Review of AirCell's October 25, 2004 Cross-Polarized ATG Band-Sharing Proposal

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Introduction and Executive Summary

On October 26, 2004, AirCell filed an *ex parte* letter with the Commission that outlines a revised proposal for accommodating multiple broadband systems in the 800 MHz Air-to-Ground ("ATG") band. That *ex parte*, which includes a technical paper [1] and supporting presentation materials [2], purports to be a "new" AirCell-Boeing proposal ([2], slide 2). However, it is essentially the same as the arrangement proposed by AirCell in June 2004 [5], except that the cross-duplexed sharing concept AirCell originally proposed in [3] has now been abandoned.

Although AirCell's June paper [5] proposed a 4-system sharing arrangement using both cross-duplexing and cross-polarization, the analysis in that paper actually investigated only a pair of cross-polarized (co-duplexed) systems. Therefore, the proposal analyzed and simulated by AirCell in [5] is essentially the same as what is being proposed as "new" in [1] and [2]. Telcordia has already submitted for the record analyses that describe the problems with this band-sharing proposal; see [6] and [9]. These problems can be summarized as follows:

- In its June analysis [5], AirCell assumed a fixed 12 dB of isolation between the vertical and horizontal polarizations, citing an AirCell report on flight test results from 1997 [7] as evidence that such a requirement is achievable. However, as Telcordia discussed in [6], detailed examination of the AirCell test report revealed no data on cross-polarization isolation. AirCell has now cited a different reference (Attachment A, Exhibit B-7 of [10]). However, that document provides only a single graph showing a small amount of data from a single test run, with no explanation of the test procedure or equipment, and no statistical summary of the results. The newly-referenced data is, therefore, inadequate as the basis for any conclusions about the statistics of polarization isolation in the air-to-ground environment.
- The results of AirCell's earlier analysis [5], which assumed a fixed 12-dB polarization isolation, showed that with two cross-polarized systems sharing the same spectrum, there would be high interference levels at the base station receivers in the airport scenario. In its most recent version of the proposal in [1][2], AirCell shows this interference to be greatly reduced, but examination of the assumptions reveals that this has been achieved by reducing total throughput near the airports by a factor

of 12 compared to the analysis of [5]. If such a reduction is necessary to control the interference, it follows that sharing via cross-polarization cannot support the high traffic densities that occur near airports.

- Compared to other modes of isolating systems that operate in the same geographical region (e.g., adjacent frequency channels), the 12 dB isolation that AirCell claims will be realized by cross-polarization is very low. It is doubtful that any provider would seriously consider deploying adjacent-band terrestrial mobile systems that were protected from mutual interference by only 12 dB of isolation. For example, as dictated by the Commission's out-of-band emissions limits, PCS systems typically have isolations on the order of 40 to 50 dB between adjacent-band systems.
- Two cross-polarized systems would have to be operated in tandem. Because interference at CDMA base stations is limited by the admission control mechanism, it is likely that the admission controls of the two cross-polarized systems would need to be coupled, essentially requiring the two systems to act as one.
- There does not seem to be any practical way to codify a requirement in the FCC Rules to enforce polarization isolation. Compliance with such a requirement would need to be verifiable by a straightforward test, such as that used to verify compliance with out-of-band emission requirements, and no such test exists. Furthermore, polarization isolation in a mobile environment cannot be reliably maintained, and at times there may be no polarization isolation whatsoever.
- AirCell's claim that there is "virtually no intersystem impact" is inaccurate, since even under the best of conditions, the two systems would need to be tightly coordinated. Furthermore, AirCell's claim that this proposal allows both providers to support "broadband" service is unsupported, since AirCell's analyses were conducted using an average total throughput per aircraft of 48 kbps on the reverse link, and an aircraft EIRP limit of 200 mW, which is inadequate to support broadband transmissions on the reverse link (e.g., 1.8 Mbps as discussed by AirCell in [8]).
- As shown in the attached Appendix, cross-polarization interference will occur in the air-to-ground environment even under ideal propagation conditions (perfect free space path loss and no reflections) due to the difference in altitude between the aircraft and the base station. This effect is particularly severe when high-altitude aircraft are near base stations, as will routinely happen during cross-country flights, as well as near airports, where horizontal distances between aircraft and base stations tend to be small. It is clear from the examples provided here that analysis of cross-polarization interference is more complex than suggested by AirCell's simple analysis of aircraft pitch and roll. AirCell's results are also misleading because they suggest that cross-polarization interference will be negligible at cruising altitude, which is not the case. Finally, AirCell's analysis does not account for reflections, which cause cross-coupling between vertical and horizontal polarizations.

In sum, AirCell's "new" proposal is the same as that introduced and analyzed in [5], except that the requirement of co-located base stations has been added, and the airport scenario traffic density has been reduced by a factor of 12 to minimize the interference impact shown by the analysis. The proposal still suffers from a number of major deficiencies as explained here.

Lack of Data to Support AirCell's Assumed Polarization Isolation

In its June paper [5], AirCell assumed a fixed 12-dB polarization isolation on the air-to-ground link, claiming that this was justified based on previously reported data [7]. However, as Telcordia explained in [6], a detailed examination of [7] revealed no basis for making such a claim. AirCell has now admitted that the reference to the report was an error, and a different document (Attachment A, Exhibit B-7 of [10]) should have been referenced (see [1], footnote 3). However, the referenced Attachment in [10] shows only a small excerpt from a longer report. This excerpt consists of only a single graph displaying the results of a single test run. Test procedures, conditions, and equipment are not explained.

In response to a request from FCC staff, AirCell later provided additional information regarding the test procedure in [11], explaining that the aircraft was equipped with a test receiver connected to a horizontally-polarized, belly-mounted antenna. The base station was transmitting alternating vertical and horizontal polarizations from a dish antenna. The airborne receiver recorded the received signal levels corresponding to the vertical and horizontal transmitted polarizations. However, AirCell did not specify how many other measurement runs were made or what other geometries were explored. In the final page of the excerpt provided in [10], it is stated that "cellular ground station to air mobile polarization discrimination ≥ 15 dB." However, there is insufficient information provided in [10] to support this conclusion. Moreover, the conclusion suggests that the experiment was designed to test interference between horizontally-polarized aircraft and cellular base stations, not air-to-ground base stations.[1] Finally, the use of a dish as the base station test antenna is questionable, since dish antennas are typically not used in cellular base stations. Measurements attempting to characterize polarization isolation for a particular environment should replicate the conditions of that environment as closely as possible, including antenna type. This would require the use of an actual ATG base station antenna, and measurements representing a variety of aircraft altitudes, headings, bearings with respect to the base station, and a variety of distances from the base station.

Given the deficiencies in the test procedures and data provided by AirCell, the record of this proceeding remains devoid of any measurement data useful for understanding the statistics of polarization isolation on the air-to-ground link.

AirCell's Polarization Isolation Analysis is Incomplete

In [1], AirCell provides a polarization-isolation analysis based on the statistics of aircraft pitch and roll. Even assuming perfect free-space propagation, the analysis is incomplete because it does not account for the effects of the altitude difference between the aircraft and the base station, which, as explained in the Appendix, can cause significant cross-polarization interference. The effect is particularly significant when a high-altitude aircraft is in the vicinity of a base station. It is also significant near airports, where the horizontal distance between the aircraft and the base station tends to be small. It should

[1] Cellular base station antennas are typically down-tilted, and will tend to be more resistant to interference from aircraft than will ATG base station antennas, which are up-tilted.

be noted that in the test results graph shown in Attachment A, Exhibit B-7 of [10], the aircraft altitude was very low (5000 feet, well below cruising altitude), so the effects discussed in the Appendix would be expected to be small.

It is clear from the examples shown in the Appendix that cross-polarization interference, even ignoring the effects of reflections, is more complex than suggested by AirCell's analysis of aircraft pitch and roll. In addition, AirCell's results are misleading because they suggest that cross-polarization interference will be negligible at cruising altitude, which is not the case. Finally, a complete analysis would need to account for the effect of reflections, which also contributes to cross-polarization interference.

It is also clear that the cross-polarization interference will in general be different for each aircraft/base station pair, and can vary as the heading and position of the aircraft change. As a result, polarization isolation cannot be reliably maintained, and cross-polarization interference cannot be controlled by FCC requirements. Cross-polarization therefore is not a reliable way to prevent harmful interference between two air-to-ground systems sharing the same spectrum.

Extremely High Reverse-Link Interference for the Airport Scenario

AirCell's own simulation results as documented in its June paper [5] show that for the airport scenario, two systems sharing spectrum using cross-polarization would cause a significant increase in interference to base station receivers as shown in Figure 1, which is reproduced from [5]. This increase in noise can reach levels up to 25 dB, whereas the normal upper limit on the operating range for a CDMA base station receiver is about 6 dB of noise rise. This limit is necessary to maintain system stability and linearity in the front-end amplifier of the receiver.

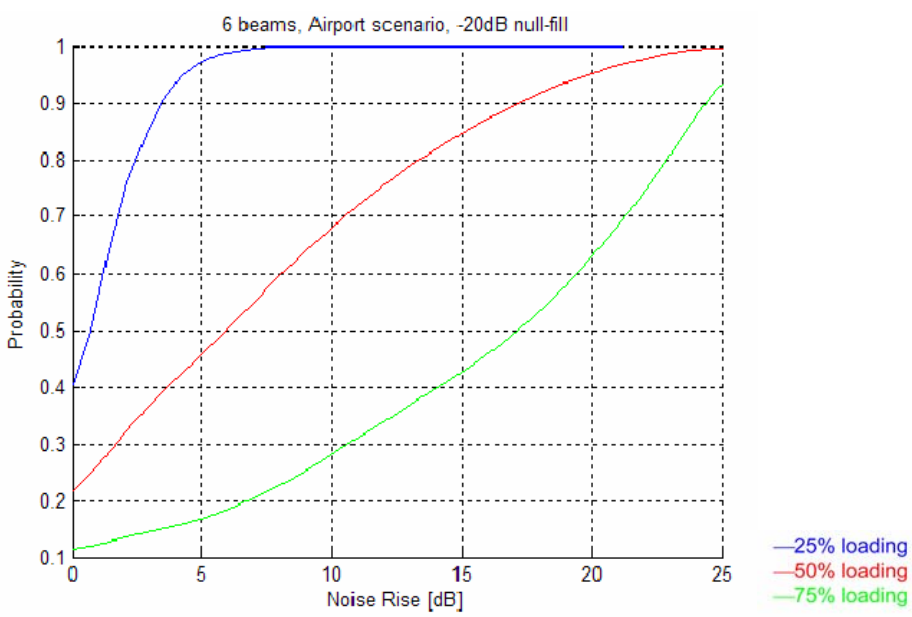

Figure 1: *Example CDF of the noise rise from [5], p. 54.*

These results were based on the arrangement shown in Figure 2 (reproduced from [5]), where $R = 12.5$ miles for the airport scenario and networks one and two are cross-polarized. Each cell had 3 sectors, so at 75% loading there were 9 aircraft per cell, or 36 aircraft per system within the circle shown (25 mile radius surrounding the airport). This model was used to simulate the high traffic density that occurs near airports.

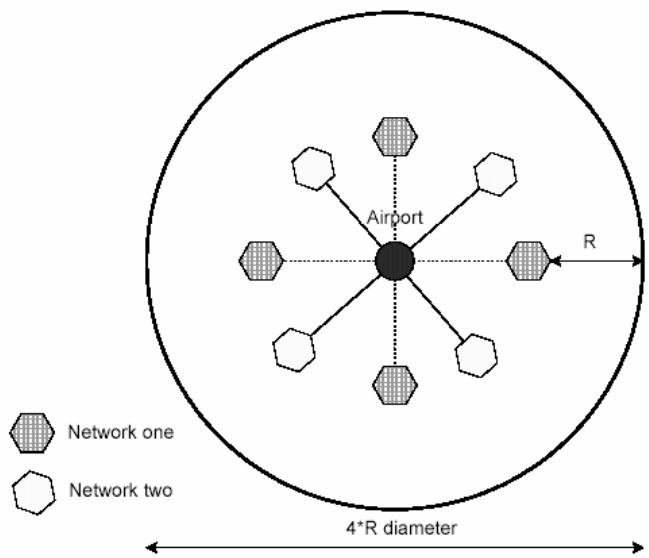

Figure 2: *AirCell simulation topology (reproduced from Figure 5.1 of [5]).*

In its latest proposal [1], AirCell provides different simulation results, which show that sharing the band through the use of cross-polarized systems would result in very little increased noise. However, to achieve these results, AirCell appears to have re-defined the "airport scenario" as shown in Figure 3. Instead of 4 cells per system serving the airport area, there is now only a single cell per system, and each cell employs omni-directional rather than sectorized antennas ([2], slide 16). As a result, with 75% loading there are only 3 aircraft per cell rather than 9 as there were in the airport scenario of [5]. The other 3 cells each appear to be about 140 miles away from the airport, which is more like the original "cross country scenario" in [5] than the airport scenario. The simulation topology employed by AirCell in [1][2] does not accurately represent an actual airport scenario, and therefore, AirCell's latest analysis does not accurately reflect the interference that would occur around airports if cross-polarization were used to accommodate multiple ATG systems.

Based on AirCell's new analysis reported in [1][2], a maximum of 3 aircraft per system (at 75% loading) can be supported by the cells near the airport, compared to 36 aircraft per system in the simulation of [5]. In short, AirCell appears to have addressed the interference problem by simply reducing the capacity of the two systems near the airport, in this case, by a factor of 12. If this is the only way to control excessive interference, then it can be concluded that sharing via cross-polarization cannot support high traffic densities.

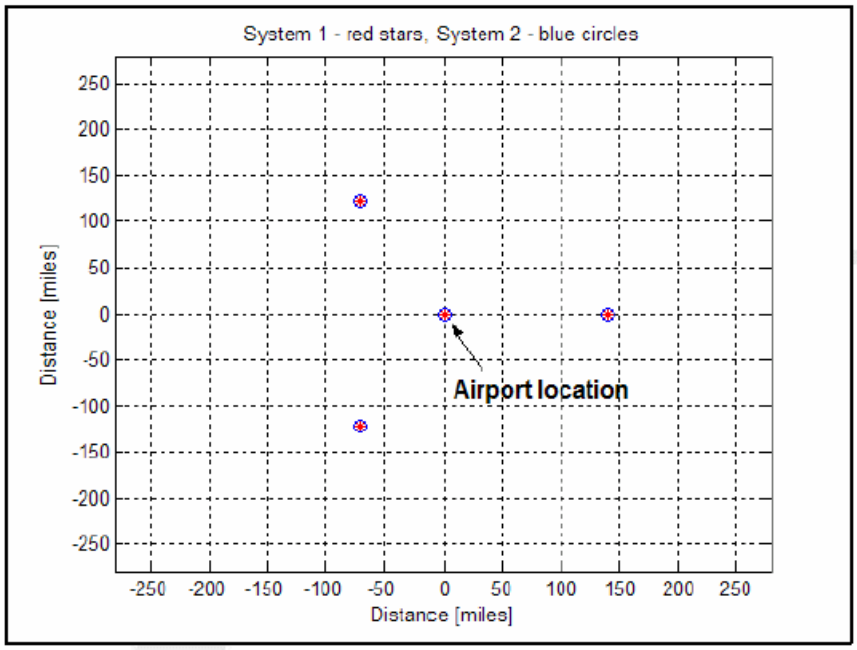

Figure 3: *Airport scenario topology from slide 16 of [2].*

Even the Claimed Isolation is Inadequate

It is useful to compare the claimed 12 dB cross-polarization isolation between the two systems to other forms of isolation. The most familiar form is frequency division, and isolation is enforced in the FCC Rules by out-of-band emission requirements. In fact, two systems sharing the same spectrum with 12 dB of isolation due to crossed polarization will affect each other in the same way as two systems operating in adjacent frequency bands with 12 dB of adjacent-frequency isolation.

For comparison, cellular and PCS systems are required to suppress out-of-band emissions by $43 + 10 \log P$ where P is the transmitter output power in watts.[2] Thus, if P is 20 watts, then the required suppression is 56 dB. This is not necessarily the adjacent channel isolation, which also depends on the frequency discrimination in the receivers, but it suggests that adjacent channel isolation with frequency-division is at least several orders of magnitude greater than the 12 dB polarization isolation that AirCell claims.

Two Cross-Polarized Systems Would Have To Be Operated In Tandem

AirCell proposes to compensate for the low isolation between the two systems by requiring base stations that are essentially co-located and provide nearly identical coverage. This is necessary to prevent near-far problems, particularly on the reverse link,

[2] FCC 22.917(a), 24.238(a).

which is tightly power controlled. However, it is not sufficient to prevent overload of the reverse link, particularly when the polarization isolation becomes low.

With CDMA, system stability and reverse link amplifier linearity are maintained by enforcing an upper limit on the "noise rise" at the reverse link receiver. This is the ratio of all received signal plus interference power plus noise to noise alone. The noise rise is typically limited to 6 dB, which corresponds to 75% of pole capacity (see [4], Annex B for a discussion of the reverse link). This noise rise limit is enforced by an admission control mechanism that controls the establishment of new communications links in the system. If admitting a new connection would cause the noise rise to exceed its limit, service is denied. If there are two systems that can contribute to each other's noise rise, admission control is no longer a reliable means of controlling interference unless the admission controls of the two systems are coupled. In that case, the two systems would be effectively operating as one and a high degree of coordination between them would be required.

Polarization Isolation Requirements Cannot be Enforced

If cross-polarization is to be used as the means of providing some degree of isolation between the two systems, then the FCC's Rules would need to include requirements to ensure its integrity, much as those Rules place limits on out-of-band emissions ("OOBE") to control adjacent channel interference. In the case of OOBE limits, compliance can be verified by fairly straightforward tests using a spectrum analyzer connected via a cable to the antenna port of the transmit power amplifier. However, there is no such practical test to verify polarization isolation, since cross-polarization interference would depend on the environment, and as demonstrated in the Appendix, the aircraft position relative to the base station.

AirCell has proposed that polarization isolation be managed by "reducing aircraft transmit power to compensate dB-for-dB for cross polarization reduction below 12 dB" ([8], p. 8). However, implementation of this concept is not practical. The polarization isolation would be path-dependent, and the polarization isolation between an aircraft and two different cross-polarized base stations would generally be different. The aircraft would need to set its power reduction based on the least-isolated cross-polarized base station. Not only would this tend to keep the aircraft transmit power low (preventing the use of high data rates on the reverse link), but it would require that either the aircraft or the base stations include a separate antenna and receive chain to monitor the "crossed" polarization. In addition, the concept would do nothing at all to alleviate forward link (base to aircraft) cross-polarization interference, which affects the forward link data rate. Finally, it would be prohibitively difficult for a third party to verify compliance with such a requirement.

AirCell's Claims are Inaccurate

AirCell claims that its proposal provides "isolation sufficient to allow two systems to operate with virtually no intersystem impacts; both broadband, both deck-to-deck" ([2], slide 3). This is misleading in three respects. First, the isolation is so low that the two

systems would need to be tightly coordinated, which is a very significant "intersystem impact." Second, to keep the noise rise at acceptable levels in its most recent set of simulations, AirCell greatly reduced the system capacity in the airport scenario as discussed above. This would have a significant performance impact on the two cross-polarized ATG systems as compared to the capacity that a single system could provide. Third, AirCell did not consider "broadband" service on the reverse link in any of its simulations. Each aircraft carried ten 9.6 kbps speech circuits, each with an activity factor of 0.5, for a total average throughput of 48 kbps per aircraft, or at 75% loading, 144 kbps per cell, as compared to the maximum 1.8 Mbps reverse link throughput cited in AirCell's filing of September 9, 2004 [8]. Thus, AirCell's analysis does not support the broadband case in its own calculations of the performance of two cross-polarized systems. In fact, AirCell has continued to limit the aircraft EIRP to 200 mW (23 dBm), which, as Airfone and Telcordia have repeatedly demonstrated, is inadequate to support broadband transmissions on the reverse link [6][9].

Appendix

Cross-Polarization Interference and Aircraft Altitude

Because of the difference in elevation between the aircraft and base station, air-to-ground (ATG) communication links are subject to a type of cross-polarization coupling that does not normally occur in the mobile terrestrial environment. To understand this, Figure 4 shows an antenna at the origin of a spherical coordinate system. The azimuth angle ϕ is the deviation from the antenna boresight in the *x*-*y* plane, and θ is the polar elevation angle.

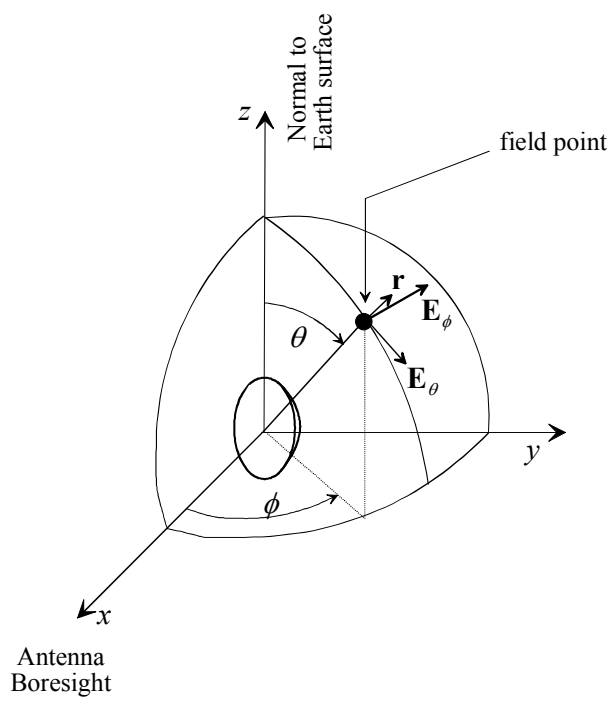

Figure 4: *Spherical coordinate geometry and E-field vector conventions*

The vector **r** represents the direction of radiated field propagation and is directed radially outward from the antenna. The complex vectors $\mathbf{E}_\theta$ and $\mathbf{E}_\phi$ are the θ and ϕ components of the electric field as shown, and they depend on antenna pattern as well as θ, ϕ, and the distance *d* between the field point and the antenna. The total *E*-field is the complex vector sum $\mathbf{E}(\theta,\phi,d) = \mathbf{E}_\theta(\theta,\phi,d) + \mathbf{E}_\phi(\theta,\phi,d)$.

The radiated *E*-field vector is confined to the plane that is normal to the direction of propagation **r**. This means that the polarization received at some point in space is generally not the same as the transmitted polarization with respect to the rectangular *xyz* coordinates. To illustrate, Figure 5 shows a vertical dipole and $\mathbf{E}_\theta$ for several different

elevation angles (in this case, $\mathbf{E}_\phi = \mathbf{0}$). For elevation angle θ_3, which is 90°, the propagation direction is horizontal and the *E*-field is vertically polarized. However, for angles θ_1 and θ_2, the *E*-field includes both vertical and horizontal components, which are shown for $\mathbf{E}_{\theta 2}$. Also shown is a horizontal dipole, which would be sensitive to the horizontal component. This is an example of a mechanism for cross-polarization interference that can occur in the ATG environment. Although a dipole was used here for illustrative purposes, the principle applies generally, because at the receiving antenna, the incident field is a plane wave with the *E*-field and *H*-field vectors defining a plane that is normal to the arrival direction.

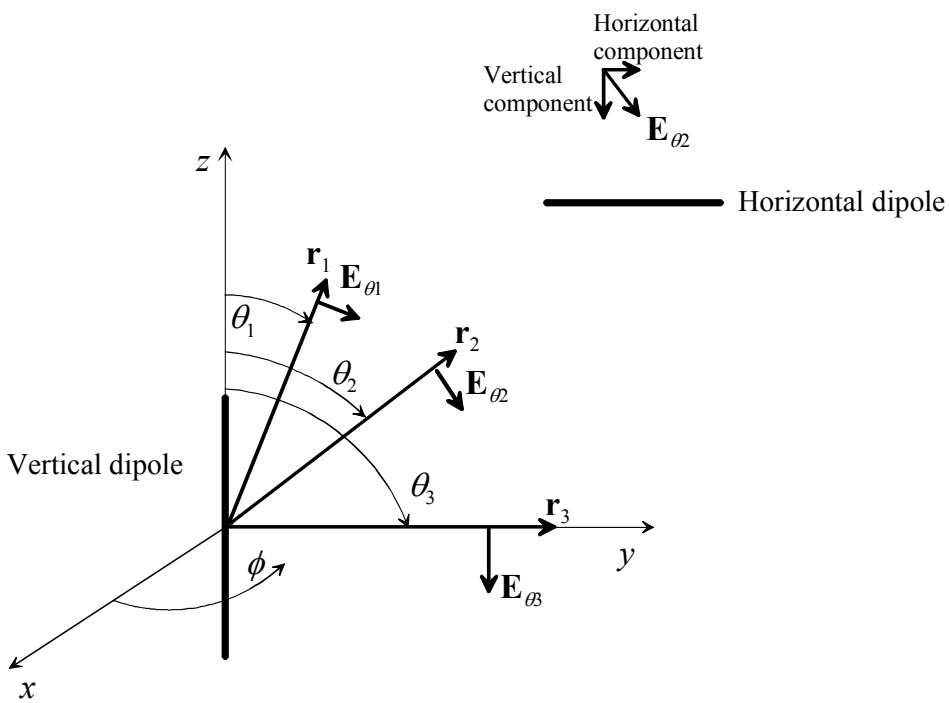

Figure 5: *Illustration of received field polarizations vs. elevation angle for* $\theta = 90^\circ$ *and "vertical" transmitted polarization.*

Note that in this case, due to symmetry about the *z* axis, $\mathbf{E}_\theta$ is independent of ϕ. The horizontal component of $\mathbf{E}_\theta$ lies in a plane defined by the dipole axis and the field point, so the effect will be greatest if the axis of the horizontal dipole lies in this plane (i.e., the axis has the same azimuth orientation as its location). For a horizontal dipole mounted on the aircraft and oriented longitudinally as shown in Figure 6 (reproduced from AirCell's Reply Comments [10]), this means that the aircraft's heading is directly toward or away from the base station.

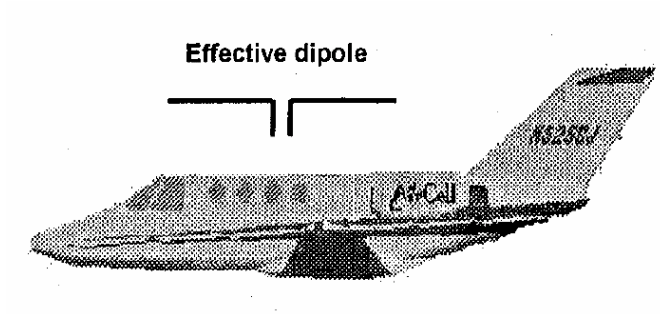

Figure 6: *Horizontally polarized dipole orientation with respect to aircraft (reproduced from [10], Exhibit B-4 ("Flight Geometry"), p. 7.*

Figure 7 shows an example for a horizontal dipole, which produces vertical field components for elevation angles other than integral multiples of $90°$. In this case, the strength of the vertical component depends on ϕ as well as θ; for $\phi = 0$ there is no vertical component for any value of θ. Also, the *E*-field in general includes both $\mathbf{E}_\theta$ and $\mathbf{E}_\phi$ components.

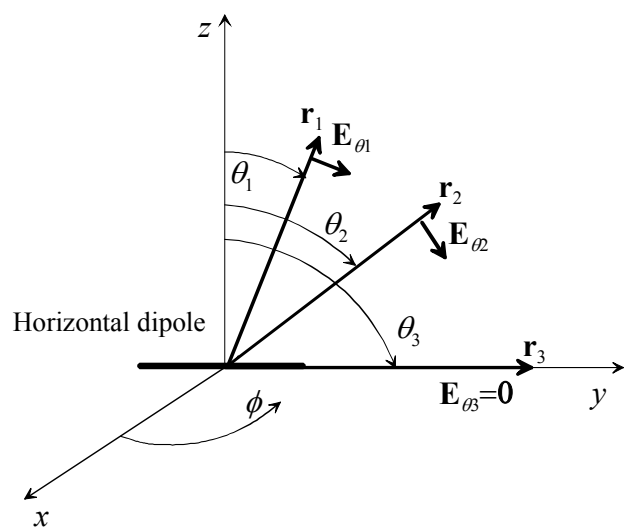

Figure 7: *Received field polarizations vs. elevation angle for $\theta = 90^\circ$ and "horizontal" transmitted polarization.*

With the above as background, it is useful to consider the cases that arise in spectrum-sharing between vertically and horizontally-polarized systems.

Horizontally-Polarized Aircraft

Figure 8 shows an aircraft approaching the vicinity of a base station, and the base station elevation angle is θ as seen by the aircraft antenna, which has a transmitted polarization parallel to the fuselage. Assume first that the aircraft is on a heading directly toward the

base station, in which case $\phi = 90^\circ$ with respect to the aircraft antenna (coordinates are as shown in Figure 7) and $E_\phi = 0$. The received vertical field component $\mathbf{E}_\mathrm{v}$ is captured by the vertically-polarized base station antenna. The directive gain of a half-wave dipole is $\cos[(\pi/2)\sin\theta]/\cos\theta$, which can be approximated by $\cos\theta$ (the pattern of a dipole that is short relative to wavelength). Using this approximation, $\mathbf{E}_\mathrm{v}$ is proportional to $\sin\theta\cos\theta$ and $\mathbf{E}_\mathrm{h}$ is proportional to $\cos^2\theta$. The extent to which $\mathbf{E}_\mathrm{h}$ is captured by the horizontally-polarized base station antenna depends on its orientation in the horizontal (*xy*) plane relative to the arrival direction of the incident field. Figure 9 shows a horizontal-plane view of the orientation of the horizontally-polarized base station antenna relative to the horizontal component of the *E*-field vector. The angle ϕ_{rx} is the azimuth angle between the antenna pattern maximum and the orientation of $\mathbf{E}_\mathrm{h}$.

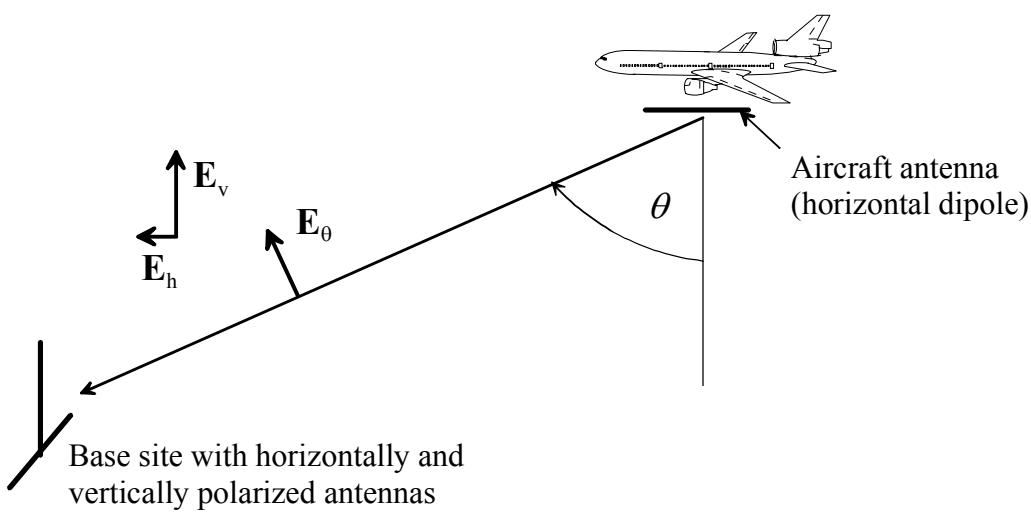

Figure 8: *Illustration of field components received at base station from a horizontally-polarized, longitudinally-oriented aircraft antenna.*

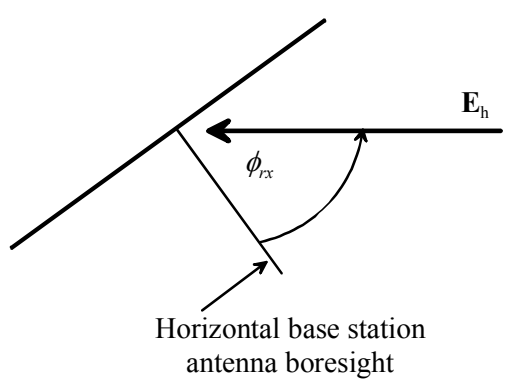

Figure 9: *xy plane view of horizontally-polarized base station antenna orientation.*

Note that if $\phi_{rx} = 0$ (the aircraft is headed directly toward the base station azimuth pattern maximum), then the horizontally-polarized antenna does not respond at all to the incoming signal. If $\phi_{rx} \neq 0$, then there is a response and its magnitude depends on ϕ_{rx}.

If the aircraft is not headed directly toward the base station, then $\mathbf{E}_\phi$, which is horizontally polarized, is non-zero (see Figure 10). The total horizontally-polarized *E*-field component $\mathbf{E}_\mathrm{h}$ at the base station will be the complex vector sum of $\mathbf{E}_\phi$ and the horizontal component of $\mathbf{E}_\theta$, but sensitivity of the horizontal antenna at the base station still depends on the angle ϕ_{rx} and Figure 9 still applies.

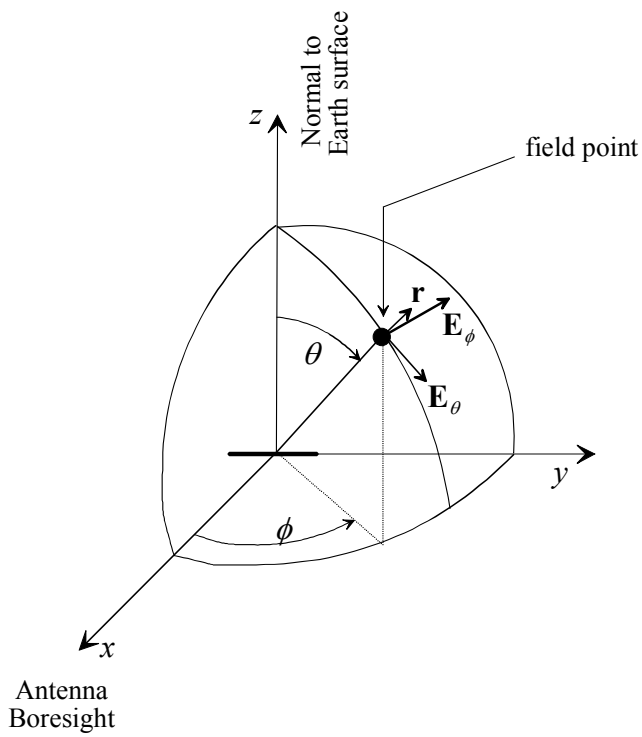

Figure 10: *Three-dimensional conventions for a horizontally-polarized antenna.*

This example highlights several points worth elaboration:

- If the aircraft is heading directly toward the base site and the aircraft antenna is oriented parallel to the length of the fuselage, then a null of the aircraft antenna is directed at the projection of base location onto the horizontal plane containing the aircraft flight trajectory. Despite this, there is still a horizontal component that can be received at the base unless the aircraft is pointed at the base (horizontal) antenna azimuth pattern maximum ($\phi_{rx} = 0$). Interestingly, in this case the base station will be most sensitive to the received horizontal component when the aircraft heading,

projected onto the horizontal plane containing the base station antenna, is aligned with the base station antenna axis; that is, aimed at the null of the base station antenna.

- Unless the base station is at the boresight of the aircraft antenna (i.e., the aircraft is oriented "broadside" to the base station in this example), there will be a vertical *E*-field component that can be received by the vertically-polarized antenna at the base station, causing horizontal-to-vertical cross-polarization interference. The strength of this vertical component will depend on the bearing of the base station with respect to the aircraft antenna.
- Taken together, the above two factors mean that for a given aircraft elevation angle θ, it is the aircraft heading with respect to the base site location that determines the horizontal-to-vertical cross-coupling in the aircraft to base direction. Indeed, it is obvious that the signal strength received at the vertical base station antenna from the horizontal aircraft antenna can exceed the signal strength captured by the horizontal base station antenna. An example of this is an aircraft heading toward the base, and into the maximum of the base station antenna azimuth pattern. If the vertical and horizontal base station antenna patterns are aligned as suggested by AirCell [1], then the vertical antenna receives a maximum and the horizontal antenna receives nothing.
- By reciprocity, the signal received by the aircraft from the horizontally-polarized base station antenna would be very low and the polarization isolation is less than 0 dB (more power is received by the aircraft from the vertically-polarized base station antenna than from the horizontally-polarized base station antenna). The aircraft might therefore connect to another cell with more favorable geometry but greater path distance. In that case, the SINR on the forward link will tend to be low due to the relatively strong interference from the nearby vertically-polarized base station antenna. Moreover, the reverse link power control will cause the aircraft transmit power to be high enough to reach the distant cell, increasing interference into the reverse link of the vertically-polarized system.

Vertically-Polarized Aircraft

Figure 11 shows a vertically-polarized aircraft antenna. By definition, the orientation of $\mathbf{E}_\theta$ is the same as for the horizontally-polarized case shown in Figure 8. However, in this case, the magnitude of $\mathbf{E}_\theta$ varies (roughly) as $\sin\theta$ whereas in the horizontal case it varies roughly as $\cos\theta$.

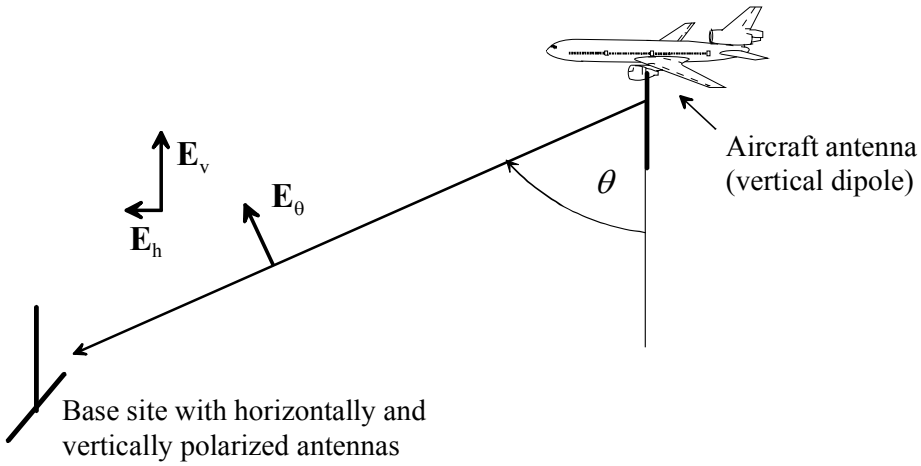

Figure 11: *Geometry for a vertically-polarized aircraft antenna.*

A more subtle but significant difference is that in this case, $\mathbf{E}_\phi = \mathbf{0}$ for all aircraft headings (azimuth orientations of the base station relative to the aircraft antenna). That is, unlike the case of the horizontal aircraft antenna, the relative values of $\mathbf{E}_v$ and $\mathbf{E}_h$ do not depend on the heading of the aircraft relative to the base station. The desired signal (received by the vertically-polarized base station antenna) is therefore independent of aircraft heading. As before, the power received by the horizontally-polarized base station antenna will depend on the azimuth orientation of the antenna relative to the aircraft's *bearing*; however, in this case it will be independent of the aircraft heading.

Observations:

- As above, if the aircraft is positioned in the boresight of the horizontal base station antenna, then no horizontal component is received. As the aircraft position deviates from the boresight, a horizontal received component begins to appear. Assuming as above that the horizontal and vertical patterns are aligned, as the aircraft azimuth angle as seen by the base station grows, the vertical (desired) component grows weaker due to a decrease in antenna pattern gain (if the vertical base station antenna has a directional azimuth pattern), and the horizontal component increases, due to increasing alignment of $\mathbf{E}_h$ with the horizontal base station antenna polarization.
- Reciprocity applies to the above, so the forward link cross-polarization interference to the aircraft will increase as the azimuth angle of the aircraft as seen by the base station (ϕ_{rx}) increases, assuming again that the horizontal and vertical antenna patterns are aligned.
- It is clear that the interference situation between the vertically- and horizontally-polarized system is not symmetric. With a horizontally-polarized base station antenna, the power levels received at the base station on both the horizontal and vertical antennas depend on the aircraft heading as well as its bearing. With a vertically-polarized base station antenna, there is no dependence on the heading.

Summary

This Appendix has shown that there will be coupling between vertical and horizontal polarizations in the air-to-ground environment due to the elevation of the aircraft and the basic principles of radio propagation. This will cause cross-polarization interference. This problem is most severe when there is a significant elevation angle between the aircraft and the base station, which occurs when aircraft at high altitude are near base stations, as well as near airports when the horizontal distances between the base stations and aircraft are small. There are cases for which the polarization isolation can be below 0 dB (the received undesired polarization is stronger than the desired polarization).

It is clear that the vertical-to-horizontal and horizontal-to-vertical coupling situations are in general not reciprocal. This is due to the fact that while "vertical" polarization at a given point in space is unambiguous (it is aligned with the *z* axis is Figure 4), "horizontal" polarization may be aligned with any vector in the *x*-*y* plane.

It is clear from the examples shown here that cross-polarization interference, even ignoring the effects of reflections, is more complex than suggested by AirCell's analysis of the effects of aircraft pitch and roll. It is also clear that the cross-polarization interference will in general be different for each aircraft/base station pair, and will vary as the heading and bearing of the aircraft change. Therefore, polarization isolation cannot be controlled by FCC requirements, and it is not a reliable way to protect two air-to-ground systems sharing the same spectrum from mutual interference.

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