

Figure A4. Normalized histogram of additional isolation due to antenna pattern and aircraft body

The normalized histogram of the difference between measured path loss and the one predicted by the free space propagation is presented in Fig. A.4. As seen the distribution of the additional loss is quite irregular. One may speculate that the exact value of this loss is highly dependent on the type of antenna, type of the aircraft and the flight pattern. Nevertheless, the additional loss is quite significant with median value of 12dB and occasional values exceeding 45dB. Furthermore, from Fig. A3, it is readily observed that the additional loss becomes larger as the aircraft are closer to each other. This essentially imposes a lower limit on the isolation loss of 102dB for all aircraft distances. In other words, even though the aircraft were flown at minimum horizontal separation of less than 500m, from the free space path loss point of view, they were never closer than 3.5 km.

Appendix B: Study of the Aircraft Density Around Major Airports

In its previous filings to the FCC [1] and this report, AirCell has analyzed various options for migration of the existing ATG spectrum to high capacity broadband services. Each of the analyzed scenarios assumed deployment of wideband CDMA technologies with channel bandwidth of 1.25 MHz. To provide clearer presentation of the simulation results, AirCell has identified two typical operational scenarios. They are listed as follows:

1. *Cross-country scenario*. This scenario models system deployment over large geographical areas located far away from major airport hubs. This scenario is characterized with large cells and relatively low aircraft density. Both [1] and this report demonstrate that in the case of cross-country scenario, a successful system deployment depends more on the link budget than on mutual inter-system interference.

2. *Airport Scenario*. The airport scenario models system deployment around major airports. This scenario is characterized with smaller cells and higher aircraft density. Since cells are small, link budget requirements are always satisfied. As a result, the most important limiting factor becomes the interference created either between systems or internal to each one of the systems.

The analysis of created interference requires knowledge of the aircraft density. Simulations presented in this report and in [1] were assuming various levels of system loading relative to the theoretical pole point of deployed systems. The nominal translation between the system loading and number of aircraft within the airport's area (for four system deployment), is provided in Table B1[4].

Table B1. Nominal translation between system loading and number of aircraft within the Airport area (Four-system deployment).

Loading [%]	# Aircraft /system	Total # of aircraft
25	12	48
50	24	96
75	36	144

For the airport scenario, all simulations have demonstrated significant dependence between the performance of deployed systems and number of aircraft within the airport area. For that reason, it is of a great importance to compare the assumptions on the aircraft density used in AirCell simulations to the actual one.

Description of Input data

To verify the assumptions on the aircraft density used in the simulations, AirCell has acquired one week of flight information for the entire US. The aircraft flight data was obtained from [8] and it covers the period between May 23rd and May 30th 2002. The data provides location of all

[4] Numbers based on 1xEvDO deployment. Details of the pole point derivation can be found in [1].

airborne aircraft above the continental US during the one-week timeframe. For the analysis of aircraft flight data, the airport area is defined as a circle with a 30-mile radius centered on the airport. This is slightly larger than the 25-mile radius used in the AirCell simulations. This is done deliberately to make sure that provided results give a somewhat conservative (i.e. higher), estimate of the aircraft density. The airports chosen for the analysis are selected in a manner consistent with a list of the ten busiest airports provided in [9]. The location information for the analyzed airports is provided in Table B.2.

Table B2. Ten busiest airports in the USA

Airport City	Airport	Latitude	Longitude
Atlanta	ATL	33.64121	84.44000
Chicago	ORD	41.97948	87.90407
Los Angeles	LAX	33.94252	118.40910
Dallas / FT Worth	DFW	32.89544	97.04256
Denver	DEN	39.85322	104.67405
Phoenix	PHX	33.43653	112.00960
Las Vegas	LAS	36.08517	115.15124
Houston	IAH	29.98844	95.34191
San Francisco	SFO	37.61821	122.38072
Minneapolis	MSP	44.88341	93.21096

Results

The summary of the results obtained for the ten airports is provided in Table B3.

Table B3. Results – Summary

Airport	Average	Max	67%	95%	< 48 [%]	< 96 [%]	< 144 [%]
ATL	53	123	78	102	38.65	91.78	100
ORD	59	134	87	115	40.45	75.35	100
LAX	57	134	84	113	40.45	77.78	100
DFW	52	139	73	113	43.97	86.38	100
DEN	28	97	39	62	78.72	99.84	100
PHX	30	75	43	64	74.26	100	100
LAS	26	61	37	51	90.38	100	100
IAH	32	91	48	75	65.73	100	100
SFO	36	90	52	73	61.58	100	100
MSP	24	69	34	57	82.55	100	100

The columns of Table B3 are interpreted as follows:

Airport - Three letter airport code.
Average - Average number of aircraft within a 30 mile radius.
Max - Maximum number of aircraft within a 30 mile radius during the processed time period.
67% - 67th percentile for the number of aircraft within 30 mile radius around the airport.
95% - 95th percentile for the number of aircraft within 30 mile radius around the airport.

<48 [%] - Probability expressed in % that the number of aircraft within 30-mile radius will be smaller that 48. Note that 48 corresponds to 25% of the pole point for the four CDMA system deployment.

<96 [%] - Probability expressed in % that the number of aircraft within 30-mile radius will be smaller that 96. Note that 96 corresponds to 50% of the pole point for the four CDMA system deployment.

<144 [%] - Probability expressed in % that the number of aircraft within 30-mile radius will be smaller that 144. Note that 144 corresponds to 75% of the pole point for the four CDMA system deployment.

From Table B3, the following may be observed:

1. The airports can be divided into two tiers. The first tier airports are ATL, ORD, LAX and DFW. On average, for the first tier airports, slightly more than 50 aircraft within 30-mile radius are expected. The remaining six airports in Table B2 are considered the second tier airports. For the second tier airports, the average number of aircraft within a 30-mile radius ranges between 24 and 36.
2. Comparing entries in Table B3 with loading numbers given in Table B1, it can be seen that all second tier airports operate well below a nominal 50% loading point. The only exception is DEN, which exceeds a 50% loading point only a fraction of one percent of the time.
3. The first tier airports operate below a 50% nominal loading point, a vast majority of time.
4. The first tier airports operate below a 75% nominal loading point all of the time.

When interpreting results given in Table B3 one should keep in mind that they are obtained for *all* aircraft located around the airport. Therefore, both passenger and commercial cargo aircraft are counted. Even though at this time one can only speculate about communication needs for different aircraft types, it is reasonable to assume that the traffic generated by cargo aircraft would be relatively small. This reduces the number of "equivalent aircraft" for AirCell simulations. Furthermore, the numbers presented in Table B.3 include aircraft at all altitudes. Assuming that the aircraft below 10,000 feet require no (or much less) service, the number of equivalent aircraft may be reduced even further. As a result, in a four-system deployment, one may never encounter airport loading which is significantly above 50% of the pole point at *any* airport within the continental US.

A typical variation of airport traffic (expressed in the number of aircraft), for one of the airports is presented in Fig. B1. The PDF and CDF curves for all airports from the list given in Table B2 are presented in Figs B2 to B11.

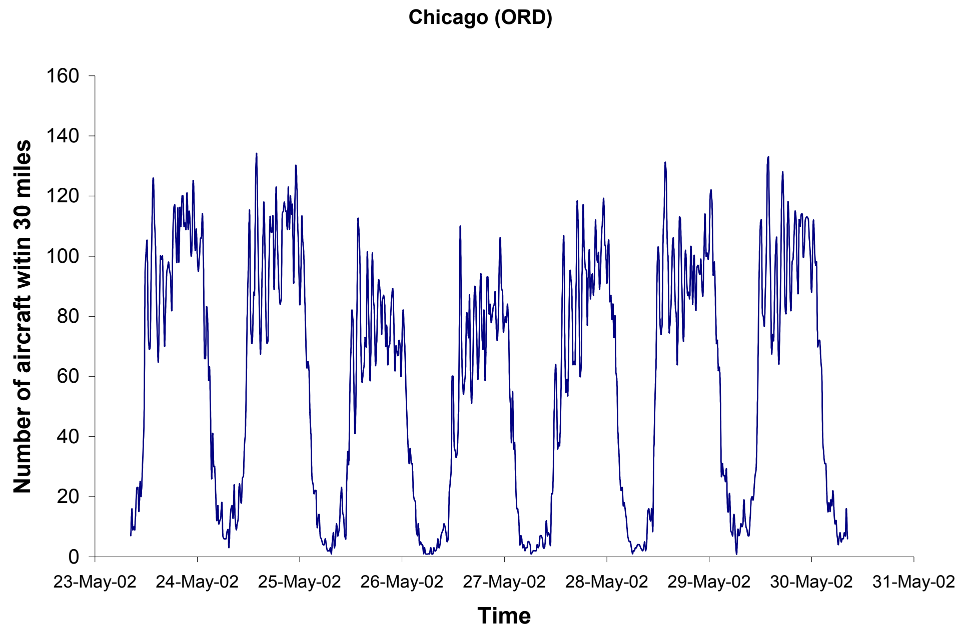

Figure B1. Typical weekly variations in the number of aircraft within a 30-mile radius around Chicago (ORD). Dates are given with respect to Greenwich Mean Time (GMT 0).

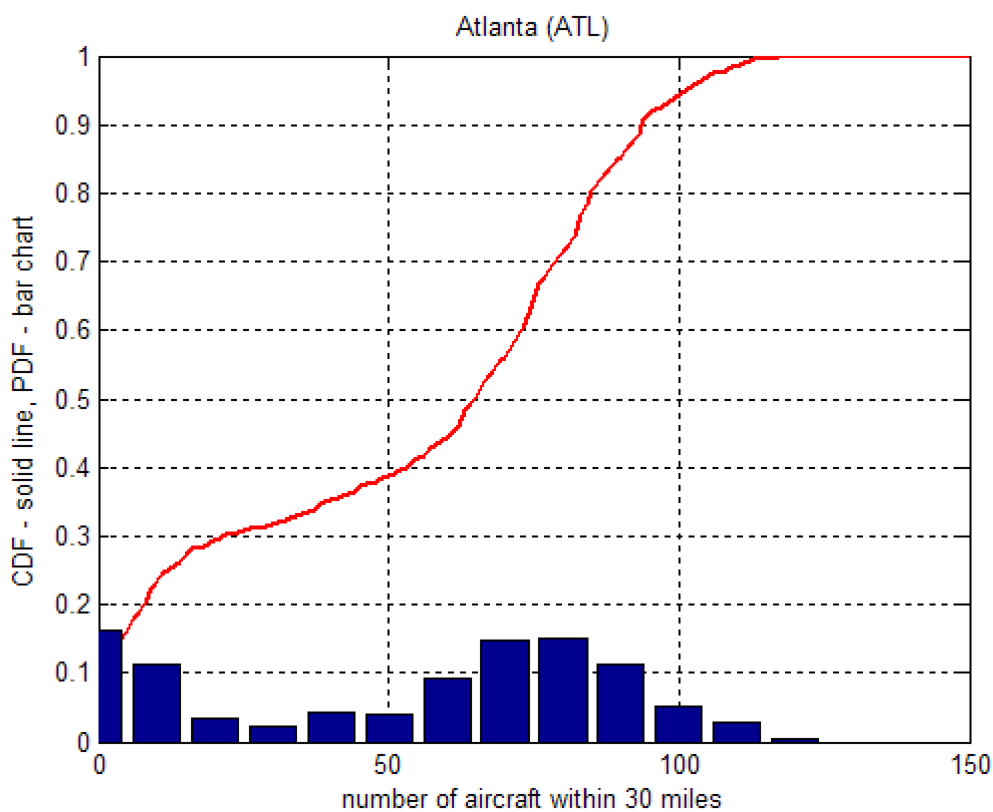

Figure B2. CDF and PDF for the number of aircraft - Atlanta

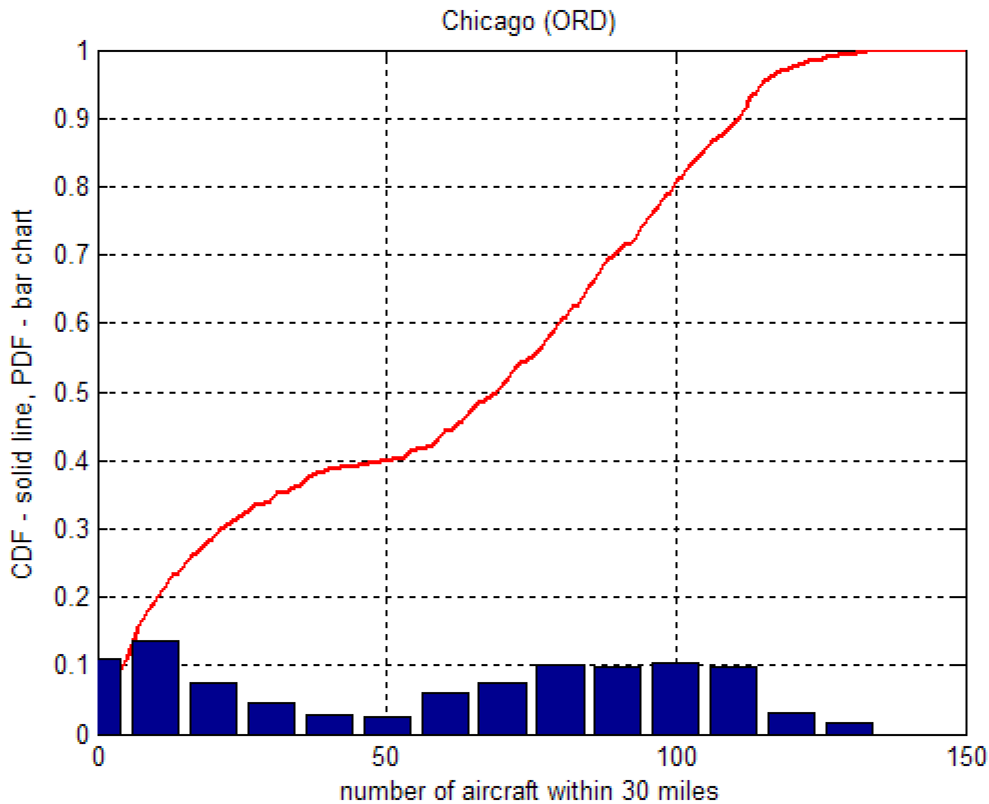

Figure B3. CDF and PDF for the number of aircraft - Chicago

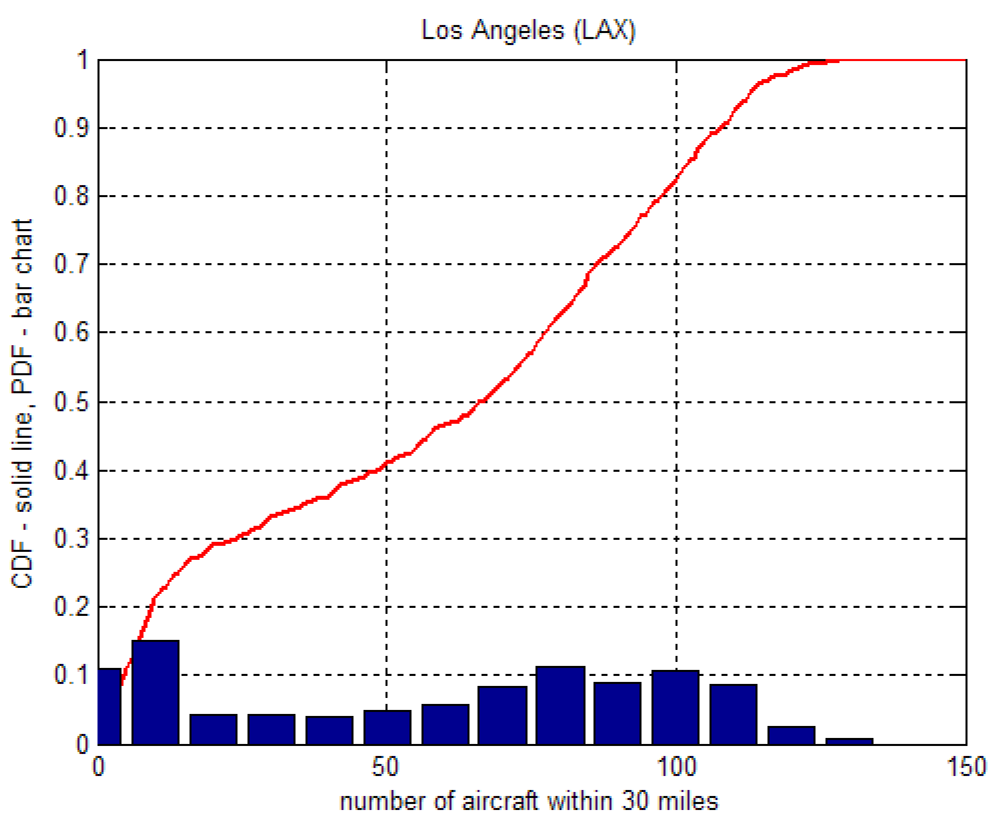

Figure B4. CDF and PDF for the number of aircraft - Los Angeles

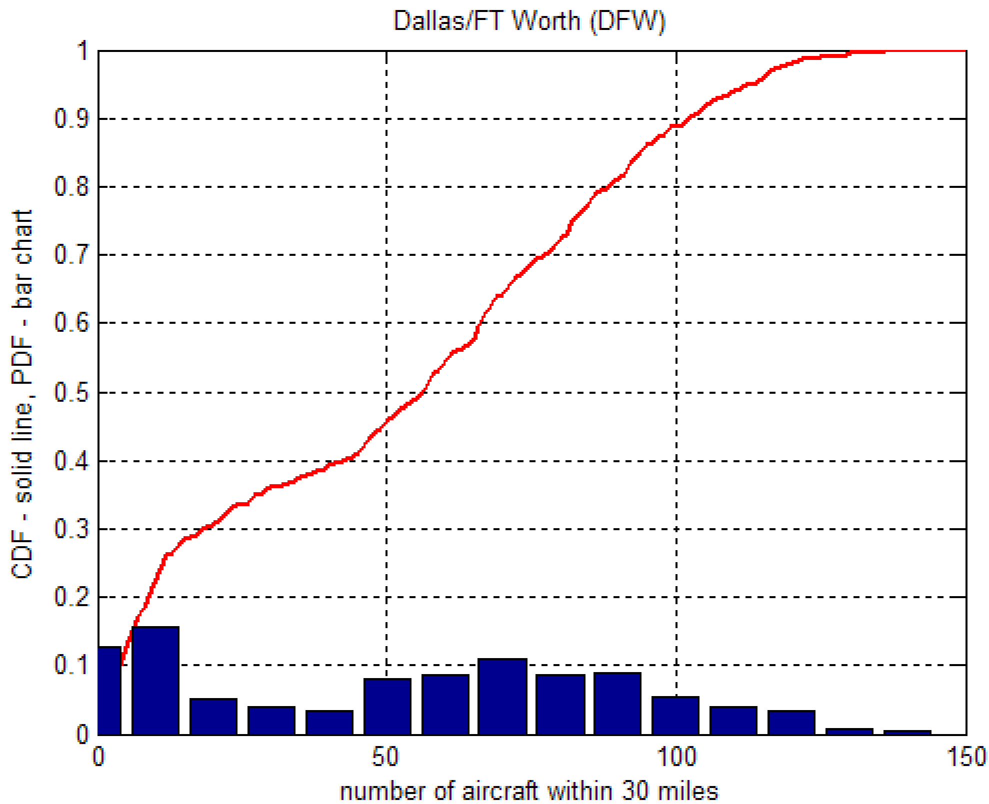

Figure B5. CDF and PDF for the number of aircraft - Dallas / FT Worth

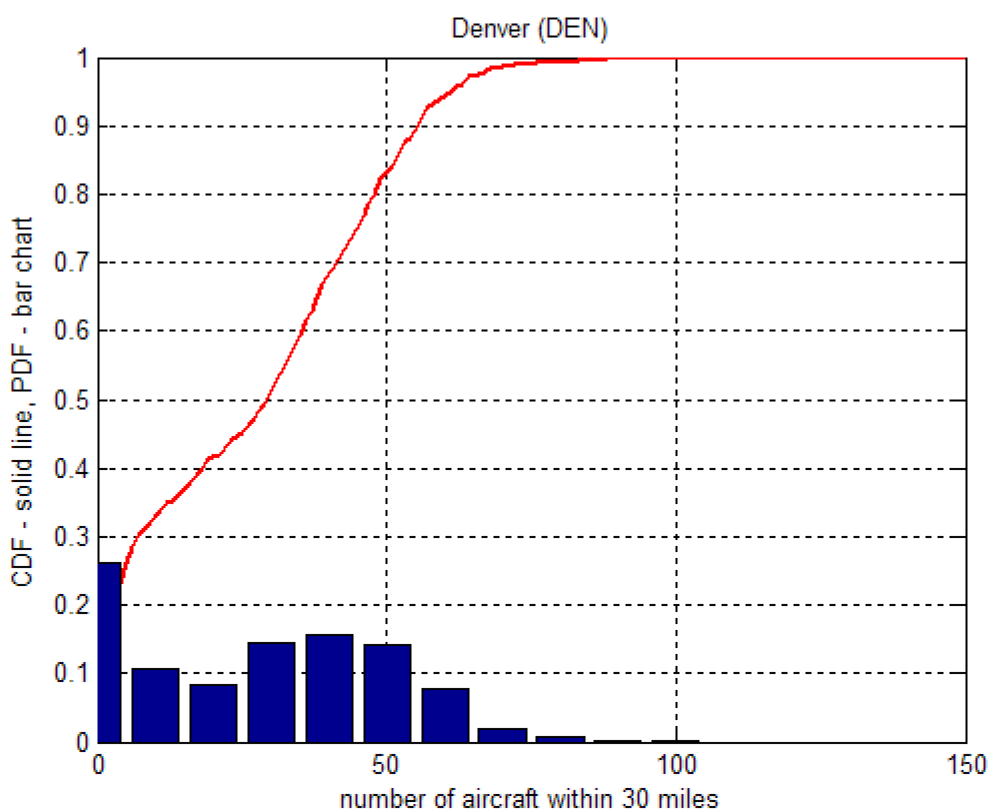

Figure B6. CDF and PDF for the number of aircraft - Denver

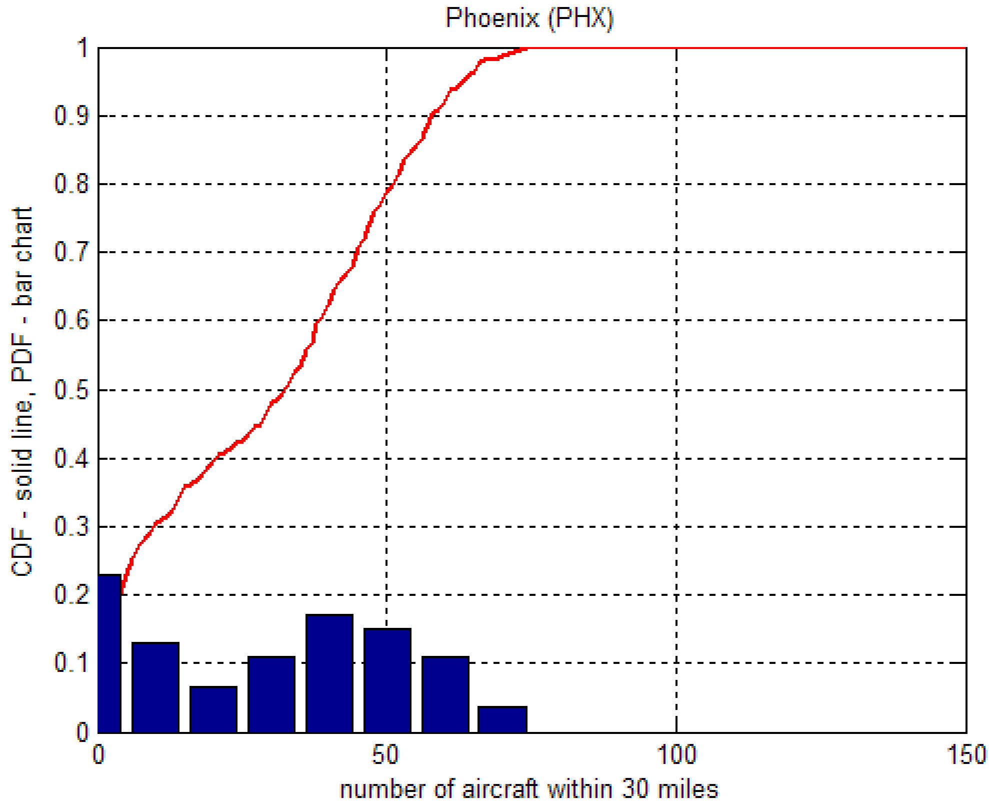

Figure B7. CDF and PDF for the number of aircraft - Phoenix

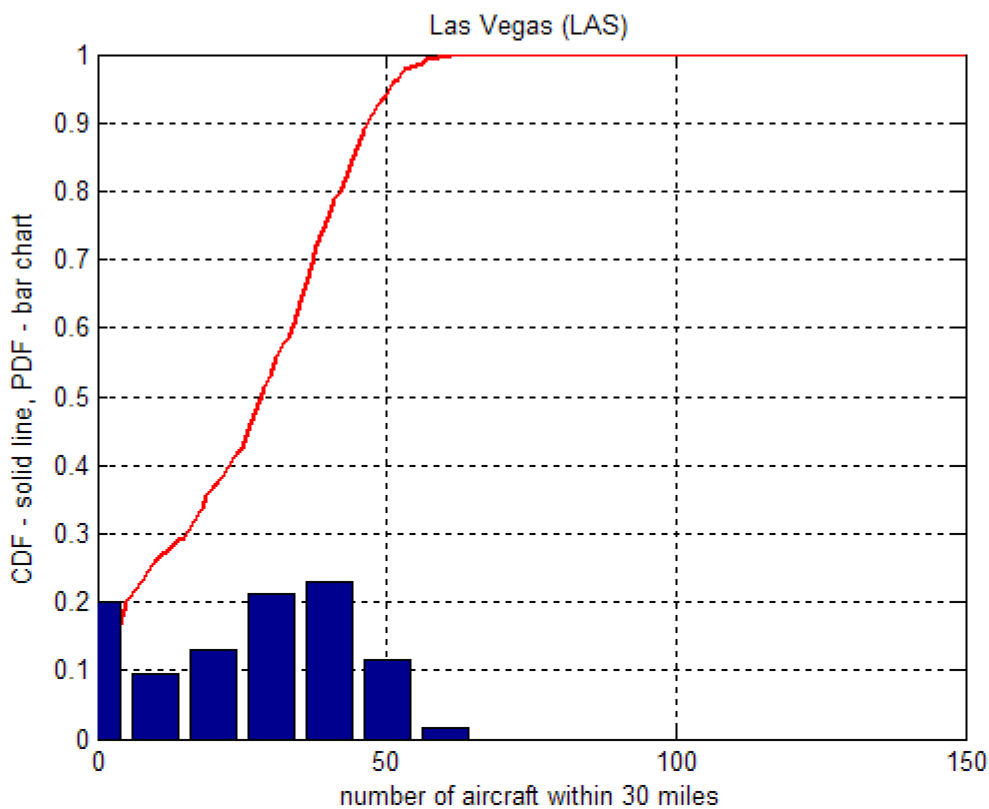

Figure B8. CDF and PDF for the number of aircraft - Las Vegas

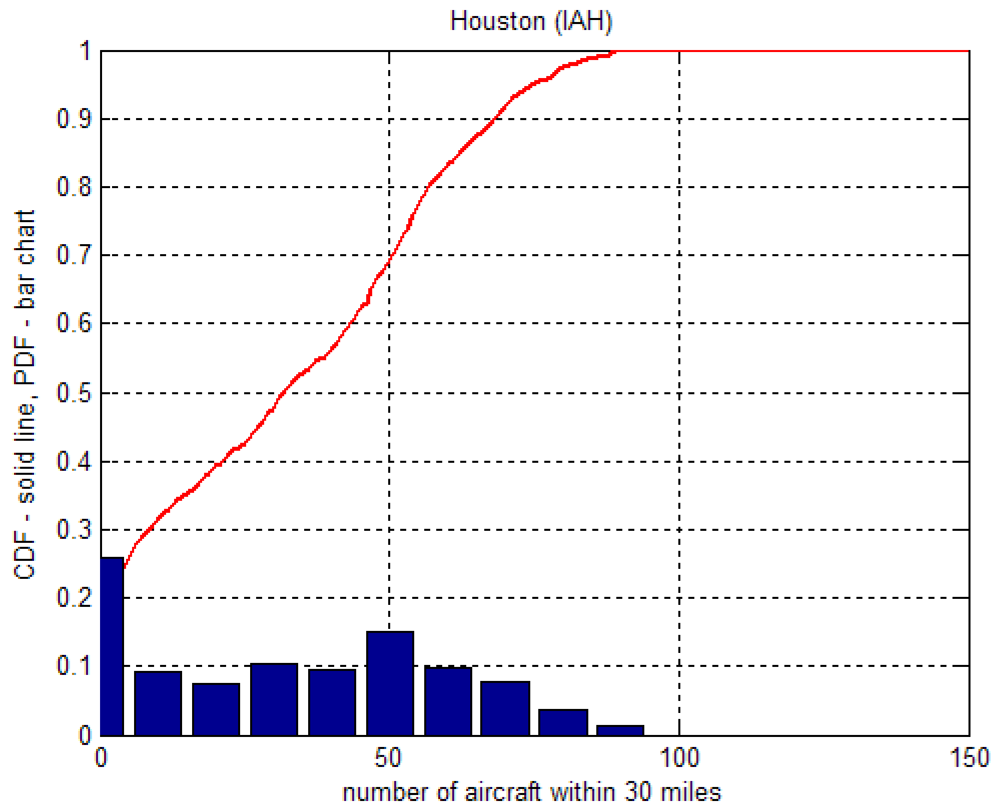

Figure B9. CDF and PDF for the number of aircraft - Houston

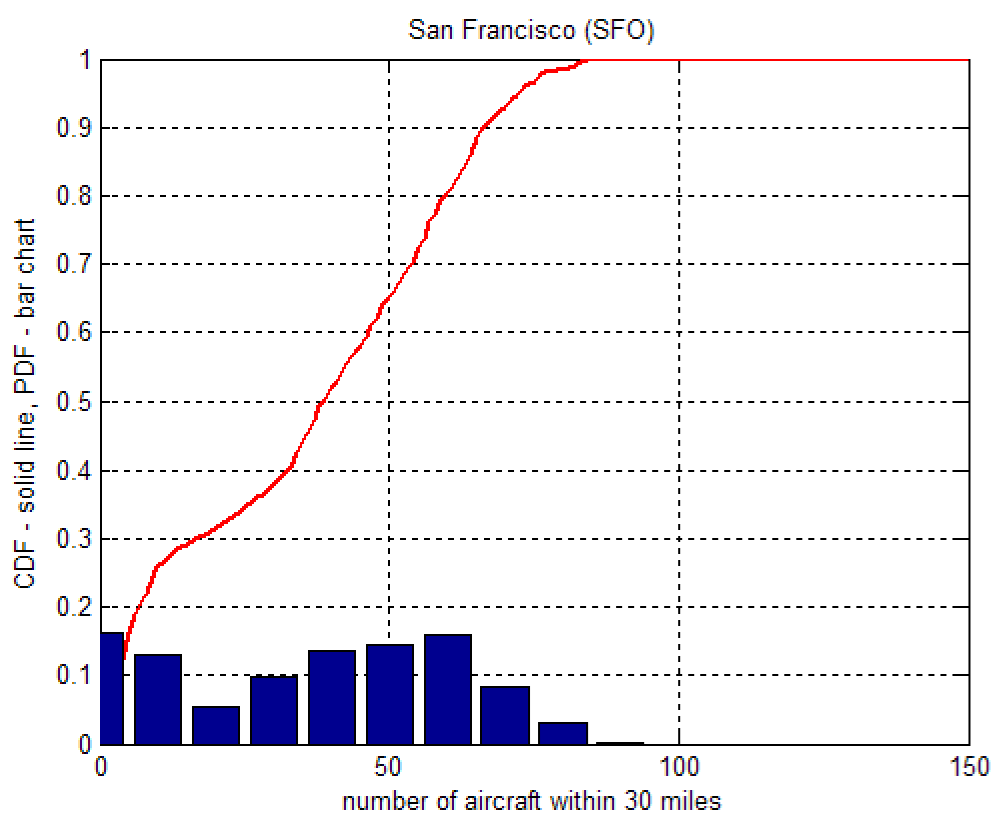

Figure B10. CDF and PDF for the number of aircraft - San Francisco

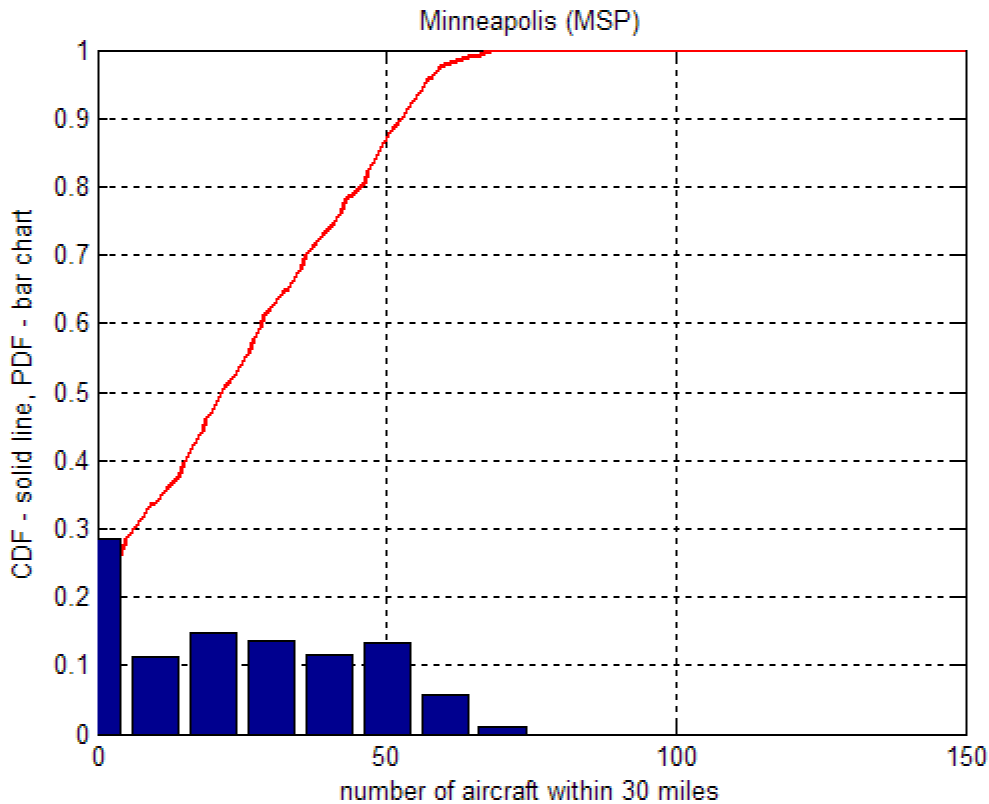

Figure B11. CDF and PDF for the number of aircraft – Minneapolis

Appendix C: Analysis of Base-to-Base Interference

In a cross-duplex deployment of two ATG systems, interference may occur on aircraft-to-aircraft or base-to-base radio paths. The aircraft-to-aircraft interference is the more complex of the two, and it was thoroughly analyzed through simulations presented in [1]. It was shown that in all cases of practical interest, this interference remains very small. The aircraft-to-aircraft interference is limited by exiting FAA regulations that dictate minimum separation between flying aircraft.

This section presents an analysis of the base-to-base interference and methods that can be used for its mitigation. For the sake of consistency with [1] and other sections of this report, the analysis of the base-to-base interference is presented for two typical operating scenarios: the cross-country scenario and the airport scenario.

Cross-country scenario

The cross-country scenario is based on a typical system operation in areas of the country that are far away from airports and major metropolitan centers. This scenario is characterized by a relatively large spacing between the cell sites. In the test bed system used for analyses presented in [1] and this report, the average cell radius in the cross-country deployment is assumed as 100 miles. Therefore, in the case of the test bed system (See Fig. 5.1), the least separation between base stations of the two systems can be calculated as

$$D_{\min} = 2R\sin(\pi/8) = 2 \cdot 100 \cdot 0.3827 \approx 76.54 \text{ miles} \tag{C.1}$$

In an actual deployment, the distances between base stations of the two systems will vary. However, it is safe to assume that they can be maintained at large distances. Under such circumstances the radio path between two adjacent base stations belonging to two systems will be obstructed by terrain and earth curvature. The terrain obstruction introduces large attenuation losses and, coupled with free space losses, effectively eliminates the potential for interference.

Consider the case of two base stations depicted in Fig. C.1. The tower with height h_1 belongs to first system, while the tower with height h_2 belongs to second one. When there is a sufficient distance between the towers, the radio path between them becomes obstructed by terrain and the interference is eliminated. The distance at which the obstruction by terrain happens depends on the height of base station towers. It can be calculated in the following manner.

With reference to Fig. C.1, one can write:

$$\cos(\theta_1) = \frac{R_E + c}{R_E + h_1}, \qquad \text{and} \qquad \cos(\theta_2) = \frac{R_E + c}{R_E + h_2} \tag{C.2}$$

where R_E is the effective radius of the Earth. (Due to refraction of radio waves, the effective radius of the Earth is roughly 4/3 of than the physical radius).

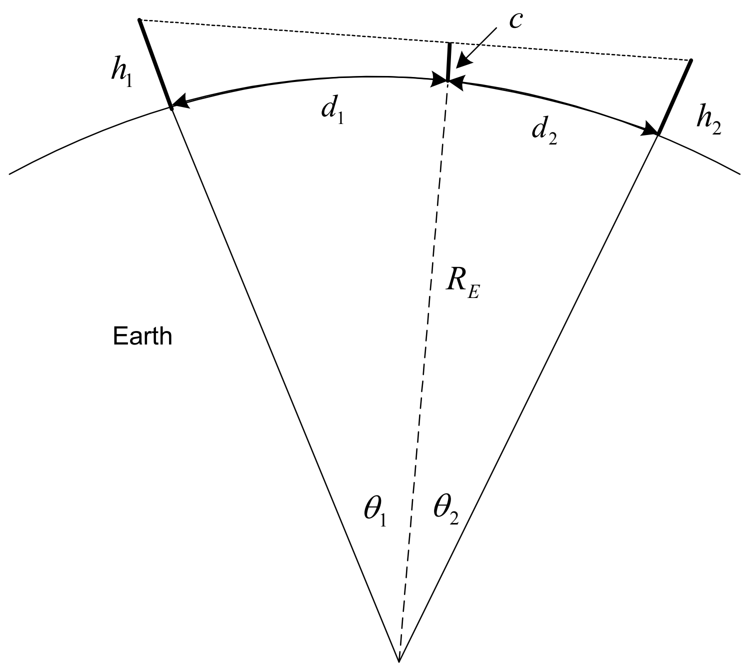

Figure C.1. Geometry for computation of LOS conditions between a pair of base stations

At distance $d = d_1 + d_2$ for which the Earth's bulge obstructs the radio path, $c = 0$ and one obtains:

$$\cos(\theta_1) = \frac{R_E}{R_E + h_1}, \qquad \text{and} \qquad \cos(\theta_2) = \frac{R_E}{R_E + h_2} \tag{C.3}$$

Therefore,

$$\theta_1 = \cos^{-1}\left(\frac{R_E}{R_E + h_1}\right), \qquad \text{and} \qquad \theta_2 = \cos^{-1}\left(\frac{R_E}{R_E + h_2}\right) \tag{C.4}$$

At the same time,

$$\theta_1 = \frac{d_1}{R_E}, \qquad \text{and} \qquad \theta_2 = \frac{d_2}{R_E} \tag{C.5}$$

Combining (C.4) and (C.5), one obtains

$$d = d_1 + d_2 = R_E \cdot (\theta_1 + \theta_2) = R_E \cdot \left[\cos^{-1}\left(\frac{R_E}{R_E + h_1}\right) + \cos^{-1}\left(\frac{R_E}{R_E + h_2}\right)\right] \tag{C.6}$$

or

$$d = R_E \cdot \left[\cos^{-1}\left(\frac{1}{1 + h_1 / R_E}\right) + \cos^{-1}\left(\frac{1}{1 + h_2 / R_E}\right)\right] \tag{C.7}$$

The use of (C.7) can be illustrated through a simple example.

Example C.1. Consider two base station towers having equal heights $h_1 = h_2 = 150$ ft. Using the effective Earth radius of 5328 miles, the distance in (C.7) can be calculated as

$$d = 5328 \cdot 2 \cdot \cos^{-1}\left(\frac{1}{1+\frac{150/5280}{5328}}\right) \approx 34.8 \text{ miles} \tag{C.8}$$

Therefore, if such base stations (with 150 ft towers) are separated by more than 35 miles, Earth curvature becomes a dominant source of signal attenuation.

Equation (C.7) was used to generate a series of curves presented in Fig. C.2. The curves provide relationship between heights of the base station towers and minimum distance for which they are below each other's radio horizon. From Fig. C.2, one notices that for all reasonable base station heights, the distance required for non-LOS propagation is well below the nominal spacing calculated in (C.1). Therefore, in typical cross-country deployment, one expects to find majority of base stations separated so that they are below each other's radio horizon.

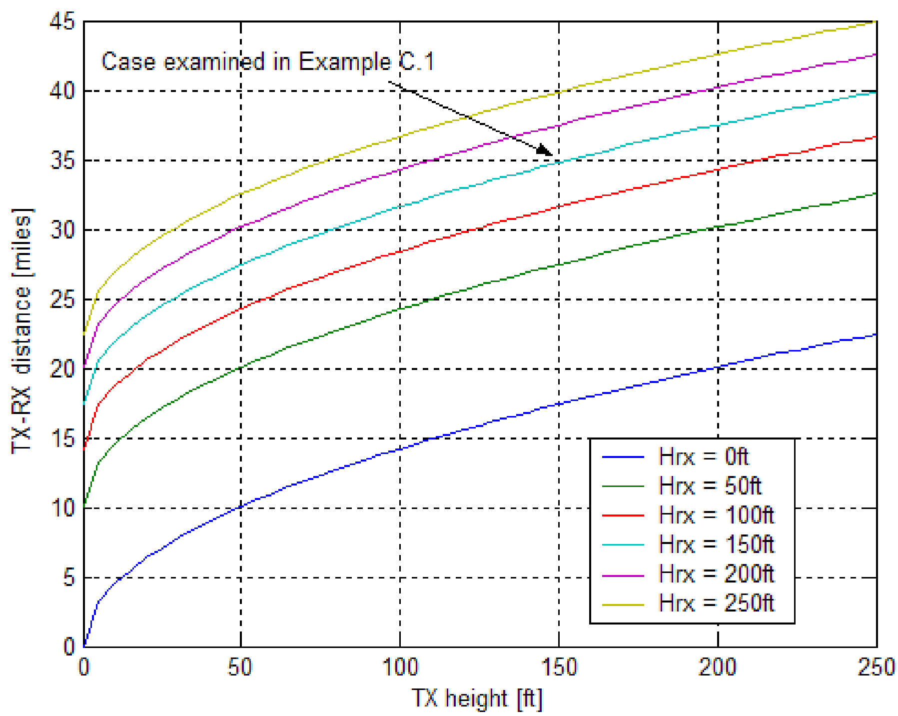

Figure C.2. Minimum distance between base stations obstructed by terrain

As a final remark, one notices that derivations leading to (C.7) are conservative for at least two reasons.

1. The attenuation due to terrain blockage occurs before the LOS is completely obstructed. As path clearance approaches zero (a grazing path), significant diffraction losses need to be added to the radio propagation path loss. Diffraction losses depend on the actual shape of terrain, and are typically in the range of 6-12 dB at grazing. A simple way to approximate these losses under assumption of the *knife-edge* like terrain obstructions can be found in [7].

2. These calculations assume that Earth can be approximated as a smooth sphere. In practice, terrain features, vegetation and man made structures may provide significant radio path attenuation even in cases when radio path is not obstructed by terrain. In such cases, base stations can be placed at distances smaller than predicted by Fig. C.2.

Equation (C.7) provides a guideline of the distance between base stations that indicates that the radio path between them may be obstructed by Earth curvature effects. However, as a result of the selection of base station locations, it may happen that two base stations placed at such a distance may not be obstructed by Earth curvature or terrain if the proposed locations are atop prominent terrain features. In such circumstances, sites may require additional distance, or additional isolation may be provided through appropriate choice of antenna patterns. Since one would encounter this situation more frequently in the case of airport deployment, isolation through antenna pattern selection guidance is provided in the following section, which analyzes the airport scenario.

Airport Scenario

The airport scenario models system operation around major airports. Due to higher aircraft densities and larger capacity requirements, this scenario is characterized by relatively small cell site radii and therefore, smaller spacing between the cells of the two systems as well. In the test bed system used for analyses in [1] and this report, the nominal cell radius is assumed to be 12.5 miles. Using the cell layout given in Fig. 5.1, the minimum spacing between cells of the two system can be calculated as:

$$D_{\min} = 2R\sin(\pi/8) = 2\cdot 12.5\cdot 0.3827 \approx 9.56 \text{ miles} \qquad \text{(C.9)}$$

From the discussion presented in previous section (see Fig. C.2), it follows that in the airport scenario one may more frequently expect LOS propagation between two base station towers of the two systems. Therefore, in this case, additional isolation needs to be achieved using appropriately chosen antenna patterns.

To determine the proper methodology for the antenna pattern selection, consider the case of two airport base stations depicted in Fig. C.3. The base stations are assumed to be relatively close to each other and therefore the effect of the Earth curvature can be neglected.

With the help of Fig C.3, the Received Signal Level (RSL) of the interfering signal at the base station receiver can be calculated as

$$\mathrm{RSL}[\mathrm{dBm}] = (P_T - CL_1 + G_{\max 1} - \Delta G_1) - \mathrm{FSPL}(d) + (G_{\max 2} - \Delta G_2 - CL_2) - \mathrm{POL} \quad \text{(C.10)}$$

where:

RSL[dBm]	- RSL of interfering signal in dBm
P_T	- transmit power of the BS transmitter in dBm
CL_1	- cable loss at the TX site in dB
$G_{\max 1}$	- maximum antenna gain on the TX side in dB
$\Delta G_1 = G_{\max 1} - G_1(\theta)$	- difference between maximum antenna gain and the gain towards the RX site for TX antenna in dB
$\mathrm{FSPL}(d)$	- free space path loss in dB
$G_{\max 2}$	- maximum antenna gain on the RX side in dB
ΔG_2	- difference between maximum antenna gain and the gain towards the TX site for RX antenna in dB
CL_2	- cable losses on the RX site in dB
POL	- interference reduction due to partial channel overlap

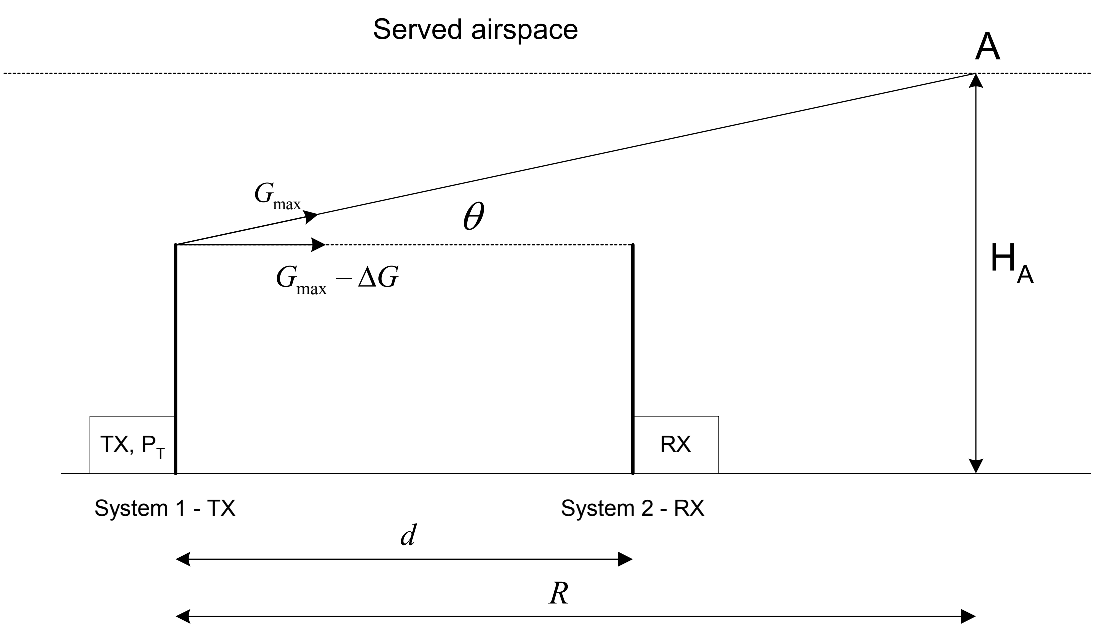

Figure C.3. Illustration of the airport scenario

The antenna system selected for the deployment in Fig. C.3, needs to satisfy two constraints:

1. The maximum antenna gain on the TX side should be placed at the elevation of point A. Point A is at the edge of the cell for System 1. The horizontal distance from the base station to point A is equal to the cell radius. The elevation of point A is equal to minimum altitude of served aircraft.

2. The antenna discrimination between the maximum antenna gain and gain towards the other site, on both TX and RX antennas, needs to be sufficient to guarantee that the interference is reduced to an acceptable level. For calculations presented here, it is assumed that the interference is permissible if it is at least 3dB bellow the noise floor. For a channel which is 1.25MHz wide and a receiver with a noise figure of 4dB, the thermal noise floor is at the level given by

$$N_0[\text{dBm}] = 10\log(kTB) + F = 10\log\left(4\times10^{-18}\,\frac{\text{mW}}{\text{Hz}}\cdot 1.25\times10^{6}\,\text{Hz}\right) + 4 = -109\ \text{dBm} \qquad \text{(C.11)}$$

To satisfy the above two constraints, the vertical patterns of the antennas selected for the two base stations need to have sufficiently steep gain roll-off in the vertical plane. They need to provide sufficient coverage throughout the cell area while maintaining a sufficiently low level of cross system interference. From (C.10) it is easily seen that both requirements can be met for a sufficiently large value of ΔG.

To simplify the analysis, the numerical values given in Table C.1 are assumed for some parameters given in (C.10). The values are consistent with the ones used in the system simulator described in Section 5.

Table C.1. Nominal values for some parameters in (C.10)

Parameter	Symbol	Value	Unit
Base station TX power	P_T	43	dBm
Cable losses	CL_1, CL_2	3	dB
Antenna gains	$G_{\max 1}, G_{\max 2}$	13	dB
Interference reduction due to partial overlap	POL	0	dB

By substituting the values from Table C.1 into (C.10), using the expression for the free space path loss (5.3), and assuming $\Delta G_1 = \Delta G_2 = \Delta G$, one obtains:

$$\begin{aligned}\text{RSL}[\text{dBm}] &= (43 - 3 + 13 - \Delta G_1) - (36.5 - 20\log(870) - 20\log(d)) + (13 - 3 - \Delta G_2) \\ &= -42.4 - 20\log(d) - 2\Delta G\end{aligned} \qquad \text{(C.12)}$$

To satisfy the above given interference constraint, the RSL of the interfering signal needs to be 3dB below the value of –109dBm, i.e., -112dBm. After substitution of this value into equation (C.12), one obtains a relationship between the distance between the base stations and the value of ΔG. That is,

$$\Delta G = 34.8 - 10\log(d) \qquad \text{(C.13)}$$

The values of ΔG for several base station separation values are provided in Table C.2. From the table, it is seen that a "horizon null" of about 30dB provides enough isolation to allow base station placement as close as 5 miles. In a more typical deployment consistent with the airport scenario outlined in the test bed system (See Fig. 5.1), the separation between the base stations is on the order of 10 miles. For a 10-mile separation, a 25dB deep horizon null provides a sufficient level of interference reduction.

Table C.2. Antenna gain reduction on the horizon

Base station separation [miles]	Antenna gain reduction on the horizon ΔG [dB]
5	27.81
6	27.01
7	26.34
8	25.77
9	25.25
10	24.80
20	21.79
40	18.78

There are several remarks that need to be made about the calculations presented for the airport scenario.

1. The calculations are conservative since they assume no obstruction loss between the two base station towers. In areas around airports, the towers are typically lower height because of their limited cell size and reduced requirements to have clearance at low elevation angles. Therefore, the radio path between them is likely to be obstructed by terrain, vegetation, or man-made structures.

2. The calculations assume full channel overlap between TX and RX side. This is consistent with initial deployment of the two systems (c.f. Section 4.5). However, after transition to 40% overlap, an additional 4dB needs to be added to the path isolation. This translates into a 2dB lower requirement for the antenna gain discrimination.

3. The numerical values obtained as results of the analysis in this section are valid only for the set of adopted assumptions. Although realistic, the numbers used as input to the analysis may vary from deployment to deployment and therefore, ΔG will vary as well. However, the procedure used to determine proper values for ΔG stays the same. Therefore, one should see the results presented in this section as a confirmation that the interference between the base stations of the two systems can be controlled through well known and proven engineering techniques. In practice, each deployment case will have to be analyzed to verify that the cross-system interference is maintained at the acceptable levels.

Summary

This section presented an analysis of the base-to-base interference between two ATG systems operating in a cross-duplex mode. It has been demonstrated that this interference can be controlled using two principle design tools. The first one is base station placement and the second one is selection of base station antenna patterns. The main conclusions of the analysis can be summarized as follows.

- In the cross-country scenario, the base station placement can be seen as the predominant way of controlling the base-to-base interference. For typical base station antenna heights of 100 feet, a separation of 30-40 miles will be sufficient to reduce interference to negligible levels. The interference is reduced due to effect of Earth curvature.

- In the airport scenario, the interference is controlled using a combination of cell placement and selection of the antenna pattern with a "horizon null". The required discrimination is a function of the distances between cells, adjusted for terrain and morphology impacts. For a typical deployment where base stations are separated by approximately 10 miles, with no path obstructions, the depth of the horizon null needs to be approximately 25dB.