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Model Rules and Regulations for the Use of Television White Spaces

v2.0, December 2017

Dynamic Spectrum Alliance

§ 1 Permissible Frequencies of Operation

(a) White space devices ("WSDs") are permitted to operate on a license-exempt basis subject to the interference protection requirements set forth in these rules.

(b) WSDs may operate in the broadcast television frequency bands, as well as any other frequency bands designated by [Regulator].

(c) WSDs shall only operate on available frequencies determined in accordance with the interference avoidance mechanisms set forth in § 2.

(d) Client WSDs shall only operate on available frequencies determined by the database and provided via a master white space device in accordance with § 3(f).

§ 2 Protection of Licensed Incumbent Services

Availability of frequencies for use by WSDs may be determined based on the geolocation and database method described in §§ 3-5 or based on the spectrum sensing method described in § 6.

§ 3 Geolocation and Database Access

(a) A WSD may rely on the geolocation and database access mechanism described in this section to identify available frequencies.

(b) Fixed WSD geolocation determination.

(1) The horizontal geographic coordinates of a fixed WSD must be provided, as latitude and longitude (WGS84), and shall be determined to an accuracy of ± 50 meters by either automated geolocation or a professional installer. Where automated geolocation is used, the device shall report the horizontal accuracy of its geolocation capability (e.g., ± 50 meters) at a confidence of ≥95% to the database.

(2) The vertical geolocation (height) of the antenna of a fixed WSD must be reported, and shall be determined by either automated geolocation or a professional installer. Height may be measured either above ground level, or above mean sea level (WGS84 datum). The device shall report the vertical accuracy of its geolocation capability (e.g., ± 5 meters) at a confidence of ≥95% to the database.

(3) A fixed WSD may report whether its antenna is situated outdoors or indoors; if it does not report its situation it will be assumed to be outdoors.

(4) The geographic coordinates of a fixed WSD shall be determined at the time of installation and first activation from a power-off condition, and this information shall be stored by the device. If the fixed WSD is moved more than 100 meters from the last location it reported to the database, or if its stored coordinates become altered, the operator shall re-establish the device's geographic location either by means of automated geolocation or through the services of a professional installer.

(c) Personal/Portable Master WSD geolocation determination.

(1) The horizontal geographic coordinates of a personal/portable master WSD must be provided, as latitude and longitude (WGS84), and shall be determined by automated geolocation. The device shall report its geographic coordinates as well as the accuracy of its geolocation capability (e.g., ± 50 meters) at a confidence of ≥95% to the database.

(2) The vertical geolocation (height) of the antenna of a personal/portable master WSD may be reported, and shall be determined by automated geolocation. Height may be measured either above ground level, or above mean sea level (WGS84 datum). The device shall report the vertical accuracy of its geolocation capability (e.g., ± 5 meters) at a confidence of ≥95% to the database.

(3) A personal/portable master WSD may report whether its antenna is situated outdoors or indoors; if it does not report its situation it will be assumed to be outdoors.

(4) Where the vertical geolocation (height) of the antenna of a personal/portable master WSD is not reported, it will be assumed to have a height of 1.5 meters above ground.

(5) Where the vertical geolocation (height) of the antenna of a personal/portable master WSD is reported and exceeds 2m, and its situation is not reported, it will be assumed to be indoors.

(6) A personal/portable master device must re-establish its position each time it is activated from a power-off condition and use its geolocation capability to check its location at least once every 60 seconds while in operation, except while in sleep mode, i.e., a mode in which the device is inactive but not powered down.

(d) Determination of available frequencies and maximum transmit powers.

(1) Master WSDs shall access a geolocation database designated by [Regulator] over the Internet to determine the frequencies and maximum transmit powers available at the device's geographic coordinates. A database will determine available frequencies and maximum transmit powers based on the algorithm described in § 4. However, in no case shall the maximum transmit power exceed the values provided in § 7 for an 8 MHz bandwidth or § 8 for a 6 MHz bandwidth.

(2) Master devices must provide the database with the device's geographic coordinates in WGS84 format, a unique alphanumeric code supplied by the manufacturer that identifies the make and model of the device, and a unique device identifier such as a serial number. Fixed master devices must, and personal/portable master devices may, also provide the database with the antenna height of the transmitting antenna specified in meters above ground level or above mean sea level.

(3) When determining frequencies of operation and maximum transmit power, the geolocation database may take into account additional information provided by a master WSD about its operating parameters and indicate to the WSD that different frequencies and/or different maximum transmit powers are available based on this additional information. This information may include out-of-

band emission behaviour (§ 7), or antenna transmission pattern, alignment, and polarity.

(4) WSDs may transmit in a range or ranges of frequencies which are indicated as available by a database, provided that the device does not exceed the indicated maximum transmit powers at any frequencies and the device complies with the out-of-band emission limits in §§ 7-8. The device's transmit bandwidth is not required to be an integer multiple of the underlying TV broadcast bandwidth (e.g. 6MHz, 8MHz), or to align with TV broadcast channels. WSDs must comply with any limits on the maximum total transmit bandwidth and maximum contiguous transmit bandwidth indicated by a database.

(5) WSD operation in a frequency range must cease immediately, or transmit power must immediately be reduced to a permissible level, if the database indicates that the frequencies are no longer available at the current operating power.

(6) A master device must access a geolocation database to re-check its available frequencies and maximum transmit powers when the device changes location by more than 100 meters from the last point location it reported to the database.

(7) A personal/portable master WSD may request available frequencies for a geographic polygon area or series of areas, and may operate on a mobile basis at all locations within each polygon using the frequencies and power limits available within that polygon. A personal/portable master WSD using such available frequencies for geographic polygon areas must contact the database again if/when it moves beyond the stated area(s) where the frequency availability data is valid.

(e) Time validity and database re-check requirements.

(1) A geolocation database shall provide master devices with a time period of validity for the frequencies of operation and maximum transmit powers described in § 3(d).

(2) A geolocation database shall provide master devices with the required polling time interval for contacting the database to confirm that its frequencies and maximum transmit powers are still valid. A WSD must immediately cease transmitting, and must not commence or re-commence transmitting, if the time since the database last indicated validity exceeds this interval, except in cases where clause (3) is in effect.

(3) A master device which is unable to contact a database due to external causes (e.g. database downtime, internet unavailability) may continue to operate with its current available frequencies and maximum transmit powers until 24 hours after the current time period of validity expires, or one polling interval after contact with the database is re-established, whichever is sooner.

(4) Before commencing transmission, a master device must report to the geolocation database the frequencies and power level(s) at which it intends to transmit. If the master device intends to change frequencies or increase its power above the reported level(s), it must report the new frequencies and power level(s) to the geo-location database before changing its transmissions.

(5) A master device must report to the geolocation database the frequencies and power level(s) at which it has instructed each of its client devices to transmit.

(f) Master device registration.

(1) Prior to operating for the first time, a master WSD must register with a database by providing the information listed in § 3(f)(3).

(2) The party responsible for a master WSD must ensure that a database has the most current, up-to-date information for that device.

(3) The database shall contain the following information for master WSDs:

(i) A unique alphanumeric code supplied by the manufacturer that identifies the make and model of the device [in jurisdictions that require a certification ID number this ID number may be used];

(ii) Manufacturer's serial number of the device;

(iii) Device's geographic coordinates as latitude and longitude (WSG84)

(iv) Device's antenna height above ground level or above mean sea level (meters, optional for personal/portable master devices);

(v) Name of the individual or business that owns the device;

(vi) Name of a contact person responsible for the device's operation;

(vii) Address for the contact person;

(viii) Email address for the contact person;

(ix) Phone number for the contact person.

(g) Client device operation.

(1) A client WSD may only transmit upon receiving a list of available frequencies and maximum transmit powers from a master WSD that has contacted a database. To initiate contact with a master device, a client device may transmit on available frequencies and power limits used by the master WSD or on frequencies and power limits that the master WSD indicates are available for use by a client device on a signal seeking such contacts.

(2) A master WSD may provide a client WSD with the same list of available frequencies and maximum transmit powers which are available to that master WSD. A master WSD may omit one or more available frequencies or provide maximum transmit powers which are lower than those available to the master WSD. These frequencies may be used by the client WSD for ongoing transmissions following its initial contact with the master WSD.

(3) A client WSD must provide a master device with a unique alphanumeric code supplied by the manufacturer that identifies the make and model of the client WSD, and the manufacturer's serial number of the client WSD.

(4) At least once every 60 seconds, except when in sleep mode, i.e., a mode in which the device is inactive but is not powered-down, a client device must communicate with a master device, which may include contacting the master device to re-verify/re-establish frequency availability or receiving a contact verification signal from the master device that provided its current list of

available frequencies. A client device must cease operation immediately if it has not communicated with the master device as described above after more than 60 seconds. In addition, a client device must re-check/re-establish contact with a master device to obtain a list of available frequencies if the client device resumes operation from a powered-down state. If a master device loses power and obtains a new frequency list, it must signal all client devices it is serving to acquire a new frequency list.

(h) Master devices without a direct connection to the Internet.

(1) If a master (fixed or personal/portable) WSD does not have a direct connection to the Internet and has not yet been initialized and communicated with a geolocation database consistent with this section, but can receive the transmissions of another master WSD, it may initiate contact with that master device in the same manner as described for a client device in § 3(g)(1).

(2) Following the initial contact, the WSD needing initialization may use the list of available frequencies and power limits to access the geolocation database, using the other master WSD as a database proxy, to receive a list of frequencies and power levels that are available for that WSD to use.

(3) After communicating with the database, the master (fixed or personal/portable) WSD must then only use the frequencies and power levels that the database indicates are available for it to use.

(4) The master (fixed or personal/portable) WSD may then in turn act as a master to other fixed or personal/portable devices in the same manner described in § 3(d).

(i) Security.

(1) For purposes of obtaining a list of available frequencies and related matters, master WSDs shall be capable of contacting only those geolocation databases operated by administrators authorized by [Regulator].

(2) Communications between WSDs and geolocation databases are to be transmitted using secure methods that ensure against corruption or unauthorized modification of the data; this requirement also applies to communications of frequency availability and other spectrum access information between master devices.

(3) Communications between devices for purposes of obtaining a list of available frequencies shall employ secure methods that ensure against corruption or unauthorized modification of the data. Contact verification signals transmitted for devices are to be encoded with encryption to secure the identity of the transmitting device. Devices using contact verification signals shall accept as valid for authorization only the signals of the device from which they obtained their list of available frequencies.

(4) Geolocation database(s) shall be protected from unauthorized data input or alteration of stored data. To provide this protection, a database administrator shall establish communications authentication procedures that allow master devices to be assured that the data they receive is from an authorized source.

§ 4 Database Coexistence Calculations

(a) The input to a geolocation database will be information from a master WSD (§ 3), use by licensed incumbents in or near the geographic area of operation of the WSD, and geographic data describing e.g. terrain elevation and the borders between regions. The database will supply a list of available frequencies and maximum transmit powers to WSDs pursuant to the algorithm provided in Annex A. The propagation model shall be that specified in Annexes B or C.[1]

(b) Information about incumbent licensed usage typically will be provided from information contained in [Regulator's] databases.

(c) Any facilities that [Regulator] determines are entitled to protection but not contained in [Regulator's] databases shall be permitted to register with a geolocation database pursuant to § 5.

§ 5 Database Administrator

(a) Database administrator responsibilities. [Regulator] will designate one public entity or multiple private entities to administer geolocation database(s). Each geolocation database administrator designated by [Regulator] shall:

  (1) Maintain a database that contains information about incumbent licensees to be protected.

  (2) Implement propagation algorithms and interference parameters issued by [Regulator] pursuant to §4 to calculate operating parameters for WSDs at a given location. Alternatively, a database operator may implement other algorithms and interference parameters that can be shown to return results that provide at least the same protection to licensed incumbents as those supplied by [Regulator]. Database operators will update the algorithms or parameter values that have been supplied by [Regulator] after receiving notification from [Regulator] that they are to do so.

  (3) Establish a process for acquiring and storing in the database necessary and appropriate information from the [Regulator's] databases and synchronizing the database with current [Regulator] databases at least once a week to include newly-licensed facilities or any changes to licensed facilities.

  (4) Establish a process for operators to register master WSDs.

  (5) Establish a process for the database administrator to include in the geolocation database any facilities that [Regulator] determines are entitled to protection but not contained in a database maintained by [Regulator].

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[1] The DSA supports models that protect incumbents but maximize spectrum utility. To that end, they support models that use point-to-point modeling. In addition, they support models that take into account the variability in terrain in calculating propagation and spectrum availability. Annex B describes the preferred model, being the Longley-Rice propagation model. However, the DSA believes that ITU-R. P-1812 is also an acceptable propagation model for this purpose as described in Annex C. Other models may also be appropriate, provided that they use point-to-point calculations and take into account terrain variability.

(6) Provide accurate information regarding permissible frequencies of operation and maximum transmit powers available at a master WSD's geographic coordinates based on the information provided by the device pursuant to § 3(d). Database operators may allow prospective operators of WSDs to query the database and determine the available frequencies at a particular location.

(7) Establish protocols and procedures to ensure that all communications and interactions between the database and WSDs are accurate and secure and that unauthorized parties cannot access or alter the database or the list of available frequencies sent to a WSD.

(8) Respond in a timely manner to verify, correct and/or remove, as appropriate, data in the event that [Regulator] or a party brings a claim of inaccuracies in the database to its attention. This requirement applies only to information that [Regulator] requires to be stored in the database.

(9) Transfer its database, along with a list of registered WSDs, to another designated entity in the event it does not continue as the database administrator at the end of its term. It may charge a reasonable price for such conveyance.

(10) Provide functionality such that upon request from [Regulator] it can indicate that no frequencies are available when queried by a specific WSD or model of WSDs.

(11) Cooperate, if more than one database is developed for a particular frequency band, with the other database administrators for that band to develop a standardized process for providing on a daily basis or more often, as appropriate, the data collected for the facilities listed in subparagraph (5) to all other WSD databases to ensure consistency in the records of protected facilities.

(b) Non-discrimination and administration fees.

(1) Geolocation databases must not discriminate between devices in providing the minimum information levels. However, they may provide additional information to certain classes of devices.

(2) A database administrator may charge a fee for provision of lists of available frequencies to fixed and personal/portable WSDs, and for registering master WSDs.

(3) [Regulator], upon request, will review the fees and can require changes in those fees if they are found to be excessive.

§ 6 Spectrum Sensing in the Broadcast Television Frequency Bands

(a) Parties may submit applications for authorization of WSDs that rely on spectrum sensing to identify available frequencies in the television broadcast bands. WSDs authorized under this section must demonstrate that they will not cause harmful interference to incumbent licensees in those bands.

(b) Applications shall submit a pre-production WSD that is electrically identical to the WSD expected to be marketed, along with a full explanation of how the WSD will protect incumbent licensees against harmful interference. Applicants may request that commercially sensitive portions of an application be treated as confidential.

(c) Application process and determination of operating parameters.

(1) Upon receipt of an application submitted under this section, [Regulator] will develop proposed test procedures and methodologies for the pre-production WSD. [Regulator] will make the application and proposed test plan available for public review, and afford the public an opportunity to comment.

(2) [Regulator] will conduct laboratory and field tests of the pre-production WSD. This testing will be conducted to evaluate proof of performance of the WSD, including characterization of its sensing capability and its interference potential. The testing will be open to the public.

(3) Subsequent to the completion of testing, [Regulator] will issue a test report, including recommendations for operating parameters described in subparagraph (c)(4), and afford the public an opportunity to comment.

(4) After completion of testing and a reasonable period for public comment, [Regulator] shall determine operating parameters for the production WSD, including maximum transmit power and minimum sensing detection thresholds, that are sufficient to enable the WSD to reliably avoid harmfully interfering with incumbent services.[2]

(d) Other sensing requirements. All WSDs that rely on spectrum sensing must implement the following additional requirements:

(1) Frequency availability check time. A WSD may start operating on a frequency band if no incumbent licensee device signals above the detection threshold determined in subparagraph (c) are detected within a minimum time interval of 30 seconds.

(2) In-service monitoring. A WSD must perform in-service monitoring of the frequencies used by the WSD at least once every 60 seconds. There is no minimum frequency availability check time for in-service monitoring.

(3) Frequency move time. After an incumbent licensee device signal is detected on a frequency range used by the WSD, all transmissions by the WSD must cease within two seconds.

§ 7 Technical Requirements for WSDs Operating in 8MHz Television Broadcast Bands

(a) Geolocation and Database method

(1) WSDs relying on the geolocation and database method of determining available frequencies may transmit using the maximum transmit powers provided by the database pursuant to § 4.

[2] In the context of television broadcast services, the DSA suggests that harmfully interfering with an *otherwise viewable* television signal would not be permitted under these guidelines.

(2) Devices must comply with the emission limits specified in ETSI EN 301 598 v1.1.1. If that document is superseded, [Regulator] may give notice that compliance with the superseding version shall be required.

(3) A device shall report its out-of-band emission behaviour as one of ETSI's Emission Classes 1-5.

(4) Maximum transmit powers provided by the database shall specify the maximum equivalent isotropically radiated power (EIRP) in 8MHz bands, which shall not exceed 40dBm/8MHz in any 8MHz band.

(5) The maximum EIRP in each 100kHz band within an 8MHz band shall be 19dB below the maximum EIRP in that 8MHz band.

(6) The conducted power delivered to the antenna system of a device in an 8MHz band must not exceed the maximum EIRP minus the amount in dB equivalent to the total directional gain of the antenna(s) in dBi.

(7) Maximum transmit powers shall be applied in a similar manner by Fixed, Personal/Portable, Master, and Client devices.

(b) WSDs relying on the spectrum sensing method of determining available frequencies may transmit at 50 mW per 8MHz and -0.4 dBm/100KHz effective isotropic radiated power (EIRP).

§ 8 Technical Requirements for WSDs Operating in 6MHz Television Broadcast Bands

(a) Geolocation and Database method

(1) WSDs relying on the geolocation and database method of determining available frequencies may transmit using the power levels provided by the database pursuant to § 4.

(2) A device's out-of-band emissions in the 6MHz bands immediately adjacent to frequencies in which it is operating shall not exceed 55dB less than the in-band emissions in those frequencies.[3]

(3) A device's out-of-band emissions in all 6MHz bands not immediately adjacent to frequencies in which it is operating shall not exceed 65dB less than the in-band emissions in those frequencies.[4]

(4) Maximum transmit powers provided by the database shall specify the maximum equivalent isotropically radiated power (EIRP), which shall not exceed 40dBm/6MHz in any 6MHz band.

(5) The maximum EIRP in each 100kHz band within a 6MHz band shall be 17.8dB below the maximum EIRP in that 6MHz band.

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[3] This limit is equivalent to FCC Electronic Code of Federal Regulations § 15.709.

[4] These limits are less stringent than FCC Electronic Code of Federal Regulations § 15.709 in cases with high-gain antennas, and are broadly comparable to those of ETSI Emission Class 1. Any device complying with the FCC regulations will also comply with these limits.

(6) The conducted power delivered to the antenna system of a device in a 6MHz band must not exceed the maximum EIRP minus the amount in dB equivalent to the total directional gain of the antenna(s) in dBi.

(7) Maximum transmit powers shall be applied in a similar manner by Fixed, Personal/Portable, Master, and Client devices.

(b) WSDs relying on the spectrum sensing method of determining available frequencies may transmit at 50 mW per 6MHz and -0.4 dBm/100KHz effective isotropic radiated power (EIRP).

§ 9 Definitions.

(a) *Available frequency*. A frequency range that is not being used by an authorized incumbent service at or near the same geographic location as the WSD and is acceptable for use by a license exempt device at a maximum transmit power indicated by a database under the provisions of this subpart.

(b) *Client device*. A personal/portable WSD that does not use an automatic geolocation capability and access to a geolocation database to obtain a list of available frequencies. A client device must obtain a list of available frequencies on which it may operate from a master device. A client device may not initiate a network of fixed and/or personal/portable WSDs nor may it provide a list of available frequencies to another client device for operation by such device.

(c) *Contact verification signal*. An encoded signal broadcast by a master device for reception by client devices to which the master device has provided a list of available frequencies for operation. Such signal is for the purpose of establishing that the client device is still within the reception range of the master device for purposes of validating the list of available frequencies used by the client device and shall be encoded to ensure that the signal originates from the device that provided the list of available frequencies. A client device may respond only to a contact verification signal from the master device that provided the list of available frequencies on which it operates. A master device shall provide the information needed by a client device to decode the contact verification signal at the same time it provides the list of available frequencies.

(d) *Fixed device*. A master WSD that transmits and/or receives radiocommunication signals at a specified fixed location. A fixed WSD may select frequencies for operation itself from a list of available frequencies provided by a geolocation database and initiate and operate a network by sending enabling signals to one or more fixed WSD and/or personal/portable WSDs.

(e) *Geolocation capability*. The capability of a WSD to determine its geographic coordinates in WGS84 format. This capability is used with a geolocation database approved by the [Regulator] to determine the availability of frequencies at a WSD's location.

(f) *Geolocation database*. A database system that maintains records of all authorized services in the frequency bands approved for WSD use, is capable of determining available frequencies at a specific geographic location, and provides lists of available frequencies to WSDs. Geolocation databases that provide lists of available frequencies to WSDs must be authorized by [Regulator].

(g) *Master device*. A fixed or personal/portable WSD that uses a geolocation capability and access to a geolocation database, either through a direct connection to the Internet or through an indirect connection to the Internet by connecting to another master device, to obtain a list of available frequencies. A master device may select a frequency range from the list of available frequencies and initiate and operate as part of a network of WSDs, transmitting to and receiving from one or more WSD. A master device may also enable client devices to access available frequencies by (1) querying a database to obtain relevant information and then serving as a database proxy for the client devices with which it communicates; or (2) relaying information between a client device and a database to provide a list of available frequencies to the client device.

(h) *Network initiation*. The process by which a master device sends control signals to one or more WSDs and allows them to begin communications.

(i) *Operating frequency*. An available frequency used by a WSD for transmission and/or reception.

(j) *Personal/portable device*. A WSD that transmits and/or receives radiocommunication signals either at unspecified locations (client) or at specified locations that may change (master).

(k) *Sensing only device*. A WSD that uses spectrum sensing to determine a list of available frequencies.

(l) *Spectrum sensing*. A process whereby a WSD monitors a frequency range to detect whether frequencies are occupied by a radio signal or signals from authorized services.

(m) *White space device (WSD)*. An intentional radiator that operates on a license exempt basis on available frequencies.

Annex A: Coexistence Calculations

1. Overview

(a) The Coexistence Framework computes a Spectrum Allocation for a White Space Device "WSD" given details about the WSD, details of incumbent users, and parameters from the regulator.

(b) It is the responsibility of the White Space Database "WSDB" to perform these calculations.

(c) The regulator will specify which channels are available for TVWS use in the country. This framework is designed to function in countries with 6MHz or 8MHz channels, and can be adapted for other bandwidths (e.g. 7MHz).

(d) A Spectrum Allocation consists of maximum transmit powers in the frequencies of each channel, combined with metadata describing the location and time ranges in which they are valid.

(e) A power limit in a given channel constrains the WSD's intentional emissions in that channel, and is specified as a limit in dBm over the full width of the channel (e.g. 6MHz or 8MHz). Regulators may specify that limits at finer bandwidths (e.g. 100kHz) shall also be specified in each channel.

(f) The framework is intended to be customisable by a regulator to their specific needs. The tuning parameters (§10) are a straightforward mechanism for balancing the level of protection to incumbents with availability of spectrum to WSDs. Furthermore, where the default protection methods detailed here do not match a regulator's needs, those methods can be customised or substituted for other methods as appropriate.

2. General Considerations

2.1. Channel Plans

(a) We define $\mathbf{I}$ formally as the set of channels which are available to TVWS at a given bandwidth b (e.g. 8MHz).

(b) This set does not need to be contiguous in channel number and/or in frequency ranges.

(c) Where there are several contiguous blocks of channels, the 'band-edge' channels are defined as the highest and lowest channel in each contiguous block.

(d) For any two TVWS channels $i, j \in \mathbf{I}$ we define Δf to be one greater than the number of bandwidths, or parts thereof, separating the nearest edges of i and j; if $i = j$ then $\Delta f = 0$.

(e) Δf may span frequency ranges which are not assigned to TVWS, which for our purposes does not present a problem.

(f) In the special case where a single contiguous block of channels is assigned to TVWS (e.g. as in the UK), then $\Delta f \equiv i - j$.

(g) We additionally define the separation Δf_{edge} between a TVWS channel i and the nearest non-TVWS frequency band to be one greater than the number of bandwidths, or parts thereof, separating the nearest edges of i and the contiguous block containing i. Where i is a band-edge channel, $\Delta f_{edge} = 1$.

2.2. Longley-Rice Propagation Algorithm Parameters

(a) Where the Longley-Rice propagation algorithm[1] is used, appropriate tuning parameters should be chosen.

(b) Climatic parameters should be chosen for each particular country or region.

(c) Where known, the polarisation of a transmitter should be taken account of.

(d) Where the signal of an incumbent user is being simulated, $q_s = q_T = 0.5$ should be used.

(e) Where the path between a WSD and an incumbent user is being simulated, $q_s = q_T = 0.1$ should be used.

(f) Broadcast mode should be used throughout.

(g) Where a different propagation algorithm is in use, equivalent parameters should be chosen.

2.3. WSDB Optimisation

(a) This coexistence framework represents a complex and expensive series of calculations which the WSDB must perform within a reasonable computation time. To address these practical constraints, a WSDB will be free to make any optimisations or approximations which have no significant effect on the power limits it computes.

(b) When considering the many nested iterations across many sets of objects, a WSDB may ignore or discard any iterations or set members at its own discretion for the purposes of performance optimisation, provided the resulting power limits do not differ significantly from an exhaustive calculation.

(c) The geometry and resolution of any spatial sampling, e.g. for calculating coverage over an area, or for terrain profiles, are left to the discretion of the WSDB.

(d) Where a path loss in channel i has been computed, it may similarly be used with a frequency-based correction to approximate the path loss in channel j at the WSDB's discretion.

(e) Some or all parts of the calculation may be precomputed or calculated on-the-fly at the discretion of the WSDB. Precomputed data may be rounded to an appropriate precision to facilitate efficient storage.

(f) Any horizontal location may be rounded to an appropriate grid by the WSDB to facilitate precomputation.

(g) The height of a WSD may be rounded by the WSDB to the nearest member of a preconfigured set (e.g. {1.5m, 5m, 10m, 15m, 20m, 30m}) to facilitate precomputation.

2.4. WSD Horizontal Location Uncertainty

(a) Where a WSD reports a region of uncertainty around its horizontal point location, or has reported its location as a polygon (e.g. for mobility purposes), the WSDB shall perform any path loss calculations by selecting at its discretion a subset of locations within the polygon, calculating

[1] George Hufford. *The ITS Irregular Terrain Model, version 1.2.2 The Algorithm*. Tech. rep. `https://www.its.bldrdoc.gov/resources/radio-propagation-software/itm/itm.aspx`. NTIA, 1995.

path loss from each of those locations, and selecting the path loss which will ultimately cause the most stringent power limit.

(b) The subset of locations should be chosen to handle cases where the path loss varies significantly within the polygon e.g. due to intervening terrain.

2.5. WSD Height

(a) Where a WSD reports its height Above Ground Level "AGL", the height is used without modification, excepting that reported heights below 1.5m are to be rounded up to 1.5m.

(b) Where a WSD reports its height Above Mean Sea Level "AMSL", it is to be converted into a height AGL by means of a terrain elevation database and bilinear interpolation. Where the AGL height is found to be below 1.5m, it is to be rounded up to 1.5m.

(c) Where a WSD reports a range of uncertainty in its height, whether AGL or AMSL, the WSDB shall perform any path loss calculations by selecting at its discretion a subset of heights within the range of uncertainty, calculating path loss from each of those heights, and selecting the path loss which will ultimately cause the most stringent power limit.

(d) Where a personal/portable WSD does not report its height, it is assumed to be 1.5m AGL with no uncertainty.

(e) Where a personal/portable WSD reports its height as being above 2m AGL, it is assumed to be indoors.

(f) An additional margin of $M_{indoor} = 7$dB is added to the power limits $\mathbf{P_{Tx:WSD}}$ of an indoor device up to but not exceeding P_{cap}.

2.6. Time Validity

(a) Typically, WSDs will request a spectrum allocation for immediate use, will periodically check that the allocation is still valid, and will request a new allocation when the period of validity expires. Typically, the set of incumbent users requiring protection will not change during this validity period, and, where unexpected changes occur, the WSDB will inform the WSD that its allocation is no longer valid.

(b) When calculating a spectrum allocation, a WSDB may know in advance that an incumbent user will start and/or stop operating (i.e. requiring protection) within the period of validity of the allocation. It may then divide the period of validity according to changes in the incumbent set so as to calculate multiple allocations which are disjoint in time. It may instead, at its discretion, compute one allocation on the simplifying assumption that any incumbent which requires protection for part of the period of validity receives protection for the whole period.

(c) Where the set of incumbents changes, or any other underlying factors change, a WSDB must evaluate which existing spectrum allocations may be affected by the change (e.g. due to geographic proximity) so that the relevant WSDs will be informed that their allocation is no longer valid. This invalidation should take place even where the availability of spectrum has increased, or where the WSD is currently not using any channels which are affected by any changes.

(d) A WSDB may, at its discretion, accept requests for spectrum allocations which begin at a limited time in the future. Such allocations will be subject to the WSD's normal validitychecking requirements. This may facilitate network planning for portable devices travelling long distances or at high speed (e.g. when on board a train).

2.7. Mathematical Notation

(a) TVWS coexistence frameworks are sufficiently complex that without a very precise notation system it is easy to conflate two similar but distinct concepts. The notation used here has been carefully chosen to be explicit and unambiguous, at the cost of brevity.

(b) Powers are denoted by P, gains and losses by G and L, and margins by M. Many variables have a number of indices. Superscripts denote channels and subscripts describe the detailed meaning of the variable. Indices are concatenated with : denoting "of", | denoting "to protect", $\rightarrow$ denoting "towards", $\leftarrow$ denoting "from", or @ denoting "at location". For example, $P^i_{Tx:WSD|TV@X}$ denotes the transmit Tx power limit P of a White Space Device WSD in channel i to protect television TV at location X.

3. WSD Power Limits

3.1. Formal Framework

(a) The Coexistence Framework is a function $\mathbb{f}$ to compute WSD power limits in each channel such that

$$\mathbf{P_{Tx:WSD}} = \mathbb{f}(\text{WSD, incumbents, terrain}) \tag{3.1}$$

where

$$\mathbf{P_{Tx:WSD}} \equiv \{P^i_{Tx:WSD} : \forall i\} \tag{3.2}$$

denotes limits on the intentional emissions of a WSD in each channel $i \in \mathbf{I}$, where $\mathbf{I}$ is the set of channels of bandwidth b made available for the use of TVWS.

(b) In the following sections we will now divide $\mathbb{f}$ into its constituent parts, each of which produces 'candidate' power limits:

$$\begin{aligned} \mathbf{P_{Tx:WSD}} &= \mathbb{g}(\text{WSD, incumbents, terrain}) \\ &= \{\min(\mathbb{g}_{TV}(\bullet)^i, \mathbb{g}_{zone}(\bullet)^i, \mathbb{g}_{band}(\bullet)^i, \mathbb{g}_{border}(\bullet)^i, P_{cap}) : \forall i\} \end{aligned} \tag{3.3}$$

where $\bullet$ is shorthand for each function's respective arguments, and P_{cap} is a constant (e.g. 40dBm) upper bound on WSD emissions in a channel.

3.2. Prerequisite Data

(a) The following properties of the White Space Device are required:

- Latitude & longitude of the WSD's antenna, either at a single point or a polygon;
- Height of the WSD's antenna above ground level "AGL" or above mean sea level "AMSL" (WGS84 datum);
- Ranges of uncertainty in the geolocation measurements;
- ETSI Emission Class (for 8MHz bandwidths only).

(b) The following additional properties improve the accuracy of the calculations:

- Directivity pattern & alignment of the WSD's antenna;
- Polarization of the WSD's antenna;
- Situation (indoors, outdoors) of the WSD's antenna.

Where not specified the WSD's antenna is assumed to be omnidirectional with vertical polarisation and situated outdoors.

(c) A Digital Elevation Model is required to describe the terrain elevation above the WGS84 datum at a good (e.g. 1 arc-second) resolution throughout the region and its surrounding area.

4. Candidate WSD Power Limits for Protecting TV Users

4.1. Formal Framework

This section defines the function $g_{TV}(\bullet)$ such that

$$\mathbf{P_{Tx:WSD|TV}} = g_{TV}(\text{WSD, TV transmitters, terrain}). \tag{4.1}$$

4.2. Prerequisite Data

(a) This section relies on data describing TV transmitters. For protection purposes, details are required of TV transmitters in or near the region where WSD operation is permitted. Additionally, for more accurate calculation of noise levels, details are required of TV transmitters in adjacent regions or countries, even if their transmissions are not to be protected.

(b) The minimum properties required for a TV transmitter are:

- Latitude & longitude (WGS84) of the transmitter;
- Height of the transmitting antenna above ground level "AGL" or above mean sea level "AMSL" (WGS84 datum);
- Effective Radiated Power "ERP", in W, kW, dBW, or dBm;
- Centre frequency of the channel used by the transmitted signal.

(c) The following additional properties improve the accuracy of the calculations:

- Directivity pattern & alignment of the transmitting antenna;
- Polarization of the transmitting antenna.

Where not specified the antenna is assumed to be omnidirectional with vertical polarisation.

4.3. Method

(1) Given WSD location W, derive a set of locations $\mathbf{X}$ to describe the area in which the WSD may cause interference. The minimum distance between W and $\mathbf{X}$ is $d_{min:WSD\to X}$ with default 60m.

(2) For each point $X \in \mathbf{X}$:

(3) Find all TV transmitters $\mathbf{T}$ within distance $d_{max:X\to T}$ (default 200km) of point X.

(4) For each transmitter $T \in \mathbf{T}$, for each of its transmit channels i, calculate the path loss $L^i_{T\to X}$ in dB between T and X using a terrain-based propagation model at the centre frequency of the channel, given the height of the transmitter and the height of a household antenna of 10m. Where the antenna pattern for the TV transmitter is known, the gain in the geodesic direction towards X is included in the path loss.

(5) Given the transmit power $P^i_{Tx:T}$ in dBm, the received power of the wanted signal at the antenna at X is

$$P^i_{Rx:T@X} = P^i_{Tx:T} - L^i_{T\to X} \tag{4.2}$$

(6) The interference caused in channel i by another TV transmitter $T' \in \mathbf{T} \setminus T$ using channel j is

$$P^{i\leftarrow j}_{int:T'@X} = P^j_{Rx:T'@X} - ACLR_{TV}(\Delta f) + G_{ant@X\to T'} \tag{4.3}$$

where Δf is defined above (§2.1), the out-of-channel emission mask[2] of the transmitter T' is (in dB)

$$ACLR_{TV} = \begin{cases} 0 & \Delta f = 0 \\ 61 & \Delta f = \pm 1 \\ 87 & \Delta f = \pm 2 \\ \infty & |\Delta f| > 2, \end{cases} \tag{4.4}$$

and the directional gain of a household antenna at X pointing towards T with respect to a co-polar signal from T' is

$$G_{ant@X\to T'}(\phi) = \begin{cases} 0 & |\phi| < 20^\circ \\ \frac{\phi-20^\circ}{40^\circ} \times -16 & 20^\circ \le |\phi| \le 60^\circ \\ -16 & |\phi| > 60^\circ \end{cases}. \tag{4.5}$$

where the angle ϕ is defined as the 'cone' angle between a geodesic joining X to T and a geodesic joining X to T', taking account of both azimuth and elevation. Where the polarity of either T or T' is not known, they are assumed to be co-polar. Where T and T' are known to have orthogonal polarity, then (in dB)[3]

$$G_{ant@X\to T'}(\phi) = -15 \tag{4.6}$$

for any value of ϕ.

(7) The cumulative noise and interference at the household antenna in channel i is

$$P^i_{noise:T@X} = 10\log_{10}\left(10^{P_{thermal}/10} + \sum_{T',j} 10^{P^{i\leftarrow j}_{int:T'@X}/10}\right) \tag{4.7}$$

where $P_{thermal}$ is the ambient thermal noise, with default values of -105.2dBm for 8MHz channels and -106.4dBm for 6MHz channels.

[2] *ETSI EN 302 296 v2.0.2*. http://www.etsi.org/deliver/etsi_en/302200_302299/302296/02.00.02_20/en_302296v020002a.pdf. 2016; ITU. *Spectrum limit masks for digital terrestrial television broadcasting*. Recommendation BT.1206-3. https://www.itu.int/dms_pubrec/itu-r/rec/bt/R-REC-BT.1206-3-201604-I!!PDF-E.pdf. ITU, 2016.

[3] ITU. *Directivity and polarization discrimination of antennas in the reception of television broadcasting*. Recommendation BT.419-3. https://www.itu.int/dms_pubrec/itu-r/rec/bt/R-REC-BT.419-3-199006-I!!PDF-E.pdf. ITU, 1992.

(8) At X the Carrier-to-Noise ratio in channel i at the tuner in dB is

$$CNR^i_{T@X} = P^i_{Rx:T@X} - P^i_{noise:T@X} - L_{Rx:noisefig} + G_{Rx:inst} - M_{Rx:imp} \tag{4.8}$$

where default values are given for the receiver noise figure $L_{Rx:noisefig} = 7$dB, net receiver antenna installation gain $G_{Rx:inst} = 9.15$dBi, and receiver implementation margin $M_{Rx:imp} = 1.5$dB.

(9) Channel i is considered to be "in coverage" at X if

$$CNR^i_{T@X} \geq CNR_{min} + M_{Rx:link} \tag{4.9}$$

where CNR_{min} is determined for each $\mathbf{T}$ based on its TV standard, modulation scheme etc., but defaults to 19.5dB for digital television, and the receiver link margin defaults to $M_{Rx:link} = 7.6$dB; otherwise it is "out of coverage".

The above method outputs a set of locations $\mathbf{Y} \subseteq \mathbf{X}$ in which at least one channel is in coverage.

(10) For each $Y \in \mathbf{Y}$, and for each in-coverage channel i at Y:

(11) Given $P^i_{Rx:T@Y}$ as calculated above, and the out-of-channel emission mask (§8) of the WSD, find the appropriate protection ratios $r(P^i_{Rx:T@Y} + G_{Rx:inst}, \Delta f)$, from[4] tables A9.5-9.9, given the wanted received power at the tuner $P^i_{Rx:T@Y} + G_{Rx:inst}$ and Δf as defined above.

(12) The maximum tolerable 'nuisance' power at the tuner in each channel $j \in \mathbf{I}$ at Y so as to protect TV reception in channel i is then

$$P^{j|i}_{Rx:nuisance@Y} = P^i_{Rx:T@Y} - r(P^i_{Rx:T@Y} + G_{Rx:inst}, \Delta f). \tag{4.10}$$

When the wanted power lies between two columns in the tables,[5] linear interpolation is used between the two relevant values of r. When $i = j$, the protection ratio r is $CNR_{min} + M_{Rx:co-channel}$, where $M_{Rx:co-channel}$ defaults to 20dB.

(13) Calculate the path loss $L^j_{WSD \to Y}$ in dB between W and Y using a terrain-based propagation model at the centre frequency of each channel $j \in \mathbf{I}$, given the height of the WSD and the height of a household antenna of 10m. Where the antenna pattern for the WSD is known, the gain in the geodesic direction towards Y is included in the path loss.

(14) The angle φ is defined as the 'cone' angle between a geodesic joining Y to the location of the in-coverage TV transmitter T, and a geodesic joining W to Y, taking account of both azimuth and elevation. The directional gain of a household antenna at Y with respect to a co-polar WSD signal from W is then (in dB)

$$G_{ant@Y \to WSD}(\varphi) = \begin{cases} 0 & |\varphi| < 20^\circ \\ \frac{\varphi - 20^\circ}{40^\circ} \times -16 & 20^\circ \leq |\varphi| \leq 60^\circ \\ -16 & |\varphi| > 60^\circ \end{cases}. \tag{4.11}$$

Where the polarity of either the WSD or T is not known, they are assumed to be co-polar. Where the WSD is known to have orthogonal polarity from T, then (in dB)[6]

$$G_{ant@Y \to WSD}(\varphi) = -15 \tag{4.12}$$

[4]Ofcom. *Implementing TV White Spaces*. `https://www.ofcom.org.uk/__data/assets/pdf_file/0034/68668/tvws-statement.pdf`. 2015.
[5]Ibid.
[6]ITU, *Directivity and polarization discrimination of antennas in the reception of television broadcasting*.

for any value of φ.

(15) The coupling gain in channel j between a WSD at W and the tuner in a household at Y is then

$$G^{j}_{WSD\to Y} = -L^{j}_{WSD\to Y} + G_{ant@Y\to WSD}(\phi) + G_{Rx:inst} \tag{4.13}$$

where $G_{Rx:inst}$ is the net antenna installation gain at Y and defaults to 9.15dB.

(16) A candidate power limit $P^{j|i}_{Tx:WSD|TV@Y}$ to protect channel i at Y is then found in each channel $j \in \mathbf{I}$ as

$$P^{j|i}_{Tx:WSD|TV@Y} = P^{j|i}_{Rx:nuisance@Y} - G^{j}_{WSD\to Y}. \tag{4.14}$$

(17) A candidate power limit $P^{j}_{Tx:WSD|TV@Y}$ to protect all in-coverage channels at Y is then found in each channel $j \in \mathbf{I}$ as

$$P^{j}_{Tx:WSD|TV@Y} = \min\left(P^{j|i}_{Tx:WSD|TV@Y} : \forall i\right). \tag{4.15}$$

The power limit in each channel j to protect all TV receivers in $\mathbf{Y}$ is then

$$P^{j}_{Tx:WSD|TV} = \min_{(m)}\left(P^{j}_{Tx:WSD|TV@Y} : \forall Y \in \mathbf{Y}\right) \tag{4.16}$$

where $\min_{(m)}$ is a function finding the minimum of a set having discarded the m lowest members, and m defaults to 0.1% of the size of $\mathbf{X}$. The final set of power limits is

$$\mathbf{P_{Tx:WSD|TV}} \equiv \{P^{j}_{Tx:WSD|TV} : \forall j \in \mathbf{I}\}. \tag{4.17}$$

4.4. Additional Considerations

(a) If reliable data are available describing the set of all household locations $\mathbf{H}$ in the country, then the intersection $\mathbf{Y} \cap \mathbf{H}$ should be used in place of $\mathbf{Y}$.

(b) Where a particular TV transmitter is to be protected only in certain geographic regions $\mathbf{G}$, then it is not considered to be "in coverage" at step 9 above where $\mathbf{X} \notin \mathbf{G}$. For example, where a TV transmitter is located in a neighbouring country, contributes tolerable but non-negligible interference, but is not eligible for protection.

(c) In both the above cases, all TV transmitters are included in the calculation of the cumulative noise and interference.

5. Candidate Power Limits for Protecting Other Incumbent Users

(a) It is probable that particular countries will have specific protection requirements here. There may be a wide variety of incumbent user types in this category and a one-size-fits-all approach is unlikely to be satisfactory for all cases.

(b) We provide here a default protection method, on the broad assumption that the incumbent is a "Protected Zone", being geographic point or polygon with a maximum nuisance power at given frequencies at a given protection height.

(c) In countries with incumbent radio microphones in the TVWS band, and where this method is not deemed to be sufficient, we recommend that Ofcom's extremely detailed protection work[7] is used as a template.

5.1. Formal Framework

This section defines the function $g_{zone}(\bullet)$ such that

$$\mathbf{P}_{\mathbf{Tx:WSD|zone}} = g_{zone}(\text{WSD}, \mathbf{Z}, \text{terrain}) \tag{5.1}$$

where $\mathbf{Z}$ is the set of protected zones.

5.2. Prerequisite Data

(a) The following properties of a Protected Zone are required:

- Latitude & longitude polygon of the boundary of the zone;
- Maximum tolerable nuisance power in each channel in which protection is required;
- Height above ground level at which to measure nuisance power.

5.3. Method

(1) For each protected zone $Z \in \mathbf{Z}$:

(2) At each of a series of points $z \in \mathbf{z}$ on the border of and/or inside Z:

(3) For each channel i in the set of channels in which the zone Z requires protection:

(4) Calculate the path loss $L^i_{WSD \to z}$ in dB between the WSD's location W and z using a terrain-based propagation model at the centre frequency of i, given the height of the WSD and the protection height of Z. Where the antenna pattern for the WSD is known, the gain in the (geodesic) direction towards z is included. If the WSD location W is within the boundaries of $\mathbf{Z}$, $L^i_{WSD \to z} = 0$.

(5) A candidate power limit in each channel j to ensure the nuisance power in channel i is not exceeded at the single point z is then

$$P^{j|i}_{Tx:WSD@z} = \begin{cases} P_{Rx:Z} - L^i_{WSD \to z} & i = j \\ P_{Rx:Z} - L^i_{WSD \to z} + ACLR(\Delta f) & i \neq j \end{cases} \tag{5.2}$$

where $P_{Rx:Z}$ is the protected zone's nuisance power limit (this may be a country-wide constant or unique to each Z; a stringent default value is the thermal noise floor), $ACLR$ is that WSD's unintentional emission behaviour (§8) and Δf is the channel separation as defined above (§2.1).

(6) A candidate power limit in each channel j to protect Z at all points $z \in \mathbf{z}$ is then

$$P^j_{Tx:WSD|Z} = \min(P^j_{Tx:WSD@z} : \forall z \in \mathbf{z}). \tag{5.3}$$

(7) The candidate power limit in each channel i to protect all zones $\mathbf{Z}$ is then

$$P^i_{Tx:WSD|zone} = \min(P^i_{Tx:WSD|Z} : \forall Z \in \mathbf{Z}). \tag{5.4}$$

[7] Ofcom, *Implementing TV White Spaces*.

The final set of power limits is

$$\mathbf{P_{Tx:WSD|zone}} \equiv \{P^i_{Tx:WSD|zone} : \forall i \in \mathbf{I}\}. \tag{5.5}$$

6. Candidate WSD Power Limits for Protecting Band Edges

It is probable that particular countries will have specific protection requirements here. We provide a default protection method.

6.1. Formal Framework

This section defines the function $g_{band}(\bullet)$ such that

$$\mathbf{P_{Tx:WSD|band}} = g_{band}(\text{WSD}, \mathbf{I}, \text{terrain}) \tag{6.1}$$

where $\mathbf{I}$ is the set of channels available for TVWS.

6.2. Prerequisite Data

(a) The following properties are required:

- Maximum tolerable WSD emissions in each channel not available for TVWS use.

6.3. Method

(1) The constant maximum power $P_{Em:WSD|band}$ which a WSD may intentionally or unintentionally emit outside the TVWS channels $\mathbf{I}$ is to be set by a regulator; a default value is $P_{Em:WSD|band} = -25$dBm per channel. Note this may take different values in different frequency ranges.

(2) For each channel $i \in \mathbf{I}$, a candidate power limit is

$$P^i_{Tx:WSD|band} = P_{Em:WSD|band} - ACLR(\Delta f_{edge}) \tag{6.2}$$

where ACLR is that WSD's unintentional emission behaviour (§8) and Δf_{edge} is the separation between i and the nearest non-TVWS frequency as defined above (§2.1).

(3) The final set of power limits is

$$\mathbf{P_{Tx:WSD|band}} \equiv \{P^i_{Tx:WSD|band} : \forall i\}. \tag{6.3}$$

7. Candidate WSD Power Limits for Protecting Country Borders And Coasts

It is probable that particular countries will have specific protection requirements here, e.g. ITU GE06[8] or bilateral treaties with neighbours. We provide a default protection method.

[8] ITU. *Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230MHz and 470-862MHz*. Tech. rep. RRC-06. `http://www.itu.int/pub/R-ACT-RRC.14-2006`. ITU, 2006.

7.1. Formal Framework

This section defines the function $g_{border}(\bullet)$ such that

$$\mathbf{P_{Tx:WSD|border}} = g_{border}(\text{WSD, borders, terrain}). \tag{7.1}$$

7.2. Prerequisite Data

(a) The following properties are required:

- Latitude & longitude (WGS84) points, lines, or polygons describing the international and maritime/coastal borders of the country;
- Maximum tolerable nuisance power in each channel;
- Height above ground level at which to measure nuisance power.

7.3. Method

The constant maximum received power $P_{Rx:WSD|border}$ which is tolerable at a point on a country border due to WSD emissions is to be set by a regulator; a default value is $P_{Rx:WSD|border} = -74$dBm/8MHz (this is roughly equivalent to the 'trigger field strength' in GE06[9] Table AP1.9).

(1) At each of a series of points B along the country's border $\mathbf{B}$:

(2) For each channel $i \in \mathbf{I}$:

(3) Calculate the path loss $L^i_{WSD\to B}$ in dB between the WSD's location W and B using a terrain-based propagation model at the centre frequency of i, given the height of the WSD and the height of a household antenna at 10m. Where the antenna pattern for the WSD is known, the gain in the (geodesic) direction towards B is included.

(4) A candidate power limit $P^i_{Tx:WSD|B}$ is then

$$P^i_{Tx:WSD|B} = P_{Rx:WSD|border} - L^i_{WSD\to B}. \tag{7.2}$$

The power limit in each channel i to protect all points on the border $\mathbf{B}$ is then

$$P^i_{Tx:WSD|border} = \min(P^i_{Tx:WSD|B} : \forall B \in \mathbf{B}). \tag{7.3}$$

The final set of power limits is

$$\mathbf{P_{Tx:WSD|border}} \equiv \{P^i_{Tx:WSD|border} : \forall i \in \mathbf{I}\}. \tag{7.4}$$

8. WSD Out-of-Channel Emissions

8.1. 8MHz Channels

(a) Where the channels have bandwidth $b = 8$MHz, the WSD's ACLR as a function of its ETSI Emission Class[10] and the separation Δf (§2.1) is:

[9] ITU, *Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230MHz and 470-862MHz.*

[10] *ETSI EN 301 598 v1.1.1.* `http://www.etsi.org/deliver/etsi_en/301500_301599/301598/01.01.01_60/en_301598v010101p.pdf`. 2014.

Δf	± 1	± 2	± 3	± 4
Class 1	55	60	65	68
Class 2	55	55	55	64
Class 3	45	55	65	68
Class 4	35	45	55	64
Class 5	24	34	45	55

Table 1: $\mathrm{ACLR}(\Delta f)$ *in dB, being the ratio between intentional WSD emissions in a channel (dBm/8MHz) and unintentional WSD emissions (dBm/8MHz) in a channel separated by* $\Delta f \times$ *8MHz*

(b) If $|\Delta f| > 4$, the function is

$$\mathrm{ACLR}(\Delta f) = \mathrm{ACLR}(4) + (|\Delta f| - 4) \times 10\mathrm{dB}. \tag{8.1}$$

8.2. 6MHz Channels

(a) Where the channels have bandwidth $b = 6\mathrm{MHz}$, the WSD's ACLR as a function of the separation Δf (§2.1) is:

Δf	± 1	± 2	± 3	± 4
Fixed, Mode I, Mode II	55	65	65	65

Table 2: $\mathrm{ACLR}(\Delta f)$ *in dB, being the ratio between intentional WSD emissions in a channel (dBm/6MHz) and unintentional WSD emissions (dBm/6MHz) in a channel separated by* $\Delta f \times$ *6MHz*

(b) If $|\Delta f| > 4$, the function is

$$\mathrm{ACLR}(\Delta f) = \mathrm{ACLR}(4) + (|\Delta f| - 4) \times 7.5\mathrm{dB}. \tag{8.2}$$

(c) For the purposes of TV protection the ACLR for ETSI Class 1 is to be used. A corrected Δf is necessary to convert ETSI's 8MHz-based ACLR into a 6MHz-based ACLR, as follows. Given two 6MHz channels i, j which range in frequency within $[f^i_{min}, f^i_{max}]$ and $[f^j_{min}, f^j_{max}]$ respectively, and assuming without loss of generality that $j > i$, the corrected value of Δf to plug into TV protection ratio function $r(P^i_{Rx:TV}, \Delta f)$ is

$$\Delta f = 1 + \mathrm{floor}\left(\frac{f^j_{min} - f^i_{max}}{8\mathrm{MHz}}\right) \tag{8.3}$$

being the number of 8MHz bandwidths separating the nearest edges of 6MHz channels i and j, rounding down.

9. Spectrum Allocation Metadata

When responding to spectrum requests, WSDB's should include several other parameters in addition to the power limits:

- Date/time range (UTC) in which the spectrum allocation is valid;

- Maximum Polling Time (s), being the maximum period within which a WSD must contact the WSDB to confirm its spectrum allocation is still valid;
- Maximum Contiguous Bandwidth and Maximum Total Bandwidth (Hz), being the amount of spectrum a WSD may use in one contiguous block and in total (e.g. by channel-bonding);
- Maximum Location Change (m), being the distance outside of its stated location (including uncertainty) beyond which the WSD's spectrum allocation becomes invalid.

10. Tuning Parameters for Regulators

The above coexistence framework depends on a series of 'tuning parameters' which may be set by regulators according to their specific requirements. We tabulate them here along with default values. Values in dBm are per channel width b.

Parameter	Default value	Description
P_{cap}	40dBm	Maximum WSD transmit power per channel
$q_{s,t:incumbent}$	0.5	Longley-Rice probabilistic parameters for incumbent wanted signals
$q_{s,t:WSD\rightarrow incumbent}$	0.1	Longley-Rice probabilistic parameters for interference signals
$d_{min:WSD\rightarrow X}$	60m	Minimum distance between WSD and a simulated household
$d_{max:X\rightarrow T}$	200km	Maximum distance between simulated household and TV transmitter
h_{Rx}	10m	Household antenna height above ground level
$L_{Rx:noisefig}$	7dB	Household antenna noise figure
$G_{Rx:inst}$	9.15dBi	Household antenna net installation gain
$M_{Rx:imp}$	1.5dB	Household antenna implementation margin
CNR_{min}	19.5dB	Minimum acceptable household DVB-T carrier-to-noise ratio
$M_{Rx:link}$	4.6dB	Household reception link margin
$M_{Rx:cochannel}$	20dB	Additional margin for co-channel WSD operation
m	0.1%	Proportion of lowest candidate power limits to discard in each channel
$P_{Rx:Z}$	-105.2dBm	Maximum co-channel nuisance power in default protected zone
$P_{Em:WSD\|band}$	-25dBm	Maximum unintentional WSD emission into a non-TVWS channel
$P_{Rx:WSD\|border}$	-74dBm	Maximum received power from a WSD measured at a country border
M_{indoor}	7dB	Additional margin applied to indoor devices to account for wall losses
duration	24 hours	Difference between start and end times of validity of spectrum allocation
maxTotalBwHz	24MHz	Maximum total bandwidth which a WSD may use at one time
maxContiguousBwHz	24MHz	Maximum contiguous bandwidth which a WSD may use at one time
maxPollingSecs	86400s	Maximum period within which a WSD must contact the WSDB
maxLocationChange	100m	Maximum distance from stated WSD location

Table 3: *Tuning parameters and default values*

Annex B: Longley-Rice Propagation Algorithm

I. Introduction

The Model Rules and Regulations for the Use of Television White Spaces contemplate that available frequencies and maximum transmit powers for a White Space Device at a given location may be determined based on a geolocation and database method.[1] In particular, database(s) designated by the regulator will provide this information based on the horizontal and vertical location of White Space Device antenna, and use by licensed incumbents in or near the geographic area of operation of the White Space Device.[2] A database will supply a list of available frequencies and permitted maximum transmit powers to White Space Devices pursuant to the procedure in Annex A.

Annex A sets forth the method by which a database operator uses the relevant inputs to indicate available frequencies and maximum power limits for White Space Devices. In order to reliably protect incumbent TV users, this method requires a model for predicting the propagation loss of VHF and UHF radio signals over irregular terrain, so as to compute the field strength of a television signal at a particular geographic location; there are several such models available. The DSA recommend the Longley-Rice radio propagation model, also known as the Irregular Terrain Model ("Longley-Rice" or "ITM").[3] Annex B (this annex) constitutes a reproduction of published material describing the propagation model along with a description of its specific application to Annex A.

Implementations of the Longley-Rice model occur as programs written in a specific computer language. For example, the Institute for Telecommunication Sciences ("ITS"), a research and engineering laboratory of the National Telecommunications and Information Administration ("NTIA") within the United States Department of Commerce, maintains the "definitive" representation of the Longley-Rice model, which is written in FORTRAN.[4] Part II of this Annex describes this algorithm. Software implementations of the Longley-Rice radio propagation model will require several inputs to perform the field strength calculation for broadcast television, as described in Part III.

II. The Longley-Rice Algorithm

The Longley-Rice model is specifically intended for computer use. The Institute for Telecommunication Sciences ("ITS"), a research and engineering laboratory of the National Telecommunications and Information Administration ("NTIA") within the United States Department of Commerce, maintains the definitive representation of the Longley-Rice model, which is written in the FORTRAN computing language.[5] In addition, ITS provides a

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[1] *See* Model Rules and Regulations for the use of Television White Spaces, § 3.

[2] *Id.* § 4.

[3] *See* U.S. Department of Commerce, National Telecommunications & Information Administration, Institute for Telecommunication Sciences, Irregular Terrain Model (ITM) (Longley-Rice) (20 MHz – 20 GHz), *at* http://www.its.bldrdoc.gov/resources/radio-propagation-software/itm/itm.aspx.

[4] *See generally* Implementation of the Irregular Terrain Model, version 1.2.2 (updated 5 Aug. 2002), *available at* http://www.its.bldrdoc.gov/media/35869/itm.pdf.

[5] *Id.*

detailed description of the algorithm used by the Longley-Rice model.[6] Because this document is widely referenced, this Annex reproduces much of the original text of the algorithm description provided by ITS, including the original numerical identifiers for sections and equations, immediately below.

1. Input.

The Longley-Rice model includes two modes – *area prediction mode* and *point-to-point mode* – which are distinguished mostly by the amount of input data required. The point-to-point mode must provide details of the terrain profile of the link that the area prediction mode will estimate using empirical medians. Since in other respects the two modes follow very similar paths, the ITS algorithm description addresses both modes in parallel.

1.1. General input for both modes of usage.

d	Distance between the two terminals.
h_{g1}, h_{g2}	Antenna structural heights.
k	Wave number, measured in units of reciprocal lengths; see Note 1.
Δh	Terrain irregularity parameter
N_s	Minimum monthly mean surface refractivity, measured in N-units; see Note 2.
γ_e	The earth's effective curvature, measured in units of reciprocal length; see Note 3.
Z_g	Surface transfer impedance of the ground—a complex, dimensionless number; see Note 4.
radio climate	Expressed qualitatively as one of a number of discrete climate types.

Note 1. The wave number is that of the carrier or central frequency. It is defined to be

$$k = 2\pi / \lambda = f / f_0 \quad \text{with } f_0 = 47.70 \text{ MHz} \cdot \text{m} \tag{1.1}$$

where λ is the wave length, f the frequency. (Here and elsewhere we have assumed the speed of light in air is 299.7 m/μs.)

Note 2. To simplify its representation, the surface refractivity is sometimes given in terms of N_0, the surface refractivity "reduced to sea level." When this is the situation, one must know the general elevation z_s of the region involved, and then

$$N_s = N_0 e^{-z_s/z_1} \quad \text{with } z_1 = 9.46 \text{ km}. \tag{1.2}$$

[6] *See generally* George Hufford, The ITS Irregular Terrain Model, version 1.2.2, the Algorithm (1995), *available at* http://www.its.bldrdoc.gov/media/35878/itm_alg.pdf.

Note 3. The earth's effective curvature is the reciprocal of the earth's effective radius and may be expressed as

$$\gamma_e = \gamma_a / K$$

where γ_a is the earth's actual curvature and K is the "effective earth radius factor." The value is normally determined from the surface refractivity using the empirical formula

$$\gamma_e = \gamma_a(1 - 0.04665\, e^{N_S/N_1}) \tag{1.3}$$

where

$N_1 = 179.3$ N-units, and $\gamma_a = 157 \cdot 10^{-9}\ \mathrm{m}^{-1} = 157$ N-units/km.

Note 4. The "surface transfer impedance" is normally defined in terms of the relative permittivity ε_r and conductivity σ of the ground, and the polarization of the radio waves involved. In these terms, we have

$$Z_g = \begin{cases} \sqrt{\epsilon_r' - 1} & \text{horizontal polarization} \\ \sqrt{\epsilon_r' - 1}/\epsilon_r' & \text{vertical polarization} \end{cases} \tag{1.4}$$

where ε'_r is the "complex relative permittivity" defined by

$$\varepsilon'_r = \varepsilon_r + iZ_0\sigma/k, \qquad Z_0 = 376.62 \text{ ohm.} \tag{1.5}$$

The conductivity σ is normally expressed in siemens (reciprocal ohms) per meter.

1.2. Additional input for the area prediction mode.

siting criteria	Criteria describing the care taken at each terminal to assure good radio propagation conditions. This is expressed qualitatively in three steps: at random, with care, and with great care.

1.3. Additional input for the point-to-point mode.

h_{e1}, h_{e2}	Antenna effective heights.
d_{L1}, d_{L2}	Distances from each terminal to its radio horizon.
θ_{e1}, θ_{e2}	Elevation angles of the horizons from each terminal at the height of the antennas. These are measured in radians.

These quantities, together with Δh, are all geometric and should be determined from the terrain profile that lies between the two terminals. We shall not go into detail here.

The "effective height" of an antenna is its height above an "effective reflecting plane" or above the "intermediate foreground" between the antenna and its horizon. A difficulty with the model is that there is no explicit definition of this quantity, and the accuracy of the model sometimes depends on the skill of the user in estimating values for these effective heights.

In the case of a line-of-sight path there are no horizons, but the model still requires values for d_{Lj}, θ_{ej}, $j = 1{,}2$. They should be determined from the formulas used in the area prediction mode and listed in Section 3 below. Now it may happen that after these computations one discovers $d > d_L = d_{L1} + d_{L2}$, implying that the path is a beyond- horizon one. Noting that d_L is a monotone increasing function of the h_{ej} we can assume these latter have been underestimated and that they should be increased by a common factor until $d_L = d$.

2. Output.

The output from the model may take on one of several forms at the user's option. Simplest of these forms is just the *reference attenuation* A_{ref} . This is the *median* attenuation relative to a free space signal that should be observed on the set of all similar paths during times when the atmospheric conditions correspond to a standard, well-mixed, atmosphere.

The second form of output provides the two- or three-dimensional cumulative distribution of attenuation in which time, location, and situation variability are all accounted for. This is done by giving the *quantile* $A(q_T,q_L,q_S)$, the attenuation that will not be exceeded as a function of the fractions of time, locations, and situations. One says *In* q_S *of the situations there will be* at least q_L *of the locations where the attenuation* does not exceed $A(q_T,q_L,q_S)$ *for* at least q_T *of the time*.

When the point-to-point mode is used on particular, well-defined paths with definitely fixed terminals, there is no location variability, and one must use a two-dimensional description of cumulative distributions. One can now say *With probability (or confidence)* q_S *the attenuation will not exceed* $A(q_T, q_S)$ *for at least* q_T *of the time*. The same effect can be achieved by setting $q_L = 0.5$ in the three-dimensional formulation.

On some occasions it will be desirable to go beyond the three-dimensional quantiles and to treat directly the underlying model of variability. For example, consider the case of a communications link that is to be used once and once only. For such a "one-shot" system one is interested only in what probability or confidence an adequate signal is received that once. The three-dimensional distributions used above must now be combined into one.

3. Preparatory Calculations.

We start with some preliminary calculations of a geometric nature.

3.1. Preparatory calculations for the area prediction mode.

The parameters h_{ej}, d_{Lj}, θ_{ej}, $j = 1{,}2$,which are part of the input in the point-to-point mode are, in the area prediction mode, estimated using empirical formulas in which Δh plays an important role.

First, consider the effective heights. This is where the siting criteria are used. We have

$$h_{ej} = h_{gj} \qquad \text{if terminal } j \text{ is sited at random.} \tag{3.1}$$

Otherwise, let

$$B_j = \begin{cases} 5 \text{ m} & \text{if terminal } j \text{ is sited with care} \\ 10 \text{ m} & \text{if terminal } j \text{ is sited with great care.} \end{cases}$$

Then

$$B'_j = (B_j - H_1)\sin\left(\frac{\pi}{2}\min(h_{g1}/H_2, 1)\right) + H_1 \qquad \text{with } H_1 = 1 \text{ m},\ H_2 = 5 \text{ m},$$

and

$$h_{ej} = h_{gj} + B'_j e^{-2h_{gj}/\Delta h}. \tag{3.2}$$

The remaining parameters are quickly determined.

$$d_{Lsj} = \sqrt{2h_{ej}/\gamma_e}$$
$$d_{Lj} = d_{Lsj}\exp\left[-0.07\sqrt{\Delta h/\max(h_{ej}, H_3)}\right] \qquad \text{with } H_3 = 5 \text{ m} \tag{3.3}$$

and finally,

$$\theta_{ej} = [0.65\,\Delta h(d_{Lsj}/d_{Lj} - 1) - 2h_{ej}]/d_{Lsj}. \tag{3.4}$$

3.2. Preparatory calculations for both modes.

$$d_{Lsj} = \sqrt{2h_{ej}/\gamma_e}, \qquad j = 1, 2 \tag{3.5}$$
$$d_{Ls} = d_{Ls1} + d_{Ls2} \tag{3.6}$$
$$d_L = d_{L1} + d_{L2} \tag{3.7}$$
$$\theta_e = \max(\theta_{e1} + \theta_{e2},\ -d_L\gamma_e). \tag{3.8}$$

We also note here the definitions of two functions of a distance s:

$$\Delta h(s) = (1 - 0.8\,e^{-s/D})\Delta h \qquad \text{with } D = 50 \text{ km}, \tag{3.9}$$

and

$$\sigma_h(s) = 0.78\,\Delta h(s)\exp\left[-(\Delta h(s)/H)^{1/4}\right] \qquad \text{with } H = 16 \text{ m}. \tag{3.10}$$

4. The Reference Attenuation.

The reference attenuation is determined as a function of the distance d from the piecewise formula

$$A_{\text{ref}} = \begin{cases} \max\left(0, A_{el} + K_1 d + K_2 \ln(d/d_{Ls})\right) & d \le d_{Ls} \\ A_{ed} + m_d d & d_{Ls} \le d \le d_x \\ A_{es} + m_s d & d_x \le d \end{cases} \tag{4.1}$$

where the coefficients A_{el}, K_1, K_2, A_{ed}, m_d, A_{es}, m_s, and the distance d_x are calculated using the algorithms below. The three intervals defined here are called the line-of-sight, diffraction, and scatter regions, respectively. The function in (4.1) is continuous so that at the two endpoints where $d = d_{Ls}$ or d_x the two formulas give the same results. It follows that instead of seven independent coefficients there are really only five.

4.1. Coefficients for the diffraction range.

Set

$$X_{ae} = (k\gamma_e^2)^{-1/3} \tag{4.2}$$

$$d_3 = \max(d_{Ls}, d_L + 1.3787\, X_{ae}) \tag{4.3}$$

$$d_4 = d_3 + 2.7574\, X_{ae} \tag{4.4}$$

$$A_3 = A_{\text{diff}}(d_3) \tag{4.5}$$

$$A_4 = A_{\text{diff}}(d_4) \tag{4.6}$$

where A_{diff} is the function defined below. The formula for A_{ref} in the diffraction range is then just the linear function having the values A_3 and A_4 at the distances d_3 and d_4, respectively. Thus

$$m_d = (A_4 - A_3)/(d_4 - d_3) \tag{4.7}$$

$$A_{ed} = A_3 - m_d d_3. \tag{4.8}$$

4.1.1. The function $A_{\text{diff}}(s)$.

We first define the weighting factor

$$w = \frac{1}{1 + 0.1\sqrt{Q}} \tag{4.9}$$

with

$$Q = \min\left(\frac{k}{2\pi}\Delta h(s), 1000\right)\left(\frac{h_{e1}h_{e2} + C}{h_{g1}h_{g2} + C}\right)^{1/2} + \frac{d_L + \theta_e/\gamma_e}{s}$$

and

$$C = \begin{cases} 0 & \text{in the area prediction mode} \\ 10\ \text{m}^2 & \text{in the point-to-point mode} \end{cases}$$

and where $\Delta h(s)$ is the function defined in (3.9) above. Next we define a "clutter factor"

$$A_{fo} = \min\left[15, 5\log\left(1 + \alpha k h_{g1} h_{g2} \sigma_h(d_{Ls})\right)\right] \qquad \text{with } \alpha = 4.77 \cdot 10^{-4}\ \text{m}^{-2} \tag{4.10}$$

and with $\sigma_h(s)$ defined in (3.10) above.

Then

$$A_{\text{diff}}(s) = (1 - w)A_k + wA_r + A_{fo} \tag{4.11}$$

where the "double knife edge attenuation" A_k and the "rounded earth attenuation" A_r are yet to be defined. Set

$$\theta = \theta_e + s\gamma_e \tag{4.12}$$

$$v_j = \frac{\theta}{2}\left(\frac{k}{\pi}\frac{d_{Lj}(s-d_L)}{s-d_L+d_{Lj}}\right)^{1/2}, \qquad j = 1,2 \tag{4.13}$$

and then

$$A_k = \mathrm{Fn}(v_1) + \mathrm{Fn}(v_2) \tag{4.14}$$

where $\mathrm{Fn}(v)$ is the Fresnel integral defined below.

For the rounded earth attenuation we use a "three radii" method applied to Volger's formulation of the solution to the smooth, spherical earth problem. We set

$$\gamma_0 = \theta / (s - d_L) \qquad \gamma_j = 2h_{ej} / d^2_{Lj}, \quad j = 1,2 \tag{4.15}$$

$$\alpha_j = (k/\gamma_j)^{1/3}, \quad j = 0,1,2 \tag{4.16}$$

$$K_j = \frac{1}{i\alpha_j Z_g}, \qquad j = 0,1,2. \tag{4.17}$$

Note that the K_j are complex numbers. To continue, we set

$$x_j = AB(K_j)\alpha_j\gamma_j d_{Lj}, \qquad j = 1.2 \tag{4.18}$$

$$x_0 = AB(K_0)\alpha_0\theta + x_1 + x_2 \tag{4.19}$$

and then

$$A_r = G(x_0) - F(x_1, K_1) - F(x_2, K_2) - C_1(K_0) \tag{4.20}$$

where $A = 151.03$ is a dimensionless constant and the functions $B(K)$, $G(x)$, $F(x, K)$, and $C_1(K)$ are those defined by Vogler.

In (4.14) and (4.20) we have finished the definition of A_{diff}. We should like, however, to complete the subject by defining more precisely the more or less standard functions mentioned above. The Fresnel integral, for example, may be written as

$$\mathrm{Fn}(v) = 20 \log\left|\frac{1}{\sqrt{2i}}\int_v^\infty e^{i\pi u^2/2}du\right|. \tag{4.21}$$

For Vogler's formulation to the solution to the spherical earth problem, we first introduce the special Airy function

$$\mathrm{Wi}(z) = \mathrm{Ai}(z) + i\mathrm{Bi}(z)$$

$$= 2\mathrm{Ai}(e^{2\pi i/3}z)$$

where Ai(z) and Bi(z) are the two standard Airy functions defined in many texts. They are analytic in the entire complex plane and are particular solutions to the differential equation

$$w''(z) - zw(z) = 0.$$

First, to define the function $B(K)$ we find the smallest solution to the modal equation

$$\mathrm{Wi}(t_0) = 2^{1/3}K\mathrm{Wi}'(t_0)$$

and then

$$B = 2^{-1/3}\mathrm{Im}\{t_0\}. \tag{4.22}$$

Finally, we also have

$$G(x) = 20\ \log(x^{-1/2}e^{x/A}) \tag{4.23}$$
$$F(x, K) = 20\ \log\left|(\pi/(2^{1/3}AB))^{1/2}\mathrm{Wi}(t_0 - (x/(2^{1/3}AB))^2)\right| \tag{4.24}$$
$$C_1(K) = 20\ \log\left|\frac{1}{2}(\pi/(2^{1/3}AB))^{1/2}(2^{2/3}K^2t_0 - 1)\mathrm{Wi}'(t_0)^2\right| \tag{4.25}$$

where A is again the constant defined above.

It is of interest to note that for large x we find $F(x, K) \sim G(x)$, and that for those values of K in which we are interested it is a good approximation to say $C_1(K) = 20$ dB.

4.2. Coefficients for the line-of-sight range.

We begin by setting

$$d_2 = d_{Ls} \tag{4.26}$$

$$A_2 = A_{ed} + m_d d_2. \tag{4.27}$$

Then there are two general cases. First, if $A_{ed} \geq 0$

$$d_0 = \min\left(\frac{1}{2}d_L, 1.908\, kh_{e1}h_{e2}\right) \tag{4.28}$$
$$d_1 = \frac{3}{4}d_0 + \frac{1}{4}d_L \tag{4.29}$$

$$A_0 = A_{\mathrm{los}}(d_0) \tag{4.30}$$

$$A_1 = A_{\mathrm{los}}(d_1) \tag{4.31}$$

where the function $A_{\mathrm{los}}(s)$ is defined below. The idea, now, is to devise a curve of the form

$$A_{el} + K_1 d + K_2 \ln(d/d_{Ls})$$

that passes through the three values A_0, A_1, A_2 at d_0, d_1, d_2, respectively. In doing this, however, we require $K_1, K_2 \geq 0$, and sometimes this forces us to abandon one or both of the values A_0, A_1. We first define

$$K_2' = \max\left[0, \frac{(d_2 - d_0)(A_1 - A_0) - (d_1 - d_0)(A_2 - A_0)}{(d_2 - d_0)\ln(d_1/d_0) - (d_1 - d_0)\ln(d_2/d_0)}\right] \tag{4.32}$$

$$K'_1 = (A_2 - A_0 - K'_2 \ln(d_2/d_0)) / (d_2 - d_0) \tag{4.33}$$

which, except for the possibility that the first calculation for K'_2 results in a negative value, is simply the straightforward solution for the two corresponding coefficients. If $K'_1 \geq 0$ we then have

$$K_1 = K'_1 , K_2 = K'_2 \; . \tag{4.34}$$

If, however, $K'_1 < 0$, we define

$$K''_2 = (A_2 - A_0)/\ln(d_2/d_0) \tag{4.35}$$

and if now $K''_2 \geq 0$ then

$$K_1 = 0, \qquad K_2 = K''_2. \tag{4.36}$$

Otherwise, we abandon both A_0 and A_1 and set

$$K_1 = m_d, \qquad K_2 = 0. \tag{4.37}$$

In the second general case we have $A_{ed} < 0$. We then set

$$d_0 = 1.908 k h_{e1} h_{e2} \tag{4.38}$$

$$d_1 = \max(-A_{ed}/m_d, d_L/4). \tag{4.39}$$

If $d_0 < d_1$ we again evaluate A_0, A_1, and K'_2 as before. If $K'_2 > 0$ we also evaluate K'_1 and proceed exactly as before. If, however, we have either $d_0 \geq d_1$ or $K'_2 = 0$, we evaluate A_1 and define

$$K''_1 = (A_2 - A_1)/(d_2 - d_1). \tag{4.40}$$

If now $K''_1 > 0$ we set

$$K_1 = K''_1, \qquad K_2 = 0; \tag{4.41}$$

and otherwise we use (4.37).

At this point we will have defined the coefficients K_1 and K_2. We finally set

$$A_{el} = A_2 - K_1 d_2. \tag{4.42}$$

4.2.1. The function $A_{\text{los}}(s)$.

First we define the weighting factor

$$w = 1/\left(1 + D_1 k \Delta h / \max\left(D_2, d_{Ls}\right)\right) \quad \text{with } D_1 = 47.7 \text{ m}, D_2 = 10 \text{ km}. \tag{4.43}$$

Then

$$A_{\text{los}} = (1 - w)A_d + wA_t \tag{4.44}$$

where the "extended diffraction attenuation" A_d and the "two-ray attenuation" A_t are yet to be defined.

First, the extended diffraction attenuation is given very simply by

$$A_d = A_{ed} + m_d s. \tag{4.45}$$

For the two-ray attenuation, we set

$$\sin\psi = \frac{h_{e1} + h_{e2}}{\sqrt{s^2 + (h_{e1} + h_{e2})^2}} \tag{4.46}$$

and

$$R'_e = \frac{\sin\psi - Z_g}{\sin\psi + Z_g} \exp[-k\sigma_h(s)\sin\psi] \tag{4.47}$$

where $\sigma_h(s)$ is the function defined in (3.10) above. Note that R'_e is complex since it uses the complex surface transfer impedance Z_g. Then

$$R_e = \begin{cases} R'_e & \text{if } |R'_e| \geq \max(1/2, \sqrt{\sin\psi}) \\ (R'_e/|R'_e|)\sqrt{\sin\psi} & \text{otherwise} \end{cases} \tag{4.48}$$

We also set

$$\delta' = 2kh_{e1}h_{e2}/s \tag{4.49}$$

and

$$\delta = \begin{cases} \delta' & \text{if } \delta' \leq \pi/2 \\ \pi - (\pi/2)^2/\delta' & \text{otherwise} \end{cases} \tag{4.50}$$

Then finally

$$A_t = -20 \log |1 + R_e e^{i\delta}|. \tag{4.51}$$

4.3. Coefficients for the scatter range.

Set

$$d_5 = d_L + D_s \tag{4.52}$$

$$d_6 = d_5 + D_s \text{ with } D_s = 200 \text{ km}. \tag{4.53}$$

Then define

$$A_5 = A_{\text{scat}}(d_5) \tag{4.54}$$

$$A_6 = A_{\text{scat}}(d_6), \tag{4.55}$$

where $A_{\text{scat}}(s)$ is defined below. There are, however, some sets of parameters for which A_{scat} is not defined, and it may happen that either or both A_5, A_6 is undefined. If this is so, one merely sets

$$d_x = +\infty \tag{4.56}$$

and one can let A_{es}, m_s remain undefined. In the more normal situation one has

$$m_s = (A_6 - A_5)/D_s \tag{4.57}$$

$$d_x = \max[d_{Ls}, d_L + X_{ae} \log(kHs), (A_5 - A_{ed} - m_s d_5)/(m_d - m_s)] \tag{4.58}$$

$$A_{es} = A_{ed} + (m_d - m_s)d_x \tag{4.59}$$

where D_s is the distance given above, where X_{ae} has been defined in (4.2), and where H_s= 47.7 m.

4.3.1. The function A_{scat}.

Computation of this function uses an abbreviated version of the methods described in Section 9 and Annex III.5 of NBS TN101.[7] First, set

$$\theta = \theta_e + \gamma_e s \tag{4.60}$$

$$\theta' = \theta_{e1} + \theta_{e2} + \gamma_e s \tag{4.61}$$

$$r_j = 2k\theta' h_{ej}, \qquad j = 1,2. \tag{4.62}$$

If both r_1 and r_2 are less than 0.2 the function A_{scat} is not defined (or is infinite). Otherwise

7 *See* P. L. Rice, A. G. Longley, K. A. Norton, and A. P. Barsis, "Transmission loss predictions for tropospheric communication circuits," U.S. Government Printing Office, Washington, DC, NBS Tech. Note 101, issued May 1965; revised May 1966 and Jan. 1967 ("TN101").

we put

$$A_{\text{scat}}(s) = 10 \log(kH\theta^4) + F(\theta s, N_s) + H_0 \tag{4.63}$$

where F (θs, N_s) is the function shown in Figure 9.1 of TN101, H_0 is the "frequency gain function", and $H = 47.7$m.

The frequency gain function H_0 is a function of r_1, r_2, the scatter efficiency factor η_s, and the "asymmetry factor" which we shall here call s_s. A difficulty with the present model is that there is not sufficient geometric data in the input variables to determine where the crossover point is. This is resolved by assuming it to be midway between the two horizons. The asymmetry factor, for example, is found by first defining the distance between horizons

$$d_s = s - d_{L1} - d_{L2} \tag{4.64}$$

whereupon

$$s_s = \frac{d_{L2} + d_s/2}{d_{L1} + d_s/2}. \tag{4.65}$$

There then follows that the height of the crossover point is

$$z_0 = \frac{s_s d\theta'}{(1 + s_s)^2} \tag{4.66}$$

and then

$$\eta_s = \frac{z_0}{Z_0}\left[1 + (0.031 - N_s 2.32 \cdot 10^{-3} + N_s^2 5.67 \cdot 10^{-6}) e^{-(z_0/Z_1)^6}\right] \tag{4.67}$$

where

$$Z_0 = 1.756 \text{ km} \qquad Z_1 = 8.0 \text{ km}$$

The computation of H_0 then proceeds according to the rules in Section 9.3 and Figure 9.3 of TN101.

The model requires these results at the two distances $s = d_5$, d_6, described above. One further precaution is taken to prevent anomalous results. If, at d_5, calculations show that H_0 will exceed 15 dB, they are replaced by the value it has at d_6. This helps keep the scatter-mode slope within reasonable bounds.

5. Variability—the quantiles of attenuation.

We want now to compute the quantiles $A(q_T, q_L, q_S)$ where q_T, q_L, q_S, are the desired fractions of time, locations, and situations, respectively. In the point-to-point mode, we would want a two-fold quantile $A(q_T, q_S)$, but in the present model this is done simply by computing the three-fold quantile with q_L equal to 0.5.

Because the distributions involved are all normal, or nearly normal, it simplifies the calculations to rescale the desired fractions and to express them in terms of "standard normal deviates." We use the complementary normal distribution

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{-t^2/2} dt$$

and then the deviate is simply the inverse function

$$z(q) = Q^{-1}(q).$$

Thus if the random variable x is normally distributed with mean X_0 and standard deviation σ, its quantiles are given by

$$X(q) = X_0 + \sigma z(q).$$

Setting

$$z_T = z(q_T), z_L = z(q_L), z_S = z(q_S),$$

we now ask for the quantiles $A(z_T, z_L, z_S)$. In these rescaled variables, it is as though all probabilities are to be plotted on normal probability paper. In the case of the point-to- point mode we will simply suppose $z_L = 0$.

First we define

$$A' = A_{\text{ref}} - V_{\text{med}} - Y_T - Y_L - Y_S \tag{5.1}$$

where A_{ref} is the reference attenuation defined in Section 4, and where the adjustment V_{med} and the deviations Y_T, Y_L, Y_S, are defined below. The values of Y_T and Y_L depend on the single variables z_T and z_L, respectively. The value of Y_S, on the other hand, depends on all three standard normal deviates.

The final quantile is a modification of A' given by

$$A(z_T, z_L, z_S) = \begin{cases} A' & \text{if } A' \geq 0 \\ A' \dfrac{29 - A'}{29 - 10A'} & \text{otherwise.} \end{cases} \tag{5.2}$$

An important quantity used below is the "effective distance." We set

$$d_{ex} = \sqrt{2a_1 h_{e1}} + \sqrt{2a_1 h_{e2}} + a_1 (kD_1)^{-1/3} \tag{5.3}$$

with

$$a_1 = 9000 \text{ km}, \qquad D_1 = 1266 \text{ km}.$$

Then the effective distance is given by

$$d_e = \begin{cases} D_0 d/d_{ex} & \text{for } d \le d_{ex} \\ D_0 + d - d_{ex} & \text{for } d \ge d_{ex} \end{cases} \tag{5.4}$$

with $D_0 = 130$ km.

5.1. Time variability.

Quantiles of time variability are computed using a variation of the methods described in Section 10 and Annex III.7 of NBS TN101, and also in CCIR Report 238-3. Those methods speak of eight or nine discrete radio climates, of which seven have been documented with corresponding empirical curves. It is these empirical curves to which we refer below. They are all curves of quantiles of deviations versus the effective distance d_e.

The adjustment from the reference attenuation to the all-year median is

$$V_{\text{med}} = V_{\text{med}}(d_e, \text{clim}) \tag{5.5}$$

where the function is described in Figure 10.13 of TN101.

The deviation Y_T is piecewise linear in z_T , and may be written in the form

$$Y_T = \begin{cases} \sigma_{T-} z_T & z_T \le 0 \\ \sigma_{T+} z_T & 0 \le z_T \le z_D \\ \sigma_{T+} z_D + \sigma_{TD}(z_T - z_D) & z_D \le z_T \end{cases} \tag{5.6}$$

The slopes (or "pseudo-standard deviations")

$$\sigma_{T-} = \sigma_{T-}(d_e, \text{clim}) \tag{5.7}$$

$$\sigma_{T+} = \sigma_{T+}(d_e, \text{clim})$$

are obtained from TN101 in the following way. For σ_{T-} we use the .90 quantile and divide the corresponding ordinates by $z(.90) = -1.282$. For σ_{T+} we use the .10 quantile and divide by $z(.10) = 1.282$.

The remaining constants in (5.6) pertain to the "ducting," or low probability, case. We write

$$z_D = z_D(\text{clim}), \ \sigma_{TD} = C_D(\text{clim})\sigma_{T+} \tag{5.8}$$

where values of z_D and C_D are given in Table 1. In that table we have also listed values of $q_D = Q(z_D)$.

Climate	q_D	z_D	C_D
Equatorial	.10	1.282	1.224
Continental Subtropical	≈.015	2.161	.801
Maritime Subtropical	.10	1.282	1.380
Desert	0	∞	–
Continental Temperate	.10	1.282	1.224
Maritime Temperate Overland	.10	1.282	1.518
Maritime Temperate Oversea	.10	1.282	1.518

Table 1: *Ducting (low probability) constants*

5.2. Location variability.

We set

$$Y_L = \sigma_L z_L \tag{5.9}$$

where

$$\sigma_L = 10k\Delta h(d)/(k\Delta h(d) + 13)$$

and $\Delta h(s)$ is defined in (3.9) above.

5.3. Situation variability.

Set

$$\sigma_S = 5 + 3e^{-d_e/D} \tag{5.10}$$

where $D = 100$ km. Then

$$Y_S = \left(\sigma_S^2 + \frac{Y_T^2}{7.8 + z_S^2} + \frac{Y_L^2}{24 + z_S^2}\right)^{1/2} z_S \tag{5.11}$$

The latter is intended to reveal how the uncertainties become greater in the wings of the distributions.

6. Addenda—numerical approximations.

Part of the algorithm for the ITM consists in approximations for the standard functions that have been used. In these approximations, computational simplicity has often taken greater priority than accuracy.

The Fresnel integral is used in §4.1.1 and is defined in (4.21). We have (for $v > 0$)

$$\mathrm{Fn}(v) \approx \begin{cases} 6.02 + 9.11v - 1.27v^2 & \text{if } v \leq 2.40 \\ 12.953 + 20 \log v & \text{otherwise} \end{cases} \tag{6.1}$$

The functions $B(K)$, $G(x)$, $F(x, K)$, $C_1(K)$, which are used in diffraction around a smooth earth, are also used in §4.1.1 and are defined in (4.22)–(4.25). We have

$$B(K) \approx 1.607 - |K| \tag{6.2}$$

$$G(x) = .05751x - 10 \log x \tag{6.3}$$

$$F(x, K) \approx \begin{cases} F_2(x, K) & \text{if } 0 < x \leq 200 \\ G(x) + 0.0134xe^{-x/200}(F_1(x) - G(x)) & \text{if } 200 < x < 2000 \\ G(x) & \text{if } 2000 \leq x \end{cases} \tag{6.4}$$

where

$$F_1(x) = 40 \log(\max(x, 1)) - 117 \tag{6.5}$$

$$F_2(x, K) = \begin{cases} F_1(x) & \text{if } |K| < 10^{-5} \text{ or } x(-\log|K|)^3 > 450 \\ 2.5 \cdot 10^{-5}x^2/|K| + 20 \log|K| - 15 & \text{otherwise} \end{cases} \tag{6.6}$$

The final approximation here is

$$C_1(K) \approx 20 \tag{6.7}$$

To complete this section we have the two functions, $F(\theta d)$ and H_0, used for tropospheric scatter. First,

$$F(D, N_s) = F_0(D) - 0.1(N_s - 301)e^{-D/D_0} \tag{6.8}$$

where

$$D_0 = 40 \text{ km}$$

and (when D is given in meters)

$$F_0(D) = \begin{cases} 133.4 + 0.332 \cdot 10^{-3}D - 10 \log D & \text{for } 0 < D \leq 10 \text{ km} \\ 104.6 + 0.212 \cdot 10^{-3}D - 2.5 \log D & \text{for } 10 < D \leq 70 \text{ km} \\ 71.8 + 0.157 \cdot 10^{-3}D + 5 \log D & \text{otherwise} \end{cases} \tag{6.9}$$

The frequency gain function may be written as

$$H_0 = H_{00}(r_1, r_2, \eta_s) + \Delta H_0 \tag{6.10}$$

where

$$\Delta H_0 = 6(0.6 - \log \eta_s) \log s_s \log r_2/ s_s r_1 \tag{6.11}$$

and where H_{00} is obtained by linear interpolation between its values when η_s is an integer. For $\eta_s = 1, \ldots, 5$ we set

$$H_{00}(r_1, r_2, j) = \frac{1}{2}[H_{01}(r_1, j) + H_{01}(r_2, j)] \tag{6.12}$$

with

$$H_{01}(r, j) = \begin{cases} 10 \log(1 + 24r^{-2} + 25r^{-4}) & j = 1 \\ 10 \log(1 + 45r^{-2} + 80r^{-4}) & j = 2 \\ 10 \log(1 + 68r^{-2} + 177r^{-4}) & j = 3 \\ 10 \log(1 + 80r^{-2} + 395r^{-4}) & j = 4 \\ 10 \log(1 + 105r^{-2} + 705r^{-4}) & j = 5 \end{cases} \tag{6.13}$$

For $\eta_s > 5$ we use the value for $\eta_s = 5$ and for $\eta_s = 0$ we suppose

$$H_{00}(r_1, r_2, 0) = 10 \log \left[\left(1 + \frac{\sqrt{2}}{r_1}\right)^2 \left(1 + \frac{\sqrt{2}}{r_2}\right)^2 \frac{r_1 + r_2}{r_1 + r_2 + 2\sqrt{2}} \right] \tag{6.14}$$

In all of this, we truncate the values of s_s and $q = r_2/s_s r_1$ at 0.1 and 10.

III. Longley-Rice Parameters

1. Environmental Parameters

In addition to the technical operating characteristics for a given broadcast transmitter and planning factors for television reception, the Longley-Rice model contemplates the use of the following parameters that describe the environment in which the transmitter is operating (or, more precisely, statistics about the environment where the transmitter operates).

- Surface Refractivity: N_s.[8] This is the refractivity of the atmosphere, measured in N-Units (parts per million), which typically ranges from 250 to 400 N-units. ITS guidance on Longley-Rice model implementation[9] includes the following values:

[8] Note that the N-Unit value for surface refractivity is a separate parameter unrelated to the symbols denoting noise in Table 1 above.

[9] *See* Hufford, G. A., A. G. Longley, and W. A. Kissick (1982)280, A guide to the use of the ITS Irregular Terrain Model in the area prediction mode, NTI301A Report 82-100. (NTIS Order No. PB82-217977).

Radio Climate	N_s (N-units)
Equatorial (Congo)	360
Continental Subtropical (Sudan)	320
Maritime Subtropical (West Coast of Africa)	370
Desert (Sahara)	280
Continental Temperate	301
Maritime Temperate, over land (United Kingdom and continental west coasts)	320
Maritime Temperate, over sea	350
For average atmospheric conditions, use a Continental Temperate climate and N_s = 301 N-units	

Table 2: *ITS Values for N_s*

- Permittivity: This is the dielectric constant of the ground. ITS guidance includes the values in Table 3 below.
- Conductivity: Soil conductivity of the ground. ITS guidance includes the values in Table 3 below.

	Relative Permittivity	Conductivity (Siemens per Meter)
Average ground	15	0.005
Poor ground	4	0.001
Good ground	25	0.020
Fresh water	81	0.010
Sea water	81	5.0
For most purposes, use the constants for an average ground		

Table 3: *ITS Values for Electrical Ground Constants*

- Climate Zone: This value is entered as per climate codes that correspond with the seven climate categories specified in Table 1 above. Together with N_s, the climate serves to characterize the atmosphere and its variability in time.
- Variability. The Longley-Rice model includes the following three kinds of variability:
  - Location Variability (reliability and confidence level): This value is expressed as a percentage from 0.1% to 99.9%. Location variability accounts for variations in long-term statistics that occur from path to path.
  - Time Variability: This value is expressed as percentage from 0 to 100%.

Time variability accounts for variations of median values of attenuation.

- Situation Variability: This value is expressed as a percentage; 50% variability is considered normal for coverage estimations. Situation variability accounts for variations between systems with the same system parameters and environmental conditions.

- Variability modes: ITS guidance contemplates the following ways in which the kinds of variability listed above are treated in combination:
  - Broadcast mode: all three kinds of variability are treated separately.
  - Individual mode: situation and location variability are combined; time variability is treated separately.
  - Mobile mode: time and location variability are combined; situation variability is treated separately.
  - Single message mode: all three kinds of variability are combined.

The values listed in Table 4 below have historically been utilized when implementing the Longley-Rice model for television signal analysis[10], and should be used to calculate the field strength of a television broadcasting station signal at a particular geographic location.

Longley-Rice Parameter	Value
Surface refractivity in N-units (parts per million)	301.0
Relative permittivity of ground	15.0
Ground conductivity, Siemens per meter	0.005
Climate zone code	5 (continental temperate)
Mode for variability calculations	Broadcast mode

Table 4: *Longley-Rice Parameter Values for Television Signal Analysis*

2. Parameters for Point-to-Point Mode

The Longley-Rice radio propagation model can be implemented in "area coverage" mode or "point-to-point" mode. The point-to-point mode is used to evaluate the predicted strength of a particular television channel at a geographic location where a White Space Device "WSD" is present. With the point-to-point mode, field strength at a particular geographic location is determined using path-specific parameters determined from detailed terrain profile data.

2.1. Terrain Profile Data

The Longley-Rice model may use terrain elevation values to create a detailed profile of a path for analysis by the program. The model was designed to use terrain data at equal increments along a path. Points not at equal increments are ignored. Consequently, field strength values are calculated values out to the last uniformly spaced point on a given radial.

A Longley-Rice implementation may achieve greater precision by utilizing values given by specific terrain datasets collected using empirical measurements. For example, the

[10] *See* OET Bulletin No. 69 at 6.

Shuttle Radar Topography Mission (SRTM) undertaken by the National Aeronautics and Space Administration (NASA) obtained elevation data on a near-global scale in order to create a high-resolution digital topographic database of most of the Earth, providing 1 arc-second (~ 30m) resolution data for most of the continents between 60 N and 60 S.[11] In many populated areas, higher resolution sources of terrain data are available.

2.2. Preparatory Calculations

Values for the effective heights, radio horizon distances, and terrain irregularity must be found for use in §3.2 of Part II above in Point-to-Point mode. Methods for deriving these values from a terrain profile can be found in the *qlrpfl* method of the FORTRAN implementation.[12]

3. Parameters for Area Coverage Mode

The Longley-Rice model uses input parameters to compute geometric parameters related to the propagation path. First, the model determines effective antenna height. Since this is an area prediction model, the radio horizons, for example, are unknown. The model uses the terrain irregularity parameter to estimate radio horizons. The model also computes a reference attenuation, using horizon distances and elevation angles to calculate transmission loss relative to free space.

The Longley-Rice model will treat the terrain that separates the television broadcast station and the white space device location as a random function characterized by Δh. The model uses a signal value Δh to represent the size of the irregularities. Roughly speaking, Δh is the interdecile range of terrain elevations—that is, the total range of elevations after the highest 10% and lowest 10% have been removed. Suggested values for Δh provided by ITS are set forth in Table 5 below.

	Δh (meters)
Flat (or smooth water)	0
Plains	30
Hills	90
Mountains	200
Rugged Mountains	500
For an average terrain, use $\Delta h = 90$ m	

Table 5: *ITS Values for Terrain Irregularity*

[11] *See generally* National Aeronautics and Space Administration, Shuttle Radar Topography Mission: The Mission to Map the World, at http://www2.jpl.nasa.gov/srtm/.

[12] *Id.*

Annex C: ITU-R. P-1812 Propagation Algorithm

I. Introduction

The Model Rules and Regulations for the Use of Television White Spaces contemplate that available frequencies and maximum transmit powers for a White Space Device at a given location may be determined based on a geolocation and database method.[1] In particular, database(s) designated by the regulator will provide this information based on the horizontal and vertical location of White Space Device antenna, and use by licensed incumbents in or near the geographic area of operation of the White Space Device.[2] A database will supply a list of available frequencies and permitted maximum transmit powers to White Space Devices pursuant to the procedure in Annex A.

Annex A sets forth the method by which a database operator uses the relevant inputs to indicate available frequencies and maximum power limits for White Space Devices. In order to reliably protect incumbent TV users, this method requires a model for predicting the propagation loss of VHF and UHF radio signals over irregular terrain, so as to compute the field strength of a television signal at a particular geographic location; there are several such models available. Annex B describes the DSA's recommendation of the Longley-Rice propagation model. However, other point-to-point, terrain-based propagation models may also serve as the basis for spectrum availability calculations. One such model is the International Telecommunication Union's Radiocommunication Sector Recommendation P-1812 (ITU-R. P-1812). Like Longley-Rice, ITU-R. P-1812 is a path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands. Further detail regarding ITU-R. P-1812, including the model itself and an explanation of its implementation is available for download on the ITU's website at https://www.itu.int/rec/R-REC-P.1812-3-201309-I/en.

1 *See* Model Rules and Regulations for the use of Television White Spaces, § 3.

2 *Id*. § 4.