WHITE PAPER: SHARING BETWEEN LTE SYSTEMS AND AERONAUTICAL MOBILE TELEMETRY (AMT) SYSTEMS IN THE BAND 1435 - 1525 MHz

This paper analyzes spectrum sharing as between aeronautical mobile telemetry and International Mobile Telecommunications systems, with a particular focus on the Long-Term Evolution-Advanced variation.

1 Introduction

1.1 Aeronautical Mobile Telemetry Systems

Aeronautical mobile telemetry (AMT) describes a particular use of the mobile service (MS) for the transmission from an aircraft station of results of measurements made on board, including those relating to the functioning of the aircraft. Examples of AMT data include engine temperature, fluid pressure, and control surface strain gauges, among many other functions.

AMT data is essential for the safety of pilots and persons on the ground during flight test activities as it is *the* critical source of real-time measurement and status information transmitted from airborne vehicles during live tests of manned and unmanned aircraft.

The band 1 435 – 1 525 MHz is a primary band used for Aeronautical Mobile Telemetry. This noise-limited band is ideal in terms of its propagation characteristics, the maturity of technology for implementing telemetry systems, and the relatively large signal wavelengths. The latter are large enough with respect to the size of aircraft structures to minimize unwanted geometrical effects, such as signal fades and destructive multipath, due to the blockage and/or reflection of the radiated telemetry signals by aircraft structures

1.2 Sharing with IMT Systems

The band 1 435 – 1 525 MHz is allocated to the Mobile Service. ITU Radio Regulation 5.343 in the Radio Regulations specifies that Aeronautical Mobile Telemetry applications have priority over other Mobile Service uses in North and South America.

Some nations have expressed an interest in deploying International Mobile Telecommunications (IMT) systems, notably Long Term Evolution-Advanced (LTE) broadband wireless “smartphones,” in this band.

This study shows that co-frequency sharing of IMT with AMT systems, in the absence of large exclusion zones, is not practical. This result is consistent with an independent study.[1],[2] Despite using country-specific parameters, the two studies independently arrive at comparable protection distances.

1.3 Purpose of This Study

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[1] For LTE parameters, documents filed with the ITU contain internationally accepted values. Many of the references that follow cite ITU documents, and these are publically available at ITU.int.

[2] Russian Federation , Contr2_JTG 4-5-6-7_Russia_engl.doc, ITU-R JTG 4-5-6-7 July 2013. This study uses propagation models contained in Rec. ITU-R P.1546, whereas the present study cites propagation models P.452 and P.528. In its notings, Rec. P.1546 compares the features of each model. Of relevance here, P.1546 uses values for important technical parameters that are specific to countries other than the U.S.

AMT systems operate at the limits of their performance. That is, all available link margin is used to permit aircraft operation at longer range from the AMT ground station, and to permit the telemetry link to be maintained during extreme maneuvers (e.g., flutter dives; spin recovery tests; flight under abnormal conditions, such as at unusual attitudes; etc.).

1.4 Study Elements

The study addresses the following study elements:

1. The impact of LTE-A handsets (i.e., user equipment, or "UE") on AMT ground stations.
2. The impact of LTE-A base stations (i.e., eNodeBs) on AMT ground stations
3. The impact of AMT transmissions from aircraft on LTE-A handsets
4. The impact of AMT transmissions on eNodeBs.

In some countries, flight test aircraft receive telemetry transmissions for relay and other purposes. In these circumstances, interference from LTE systems to flight test aircraft must also be considered. This paper does not address such scenarios.

The study takes into account:

A. The choice of propagation models, given existing ITU reports and studies.[3]

B. The application of Monte Carlo techniques for predicting aggregate emissions from ensembles of UEs, as specified by ITU-R WP-5D to JTG 4-5-6-7.[4]

2 Background

Several ITU-R Reports and Recommendations are relevant to the study described herein. First and foremost is Recommendation ITU-R M.1459, which provides the protection characteristics for AMT ground stations.

Other documents, including ITU-R Reports M.2118, M.2219, and M.2238; Recommendations SA.1154 and M.1828; and CPM text from WRCs 2003, 2007, and 2012, which also provides relevant data and analyses.[5,6]

The possible use of the band 1 435 – 1 525 MHz for terrestrial mobile systems has been addressed, with respect to IMT-2000, in ITU-R Reports M.2023 and M.2024. The latter states, with regard to the use of 1435-1527 MHz in the United States, " telemetering, telecommand, aeronautical telemetry. Vital and extensive use for aeronautical telemetry supporting U.S. test flight and equipment. Not suitable or available for IMT-2000." (id., page 8).

Parameters of LTE-A systems can be found in various working papers. Details of LTE-A systems are captured in the Third Generation Partnership Process (3GPP) archives, which are found online at www.3GPP.org. However, for the analyses developed here, LTE parameters have been taken from available ITU-R contributions and Recommendations, notably 5D/Temp/171-E of 5 February

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[3] Annex 1 to Document 4-5-6-7/236-E Summary of Previous IMT Sharing Studies, 15 Jul 2013.

[4] Per Annex 2 to Document 4-5-6-7/236-E, Monte Carlo simulation assumptions and methodology for use in modelling IMT networks.

[5] Reports ITU-R M. 2118 and M. 2219 are not included in Annex 1 to Document 4-5-6-7/236-E Summary of Previous IMT Sharing Studies, 15 Jul 2013; these documents, although relevant, do not specifically consider sharing with IMT systems.

[6] Recommendation SA.1154 is discussed in several of the documents cited previously.

2013, and Annexes 1 and 2 cited previously, to Document 4-5-6-7/236 for LTE equipment and system characteristics, as well as ITU-R Recommendation F.1336 for antenna pattern information with respect to the effects of down-tilt.

For propagation analyses, ITU-R Recommendation P.528 is available for air-to-ground studies, and Recommendations P.452 and P.1546 for ground-to-ground studies P.452 has much in common with the Longley-Rice and Irregular Terrain (ITM) models), which are also widely used. The analyses that follow are consistent with Recommendations P. 452 and P. 528. All three recommendations have been used in documents cited earlier.

3 Technical characteristics

3.1 Introduction

Sharing studies for LTE systems involve two distinguishing characteristics. The first is the use of dynamic power control by the LTE handsets (UEs). That is, in order to maintain its communication link with a base station (eNodeB) while minimizing co-channel interference to other handsets operating in adjacent cells, a handset can vary its transmitter power (EIRP), and hence interference to other, non-IMT systems, by two orders of magnitude. Annex 2 to JTG document 4-5-6-7/236-E demonstrates this via the use of cumulative distribution functions that describe an LTE-specific metric, IoT, which refers to *Interference over Thermal*. This equates system loading to the percentage of handsets served by a given set of IMT cells that are operating at maximum power. Of importance here is the suggestion by WP-5D that the most appropriate assumption for the “Portion of UE with maximum output power” in an ensemble of UEs is 2.6%. The analyses below use this value, although the rural value of 26.2% is often appropriate.

The propagation characteristics of the channel (the free-space path) between the UE and the eNodeB depend upon terrain and clutter, the latter referring to the effects of foliage, buildings, other man-made structures, and so forth. Short-range clutter effects are captured in empirical models designed to predict coverage. These include the COST-231 HATA products, for example. Long term propagation characteristics that include the effects of terrain are reliably captured in Rec. P. 452 and the Irregular Terrain Model or its predecessor, the Longley-Rice model. No single model merges, in a demonstrably accurate manner, the combined effects of short range clutter and long range terrain attenuation. Clutter attenuation in an urban environment can add 10 – 20 dB of additional path loss, for example. But, terrain effects can enhance propagation by a comparable amount, such as when the relevant antennas are mounted on hill-tops. Or, terrain can eliminate interference, as when victim receivers are protected by interference due to extreme terrain blockage. Given these difficulties, the approach taken here is to model geographical scenarios which are likely to occur, but for which existing propagation models are adequate.

Likewise, sharing studies that involve AMT systems are complex. The location of the aircraft, its high operating speeds, and its widely varying attitudes (pitch, roll, and yaw) with respect to the ground, introduce considerable dynamics in the computation of link and interference budgets. For example, telemetry signal fades of 15 – 30 dB are the rule, not the exception.

It is also important to note that even a single ground multipath reflection, as captured in the widely-used two-ray propagation model, not only introduces deep fades in the received AMT telemetry signal, but changes the path loss dependence on distance r from $1/r^2$ to $1/r^4$, thus reducing greatly the strength of the signal received at the AMT ground station.

These issues can be addressed in great detail on a case-by-case basis for specific geographic locations and in areas of operations for which detailed geographic terrain and clutter data bases exist. However, generalized analyses based can be used to bound the sharing problem, to identify the geographical boundaries for which sharing between IMT and AMT can be made possible, and the protection distances within which sharing is not possible. This is done in the material that follows.

An abbreviated summary of AMT and LTE system characteristics is provided in the next sections.

3.2 Aeronautical Mobile Telemetry characteristics

Although there exists a variety of possible AMT implementations, the fundamentals of each are the same. AMT systems operate at the limit of their performance, meaning that all available link margin is used to extend the range and/or complexity of aircraft operations. In addition, AMT systems are noise-limited, with noises figures of low noise amplifiers as low as 0.1 dB and end-to-end system noise temperatures of 25 – 250 Kelvin.

ITU-R Recommendation M.1459, which provides the interference protection criteria for AMT systems, is nonetheless generous in its permissible aggregate I/N budget. An aggregate I/N of -4 dB is permitted, versus the value of -6 dB for I/N commonly used for protection of other systems, and protection levels as high as -10 dB for some systems, like radars.

The protection levels specified in Rec. M.1459 are strict not because the AMT ground station receiver needs more protection than, for example, satellite ground station receivers. Instead, the higher level protection is required because AMT antennas typically operate at elevation angles of zero degrees with respect to the horizon. This is in contrast to satellite ground stations, which typically operate at a minimum elevation angle of 3-5 degrees. At the outset, this makes approximately a 15 dB difference in protection levels. Comparison of Recommendations M. 1459 and SA. 1154 demonstrates this.

Finally, aircraft testing involves operation of the test aircraft under conditions that can be considerably different from what are considered normal operational constraints. As stated above, this causes considerable signal fades (15 – 30 dB) due to aircraft maneuvers, signal blockage by and diffraction around aircraft structures, and ground multipath.

3.2.1 AMT Ground Station specifications

The protection criteria for AMT ground stations specified in Recommendation ITU-R M.1459 are a set of not-to-exceed power flux density (pfd) levels measured at the aperture of an AMT ground station receive antenna. The pfd levels are a function of the elevation angle of the AMT ground-station parabolic dish tracking antenna with respect to the horizon. Since the maximum operating altitude of an aircraft is typically about 60,000 feet, the maximum distance to the aircraft decreases as the elevation angle increases. A consequence of this is that pfd protection levels are less stringent for high AMT ground station antenna elevation angles than for low angles.

However, flight test aircraft also typically operate at speeds from 250 knots to well over the speed of sound (which at sea level is approximately 700 knots). Thus, aircraft do not dwell for long periods of time at high elevation angles with respect to the ground station. Instead, they operate frequently at ranges up to 250 miles, and even 300 miles from the ground station for aircraft and air vehicles that operate at altitudes of over 80,000 feet. The corresponding ground station antenna elevation angles, depending on the location and placement of the AMT ground station antenna with respect to terrain, range from -2 degrees to + 2 degrees with respect to the horizon. (AMT antennas are typically located on towers, at 30 meter height above terrain, and these towers are often located on hilltops or mountains.)

Thus, an AMT antenna can point for extended periods of time at 0 degrees elevation and at any azimuth angle. And, aircraft cannot instantly and randomly “jump” from one location to another. In consequence, Monte Carlo techniques for predicting the location of the aircraft are seldom accurate, and Rec. M.1459 makes clear that such stochastic approaches to modelling interference are not appropriate. In addition, even momentary interference can cause the AMT receive antenna tracking control loop to lose lock, or cause bit synchronization within the AMT digital receiver and bit de-commutator circuits to be lost. As a result, interference analyses must contemplate circumstances where the interference may occur even for only a few seconds. As seen on ground station displays of telemetry data, a consequence of even momentary telemetry dropouts can be a graphical indication that an aircraft is in a high speed dive, when in fact it is flying straight and level. Confusion created by compromised telemetry makes more difficult the conduct of safe, efficient flight test operations.

For interfering signals at low elevation angles of arrival at the AMT ground station, the value for protection of L-band telemetry is -181 dBW per meter^2 in 4 kHz. This sensitive value is a consequence of a noise-limited system that operates with high gain (30 – 40 dBi) ground station tracking antennas. Furthermore, these are tracking antennas that often use servo-control loops in conjunction with a conical scan antenna feed. If the antenna control unit (ACU) loses lock, recovery of the AMT downlink can take many minutes, if it can even be accomplished without restarting the flight test segment. This is an expensive and time- consuming proposition, and is not without risk to the flight crew and aircraft.

3.2.2 *AMT Aircraft Transmitters and Antennas*

AMT aircraft in the U.S. typically use two omni-directional antennas, one located on top of, and one located below the fuselage, respectively. The link is usually one way, from air to ground.[7]

Typical aircraft transmit antenna gains are 2 dBi, and transmitter power levels range from 5 - 10 Watts for 1 – 5 MHz wide channels, and 20 Watts or more for 10 – 20 MHz channels, with system-to-system variability between these extremes. Modulation techniques range from PCM-FM-NRZ to advanced digital modulation techniques.

In general, the signal to noise ratio at the AMT ground station receiver needs to be a least 12 -15 dB in order to maintain bit synchronization.

3.2.3 *AMT Aircraft to Ground Propagation Characteristics*

Because AMT ground station antennas typically point at or near the horizon, terrain effects can be significant when predicting the amount of interference arriving at the ground station from a ground-to-ground path. But, modelling of the air-to-ground path of the flight test telemetry signal is already taken into account in Rec. M. 1459 via its analysis of channel fading. Thus, the only modelling that need be done is the computation of interference from terrestrial sources. ITU-R Recommendation P. 452, which models such ground-to-ground propagation, is appropriate for IMT to AMT ground station interference analyses.[8]

However, with respect to interference from AMT aircraft transmitters to, for example, eNodeB LTE base stations, the geometries under which interference occurs, namely from aircraft at a relatively high elevation angle with respect to a victim eNodeB antenna on the ground, make the use of Recommendation P. 528 more appropriate.

3.3 *LTE characteristics*

3.3.1 *LTE handsets/UEs*

The analysis herein is consistent with information published by 3GPP and captured in ITU documents 5D/Temp/171, and more recently in 5D/Temp/232(Rev.1), and in the JTG documents

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[7] Although, as noted previously, in some countries ground-to-air links are also used.

[8] In the U.S. Recommendation P.452 corresponds to a tool known as the Irregular Terrain Model which, in turn, is based on the Longley-Rice model.

cited previously.[9] Specifically, it is assumed here that LTE handsets transmit a maximum EIRP of 100 mW (20 dBm) across a bandwidth of 5 MHz, such that, within a 10 MHz AMT channel, two handsets per eNodeB sector (typically 120 degrees, with 3 sectors per base station tower) are simultaneously operational. The EIRP assumption includes 3 dB of antenna loss. Body absorption, specified by the JTG, is assumed to be -4 dB. However, as this is highly variable, and can often be zero, it is not considered in the analyses that follow.

The height above ground for handsets is typically assumed to be 1.5 meters, although it is common for handsets to be used indoors, near windows and in the upper stories of buildings, well above the local level of terrain. In general, there can be considerable variability with respect to bandwidth assumptions, as LTE systems can dynamically adjust channel sizes and allocations in real time to suit demand. Also, handsets utilize dynamic power control in order to minimize cross-cell interference to other users in the same network.

LTE UE characteristics from the JTG documents cited above and available at www.ITU.int are reproduced in Table I, below.

Table I.

User Terminal Characteristics

User terminal characteristics	Macro rural	Macro suburban	Macro urban	Small cell outdoor / Micro urban	Small cell indoor / Indoor urban
Indoor user terminal usage	50 %	70 %	70 %	70 %	100%
Indoor user terminal penetration loss	15 dB	20 dB	20 dB	20 dB	20 dB
User terminal density in active mode	0.17 / 5MHz/km^2	2.16 / 5MHz/km^2	3 / 5MHz/km^2	3 / 5MHz/km^2	depending on indoor coverage/ capacity demand
Maximum user terminal output power	23 dBm	23 dBm	23 dBm	23 dBm	23 dBm
Average user terminal output power[10]	2 dBm	-9 dBm	-9 dBm	-9 dBm	-9 dBm
Typical antenna gain for user terminals	-3 dBi	-3 dBi	-3 dBi	-3 dBi	-3 dBi
Body loss –	4 dB	4 dB	4 dB	4 dB	4 dB

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[9] Liaison statement 4-5-6-7/236-E from WP-5D, 18 July 2013, containing Preliminary Draft New Report ITU-R [IMT.ADV.PARAM], Characteristics of terrestrial IMT Advanced systems for frequency sharing/interference analyses.

[10] According to JTG5-6/180 Annex 2 (except for small cell indoor scenario, which was not covered in that document).

The actual EIRPs for a large ensemble of UEs operating with the multiple eNodeBs that, under a sharing scenario, will be visible within the main-beam and side-lobes of an AMT antenna, will vary according to a statistical probability distribution, the *CDF*, or *cumulative distribution function*. This is a consequence of the use of dynamic power control as well as the peak-to-average signal variations that result from the LTE modulation techniques used in both the handset and eNodeBs.

Table II (cf. Reference 10) shows possible interference from UEs to other systems. Probability analyses typically attempt to identify the average behaviour of an ensemble of emitters, and the smaller portion of the ensemble of UEs which, in this case, will be transmitting at maximum power. With respect to interference to AMT systems, it is the worst-case behaviour of an ensemble of interferers that matters, and determination of this worst-case condition does not typically require statistical analysis. This is because short term interference has long-term impact, as discussed in section 3.2.1, above.

For example, Table II provides worst-case power levels for UEs under three different power control (PC) scenarios. The JTG recommends that Power Control setting 2 be used for simulations. But, even the conservative estimate of power control setting 2, for which 2.6% of UE’s are transmitting at maximum power at any given instant, describes a situation in which the likelihood of an AMT ground station encountering at least one instance of harmful interference in a multi-hour flight, in which a single device operating co-frequency produces interference that causes a long term telemetry dropout, approaches100%. Thus, the actual distribution of UE power levels in terms of average power, or in terms of a Gaussian distribution having a well-defined standard deviation, is not relevant to most AMT analyses. Nevertheless, Table II provides the important statistic, namely the percentage of UEs in a geographically and/or temporally distributed ensemble that transmit at maximum power.

TABLE II.

Simulation results of different PC settings

	PC setting 1	PC setting 2	PC setting 3
PLxile in dB	115	122	130
γ	1	1	1
Portion of UE with maximum tx power	24.8%	2.6%	0.003%
Average IoT in dB	14.00	8.81	0.89
Average throughput (b/s/Hz)	0.522	0.417	0.252
5% CDF throughput (b/s/Hz)	0.167	0.177	0.141

3.3.2 LTE eNodeB base stations

LTE base stations, per the JTG documents cited in the previous footnotes, are assumed to have sectorized antennas with a nominal gain of ~15 dBi, including 3 dB of feeder loss, and a corresponding beamwidth per sector of approximately 120 degrees. These are typically mounted on towers above local terrain. Details of cell size, antenna height, and power levels, as provided by the JTG (cf. Footnote 10) are shown in Table III. However, taking into account an activity factor (e.g., network loading) of 50%, the average base station EIRP is given as 55 dBm in 5 MHz.

In dense deployments, antenna *down-tilt* is used to reduce interference to adjacent LTE cells. Down-tilt is reduced when coverage, rather than capacity, is the goal. Note that mechanical down-tilt of eNodeB antennas by 3 degrees or more is typically a remote-controlled operation that does not require any modification to the original antenna installation. The effects of down-tilt on eNodeB antenna gain are described in ITU-R Recommendation F. 1336. Values for down-tilt and average antenna tower height are also provided in Table III. Note that "activity", or "activity factor" are referred to as "load factor" or "network loading".

TABLE III.

Deployment-related parameters for bands between 1 and 3 GHz

	Macro rural	Macro suburban	Macro urban	Small cell outdoor / Micro urban	Small cell indoor / Indoor urban
Base station characteristics / Cell structure					
Cell radius / Deployment density (for bands between 1 and 2 GHz)	> 3 km (typical figure to be used in sharing studies 5 km)	0.5-3 km (typical figure to be used in sharing studies 1 km)	0.25-1 km (typical figure to be used in sharing studies 0.5 km)	1-3 per urban macro cell[11] <1 per suburban macro site	depending on indoor coverage/ capacity demand
Cell radius / Deployment density (for bands between 2 and 3 GHz)	> 2 km (typical figure to be used in sharing studies 4 km)	0.4-2.5 km (typical figure to be used in sharing studies 0.8 km)	0.2-0.8 km (typical figure to be used in sharing studies 0.4 km)	1-3 per urban macro cell[4] <1 per suburban macro site	depending on indoor coverage/ capacity demand
Antenna height	30 m	30 m (1-2 GHz) 25 m (2-3 GHz)	25 m (1-2 GHz) 20 m 2-3 GHz)	6 m	3 m
Sectorization	3-sectors	3-sectors	3-sectors	single sector	single sector
Down-tilt	3 degrees	6 degrees	10 degrees	n.a.	n.a.
Frequency reuse[12]	1	1	1	1	1

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[11] Outdoor small cells would typically be deployed in very limited areas in order to provide local capacity enhancement. Within these areas, outdoor small cells would not need to provide contiguous coverage since there would typically be an overlaying macro network present.

[12] If the IMT network consists of three cell layers – macro cells, small outdoor cells and small indoor cells – they will not all use the same carrier. Two layers may use the same carrier, although separate carriers in the same or different bands are also possible.

Antenna pattern	Recommendation ITU-R F.1336 Annex 10 (see “Antenna Pattern” section) • $k_a = 0.7$ • $k_p = 0.7$ • $k_h = 0.7$ • $k_v = 0.3$ Horizontal 3 dB beamwidth: 65 degrees Vertical 3 dB beamwidth: determined from the horizontal beamwidth by equations in Recommendation ITU-R F.1336. Vertical beamwidths of actual antennas may also be used when available.			Recommendation ITU-R F.1336 omni	
Antenna polarization	linear / +- 45 degrees	linear / +- 45 degrees	linear / +- 45 degrees	linear	linear
Indoor base station deployment	n.a.	n.a.	n.a.	n.a.	100 %
Indoor base station penetration loss	n.a.	n.a.	n.a.	n.a.	20 dB (horizontal) P.1238, Table 3 (vertical)
Below rooftop base station antenna deployment	0 %	0 %	30 % (1-2 GHz) 50 % (2-3 GHz)	100 %	n.a.
Feeder loss	3 dB	3 dB	3 dB	n.a	n.a
Maximum base station output power (5/10/20 MHz)	43/46/46 dBm	43/46/46 dBm	43/46/46 dBm	35 dBm	24 dBm
Maximum base station antenna gain	18 dBi	16 dBi	16 dBi	5 dBi	0 dBi
Maximum base station output power (EIRP)	58/61/61 dBm	56/59/59 dBm	56/59/59 dBm	40 dBm	24 dBm
Average base station activity	50 %	50 %	50%	50 %	50 %
Average base station power/sector	55/58/58 dBm	53/56/56 dBm	53/56/56 dBm	37 dBm	21 dBm

3.3.3 *Applicability of LTE system characteristics to the problem of co-channel sharing between LTE and AMT*

Although the data in Tables I-III provide information that is essential for the completion of many sharing studies, many of the details have relatively little impact on the final results of *this* sharing study. Specifically, cell size, antenna down-tilt, deployment density, average UE power, assumptions about clutter and propagation, and so forth, are shown to have little impact on the final results developed herein. This is because of two key features that distinguish AMT systems from other systems being considered by the JTG:

- AMT ground station tracking antennas operate, by necessity, at elevation angles of two degrees or less. This is an unavoidable consequence of the need to track aircraft at long distances. As a result, interference from terrestrial systems arrives in the main-beam of the high gain (30 – 40 dBi) AMT ground station antenna, which can point in any azimuth direction for extended periods of time.

- Since the aircraft are moving at high speed, momentary signal dropouts cause loss of antenna track and bit synchronization, thus turning a short duration (fractions of a second) signal into a long term (several minutes) loss of telemetry.

3.3.3.1 Cell size and down-tilt

Consider a 10 MHz wide AMT telemetry link for which the AMT ground station is within radio line of sight of several dozen eNodeB towers of height 30 meters above terrain. Depending on the urban/suburban/rural nature of the deployments, the number of base stations within the main-beam of a 30 dBi AMT ground station antenna, pointing at the horizon at 0 degrees elevation angle, will vary considerably. However, as the number of base stations and UEs in simultaneous view of an AMT ground station increases, the power per base station and the power per handset often decreases by the same factor. This is accomplished by down-tilt and static power settings for the eNodeBs, and by dynamic power control for the UEs. Consequently, the aggregate interference at the AMT ground station becomes, to a first approximation, independent of the number of UEs and of the number of eNodeBs in view.

3.3.3.2 Statistical variation of UE power levels and load factors

As stated above in reference to Table II, the maximum UE power levels, not the average UE power levels, are of concern. Elaborating upon the previous comments, even if only 2.6% of UEs emit at maximum power, the fact that the maximum power is so large (+20 dBm) compared to the average power (-9 dBm) in the tables reproduced above, and given that even low-duty cycle interference to AMT can be dangerous, the maximum excursions must be considered first. If these excursions interfere with AMT operation, there is little need to analyze the more challenging and controversial details of average interference, which depend critically on considerations of clutter and the choice of propagation model, as discussed below.

Stated differently, because of the unique nature and safety-related functions of AMT operations, harmful interference that occurs for 2.6% of time (cf. Table II) is not mitigated by the 97.4% of time for which a UE transmits at levels below the predicted average. If one chooses to analyze the spatial, rather than temporal, case, interference to AMT is likewise not mitigated by the 97.4% of handsets that transmit at average power levels all of the time, versus the 2.6% that always transmit at maximum power.

In the rural case (corresponding to the coverage, rather than capacity limit), the smaller number of handsets is offset by the 26.2% that are operating at full power, presumably under conditions in which clutter and building attenuation are of significantly less importance than are the case for urban and suburban deployments.

With respect to network activity (or load) factor, peak network usage times will not be weekends or in the middle of the night. Instead, they will be during business hours, when most flight test activities are also conducted.

3.3.3 LTE Ground to Ground Propagation Characteristics

LTE system designers strive to achieve coverage as a first criterion in system design. This is accomplished by using propagation models that ensure real-time LTE signals are powerful enough to close the UE to/from eNodeB link. Terrain and clutter effects are critical to the analysis and prediction of the propagation conditions that permit this mobile service to operate successfully.

For modelling the effects of terrain in the absence of clutter, ITU-R Rec. P. 452 (or the Irregular Terrain Model) is appropriate. Most LTE cells will be a few kilometers (urban) to only tens of kilometers (rural), not hundreds of kms, in radius. However, in accordance with Table III, average LTE cell radii used for simulation purposes should be 5 km, 1 km, and 0.5 km, respectively for rural, suburban, and urban population zones. The resulting LTE propagation distances are short, in contrast with flight test telemetry link distances, which are several hundred kilometers.

Accurate modelling of terrain is achievable due to the world-wide availability of terrain data bases. In the U.S. 1 - 3 arc-second terrain data is available from public data bases. This makes practical the use of site-specific models. However, the use of terrain data within the various propagation models is often achieved through the introduction of statistical averages and other probabilistic assumptions.

3.3.4 Consideration of Clutter

As shown below, the presumption that a small percentage of emitters operating under worst-case conditions dominate the LTE to AMT interference problem makes a detailed discussion of clutter unnecessary. This is particularly true when, as discussed above, dynamic power control and antenna down-tilt combine to offset increased numbers of LTE users and eNodeBs.[13]

In terms of the present situation, the specifics of cell size, antenna down-tilt, and average LTE equipment power levels are of secondary importance. And, even if clutter in urban, and perhaps suburban, regions mitigates interference from within the coverage area, the edge of the coverage area that faces an affected AMT ground station will not benefit from this mitigation. Consequently, it is the interference from the edge of the urban or suburban area that will dominate the interference analysis.

This situation increases the dependence of the interference computations on the choice of long-range propagation model that is used. But it reduces significantly the importance of having an accurate clutter model.

A UE might, for example, be on the near side of a suburban cluster of buildings with respect to an AMT ground station. The presumed 20 dB of clutter caused by the buildings with respect to the line of sight path between the UE and its eNodeB will require the UE to use maximum power in order to close the LTE link. This leads to the conclusion of a rural, clutter-free path between the UEs and the victim AMT ground station antenna, while remaining consistent with the suburban deployment assumption of significant clutter.

Because of the omni-directional antenna used on the UE, the full brunt of the 100 mW signal will be “felt” by the victim AMT ground station antenna, which can point in the direction of the suburban area for extended periods of time while tracking a flight test aircraft operating at a typical maximum range of 320 km.

Under these conditions, and using the PC1 power control characteristics from Table II, as appropriate for UEs on the rural side of the suburban/rural interface, each UE operates at maximum power for 26.8% of time and the situation becomes even more serious. And, there is approximately a 6.4% chance that at any moment not just one, but two or more UEs are transmitting at maximum power simultaneously. This accounts explicitly for the presumed 50% activity factor; no additional factor of 3 dB need be added. Nor is a clutter model or correction needed, as the UEs of interest in this scenario lie on the edge of the suburban/rural boundary, outside of the suburban clutter zone.

In addition, because of the manner in which AMT links transmit packets and rely on antenna tracking loops, as well as bit synchronizers and de-commutators, jamming signals that have a 1/16 duty cycle are as disruptive as jammers that have 100% duty cycles.

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[13] Cf. section 3.3.3.1.

Furthermore, although this particular scenario accounts for only a small percentage of UEs and base stations, it will nevertheless be a common situation at the boundaries between urban and suburban regions, and the boundaries between suburban and rural areas. As shown below, the interference from these boundary regions, with no regard to the more challenging problems of modelling LTE systems within urban and suburban regions, demonstrates that co-channel sharing between LTE and AMT is problematic.

4 Summary

4.1 LTE protection criteria

In the summary computations below, a range of conditions is determined for which LTE signals, from UEs or eNodeBs, when received an AMT ground station site, will exceed the pfd level of -181 dBW per meter^2 in 4 kHz specified in Rec. M.1459. However, the information provided by ITU-R Working Party 5D to the JTG, summarized in Tables I – III, says little about the interference protection criteria to be used in assessing interference <u>to</u> LTE systems <u>from</u> aircraft telemetry signals. An Interference Protection Criterion of I/N = - 6 dB from AMT systems to LTE systems is assumed. Further, it is also assumed (from previous studies in the U.S.[14]) that LTE handsets have a typical noise figure of 9 dB, and eNodeBs a noise figure of 5 dB.

Since the propagation path from an aircraft to the ground is modeled by Recommendation P. 528, for which free space propagation dominates, it is straightforward to adjust the results presented below to a different protection level, if appropriate. For example, a change of 6 dB in protection implies a factor of two change in the protection distance, a consequence of the long range characteristics of air-to-ground propagation.

The pertinent results, presented below, are the typical distances within which the calculations show that interference will exceed the Rec. M. 1459 levels for AMT ground stations, or the I/N criteria for LTE systems.

4.2 Study element 1: The impact of LTE-A terrestrial systems, namely handsets (i.e., user equipment, or "UE") on AMT ground stations.

Considering only UEs that have a clear propagation path to the victim AMT receiver, protection distances equate to the spherical earth line of sight distance of about 24 km. If idealized line of sight is the only consideration, the protection pfd levels given by Rec. M.1459 don't come into play.

However, terrain effects and refraction must also be considered. The latter increases the effective line of sight distance by a factor of $\overline{\qquad}$, from 24 km to 28 km. And, if one performs a full E&M analysis using the pfd levels from M.1459, the aggregation and statistical parameters in Tables I - III subject to the worst-case UE transmit power conditions outlined above, and a terrain-based propagation model such as P.452, typical protection distances increase to 47 km and more. This is because the additional propagation loss for distances greater than 28 km, although significant, must be very large in order to offset the enormous sensitivity of AMT ground stations. Noise-limited AMT systems have large tracking antennas with high values of gain (30 – 40 dBi) connected to low noise amplifiers having noise figures as low as 0.1 dB.

4.3 Study element 2: The impact of LTE-A base stations (i.e., eNodeBs) on AMT ground stations

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[14] Commerce Spectrum Management Advisory Committee (CSMAC), Working Group 5, available online at the CSMAC website.

The analysis of interference from eNodeBs to AMT ground stations follows an approach similar to that described above for UEs. However, the power levels are significantly higher, with average EIRPs of 55 dBm per 10 MHz, per Table III, including a 3 dB reduction for antenna downtilt and including the 50% activity factor.[15] Combined with nominal eNodeB tower heights of 30 meters, exclusion zones will be, at a minimum, the line of sight distances required for UEs, as described above, but adjusted for 30 meter average eNodeB tower height. Thus, a line of sight distance of 27 km for a UE becomes 45 km for a single eNodeB tower. However, this is a lower limit. When beyond line of sight distances are included in propagation models, the distance at which an eNodeB needs to be from an AMT ground station in order to comply with M.1459 exceeds 100 km, even for “typical” terrain.[16]

This does not include aggregation, which can be significant. And, because of the scaling effects described previously, reduction of cell size and the use of larger down-tilt angles for suburban and urban deployments will typically be offset by the increased number of cells, resulting in similar levels of aggregate interference for all three deployment scenarios: rural, suburban, and urban.

This leaves clutter effects as the remaining mitigation factor. These will be of no benefit for rural scenarios. And, the 30 meter tower height stipulated for use in sharing studies places eNodeBs above the height for which attenuation due to clutter will be significant for suburban and urban scenarios.

4.4 *Study element 3: The impact of AMT transmissions from aircraft on LTE-A handsets*

Suppose that UEs are configured to receive (FDD operation), or receive and transmit (TDD operation) in the 1 435 – 1 525 MHz AMT band. In these cases, transmission of signals from an aircraft to a UE will cause interference.

Quantitatively, consider a UE with a noise figure of 9 dB and a corresponding noise temperature of 2000K operating over a bandwidth of 5 MHz. Its noise floor over this bandwidth is -129 dBW. If an allowable I/N of -6 dB for the handset and an omnidirectional UE receive antenna with a gain of -3 dBi are assumed, then a 10 Watt,10 MHz bandwidth AMT transmission through a 2 dBi gain aircraft antenna will exceed I/N = -6 dB at a distance of 45 km. However, this is the distance from the aircraft to the UE. Since the aircraft may be up to 320 km from the AMT ground station, this yields an exclusion zone of 365 km.

When body-blocking or loss associated with the handset positioning with respect to its user attenuate the AMT signal, improvement will occur. But this will only be the case when blockage does not also, simultaneously, reduce the desired eNodeB signal. Note then when used as a internet “hotspot”, it is common to deliberately place a UE that is tethered to another device (e.g., laptop or “pad”) so as to minimize body attenuation.

All UEs within this interference distance from the aircraft, which can be a very large number, will be affected.

Even if the interference criterion were to be relaxed from, for example, I/N = -6 dB to I/N = -3 dB, significant interference from AMT transmissions to UEs would remain.

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[15] As stated, short-term interference to AMT systems causes long-term dropouts. Hence, 50% activity factor might not provide mitigation against the inevitable worst-case maximum power situation. The exception is when aggregate effects are significant enough that the use of average power per eNodeB is appropriate. However, in this limit, the deleterious effects of aggregation will likely outweigh the benefits to sharing that result from the use of average values.

[16] e.g., 90 meter average terrain variation, which is common in the U.S.

4.5 Study element 4: The impact of AMT transmissions on eNodeBs

The above results become worse when eNodeBs are the victims. Even with down-tilt, their main-lobe gain in the direction of an aircraft can be high (5 – 15 dBi). And, because of sectorization, at least one-sector, or one third of the capacity of each eNodeB, will be affected by an aircraft telemetry signal when the aircraft is in sight. Furthermore, the noise figure for a base station is 4 dB better than that of a handset. Hence, system performance levels that depend on I/N criteria are correspondingly more difficult to achieve than for the case where a UE is the victim receiver.

In any case, exclusion zones will be considerably larger than the 365 km computed above for interference to UEs. Thus, the interference from AMT aircraft to eNodeBs will also be severe.

The determination of which of the four scenarios above applies to a particular LTE deployment scenario turns on whether the LTE system is operated in Time Division Duplex (TDD) or Frequency Division Duplex (FDD) mode. Both TDD and FDD implementations of LTE can be used in any band, subject to equipment design and network implementation, as the 3GPP specification supports both TDD and FDD.

For both TDD and FDD, when UEs transmit in the AMT band, the eNodeBs must receive in the AMT band. As a consequence, the large exclusion zones needed to prevent UE signals from interfering with AMT ground station receivers will be eclipsed in size by the larger exclusion zones needed to protect eNodeBs from AMT aircraft transmissions.

Alternatively, if eNodeBs transmit, rather than receive, in the AMT band, interference to AMT from UEs transmitting in a different FDD band will not occur. However, the exclusion zones needed to protect AMT ground stations from eNodeB transmissions will be prohibitively large, and the distances required for protection of UEs from AMT transmissions will be even larger.

4.6 Conclusion

The required separation distances needed in order to meet protection levels of -181 dBW/m^2 in 4 kHz (interference from LTE to AMT) and I/N = -6 dB (interference from AMT to LTE), are significant in all cases. For interference to AMT ground stations, peak, rather than average interference levels must be considered. This is because short-term interference causes long term telemetry signal dropouts. And, if clutter in urban and suburban deployments is found to provide significant interference mitigation, the ability of a few interference sources located at the interface between urban/suburban and suburban/rural deployments will still cause harmful interference to AMT ground stations.

Sharing between IMT and AMT in the band 1 435 – 1 525 MHz is not practical due to the large exclusion zones required for all of the possible uplink/downlink combinations, whether TDD or FDD is used.

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