ATG Spectrum Migration

Evaluation of the ATG Spectrum Migration Concept

Prepared for

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Prepared by

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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. It uses expensive, proprietary technology that never achieved commercial economy of scale or optimum spectral efficiency. With the retirement of all but one remaining network operator, this legacy narrowband and low data rate architecture fails to best serve the public—a public that is becoming accustomed to high speed connectivity anywhere, anytime.

In contrast, the advent of 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 capability 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. The spectral migration concept described herein enables spectral efficiency to soar 16-fold over the current paradigm and offers true broadband telecommunication connectivity to and from airborne aircraft.

This technical research paper critically evaluates the deployment of 1.25MHz CDMA waveforms in the ATG 2 MHz bands. Through the use of sophisticated Matlab™ computer simulations, RF systems modeling is integrated with situational aircraft flight profiles to "measure" the likelihood of self-, cross- and inter-network interference potentials. Through this approach, key input variables are modified to evaluate specific scenarios such as operation near an airport or while in cross-country flight. More specifically, CDMA2000's data architecture, 1xEvDO, is examined in detail to assess ATG band spectral efficiency and operational compatibility.

Key technical and operational objectives of the ATG spectral migration include:

- Creating an evolutionary path for the incumbent operator to transition from the present narrowband paradigm to broadband CDMA,
- Enabling the operation of two concurrent CDMA network service providers (duopoly) during the evolutionary (transitional) period as well as when CDMA is exclusively deployed by both operators (mature project phase),
- Ensuring compatibility of ATG systems with adjacent cellular B' and SMR operations, and
- 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.

1.1 *Concept Description*

Through innovative migration of the ATG spectrum, substantive spectral efficiency is realized. As shown in Figure ES1, two 1.25 MHz wide CDMA carriers co-exist within the 2 MHz composite ATG bandwidth. Of particular note, observe that the air-to-ground and ground-to-air allocations are swapped between the two respective networks, System 1 and System 2. Despite the allocation's overlap of 500 KHz, the corresponding cross-interference potential is virtually negligible at nominal network loading (50% of the pole point). This is true even when both System's 1 and 2 are co-polarized (e.g. both are vertically polarized). If the systems' are orthogonally polarized[2], an additional 12-15 dB of isolation is realized; and in this case, cross-interference is for all practical purposes nonexistent. However, the results presented in this report demonstrate that orthogonal polarization between System 1 and System 2, is not required for this concept to be viable.

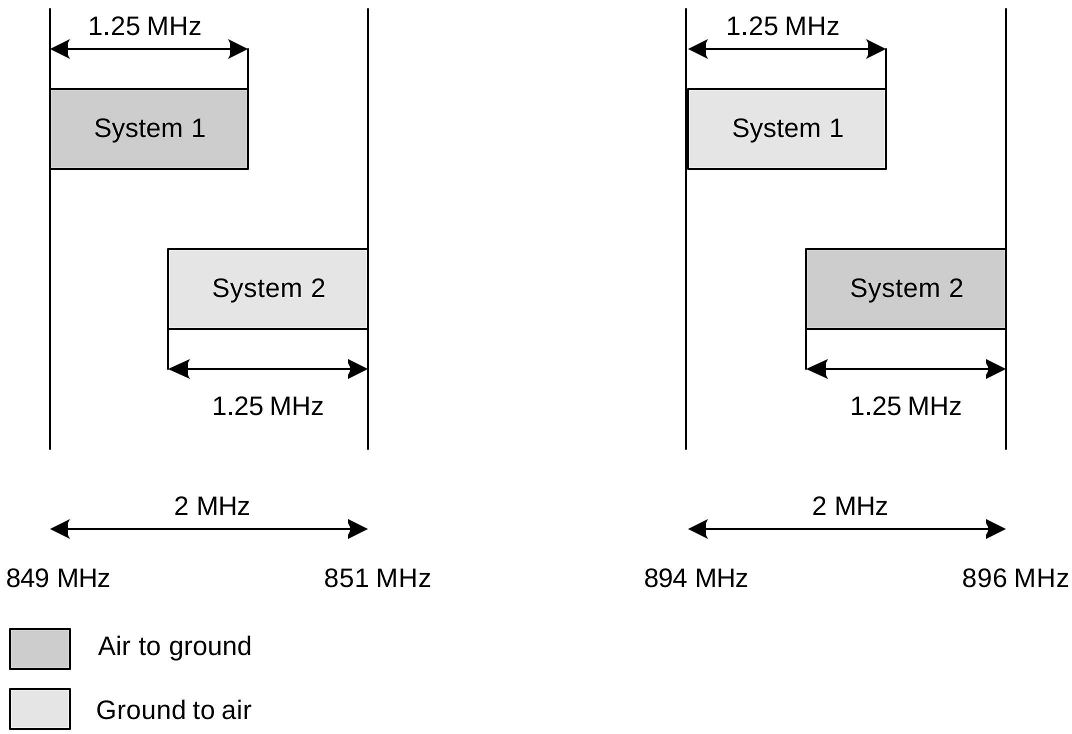

Figure ES1. CDMA spectrum plan for reallocated ATG band

Because the spectrum allocations for two communication links are swapped, the only two cross-interference paths are: aircraft-to-aircraft and base-to-base. No other interference paths are possible. Figure ES2 shows possible cross interference paths; the aircraft-to-aircraft interference path is analyzed in detail in this report.

[2] For example, one network is vertically polarized and the other network is horizontally polarized.

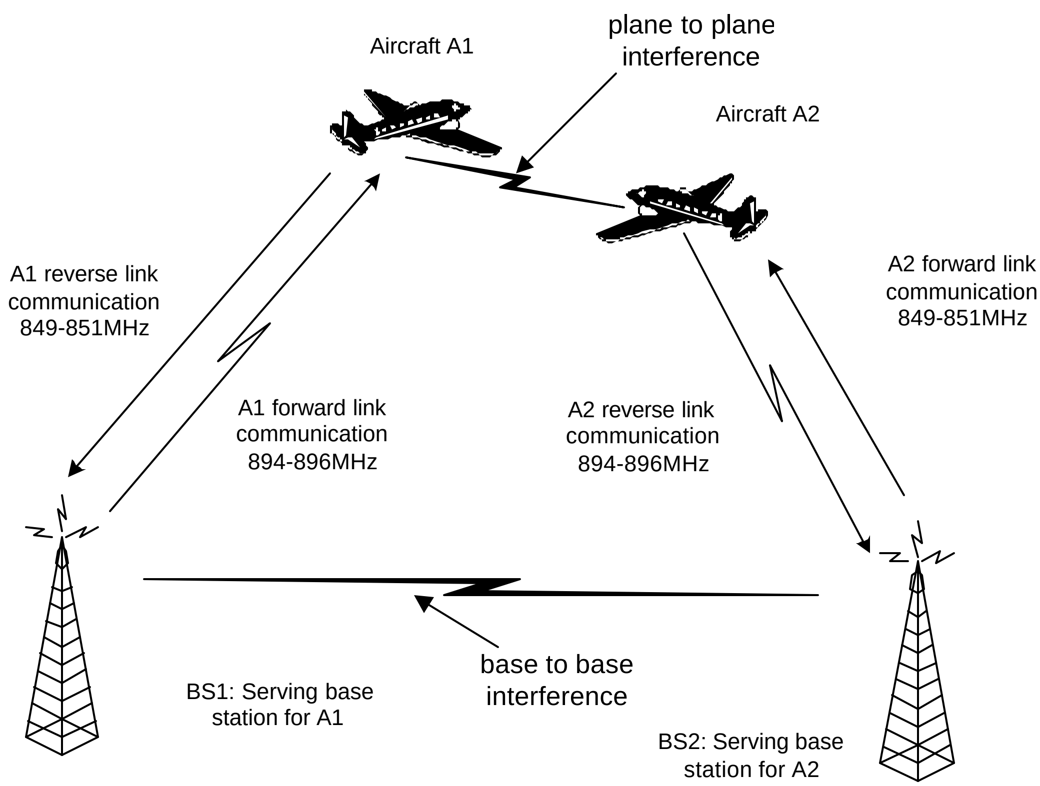

Figure ES2. Possible cross interference paths

Base-to-base cross interference between System 1 and System 2 is essentially zero. This interference is controlled by spacing the two network's respective base stations, System 1 and System 2, more than 5-10 miles apart (terrain and antenna height dependent) and by using up-tilted base antenna patterns[3] (which are also required to manage own-network multipath).

Aircraft-to-aircraft cross-interference is limited due to their physical separation. FAA regulations define minimum altitude and horizontal separation distances (see report for details). This physical separation between the aircraft of System 1 and System 2 creates substantial isolation. Even at airports, where the spacing between aircraft is reduced, the transitory effects of cross-interference are not material to network operations. When a CDMA network experiences interference, it self-manages the transitory interference event by modifying the link's data rate, modulation type, and/or coding rate to ensure that the communication link remains active, albeit at a lower throughput data rate. In short, when cross interference does occur, the CDMA system naturally experiences "graceful degradation" by reducing the data rate temporarily while retaining a high quality link. At no time does either System 1 or System 2 experience an outage or sustained harmful interference as a result of cross-interference from aircraft to aircraft.

[3] Through previous studies and reports to the FCC, AirCell has shown that the Cellular Geographic Service Areas (CGSA) of base stations with up-tilted antenna patterns are very small.

Not only is this aircraft-to-aircraft cross system interference manageable by the CDMA network, but more important, its impact is virtually negligible to operation of either System 1 or System 2. The results presented in this report demonstrate that the aggregate effect of the cross-system interference on overall data throughput and system capacity is insignificant.

1.2 *Modeling Results*

Aircraft-to-aircraft transitory cross interference only affects the forward path data rate; the forward path is from the base station to the aircraft. The reverse path, aircraft-to-base, is not impaired for either network- System 1 or System 2. As previously discussed, when a transitory cross-interference event occurs, it is managed automatically by the affected network. As soon as the affected network determines the transitory cross-interference event is over[4], the forward path data rate increases to its nominal value.

With this understanding, the modeled results show a "before and after" comparison of overall throughput data rates— "before" being a cross-interference free scenario; "after" being a scenario that has transitory aircraft-to-aircraft cross interference.

The two scenarios modeled are:

- The Airport scenario
- The Cross country scenario

The Airport scenario model assumes that the aircraft from both networks (1 and 2) are in/around a localized region. The aircraft are flown at various altitudes, velocities and directions consistent with an airport location. Similarly, the Cross country scenario simulates aircraft flying between airport destinations, typically at relatively constant altitudes and horizontal separation as specified by FAA regulations.

For each of these scenarios, two specific cases need to be considered:

- Phase 1: 100% CDMA Carrier spectrum overlap (this is during the evolutionary period when narrowband ATG operation co-exists with broadband CDMA operation)
- Phase 2: 40% CDMA Carrier spectrum overlap (this is when the narrowband ATG operation is terminated and only CDMA operation is present).

As shown in Figure ES3, Phase 1, expected to be 12 months or less, is where narrowband FDMA ATG co-exists with broadband CDMA access. This is the transitional period which allows the incumbent ATG operator a graceful migration to pure CDMA operation. After the phase-out of narrowband ATG, Phase 2 has only CDMA operating for both System 1 and 2. Phase 2 has greater spectral system capacity relative to Phase 1 since cross-interference is reduced.

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[4] Through self-determined methods inherent in the existing CDMA networks operation; the network continuously monitors forward link Signal to Interference and Noise Ratio (SINR) and adaptively adjusts data rates to maintain a high quality link.

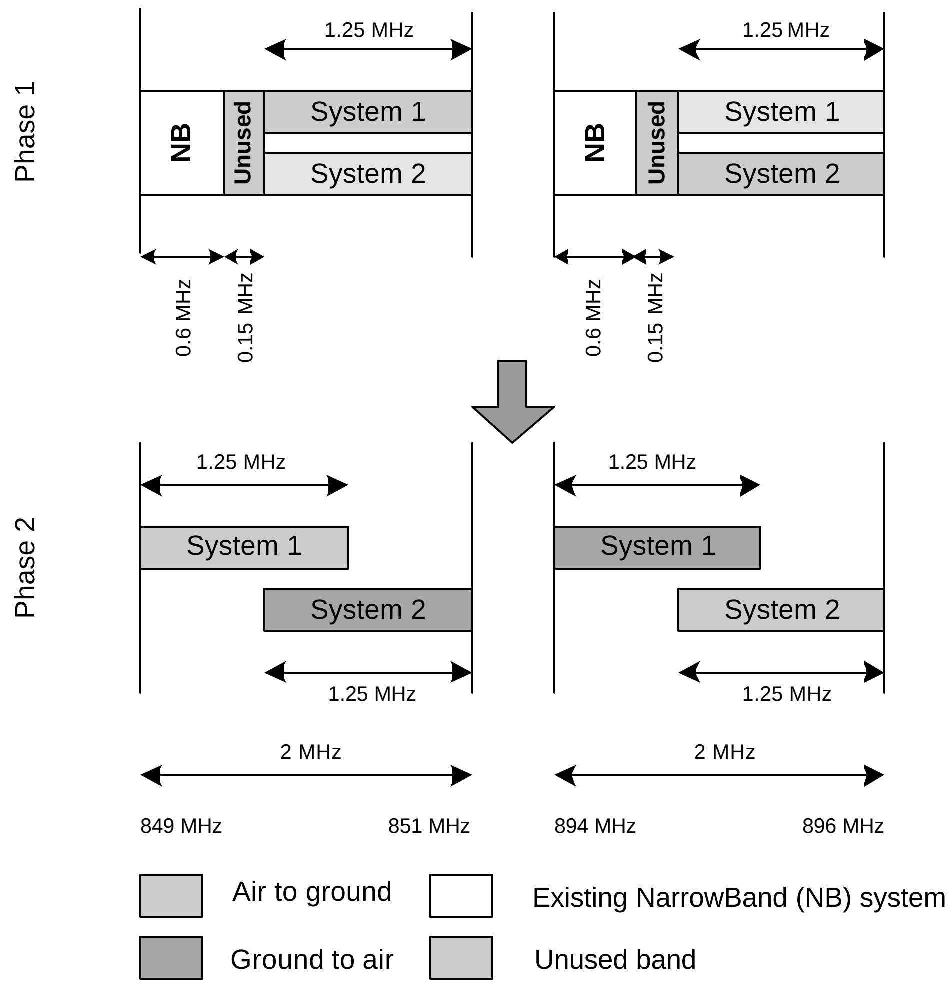

Figure ES3. Spectral migration plan

Thus, four specific models have been simulated in Matlab™ and the summary of the results from each is presented 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 ES 1 and ES2. Table ES1 (a) and (b) show the results for the Airport scenario while Tables ES2 (a) and (b) are derived for the Cross-country scenario.

Table ES1 (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 ES1 (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 ES2 (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 ES2 (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

The 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 cross-system interference is not present. This is clearly not an issue and certainly does not even approach the definition of "Harmful Interference".

The results, and conclusions, only get better from this worst-case scenario. The results for the Cross country scenario with 100% overlap are shown in Tables ES2 (a) and (b). Notice that for a typical loading scenario of 50%, the relative reduction of forward path throughput dropped from 1.09% to 0.55%. This decrease can be explained by increased aircraft spacing in the cross-country scenario and corresponding decrease in probability of their close encounter.

In the second phase of deployment, the narrowband ATG system is retired and both networks transition to CDMA operation with 40% mutual spectrum overlap. The results of simulations for the second phase of deployment and two typical operating scenarios are provided in Tables ES3 and ES4.

Tables ES3 (a) and (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% - neither number being problematic. The improvement in the data rate is the result of reduced cross system interference.

Table ES3 (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 ES3 (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

Finally, Tables ES4 (a) and (b) provide summary of the results obtained for cross-country scenario and 40% spectrum overlap. In a typical scenario when the system loading is about 50%, the reduction of the forward link data rate dropped from 0.55 to only 0.21%. This improvement in the forward link throughput can be explained by smaller cross system interference.

Table ES4 (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 ES4 (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

1.3 *Conclusions*

Significant improvement in operational and spectral efficieny result from the concepts proposed herein. The cross system interference effects are negligible for all considered scenarios, both transitional and full operation. Substantive public benefit is realized from reallocating the ATG spectrum. Therefore, the FCC should adopt the spectral migration proposed herein.

2 Introduction

This report presents a study evaluating the reuse possibility for the spectrum allocated to the Air To Ground (ATG) service. The study was performed using extensive computer simulations of two cellular-like systems operating in the ATG frequency band. The principal goal of the study is to examine the likelihood of a harmful interference between the systems, the impact of such interference on the spectral capacity, as well as to outline some methods that can be used for the interference mitigation.

2.1 *Review of Proposed ATG Spectrum Migration*

The ATG is allocated a pair of frequency bands in the VHF portion of the radio spectrum. The two bands are occupying frequencies from 849 to 851 MHz, and from 894 to 896 MHz. Each band is 2MHz wide and supports one communication link of a system utilizing frequency division duplexing. This means that one of the bands is used for communication from *ground to air*, while the other one is used in the opposite direction.

Two proposals for migration of the ATG spectrum are considered in this study. The first proposal is less aggressive and it is envisioned as a solution that can be used in high capacity scenarios. The second proposal is more aggressive and it is well suited for situations of lower spectrum loading.

The first proposal for the frequency reuse of the ATG spectrum analyzed in this study is presented in Fig. 1. As seen, the pair of spectrum bands is hosting two CDMA systems. The systems are based on 1xEvDO technology and each has a channel bandwidth of 1.25MHz.

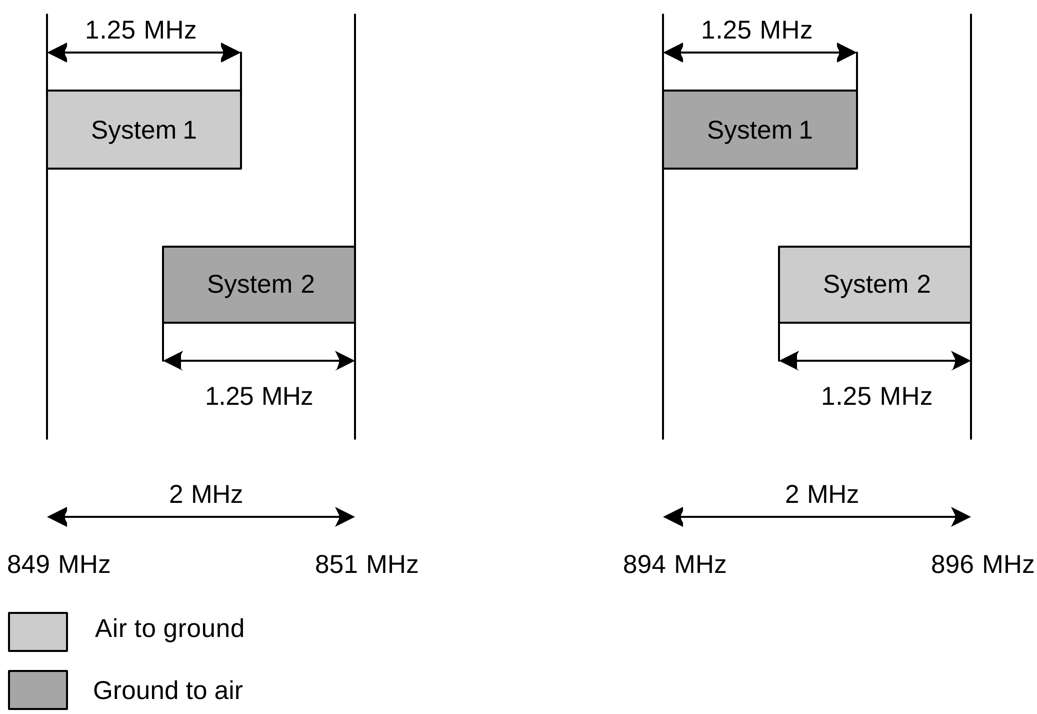

Figure 1. The first proposal for ATG spectrum migration

Therefore, there is a 500 kHz spectrum overlap between the two CDMA carriers. To reduce the interference between the systems, the allocations of the ATG bands are swapped. In particular, 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. With swapped allocation of the ATG bands, the interference potencial results from 0.5 MHz of spectrum overlap, and it occurs on paths between aircraft or between base stations. As illustarted in Fig. 2, the air to ground communication for aircraft A1 occurs in the frequency band from 849-851 MHz and it may potencially interfere with the ground to air communication for aircraft A2. Similarly, the air to ground communication for aircraft A2 may present an interference source for the ground to air communication of aircraft A1. The interference potencial exists between two base stations as well. However, this interference is easily managed through proper base station separation and appropriately chosen base station antenna patterns. Therefore, with the spectrum allocation as indicated in Fig. 2, the dominant type of interference is the one occuring on the path from aircraft to aircraft. For that reason, this type of interference is the main focus of this study.

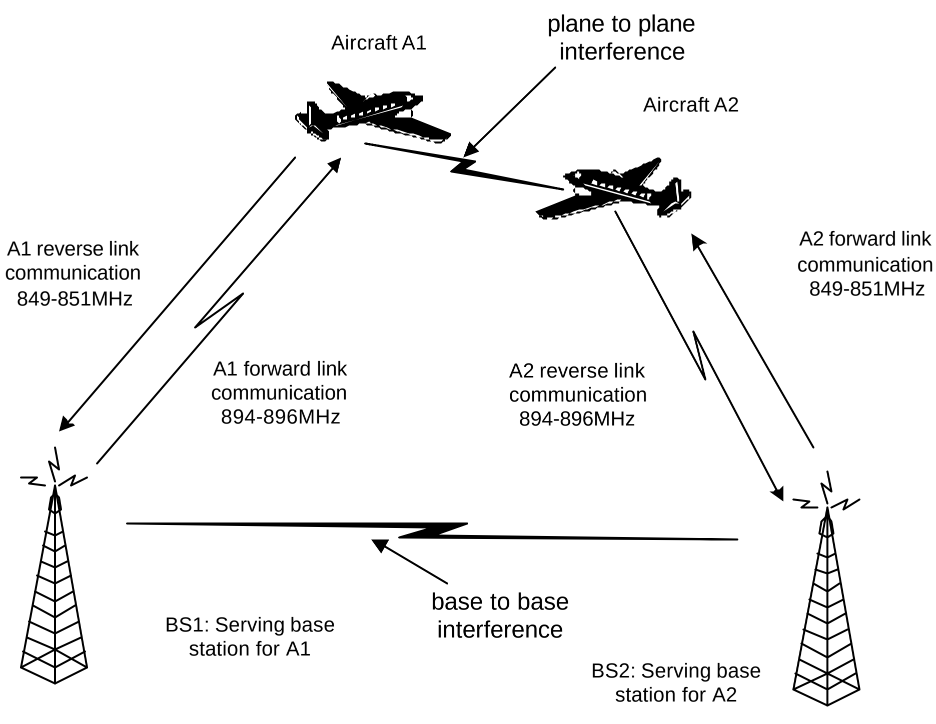

Figure 2. Illustration of potential interference in the ATG frequency reuse

The second proposal for migration of the ATG spectrum is presented in Fig. 3. In this case, the channels of the two CDMA carriers are overlapping over their entire bandwidth. As a result of the one hundred percent overlap, CDMA carriers do not occupy the entire ATG band. The non-occupied portion of spectrum can be used for support of existing narrowband technology. In the second scenario, the interference potential between the two CDMA carriers is higher than in the case of the first scenario. For that reason, the second scenario is envisioned as a solution for initial deployment when the CDMA traffic capacity served by the two systems is relatively small.

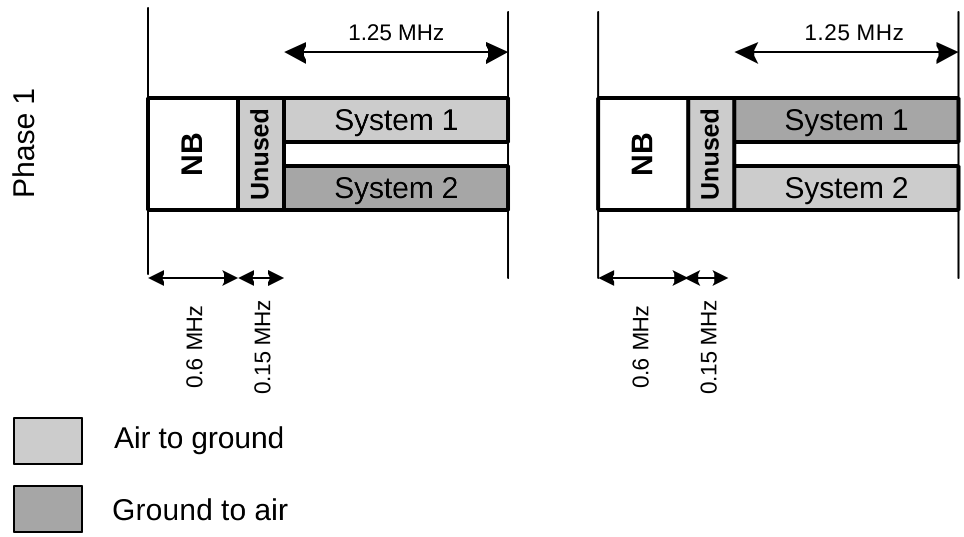

Figure 3. The second proposal for ATG spectrum migration

2.2 *Public Benefits from ATG Spectrum Migration*

The present ATG architecture, comprised of FDMA separated 6KHz carriers, is woefully outdated in terms of its ability to deliver modern telecommunication services to aircraft while in flight. Comparing the existing ATG architecture capacity and data rates to the architectures proposed by AirCell (using 1.25 MHz CDMA carriers), the comparative advantages are nothing short of stunning. The migration of the ATG spectrum enables compelling services to: airline passengers, airline operators and TSA security officials. Additionally, the proposed CDMA architecture offers a duopoly structure ensuring competition that will drive innovative product and service offerings as well as economic advantages to subscribers.

First, the migration of the ATG spectrum realizes dramatic enhancement to ATG spectral efficiency. For example, at a given airport region:

- Using the existing ATG 6 KHz architecture- only 29 voice channels can be supported.
- Using the Reallocated ATG 1.25 MHz CDMA architecture- at 50% pole point loading, 240 voice channels per network or 480 voice channels total (both System 1 and System 2 networks combined).
- This realizes a spectral efficiency improvement of 16 times.

Average per plane data rates from a system perspective soar from merely tens of kilobits per second in aggregate to megabits per second. These broadband wireless air-to-ground pipes enable telecommunication services never before thought possible:

- High speed internet access (cabin, cockpit)
- High volume voice telephony (cabin, cockpit)
- Live multimedia services for passengers (live radio broadcasts)
- Live weather maps to the cockpit

- Airline operations data traffic
- Airline safety data traffic
- Airline preventive maintenance such as real-time engine monitoring
- Real-time "black box" data links to the ground
- TSA security communications
- Live, real time voice/data links for air marshals

The need for these types of telecommunication services seem almost obvious, and yet, today's air-to-ground telecommunication systems fall dramatically short. The migration of the ATG spectrum is the "enabler" that creates the setting which makes the above and much more possible.

2.3 *Outline of the Report*

As already mentioned, the main purpose of this report is to evaluate the cross systems interference resulting from the migration of the ATG spectrum in one of the ways presented in Figs 2 and 3. To accomplish the task, AirCell has developed a real time dynamic simulator of the 1xEvDO system operating in accordance with the proposed ATG spectrum plans. A detailed description of the simulator and simulation parameters used for different scenarios considered in this study is presented in Section 3. Theoretical analyses of two major aspects of system performance are presented in Sections 4 and 5. Section 4 estimates the capacity of an 1xEvDO system under assumptions of this study, while Section 5 performs the analysis of the worst case cross system interference scenario. The derivations in Sections 4 and 5 are analytical and they are used mainly to establish the boundaries of the systems' theoretical performance. The results presented in these two sections help determine some of the parameters used in the Monte Carlo simulations described in later sections. Simulation results are presented at length in Section 6. Concluding sections 7 and 8 outline the migration plan for the incumbent provider and discuss the interference potential between systems operated by CDMA ATG providers and adjacent cellular and SMR. The results of the study are summarized in Section 9.

3 Description of the Simulator

Due to the relative complexity of the proposed ATG spectrum reuse scenario, any analytical approach to the cross system interference analysis would have had to incorporate a set of significant 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 operating conditions. During the simulations, numerous 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.

For the MC simulations presented in this report, AirCell has developed a custom 1xEvDO simulator. The simulator is developed using the Matlab™ simulation platform. The simulations are performed in a dynamic manner, which allows a *time domain* tracking of the systems' performance. A more detailed description of the simulator is provided below.

3.1 *1xEvDO Simulator*

During simulations, the 1xEvDO simulator used to analyze the reuse of the ATG frequency band performs the following five steps.

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 cross 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.

More detailed explanations for each of the steps are provided as follows.

Step 1. In the first 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. 4. 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. One example of a typical initial scenario is presented in Fig. 4. Locations of the aircraft for the two systems are presented as either red or blue dots.

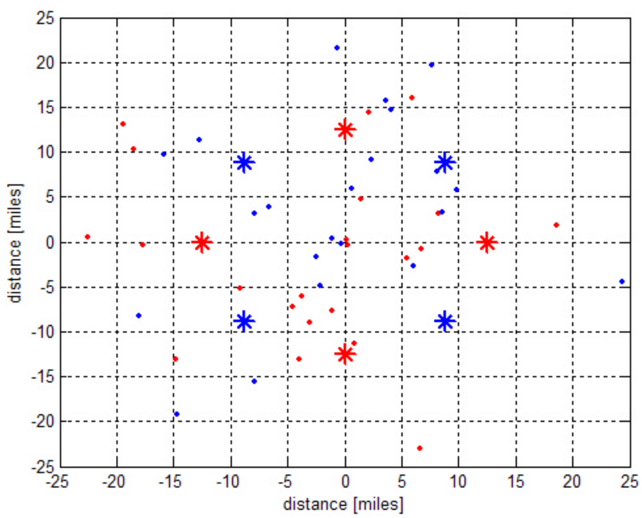

Figure 4. Example of an initial scenario; CDMA system 1 – red; CDMA system 2 – blue;

Step 2. For calculation of propagation path losses between a base station and an aircraft, the simulator uses a formula given by

$$PL = PL_{FS} + CL - AG(q,f) \tag{1}$$

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
$AG(q,f)$	- antenna gain of the base station expressed in dB

In (1), the free space path loss is calculated in accordance with [1]

$$PL_{FS} = 36.5 + 20\log(f) + 20\log(d) \tag{2}$$

where

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

As indicated in (1), 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. To simplify the simulations, the aircraft antenna is assumed as 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 aircraft antenna selectivity. For example, there is no blockage looking straight up.

For calculations of the path loss between a pair of aircraft, the simulator uses free space formula given in (2). Again, the effects of the antenna pattern as well as the body of the aircraft are neglected. As discussed, this leads to somewhat conservative interference predictions.

Step 3. The Key Performance Indicator (KPI) used to evaluate the impact of the cross 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. The quality of the pilot is expressed through a quantity called Signal to Interference and Noise Ratio (SINR). Formally, the SINR measurement is defined as [2]

$$SINR = \frac{S}{I_1 + I_2 + \cdots + I_N + N_0} \tag{3}$$

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.

One should notice that there is a difference between SINR in (3) 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 (3) 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. More specifically, depending on the reported SINR measurements, a base station determines its forward link data rate. One typical mapping between the forward link pilot SINR and the corresponding data rates is given in Table 1 [2].

Table 1. 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

For all calculations performed in the third step, the cross system interference is not taken into account. Therefore, each system is operating as if it were on its own. The results obtained this way are treated as a baseline performance.

Step 4. In this step, the SINR computations are performed while taking the cross system interference into account. As already mentioned in the previous section, the dominant cross system interference is coming from the reverse link (airplane 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 and this ultimately causes degradation in the forward link transmission rate. To calculate the interference, the simulator determines the reverse link transmission power. This is done in an iterative manner. The power of each aircraft is increased so that the signal at the serving base station meets a desired Eb/Nt threshold. The data rate on the reverse link is chosen as a function of the number of active mobiles within the aircraft. This is best illustrated through a simple example.

Example 1. Consider an aircraft with ten phone conversations. Assuming that each conversation uses 9.6kb/sec vocoder and that the voice activity is 0.5, the average aggregate data rate for the aircraft is

$$R_{aggregate} = 9.6 \times 0.5 \times 10 = 48 \text{ kb/sec} \tag{4}$$

However, when calculating the average data rate, several factors need to be taken into account. First, the aggregate rate as calculated in (4), is just a mean value. In any given time instant, the actual data rate is a random variable varying between 0 and 96kb/sec. Secondly, 1xEvDO supports only a discrete set of data rates [2]. Throughout the simulations, the aggregate data rate is rounded up to the closest 1xEvDO available rate.

For the results presented in this study, it is assumed that the dominant traffic type is voice. However, through manipulation of the activity factor and distribution of instantaneous traffic, other types of communication services can be simulated as well.

Once the necessary power for the reverse link transmission is determined, the SINR can be recalculated. The difference between the SINR calculated in this step, and the one calculated in Step 3, is used as a major indicator of the cross system interference.

Step 5. In this final step, the positions of the aircraft are recalculated in accordance with

$$\boldsymbol{r}(k+1) = \boldsymbol{r}(k) + \boldsymbol{v} \cdot \Delta t \tag{5}$$

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

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 market area is kept constant during the entire simulation.

3.2 *Description of the Simulation Test Bed*

The test bed used for simulations in this report is presented in Fig. 5. As seen, there are two systems, each having four base stations. The market of interest is assumed as circular with the cell sites of the two systems placed as indicated in Fig. 5. The aircraft are flown in a random fashion over the market area. The general parameters of the simulator are provided in Table 2. These parameters are kept the same for all simulations. Additional parameters that were adjusted to simulate particular scenarios are documented in appropriate sections.

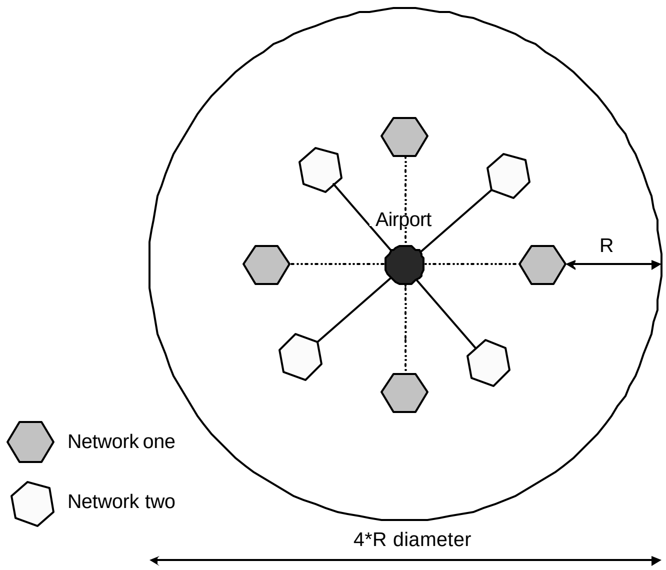

Figure 5. Topology of the test bed scenario

Table 2. Parameters of the simulator

Parameter	Value	Unit	Description
SIM_TIME	7200	Seconds	Duration of the simula tion 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, c.f. Fig. 5

[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 standard 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 purposes of the simulations. Horizontal separation is 3 to 5 miles minimum with 5 miles or greater the typical separation. AirCell chose 5 miles for the purposes of the simulation.

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 typical systems' operation in the areas along the cross-country airplane flight corridors. This scenario is characterized by 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 a 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)
- Small cell site radii (set to 12.5 miles)
- Lower altitudes of serviced planes (from 1000 to 40,000 feet)
- Lower aircraft velocities (from 180 to 250 knots)

As seen, the 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 report. In practice, there may be some configurations that are neither cross-country, nor airport like. However, these configurations can be seen as being *in-between* and their performance is bounded by the results obtained for airport and cross-country scenarios.

4 Pole Point Capacity of the 1xEvDO Voice System

From the standpoint of 1xEvDO networks in this study, each aircraft represents a single mobile. The voice traffic generated within each aircraft is aggregated and sent towards the base station through a common data pipe. Likewise, the traffic aggregation on the forward link is performed in a similar fashion. On the reverse link, the signal coming from a single aircraft needs to meet a desired Eb/Nt threshold given by

$$\left(\frac{E_b}{N_t}\right)_j = \frac{P_j \frac{W}{R_{bj}}}{\sum_{i \neq j} P_i \cdot \left(1 + I_{adj}\right) + N_0} \tag{6}$$

where

$\left(\frac{E_b}{N_t}\right)_j$	- Eb/Nt threshold for the signal coming from the jth aircraft
P_j	- power of the signal received from the jth aircraft
P_i	- power received from the ith aircraft within the same cell
W	- chip rate ($W = 1.2288 \cdot 10^6$ chips/sec)
R_{bj}	- data rate of the jth mobile
N_0	- power of the thermal noise
I_{adj}	- ratio of the out of cell to the in-cell interference (measure of self-interference)

To simplify the analysis, it is assumed that all of the aircraft serve the same number of voice users. As a result, their average aggregate data rates are the same as well. Furthermore, due to a tight 1xEvDO reverse link power control scheme, the received powers of the aircraft at the base station receiver are approximately the same and the expression in (6) simplifies as

$$\left(\frac{E_b}{N_t}\right)_j = \frac{P \frac{W}{R_{bj}}}{(N-1)P\left(1 + I_{adj}\right) + N_0} \tag{7}$$

When the base station is operating in the vicinity of its theoretical capacity, the thermal noise term can be neglected relative to other powers in the denominator of (7). Therefore, (7) can be rewritten as

$$\left(\frac{E_b}{N_t}\right)_j = \frac{\frac{W}{R_b}}{(N-1)\left(1 + I_{adj}\right)} \tag{8}$$

which gives

$$N = 1 + \frac{W / R_b}{(E_b / N_t)(1 + I_{adj})} \tag{9}$$

The expression in (9) is commonly referred to as the *Pole Point* of the 1xEvDO system. The pole point is the theoretical maximum capacity of a CDMA system. The use of (9) can be illustrated by the following simple example.

Example 2 Assume that each aircraft in the system serves an average of ten voice users. Other parameters in (9) assume the following numerical values:

- Voice activity $a_f = 0.5$
- Vocoder data rate $R_b = 9.6$ kb/sec
- Eb/Nt requirement of 4dB $\rightarrow$ 2.5
- $I_{adj} = 1.0$ [5]

First, the average data rate for each aircraft is given by

$$R_{aggregate} = 10 \times a_f \times R_b = 10 \times 0.5 \times 9.6 = 48 \text{ kb/sec} \tag{10}$$

The data rate given in (10) is not supported by the 1xEvDO reverse link. The closest data rate is 76kb/sec and for that reason, $R_{aggregate}$ is rounded up to 76kb/sec. Substituting numerical values in (9), one obtains

$$N = 1 + \frac{1.2288 \cdot 10^6 / 76 \cdot 10^3}{2.5(1+1)} = 4.23 \tag{11}$$

Therefore, each cell site can support a theoretical maximum of approximately four aircraft. In common engineering practice, CDMA systems are designed to operate at a certain fraction of the pole point capacity. Most commonly, the systems are dimensioned to support traffic between 50% and 75% of the pole point. For the above example this yields two to three aircraft per base station.

There are several remarks that need to accompany derivations presented in this section. They are given as follows.

Remark 1. The derivations are performed under the assumption of voice traffic. The voice traffic is symmetric, i.e., the activities of the forward and reverse link are approximately the same. Most of the data services are asymmetric in nature and with activities significantly smaller than voice activity. For a mixture of traffic types, the capacity analysis presented above may not be completely applicable.

Remark 2. From (9), it is seen that the value of I_{adj} plays an important part in the evaluation of the system's capacity. I_{adj} depends on many factors including distribution of the aircraft, antenna patterns, and the layout of cell sites. In real systems, the value of the I_{adj} is different for

---

[5] The value of $I_{adj} = 1.0$ is obtained as one of the simulation outputs.

each cell site. Furthermore, as the positions of the aircraft change, the value of the I_{adj} changes as well. Due to all of these factors, the pole point equation in (9) should be treated as only a rough estimate of the system's capacity. In practical scenarios, it is possible that a given cell can support more than four aircraft, or vice versa, the cell can reach the pole point when the number of aircraft is smaller than four. Dependence of the pole point on the value of I_{adj} is presented in Fig. 6.

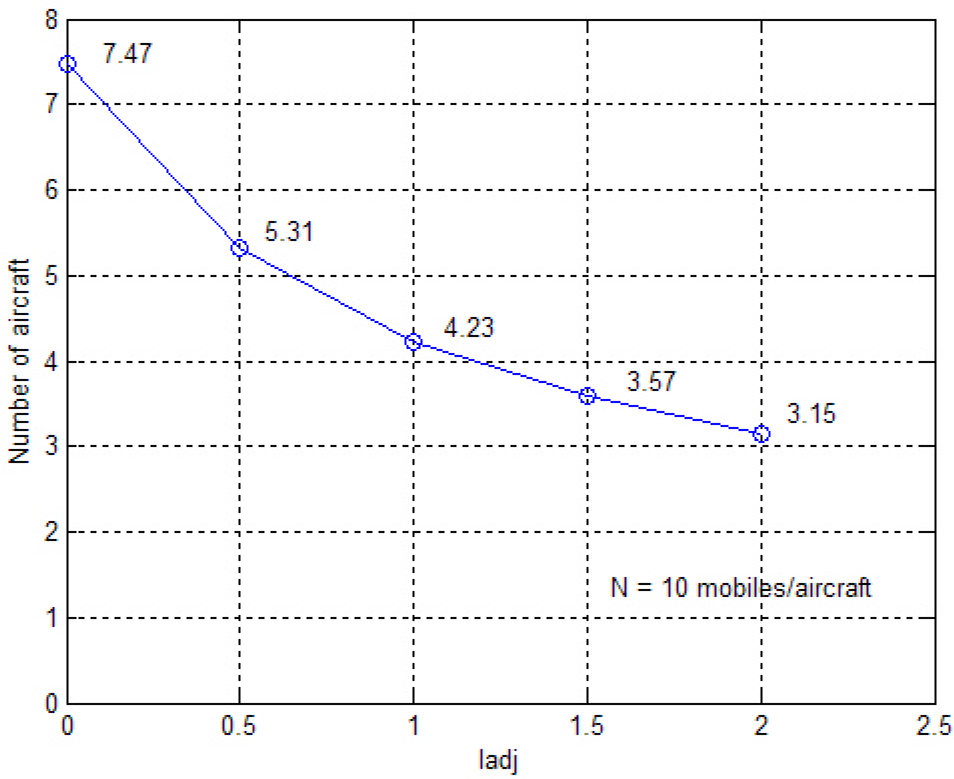

Figure 6. Dependence on the pole point capacity on I_{adj} - Equation (9)

Remark 3. The derivations presented in this section assume that the capacity of the system is limited by the reverse link. This is certainly true in the case of voice traffic. However, for asymmetric data types, the capacity of the system may be limited by the highest data rate supported on the forward link.

5 Analysis of the Worst-Case Interference Scenario

The scenario resulting in the worst case cross system interference is presented in Fig. 7. Two aircraft in Fig. 6 are served by two different 1xEvDO systems with frequency allocations as described in Section 2.1. They are located in the area close to the edge of the system and are flying within close proximity of each other.

From the cross-system interference standpoint, the scenario presented in Fig. 7 represents the *worst-case* for the following reasons.

1. The served aircraft (A1) is located far away from its serving base station. Therefore, the serving signal is at the minimum level.
2. The interfering aircraft (A2) is at the maximum distance from its base station as well. To complete the reverse link, the interfering aircraft needs to transmit at a relatively high power level.
3. The two aircraft are at the minimum separation allowed by FCC regulations, and therefore, the path loss between them is at its minimum.

Accordingly, the level of cross system interference is at its maximum.

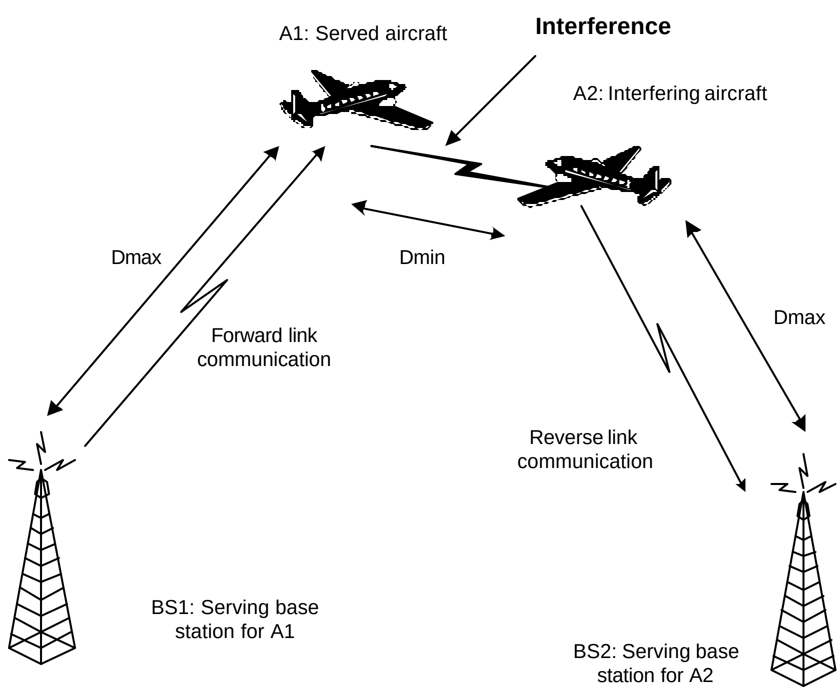

Figure 7. Illustration of the worst-case interference

5.1 *Maximum Path Loss*

The maximum path loss for the system topology presented in Fig. 8 can be derived using the simple *cosine theorem*. Given that the radial size of the market is *D*, and with the aid of Fig. 8, one may write

$$D_{\max}^2 = D^2 + \left(\frac{D}{2}\right)^2 - 2D\frac{D}{2}\cos(a) \tag{12}$$

It is easily seen that $a = p/8$. Therefore,

$$D_{\max}^2 = D^2 + \frac{D^2}{4} - D^2\cos(p/8) = [1.25 - \cos(p/8)] \cdot D^2$$

or

$$D_{\max} = D\sqrt{1.25 - \cos(p/8)} \approx 0.5711D \tag{13}$$

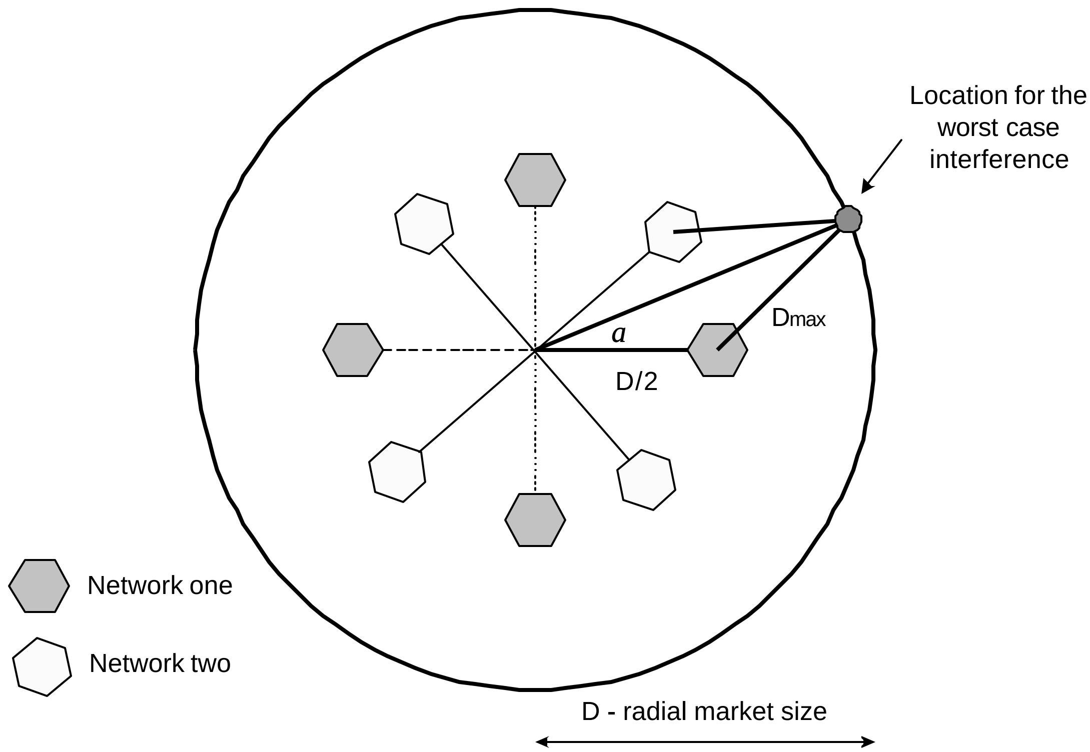

Figure 8. Calculation of the maximum distance – worst-case interference point

Two scenarios considered in this report have different radial market sizes. For the airport scenario $D = 25$ miles and for the cross country scenario $D = 200$ miles. Substituting these values into the path loss equation given in (2), one obtains

$$L_{\max A} = 36.5 + 20\log(f) + 20\log(D_{\max A}) = 36.5 + 20\log(870) + 20\log(14.27) = 118.4 \tag{14a}$$

$$L_{\max CC} = 36.5 + 20\log(f) + 20\log(D_{\max CC}) = 36.5 + 20\log(870) + 20\log(114.22) = 136.45 \tag{14b}$$

5.2 *Minimum Path Loss*

The minimum separation between two aircraft is subject to strict regulations. For most flying conditions, planes need to be separated by at least 5 miles in the horizontal plane and at least 1500 feet in the vertical plane. Therefore, the minimum distance between the planes given in miles can be calculated as

$$D_{\min} = \left[5^2 + (1500/5280)^2\right]^{1/2} = 5.0081$$

Therefore, the minimum path loss between the aircraft antennas can be calculated as

$$L_{\min} = 36.5 + 20\log(870) + 20\log(5.0081) \approx 109.29 \text{ dB} \tag{15}$$

5.3 *Signal to Interference Ratio on the Forward Link*

As a result of the cross system interference, the forward link SINR becomes degraded. The maximum degradation occurs if the interfering aircraft is transmitting at full power of its PA while being at the minimum distance from the interfered aircraft. Using (15), and keeping in mind the partial overlap between the channels, the maximum power of the interfering signal can be calculated as

$$I_{\max} = P_{TX\max} - L_{\min} - G_{pol} = P_{TX\max} - 109.29 - G_{pol} \tag{16}$$

In G_{pol} represents the interference reduction due to partial overlap between the two channels. For the case of the first spectrum reuse proposal, the spectral overlap is 40% and therefore, $G_{pol} = 10\log(1.25/0.5) = 3.98$ dB. In the case of the second reuse proposal, the overlap is 100% and as a result $G_{pol} = 0$. One should note that the value in (16) represents a conservative estimate of the interfering power since it neglects the selectivity of the aircraft antenna.

On the other hand, at the worst-case interference point, the power of the serving signal is at its minimum, which can be calculated as

$$S_{\min} = P_{BTS} - CL - L_{\max} + AG(q, f) \tag{17}$$

where CL represents the losses due to cables along the base station transmission path and $AG(q, f)$ is the antenna gain of the base antenna which depends on the aircraft azimuth and elevation. Assuming nominal value of the cable losses of 3dB, and substituting the values for $L_{\max}$ given in (14), one obtains the minimum serving levels for the airport and cross-country scenarios as

$$S_{\min A} = P_{BTS} + AG(q, f) - 121.4 \tag{18a}$$
$$S_{\min CC} = P_{BTS} + AG(q, f) - 139.42 \tag{18b}$$

Combining (16) and (18), the expression for the difference between the serving signal and the interferer becomes

$$\begin{aligned} S_{\min A} - I_{\max} = SIR_{Acs} &= P_{BTS} + AG(q, f) - 121.4 - P_{TX\max} + 109.29 + G_{pol} \\ &= P_{BTS} + AG(q, f) - P_{TX\max} + G_{pol} - 12.11 \end{aligned} \tag{19a}$$

and

$$
\begin{aligned}
S_{\min CC} - I_{\max} = SIR_{CCcs} &= P_{BTS} + AG(q,f) - 139.42 - P_{TX\max} + 109.29 + G_{pol} \\
&= P_{BTS} + AG(q,f) - P_{TX\max} + G_{pol} - 30.13
\end{aligned}
\tag{19b}
$$

From (19), it is seen that for a given spectrum reuse option, the level of the cross system interference depends on three parameters: base station transmit power or EIRP, maximum aircraft PA power, and the gain of the base station antenna. The nominal values for the base station transmit power and the maximum aircraft PA power are 43 and 23 dBm respectively [4]. With these numerical values, the difference between the serving signal and the cross system interference simplifies as

$$
SIR_{Acs} = 43 - 23 - 12.11 + G_{pol} + AG(q,f) = 7.89 + G_{pol} + AG(q,f) \tag{20a}
$$

and

$$
SIR_{CCcs} = 43 - 23 - 30.11 + G_{pol} + AG(q,f) = -13.11 + G_{pol} + AG(q,f) \tag{20b}
$$

The results obtained using (20), for different cases of spectrum reuse and different operation scenarios are summarized in Table 3.

Table 3. Worst-case SIR for different reuse and operational scenarios

Spectrum reuse scenario	Operation scenario	Worst case SIR [dB]
40% Overlap	Airport	$11.86 + AG(q,f)$
	Cross-country	$-9.13 + AG(q,f)$
100% Overlap	Airport	$7.89 + AG(q,f)$
	Cross-country	$-13.11 + AG(q,f)$

According to Table 3, for the airport scenario, the SIR "budget" is about 10dB and as long as the antenna gain of the serving cell is positive, the impact of the interference becomes negligible even in the worst-case scenario. For the cross-country scenario, the situation is somewhat different. At the system's edge, the power of the serving signal is small and the signal becomes vulnerable to any kind of additional interference. However, due to a large market area and relatively low traffic loading, the probability of spatially encountering a worst-case interference scenario in the cross-country operational case is very small.

6 Simulation Results

When the analysis of a communication system is performed using Monte Carlo (MC) simulations, one can record many different performance indicators. The simulator used in this study also provides the same flexibility. However, by presenting all collected parameters, it is possible to defocus the results of the study. For that reason, in this initial report the results are presented through only five representative types of plots. A sample for each of the plot types used in this report and appropriate explanations are given as follows.

Plot 1. Time domain SINR degradation plot. A sample of a time domain SINR degradation plot is presented in Fig. 9. As seen, the plot is three-dimensional. Along the x-axis is the simulation time and along the y-axis is the ID of the aircraft. Along the z-axis is the difference between the SINR recorded when cross system interference is ignored, and the SINR recorded when the cross system interference is taken into account.

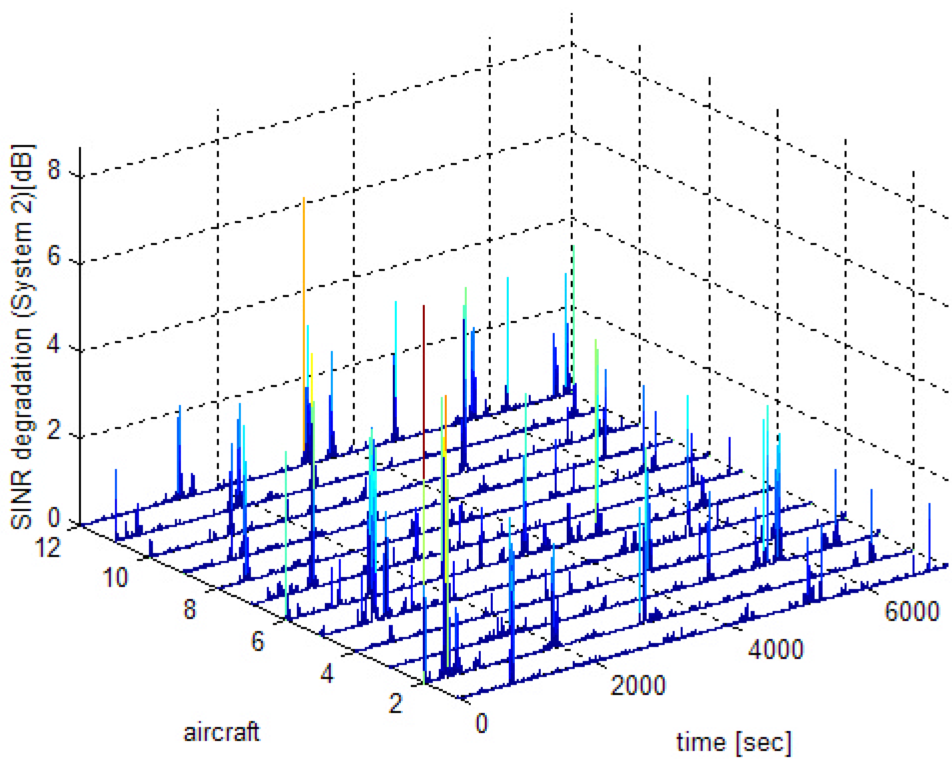

Figure 9. Example of the *Time Domain SINR Degradation* plot

For example, for the plot presented in Fig. 9, the simulations are performed over a 7200 second time interval and there are twelve aircraft "flying" over the market area. The degradations can occasionally exceed several dBs. As an example, consider the trace recorded for the 12th aircraft. At the time stamp around 3,000 seconds, the degradation of the SINR exceeds 6dB for a short time interval. The time domain SINR degradation plot provides a good visual indication of the cross system interference. Therefore, this plot should be treated in a more qualitative rather than a quantitative manner.

Plot 2. Probability of the SINR degradation. A sample plot for probability of the SINR degradation is presented in Fig. 10. This plot represents a prime indicator of the cross system interference level. Along the x-axis is the level of the SINR degradation expressed in dB, while along the y-axis one finds the probability of an aircraft experiencing a given degradation level. For example, for the plot presented in Fig. 10, one reads that the probability of a 1dB SINR degradation (shown on the graph as 10^0) is approximately 6×10^{-3}. For the sake of reference, the results presented in Figs 9 and 10 are obtained for the same simulation scenario.

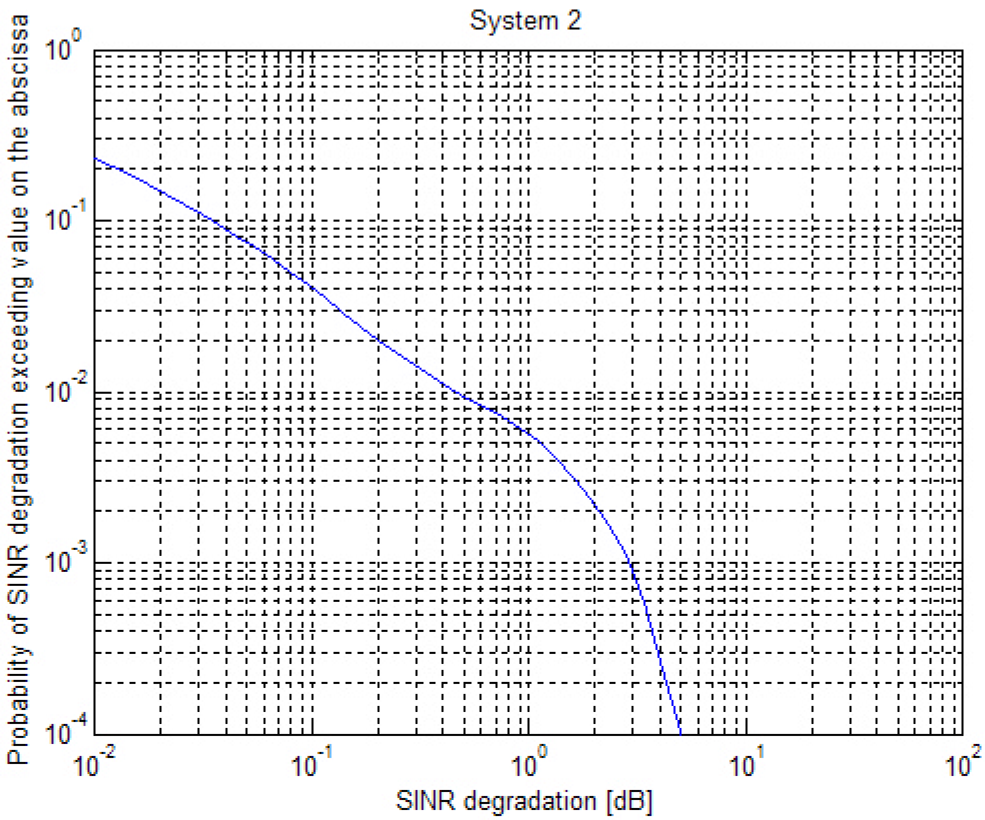

Figure 10. Example of the *Probability of SINR degradation* plot

Plot 3. Distribution of the Aircraft TX power. A sample plot presenting a distribution of the aircraft transmit power is presented in Fig. 11. Along the x-axis is the power value in dBm, and along the y-axis is the percentage of time (i.e. probability), that the aircraft would transmit given power level. This is an aggregate plot for all aircraft served by one of the two systems. In Fig. 11, one notices a distribution peak at 23dBm. This peak is the result of the maximum aircraft transmit power, which was set to 23dBm for all the simulations conducted in this study (c.f. Table 2).

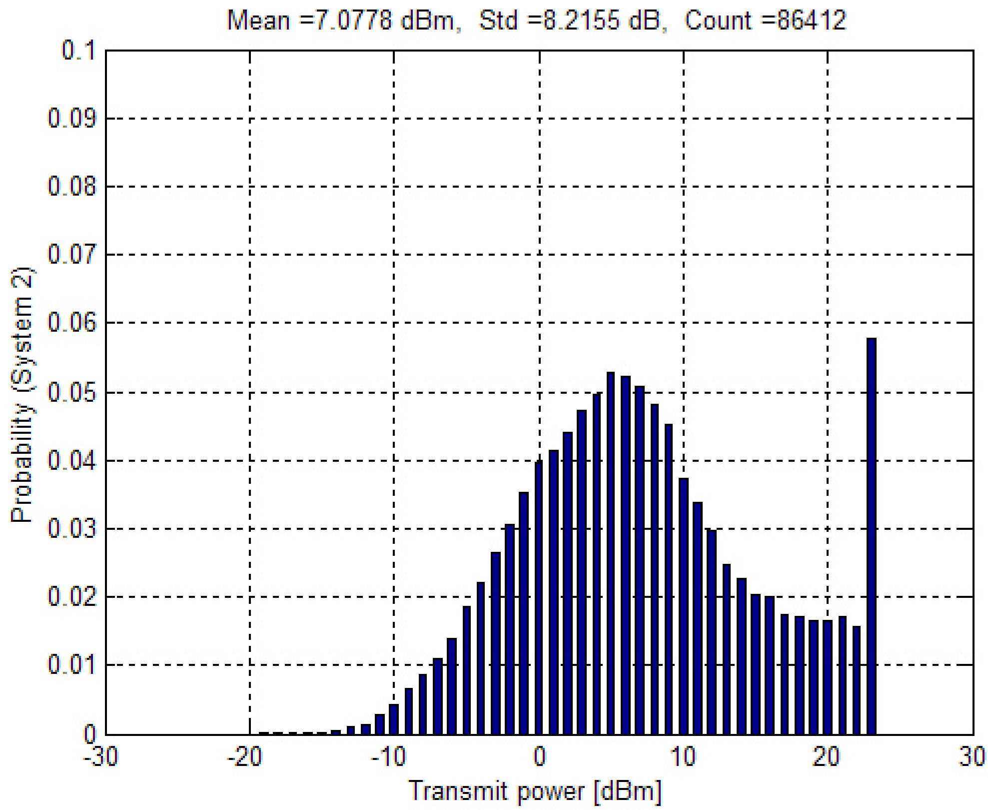

Figure 11. Example of the *Distribution of the Aircraft TX power* plot

Plot 4. Average forward link throughput reduction. A sample plot used to demonstrate the absolute reduction of the forward link throughput is presented in Fig. 12. Along the x-axis one finds the loading of the system expressed as a percentage of the pole point. Along the y-axis is the average forward link throughput reduction recorded through the simulations. The throughput reduction is determined as a difference between average forward link data rate when there is no cross system interference, and the average forward link data rate when the interference is taken into account. For example, in Fig. 12, one reads that for 75% pole point loading, an average decrease in throughput perceived by the aircraft is 9.44kb/sec.

Plot 5. Relative forward link throughput reduction. A sample plot used to demonstrate the relative reduction of the forward link throughput is presented in Fig. 13. Along the x-axis is the loading of the system and along the y-axis is the relative decrease in the forward link throughput. The relative decrease in the forward link throughput is determined as a ratio between the absolute decrease and average forward link data rate. For example, from Figs 12 and 13, at 75% loading the absolute throughput decrease is 9.44kb/sec, which is about 0.87% of the average forward link throughput.

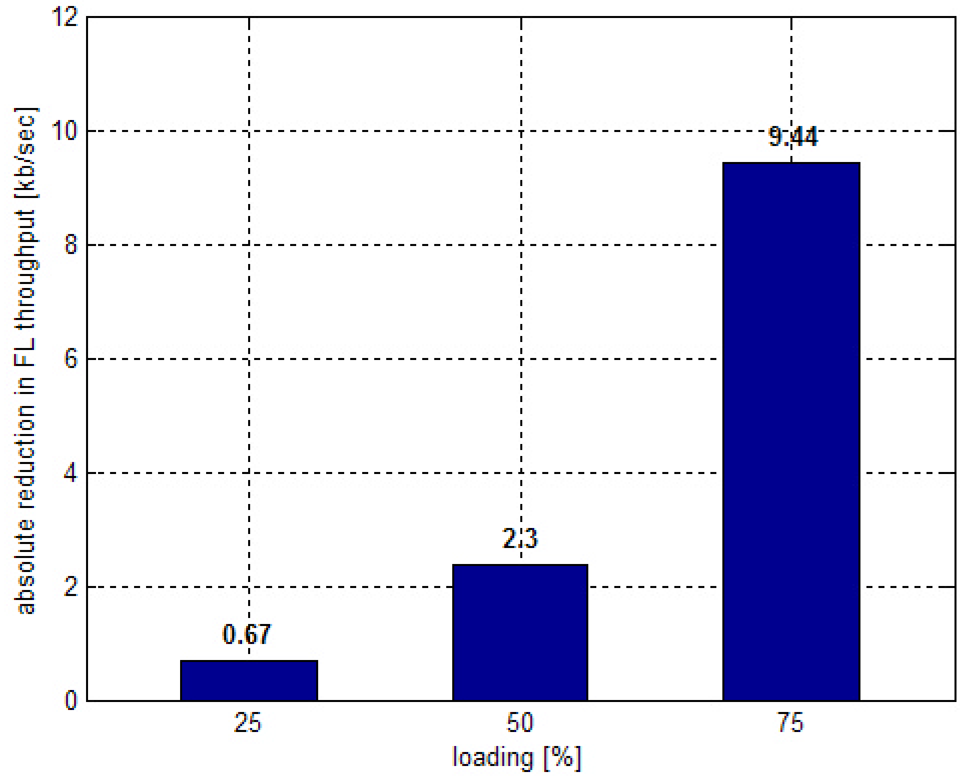

Figure 12. Example of the *Average Reduction in the Forward Link Throughput* plot

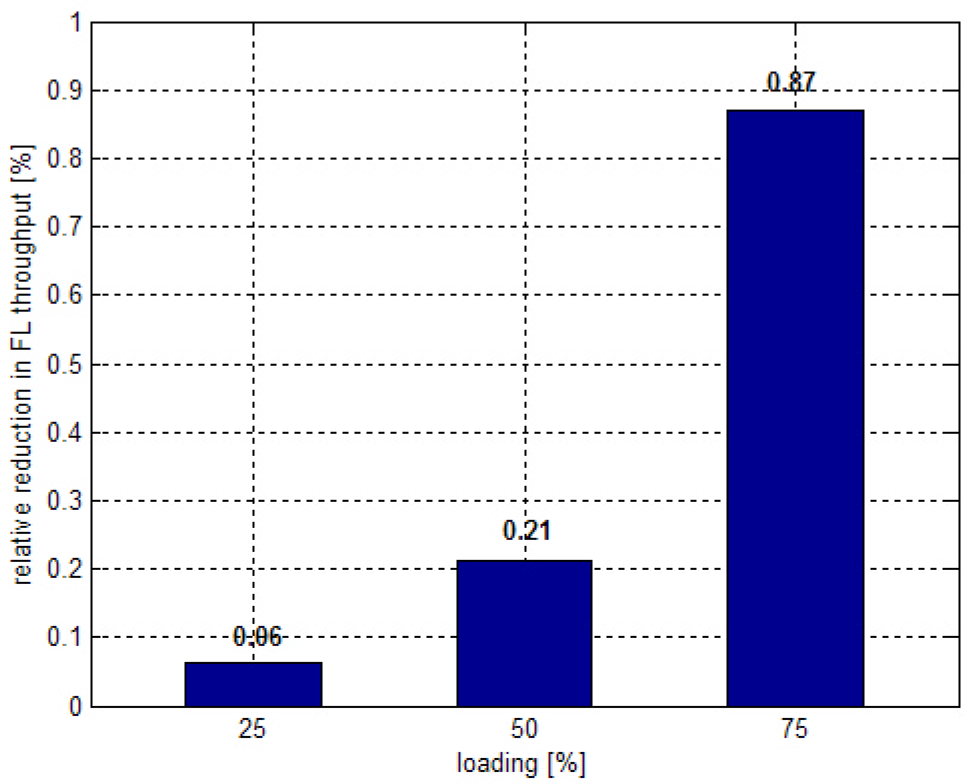

Figure 13. Example of the *Relative Reduction in the Forward Link Throughput* plot