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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Access networks – Metallic access networks

Multi-gigabit fast access to subscriber terminals (MGfast) – Power spectral density specification

Recommendation ITU-T G.9710

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Recommendation ITU-T G.9710

Multi-gigabit fast access to subscriber terminals (MGfast) – Power spectral density specification

Summary

Recommendation ITU-T G.9710 specifies power spectral density (PSD) mask requirements for multi-gigabit fast access to subscriber terminals (MGfast), a set of tools to support reduction of the transmit PSD mask, and a methodology for transmit PSD verification. It supports operation over both twisted pair and coaxial cable media.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
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Recommendation ITU-T G.9710

Multi-gigabit fast access to subscriber terminals (MGfast) – Power spectral density specification

1 Scope

This Recommendation specifies the power spectral density for multi-gigabit fast access to subscriber terminals (MGfast), which supports transmission at an aggregate net data rate (the sum of upstream and downstream rates) up to approximately 10 Gbit/s on metallic wires, including twisted pairs and coaxial cables. The adaptations to these two media are specified in Annexes P and Q respectively. In this edition of the Recommendation, only one peer MTU-R/NT is connected to the MTU at the optical network unit (MTU-O); multiple MTU-R/NTs connecting to a single MTU-O is out of scope of this edition of the Recommendation. MGfast spectral usage complies with the 424 MHz and 848 MHz PSD types, while in this edition of the Recommendation only the 424 MHz power spectral density (PSD) type is specified.

It specifies:

- power spectral density (PSD) limit mask requirements;
- a set of tools to support reduction of the transmit PSD mask; and
- a methodology and termination impedance requirements for transmit PSD verification.

This ensures that the technology can address:

- regional requirements;
- operator deployment requirements, for example, compatibility with other digital subscriber line (DSL) technologies;
- applicable electromagnetic compatibility (EMC) regulations or standards; and
- local EMC issues.

Conformance of equipment with this ITU-T Recommendation may not ensure compliance with specific national or regional regulations on electromagnetic compatibility when installations are taken into service.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.993.2] Recommendation ITU-T G.993.2 (2019), *Very high speed digital subscriber line transceivers 2 (VDSL2)*.

[ITU-T G.997.2] Recommendation ITU-T 997.2 (2019), *Physical layer management for G.fast transceivers*.

3 Definitions

3.1 Terms defined elsewhere

None.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

3.2.1 **ceiling(*x*)**: The smallest integer which is not less than *x*.

3.2.2 **floor(*x*)**: The largest integer which is not greater than *x*.

3.2.3 f_{SC}: A parameter representing the frequency of subcarrier spacing.

3.2.4 **subcarrier**: A fundamental element of a discrete multitone (DMT) modulator. The modulator partitions the channel bandwidth into a set of parallel subchannels. The centre frequency of each subchannel is a subcarrier onto which bits may be modulated for transmission over a channel.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

DAB Digital Audio Broadcasting

DMT Discrete Multitone

EMC Electromagnetic Compatibility

ESD Energy Spectral Density

FDS Full duplex compatible Downstream Sub-frame

FDX Full Duplex

FM Frequency Modulation

FUS Full duplex compatible Upstream Sub-frame

IAR International Amateur Radio

LESM Low-frequency Edge Stop-band Mask

LPM Limit PSD Mask

MGfast Multi-gigabit Fast Access to Subscriber Terminals

MIB Management Information Base

MTU MGfast Transceiver Unit

MTU-O MTU at the Optical Network Unit

MTU-R MTU at the Remote Site (i.e., subscriber end of the loop)

NM Notching Mask

PSD Power Spectral Density

PSM PSD Shaping Mask

RFI Radio Frequency Interference

SM Subcarrier Mask

TDD Time-Division Duplexing

TxPSDM Transmit PSD Mask

VHF Very High Frequency

5 Conventions

None.

6 Transmit PSD mask

6.1 Overview

The transmit PSD mask (TxPSDM) is constructed from the combination of the following masks:

− limit PSD mask (LPM);
− subcarrier mask (SM);
− PSD shaping mask (PSM);
− notching mask (NM); and
− low-frequency edge stop-band mask (LESM).

The TxPSDM applied to the MGfast transceiver unit (MTU) at the optical network unit (MTU-O) or at the MTU remote site (i.e., subscriber end of the loop) (MTU-R) may be different.

For an MTU, the PSD of the transmit signal at any frequency shall never exceed the TxPSDM.

The LPM (see clause 7.2.1) specifies the absolute maximum limit of the TxPSDM. The subcarrier mask (SM), PSD shaping mask (PSM), notching mask (NM) and low-frequency edge stop-band mask (LESM) provide reduction of the TxPSDM using the following mechanism:

− subcarrier masking;
− notching of specific frequency bands;
− PSD shaping; and
− low-frequency edge stop-band masking.

Support of these mechanisms is mandatory in both the MTU-O and the MTU-R.

The TxPSDM shall comply with applicable national and regional regulatory requirements.

NOTE 1 – When determining the correct PSD to use in a particular jurisdiction, operators should use tools provided to ensure compliance with national and regional electromagnetic compatibility (EMC) regulations giving special consideration to protecting receivers for the safety of life services which may not be immediately adjacent to the drop wires carrying MGfast signals. Examples include various very high frequency (VHF) aeronautical radio navigation channels in the band 108-117.975 MHz, smart grid utility management systems channels in the band 450-470 MHz, and aeronautical emergency communications channels (e.g., 121.5 MHz, 406 MHz) and maritime emergency communications channels in the HF and VHF bands.

NOTE 2 – TXPSDM is defined in various averaging bandwidths according to frequency as defined in Table 8-1, except in sub-bands at the low frequency band edge and in the region of management information base (MIB) defined notches, where TXPSDM_W (1 MHz wideband) and TXPSDM_N (10 kHz narrowband) masks apply as described in clauses 6.5 and 6.6.

NOTE 3 – In point-to-multipoint operation, multiple MTU-Rs are connected to one MTU-O. In this mode of operation, the MTU-O controls transmission levels of upstream signals of each individual MTU-R to ensure compliance to the TxPSDM during upstream transmission.

6.2 Limit PSD mask (LPM)

The limit PSD mask (LPM) defines the absolute maximum PSD limit of the TxPSDM that shall never be exceeded. All the other mask definitions and mechanisms used to construct the TxPSDM can only result in a reduction of the mask from the limits established by the LPM.

6.3 Subcarrier masking

Subcarrier masking shall be used to eliminate transmission on one or more subcarriers. The subcarrier mask (SM) is configured in the distribution point management information base (DP-MIB) by use of the ITU-T G.997.2 parameter CARMASK. The transmit power of subcarriers specified in the SM shall be set to zero (linear scale). The SM shall override all other instructions related to the transmit power of the subcarrier.

The SM is defined as a number of masked frequency bands. Each band is specified by a start subcarrier index (x_L) and a stop subcarrier index (x_H), as {x_L, x_H}. An SM including S bands can be represented in the following format:

$$\mathrm{SM(S)} = [\{x_{L1}, x_{H1}\}, \{x_{L2}, x_{H2}\}, \ldots \{x_{LS}, x_{HS}\}]$$

All subcarriers within the band, i.e., with indices higher than or equal to x_L and lower than or equal to x_H, shall be switched off (transmitted with zero power).

NOTE – The SM is intended to incorporate both masked subcarriers that are defined by an annex defining regional requirements so as to comply with local regulations and masked subcarriers that are defined by the user or service provider to facilitate local deployment practices. Protection of radio services is not intended to be addressed by subcarrier masking; it is addressed by notching (see clause 6.5).

6.4 Power spectral density shaping

Power spectral density (PSD) shaping allows reduction of the TxPSDM in some parts of the spectrum, mainly for spectrum compatibility and coexistence with other access and home network technologies. The PSD shaping mask (PSM) is configured in the DP-MIB by use of the ITU-T G.997.2 parameter PSDMASK.

The PSM is defined on the frequency range between the lowest subcarrier x_1 (with x_1=ceiling(f_{tr1}/f_{SC})) and the highest subcarrier x_H (with x_H=floor(f_{tr2}/f_{SC})), and consists of one or more frequency segments. The boundaries of the segments are defined by set breakpoints. Within each segment, the PSM may either be constant or form a linear slope between the given breakpoints (in dBm/Hz) with the frequency expressed in a linear scale.

Each breakpoint of the PSM is specified by a subcarrier index x_n and a value of PSD_n at that subcarrier expressed in dBm/Hz, {x_n, PSD_n}. PSD_1 shall also apply to subcarriers below x_1, and PSD_H shall also apply to subcarriers above x_H. A PSM including S segments can be represented by (S+1) breakpoints in the following format:

$$\mathrm{PSM}(S) = [\{x_1, PSD_1\}, \{x_2, PSD_2\} \ldots \{x_S, PSD_S\}, \{x_H, PSD_H\}]$$

An MTU shall support configuration of at least 32 PSM breakpoints.

If one or more PSM breakpoints are set above the LPM, the transmit PSD mask shall be set to: TxPSDM = min(PSM, LPM). All values of PSD_n of PSM breakpoints shall be set above –90 dBm/Hz.

6.5 Notching of specific frequency bands

The MTU shall be capable of being configured to notch one or more specific frequency bands in order to protect radio services; for example, amateur radio bands or broadcast radio bands. The international amateur radio (IAR) bands to be notched are referred to as IAR bands, whilst the rest of the bands to be notched are referred to as radio frequency interference (RFI) bands.

For RFI bands, each notch in the notching mask (NM) shall be defined in terms of subcarrier indices SC_{start} and SC_{stop}.

The valid range of notch start tone index, SC_{start}, is all valid tone indices that are less than or equal to the minimum frequency of the protected radio band minus $f_{SC}/2$. The valid range of notch stop tone index, SC_{stop}, is all valid tone indices that are higher than or equal to the maximum frequency of the protected radio band plus $f_{SC}/2$.

An MTU shall support notching of 32 RFI bands simultaneously.

In addition, an MTU shall support notching of 15 IAR bands. The frequency of these IAR bands is detailed in Appendix I. MTUs should be capable of being configured to notch amateur radio bands individually based on the needed protection.

Within a notch, all subcarriers shall be turned off and the notching mask (NM) shall be equal to LPM −20 dB.

NOTE 1 – Subcarriers at either side of the masked subcarriers may also need to be turned off in order to meet the requirement on TxPSDM notch depth.

For a notch, two PSD masks are defined:

– Narrowband transmit PSD mask (TXPSDM_N)

  This mask is defined to verify the PSD using an MBW=10 kHz centred on the frequency in question.

  The TXPSDM_N is defined as the maximum of the NM and a lower limit of −100 dBm/Hz:

$$TxPSDM\_N = \max[NM, -100 \text{ dBm/Hz}].$$

– Wideband transmit PSD mask (TXPSDM_W)

  This mask is defined to verify a mathematically calculated wideband average PSD (PSD_W), obtained by averaging the narrowband measurements (PSD_N) (measured in an MBW=10 kHz) over a 1 MHz window centred on the frequency in question:

$$PSD\_W(f) = 10 \times \log 10\left(\left(\frac{1}{100}\right) \times \sum_{i=(-49)}^{50} 10^{\left(\frac{PSD\_N(f + i \times 10kHz)}{10}\right)}\right)$$

with:

PSD_N(f) the narrowband measurement at frequency f, expressed in dBm/Hz

PSD_W(f) the mathematically calculated wideband average PSD at frequency f, expressed in dBm/Hz.

The TXPSDM_W is defined as the maximum of the notch mask (NM) and a lower limit as defined in Table 6-1 for the frequency in question:

$$TxPSDM\_W(f) = \max[NM(f), \text{lower limit}(f)].$$

Table 6-1 – TXPSDM_W lower limit requirements

Frequency MHz	TXPSDM_W lower limit [dBm/Hz]
2.0-4.0	–100
4.0-5.0	–110
> 5.0	–112

For notches that are narrower than 1 MHz:

– the transmit PSD is only required to satisfy the narrowband transmit PSD mask TxPSDM_N, and this for frequencies ($SC_{start} \times f_{SC}$ + ½×MBW) < f < ($SC_{stop} \times f_{SC}$ − ½×MBW).

For notches that are 1 MHz or wider:

– the transmit PSD is required to satisfy the narrowband transmit PSD mask TxPSDM_N for frequencies (SC_{start}×f_{SC} + ½×MBW) < f < (SC_{stop}×f_{SC} – ½×MBW), and

– the wideband average transmit PSD (PSD_W(f)) is required to satisfy the wideband transmit PSD mask TxPSDM_W for frequencies (SCstart×f_{SC} + ½×MBW + 0.5MHz) < f < (SC_{stop}×f_{SC} − ½×MBW − 0.5MHz). The mask value to be compared against shall be the maximum value the mask takes within the 1 MHz window [f – 0.5 MHz, f + 0.5 MHz].

Appendix II details the frequencies for the broadcast radio services (frequency modulation (FM), digital audio broadcasting (DAB), aeronautical communication and radio navigation).

FM, DAB and other radio services may require different notch configurations depending on the characteristics of the specific radio service.

NOTE 2 – NM may be used to notch individual broadcast stations depending on spectrum utilization.

6.6 Low frequency edge stop-band masking

For the low frequency edge stop-band mask (LESM), two PSD masks are defined:

– Narrowband transmit PSD mask (TXPSDM_N)

This mask is defined to verify the PSD using an MBW=10 kHz centred on the frequency in question.

The TXPSDM_N is defined as shown in Figure 6-1, where PSD_{tr3} is the value of the in-band LPM at frequency f_{tr3}. The mask values in the transition band are obtained using linear interpolation in dB over a linear frequency scale.

The transmit PSD is required to satisfy the narrowband transmit PSD mask TxPSDM_N, for frequencies (0.5 MHz + ½×MBW) < f < (f_{tr3} − ½×MBW), where $f_{tr1} \leq f_{tr3} \leq$ 30 MHz. The PSD values above the transition frequency f_{tr3} are considered as in-band and defined in clause 7.2.1.1.

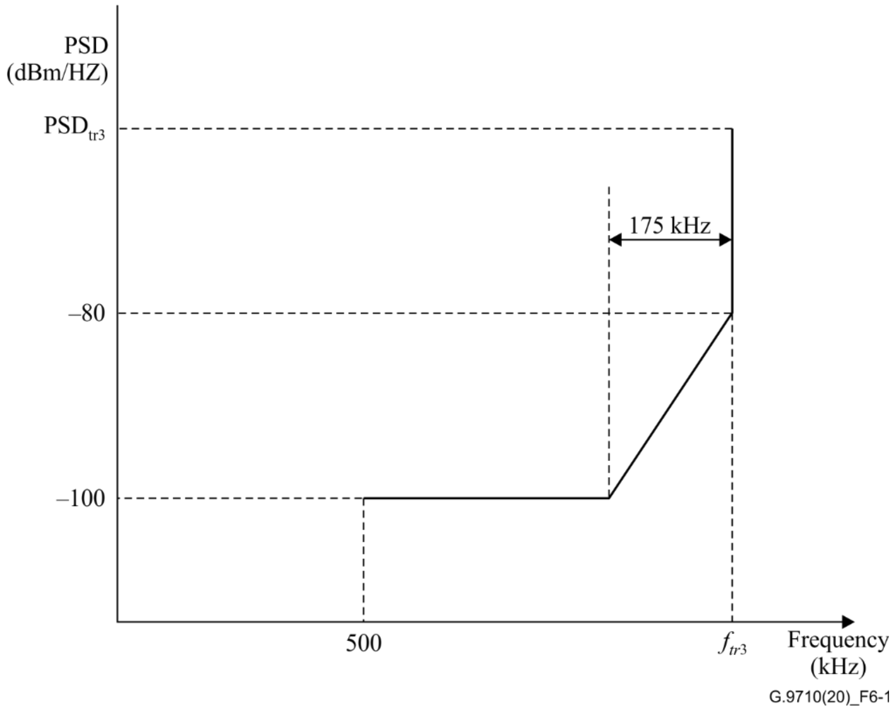

Figure 6-1 – Low-frequency edge stop-band mask

– Wideband transmit PSD mask (TXPSDM_W)

This mask is defined to verify a mathematically calculated wideband average PSD over a 1 MHz window (PSD_W(f)) as defined in clause 6.5.

The TXPSDM_W(f) is defined in Table 6-2 for the frequency in question.

The wideband average transmit PSD (PSD_W(f)) is required to satisfy the wideband transmit PSD mask TxPSDM_W for frequencies (2.0 MHz + ½×MBW + 0.5 MHz) < f < (f_{tr3} − 175kHz − ½×MBW − 0.5 MHz). The mask value to be compared against shall be the maximum value the mask takes within the 1 MHz window [f – 0.5 MHz, f + 0.5 MHz].

Table 6-2 – LESM TXPSDM_W requirements

Frequency (MHz)	LESM TXPSDM_W (dBm/Hz)
2.0 to 4.0	−100
4.0 to 5.0	−110
> 5.0	−112

7 Specification of spectral content

7.1 PSD type

Each PSD type specifies normative values for the following parameter:

− the limit PSD mask (LPM);

Table 7-1 shows the valid parameters for each PSD type.

Table 7-1 – PSD type parameters

Parameter	PSD type (Note)	
	424 MHz	848 MHz
LPM	See clause 7.2.1	for further study
NOTE – Future PSD types may be defined provided that they are within the bounds of the limit PSD mask specified in this Recommendation.		

7.2 PSD mask specifications

7.2.1 Limit PSD mask (LPM)

The limit PSD mask (LPM) represents the absolute maximum that the TxPSDM shall never exceed. The in-band LPM for the 424 MHz PSD type is presented in clause 7.2.1.1. The out-of-band LPMs are defined in clause 7.2.1.2.

7.2.1.1 In-band LPM

The in-band LPM for the 424 MHz PSD type is shown in Figure 7-1. The parameters for this LPM is presented in Table 7-2.

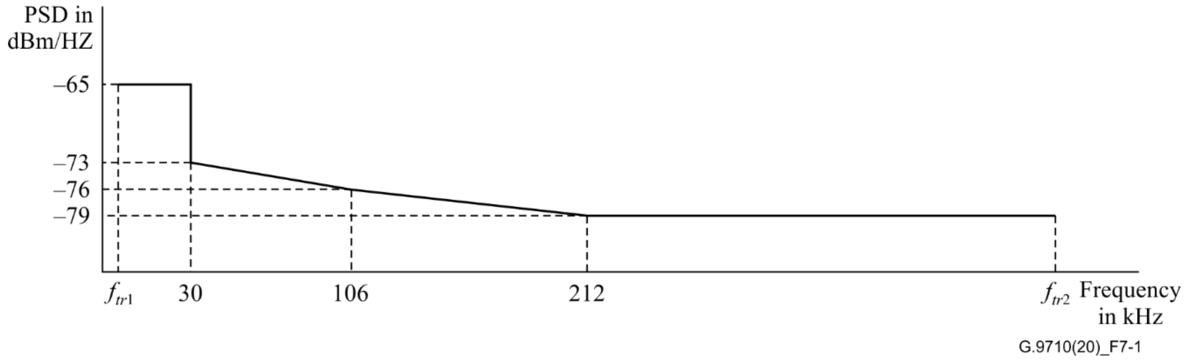

Figure 7-1 – In-band limit PSD mask for 424 MHz PSD type

Table 7-2 – Parameters of in-band LPM for 424 MHz PSD type

Parameter	Frequency (MHz)	PSD (dBm/Hz)	Description
f_{tr1}	2	–65	The LPM below f_{tr1} is defined in clause 7.2.1.2.
	30	–65	
	30	–73	The PSD limit values between the points listed shall be obtained by linear interpolation in dB over a linear frequency scale. The LPM above f_{tr2} is defined in clause 7.2.1.2.
	106	–76	
	212	–79	
f_{tr2}	424	-79	

NOTE – When additional spectrum shaping is used as described in clause 6 (for example, to provide spectrum compatibility or to comply with wideband power limit), various parts of the TxPSDM could be reduced by switching subcarriers off or reducing their transmit power. Additional frequency notches may also be applied if required.

7.2.1.2 Out-of-band LPM

The out-of-band LPM shall be as shown in Figure 7-2 for the low-frequency edge, and in Figure 7-3 for the high-frequency edge, where PSD_{tr1} is the value of the in-band LPM at frequency f_{tr1} and PSD_{tr2} is the value of the in-band LPM at frequency f_{tr2}. The parameters for these LPMs are presented in Table 7-3 and Table 7-4, respectively.

The out-of-band LPM applies for frequencies below the low-edge transition frequency f_{tr1} and for frequencies above the high-edge transition frequency f_{tr2}. The PSD values between the transition frequencies f_{tr1} and f_{tr2} are considered as in-band and defined in clause 7.2.1.1.

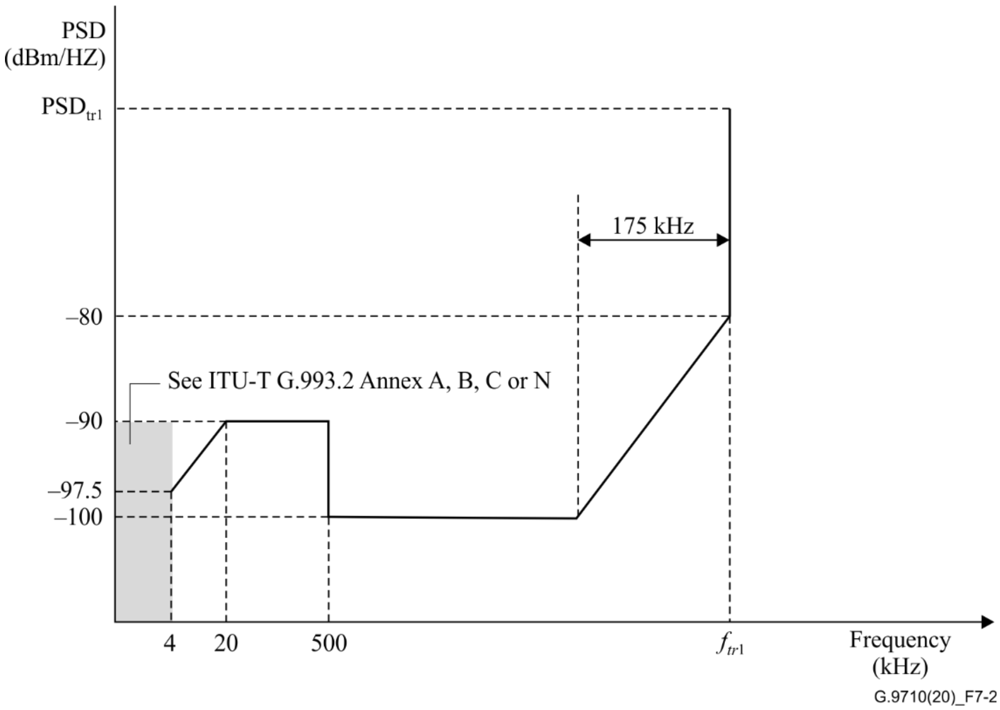

Figure 7-2 – Low-frequency edge out-of-band LPM

Requirements for frequencies below 4 kHz are specified in Annexes A, B, C and N of [ITU-T G.993.2] for the regions of North America, Europe, Japan and China, respectively.

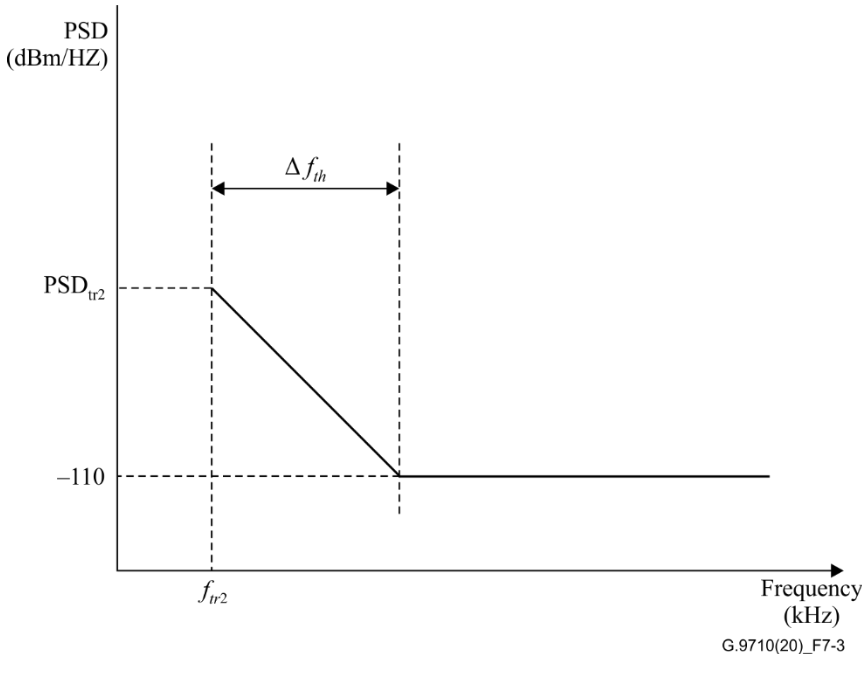

Figure 7-3 – High-frequency edge out-of-band LPM

Table 7-3 – Parameters of low-frequency edge out-of-band LPM

f_{tr1} (MHz)	PSD_{tr1} (dBm/Hz)	Description
2	–65	The PSD limit at transition frequency f_{tr1} drops from PSD_{tr1} to −80 dBm/Hz. The PSD limit in the transition band shall be obtained by linear interpolation in dB over a linear frequency scale. The PSD limit between 4 and 20 kHz shall be obtained by linear interpolation in dB over a log(f) scale. Subcarriers below f_{tr1} shall not be used for transmission (neither data nor any auxiliary information).

Table 7-4 – Parameters of high-frequency edge out-of-band LPM

f_{tr2} (MHz)	PSD_{tr2} (dBm/Hz)	Transition band, Δf_{th} (MHz)	Description
424	−79	80	The PSD limit in the transition band (Δf_{th}) shall be obtained by linear interpolation in dB over linear frequency scale. Subcarriers above f_{tr2} shall not be used for transmission (neither data nor any auxiliary information).

7.2.2 Permanently masked subcarriers

For the 424 MHz PSD type, subcarriers with indices from 0 to 39 (inclusive) shall be permanently masked. They shall not be used for transmission (neither for data nor for any auxiliary information).

8 Transmit PSD verification

The values of the transmit PSD mask are defined in this Recommendation under the assumption that transmission is continuous. In systems using time-division duplexing (TDD) mode, transmission in a particular direction is not continuous but occurs only during designated time periods. In systems using full duplex (FDX) mode, in a given transmission direction, the transmit PSD in the full duplex compatible downstream sub-frame (FDS) may be different from that of the full duplex compatible upstream sub-frame (FUS). These shall be taken into account by the applied measurement procedure.

The measurement bandwidth (MBW) for evaluation of the PSD shall be as defined in Table 8-1. The measurement bandwidth shall be centred on the frequency in question.

The mask value to be compared against shall be the maximum value the mask takes within a window $[f - ½×MBW, f + ½×MBW]$.

NOTE – If in a certain frequency range both a narrowband transmit PSD mask (TXPSDM_N) and a wideband transmit PSD mask (TXPSDM_W) are defined, the MBW values defined in this clause relate to the narrowband PSD measurements PSD_N.

PSD masks are specified with respect to a reference termination impedance, as defined in clauses P.1 and Q.1.

Table 8-1 – Measurement bandwidth settings for transmit PSD verification

Frequency band	Measurement bandwidth (MBW)
4 kHz < f < 20 kHz	1 kHz
20 kHz < f < f_{tr1}	10 kHz
(f_{tr1} + ½×MBW) to (30 MHz – ½×MBW)	1 MHz
(30 MHz + ½×MBW) to (f_{tr2} – ½×MBW)	1 MHz
> f_{tr2} to 300 MHz	100 kHz
Any notched frequency band	10 kHz

Annex A to Annex O

Annex A to Annex O have been intentionally left blank.

Annex P

Adaptation to the twisted pair medium

(This annex forms an integral part of this Recommendation.)

P.1 Termination impedance

For a transceiver operating over twisted pairs, a termination impedance of R_V = 100 Ohm, purely resistive, at the U interface, shall be used for both the MTU-O and the MTU-R. In particular, R_V = 100 Ohm shall be used as a termination for the transmit PSD and aggregate transmit power definition and verification.

Annex Q

Adaptation to the coaxial cable medium

(This annex forms an integral part of this Recommendation.)

Q.1 Termination impedance

For a transceiver operating over coaxial cables, a termination impedance of R_V = 75 Ohm, purely resistive, at the U interface, shall be used for both the MTU-O and the MTU-R. In particular, R_V = 75 Ohm shall be used as a termination for the transmit PSD and aggregate transmit power definition and verification.

Q.2 Transmit PSD verification

In systems operating over coaxial cables using FDX mode, in a given transmission direction, the transmit PSD shall be the same for both FDS and FUS. This shall be taken into account by the applied measurement procedure.

Appendix I

International amateur radio bands

(This appendix does not form an integral part of this Recommendation.)

Table I.1 lists the international amateur radio bands in the frequency range 1.8 MHz - 900 MHz.

Table I.1 – International amateur radio bands in the frequency range 1.8 MHz - 900 MHz

Band start (kHz)	Band stop (kHz)
1 800	2 000
3 500	4 000
5 351.5	5 366.5
7 000	7 300
10 100	10 150
14 000	14 350
18 068	18 168
21 000	21 450
24 890	24 990
28 000	29 700
50 000	54 000
69 900	70 500
144 000	148 000
219 000	225 000
420 000	450 000

Appendix II

Other aeronautical communication, radio navigation and broadcasting services

(This appendix does not form an integral part of this Recommendation.)

Table II.1 lists other aeronautical communication, radio navigation and broadcasting services in the frequency range 1.8 MHz - 900 MHz.

Table II.1 – Other aeronautical communication, radio navigation and broadcasting services in the frequency range 1.8 MHz - 900 MHz

Service	Band start (kHz)	Band stop (kHz)
FM	87 500	108 000
Digital terrestrial television (Region 2)	174 000	216 000
Digital terrestrial television/Digital audio broadcasting (Regions 1 and 3)	174 000	230 000
Smart grid utility management systems	450 000	470 000
COSPAS-SARSAT EPIRBs	460 000	460 100

Appendix III

Definition of transmitter PSD (TXPSD) for non-continuous transmissions

(This appendix does not form an integral part of this Recommendation.)

This appendix provides a formal definition for transmitter power spectral density (TXPSD) for signals comprising a stream of symbols including quiet periods, such as those produced by time division duplexed DMT systems.

This appendix defines TXPSD that is applicable to a stream of transmitted symbols, a punctured stream of symbols, or a continuous stream of symbols. Transmitted symbols are all symbols transmitted in the transmission period for the transmission direction. There are two transmission periods namely FDS and FUS in the PDX frame. The measurement of TXPSD is performed separately for the FDS and FUS transmission period. The quiet symbol positions in the transmission period are excluded. The particular measurement technique is beyond the scope of this Appendix.

This appendix defines TXPSD in terms of an intermediate variable, "Transmitter Symbol PSD" (TXSPSD). TXSPSD is defined in relation to the expectation of the energy spectral density (ESD) of symbols transmitted in a particular direction.

The ESD of a symbol voltage waveform $V_S(t)$ is derived into a reference impedance of 100 Ω.

$$ESD(V_S, f) = \frac{1}{R_0}\left|\int_{-\infty}^{\infty} V_S(t).\, e^{-i2\pi ft} dt\right|^2 (in\ unit\ of\ Joule/Hz)$$

$$R_0 = 100\ \Omega$$

TXSPSD is derived from the Expectation of the ESD over a set of transmitted symbols within a transmission period (FDS or FUS).

$$TXSPSD(f) = f_{DMT}.\, \mathrm{E}[ESD(V(t), f);\ V \in S]\ \text{(in unit of W/Hz)}$$

$$S = \{S_0, S_1 \ldots S_N\}$$

$S_0, S_1 \ldots S_N$ is a valid sequence of transmitted symbols within a transmission period (FDS or FUS)

$E[x]$ is the statistical expectation of x.

This normalization by the period of the symbol ensures that in the limit an infinite sequence of symbols has TXSPSD that converges to the classical PSD derived from the Fourier transform of the autocorrelation function.

The verifiable TXPSD is defined in a particular bandwidth *bw* as follows:

$$TXPSD(bw, f) = 30 + 10 \times log_{10}\left(\frac{1}{bw}\int_{f-\frac{bw}{2}}^{f+\frac{bw}{2}} TXSPSD(f_b) df_b\right)\ \text{(in unit of dBm/Hz)}$$

TXPSDM(*f*) is the maximum permitted level for *TXPSD*(*bw*,*f*) of a long symbol sequence.

Methods for compliance verification are out of the scope of this Recommendation.

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