Regulating and Standardizing Directive Antenna Patterns to Improve Coexistence

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Abstract— The antenna limits imposed in America and Europe are compared with the patterns in an ITU-R Recommendation. As most of RF interference emanates from the sidelobes of the transmitting antennas and enters through those of the receiving antennas, the regulation and standardization of antenna patterns is essential to optimize RF spectrum reuse. Since there are no regional standards in Asia and Africa for directional point-to-point antennas, the reference envelopes defined by the ITU, the European-based ETSI and the USA-based FCC are adopted globally. Depicting these limits, next to measured antenna patterns from two different suppliers, reveals that the ETSI limits are more restrictive than those of the FCC. New theoretical evidence is provided for the 2018 revision of the ITU Recommendation. Proposals are provided to tighten FCC limits and to loosen those of ETSI.

Index Terms— Antenna radiation patterns, directive antennas, dual band, electromagnetic analysis, electromagnetic microwave antennas, modelling, radio-frequency interference, radio link, radio spectrum management, antenna polarization, standardization, transmitting antennas.

I. INTRODUCTION

The transmitter's antenna pattern and spurious emissions are crucial for RF coexistence and efficient spectrum utilization. The worst-case interference scenario occurs when the aggressing transmitter and the victim receiver operate in the same frequency band and are oriented such that their antennas are within their main beam, and their directionality offers no or little relief. In Europe the regulation and standardization of spurious emissions are more restrictive than in the Americas and in Japan [1]. Europe adopts Category B, which follows more stringent spurious emission limits when compared to the Japanese Category D, as well as to the liberal Category A limits, which is adopted in the Americas.

The radiation pattern in a high-performance antenna usually involves a tradeoff between reduced interference and the cost/size/weight of the antenna, as well as the difficulty in achieving optimal alignment. The choice of the antenna pattern depends on the application targeted, the coexistence scenarios envisioned, the requirements of the operators and the governing entity. From a spectrum utilization point of view, i.e. minimum interference, the preferred condition is when the required EIRP is obtained with the highest antenna gain and the lowest output power.

Fig. 1 depicts an interference scenario, involving two directional systems; see Report ITU F.2059 Fig. 1 (with ITU permission). Additional explanations may be found in [2]. The area S is bounded by a geographic power density contour repressing the area in which an interfering signal in excess of a certain level will adversely impact the reception at victim receiver A. Effectively, S may deny the use of this spectrum in S', used by system A, due to the geographical overlap and the relative orientation. As shown in this example, the main beam of transmitter TxB is also received by the antenna sidelobe of receiver RxA. Reducing the relative level of the sidelobe of RxA would effectively reduce the overlap between S and S', allowing TxB to operate at higher power levels, thereby improving the spectrum sharing between the two systems.

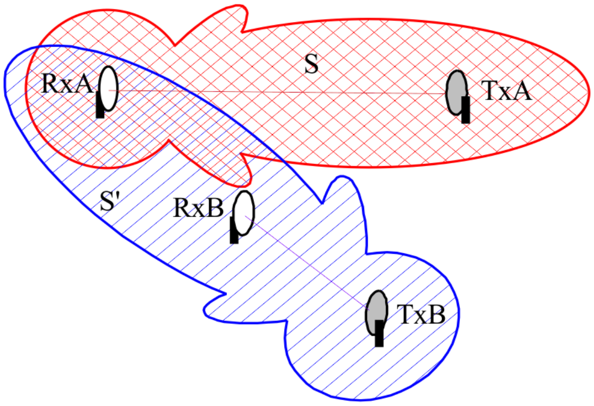

Fig. 1. General interference scenario between systems with directional antennas

The current most relevant standards on antenna patterns, which are intended to address such scenarios, are:

1. Recommendation ITU-R F.699 [3],
2. ETSI EN 302 217-4 V2.1.1 [4], and
3. 47 CFR- §101.115 of the FCC [5].

The patterns defined by the ITU and ETSI refer to maximum antenna gains (specified in dBi), while the FCC mask provides attenuation relative to the main beam (specified in dB). The FCC limit also specifies minimum antenna gain. The figures and original tables depict parallel and cross polarized patterns, mainly at 10.6 GHz and 72 GHz (gain $\geqslant$ 50 dBi) for different categories/classes of antenna performance.

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As ETSI uses four classes and FCC only two categories, ETSI figures focus on classes 2 and 4, which are to be compared with the two FCC categories A and B. The way these institutions classify the patterns is different: ETSI uses 7 frequency ranges and FCC uses 37. As the pattern's change in general is monotonic with frequency, it is sufficient to analyze two bands (2 and 7) out of the seven frequency ranges of ETSI. Hence, the conclusion is robust, especially as two distinct variables (parallel and cross polarizations) are surveyed.

In the absence of globally adopted standards for antenna patterns, in its "Resolução nº 609" [6], Brazil is inspired by ETSI [4] and IEEE [7] standards. Vietnam approved technical regulations on point-to-point (P2P) [8], where the antenna parameters (gain, co-polar and XPD), similar to Brazil, comply with ETSI [4]. In Japan, the regulations for antenna characteristics are based on the government's "Equipment Regulation" clause 49.19 [9]. Specifically, Section 2.4 of ARIB STD-T58 provides EIRP masks for the 22, 26 and 38 GHz bands. The masks defined there are more liberal than those in ITU Recommendation F.699, practically all over the sidelobes, for transmitters with power levels below 42.4 dBm (18 Watts). This applies to nearly all Japanese point-to-point transmitters. When examining the regulations in other Asian, American and Africa[1] administrations, one may note that the operation of antennas in most countries around the world follows the ITU, ETSI or FCC masks.

The use of millimetric band and carrier aggregation, e.g., 38 GHz and 80 GHz on the same link, allows for high backhauling capacity, but requires dual-band antennas. Getting high attenuated sidelobes at these dual-band antennas, to meet the most restrictive ETSI class 4 limit, is technically challenging.

This paper compares the European and American limits for patterns to the international and commercial antenna sidelobes and proposes amendments to them, based on antenna theory and practical international experience.

II. ANTENNA PATTERNS: ITU, EUROPE, AND USA

A. Recommendation ITU-R F.699

Recommendation ITU-R F.699, titled "Reference radiation patterns for fixed wireless system antennas" [3], serves also as an informing reference in ETSI Standard EN 302 217-4, titled "Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 4: Antennas" [4]. While ETSI and FCC standardized patterns serve as regulatory limits, Recommendation ITU F.699 serves as an international reference, denoting average of worldwide patterns, to assist RF interference studies.

The patterns defined in ITU Recommendation F.699 are based only on the antenna length or diameter D, expressed in the same unit as the wavelength λ. The F.699 limits are divided into two distinct types of antennas, where the ratio between the diameter and the wavelength (D/λ) is less or more than 100. The F.699 revision published in March 2018 introduces an extended roll-off in the sidelobe (ends at 120^0, instead of 48^0), thereby lowering the floor antenna gain by 10dB. Following the author's contributions on behalf of ATDI, F.699 revision implements more restrictive equations that apply only above 70 GHz.

As the comparison figures refer to 10.6 GHz and 72 GHz, the selected equations reflect a ratio D/λ below 100 for 10.6 GHz (where D is less than 3 m.), and above 100 for 72 GHz (where D is greater than 43 cm.). According to subsection 2.1.2 in F.699, for off-boresight φ (absolute value in degrees), the sidelobe level gain $G(\varphi)$ (in dBi), for $D/\lambda > 100$ in the range 70 GHz – 86 GHz should follow:

$$G(\varphi) = 32 - 25\log(\varphi) \qquad \text{for } \varphi < 120^0 \tag{1}$$

$$\text{and } G(\varphi) = -20 \qquad \text{for } 120^0 \le \varphi \le 180^0 \tag{2}$$

And according to subsection 2.2.1, for $D/\lambda \le 100$ and frequencies in the range 1 – 70 GHz:

$$G(\varphi) = 52 - 10\log\frac{D}{\lambda} - 25\log(\varphi) \qquad \text{for } \varphi < 48^0 \tag{3}$$

$$G(\varphi) = 10 - 10\log\frac{D}{\lambda} \qquad \text{for } 48^0 \le \varphi \le 180^0 \tag{4}$$

For one principal plane, the wave number is $k = 2\pi/\lambda$, the normalized electric-field distributions are $f(x)$ for square and $f(r)$ for circular apertures. The following two Fourier Transforms explain the F.699 formulas. Equations (5) and (6) transfer the square $f(x)$ and circular $f(r)$ domains, to the far-field normalized E antenna patterns; see [10], [11].

$$E(\varphi) = \int_x f(x) \times e^{-jkx\sin\varphi}\,dx \quad \text{for a square aperture} \tag{5}$$

$$E(\varphi) = \int_r f(r) \times e^{-jkr\sin\varphi}\,dr \quad \text{for a circular aperture} \tag{6}$$

In the cases of uniformly illuminated apertures, which cause narrow beamwidth but high sidelobes, the electric-field distributions $f(x)$ and $f(r)$ equal 1. For these symmetric apertures, the far-field pattern $G(\varphi)$ is proportional to:

$$\frac{\sin(\pi\frac{D}{\lambda}\sin\varphi)}{\pi\frac{D}{\lambda}\sin\varphi} \quad \text{for a square aperture} \tag{7}$$

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[1] There are no definitive standards on P2P antenna patterns in Australia, Bhutan, China, Israel, Korea, New Zealand, and Zambia

$$\text{or to } \frac{J_1(\pi \frac{D}{\lambda}\sin\varphi)}{\pi \frac{D}{\lambda}\sin\varphi} \quad \text{for a circular aperture} \quad (8)$$

1. For a square aperture (7) the beamwidth (in degrees) is $51\cdot\lambda/D$ and first sidelobe is -13.2 dB below the main lobe, and
2. for a circular aperture (8), the beamwidth is (higher) $58\cdot\lambda/D$ and the first sidelobe is (lower) -17.6 dB below the main lobe [10].

The normalized pattern (in dB) is defined as $20\cdot\log E(\varphi)$. The envelope of the square aperture sidelobe 'skirt' follows a $\underline{20}\cdot\log\varphi$ attenuation rate [11], sinc function $\left(\pi\frac{D}{\lambda}\sin\varphi\right)$. That is in contrast with the faster decay of the circular aperture envelope, which follows a $\underline{30}\cdot\log\varphi$ 'skirt' for the Bessel function of the first kind (J_1) [11]. The proposed slope in F.699, $\underline{25}\cdot\log\varphi$, shown in eq. (1) and eq. (3), was chosen, being the geometrical average of the square $\underline{20}\cdot\log\varphi$ and circular $\underline{30}\cdot\log\varphi$ decays.

However, no reference could be found to explain the following:

1. Why does the steeper decay increase the antenna 3dB beamwidth; e.g., circular aperture provides wider beamwidth and lower first sidelobe, as compared to the square aperture?
2. Why do higher gains impose lower sidelobes (steeper decay), as exemplified by eq. (3) and eq. (4) that show that the sidelobes increase with $10\cdot\log(D/\lambda)$?

In the equations of ITU Recommendation F.699, the ratio D/λ and the analysis above provide responses to these questions, based on the law of conservation of energy:

1. The uniform illuminated square aperture offers the slowest decay $20\cdot\log\varphi$, lowest beamwidth $51\cdot\lambda/D$ and highest antenna gain. In the circular aperture pattern, for the same EIRP as the square antenna, more energy is directed via a larger beamwidth ($58\cdot\lambda/D$), hence, the sidelobes are lower: $30\cdot\log\varphi$ versus $20\cdot\log\varphi$.
2. For the same dual band antenna, lower beamwidth (higher D/λ) drives higher energy and gain in the mainlobe, as the maximal antenna gain equals $G_{max}(\text{dBi}) = 44.8 - 20\log\varphi_{3dB}$;see equation 5.4 in [2]. Therefore, less power in the sidelobes, and higher decay of the pattern.

Fig. 2 compares the $25\cdot\log\varphi$ in (1) for $D/\lambda=100$, half beamwidth 0.5^0, gain 50 dBi, 2 feet dish antenna. F.699 $G(\varphi)$ equals $32\text{-}25\cdot\log\varphi$ (1).

For maximal gain of 50 dBi, the attenuation relative to boresight may be expressed as:

$$G(\varphi) - 50 = 32 - 25\log\varphi - 50 = -18 - 25\log\varphi. \quad (9)$$

Fig. 2 depicts that the red plot suggested by F.699, given by eq. (1), has a decay that is faster than the square aperture $20\cdot\log$ of eq. (7) (blue pattern) and slower than the circular aperture $20\cdot\log$ of eq. (8) (black pattern).

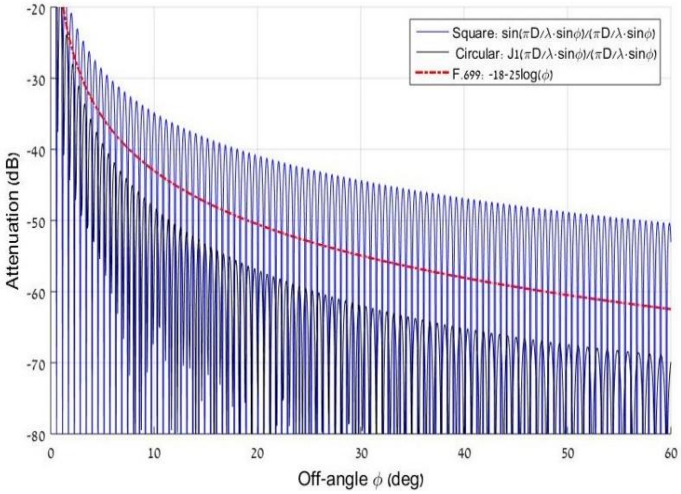

Fig. 2 ITU Recommendation F.699 antenna patterns compared to the theoretical square and circular apertures

B. ETSI 302 217-4 Point-to-Point Antennas

ETSI standard EN 302 217-4 defines the characteristics and requirements of antennas for P2P radio equipment, operating in the frequency range from 1 GHz to 86 GHz [4]. The electrical characteristics are given as a function of specific classification of the antennas. With respect to the Radiation Pattern Envelope (RPE), four classes (1 to 4) have been identified according to maximum co-polar limit templates for any actual RPE mask. For the EU market, the CE mark on radio equipment operating above 3 GHz is viable only for antenna class 2 or higher, whereas the patterns of class 1 address the worldwide market needs. IEEE publications mention the patterns of ETSI classes [12], [13]. Reference [12] compares the ETSI classes and proposes to classify IEEE 802.16 antennas by these classes.

ETSI standardizes (by figures and tables) the co-polarization and cross-polarization RPE patterns, used for regulatory assessment [4]. Fig. 3 (Fig. 40 from [4]) exemplifies the most restrictive mask 'class 4', for parallel polarization and cross-polarization discrimination (XPD), RPE frequency range 7 (71 – 86 GHz).

It is interesting to note that when the XPD angle of azimuth relative to the main beam axis is greater than 15^0, there is no difference between parallel and XPD sidelobes, so XPD is not relevant for distant sidelobes.

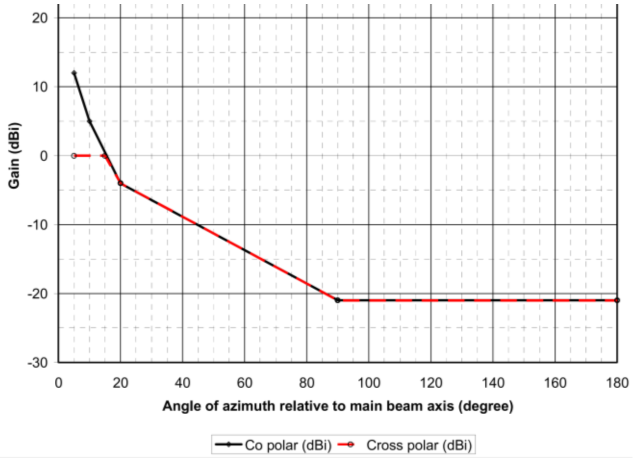

Fig. 3 ETSI RPEs for class 4 antennas in 71– 86 GHz (from [4])

Table I summarizes the co-polarization (CO) and cross-polarization (XP) absolute gains (dBi) versus the angle (degrees).

TABLE I

ETSI RPE CLASS 2 AND 4, ABSOLUTE GAIN VERSUS ANGLE

	3–14 GHz				**71–86 GHz**			
	class 2		**class 4**		**class 2**		**class 4**	
Angle [°]	**CO**	**XP**	**CO**	**XP**	**CO**	**XP**	**CO**	**XP**
5	26	10	16	5	25	5	12	0
10	20	5	5	0			5	
13				-5				
15		5			10	5		0
20	12		-7	-15	7	0	-4	-4
30		-3		-20				
40				-24	2			
45				-24				
50	5		-18					
60						-8		
65	2							
70		-3	-20	-25	-2			
80	2							
85			-24	-25				
88.75					-7			
90							-21	-21
100		-20			-7	-10		
100					-10			
105	-20		-30	-33				
180	-20	-20	-30	-33	-10	-10	-21	-21

C. FCC 47 CFR- §101.115 Directional Antennas

FCC standard §101.115 defines in two categories A and B the requirements for directional antennas operating in the frequency range from 932.5 MHz to 95 GHz, for 37 different RF ranges [5]. Category A specifies more restrictive antenna patterns. In areas not subject to frequency congestion, antennas meeting category B are also used. FCC may require the use of higher performance antennas to reduce interference.

The requirements for the licensees are to comply with:

1. either the maximum 3 dB beamwidth or with the minimum antenna gain requirement, and
2. the minimum radiation suppression to angle.

For the two FCC bands 10 and 72 GHz, there is no difference between categories A and B for:

1. maximum 3 dB beamwidth: 3.5^0 degrees for 10 GHz and 1.2^0 at 72 GHz, and
2. minimum antenna gain: 33.5 dBi for 10 GHz and 43 dBi at 72 GHz.

Table II specifies the co-polar (CP) and cross-polar (XP) radiation suppression (in dB) to angle (in degrees) from centerline of the main beam, for the 10.6 and 72 GHz bands, for the two categories A and B.

TABLE II

FCC ANTENNA CATEGORY (A OR B), ATTENUATION

Frequency (MHz)	**Category**	**Minimum suppression (dB)**						
		5°–10°	**10–15**	**15–20**	**20–30**	**30–100**	**100–140**	**140–180**
10,550–10,680; CP, no details on XP	A	18	24	28	32	35	55	55
	B	17	24	28	32	35	40	45
71,000–76,000 CP	Above 71 GHz, no difference between categories A and B	35	40	45	50	50	55	55
71,000–76,000 XP		45	50	50	55	55	55	55

While only the FCC limits the maximum beamwidth and the minimum gain, it is generally more straightforward than ETSI, having only five versus 40 pages (before annexes) in its standard and only two categories (including XPD) versus the four different classes defined by ETSI [5].

III. COMPARING PATTERNS: ITU, ETSI, FCC

Section *II* detailed separately the FCC, ETSI and ITU patterns. This section compares and contrasts them, by depicting the patterns side by side, including measured antenna patterns from two different vendors (RFS and MTI).

As the co-pol and XPD masks depend on frequency, the analysis and figures are separated into two relevant frequencies. The figures describe patterns from 5^0 (not 0^0) to 180^0 off-bore axis, in order to highlight the sidelobes; not the mainlobe, which is out of scale of the vertical axis.

ITU Recommendation F.699 provides general interference paths, considering the XPD response of the victim and interfering system antennas. As there are no specific equations to limit the XPD pattern outside the mainbeam in F.699, only the ITU parallel polarization case is considered in the following analysis and figures.

A. *Co-polar, 10.6 GHz and 72 GHz; ITU, ETSI, FCC*

Fig. 4 compares the co-polar gain (dBi) limits and measurement at 10.6 GHz:

1. ITU F.699 subsection 2.2.1: $D/\lambda < 100$, for frequencies below 70 GHz,
2. ETSI [4] classes 2 and 4,
3. FCC [5] categories A and B, given gain equals 40 dBi,
4. 4-feet dish, RFS UXA4-100DD2, 10.0–10.7 GHz, 40 dBi, θ_3=1.7^0, D/λ=40, vertical polarization.

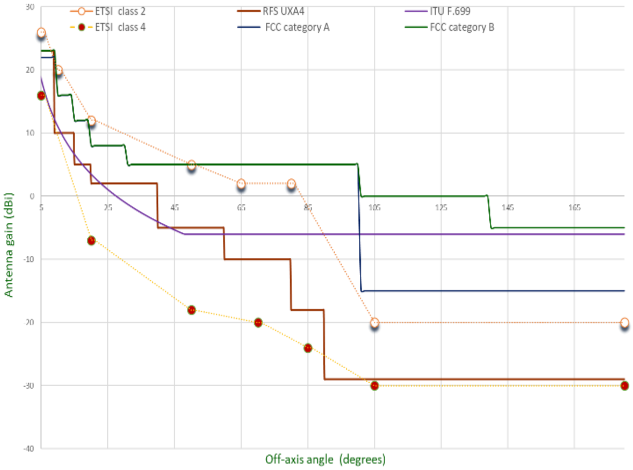

Fig. 4 Co-polar; 10.6 GHz; ITU, ETSI, FCC versus RFS-UXA4

ETSI class 4 is more restrictive (lower sidelobes in dBi) than ETSI class 2, and FCC category B is more relaxed than FCC category A. Fig. 4 illustrates that up to 85^0 all lines are around ITU F. 699, whereas at higher angles, F.699 is more tolerant. ATDI will propose again to ITU-R Study Group 5 to use the same restrictive attenuation also below 70 GHz: lowering the gain values by up to 10 dB, at off mainbeam angles above 48^0.

FCC category B is more liberal than ETSI class 2 above 50^0. FCC category A is 10–25 dB more tolerant than ETSI class 4, all over the off-axis angles.

Antenna RFS UXA4, shown in Fig. 4, complies with FCC category A and ETSI class 2, but not with ETSI class 4, as all sidelobe gains above 90^0 are higher than the class 4 limit.

Fig. 5 compares the masks at 72 GHz:

1. According to ITU F.699 subsection 2.1.2, for D/λ>100, for frequencies above 70 GHz,
2. ETSI [4] classes 2 and 4,
3. FCC [5] maximal gain 50 dBi, and
4. 2-feet dish antenna MT-799001/W 71–76 GHz, θ_3 =0.5^0, D/λ=144, vertical polarization.

FCC and ETSI class 2 limits are similar. The pattern of ETSI class 4 above 90^0 is 20 dB lower than the FCC mask. For ETSI class 4, de facto, there are no antennas on the European market and most applications use the intermediate class 3.

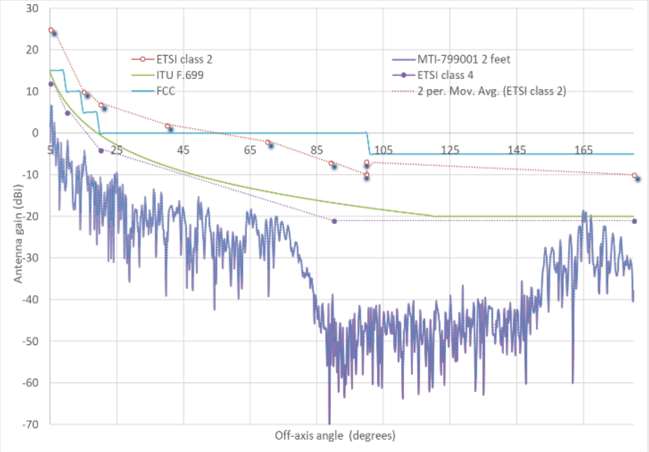

Fig. 5 CP; 72 GHz; ITU, ETSI, FCC, MT-799001

Fig. 5 shows that beyond 20^0 the F.699 mask lies between ETSI classes 2 and 4, closer to class 4. Fig. 5 provides further evidence to justify the March 2018 F.699 revision, lowering sidelobe above 48^0.

Antenna MT-799001 can be certified only under FCC, and not ETSI class 4, since its sidelobes between 164.5–166^0 are higher by up to 2.3 dB (its measured gain in that portion of the pattern is -18.7dBi, 2.3 dB higher than the ETSI -21dBi class 4 limit). The mask is also up to 1.3dB higher than the ITU limit (-20 dBi).

B. *XPD patterns for 10.6 GHz and 72 GHz; ETSI, FCC*

As there are no reference XPD formulas set in F.699, and no XPD values in FCC *§101.115* at 10.6 GHz, Fig. 6 compares the XPD power (dBi) only at 72 GHz:

1. ETSI [4] classes 2 and 4,
2. FCC [5] maximal gain 50 dBi, and
3. 2-feet dish antenna MT-799001 71–76 GHz, 0.45^0, vertical polarization.

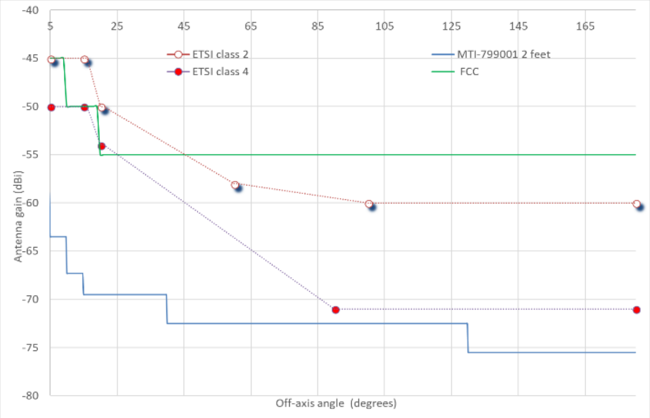

Fig. 6 XPD at 72 GHz; ETSI and FCC limits and measurement

For off-axis angles above 45^0, even ETSI class 2 is more restrictive than the FCC mask. As all its XPD sidelobes rest below all the depicted masks, antenna MT-799001 can be certified for FCC and ETSI class 4.

IV. CONCLUSION

The ETSI and FCC have each defined standards for antenna patterns in their respective regions in Europe and the USA, and some of these have been adopted in other regions around the world. The US regulation is generally simpler than the European. Similar to the policy of '*laissez faire laissez passer*' for the transmitter spurious emissions, regarding antenna patterns, USA and Japan are more reluctant to constraints, whereas Europe is more restrictive. It can be explained by Europe having many borders among countries (when compared to the USA and Japan) and having a higher population density.

Administrations may refer also to cost and availability constraints. In Europe, a balanced target may be limited to ETSI class 3 (between classes 2 and 4), which is already a step forward compared to the present average usage. In the USA the actual antenna patterns seem more restrictive than FCC masks; the USA may aim to category A limits. For the dual band antennas, the implementation of the strictest ETSI class 4 in both bands has to be evaluated.

This paper provided original explanations relating to the antenna pattern decay for square and circular apertures' and the D/λ ratio.

The envelope proposed here and in ITU Recommendation F.699 offers improved spectrum sharing for backhaul, which would also benefit 5G networks, while maintaining system performance and implementation feasibility. An extension of this contribution, to be based on the same mathematical modeling, will be used to reduce the envelope of the far sidelobes also for RF bands below 70GHz.

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