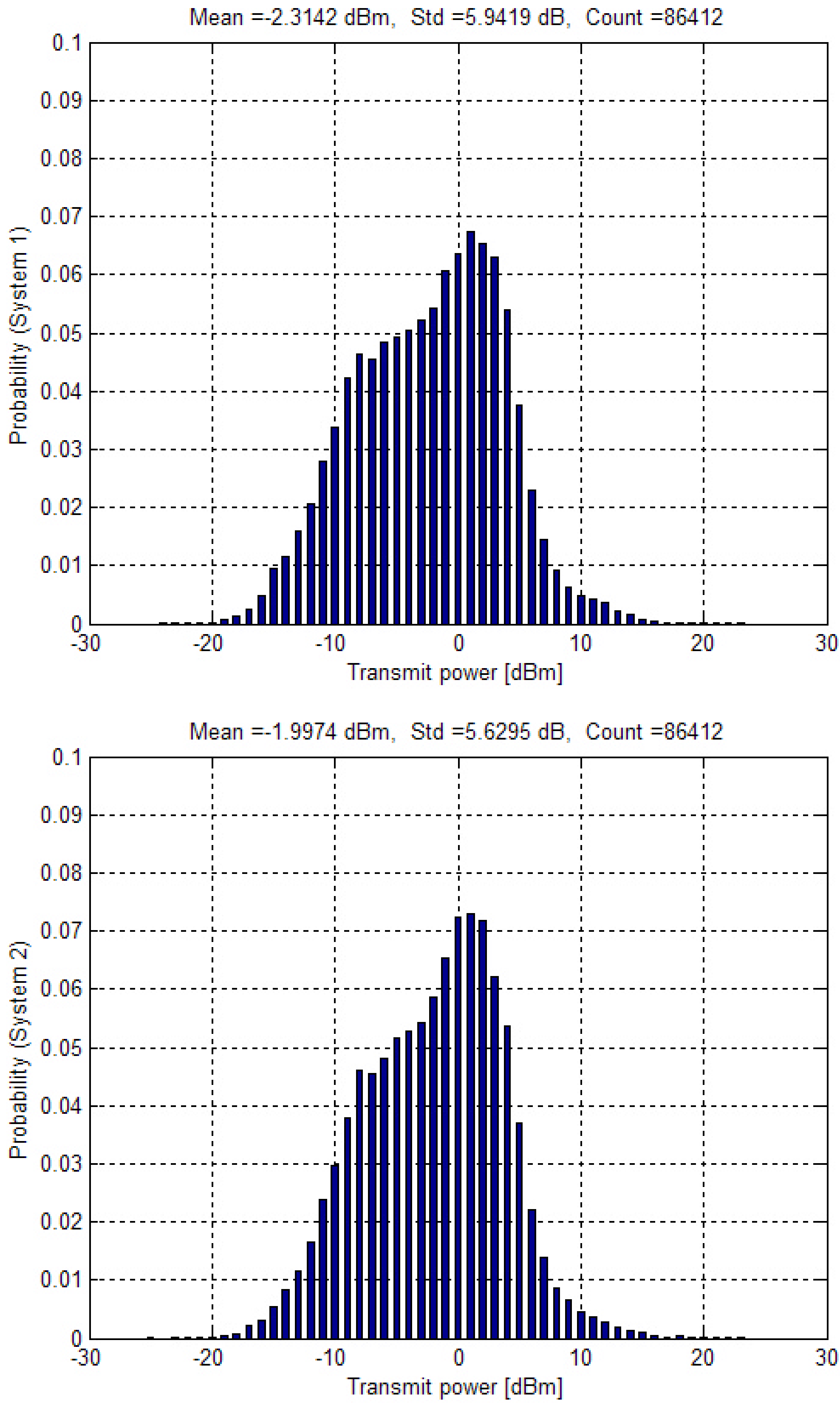


Figure 48. Distribution of the aircraft transmit power for airport configuration, 25% pole point loading and 100% spectrum overlap

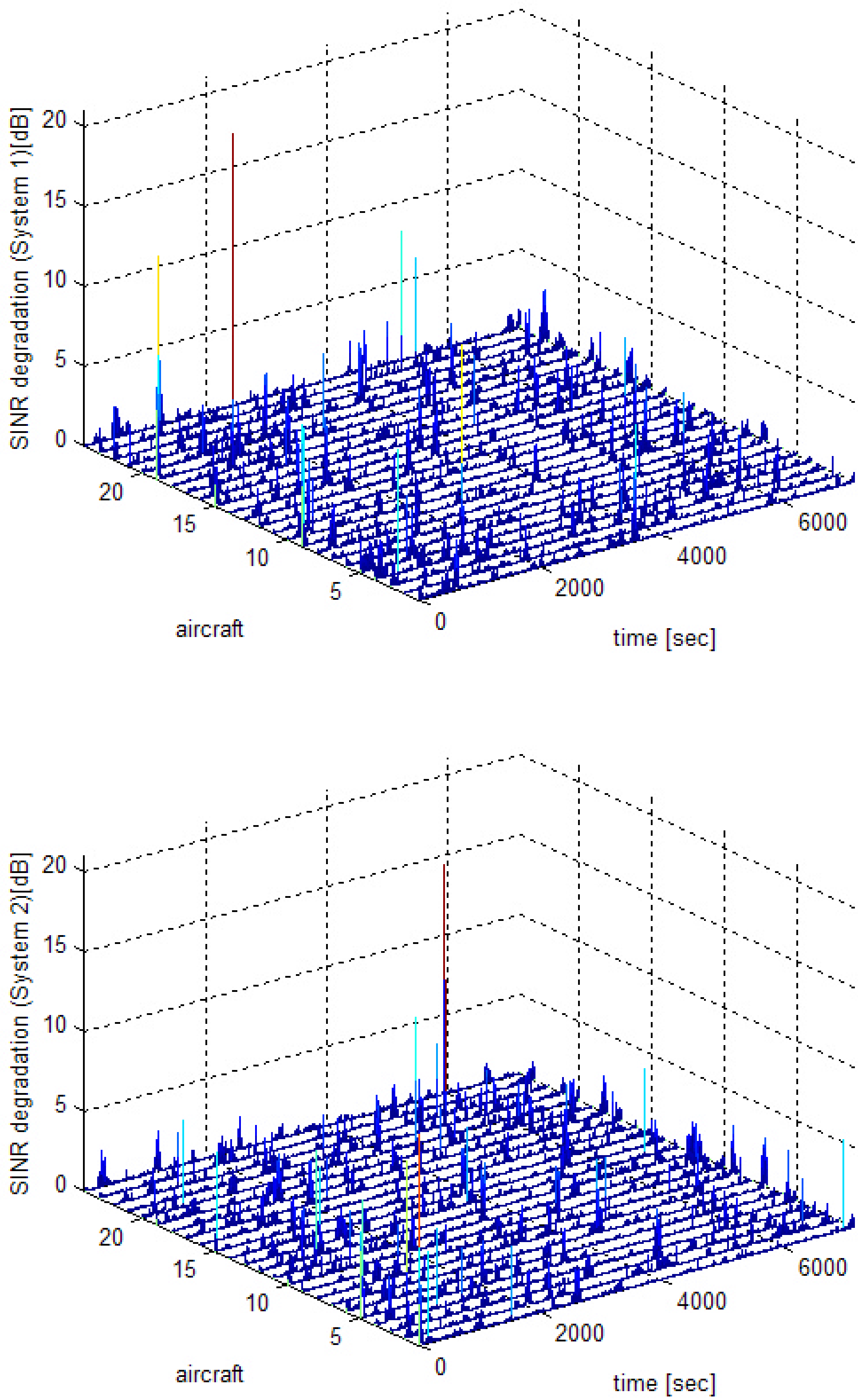


Figure 48. Time domain SINR degradation for airport configuration, 50% pole point loading and 100% spectrum overlap

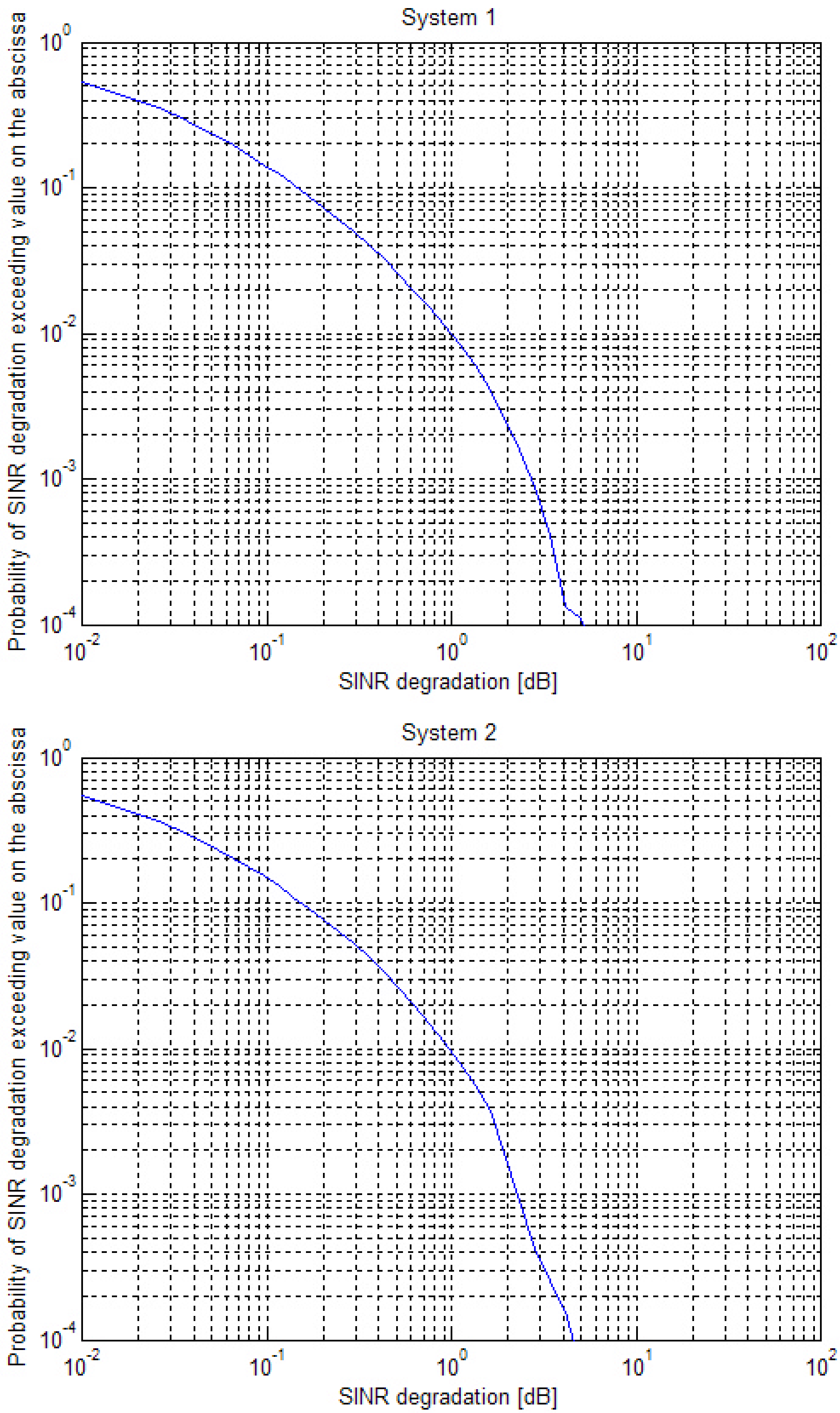


Figure 50. Probability of the SINR degradation for airport configuration, 50% pole point loading and 100% spectrum overlap

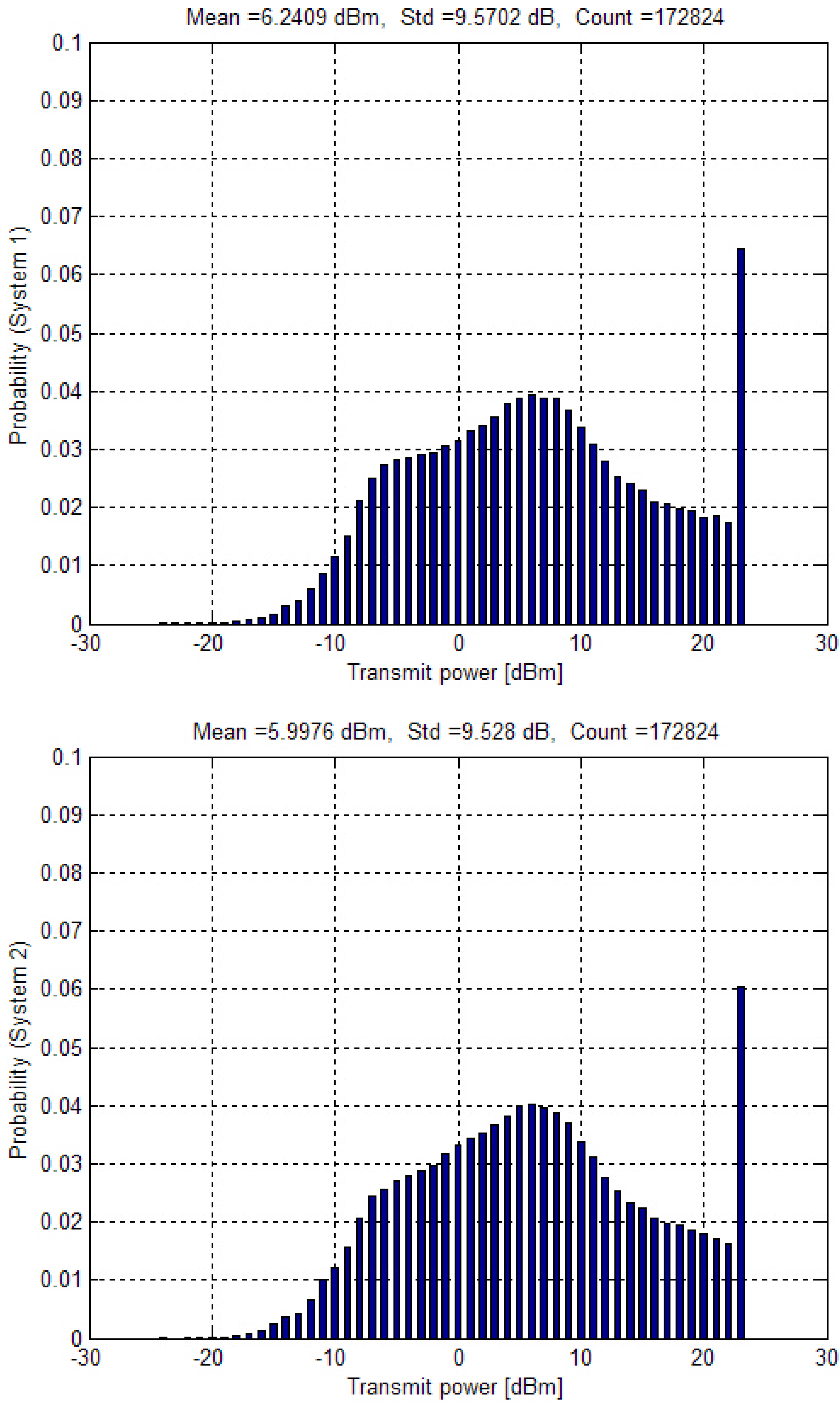


Figure 51. Distribution of the aircraft transmit power for the airport configuration, 50% pole point loading and 100% spectrum overlap

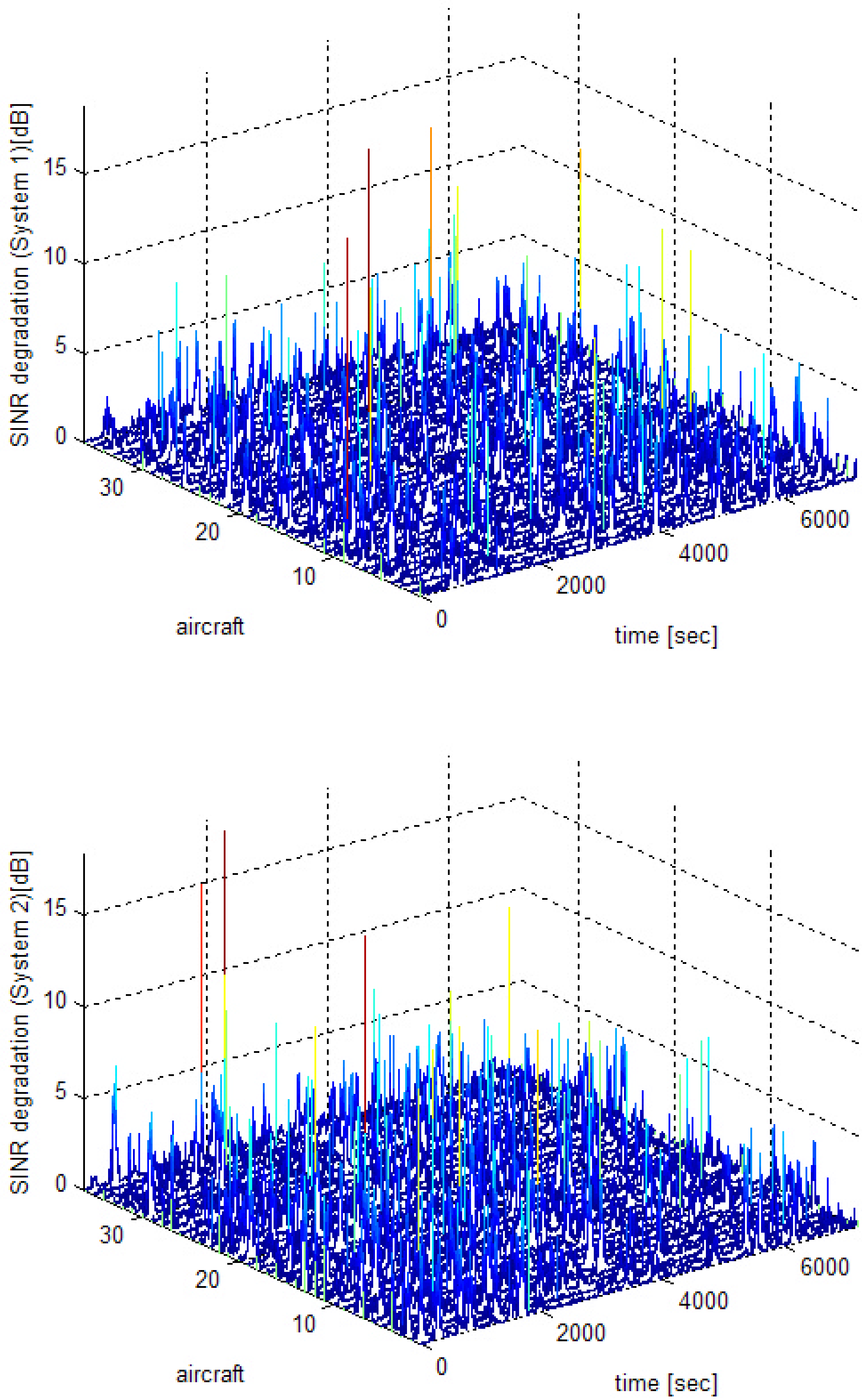
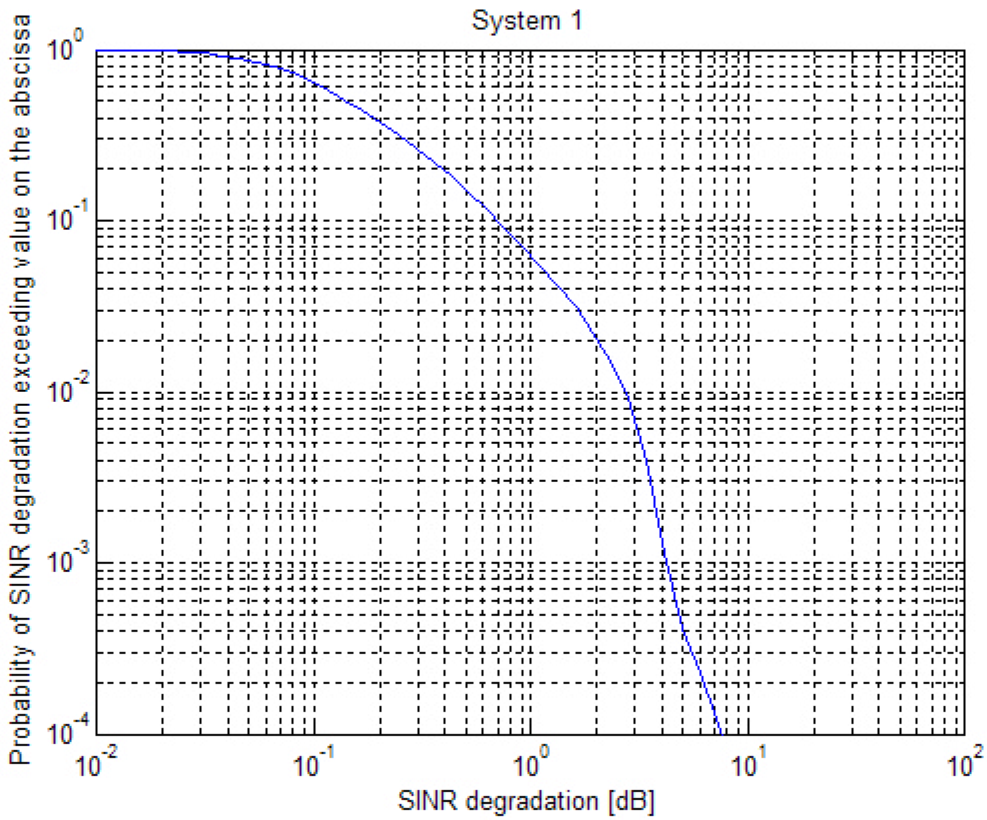


Figure 52. Time domain SINR degradation for the airport configuration, 75% pole point loading and 100% spectrum overlap



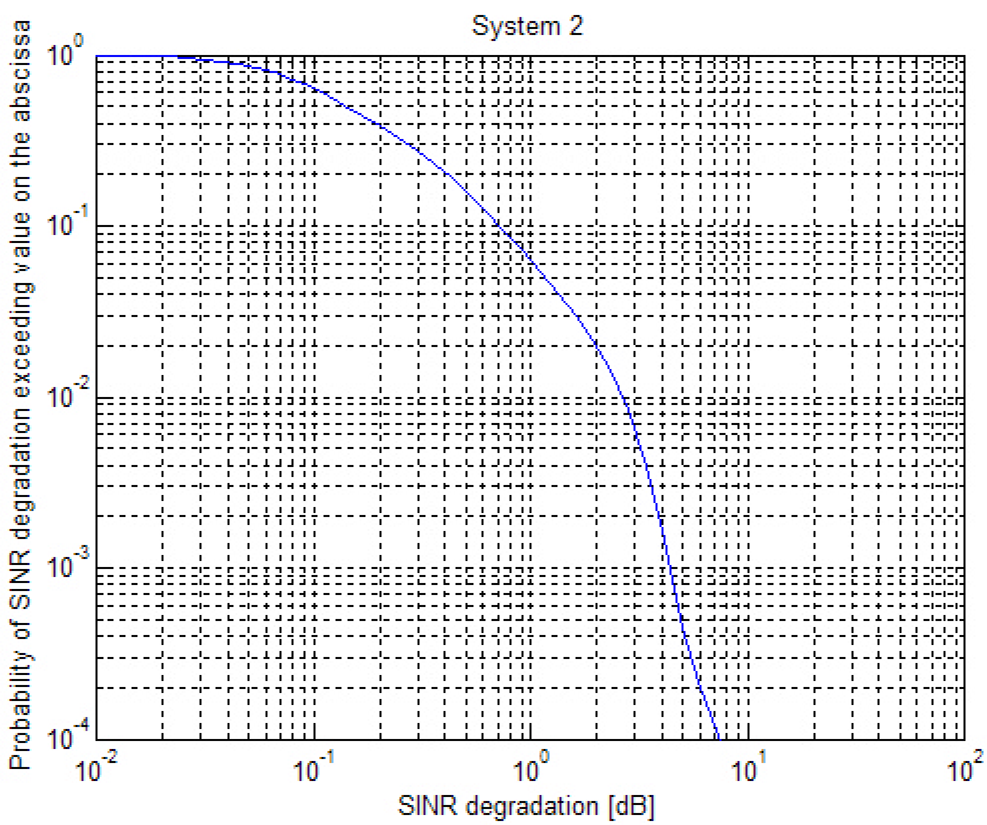


Figure 53. Probability of the SINR degradation for the airport configuration, 75% pole point loading and 100% spectrum overlap

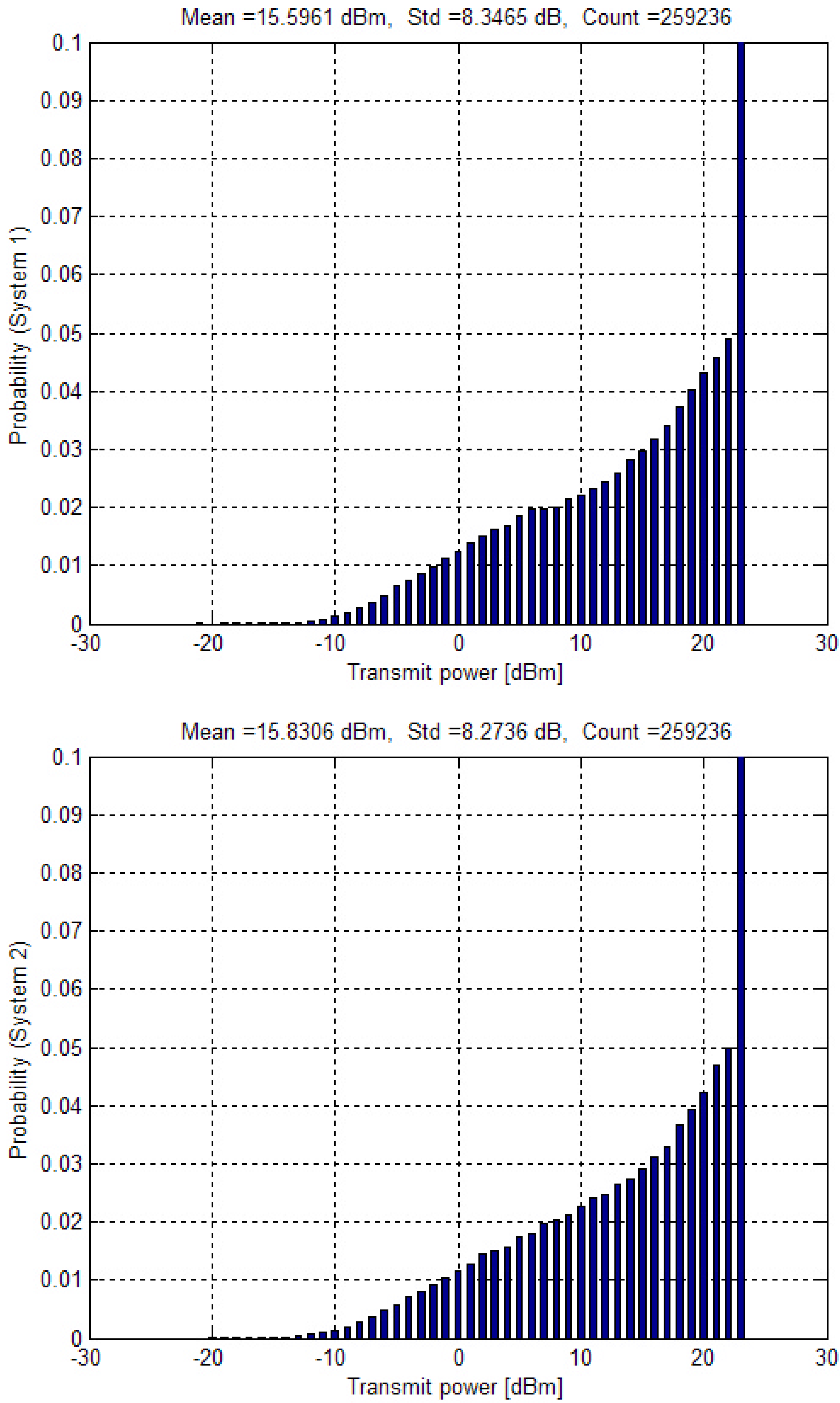


Figure 54. Distribution of the aircraft transmit power for the airport configuration, 75% pole point loading and 100% spectrum overlap

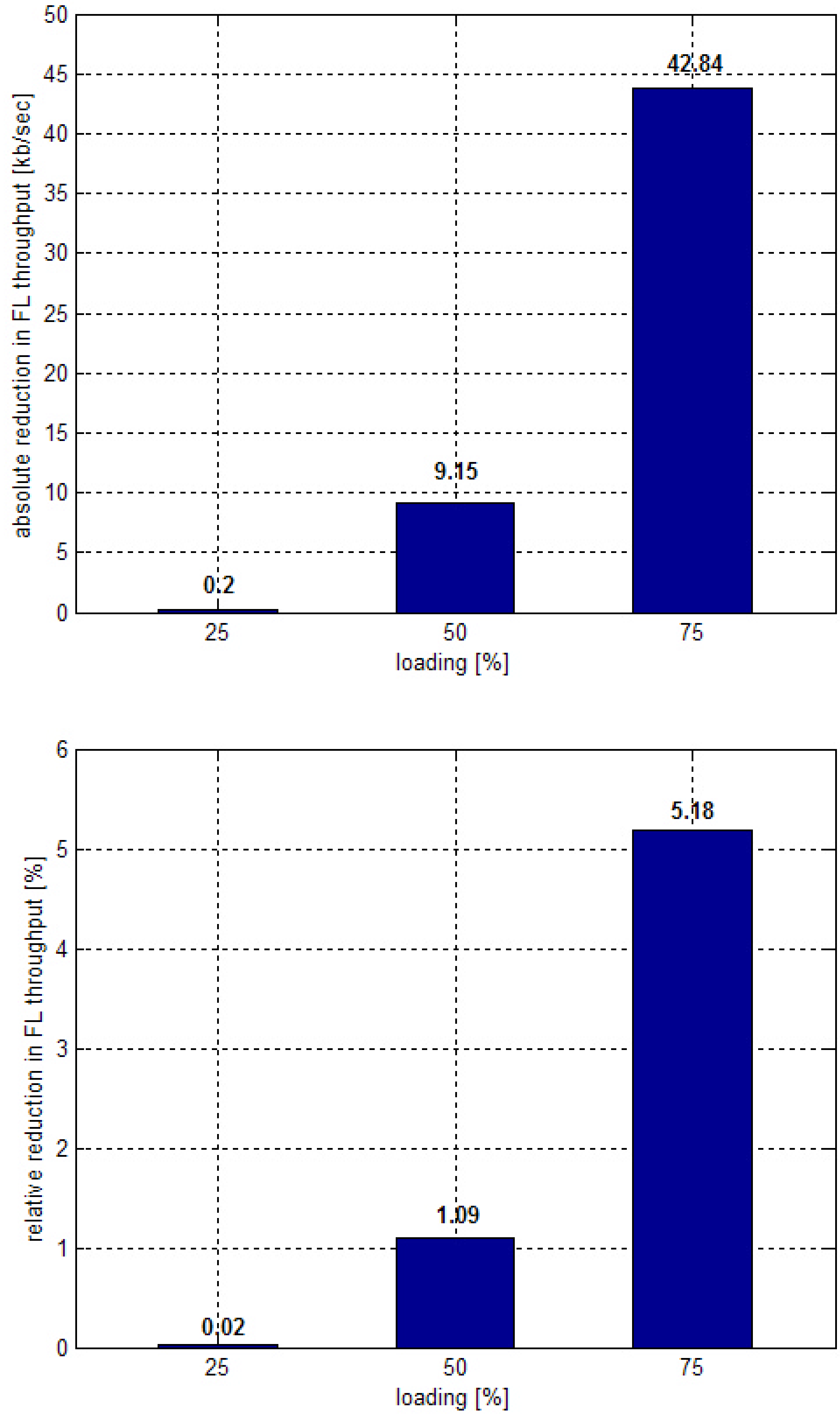


Figure 55. Absolute and relative reduction of FL throughput for the airport configuration and 100% spectrum overlap

7 Migration Strategy for Spectrum Migration

Since an incumbent operator exists in the ATG band using narrowband 6 kHz digital FDMA access, it is necessary to have a migration strategy where this operator can continue to operate the 6 kHz network while transitioning to a CDMA architecture.[6] Also, during the transitional period of Phase 1, the second CDMA operator begins building and commissioning their network.

The incumbent 6 kHz operator must undergo a technology transition independent of whether a single or dual CDMA ATG migration is pursued. Since a dual CDMA allocation is not only technologically viable but best serves the public interest, this is clearly the preferred approach. The dual CDMA network migration causes no harm to the incumbent operator. The proposed transitional timeframe is 6-9 months.

Figure 56 describes how the migration path is realized—transitioning from Phase 1, where both narrowband and broadband access occurs, through to Phase 2, where only broadband access occurs.

In Phase 1, the left hand spectrum allocation of 600 kHz (0.6 MHz)[7] enables the incumbent narrowband ATG operator to continue to offer narrowband services while building a CDMA overlay. This 600 kHz allocation affords a K=3 spectral re-use plan which is wholly adequate for today's air-to-ground communications needs (this network is lightly loaded). The frequency re-use scheme of K=3 is the smallest re-use plan that retains a sufficient degree of self-interference protection for air-to-ground network design (See Appendix A of this report). Each of the three channel blocks has 29 voice channels, which is more than adequate, especially considering that the incumbent operator will also begin to add substantial incremental capacity as CDMA sites are brought on-line.

In Phase 1, a portion of the ATG spectrum is unused and this is shown as a 150 kHz guard band. Note that this is not intended to be a guard band per se; rather, it is spectrum that, during the Phase 1 transition, has no designated use. In areas with high traffic load requirements, this spectrum may be used to provide additional narrowband channels. Finally, 1.25 MHz is allocated for CDMA access.

During Phase 1, System 1 and System 2 CDMA allocations are 100% overlapped. Provided that the networks, System's 1 and 2, are only operated at around 25% of the network's pole point, this 100% overlap does not increase cross-interference levels to significant levels. In fact, even during this 100% overlap period, at 25% of the pole point, the relative forward path data rate reduction is only 0.03%, which is virtually meaningless in terms of impact (c.f. Section 6.4). Thus, 25 % loading is ultra-conservative (at 50% loading the relative data rate reduction is only 1.07%).

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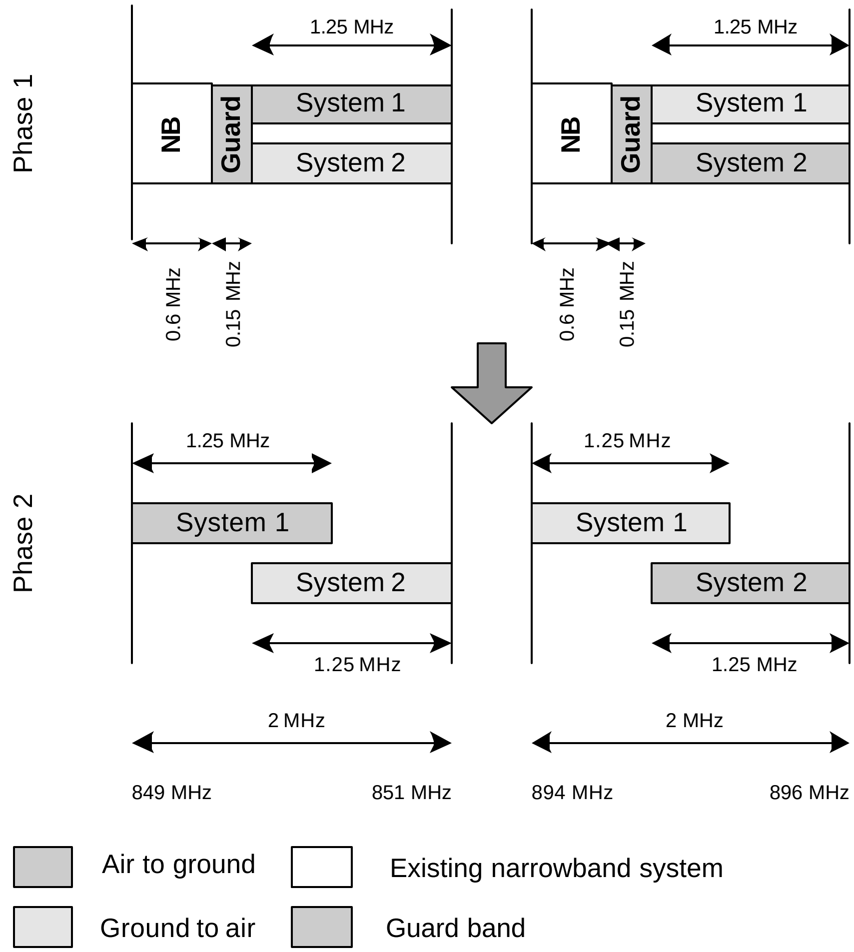
[6] The incumbent ATG operator has indicated a desire to transition to CDMA access (reference Verizon FCC filing dated December 4, 2003).

[7] Labeled "NB" for "Narrowband"



Phase 1

- CDMA overlap100%
- Lower CDMA system loading of 25%during this phase
- K=3 spectral plan dor 6kHz NATS operator (three shannel blocks at bottom band)

Phase 2

- Two CDMA systems
- Spectrum overlap of 40% (.5/1.25)
- No legacy systems
- High system loading

Figure 56. Migration strategy spectral map

After the 6-9 month transition period is completed, Phase 2 becomes fully operational. In the described migration path of Fig. 56, System 1, over a short pre-determined time-frame (of weeks not months), would retune its entire network 750 kHz lower. The resulting spectral map of Phase 2 is now realized.

At this point and going forward, no legacy narrowband ATG operations are permitted - only CDMA operation is allowed. The CDMA network loading can now be permitted to increase since the 40% overlap offers increased spectral isolation. These CDMA networks, System 1 and System 2, can nominally operate at 50% of their pole point, and even sometimes at higher loadings to serve transient traffic load surges.

The described migration strategy has been well studied and shown to be technically viable. It grants the incumbent operator a transitional period, enables the new operator to build its CDMA network, enables the incumbent operator to build its CDMA network and finally, permits both operators to operate CDMA networks at loadings which yield a combined capacity of 480 voice channels (or channel equivalents) for a given geographic region such as an airport.

8 Interference to Adjacent Radio Systems

Systems deployed in ATG band may interfere with other radio systems operating in adjacent frequency bands. This section analyzes the possibility of such interference and proposes some methods for its elimination.

8.1 *Interference to Adjacent Cellular Systems*

Out of the two ATG spectrum reuse proposals discussed in this report, the proposal for Phase 2 has a potential of causing some interference to existing terrestrial cellular systems. Consider the frequency allocation of the ATG spectrum as shown in Fig. 57. As can be seen, the spectrum block assigned to System 1 has no guard band towards the B' portion of the spectrum allocated to the B-side cellular provider. Therefore, there exists a possibility of cross system interference. From Fig. 57, it is seen that there are two interference possibilities given as:

1. Ground to air communication of System 1 interfering to cellular system downlink (base to mobile)
2. Air to ground communication of System 1 interfering with cellular system uplink (mobile to base)

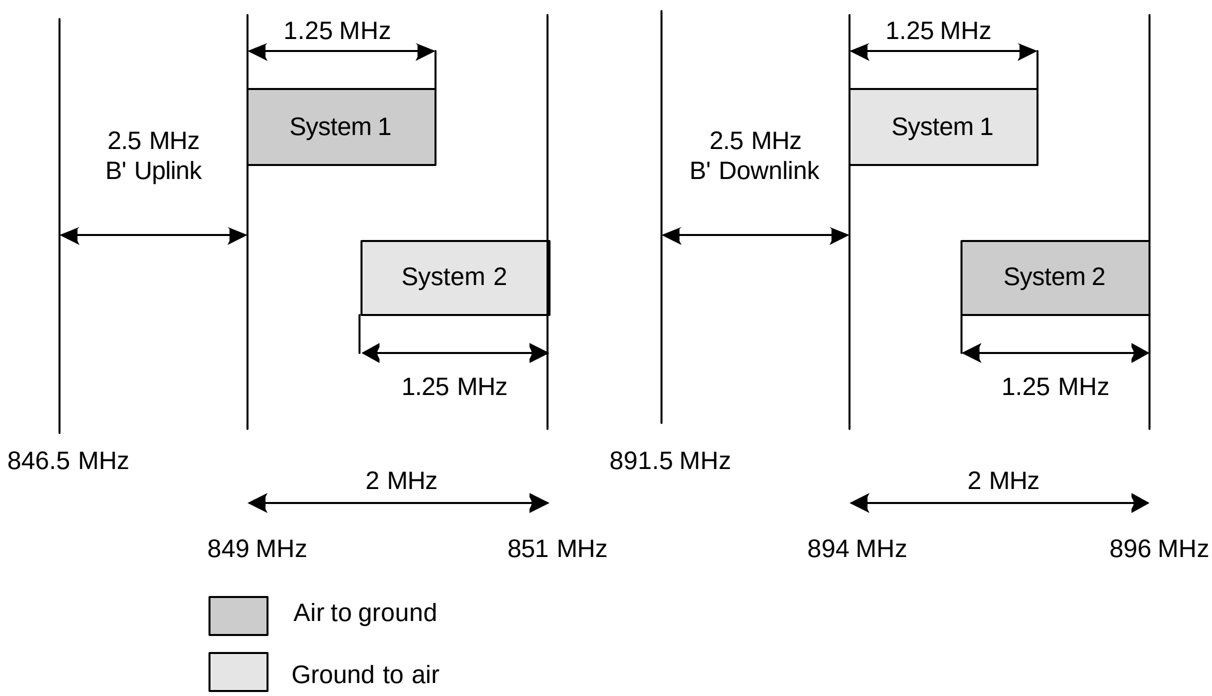


Figure 57. ATG spectrum migration relative to existing cellular systems

An illustration of the interference paths between ATG System 1 and the terrestrial cellular system is provided in Fig. 58. As can be seen, from the two interference possibilities, the first one is less of a problem. To avoid the interference to System 2, the antennas of System 1 base stations have to be uptilited (c.f. Section 2). Therefore, System 1 radiation towards the ground is reduced. On the other hand, the second interference possibility is a more challenging one for at least two reasons. Firstly, the radiation from the aircraft antennas is close to being omnidirectional and therefore it illuminates terrestrial base stations. Secondly, the aircraft are mobile and hence, there is a potential of an aircraft flying in proximity of a terrestrial base station antenna system. This is especially the case in areas close to major airports.

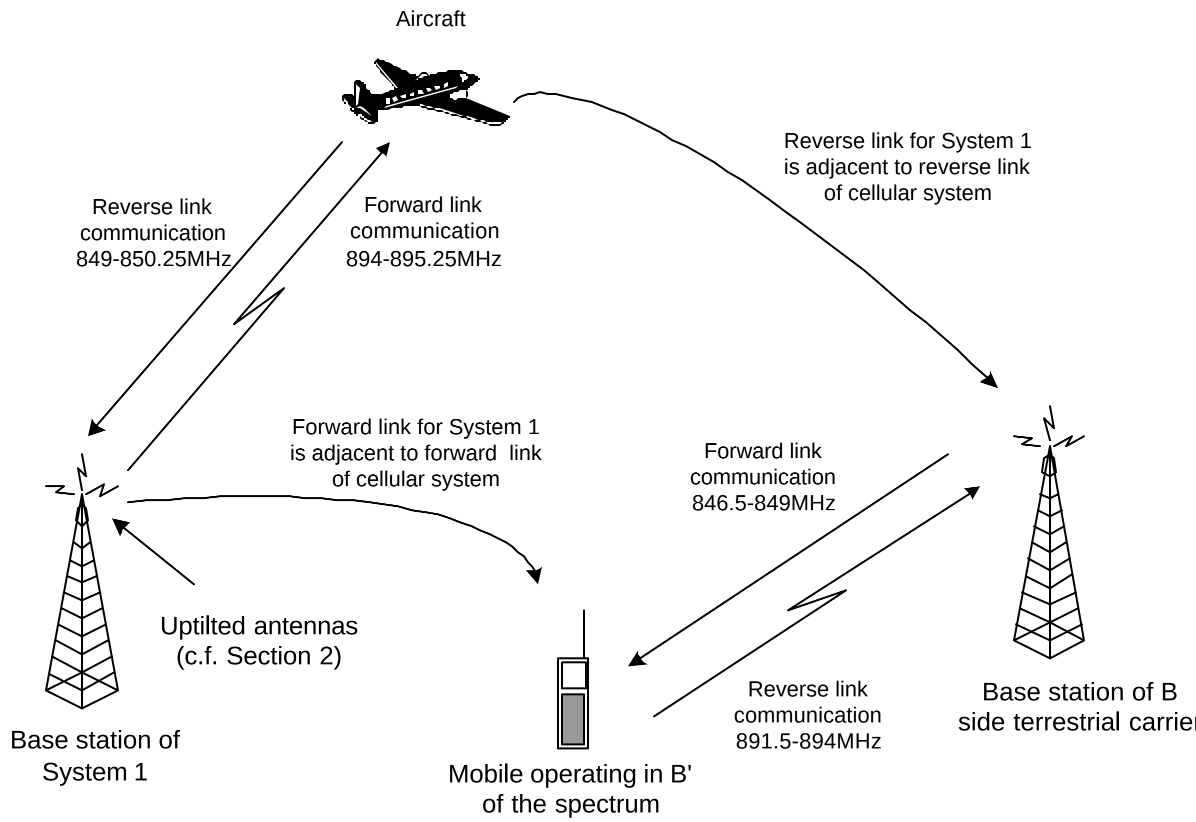


Figure 58. Illustration of the interference paths between ATG System 1 and terrestrial cellular system operating in B' part of spectrum

This section focuses on the analysis of the interference from System 1 air to ground communication to the uplink of the terrestrial cellular system. It is assumed that the interference potential between the System 1 ground to air communication and the terrestrial downlink can be controlled through proper antenna pattern selections.

8.1.1 3GPP2 Specification on Spurious Emission

The portion of the RF energy that causes interference from System 1 to the B-side cellular carrier is out of the band that is allocated to the CDMA ATG channel. Therefore, it is referred to as the spurious emission. The spurious emission of a CDMA phone is regulated by cdma2000/1xEvDO standards [5] for all frequency bands where operation of these technologies is allowed. Since there are no 1xEvDO systems in ATG spectrum, there are no appropriate standard specifications. However, it is reasonable to assume that they would have been similar to the ones implemented for operation in neighboring cellular bands.

Within the Standards document [5], the 800 MHz cellular band is referred to as the Band Class 0. Appropriate out of band emission requirements for Band Class 0 are summarized in Table 13.

Table 13. Band Class 0 transmitter spurious emission limits for spreading rate 1[8]

For $\lvert\Delta f\rvert$ within range	Emission limits
885 kHz to 1.98 MHz	Less stringent of -42 dBc/30kHz or –54 dBm/1.23MHz
1.98 MHz to 4.00 MHz	Less stringent of -54 dBc/30kHz or –54 dBm/1.23MHz

In a scenario when the transmission is at its maximum (23 dBm), the emission limits from Table 13 can be translated to the power spectrum mask presented in Fig. 59. To simplify the interpretation of the results, the radiated power spectrum density (PSD) is expressed in dBm per 30 kHz of bandwidth.

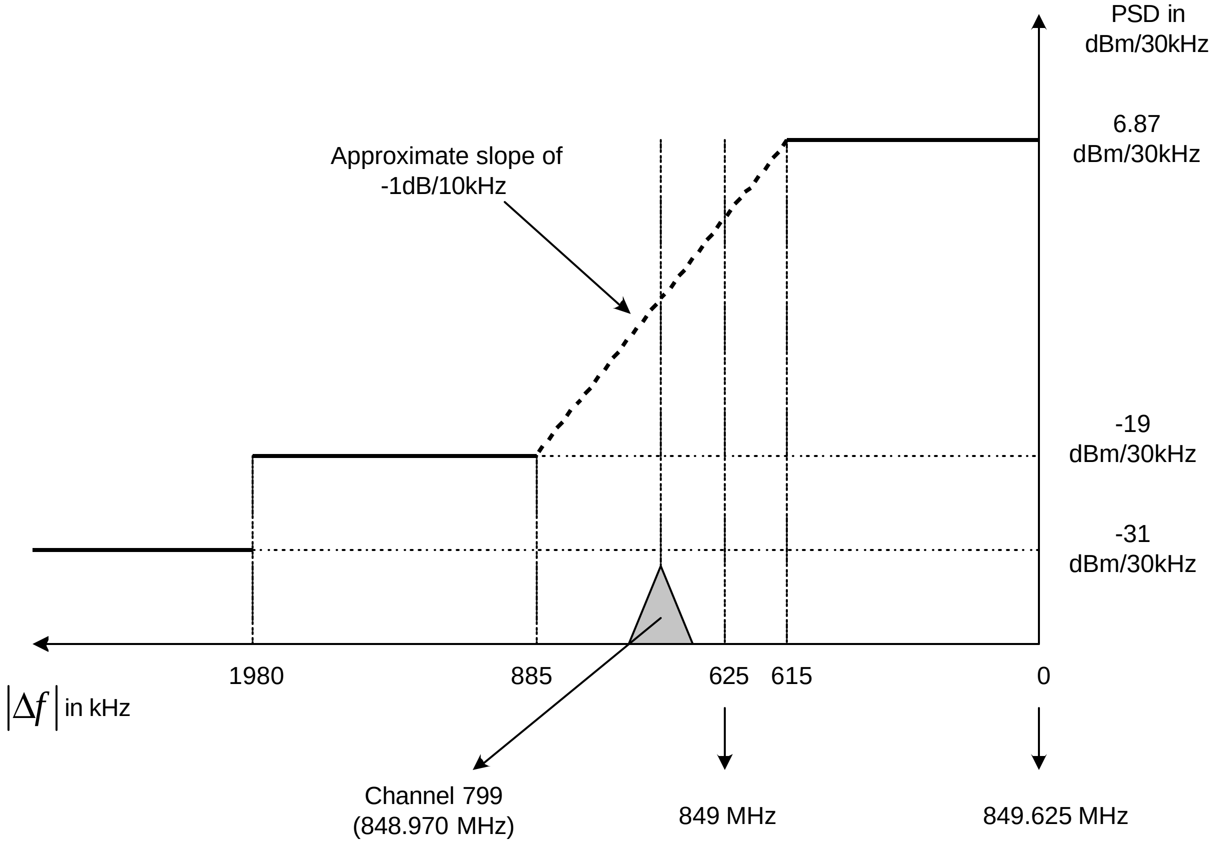


Figure 59. Transmission spectrum mask for 1xEvDO carrier at maximum ERP (23dBm)

The values shown along the y-axis of Fig. 59 are obtained by using the following equations.

1. Energy in 30 kHz bandwidth of the CDMA channel

$$E_1 = 23 + 10\log(30/1230) = 6.87 \text{ dBm/30kHz}$$

[8] Reproduced from Table 4.5.1.3.1-1 in [5].

2. Energy in 30KHz bandwidth for $\Delta f > 885$ kHz

$$E_2 = 23\text{dBm} - 42\text{dBc/30kHz} = -19\text{dBm/30kHz}$$ [9]

3. Energy in 30KHz bandwidth for $\Delta f > 1980$ kHz

$$E_2 = 23\text{dBm} - 54\text{dBc/30KHz} = -31\text{dBm/30KHz}$$

The last channel in the B' portion of the cellular spectrum is subject to the worst-case interference. This is channel 799. The center frequency of this channel is 848.970 MHz.

Table 13 does not specify the spurious emission levels for frequency offsets in the range 615 kHz to 885 kHz. To estimate the level of interference experienced by channel 799, in the first approximation, the spectrum mask can be linearly interpolated as shown in Fig. 59. The interpolation results in a line segment with a slope of 0.1dB per every kHz of frequency separation. Therefore, the spurious emission at the frequency associated with channel 799 can be estimated as:

$$E_{799} = 6.87\text{dBm/30kHz} + (848.970 - 849.010)\cdot 1000 \cdot (0.1\text{dBm/kHz}) = 2.87\text{dBm/30kHz} \qquad (21)$$

8.1.2 Maximum Interference Levels

The path loss between the cellular tower and an airplane antenna can be calculated in accordance with the free space path loss formula given by (1) and (2) in Section 3. Using free space path loss and abbreviating $G(q,f)-CL$ as g, one obtains values given in Table 14. Columns 3 and 4 of Table 14 provide the received signal level of the interfering signal for two boundary channels in B' spectrum. Column 3 corresponds to channel 799, while column 4 corresponds to channel 717. The frequencies allocated to these channels are 849.970 and 846.51 MHz respectively.

In the interpretation of the data provided in Table 14, one needs to be aware that they represent the worst-case interference scenario for at least three reasons, given by

- The aircraft is transmitting at full power. A review of histograms of the aircraft transmit power presented in Section 6 reveals that even in the worst case loading scenarios, an aircraft transmits at its maximum power for less than 10% of the time.
- Channel 799 is on the edge of the B' spectrum band and hence the most susceptible to interference. Other channels experience lower interference levels. For that reason, Table 14 presents the interference levels for Channel 717, which is on the other edge of the B' spectrum. As seen, the interference to channel 717 is for the most part negligible.
- Antennas of terrestrial cellular towers are usually downtilted. Since the aircraft would be outside of the antennas' main beams, the gain of the antennas would be reduced.
- If the operation of the ATG communication is suspended during takeoff and landing, the issue of interference to B' largely goes away (c.f. Table 14).

[9] Definition of dBc can be given as follows [5]: **dBc** – The ratio (in dB) of the sideband power of the signal measured in a given bandwidth at a given frequency offset from the center frequency of the same signal, to the *total inband* power of the signal.

Table 14. Interference levels for some B' channels

Distance [feet]	Path loss: PL[dB]	RSL_{799}[dBm]	RSL_{717}[dBm]
500	70.8 - *g*	-67.88 + *g*	-101.75 + *g*
1000	76.8 - *g*	-73.91 + *g*	-107.78 + *g*
2000	82.8 - *g*	-79.93 + *g*	-113.80 + *g*
4000	88.8 - *g*	-85.95 + *g*	-119.82 + *g*
8000	94.8 - *g*	-91.97 + *g*	-125.77 + *g*
16000	100.86 - g	-97.99 + *g*	-131.86 + *g*
32000	106.99 - *g*	-104.00 + *g*	-137.87 + *g*

However, even though the numbers in Table 14 are derived for the worst-case interference scenario, they indicate a significant interference potential between System 1 and the B-side cellular carrier. To completely avoid the possibility of this interference, the implementation of the ATG spectrum migration proposal presented in Fig. 57 requires additional filtering on the aircraft transmission path. In other words, the spectral mask of the aircraft transmission needs to be tighter than the one prescribed by the current standards. The emission specifications listed in Table 13 are written with a CDMA mobile phone in mind. Since mobile phones are mass-produced devices with strict cost and size requirements, the specifications given in Table 13 are designed so that they can be met with inexpensive filtering designs. If a filter with additional 30dB of stopband attenuation were introduced in the transmission chain, the interference between the ATG system and cellular B-side carrier would be reduced to negligible levels. Crystal or SAW filters with specifications that meet such requirements are commercially available and can be easily incorporated into the aircraft's signal transmission path. Therefore, this issue is manageable through known engineering means.

8.2 *Interference to Radio Systems Above ATG Spectral Bands*

Both ATG spectrum reuse proposals discussed in this report (Phase 1 and Phase 2) may cause interference to the radio spectrum operating in adjacent bands above ATG spectrum. For the same reasons discussed in the previous section, the significant interference potential exists only from air to ground communication links. In the case of Phase 1 ATG reuse proposal, the interference may be created to radio systems operating above 851 MHz and 896 MHz. Similarly, in the case of the Phase 2 proposal, the interference may be created to radio systems above 896 MHz. Both cases are illustrated in Fig. 60.

The spurious emission of a CDMA mobile is regulated by cdma2000/1xEvDO standards [5] for all bands where operation of these technologies is allowed. Since there are no 1xEvDO systems in the ATG band, there are no appropriate standard specifications. However, one can assume that the requirements would have been similar to the ones regulating operation in other spectral bands.

The closest spectral band that can host a cdma2000/1xEvDO system is 800MHz cellular band. Within the standard's documents [5], this band is referred to as the Band Class 0. On its lower end, Band Class 0 boarders with SMR radio systems similar to the ones operating in portions of spectrum above ATG band. Therefore, one might expect that the requirements on the spurious emission on the ATG 1xEvDO systems should be similar to requirements placed before systems operating in Band Class 0.

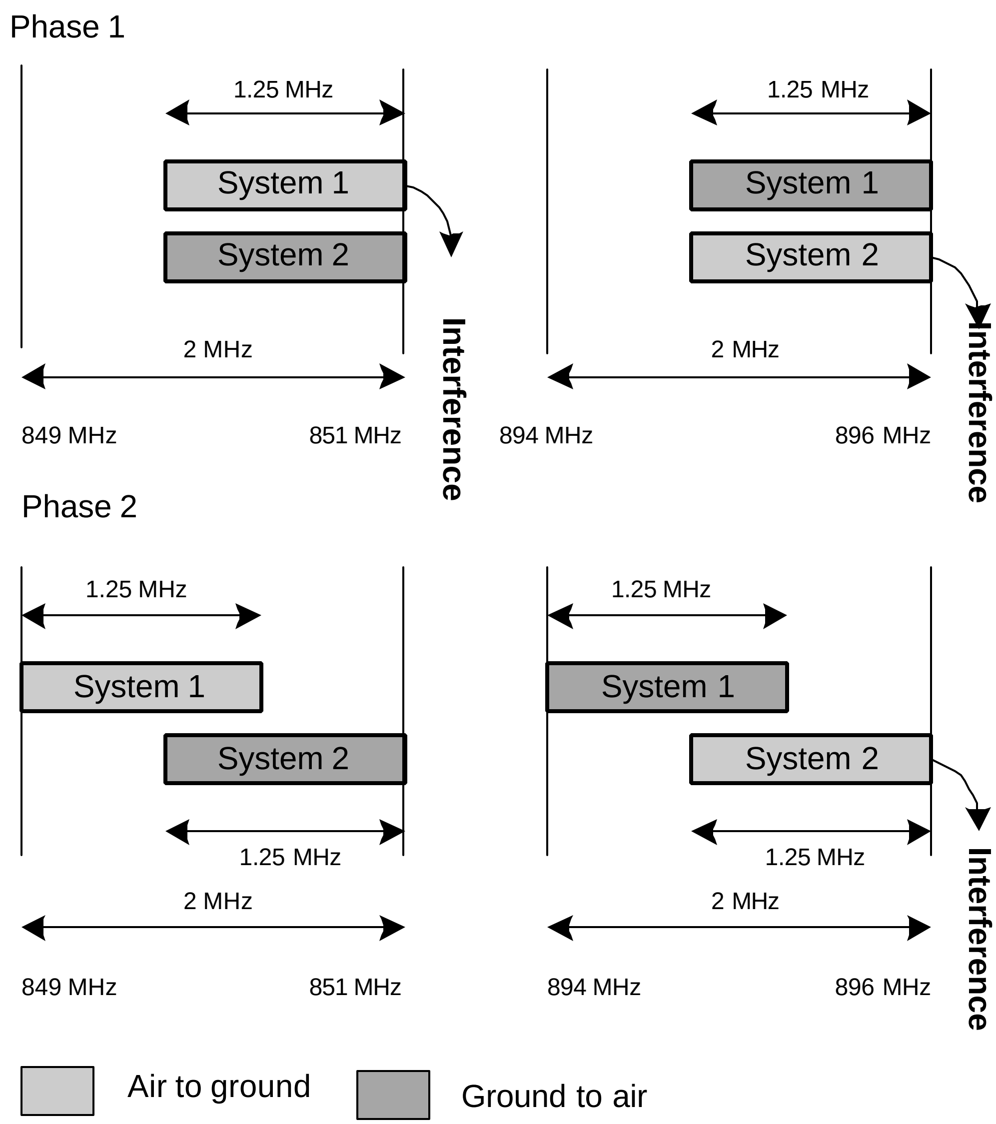


Figure 60. Illustration of the interference potential to radio systems above ATG spectrum

The closest cdma2000/1xEvDO channel allocation towards the lower end of the Band Class 0 is channel 1013 in A'' portion of the spectrum. The carrier frequency corresponding to channel 1013 is 824.7 MHz. Using the Band Class 0 spurious emission requirements given in Table 13 and assuming maximum transmit power of 23 dBm, a transmission spectrum mask for CDMA carrier using channel 1013 becomes as shown in Fig. 61. For ease of comparison, the power spectrum density of the signal is given in units of dBm/30kHz.

From Fig. 61, it is seen that spurious emission of the CDMA mobile at the beginning of the adjacent SMR frequency band reaches –1.63 dBm/30kHz with a roll-off of –1 dB/10kHz.

Consider the CDMA carrier aligned with the upper end of either ATG spectrum blocks. Its transmission spectrum mask is presented in Fig. 62. This spectrum mask is generated assuming transmission of full power (23 dBm). For ease of comparison, the power spectrum density of the signal is expressed in dBm/30 kHz. Comparing Figs 61 and 62, one observes that in the case of ATG spectrum allocation, the spurious emission level is higher by

$$\Delta P_{TX} = 5.87 - (-1.63) = 7.5 \text{ dBm/30kHz} \quad (21)$$

Therefore to make two systems comparable, additional filtering is needed for ATG spectrum allocation. The amount of additional filtering is only 7.5 dB and it can easily be achieved with commercially available filters of moderate selectivity. However, in the case when the operation of ATG is suspended during take off and landing, the additional filtering may even be unnecessary.

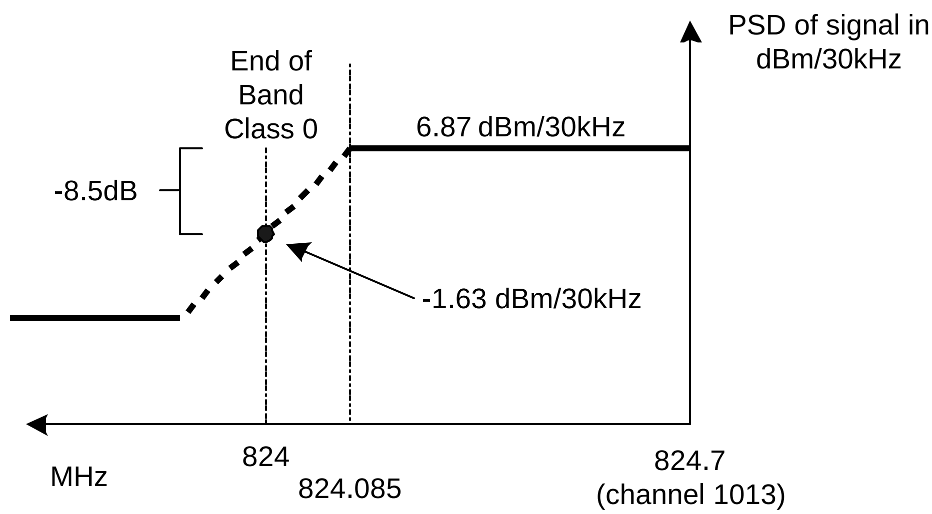


Figure 61. Transmission spectrum mask for 1xEvDO carrier at channel 1013 of Band Class 0

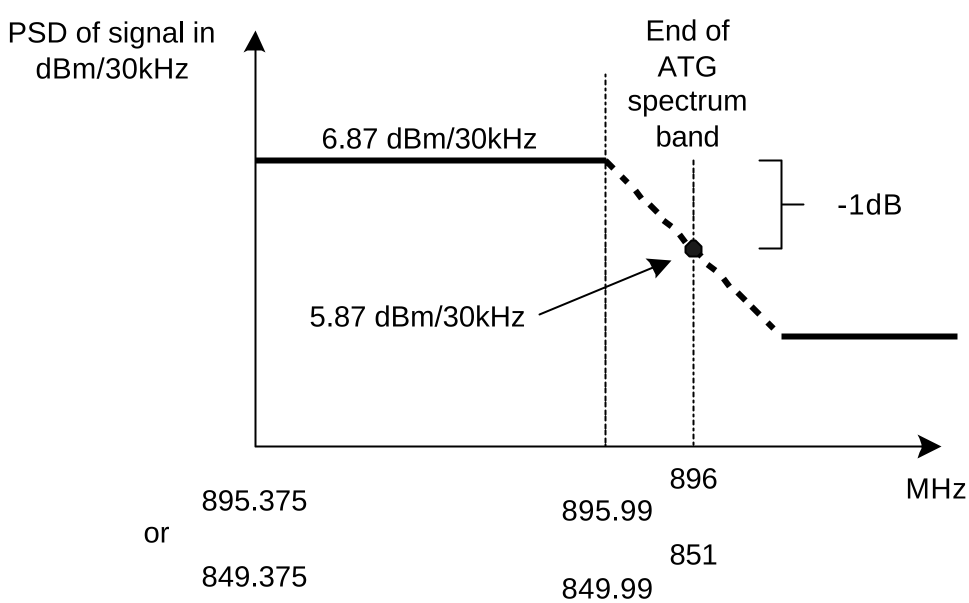


Figure 62. Transmission spectrum mask for 1xEvDO carrier at the upper end of an ATG spectrum band

9 Summary and Conclusions

This concept of swapping up/down allocations in the ATG band has been rigorously studied through the use of sophisticated Matlab™ simulations. These simulations compare a before and after ATG system for two key cases: an Airport Scenario and a Cross Country Scenario.

The results presented in the previous sections confirm the viability of the ATG spectrum migration proposal. The reuse of the spectrum and partial frequency overlap create potential for cross system interference, aircraft-to-aircraft and base-to-base. Only aircraft-to-aircraft cross system interference is considered; base-to-base cross system interference is negligible. Aircraft-to-aircraft cross system interference is quite small and easily managed using just a few relatively simple techniques.

In Summary:

- The spectrum allocations for the up/down communication links are swapped between System 1 and System 2.
- As a result of the spectrum swap, potential interference is possible between aircraft-to-aircraft and base-to-base of the two respective systems.
- The interference between base stations is easily controlled by maintaining proper base-to-base separation and by choosing antenna patterns with up-tilted elevation patterns and a sharp roll-off on the horizon.
- The interference between the aircraft is minimized through management of the systems' loading, base station antenna selection, and by using polarization isolation (polarization isolation is not an essential element of this concept).
- Simulations have demonstrated that when loading of the systems is at or below 50% of the pole point, the cross interference becomes negligible.

In addition:

- This proposal includes a viable migration strategy for the incumbent ATG operator as the ATG spectrum is reallocated to accommodate broad-band telecommunication services.
- Careful consideration has been studied with respect to possible interference to frequency bands adjacent to the reallocated ATG band. This study shows no major issues are present.

Finally, the simulator results speak for themselves and are shown again in Figs 62 and 63. Graphs in Fig. 62 are generated for the Airport scenario, while Fig. 63 presents graphs obtained for the Cross-country scenario.

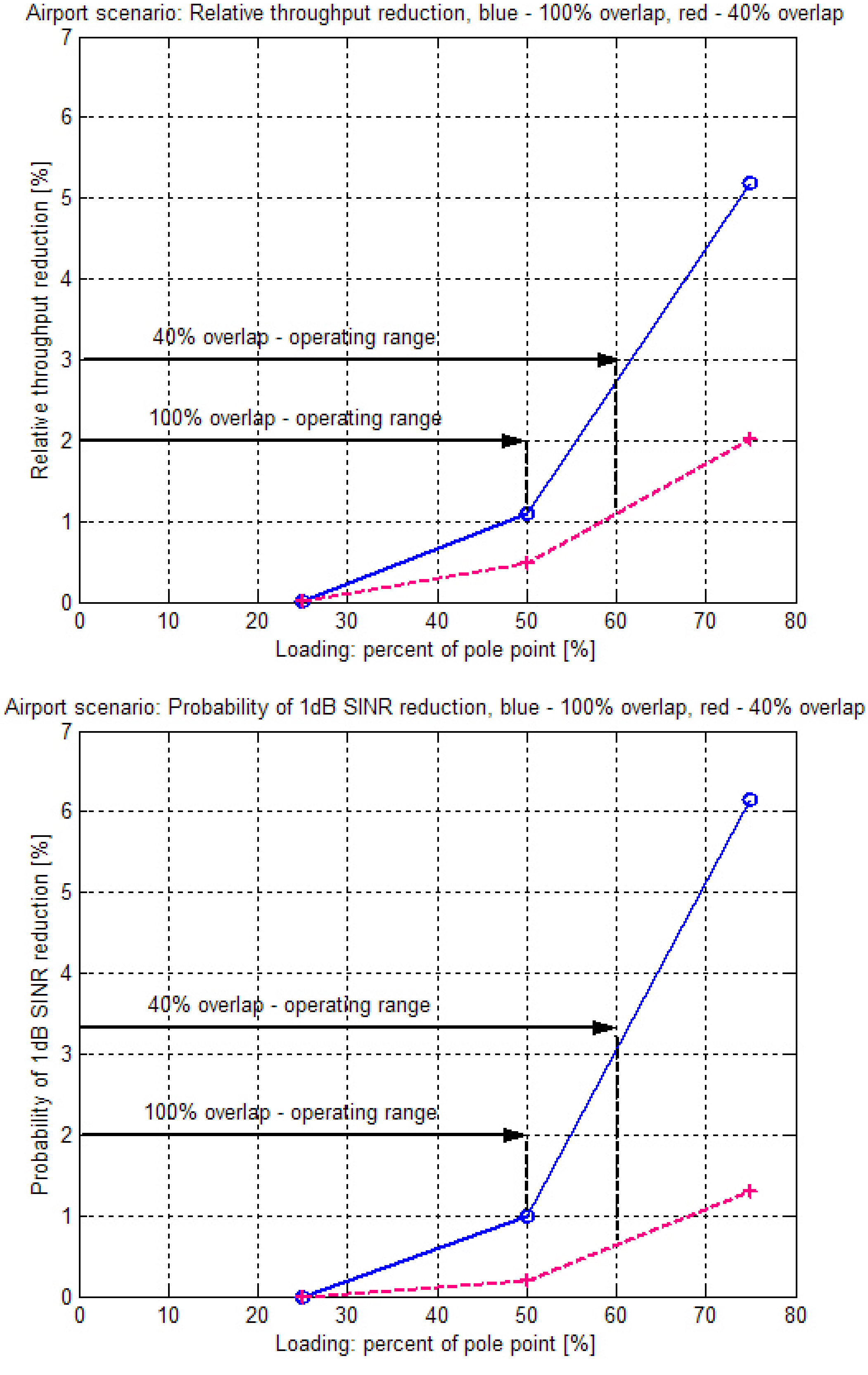


Figure 62. Performance curves for Airport scenario

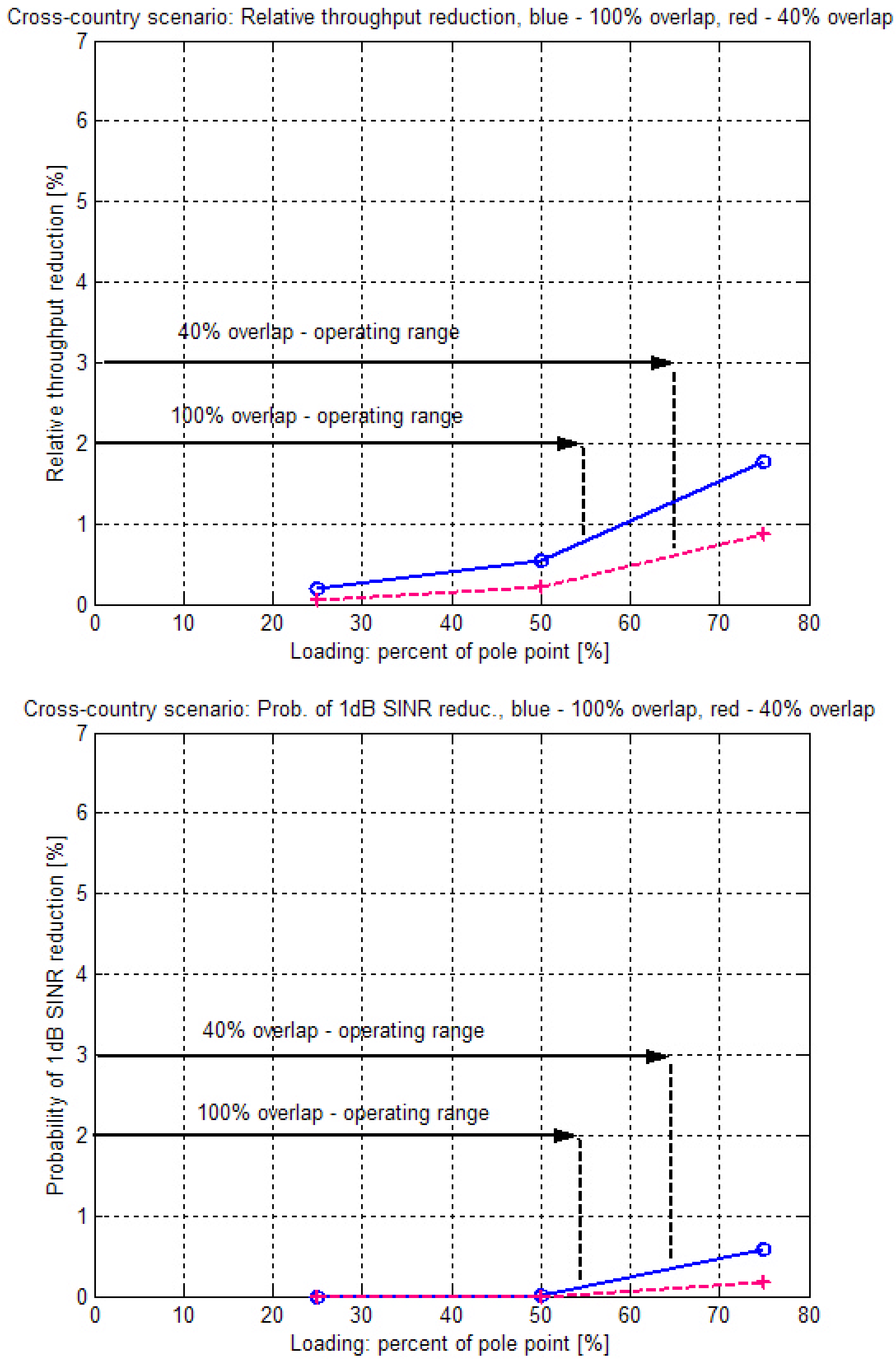


Figure 63. Performance curves for Cross-country scenario

In all cases, by looking at either the relative throughput reduction (before to after), as well as the probability of a 1 dB SINR reduction (again, before to after), each CDMA system, System 1 and System 2, is capable of operating near 50% of the pole point. By all standard measures, this is considered a nominal operation of a CDMA network. In the cross-country case, the individual system loadings can be slightly higher than 50% of the pole point.

Given that the public benefit is being served by adopting this spectrum migration concept, and that the concept is technically viable, AirCell strongly recommends that the FCC adopts this proposal in a timely fashion.

10 Appendix A: Analysis of the Worst-Case C/I Ratio in K=3 Frequency Reuse Scenario

Consider an ideal ATG cellular system implementing a narrowband FDMA technology with a frequency reuse pattern of K=3. A geographical layout of such a system is presented in Fig. A.1. From Fig. A.1, it is seen that the worst-case *C/I* occurs at point A. This point is at the edge of the serving site's coverage area. As a result, the signal from the serving site is at the lowest possible level. At the same time, point A is in the closest proximity of the first tier co-channel interferers and the level of interference is the highest. As seen, there are six interferers in the first tier[10] and in the worst-case scenario all of them are active at the same time. Assuming the same ERP for all the sites in the system, the *C/I* ratio at point A depends on three factors: the distance between point A and the serving cell site (i.e. cell site radius), distances between point A and the first tier interferers and radiation patterns of utilized antennas.

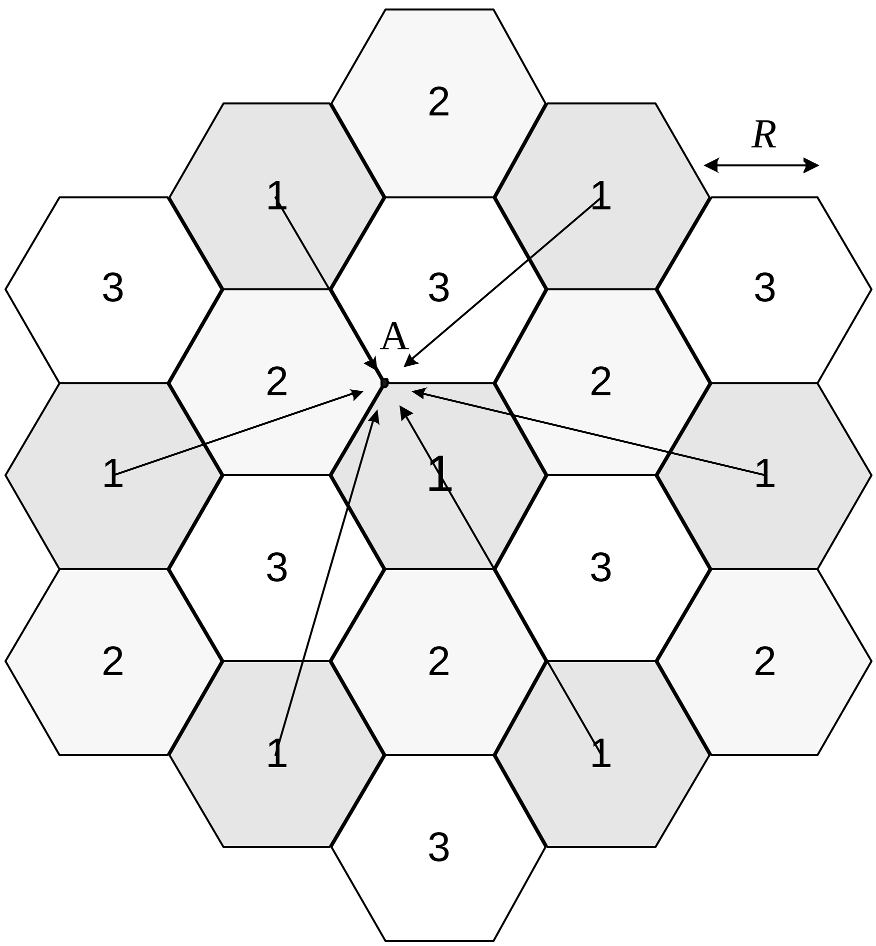


Figure A.1. Illustration of an ideal system with K=3 frequency reuse

[10] The impact of the second tier interferers can be safely neglected. They are far away from considered bcation (point A) and their signals are weak. Additionally, for large cells, the second tier interferers are shadowed by the Earth's surface.

From Fig. A.1, the distances between point A and appropriate cell sites can be calculated as:

Distance to serving site

$$d_s = R \tag{A.1}$$

Distances to interfering sites

$$d_1 = 2R \tag{A.2}$$
$$d_2 = d_3 = R\sqrt{7} \tag{A.3}$$
$$d_4 = d_5 = R\sqrt{13} \tag{A.4}$$
$$d_6 = 4R \tag{A.5}$$

Therefore, the worst case *C/I* ratio is given by

$$\left(C/I\right)_{WC} = \frac{G_s d_s^{-n}}{\sum_{i=1}^{6} G_i d_i^{-n}} \tag{A.6}$$

where

- G_s - antenna gain of the server in the direction of the aircraft
- G_i - antenna gain of the *i*th interferer in the direction of the aircraft
- d_s - distance from point A to the serving cell
- d_i - distance to the *i*th interferer
- n - path loss exponent

Substituting, (A.1) to (A.5) into (A.6) yields

$$\left(C/I\right)_{WC} = \frac{G_s R^{-n}}{G_1\left(2R\right)^{-n} + \left(G_2 + G_3\right)\left(R\sqrt{7}\right)^{-n} + \left(G_4 + G_5\right)\left(R\sqrt{13}\right)^{-n} + G_6\left(4R\right)^{-n}} \tag{A.7}$$

or

$$\left(C/I\right)_{WC} = \frac{G_s}{G_1\frac{1}{2^n} + \left(G_2 + G_3\right)\frac{1}{7^{n/2}} + \left(G_4 + G_5\right)\frac{1}{13^{n/2}} + G_6\frac{1}{4^n}} \tag{A.8}$$

The equation of the form provided in (A.8) is frequently used to estimate the worst case *C/I* in terrestrial cellular systems [1]. As a reasonable simplification, it is usually assumed that the antenna gains in the direction of the mobile are approximately the same and that the cell sites are of a relatively small size so that the effects of the Earth's curvature can be neglected. Under these assumptions, and using typical terrestrial value of $n = 4$, (A.8) can be evaluated as

$$\left(C/I\right)_{WC} = \frac{1}{\frac{1}{2^4} + \frac{2}{7^2} + \frac{2}{13^2} + \frac{1}{4^4}} = 8.40 \rightarrow 9.24 \text{ dB} \tag{A.9}$$

The terrestrial propagation environment is characterized with severe Rayleigh fading. For that reason, the *C/I* ratio of just 9.24dB is usually insufficient to guarantee a sufficient level of call quality. As a result, the reuse of $K = 3$ is rarely found in terrestrial cellular systems.

Use of (A.8) in the case of ATG cellular systems requires some additional considerations. First, in ATG systems the radii of the cell sites are usually quite large. Therefore, the effects of the Earth's curvature cannot be neglected. Second, the aircraft are at altitudes that usually exceed 20,000 feet. High altitudes make the aircraft visible from greater distances. Finally, the propagation conditions are essentially free space with $n = 2$. Taking these considerations into account, (A.6) can be modified as

$$(C/I)_{WC} = \frac{G_s(d_s, h_A, h_B)d_s^{-2}}{\sum_{i=1}^{6} G_i(d_i, h_A, h_B)d_i^{-2}} \tag{A.10}$$

where

h_A - altitude of the aircraft

h_B - radiation centerline of the base station

and other quantities are as defined in (A.6).

In (A.9), it is explicitly noted that the gain of the antenna in the direction of the aircraft depends on three factors: the distance between the aircraft and the base, the radiation centerline of the base and the aircraft altitude. However, the gain of the antenna applies only if the aircraft is above radio horizon. At large distances from the base, the aircraft falls into the Earth's radio shadow, and the amount of the received energy becomes vary small.

10.1 *Earth Shadow in ATG Cellular Systems*

Consider the situation depicted in Fig. A.2. It is seen that at any given aircraft distance d_A, that is larger than the distance to radio horizon, there exist a minimum altitude below which the aircraft flies inside the Earth's shadow. From figure A.2, the following relations hold.

$$\cos(a) = \frac{R_E}{R_E + h_B} \Rightarrow a = \cos^{-1}\left(\frac{R_E}{R_E + h_B}\right) \tag{A.11}$$

$$d_H = R_E a = R_E \cos^{-1}\left(\frac{R_E}{R_E + h_A}\right) \tag{A.12}$$

$$d_A = bR_E \Rightarrow b = \frac{d_A}{R_E} \tag{A.13}$$

From triangle BOD

$$\cos(b - a) = \frac{R_E}{R_E + H_{\min}} \Rightarrow H_{\min} = \frac{R_E}{\cos(b - a)} - R_E \tag{A.14}$$

where $H_{\min}$ is the height of the Earth's shadow at the aircraft distance.

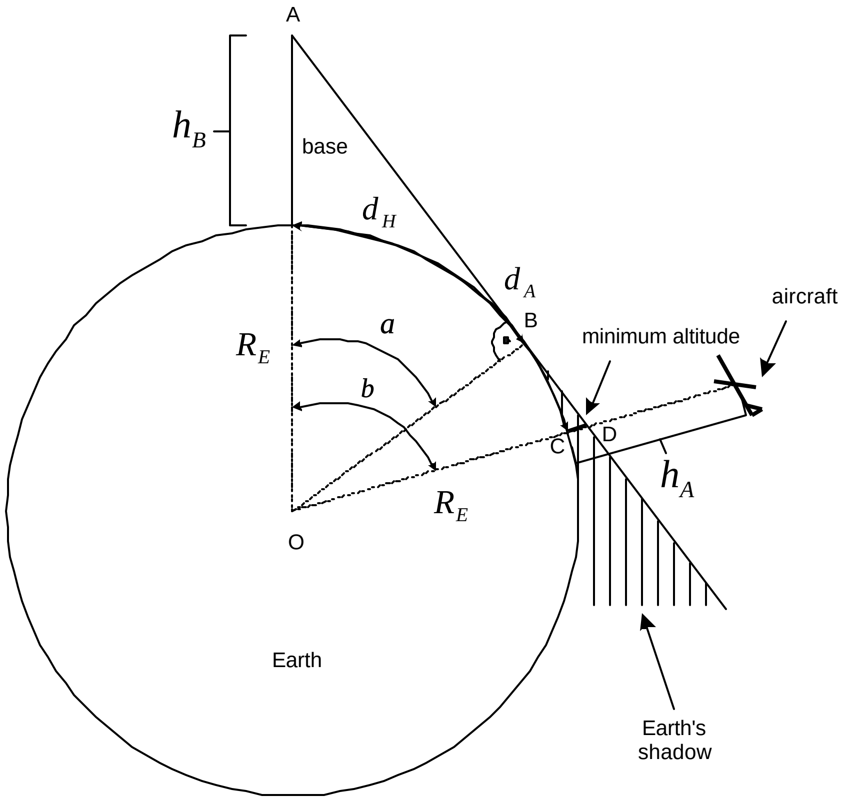


Figure A.2. Earth's shadow effect

Substituting (A.11) to (A.13) into (A.14), yields

$$H_{\min} = \frac{R_E}{\cos\left[\dfrac{d_A}{R_E} - \cos^{-1}\left(\dfrac{R_E}{R_E + h_B}\right)\right]} - R_E \tag{A.15}$$

Equation (A.15) provides the relationship between the aircraft to the base distance, the radiation centerline of the base, and the height of the radio horizon at the aircraft's distance. To illustrate use of (A.15), consider the following simple example.

Example A.1. Consider an aircraft at a distance of $d_A = 264$ miles form an ATG cell site. If the cell site has a radiation centerline of $h_B = 130$ feet, determine the minimum altitude of the aircraft so that it flies above the radio horizon. Assume a normal propagation condition, i.e., $R_E = 4/3 \cdot R_{E0}$, where $R_{E0} = 3963$ miles [6].

Typical radio radius of the Earth is given as

$$R_E = 4/3 \cdot 3963 \cdot 1.609 = 8501.96 \text{ km} \tag{A.16}$$

Using (A.15),

$$H_{min} = 8501.96\left\{\frac{1}{\cos\left(\frac{264 \cdot 1.609}{8501.96} - \cos^{-1}\left(\frac{8501.96}{8501.96 + 0.04}\right)\right)} - 1\right\} = 9.35 \text{ km} \rightarrow 30{,}690 \text{ feet} \quad \text{(A.17)}$$

Therefore, at a distance of 264 miles from the base, the aircraft that are flying at altitudes below 30,052 feet are in the Earth's radio shadow. As a result, the base station signal will be attenuated to the point at which its presence at the aircraft antenna can be safely neglected.

For some nominal values of base station radiation centerlines and typical propagation conditions, (A.15) is used to generate the family of curves presented in Fig. A.3. For a given base station height, the curves provide a relationship between the distance to the aircraft and the height of the Earth's shadow at the aircraft's distance. For example, if the radiation centerline of the base is 150 feet (green line), and the aircraft's flying altitude is 30,000 feet, the aircraft will be in the Earth's shadow for distances greater than 260 miles. For aircraft to base distances above 300 miles, the aircraft will be in the Earth's shadow for all altitudes used in commercial flights.

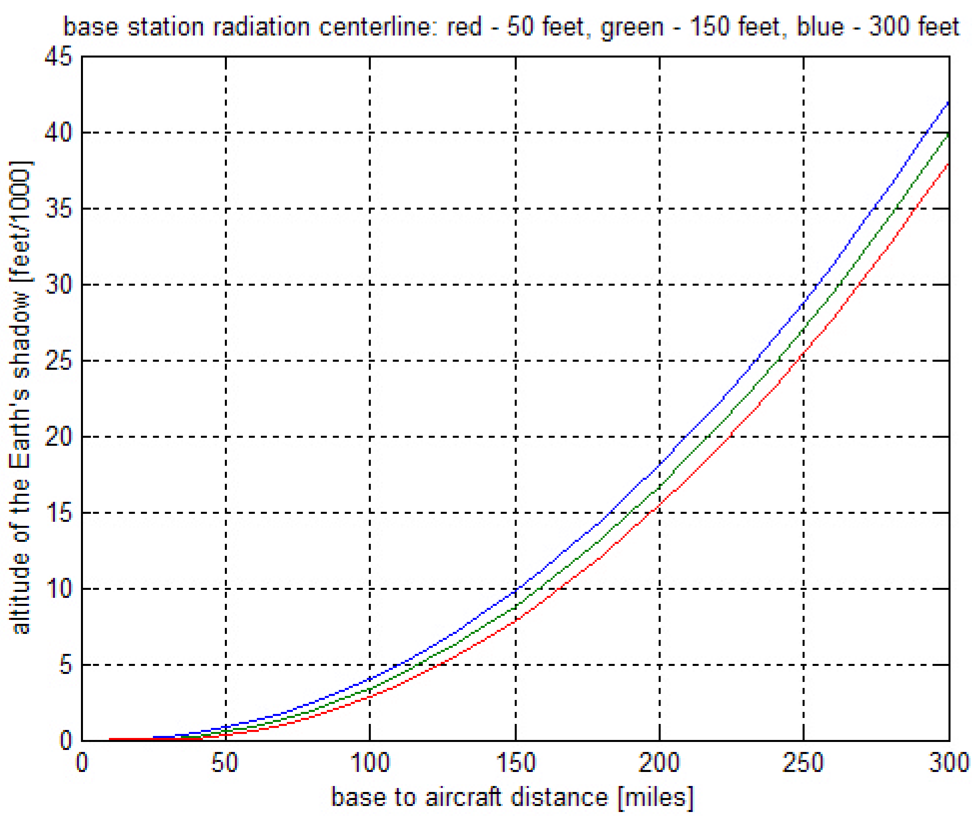


Figure A.3. Relationship between aircraft distance and the altitude of the Earths shadow

The curves presented in Fig. A.3 are derived assuming that there is no significant terrain blockage of the radio path. Existence of such blockage increases the required aircraft altitude for a given base to aircraft distance.

10.2 *Antenna Pattern Effects*

Equation (A.15) can be used to determine the altitude of the Earth's shadow. For an aircraft flying in the shadow of the Earth, the radio path is obstructed and the energy received from the base station becomes very small. For an aircraft that is flying above the Earth's shadow, the level of the received signal depends on the shape of the base antenna pattern. To control negative impact of multipath propagation in ATG systems, it is common practice to implement antennas with uptilted vertical patterns like the ones used for simulations presented in Section 3 of this report.

Consider the situation depicted in Fig. A.4.

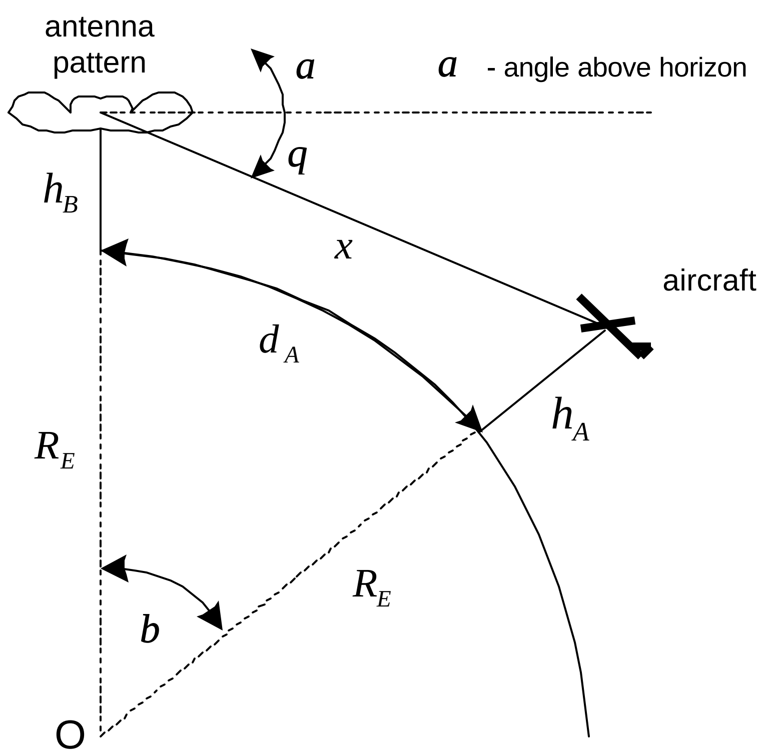


Figure A.4. Effects of uptilted antenna pattern in cellular systems

From figure A.4, the following relations hold.

$$b = \frac{d_A}{R_E} \tag{A.18}$$

$$x = \left[(R_E + h_A)^2 + (R_E + h_B)^2 - 2(R_E + h_A)(R_E + h_B)\cos(b)\right]^{1/2} \tag{A.19}$$

Using sine theorem

$$\frac{x}{\sin(b)} = \frac{R_E + h_A}{\sin(p/2 - q)} \tag{A.20}$$

Therefore,

$$q = p/2 - \sin^{-1}\left[\frac{1}{x}(R_E + h_A)\sin\left(\frac{d_A}{R_E}\right)\right] \qquad \text{(A.21)}$$

where x is given by (A.19) and $a = -q$.

Equation (A.21) is used to generate the family of curves shown in Fig. A.5. The curves are generated using typical base station height of 150 feet and assuming a typical base uptilt of four degrees.

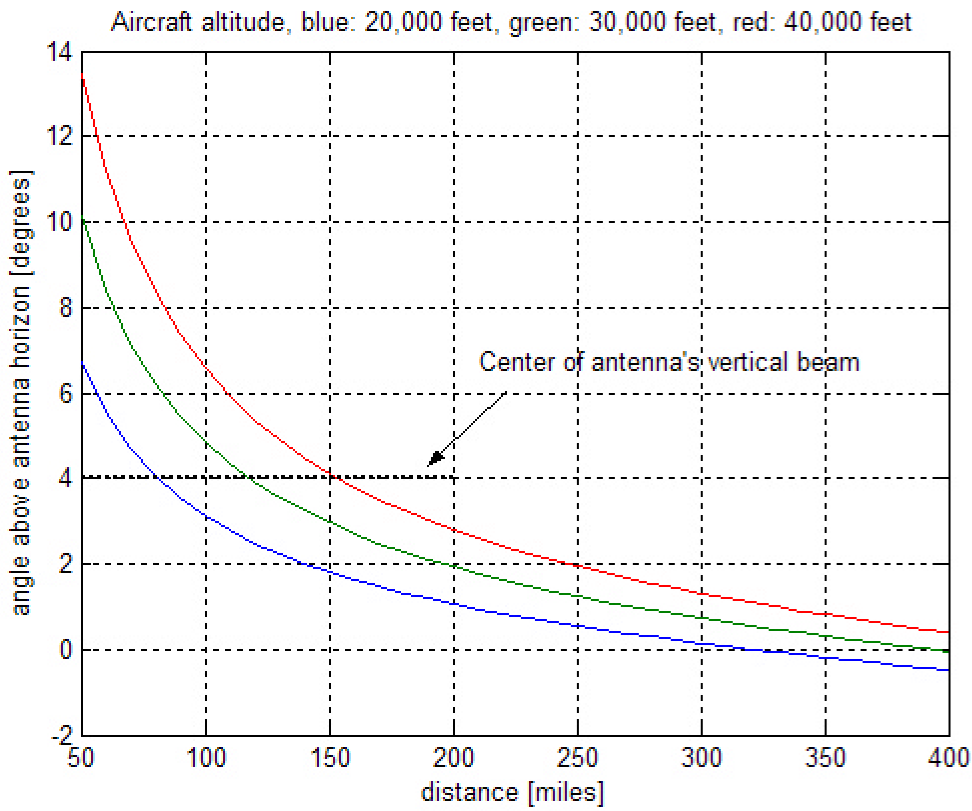


Figure A.5. Elevation angle of the aircraft as a function of aircraft to base separation

Using Fig. A.5, two important observations can be made.

1. Due to uptilted pattern of the base antenna, the aircraft that fly close to the base (50-150 miles) experience the highest gains. For example, an aircraft that flies at altitude of 30,000 feet (green line), is in the center of the main beam at a distance of approximately 115 miles from the base.
2. As the aircraft is further away from the base, its angular position approaches zero degrees and eventually becomes negative (see blue line in Fig. A.5). Therefore, the aircraft at

large distances are outside of the antenna's main beam and therefore the antenna gain in their direction becomes reduced.

10.3 *Evaluation of the Worst-Case C/I*

Results of the analysis provided in Sections 10.1 and 10.2 are used to predict the worst-case *C/I* in two operational scenarios analyzed in this report. Both scenarios are evaluated assuming standard propagation conditions [6]. The system configuration parameters are consistent with the simulation parameters provided in Section 3.

10.3.1 Worst-Case C/I in Cross-Country Scenario

In the cross-country scenario, the radii of the cell sites are $R = 100$ miles. Therefore, the distances from the aircraft in point A (c.f. Fig. A.1) to the first tier interfering sites may be calculated as:

$$d_1 = 2R = 200 \text{ miles} \tag{A.22}$$

$$d_2 = d_3 = R\sqrt{7} = 264.56 \text{ miles} \tag{A.23}$$

$$d_4 = d_5 = R\sqrt{13} = 360.56 \text{ miles} \tag{A.24}$$

$$d_6 = 400 \text{ miles} \tag{A.25}$$

Comparing values in (A.22) to (A.25) with curves presented in Fig. A.3, one observes that for all altitudes used in commercial flights, the aircraft is in the Earth's shadow for interferers 4, 5 and 6. Therefore, their impact on the *C/I* value is negligible.

Furthermore, from Fig. A.5, it is seen that for interferers 2 and 3, the elevation angle of the aircraft is around one degree. Since ATG antennas are usually designed with a radiation pattern null on the horizon, the interference coming from interferers 2 and 3 becomes significantly reduced.

As a final result, one observes that the only significant interference comes from the first interferer. Therefore, the worst-case interference in the cross-country scenario becomes

$$(C/I)_{WC} = \frac{1}{x1/4} = 4\frac{1}{x} \tag{A.26}$$

where x is the gain of the antenna from the first interferer in the direction of the aircraft. The maximum value of x is 1 and the worst-case interference in the cross-country scenario is always grater than 4 (6dB).

The value of $(C/I) = 6$ dB is insufficient to guarantee good quality communication for most terrestrial cellular systems due to Rayleigh fading nature of the propagation environment. However, the ATG channel does not experience severe Rayleigh fading and can be more closely modeled as AWGN[11] channel. For an AWGN channel, the *C/I* value of 6dB is sufficient to provide an acceptable performance level for many digital modulation schemes [7].

[11] AWGN is an acronym for Additive White Gaussian Noise channel

10.3.2 Worst-Case C/I in Airport Scenario

In the case of airport scenario, the radii of the cell sites are $R = 12.5$ miles. Therefore, the distances to the first tier of interfering sites can be calculated as:

$$d_1 = 2R = 12.5 \text{ miles} \quad \text{(A.27)}$$

$$d_2 = d_3 = R\sqrt{7} = 33.07 \text{ miles} \quad \text{(A.28)}$$

$$d_4 = d_5 = R\sqrt{13} = 45.07 \text{ miles} \quad \text{(A.29)}$$

$$d_6 = 50 \text{ miles} \quad \text{(A.30)}$$

Due to relatively small distances, all of the interferers see the aircraft above the Earth's shadow.

As it was discussed in Section 3, due to capacity reasons, the cells around the airports are usually sectorized. For sectorized sites, the interference scenario in an ideal system is illustrated in Fig. A.6. As seen, due to orientation of the sectorized antennas, the interference becomes reduced. Interferers 1, 2 and 3 are radiating away from point A.

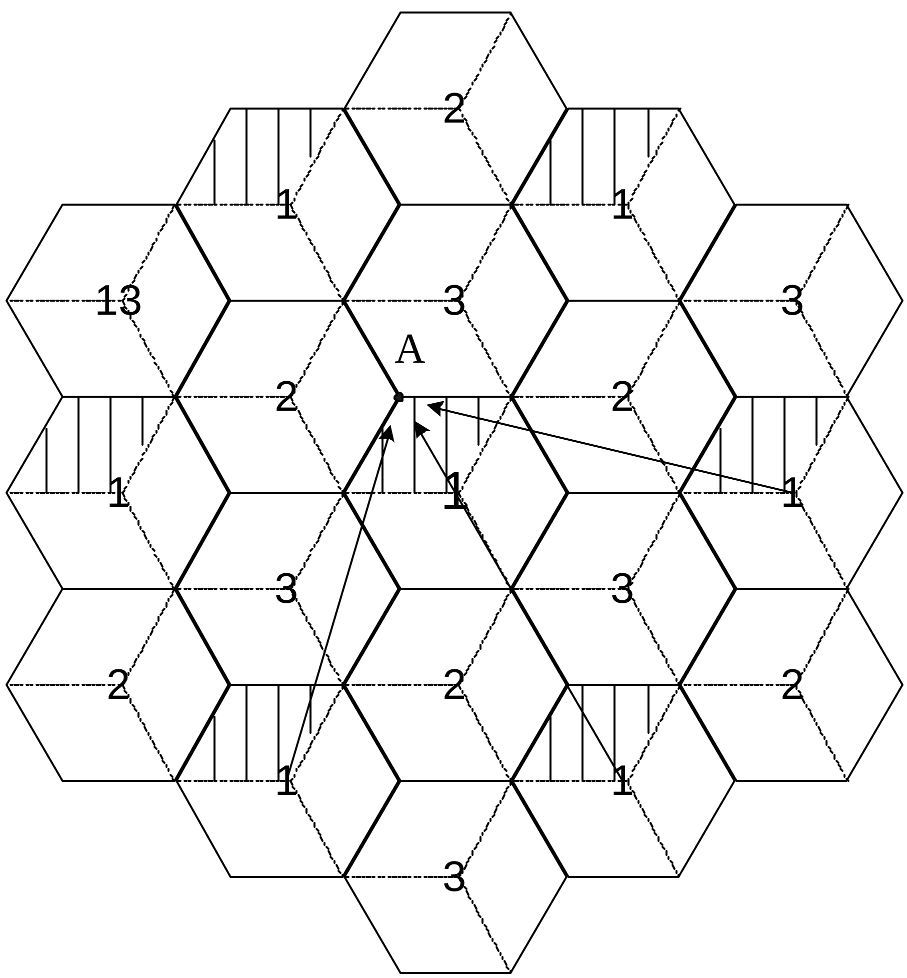


Figure A.6. Illustration of the interference scenario in sectorized cell layout around airports

Therefore, in the case of airport scenario, the only significant interference comes from interferers 4, 5 and 6. The worst-case interference can be calculated as

$$(C/I)_{WC} = \frac{1}{2/13 + 1/16} = 4.633 \rightarrow 6.64 \text{ dB} \tag{A.31}$$

Therefore, in airport scenario, the *C/I* is slightly higher than in the case of cross-country scenario. Due to predominantly AWGN nature of the ATG channel, the *C/I* of 6.64 dB is sufficient to guarantee acceptable performance for many digital modulation schemes.

At the end of this analysis, it is important to make the following observations:

- The *C/I* values calculated in the cross-country and airport scenarios represent the absolute worst-case. The worst-case interference occurs above a single geographical location at the edge of the serving cell site's coverage area. For all other points that are inside of the cell, the *C/I* values are better than what is predicted by (A.26) and (A.31).
- The *C/I* values in (A.26) and (A.31) assume simultaneous activity of all co-channel sites. Even in the case of significant traffic loading this is an event with a very low probability.
- The worst-case *C/I* values are calculated assuming full cellular deployment. In other words, the cells are populating all places in a hexagonal grid. However, in practical ATG systems, the cells are placed along major airplane corridors in a "string of pearls" configuration. For such configuration, the number of interferers is significantly reduced and the worst-case *C/I* improves.

11 References

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