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Radio Propagation in Terrestrial Broadcasting Television Systems: A Comprehensive Survey

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ABSTRACT During the last two decades, terrestrial TV broadcasting has evolved from analog to digital technology, permitting a better spectrum efficiency, being more resistant to noise and interference as well as improving signal quality. High Definition TeleVison (HDTV) has been introduced to enhance the viewer's experience. HDTV and Ultra High Definition TeleVision bring the challenge of having a quasi-error free performance at a bit error rate as low as 10^{-12}; i.e. less than one uncorrectable error during one hour's continuous transmission of 5 Mbps data stream. Such low error rates require robust standards, careful network planning and optimized service operation. Propagation phenomena have a direct (and possibly critical) impact on those three pillars. This paper fills the current gap of a thorough survey on propagation methods and models for broadcasting. We contribute to this field with a description and analysis of propagation phenomena concerning different aspects of the broadcast network planning, broadcast standard evaluation, and broadcast service operation. The paper provides also a technical perspective of state-of-the-art TV broadcast standards and discusses the relevancy of propagation studies with future and development and regulation challenges.

INDEX TERMS Broadcasting, digital terrestrial television, radio propagation.

I. INTRODUCTION

The first broadcasts around the world started in the 1930s with the USA, Germany, and the UK being some of the first countries that started transmissions. In the 1950s TV became the preferred medium for homes, replacing radio and movies in the USA [1]. Analog TV standards such as NTSC (Americas), SECAM (France), and PAL (Europe) were used since then, employing VHF/UHF frequency bands for video and only VHF for audio. The picture information was transmitted using vestigial sideband modulation (VSB) on one channel, whereas audio was transmitted using FM.

Until the late 1990s, digital television broadcasting to the home was thought to be impractical and costly to implement, but once the Digital Video Broadcasting (DVB) alliance was formed in Europe, it was clear that the analog standards had to give way to all-digital technology. In this context, digital satellite and cable broadcasting systems were the first ones to be developed, followed by digital terrestrial television. The first standard was the DVB-S (satellite) in 1993, followed by DVB-C (cable) in 1994. The DVB-T (terrestrial) was more complex since it was intended to cope with noise and multipath. Moreover, it was one of the first commercial wireless systems to use Orthogonal Frequency Division Multiplexing (OFDM) [2].

DVB-T was standardized in 1997 and was not implemented until 2002. In addition to DVB-T, other popular first-generation DTTB standards were: the Integrated Service Digital Broadcasting - Terrestrial (ISDB-T) in Japan and the Philippines; and the Digital Television Multimedia Broadcasting - Terrestrial (DTMB-T) in China. In the decade of 2000, further standards were developed. DVB-H, targeted

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TABLE 1. First generation DTTB standards.

	DVB-T	ISDB-T	ATSC	DTMB
History	Announced by ETSI in 1997, most widely adopted standard (more than 60 countries)	Developed by Japan in May 1999, mainly applied in Japan, Brazil, Peru, and other Central and South American countries	Proposed by the U.S. in September 1995, it has been deployed in the U.S., Canada, Korea, and other five countries	Launched by China in August 2006, has been adopted by Hong Kong, Macao, Laos, Cambodia, and Cuba
Bandwidth	6, 7 and 8 MHz	6, 7 and 8 MHz	6 MHz	6, 7 and 8 MHz
Transmission scheme	COFDM with 2k and 8k FFT size	BST-OFDM with 2k, 4k and 8k FFT size	Single carrier	TDS-OFDM with 3780 FFT size + single carrier
Modulation scheme	QPSK, 16-QAM and 64-QAM	DQPSK, QPSK, 16-QAM and 64-QAM	8-VSB	QPSK, 4-QAM, 16-QAM, 32-QAM and 64-QAM
Supported scenarios	Indoor and outdoor fixed reception, portable and mobile services	Indoor and outdoor fixed reception, portable and mobile services	Mainly outdoor fixed HDTV	Indoor and outdoor fixed reception, portable and mobile services
Data rate	4.98-31.67 Mbps	3.65-23-23 Mbps	19.39 Mbps	4.81-32.49 Mbps
Channel coding	Punctured convolutional codes	1/2, 2/3, 3/4, 5/6, 7/8 +RS (204, 188, t=8)	Rate 2/3 Trellis code + RS (207, 187, t=10)	LDPC(7488,3008/4512/6016) + BCH (752, 762)

for handheld receivers, was standardized in 2004 [3]. Table 1 gathers the first generation standards with wide acceptance during the last three decades [4].

The analog switch-off (ASO) or digital switchover (DSO) started in Europe in 2005. Older analog TV broadcasting standards were replaced by digital counterparts, thus reducing broadcasting costs, increasing the number of available frequencies, and providing improved viewing quality. As a consequence of DSO processes, the spectrum was and continues currently being released for the better efficiency of the digital standards. In addition, there have been technical proposals to enable the so-called white spaces between 50 MHz and 700 MHz - which can therefore be used by other technologies. The free spectrum on both VHF and UHF bands is under consideration for wireless broadband Internet access, especially in rural areas, although part of the lower VHF spectrum has already been pursued by cellular operators, taking advantage of the lower path loss at these frequencies. Afterwards, the second generation of DTTB standards, namely DVB-T2 [5] and ATSC 3.0 [6], were standardized in 2010 and 2018 respectively. These second-generation systems have efficiencies very close to the Shannon limit and are extremely flexible to suit an increasing variety of use cases and business models in broadcasting. These standards have been released with new features and capabilities as shown in Table 2.

In the early days of TV, research in propagation was focused on understanding and characterizing different effects (e.g. wave refraction, earth reflection, diffraction, etc.) that affected the signal quality on a broad scale. The efforts were strongly motivated by the boom in the deployment of TV services to the home occurring around those years [7]–[9]. Later on, with the advent of more processing power, the development of propagation models mainly to estimate point-to-area coverage became popular and propagation curves could be issued for network design; e.g. Okumura-Hata [10], Longley-Rice [11], etc. Models to characterize the most significant propagation effects were also developed, e.g. diffraction, rain attenuation, etc. With the development of the most recent standards that incorporate mobility, Doppler effects and building entry losses had to be incorporated for accurate signal level estimations at the receiver side. Additionally, interference control became essential since newer wireless technologies co-exist in frequencies near those licensed for Digital TV.

To the best of the authors' knowledge, this is the first survey dedicated to radio propagation for TV broadcasting aimed at covering radio aspects affecting terrestrial systems. Other efforts have focused on channel modelling (not for broadcasting), propagation only on certain aspects, such as channel modeling, or only on satellite broadcast networks. The handbook in [12] presents guidance to engineers to implement DTTB including newer digital broadcasting technologies, regulatory and implementation issues, which can be a good starting point for those new to terrestrial broadcasting technologies.

A survey on digital TV broadcasting transmission techniques is presented in [35], where a brief history of TV broadcasting is given followed by a thorough description of first and second-generation standards, emphasizing system aspects (modulation, coding, FFT size, guard intervals, etc.), but not including any propagation aspects. On the other hand, other surveys have focused on propagation effects and models, but not in broadcasting. For example, the authors in [36] provide an extensive review of various methods to predict path loss following empirical, deterministic, or hybrid approaches, including a brief description of propagation effects.

Classical models are included in the survey, some of which have been considered for fixed links and broadcasting until 2013. The work in [37] focuses only on reviewing indoor, narrowband propagation models and effects. Table 3 shows a summary of the most relevant surveys that focus either on radio propagation aspects or on broadcasting. In summary, this paper fills the current gap of a thorough survey on propagation methods for broadcasting. We contribute to this field with a description and analysis of propagation phenomena concerning different aspects of the broadcast network planning, broadcast standard evaluation, and broadcast service operation.

TABLE 2. Next generation DTTB standards.

Standard	Release history	Characteristics	Comments	References
ATSC-M/H	Launched in April 2009 in the U.S.	Specially designed for Mobile/Handheld, backward compatible with ATSC, supports real-time interactive services. It also can provide wireless localization	Most prominent feature was the capability of mobile reception	[13]–[16]
DVB-T2	Launched by ETSI in September 2009 as an extension to DVB-T	Based on DVB-T but not compatible, increased spectral efficiency by more than 30% incorporating cutting-edge signal processing techniques (enhanced OFDM, LDPC/BCH code, transmit diversity, etc.)	High spectral efficiency, reliable performance and flexible configuration.	[5], [16], [17]
ISDB-TMM	Launched in Japan in July 2010 (ISDB for terrestrial multimedia broadcasting)	Highly compatible with ISDB-T, provides a variety of interactive services and multimedia materials (e-books, news, music, etc.) that can be downloaded to mobile handsets at high speed. Variable transmission bandwidth can be supported.	Potential use of MIMO and other higher order modulation schemes to maximize system capacity	[16], [18]
ATSC 2.0	ATSC 2.0 was a new revision of the standard, backward compatible with ATSC 1.0.	Supports connectivity to the Internet. Non-real time and interactive services are also incorporated. It was not rolled out successfully.	Designed to take the TV experience on fixed receivers to the next level	[19]–[21]
ATSC 3.0	First major deployments occurred in South Korea in May 2017.	Flexible and robust transmission system, greater capacity, capacity vs. robustness trade-off, integrated M/H capabilities, flexible bit rate and coverage area, robust indoor and mobile reception, higher spectrum efficiency. The first fully IP-based digital television standard.	Provision of: UHDTV, multicasting for multimedia, 5.1 digital surround sound, electronic program guides, enhanced closed captioning, etc.	[16] [22]–[26]
DTMB-A	Enhanced version called DTMB-Advanced, released in China in 2015.	Higher efficiency than DTMB in terms of noise and interference immunity due to advanced error correction, interleaving and constellation mapping methods. Supports higher bit rates (up to 49.31 Mbps in a 8-MHz channel)	Can work in single and multiple frequency networks	[16] [27] [28]
DVB-NGH	Research began around 2007. Standardization never completed at ETSI level.	Handheld evolution of DVB-T2. First to incorporate MIMO, thus 3^{rd} generation.. Exploits diversity in all dimensions (frequency, time, spatial, etc.). Use of time-frequency slicing (TFS).	Many enhancements over DVB-T and DVB-T2. Not approved for commercial reasons.	[16] [29]–[32]
eMBMS	Evolved Multimedia Broadcast Multicast Service, LTE Release 14 (2016)	Allows point-to-multipoint transmissions via SFN using LTE network, include mobile TV and radio broadcasts as well as emergency alerts. Uses cooperative HPHT and LPLT architectures Receive-only mode that enables free-to-air reception. All channel can be used for broadcast..	Event-TV, Mobile-TV and Fixed-TV scenarios. The 700-MHz band in Europe is planned to allocate these services.	[16], [33]
NR-MBMS	New Radio MBMS, outlined for 5G deployments	Extends 5G NR Rel. 15 and 16 to broadcasting. NR carrier can be used to allocate up to 100% broadcast data in time and frequency. LPLT and HPHT are possible. SFN may be used with a trade-off coverage vs mobility.	Different reception scenarios at high speed and static reception. Higher bandwidth utilization than eMBMS.	[34]

This paper is organized as follows: Section II discusses implementation scenarios typical of broadcasting terrestrial TV networks; Section III presents a summary of propagation effects that are relevant to broadcasting; Section IV describes models used for point-to-area cases; Section V presents wide-band channel models used in broadcasting, and Section VI describes relevant regulatory considerations.

II. ARCHITECTURES AND IMPLEMENTATION SCENARIOS

The ITU established a reference DTTB model depicted in Fig. 1 [12]. The model includes source coding and compression, service multiplex and transport, RF channel coding, modulation, and propagation. On the receiver side, a demodulator, channel decoder, and content decompression are included.

The parameters of DTTB networks in deployment scenarios presented in this section are gathered in Table 4 [12]. Digital broadcast network design and efficient frequency planning involve criteria such as maximum power levels, protection ratios, inter-transmitter distance, transmitting antenna heights, and reception mode. Interference is an important limiting factor. The rapid transition from near-perfect DTTB reception to no reception at all can occur if coverage areas are not protected properly.

A. ARCHITECTURES

1) BASED ON SPECTRUM USAGE

Depending on how frequencies are associated with each transmitter, there are three basic broadcast network architectures. In Single-Frequency Networks (SFN), all transmitters use the same frequency and provide the same content at the same time, which involves tight frequency and time synchronization. The network should be designed to minimize self-interference by using OFDM and Guard Intervals (GI). Echoes from different SFN transmitters as well as multipath will have a minor impact on signal reception quality if they arrive within the guard interval. In Multi-Frequency Networks (MFN), cochannel interference is avoided by assigning different frequencies to each transmitter. In practice, frequencies will be reused at a sufficient distance not to cause unacceptable cochannel interference. MFNs do not require synchronization among the different transmitters. In cases where complete coverage cannot be provided by high-power main stations within an MFN, then lower power repeater

TABLE 3. Surveys related to radio propagation aspects or TV broadcasting.

Field	Remarks	Comments	Year	References
Broadcasting	Transmission techniques for TV broadcasting	Emphasizes on system aspects for TV broadcasting, does not include propagation aspects	2013	[35]
Propagation	Small cells and indoor radio propagation models	Only focuses on indoor propagation	2020	[37]
Propagation	Propagation models for mobile communications	Excellent tutorial paper for general propagation aspects affecting mobile systems, not including fixed links or broadcasting	2003	[38]
Propagation	Models for tunnels and underground environments	Deterministic and empirical approaches for enclosed spaces, not relevant for broadcasting	2013-2014	[39] [40]
Broadcasting	Overview of trends in TV broadcasting technology in Japan, including imaging and display technologies, content production and management	Focused on descriptive analysis rather than highlighting technical aspects. Does not include any propagation sections	2013	[41]
Propagation	Update on path loss prediction methods	Survey on path loss calculation methods for general wireless applications. Does not cover channel modelling and does not include some of the most used path loss calculation methods for point-to-area planning published after 2010.	2013	[36]

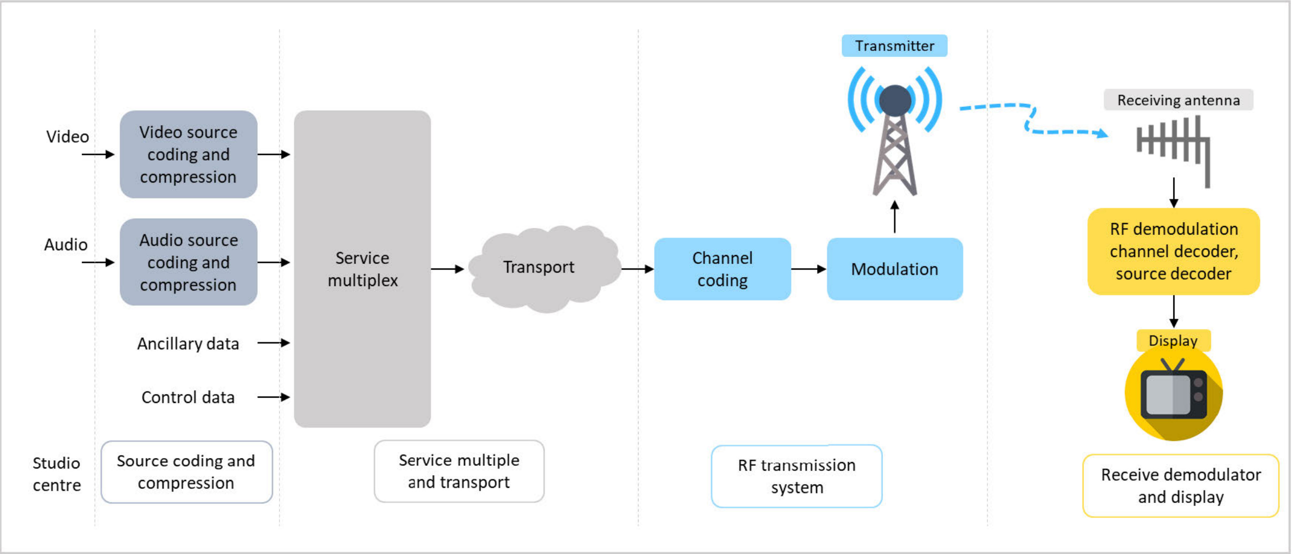

FIGURE 1. Digital TV model, adapted from [12].

stations, also known as gap-fillers, could complete the coverage using the same frequency as the associated main station (part of an SFN) or as separate assignments in an MFN. This is known as a mixed MFN-SFN.

2) BASED ON TRANSMITTER SITE (HPHT VS. LPLT)

In general, there are two main architectures for terrestrial broadcast networks commonly used depending on transmit power levels and transmit antenna heights. The traditional High-Power High-Tower (HPHT) network, which consists of elevated transmitting sites that have Effective Radiated Power (ERP) values in the range of dozens of kW. Transmitting antenna heights typically range from 150m to 300m. These values change amongst network operators and country regulations, but are usually taken as a reference. On the other hand, Low-Power Low-Tower (LPLT) networks have typical transmitting antenna heights of up to 40m and ERP of a few kW. In the literature, there are studies comparing the efficiency of these approaches [42].

B. IMPLEMENTATION SCENARIOS

1) OUTDOOR

The deployment of DTTB networks is not unique and depends on network requirements. From a theoretical perspective, the planning parameter combinations are infinite but in practice, a limited number of cases are defined. Table 5 gives implementation examples for DVB-T2, taken from [12]. Note the flexibility in the selection of parameters depending on the application; for example, if scenario 2 is analyzed, the use of a relatively robust DVB-T2 mode is envisaged.

2) INDOOR

DTTB transmitters are usually located at high elevation sites for wide coverage and are often operated at high EIRPs. Despite those features, the propagation characteristics of signals in an outdoor-to-indoor scenario generate coverage gaps inside buildings, mainly being caused by high building penetration losses. These shadow areas can be covered with

TABLE 4. **Summary of basic parameters for DTTB networks [12].**

Parameter	Description	Classification	Comments
Frequency	Frequency bands allocated for broadcast service	Bands III (VHF), IV and V (UHF). (see Appendix and Table 17 for more details)	Different bands in ITU-R regions 1-3
Coverage area	Area within which the wanted field strength is equal to or exceeds usable field strength defined for certain reception conditions	Level 1 (receiving station) Level 2 (small area coverage) Level 3 (coverage area)	The three-level approach is taken on defining coverage area for a reception condition
Reception modes	Types of reception allowed for the broadcasting network	Fixed rooftop antenna reception Portable for static reception Handheld pedestrian reception Mobile in-vehicle reception	The difference between portable and handheld is determined by the height above ground of the receiving antenna
Assignment planning	A specific channel is assigned to an individual transmitter location with defined transmission characteristics		Examples of such characteristics are radiated power, antenna height, etc.
Allotment planning	A specific channel is given to an administration to provide coverage within a defined area		Transmitter sites and their characteristics are unknown at the planning stage and defined at the time of the conversion of the allotment into one or more assignments
Nuisance field strength	Field strength for 50% of locations and for a given percentage of time of an unwanted (interfering) signal		Receiving antenna directivity and polarization discrimination (dB) should be considered if appropriate. If multiple unwanted signals are present, their power should be added for a composite nuisance field strength
Usable field strength	Minimum value of the wanted field strength required to permit a desired reception quality		The usable field strength is taken in the presence of natural and man-made noise and of interference
Network configurations	Choice of architectures for the transmission infrastructure	MFN, SFN, Mixed MFN-SFN	The choice depends on the availability of frequencies, the type of coverage required, and the number of multiplexes provided
Service types	Types of services offered by the broadcasting network	Fixed Portable class A (outdoor) Portable class B (indoor) Mobile class C (in-vehicle handheld) Mobile class D (vehicle built-in antenna)	The architecture of a broadcast network is a compromise between quality of service (QoS) and associated cost

TABLE 5. **Examples of implementation scenarios for DVB-T2.**

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Description	MFN rooftop reception and transition case	SFN rooftop reception, maximum coverage	SFN rooftop reception, moderate coverage	Portable reception, maximum data rate	Portable reception, maximum coverage area extension	Portable reception, optimal spectrum usage	Mobile reception, 1.7 MHz bandwidth in Band III	Portable and mobile reception, multiple PLP
Applications	Suitable for high-capacity network. Could also be moving from DVB-T to DVB-T2	Intended to maximize coverage in a SFN while providing rooftop reception	Either for replacing a DVB-T SFN or to create a large area DVB-T2 of "unlimited" size	Designed for portable reception and based on a SFN approach (diameter of approx 150km)	DVB-T2 used to extend an existing DVB-T coverage while keeping the DVB-T data rate	DTTB service areas with the same MUX content are covered by one very large SFN	Implementation compliant with DAB frequency block structure. Audio and low bit rate TV services are supported	Joint usage of DVB-T2 multiplex for different services; e.g audio/mobile TV and SD/HDTV
C/N (Rice)	19.7 dB	11.6 dB	20.5 dB (limited SFN) 21.2 dB (large area SFN)	17.8 dB	9.6 dB	18.2 dB	10.0 dB	18.2 dB (TV) 10.0 dB (audio/mobile TV)
Data rate	40.2 Mbps	16.7 Mbps	37 Mbps (limited SFN)	27.7 Mbps	13.1 Mbps	22.6 Mbps	2.5 Mbps	22.4 Mbps (TV) 11.2 Mbps (audio/mobile TV)

low power gap-fillers, where appropriate frequencies can be found in an MFN system to cover small shadow areas. The use of low power and low heights keeps interference minimized. On-channel repeaters are used to receive a terrestrial DTTB transmission at a particular VHF/UHF frequency, amplify the received channel and retransmit it on the same frequency. The purpose is to extend the coverage of an existing network through transmissions on a single frequency without the need for additional transmitters. An example scenario in the use of gap fillers for indoor coverage is presented in [43] for the DVB-H standard for handheld terminals.

3) MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO)

In recent years, the use of MIMO has become popular for increasing significantly the capacity in wireless systems. The gain associated with MIMO is particularly advantageous in rich multipath environments. HDTV, for instance, is viable in ISDB-T if MIMO based 64-QAM is employed [44], [45]. In more harsh scenarios such as SFN, a combination of transmission and reception diversity is recommended to improve system reliability. Large scale MIMO [46] is intended to provide a spectral efficiency up to several tens of bps/Hz or higher, using tens of antennas instead of a small number of elements. In [47] a transmission system was proposed using ultra-multilevel OFDM and dual-polarized MIMO for ISDB-T. QEF (Quasi-error free) operation was obtained using 4096-QAM, a four-element twin-loop transmitting antenna, a dual-polarized Yagi receiving antenna at a frequency of 600 MHz in a 6-MHz channel. Saito *et al.* [48] conducted simulations and field tests to show the viability of broadcasting UHDTV 8K (91 Mbps) terrestrially by using high-order modulation OFDM and dual-polarized MIMO in an SFN over 27km. Using a 4×2 MIMO the received signal was increased by 3dB over that of a conventional SFN. The latest developed DTT standard, namely ATSC 3.0, has also adopted MIMO as an optional tool for providing a higher special efficiency [49]. The theoretical results show that a gain of more than 7 dB can be obtained for the Modified Guildford Model (MGM) channel. In [50], the authors analyze the different pilot patterns for the two MIMO pilot encoding algorithms present in the standard. In [51], the existing three precoding blocks are studied. Considerations such as proper antenna placement for independent MIMO channels, low complexity detection algorithms for practical implementation, and channel estimation of the large-size MIMO channel amongst others are key elements that need to be accounted for if maximum spectral efficiency is desired.

4) DISTRIBUTION OVER CELLULAR NETWORKS

Recently, other approaches have been considered for the distribution of broadcast content over cellular networks. Preliminary efforts were reported in [42] where a study of the delivery of broadcast content and services over the so-called Long-Term Evolution (LTE) networks was carried out in the EBU Project group CTN-Mobile. Another good example of the distribution of video over LTE is reported in [52], where spectral efficiency and flexibility of LTE broadcast are analyzed. In [53], mobile broadband studies that deal with the distribution of linear broadcast contents via cellular mobile broadband networks, in particular, LTE, are presented and discussed for different reception scenarios (fixed, light indoor, in-car, and deep indoor). The authors conclude that LTE LPLT networks with a very high density of base stations have the lowest spectrum consumption, which is considered up to around 5 km of inter-site distance to perform slightly better than HPHT DVB-T2 networks. As this distance is increased, the performance is better in HPHT DVB-T2 networks. The economic aspects of the distribution of TV content via cellular networks are discussed in [54]. Their study concluded that although at the time of the technical review it was not convenient to provide mass TV content over cellular, a converged network capable of transmitting broadcast and unicast content seemed a very attractive proposition, which may be alleviated with the upcoming deployment of 5G networks.

III. PROPAGATION EFFECTS IN BROADCASTING LINKS

The propagation of radio signals in a TV broadcasting system is affected by the interactions of the electromagnetic wave with the propagating medium, causing various sorts of effects that need to be considered in system evaluation, network planning, and broadcast service operation. Changes in velocity, phase, dispersion, signal degradation, etc. can be modelled depending on the occurrence of specific propagation effects. DTTB can suffer from coverage holes caused by propagation characteristics of the frequency bands, terrain obstructions, and man-made clutter. Analogue TV does not require accurate predictions, but digital TV does [55]. Fig. 2, summarizes changes in signal properties for NLOS and terrestrial fixed links.

A. *DIFFRACTION*

Diffraction is an effect in which some energy propagates into the so-called shadow region behind an obstruction, following Huygen's principle [56]. The mean atmospheric refraction of the transmission path needs to be analyzed to evaluate geometrical parameters situated in the vertical plane of the earth, such as the angle of diffraction, radius of curvature, and the height of obstacle. For this purpose, the path profile has to be traced with the appropriate equivalent Earth radius value [57]. In general, diffraction is affected by terrain irregularities.

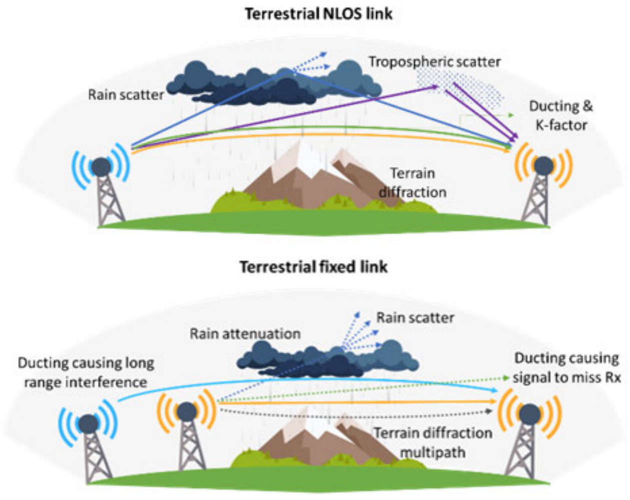

FIGURE 2. **Propagation mechanisms affecting DTTB systems.**

Any obstructions which do not enter the first Fresnel zone (the area around the direct ray where all path contributions are in-phase) will have little effect on the received signal (60% clearance) [56]. Digital TV links are placed in towers at the appropriate height to guarantee the First Fresnel zone clearance. Indoor DTV reception is becoming popular and diffraction on the windows and sharp edges of buildings play an important role in the path propagation phenomena. Furthermore, diffraction is inversely proportional to wavelength, so terrain will have a higher impact at higher frequencies (UHF). The consequence is a larger number of relay stations for digital TV in the UHF band than in VHF [58].

According to [59], the surface of the obstacle has irregularities that can be measured with the value of the parameter $\Delta h = 0.04\sqrt[3]{R\lambda^2}$ where R is the obstacle curvature radius [m] and λ is the wavelength [m], used to define the degree of terrain irregularities and therefore the methods used to calculate diffraction vary. Table 6 shows a summary of the different propagation scenarios in which diffraction may be present, along with the corresponding references and comments on their usage.

B. REFLECTION

When an incident wave impinges upon a surface and depending on its constitutive parameters (permittivity, permeability, and conductivity), a reflected wave is produced and if the reflecting surface is considered smooth according to Rayleigh criterion, specular reflection occurs [56]. There is a special case, which is of particular relevance to broadcasting when a direct ray and a reflected ray are considered to reach the receiver (two-ray case). This is especially critical when specular reflection on buildings occurring at VHF frequencies [58] cause deep fades in the received TV signal. Also, tidal water at estuaries in the path between a broadcast transmitter and a TV receiver may cause specular reflections that create slowly varying deep fades in the UHF band [58]. If a certain degree of roughness is present, rough surface scattering is experienced. Since rough surface scattering depends on wavelength, UHF broadcast signals will be more affected by scattering and therefore the effects of deep fades produced by specular reflections will be less significant than at UHF [58].

C. MULTIPATH

When multiple reflections are present near a TV receiver, the different signal versions are added constructively and destructively, thus producing multipath. At a minimum, it will be expected that a ground reflection component is present. The ground-reflected wave is coherent with the direct wave and causes the received signal to vary with receiver antenna height, but waves reflected from nearby objects have random amplitudes and phases. Even if the receiver is fixed, moving scatterers produce fast fading or deep changes in field strength. In addition, long-distance scatterers can produce large echoes that, in case of delays exceeding the symbol period, create Inter-Symbol Interference (ISI) [73]. Multipath propagation is described by parameters in three categories. For the first category, delay profile, the average delay, rms. delay spread, delay window, delay interval and many multipath components are defined as statistical parameters. For the second category, the direction of arrival, average azimuth or elevation angle, angle of arrival power profile, r.m.s. azimuth or elevation angular spread, azimuth or elevation angle angular window, and the angle interval are specified. Finally, for the last category, received signal variations, the coherent bandwidth, coherent time, level crossing rate, and average fade duration, level crossing frequency, and average fade bandwidth are indicated. Detailed formulas for calculating these parameters can be found in [74] and used to describe the characteristics of multipath propagation affecting a broadcasting signal. The sharp transition from quasi-perfect BER to the perceivable picture and audio artifacts make DTTB systems more sensitive to channel degradation in the presence of fading and multipath distortion – more data bits decoded in error at the receiver [75]. This phenomenon has been referred as ''brick-wall'' behavior of digital systems [76], [77]. Thus, a TV receiver must be able to cope with the signal distortion arising from echoes in the channel as well as with the rapid changes in the nature of this distortion. Such characteristics are described by the power delay profile and the Doppler spectra, both of which can be obtained using wideband channel sounder measurements [74]. The traditional way to minimize the effects of multipath in DTTB systems is by using a directional antenna (Yagi) installed on a rooftop [58].

D. DEPOLARIZATION

In TV broadcasting systems some or all the transmitted energy may be scattered out of the original polarization due to diffraction and reflection of the radio wave, even for cases when the receiver is stationary. A cross-polarization discrimination factor XPD needs to be considered [59]. XPD does not depend on the link distance but increases with decreasing frequency, and is log-normally distributed with a frequency depending standard deviation [78]. Although depolarization effects were much more significant for analogue TV systems, some considerations are required for modern DTV. In [79] the authors report polarization rotation of waves upon reflections on the Es-layer in the ionosphere (i.e., Faraday rotation) in the VHF band. Reflections arriving from the ionosphere Es layer cause serious interferences on DTV services in the VHF broadcasting band, so to design anti-interference systems, polarization information is important to be determined at the receiver. The authors performed a series of measurements at 55.25 MHz establishing links from Seoul to Tokyo using horizontal polarization. Elliptical polarization was observed at the TV receiver station. Previously, another study [80] had analyzed the effect of using circular polarization in environments with changes in polarization upon reflections from buildings and mountains, which indeed pose a rather unpredictable behavior of how reflections will affect polarization.

TABLE 6. Summary of diffraction models and characteristics for propagation work.

Terrain profile	Method	Scenario	Refs.	Description
Smooth	Diffraction over spherical Earth	Diffraction loss for over-the-horizon paths	[60] [61]	Numerical or nomogram calculation. If numerical, the electrical characteristics of the surface of the Earth should be considered.
		Diffraction loss for any distance above 10 MHz	[62]	For over-the-horizon use method described above; for other distance use interpolation based on a notional effective Earth radius.
Isolated obstacles	Diffraction over single knife-edge	Single knife-edge	[56] [60]	Wavelength is small in relation to size of obstacles. Obtain v parameter from geometry. Calculate loss from Fresnel integral solution.
	Diffraction over rounded obstacles	Single rounded obstacle	[60]	Obtain Fresnel-Kirchhoff diffraction loss as for single knife-edge and add attenuation due to curvature of the obstacle.
	Diffraction over multiple knife-edges	Double isolated edges		Apply successive single-knife edge theory with top of the first obstacle acting as a diffraction source.
	Diffraction over multiple isolated cylinders	Multiple cylinders		Each obstruction is treated as a cylinder. Diffraction is obtained as the sum of diffraction losses over the cylinders, diffraction losses between cylinders and adjacent terminals and a correction term to correct for spreading loss for diffraction over successive cylinders.
	Deygout method	Multiple knife-edges	[62]	Designate a main edge with largest v parameter, use it to split the path into sub-paths, obtain new parameters, compute diffraction losses as for single knife-edge case and sum all excess losses.
	Causebrook correction		[63]	Correction for Deygout as it overestimates true path loss with large number of edges. Only the edges that lie above the relative line-of-sight paths are taken into account.
	Bullington method		[64]	The real terrain is reduced to a single equivalent knife-edge at a point at which the extended lines joining the transmitter and receiver to their respective dominant obstacles meet, and diffraction loss is computed using single knife-edge approach.
	Giovanelli method		[65]	A main edge is identified, a reference field point is obtained and diffraction loss is calculated adding the losses from each knife-edge and the field point.
	Multiple-edge diffraction integral		[66]	Powerful method provided that efficient methods of evaluating the integrals are found. The integral is transformed into a series, which is computationally intensive and slow and allows a maximum of 10 knife-edges to be solved.
	Slope-UTD multiple-edge diffraction		[67]	Improves the Vogler method in speed and computational resources. UTD diffraction coefficients are cascaded for multiple diffraction edges.
Rolling terrain	Integral equation	Irregular terrain, multiple hills, exact terrain profile is used	[68] [69]	Full-wave method, calculates field strength over irregular terrain, tested from 145 MHz to 1.9 GHz, sum of current elements from scattered contributions. It is not considered a diffraction method
	Parabolic equation		[70]–[72]	Partial differential wave equation derived from Maxwell's curl equations and taking into account the curvature of Earth. Solution to the PE equation can be discretized using numerical techniques and thus reasonable speed.

E. INDOOR TV RECEPTION AND BUILDING PENETRATION LOSSES (BPL)

One of the main factors affecting indoor DTTB reception is the transmission loss produced by building walls and partitions, windows, etc. In fact, one of the major problems of designing a transmission system for indoor reception is the lack of knowledge of building attenuation and the variation characteristics of indoor TV reception sites [77]. Radio waves that interact with a building will produce losses that depend on the constitutive parameters of the building materials (permittivity, permeability, and conductivity) and material structure. For non-magnetic building walls, conductivity has been reported to increase with frequency whereas relative permittivity remains constant for frequencies around 10 GHz and then starts to decrease [81]. The use of rooftop antennas is declining and indoor reception is becoming more popular. In consequence, the effects of signal penetration need to be accounted for in various ways:

- Building entry loss, where the transmitter is located outside of the building and the receiver is indoors. This building loss is relevant for the path loss component and its dependence on frequency, elevation angle and depth should be considered.
- Internal building losses, where walls and floors have an impact on the received signal strength.
- Shadowing variations, which are especially relevant for cluttered buildings and households.

In other words, two parameters outstand for planning indoor reception: building entry loss (BEL) and the variation of this loss due to different building materials. Works for general-purpose planning and cellular systems planning have recommended values extracted from extensive measurement campaigns. A report on propagation losses into and within buildings was carried out in [82] where an investigation of these losses for 800, 900, 1800, 2100, and 2600 MHz was conducted for Ofcom, including depth, frequency, and

TABLE 7. Building entry loss for point-to-area applications below 3 GHz.

Frequency [MHz]	Median value [dB]	Standard deviation [dB]
200	9	3
600	11	6
1500	11	6

building type and geometry dependencies. Subsequently, in [83] a study was conducted on behalf of Ofcom to extract building entry loss values and their relationship with building materials and frequency (measurements at 88, 217, 698, 2410, and 5760 MHz). There are numerous studies on building entry and material losses at various frequencies and scenarios [81], [83]. A comparative analysis of all the values available shows inconsistencies and unveils the limited reliable information available. Table 7 shows the ITU-R recommended for point-to-area systems below 3 GHz [84]. The literature provides a significant amount of building loss sources. Nevertheless, most recent publications focus on bands above UHF and mm-wave frequencies. Only a few campaigns reported VHF/UHF data applicable to DTTB [85]–[87]. The specific room geometry and clutter have a significant effect on signal propagation. In [77] measurements were conducted in the UHF band, at 762 MHz for a 7-MHz OFDM signal used in DTTB. The building penetration loss for 90% of the buildings was reported to be below 15 dB, and a decrease in height of an outdoor receiving antenna will produce a decrease in signal strength due to building transmission loss. A BPL of 5 dB to 9 dB is reported, depending on the floor level.

F. ATTENUATION IN VEGETATION

In the case of vegetation present in a broadcasting TV link and more specifically trees, there will be significant penetration losses, which will depend strongly on the frequency and on the types of trees. Due to the characteristics of foliage, random distribution of branches, leaves, etc. the involved physical processes in the propagation of radio waves is rather complex so approximate and empirical modelling approaches are used in practice. The simplest way to account for propagation through trees is to estimate the length of the path which passes through the them and to multiply this length by an appropriate value for the specific attenuation in decibels per meter [88]. Note that the specific attenuation depends strongly on the frequency and to a lesser extent on the polarization, with vertical polarization being more heavily attenuated due to the presence of vertical tree trunks. To an even lesser extent, the attenuation is increased by the presence of leaves on the trees. A summary of the studied propagation methods for the attenuation in the vegetation is shown in Table 8.

G. TROPOSPHERIC REFRACTION AND DUCTING

This effect typically occurs in unusual atmospheric conditions associated with a temperature inversion and sub-refractive conditions. The refractive index gradient may be high enough so a ray launched from the transmitter with a large elevation angle may return to the receiver, when it would normally be lost into space (see Fig. 3). In hot climates, and over the sea, ducting conditions may be present almost continuously. In temperate climates, ducting usually occurs at sunset. Also, trans-horizon propagation is possible over mixed land-sea paths [38] and can be a source of interference for TV broadcasts [97]. Attempts to model ducting effects on VHF/UHF are presented in [98]. Note that tropospheric refraction can cause time variability in VHF/UHF signals due to the changes in refractivity in the atmosphere, with diurnal or seasonal variations [59].The tropospheric effects defined above can cause serious interference problems for digital TV and pose a challenge for country frequency coordination, especially in coastal regions around a common sea area. A study reported in [99] described abnormal propagation causing severe interference effects in links between India and Sri Lanka over mixed land-sea paths in the VHF band, where propagation was mainly due to scattering, reflections and ducting, recording observed values of 10 dB below free-space loss. Finally, a recent work [100] investigated the distribution of refractivity its and impact on VHF/UHF propagation in the first km of the English Channel for oversea propagation. The study concluded that the evaporation duct height is the main factor to evaluate how refractivity is affecting communication. Finally, the trapping of a signal in a duct does not only depend on the frequency of the propagating wave but also on the incidence angle of the interfering source.

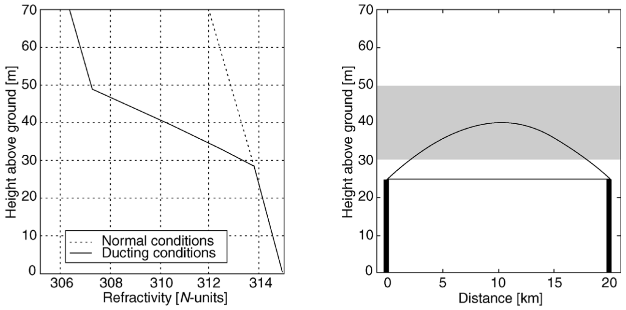

FIGURE 3. Example refractivity profile and two corresponding ray paths during ducting conditions.

H. TRANSEQUATORIAL PROPAGATION (TEP)

This type of propagation is sometimes experienced when transmitting across the equator. It was first noticed in the late 1940s by the military in frequencies of around 60 MHz. It is thought that TEP is linked to increasing levels of ionization in equatorial regions. Ionization enables signals that enter the ionosphere at the correct angle to be propagated across the equator. Signals should enter the ionosphere in a North-South direction, undergoing two reflections by the ionosphere before returning to Earth. This is known as afternoon TEP and typically occurs between 3 pm and 7 pm local time, having a maximum usable frequency of up to 60 MHz. This case produces strong signals with limited fading and distortion. Typical path lengths will be in the order of 5000 to 6500 km. Signals propagated using this mode tend to suffer

TABLE 8. Propagation in vegetation.

Model	Classification	Refs.	Characteristics	Frequency range
ITU-R woodland exponential model	Empirical	[88]	Takes specific attenuation from measurements and multiplies it by path length	30 MHz to 30 GHz using variations and different techniques indicated in Annex 1 of the reference
Exponential decay model	Empirical	[89]	Specific attenuation as a function of path length and frequency	200 MHz to 95 GHz
Modified exponential decay model	Empirical	[90]	Ray path is blocked with dense, dry, in-leaf trees found in temperate climates. Propagation is likely to occur through a grove of trees rather than by diffraction over treetop	230 MHz to 95 GHz
COST 235 model	Empirical	[91]	Based on mm-wave measurements performed over two seasons to consider out-of-leaf and in-leaf foliage scenarios	200 MHz to 95 GHz
Fitted ITU-R model	Empirical	[92]	Modified ITU-R woodland model for out-of-leaf and in-leaf scenarios	200 MHz to 95 GHz
Meng integrated model	Empirical	[93]	Combines foliage induced effect and ground effect, for near ground path loss model using an optimized plane earth model	240 MHz to 700 MHz
Four-layered forest model	Deterministic	[94] [95] [96]	Layered representation of vegetation using a four-layered forest model. Lateral wave at long distances. At short distances edge of forest is a source of diffraction	200 MHz to 3 GHz

some multipath distortion. A slightly different type of TEP seems to occur between 7pm and 11pm, and thus it is often called evening TEP. It is believed to arise from some form of equatorial spread F effect. When spread F occurs, this region of the ionosphere appears to break up into a number of bubbles of ionization, which support propagation via some form of field guided mode. When using this mode of TEP, the signals are subject to fast fading, considerable Doppler shifts, and significant distortion. Path lengths are usually between 3000 and 8000 km and support communication on frequencies up to about 450 MHz.

I. DOPPLER EFFECT

The Doppler Effect results in a change of the apparent frequency of the arriving wave, as observed by a mobile receiver, by a factor proportional to the component of the mobile speed in the direction of the wave. If the mobile is moving towards the source of the wave, the apparent frequency is increased, the apparent frequency decreases for motion away from the source. The various signal components can be Doppler shifted by the movement of the receiver or of reflecting objects such as vehicles, people, etc. When multipath propagation occurs, waves arrive in several directions, each of which has its own associated Doppler frequency. The bandwidth of the received signal is, therefore, spread relative to its transmitted bandwidth, and this phenomenon is known as Doppler Spread. Since speed determines the amount of Doppler Shift of the incoming radio wave, this effect is more noticeable in wireless systems on board of high-speed trains, cars, and low-earth orbit (LEO) satellites. The Doppler spread is associated to the average duration of fading and temporal variations in the channel can be modelled using the Doppler spectrum of the signal. The effects of Doppler spread in received DTV signals have been analyzed and modelled throughout the years. In [3] the degradation caused by Doppler for high-speed DVB-H receivers is described. Doppler spread severely affects the quality of the link as the receiver speed is increased and orthogonality of the sub-carriers is destroyed due to these temporal channel variations over one OFDM symbol duration [101]–[103]. Methods to reduce the impact of the Doppler effect in DTV systems are presented in [104]–[106]. Recently, it has been proved that Doppler is not critical if the operational SNR is low [107].

J. NOISE EFFECTS

The type and level of noise are the key factor that contribute to the performance of a radio link. Two types of sources for noise are attributed: receiver noise or internal noise due to the radio system itself, and environmental noise or external noise from sources outside the radio system. In [108], antenna noise figure information is provided for systems operating from 0.1 Hz to 100 GHz. Three types of environmental noise are considered: atmospheric, galactic, and man-made noise. For the frequency range at which DTV systems operate, atmospheric noise can be considered negligible. Man-made noise is greatest in urban environments and least in quiet rural environments, whereas galactic noise is about 5 to 10 dB greater than quiet rural noise. The levels for radio (including man-made) noise are usually taken from [[108], where most of the reported levels were based on measurements taken in the 1960s and 1970s. Man-made noise can be either gaussian or impulsive. For the latter, class A (narrowband) and class B (wideband) are identified [109]. Impulsive noise occurs typically in urban and suburban areas, whereas the gaussian occurs mostly in rural areas. In order to characterize the effects of noise in VHF and UHF, several studies have been conducted. Some have been associated with the study of white spaces and hidden node margins, such as those in [110], [111]. These studies have shown that man-made noise levels can be remarkable in urban scenarios, whereas negligible in the rest of the cases. In particular, the impact of man-made noise on DVB-T and DVB-T2 has been assessed in [112], where it is shown that

TABLE 9. Summary of DTV terrestrial propagation effects.

Propagation effect	Frequency	Characteristics	Effects on DTV
Diffraction	Low frequencies diffract more efficiently; e.g. VHF is more efficient than UHF	Caused by sharp edges and terrain irregularities, allows radio signals to travel over and around obstacles	Can be beneficial to illuminate shadow coverage regions especially indoor or affect link performance if causing diffraction loss on a DTV link
Specular reflection	Present at low frequencies, VHF and UHF	Depend on constitutive parameters of walls and obstructions and angle of incidence on 'smooth' surfaces	Multiple reflections in the vicinity of the TV receiver can cause multipath and delays that potentially set up an upper limit in data rates
Rough surface scattering	Surface irregularities more noticeable on high frequency links, above UHF	Scattered energy due to surface 'roughness' in addition to specular reflection	Negligible for most practical walls and obstructions at VHF/UHF
Multipath	Present at all frequencies of interest for DTV	Produced by constructive and destructive versions of the signal due to multiple reflections. More significant in the vicinity of the receiver	Fast fading even for stationary paths. If long distance scatterers are present, maximum data rates are constrained due to ISI
Depolarization	Depends on frequency according to [78]	A transmitted radio wave is depolarized after reflections, diffraction and refraction, thus arriving to the receiver with a different polarization	A depolarization mismatch loss is produced on receive antennas
Building penetration loss	Tendency shows that penetration loss increases with frequency being more significant for UHF than for VHF or low frequency	Due to the constitutive parameters of walls, windows and building materials the radio wave undergoes a refraction effect that generates loss	Modern DTV receive antennas are located inside buildings, thus more losses are expected, and the installation of signal repeaters may be necessary
Attenuation in vegetation	More severe for high frequencies; relevant at UHF, less important for VHF and low frequencies	Trees, leaves, branches and foliage in general cause the radio waves to diffract and scatter, thus generating an excess loss	Trees are often located nearby households, which obstruct TV signals causing scattering and losses to the received signal
Ducting	Present in all frequencies of interest to DTV	Changes in refractive index in the troposphere and especially over the sea (evaporation ducts) cause the signal to be reflected as if it were travelling on a waveguide. Often occurs with changes in temperature and humidity	In places near the sea, some TV broadcasting stations can suffer interference from remote stations that are propagated through ducting
Transequatorial propagation	Up to 60 MHz for afternoon TEP and up to 450 MHz for evening TEP	Changes in refractive index at the ionosphere causing ray bending and traveling distances of around 5000 km near the equator	Signals are distorted if propagated through TEP, some can cause interference to other systems, although seen occasionally on evening TEP

the VHF band suffers significantly higher levels of man-made noise compared to those in the UHF band. A detailed compilation of measurements and results of man-made noise is shown in [109]. Since all modern DTTB standards are based on multi-carrier OFDM, impulsive noise greatly affects its performance and therefore several studies were made to assess the impact. In [112] some tests were performed under controlled conditions to simulate switch-on and switch-off events similar to impulsive noise for DVB-T systems, using mitigation techniques such as blanking nonlinearity in the VHF band. The effects of impulsive noise for horizontal and vertical polarization UHF signal is presented in [113], showing some degree of correlation between the amplitudes of both polarizations. Other techniques to mitigate impulsive noise are explored in [114], such as the use of orthogonal polarization for DVB-T signals based on the correlation results shown in [113]. Other recent works performed at UHF to measure and evaluate the effects of impulsive noise are presented in [115], [116]. Some standards, such as the Chinese DTTB include pseudo-noise sequences on the pre-amble sections of the physical layer frame in order to counteract the impact of impulsive noise [117]. Eventually, Table 9 shows a summary of the different propagation effects in broadcasting links.

IV. POINT-TO-AREA PREDICTION METHODS

Terrestrial broadcast network planning is a complex task. The design of broadcasting networks involves frequency management aspects and databases with equipment-related information; accurate knowledge of terrain data where the system is to be deployed; and detailed information on the distribution of the population inside the service area. In addition, the nature of the propagation model in use will be of paramount importance for realistic predictions and efficient and precise network dimensioning. This section surveys the most widely accepted point-to-area propagation models for broadcast network planning. The background of each model is different; some of them are empirical, some others deterministic, and others make use of a combination of empirical and deterministic components. A classification of propagation models is displayed in Fig. 4. In most planning activities related to terrestrial broadcasting, the most common prediction methods belong to the group of empirical models. The motivation is twofold. On the one hand, the usual service area and the transmitter and receiver effective antenna heights are not compatible with deterministic and some semi-empirical methods. On the other hand, the tradeoff between prediction error, required terrain height accuracy, clutter database granularity, and calculation complexity favors empirical [118].

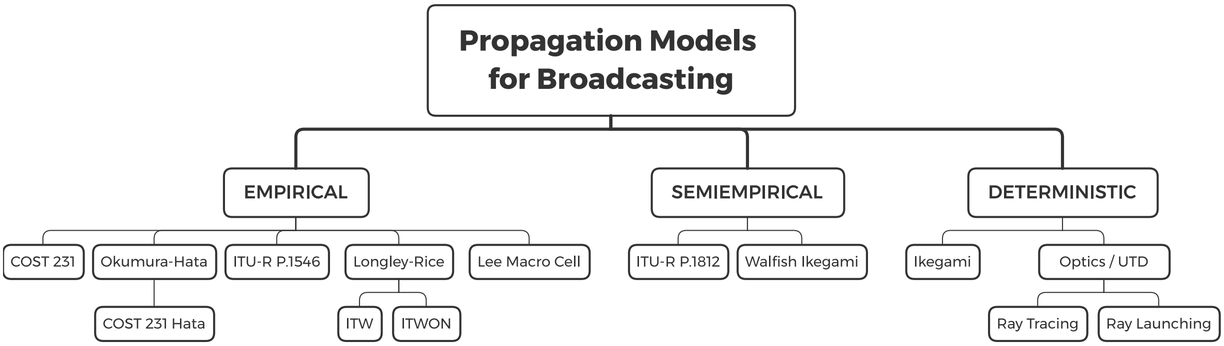

FIGURE 4. Path loss models used in broadcasting.

Finally, broadcasting planning requires spectrum use coordination, essential in having a worldwide agreement on certain prediction tools.

A. EMPIRICAL

1) ITU-R P.1546

The ITU Recommendation ITU-R P.1546 [119] describes a point-to-area field-strength calculation method in the range of 30 to 4000 MHz. The method estimates the path attenuation associated with any tropospheric radio circuit part of a terrestrial radiocommunication service. It provides results for land, sea, or mixed land-sea paths under certain distance and effective antenna height (h_{eff}) limitations (paths up to 1000 km and h_{eff} values up to 3000 m). The method is based on interpolation and extrapolation from empirically derived field-strength curves. The curves represent the relationship between link distance, transmitter antenna height, frequency and percentage of the time. The propagation curves were obtained from measurements carried out in temperate climate regions (mostly Europe and North America) that include cold (North Sea) and warm (Mediterranean) seas. It is important to note that this recommendation does not differentiate between horizontal and vertical polarization. The calculation procedure includes corrections to the results obtained from the curves that account for terrain clearance and terminal clutter obstructions. The P.1546 model is extensively used for field strength prediction required for terrestrial broadcast coverage estimation. The frequencies covered by the recommendation, as well as the prediction ranges perfectly fit the usual requirements for broadcast service area dimensioning: UHF bands and target service over dozens of km around a transmitter, mainly on land paths. Table 10 summarizes the application ranges of ITU-R P.1546 model and other point-to-area prediction models. This recommendation is also applicable to interference and coordination procedures. Broadcast systems should be protected during 99% of the time, and thus 1% field estimation curves are required for interference calculations. In addition, the recommendation provides results for long-distance (up to 1000 km) paths and curves for estimating values in paths over the sea (including mixed sea/land paths), typical cases of long-distance interference situations.

Unlike other propagation methods, this recommendation does not necessarily require terrain elevation databases. In consequence, it is very useful in cases where terrain elevation data is either not available or inaccurate. The current version in force of ITU-R P.1546 is version 6, updated in 2019. The P.1546 was first released in 2001 and the evolution of different versions has been associated with new calculation procedures related to the effective height of transmitting antenna, the terrain clearance angle (TCA), the receiver antenna height, as well as other aspects such as mixed paths [120]. The latest updates to the prediction are related to short-range predictions (less than 1 km), clutter shielding the transmitting antenna, and other corrections associated with short path predictions that usually do not have an impact on broadcast service planning calculations. The recommendation proposes a list of input parameters and associated limits. Table 11 highlights the relevant information for broadcast applications (land paths with distances longer than 1 km).The ITU-R P.1546 recommendation requires frequency, path distance, antenna height, and target percentage of time as basic input parameters. If terrain data are available, the transmitter antenna height needs to be corrected considering the average terrain height around the transmitter location. The method contains field-strength curves for specific discrete values of frequencies, effective transmitter antenna heights, path type (land, sea, mixed), and target percentages of time. If the transmitter coverage under study matches the frequency, transmitter antenna height and time percentage values of the curves, a value for reference field strength is obtained directly from the curves. Otherwise, the recommendation provides interpolation procedures and correction formulas to provide the resulting field strength value. This field strength is normalized to a transmitter Equivalent Isotropic Radiated Power (EIRP) of 1 KW and in consequence, the value obtained needs to be adjusted to the real equipment installed on the broadcast site. Once the reference field strength value is obtained, the addition of a list of potential corrections should be evaluated. Those corrections include factors related to the receiver antenna height to

TABLE 10. Point-to-area models application range.

Model		Frequency (MHz)	Range (km)	Tx height (m)	Rx height (m)
ITU-R P.1546		300-400	1-1000	Up to 3000	>1 m (land),>3 m (sea paths)
Longley-Rice ITM		20-20000	1-2000	0.5-3000	-
ITU-R P.812		30-300	0.25-3000	Upto 300	-
Okumura Model	Okumura	150, 450, 900 1500	1-100	30-100	1-3
	Hata	150-1500	1-20	30-200	1-10
	ITU-R Rec P.529	150-1500	1-100	30-200	1.5
	Davidson	-	-	Up to 2500	-
	COST 231-Hata	1500 - 2000	1-20	30-200	1-10

account for the receiver environment and surrounding clutter height (dense urban, urban, and suburban/rural). Other potential corrections depending upon the TCA, non-standard location variability targets, clutter near the transmitter antenna, and tropospheric scattering should be applied to the reference field strength. These corrections would not apply to most coverage estimations but might be useful in service areas with challenging terrain configurations and suboptimal transmitter locations. In special cases where the service area or where the link associated with an interference problem is a mixed land and sea path, the recommendation describes a special procedure to combine two field strength values, obtained as if the entire path was sea and land respectively. The combination takes into account the weight of each path on the total link distance and it is based on the proposed method of the GE06 [118]. Regarding scientific references, there is a multitude of papers comparing simulations and measurements [120]–[123]. Recent studies based on versions 4 [124] and 5 of the recommendation [125] confirm that the standard deviation of the prediction error remains below 15 dB [120], which is the traditional industry practice value for empirical methods. According to Kasampalis *et al.* [125], if the link distance is shorter than 50 km, the error remains below 5 dB. This result is also confirmed by Lee *et al.* [126]. Many other studies focus on the influence of very specific cases and factors to study the difference between measurements and predictions. These factors include the impact of vegetation attenuation [127], polarization [128], trans-horizon mixed paths [129] and rural [130] vs. urban propagation [131].

TABLE 11. ITU-R P.1546 input parameters.

Parameter	Units	Definition	Limits
f	MHz	Operating frequency	30-3000 MHz
d	km	Horizontal path length	< 1000 km
p	%	Percentage of time	1-50%
h_1	m	Transmitter antenna height	< 3000 m
h_a	m	Transmitter antenna height above ground	> 1
h_b	m	Effective Antenna Height of transmitter	None
h_2	m	Receiver antenna height above ground.	$1 < h_2 < 3000$
R_1	m	Clutter height around transmitter	None
R_2	m	Clutter height around receiver	None
θ_{tca}	degrees	Terrain clearance angle (TCA)	0.55° to 40°
θ_{eff} θ_{eff1} θ_{eff2}	degrees	Transmitter Effective TCA	> 0°

2) NTIA LONGLEY-RICE MODEL AND DERIVATIONS

The Longley-Rice method, officially referred to as Institute for Telecommunication Sciences Irregular Terrain Model (ITS-ITM), is an evolved version of the model developed by Anita Longley and Phil Rice from the National Telecommunications and Information Administration (NTIA) in 1968 for different services operating mostly in the VHF band [11]. This may be the most widely known general-purpose path loss model [132] and it is included in practically all network planning tools. Longley Rice calculations are based on electromagnetic theory principles such as diffraction and refraction effects, including possible variations associated with different climates. The method is similar to the ITU-R recommendation P.452 [133] and the overall path loss contemplates several components: free space loss, knife-edge loss, losses caused by the earth‘s curvature and tropospheric scatter losses. The Longley-Rice model is used in broadcast applications for point-to-area coverage predictions as well as point-to-point and point-to-area interference calculations. This method is the reference model in North America and its use is mandatory in reporting, service area protection/interferences, frequency assignment and other regulatory matters [73], [74]. The method was originally designed for the classical use case of a high-power transmitter located on a dominant site over a large coverage area. Table 10 summarizes the application ranges of the Longley-Rice ITM method. After an intensive use during several decades, some authors have identified various limitations of the ITM method [134], [135]. The model was designed to work with terrain data granularities much higher than the currently available 1/10 arcsecond databases, and in consequence, profile geometry calculations, terrain irregularity factors, obstacle identification, profile averaging do not improve with higher terrain accuracy. In addition, the approximations used for diffraction, including multiple obstacles, obstacles close to the transmitter in the line-of-sight range is a known source of errors. The first version of the model is described in the already famous Technical Note 101 (vols. 1 and 2) [136] that was later translated into a computer model [137], which evolved up to version 1.2.2 (1985) by Hufford [138]. The current version of the ITM has not undergone major changes, but several

TABLE 12. **ITM Longley-Rice input parameters.**

Parameter	Units	Definition	Limits
f	MHz	Operating frequency	20-20000
d	km	Horizontal path length	1-2000
p	%	Percentage time	0.1-99.9%
h_1	m	Transmitter antenna height	< 3000
h_a	m	Transmitter antenna height above ground	> 0.5
h_b	m	Effective Antenna Height of transmitter	None
h_2	m	Receiver antenna height above ground.	$0.5 < h_2 < 3000$
Δh	m	Terrain Irregularity	0-500
N_s	N-units	Mean Surface Refractivity	ITU-R Rec. P.527
$\sigma - \epsilon_r$	mho/m	Ground Constants (conductivity/permittivity)	Function of the surface type (tables available)

inconsistencies and improvement areas have been identified already. The ITWOM (Irregular Terrain with Obstructions Model), includes clutter corrections as well as modifications on the attenuation associated to the early diffraction range [135], [139], [140]. Table 12 highlights relevant information in the use of the Longley-Rice model for broadcast applications (land paths with distances longer than 1 km). The terrain irregularity and ground constants are usually given in categories associated to generic types of terrain and climate selected by the planning engineer. If specific values are available or can be calculated, accuracy will be improved. The path loss calculation is based on evaluating the excess attenuation ($A_r ef$) relative to the free space component. The excess attenuation is a continuous function calculated using different propagation methods on three distance regions: line-of-sight, diffraction, and scatter. The line-of-sight region is based on the two-ray optics model. The diffraction range calculation is a composed weighted average to estimate diffraction attenuation over a double knife-edge and irregular terrain. Finally, at greater distances, well beyond the radio horizon, the dominant propagation mode is usually forward scattered, and the attenuation calculations are based on the model proposed by the same authors in the famous TN101 [136]. There have been numerous studies to evaluate the accuracy of the ITM algorithm. The standard deviation of the prediction error ranges published vary from 4 to 15 dB, depending on the profile types, frequency and distance range. The maximum values are in line with other general-purpose methods like ITU-R P.1546 and ITU-R P.1812. In addition, efforts to improve the method have proved beneficial [135], [140] but (ITWOM) not for all the application frequency and range [141].

3) OKUMURA-HATA AND DERIVATIONS

Amongst the most used point to area propagation, prediction methods in Low Power Low Tower LPLT broadcast applications are any of the versions of the Okumura-Hata model family. The original Okumura's method [10] was based on propagation curves obtained from an extensive series of measurements carried out in Japan in frequencies between 200 MHz and 2 GHz. Okumura obtained curves as a function of the path distance, frequency, transmitter height, and environment. This model was translated into an empirical formula by Hata [142]. Hata's analytical expression depends on the environment, antenna heights, and frequency. The model was also revisited by COST 231 action (European Union funded research) in order to extend the original Okumura-Hata analytical model to the input parameter ranges required by the cellular communications industry [143], [144]. In addition, there is also a version of the model standardized in 1997 by the ITU-R on Recommendation P.529 [145] and later superseded in 2001. Table 10 provides a summary of the input parameter ranges and applicability of the Okumura family models. Models evolved from Okumura have been extensively used in planning land mobile systems in cases where accurate terrain and clutter data are not available. The simplicity of the calculations involved makes them good candidates to be used in preliminary network dimensioning when the target involves large service areas. In addition, the accuracy of these methods in rural and scarcely populated suburban environments is similar to reference ITU-R P.1546 and P.1812 models when the service area is small (< 20 km). Input parameter ranges limit the application in terrestrial broadcasting to mostly mobile and portable services and LPLT networks [146]–[150], which to date is still far from being a commercial deployment use case. Only in certain specific planning exercises, linked to small gap fillers mounted on low height masts in rural environments, and targeting very small service areas, Okumura-Hata and derivations can be considered realistic planning tools. Okumura-Hata and derivations rely on a path loss prediction analytical expression that depends on frequency, transmitter antenna height (usually referred to as base station height), receiver height, and path distance. The Okumura family expressions include coefficients whose values depend on the application environment, namely Open, Suburban, and Urban Areas. As an illustration example, the path loss in Urban Areas is calculated using Eq. (1):

$$
\begin{aligned}
L_{urban} = C_k + C_F \log(f) + C_{ht} \log(h_b) - a(h_m) \\
+ (44.9 - 6.55 \log(h_t)) \log(d^b) \qquad (1)
\end{aligned}
$$

where L_{urban} is the path loss (dB), f is the frequency (MHz), h_b is the transmitter effective antenna height (m), h_m is the receiver antenna height (m), b is 1 except for distances higher than 20 km [145] and the rest of parameters are coefficients calculated as shown in Table 13.

Okumura's predictions have been found useful in many cases [93], particularly in suburban areas. The accuracy of this family of models is similar to other semi-empirical methods like Longley-Rice [151], [152]. However, other measurements have been in disagreement with these predictions; the reasons for this error are often cited as the difference in the characteristics of the area under test with Tokyo, where the original measurements were conducted. Other authors such

TABLE 13. Coefficients in Okumura-Hata models (dB).

Okumura-Hata		COST 231-Hata	
$f < 1500MHz$		$1500MHz < f < 2GHz$	
$h_t \leq 200$ m	$h_t \geq 200$ m	$h_t \leq 200$ m	$h_t \geq 200$ m
$C_k = 69.95$	$C_k = 92.93$	$C_k = 43.3$	$C_k = 67.63$
$C_f = 26.16$	$C_f = 26.16$	$C_f = 33.9$	$C_f = 33.9$
$C_{HT} = 13.82$	$C_{HT} = 23.5$	$C_{HT} = 13.82$	$C_{HT} = 23.5$

as [153] have attempted to modify Okumura's method to include a measure of building density. Other approaches have modified correction factors using new sets of measurements in different countries [154]–[158]. None of the new proposals after COST 231-Hata corrections have found common acceptance.

B. SEMI-IMPIRICAL

1) ITU-R P. 1812

The ITU Recommendation ITU-R P.1812 [159] describes a point-to-area field strength prediction method that covers the same frequency range as ITU-R P.1546 (i.e. 30 to 3000 MHz). The method provides field strength values at the median of the multipath distribution exceeded for a given percentage of time, p (%), in the range $1\% \leq p \leq 50\%$ and a given percentage of locations, p_L, in the range $1\% \leq p_L \leq 99\%$. The method is based on a detailed analysis of the transmitter-receiver path profile and, in consequence, can be used to predict both service area and availability for the desired signal level (coverage), as well as the reductions in service area and availability, originated by interference. Recommendation P.1812 provides results for land paths under certain distance and effective antenna height h_{eff} limitations (paths up to 3000 km and h_{eff} values up to 3000 m). The ITU-R P.1842 is appropriate for accurate field strength prediction required for terrestrial broadcast coverage estimation in cases where detailed terrain information is available. Similar to ITU-R P.1546, this recommendation perfectly fits the usual requirements for broadcast service area dimensioning. The applicable frequency range, coverage percentage, antenna heights, and distance ranges are practically the same as those from P.1546. A specific feature of P.1812, associated with the calculation model for troposcatter propagation [160] is that it is suited for low gain antennas. Table 10 summarizes the application ranges of ITU-R P.1812. In principle, this recommendation does not impose restrictions on the receiver antenna height, but for coherence purposes, as this recommendation is complementary to ITU-R P.1546, one could expect the same specification as the latter. The P.1812 provides a deeper consideration of potential propagation phenomena and it will provide more accurate path loss results in some specific links. In consequence, ITU-R states that P.1812 should be used for the detailed evaluation of point-to-area signal levels. The current version in force of ITU-R P.1812 is version 5, updated in 2019. The recommendation proposes a list of input parameters and associated limits. Table 14 highlights the relevant information for broadcast applications (land paths with distances longer than 0.25 km). The prediction procedure requires two radio-meteorological parameters to describe the variability of atmospheric refractivity: sea-level surface refractivity, used by the tropo-scattering model, and the average radio-refractive index lapse-rate through the lowest 1 km of the atmosphere. In addition, for higher accuracy, it is desirable to have information on the ground cover (clutter) along the path. This prediction model considers only a few propagation mechanisms and provides a calculation model for the contribution of each phenomenon to the overall path loss. The method includes the basic line of sight scenario as well as a diffraction component embracing smooth-Earth, irregular terrain and sub-path cases. These diffraction calculations are based on the Deygout method limited to a maximum of three obstacles [60], [62], [161]. Tropospheric scatter is also considered, and the model is based on low gain antennas. However, the change in accuracy when high-gain antennas are used is small (40 dBi antennas at both ends of the link creates an overestimation of only about 1 dB). Anomalous propagation impact is also modeled on the calculation method, including ducting and layer reflection/refraction. Finally, clutter and the associated height-gain variation are also considered. The method is complemented with Recommendation ITU-R P.2040 to add building penetration losses in those cases where one of the links ends is located indoors. As in the case of ITU-R P.1546 field strength is normalized to a transmitter Equivalent Isotropic Radiated Power (EIRP) of 1 KW and in consequence, the value obtained needs to be adjusted to the real equipment installed on the broadcast site. Accounting for terrain obstacles does not always provide better statistical results in point-to-area prediction statistical behavior. ITU-R P. 1812 is not an exception, and the studies available do not show remarkable accuracy differences with ITU-R P.1546, with standard deviation values of the prediction error as high as 11 dB [124], [162] that in some cases reduces to 5.5 dB provided a rural scenario with short paths [124].

2) COST-231 WALFISCH-IKEGAMI

The Okumura family models present poor estimation error performance in dense urban environments. As an alternative, the COST 231 Walfisch-Ikegami (COST231-WI) Model [144] provides a better tool to estimate the field strength in urban service areas with LPLT transmitters. The model is based on studies by Ikegami [163], [164]. These models consider the transmitter-receiver path obstructed by a series of parallel diffraction edges (buildings) plus a scattering component (rooftop of last building) to predict average signal strength at street level. The urban propagation loss is a sum of three terms: free space losses, rooftop to street losses, and multiple diffraction losses. This method is recommended exclusively for predicting DTV coverage to mobile and portable receivers at street level if the service is being broadcasted by LPLT antennas installed above the rooftop level. The method considers a statistical distribution model of buildings and no topographical database of the buildings is considered. In addition, the model does not contemplate

TABLE 14. ITU-R P. 1812 recommendation input parameters.

Parameter	Units	Definition	Limits
f	GHz	Frequency	30-3000 MHz
p	%	Percentage of average year for which the calculated signal level is exceeded	< 1000 km
p_l	%	Percentage of locations for which the calculated signal level is exceeded	1-99%
φ_t, φ_r	degrees	Latitude of transmitter, receiver	-80, 80 degrees
ψ_t, ψ_r	degrees	Longitude of transmitter, receiver (positive = East of Greenwich)	-180,180 degrees
h_{tg}, h_{rg}	m	Antenna center height above ground level	1-3000 m
Polarization		Signal polarization, e.g. vertical or horizontal	$1 < h_2 < 3000$
w_s	m	Width of street. The value of 27 should be used unless specific local values are available.	1-100 m

the fact that multipath reliability will decrease in irregular terrain. The maximum range of the COST231-WI is 5 km. The expected service area and the transmitter effective height of this method are applicable to an eMBMS network [165], [166]. It should be noted that this method is recommended for frequencies starting at 800 MHz and in consequence, it can be used only at the upper part of the UHF band. A detailed explanation of the application and associated calculations can be found in [143]. The studies in the COST 231 project demonstrated that the method matches measurements for base station antenna heights above the rooftop level (standard deviations of the estimation error below 8 dB [167]). Other situations where the transmitter antenna is located under the average rooftop level show worse behavior, but these cases are not typically found in broadcast networks. Shortly after being developed, the model performance was analyzed with empirical measurements and the observed estimation error strongly depended on the specifics of each field trial [167]–[169]. Recent studies with IoT (Internet of Things) networks confirm those older findings [170], [171]. Its usefulness remains on its simplicity and the absence of complex building database requirements for urban prediction.

C. DETERMINISTIC: RAY TRACING

Ray Tracing (RT) deterministic methods are based on the ray-optic approximation of the propagating field [172]–[174] and the Uniform Theory of Diffraction UTD [175]. These deterministic approaches provide the best prediction results in micro and nanocell environments. As Okumura and COST231WI, their application is restricted to short-range service areas, LPLT transmitters, and urban areas. Deterministic methods require accurate calculations and very detailed information on the service area. These databases contain a 3D geometrical description of the environment that usually include building and other man-made structures. The database should also describe the electromagnetic properties of each one of its records. In addition, an adaptation to the propagation problem (e.g., limiting the number of useless diffracting edges, internal courts, and vertical details) is required [176]. There is a family of methods, referred to as Ray Launching [177], that limit the number of possible paths by applying a spatial discretization that reduces the number of required calculations at the cost of lower accuracy. In addition to the calculation complexity, the major limitation to their applicability to terrestrial broadcast planning is related to frequency band limitations. Most developments in the last decade have focus the research in bands above 1 GHz [178] and more specifically on the mmWave frequencies [179], [180]. The multi-path nature of the underlying propagation calculations in RT s this technique adequate to applications where this propagation phenomenon dominates. In consequence, it is especially accurate in systems operating in NLOS conditions and those applications where the existence of different paths is relevant (MIMO).

D. SPATIAL VARIATION: STATISTICAL MODELS

Shadowing and the associated statistical calculation of the received field strength are of key relevance for terrestrial broadcast systems. All path-loss calculation methods described in previous sections provide the median received field strength value. These values were sufficient for planning analogue broadcasting networks, where the perceived degradation of image and the sound quality was in a higher range of dB than the variation of the received signal level due to shadowing [181], [182]. In digital broadcasting systems, the transition from perfect to impaired reception differs only in a few decibels and shadowing can be a critical factor. ITU-R defines the shadowing margin as the variability of field strength over a small area, typically represented by a square with a side of 50 m to 1 km [119]. This factor is a correction that adds to the median estimated field strength according to a specific distribution function, a standard deviation value, and a % of locations where the field strength value is exceeded. For decades, the log-normal distribution has been unanimously accepted by industry practice and described by ITU-R reference recommendations such as the ITU-R Rec P. 370 [183]. The log-normal assumption has been widely proposed and used in scientific papers and legacy regulatory reports [184]–[189]. Using data from different measurement campaigns in Belgium and Spain the log-normal distribution has been confirmed in [190]. This study included a comparison between Multiple Frequency Networks (MFN) as well as Single Frequency Network (SFN) reception conditions, with negligible differences exception make for the last 1st percentile. A standard deviation of 5.5 dB is the widespread reference value for including the shadowing margin in the link budget [191], [192]. Nevertheless, it should be noted that measurements have demonstrated that much lower values can be expected in reality. Different measurement campaigns have studied the spatial distribution of received field strength and values in the range of 1 to 3 dB dominate. Specifically, a measurement campaign in suburban areas of Madrid and Bilbao (Spain) led to distribution shapes more skewed than the normal distribution and the standard deviation value found was 2.37 [188]. Later in 2007 and 2009, measurements in Belgium led to values even lower than 2 dB [190]. In addition, the standard deviation will depend on the prediction grid accuracy (terrain database resolution) and it will be frequency dependent. ITU-R recommendations offer different expressions to address this effect in generic field strength predictions [78]. The expression for point to area prediction can be found in ITU-R Rec. P.1546-6 [119]:

$$\sigma_L = \left(\frac{0.0024f}{1000} + 0.52 \right) w_a^{0.28} \tag{2}$$

where f is the operation frequency (MHz) and w_a is the database terrain resolution (m).

E. TIME VARIATION STATISTICS IN BROADCAST RECEIVERS

In addition to a spatial variation, the received signal suffers a temporal signal variation. Time variation statistics can lead to critical planning thresholds. In general, the value which exists at a given location for 50% of the time will be very similar to the value which exists for 90 or even 99% of the time. This value seldom exceeds 2 or 3 dB [193] but it can be much larger. In [182], according to the Federal Communications Committee (FCC), the simultaneous consideration of spatial and time variation statistics can lead to margins higher than 20 dB if the 95% of the locations and 99% of the time targets are sought. These high values strongly depend on the nature of the terrain [133] and the transmitter-receiver path length. The standard deviation in a land path of 50 km is 2 dB but can rise up to 20 dB in 150 km sea paths [78]. In practice, most service areas in broadcasting are limited to ranges well below 100 km, where time variability is negligible for minimum field strength calculation purposes. Nevertheless, time variability is relevant for interference calculations in network planning and especially in frequency management. Broadcast systems are planned with interference-free operation 99% of the time. In consequence, the 1% signal predictions, usually at long distances (higher than 100 km), sometimes over mixed paths, needs statistical characterization as defined in [78].

F. OUTDOOR-TO-INDOOR RECEPTION PLANNING

Outdoor to Indoor planning pertains to portable reception, as described in Section II. Network planning considers two components of outdoor to indoor attenuation: wall loss and other losses not associated with walls (free space loss, diffraction, waveguiding, etc.). Wall attenuation strongly depends on wall materials and the incident angle of the LOS component (if any) on the building facade. A large group of papers has presented empirical results, mostly associated with cellular mobile systems in different bands. Turkmani et al. performed an extensive set of measurements at frequencies starting at 900 MHz up to the 5 GHz band [194]–[196]. Even covering various frequencies, the largest part of the works focused on cellular mobile systems working on bands around 2 GHz. Lower frequencies have also been studied (VHF) for their relevance for digital radio broadcasting (DAB) [197].

In all cases, there is a large variation (2-15 dB) of measured values depending on the material [198], [199], building type [194], [200], and the number of facades illuminated from the transmitter [86]. A summary of planning values for mobile cellular systems can be found in [56], [86]. Plets *et al.* [86] carried out a study in Ghent (Belgium) with a comprehensive analysis of the different factors usable for planning. They also provided a detailed comparison between existing literature and their measurements. This latter reference is the only one that has focused on a broadcast system (DVB-H) at frequencies currently used for digital terrestrial television (602 MHz). The distance between the transmitter and the receivers is very short in comparison with typical use cases in terrestrial broadcasting for the reported works on building penetration measurements. In addition, these studies are based on measurements in service areas of LPLT transmitters (see Section II), whereas the traditional effective height of broadcast stations is usually higher than 300 m above the average service area. The second component of the attenuation is related to the variation between different floors of a multi-storey building. Plets *et al.* confirmed the results displayed by previous references gathered in [201] where a sharp decrease in attenuation is observed on higher floors. The variability in the results is even higher in this floor to floor component [202]. The recommended practice from regulatory bodies and coordination agencies has simplified the procedure to consider the outdoor-to-indoor reception. In Recommendation P.1238 [201], the ITU-R has compiled results from different sources and provides guidelines and reference values. This recommendation was updated in 2015 to cover UHF frequencies, but most empirical values provided there still apply to much higher frequencies, difficult to use for planning terrestrial broadcast systems. In addition, the results are applicable to short range links, usually not the case in terrestrial broadcasting. The DVB Consortium, the European Broadcasting Union and the FCC have provided simplified values for planning in [203], [204] and recently in [192]. The European Telecommunications Institute (ETSI) gathers in [203] empirical references to conclude that there is not a clear criterion to use the myriad of different values from multiple sources. In consequence, a median value 11 dB (6 dB std. dev) is recommended. This recommendation has not been changed in references from ITU-R such as [192]. The floor attenuation, usually referred to as Floor Attenuation Factor [205], should be on the range 3 to 12 dB according to [201] and [206]. Finally, planning for indoor portable receivers is performed at the lowest floors in a building (worst case), so the overall attenuation planning value will be the outdoor to indoor attenuation coefficient (11 dB) plus the Floor Attenuation Factor multiplied by the average number of floors in buildings inside the service area.

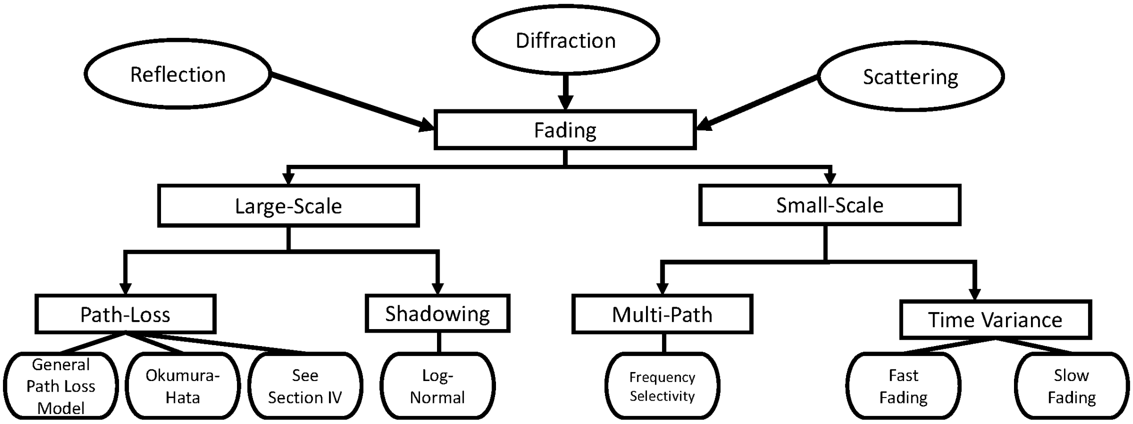

FIGURE 5. Characterization of propagation mechanisms.

V. CHANNEL MODELLING CLASSIFICATION

A. CHARACTERIZATION OF PROPAGATION MECHANISMS

The wireless channel is a dynamic and unpredictable phenomenon, which can severely degrade the quality of point-to-multipoint communication links [207], [208]. The signal is propagated according to the various mechanisms discussed in Section III for broadcasting systems, but mainly affected by diffraction, scattering and reflection. As a result, propagation can be mathematically and physically characterized by a phenomenon known as fading, which can be divided into large-scale and small-scale fading (See Fig.5). Large-scale fading is mainly associated with path loss and shadowing as explained in Section IV. Small-scale fading is caused by the variation of the received signal due to constructive and destructive addition of multipath signal components over very short distances [56], [209] [210]. Slow-scale fading is characterized by the time-variant Channel Impulse Response (CIR). The channel coherence bandwidth determines the frequency selectivity whereas the channel coherence time is related to the channel time variability. The theoretical background to the stochastic description of the CIR was covered in [211], [212], where Bello described for the first time the wireless channel as wide-sense stationary uncorrelated scattering (WSSUS). In the early days of stochastic modeling, system performance simulation mainly utilized this model with a constant Power Delay Profile (PDP) and Doppler Power Spectrum [213], [214]. A simplified channel representation has been predominant in the representation of this channel model for broadcasting networks: the Tapped-Delay-Line (TDL) [215], which can be understood as a physical representation of the wideband multipath propagation channel or small-scale fading [216].

B. WIDEBAND CHANNEL MODELS FOR SMALL-SCALE FADING

Wireless system design needs accurate channel models for successful validation. Depending on the application, those models can be either generic or specific. The latter makes use of available geographical and morphological information [223]. According to the modeling approach, small-scale fading channel models can be classified into physical and analytical models [224], [225], where Physical channel models can be further divided into deterministic and stochastic. Deterministic channel modeling is based on a brute force approach that relies on the full solution of Maxwell's equations under specific electromagnetic boundary conditions. This allows the determination of the field strength at all points during the 100% of the time. The main drawbacks are the requirement of detailed knowledge of the propagation environment/geometry and computational complexity. Within this group are ray launching and ray tracing as discussed in Section IV. This family is used for planning of LPLT and indoor coverage in cellular systems [226]–[229], but rarely in broadcast networks. The stochastic approach describes the fading using its first- and second- order statistics in time and frequency domain. These parameters can be generated directly from the Probability Density Function (PDF) obtained from a set of measurements (non-geometric) or derived from the knowledge of signal propagation mechanism in the wireless environment (geometric). This approach has gained much attention in MIMO channel modeling due to its capability of modeling spatial and temporal correlation properties. In analytical models, the channel is obtained without considering electromagnetic wave propagation and they can be normally divided into correlation-based and propagation-motivated ones. Eventually, there are also reference models that are used in the communications standards. They can be analytical, physical or both. These models, for instance, can specify the geometric properties of the environment with a physical model and simultaneously provide an analytical model for easier implementation.

C. REFERENCE MODELS FOR DTTB

The most widespread channel models for testing the DTTB standards are a particular case of physical stochastic channel models. These models are mostly based on measurement

TABLE 15. Summary of wideband channel models for DTT.

Table	Model	Stationary	Line of Sight	DTTB Standard	References
Outdoor	AWGN	Yes	Yes	DVB-T, DVB-T2, ATSC 3.0, DMTB-A	[28], [203], [217]
	DVBT-F1	Yes	Yes	DVB-T, DVB-T2, ATSC 3.0 DMTB-A	[217], [203], [28]
	DVBT-P1	Yes	No	DVB-T, DVB-T2, ATSC 3.0 DMTB-A	[217], [217], [28]
	0-dBEcho	Yes	Yes	DVB-T2, ATSC 3.0, DMTB-A	[203], [28]
	Rice MISO	Yes	Yes	DVB-T,DVB-T2, ATSC 3.0	[203]
	Rayleigh MISO	Yes	No	DVB-T,DVB-T2, ATSC 3.0	[203]
	Pedestrian Outdoor (PO)	No	No	DVB-T,DVB-T2, ATSC 3.0	[218]
	Brazil C	Yes	No	ISDB-T, ATSC 3.0	[219], [220]
	Brazil E	Yes	Yes	ISDB-T, ATSC 3.0	[219], [220]
	Pedestrian A	No	Yes	ATSC 3.0	[221]
	Pedestrian B	No	Yes	ATSC 3.0	[221]
Indoor	Pedestrian Indoor(PI)	No	No	DVB-H	[218]
	Indoor Office A (IOA),	No	No	ATSC 3.0	[221]
	Indoor Office B (IOB)	No	No	ATSC 3.0	[221]
	Brazil D	No	No	ISDB-T	[219]
Mobile	TU-6	No	No	DVB-T, DVB-T2, ATSC 3.0, DVB-H	[28], [218]
	VU (Vehicular Urban)	No	No	DVB-H	[222]
	MR (Motorway Rural)	No	No	DV-H	[222]
	Vehicular A	No	Yes	ATSC 3.0, DMTB-A	[221]
	Vehicular B	No	Yes	ATSC 3.0, DMTB-A	[221]

campaigns, which eventually lead to the definition of a TDL structure easier to emulate [222], [229]–[232].

The channel models complexity increases together with the number of included KPIs: LOS/NLOS, multi-path, doppler spread, frequency diversity, etc. In principle, non-stationary user scenarios are characterised by higher doppler spread and rich multi-path environments, whereas in the stationary cases the system performance is highly dependent on the LOS/NLOS and the multi-path.

The different DTT standards evolution has incorporated new user scenarios to the traditional broadcasting ecosystem, such as handheld reception, mobile reception in vehicles, and SFN or MIMO receptions. Consequently, new channel models have also been developed to pace the evolution of those new scenarios. DVBT-PI and DVBT-PO, for instance, where developed under the umbrella of the DVB-H standard, whereas the SFN channel was proposed together with the DVB-T2 standard.

The performance of the first Digital Terrestrial Television standard (DVB-T) was tested against AWGN, DVBT-F1 and DVB-P channel models [217], all of them stationary. The first one, the AWGN, just added Gaussian noise to the receiver part, whereas DVBT-F1 was used to describe the fixed outdoor rooftop condition. The DVBT-P1 model was a Rayleigh-fading channel with 20 taps addressing NLOS reception conditions. Later, when the second generation DTTB was developed in Europe (DVB-T2), apart from the previous channels the TU-6 model, intended for mobile environments was also considered. In addition, the 0 dB Echo analytical model was included to test the performance of SFN networks and the memoryless Rayleigh channel with erasures to test the BICM modules during the developing phase [233]. DVB addressed DTTB mobile delivery with the DVB-H standard [222]. In this case, two new channel models were proposed in order to validate the standard: the Portable Indoor (PI) and the Portable Outdoor (PO) models. PI and PO were obtained through comprehensive measurement campaigns under the Celtic WING-TV project. Apart from those, the Vehicular Urban (VU) and Motorway Rural (MR) at speed of 100 km/h with 12 paths were also proposed.

In 2018, ATSC 3.0 published the A/325 ''ATSC 3.0 Lab Performance Test Plan'', in which the main scope was to test the RF performance of ATSC 3.0 in a laboratory environment [244]. In addition to the other channel models, the use of Brazil C and E models was also recommended [245]. The first one incorporated reception conditions in an environment with mountains and NLOS, whereas the second one described reception in an SFN. In addition, the CRC modified ensembles were included, which were developed to represent four different reception conditions that have been used to test ATSC 1.0 equalizer in Canada, and eventually, the Pedestrian A and B ensembles, and the vehicular A and B ensembles, which were described in [220]. The ISDB-T standard, which is mostly used in Japan and Brazil, was also tested against several of the previously presented channels [221], [246], [247], as well as the UK short and long delay channels [219]. Finally, the Chinese DTMB-A performance has also been studied against the same sort of channels as previous standards [27]. A summary of the most widely used channel models for the various DTTB standards is shown in Table 15, where specific characteristics and suitable references can be found. Each model is often identified by a unique name that describes its usage.

VI. REGULATORY SOURCES AND INTERFERENCE

As it is the case with the majority of wireless services, terrestrial broadcasting is a matter of regulation by each country's authorities. Those regulations are based on both generic and service specific recommendations, reports and handbooks originated in transnational organizations such as ITU, EBU, ABU, and others. The use of propagation methods for coverage planning and protection from interference is also

TABLE 16. Regulatory sources related to propagation in terrestrial TV broadcasting.

Body	Document	Purpose	References
ITU-R	Rec. BT.1895	Criteria for applying PRs for terrestrial broadcasting systems.	[234]
	Rec. BT.1368	Planning parameters and methods for fixed and handheld legacy and second generation DTV systems	[191] [235] [236]
	Rec. BT.2052		
	Rec. BT.2033		
	Rec. P.1546	Point to area prediction methods	[119], [159]
	Rec. P.1812		
	Rec P.452	UHF General propagation effects in band and specific prediction method for interference calculations	[78], [133]
	Rec P.1406		
	Report BT.2137	General guidelines for coverage planning and system dimensioning	[12], [55]]
	RRC-06 Acts	Coordination procedures (and propagation models – ITU-R P.1546 guidelines) for DTV in Europe	[118]
EBU	Tech 3348	Frequency & network planning aspects of DVB-T2	[237]
	Tech 023	Spectrum and network planning for DVB-T implementation	[238], [239]
	Tech 022		
FCC	OET B.N. 74	Method for Interference prediction	[240]
	OET B.N. 73	Point to point calculation procedures (DTV)	[241]
	OET B.N. 72	Point to area calculations using Longley-Rice	[242]
	OET B.N. 69	Interference calculation using Longley-Rice	[243]

covered by regulatory documents. Table 16 gathers the most relevant inputs from worldwide (ITU-R) and regional (EBU) bodies, including an example of the Federal Communications Committee (FCC) the from USA. Interference is managed in terrestrial broadcasting by means of a planning parameter referred to as protection ratio (PR) [248] and defining the service area where the PRs are guaranteed. The PR (expressed in dB) is the minimum value of the power of the wanted signal to the total power of interfering signal(s), evaluated at the receiver input. A PR is defined to provide a specific reception quality under specified conditions at the receiver input, which involves different values depending on the nature of the interference [249]. PRs depend also on the specific physical layer of the standard being deployed. Moreover, within one standard, each operation mode will have a recommended value, mostly associated with the modulation and channel coding choice. PR values for each standard (DVB and ATSC systems) can be found in ITU-R recommendations [234], [235] (DVB, ISDB-T, DTMB and ATSC systems) and reports [250]. Each standardization organization (SDO) and regional regulatory body also include recommended values in their system deployment guidelines [203], [237]. The nature of interference is important for planning considerations. The variety of nuisance fields is wide: noise-like, continuous wave, impulse, same as the desired signal, etc. Temporal statistics are also relevant (short term and long term). For practical purposes, the protection ratios for terrestrial systems apply to two potential situations: continuous interferers and/or tropospheric interfering sources. Continuous interferers refer to long-term interfering signals at levels that are not exceeded for a large percentage of the time (e.g., 50%) and generally serve as the baseline for establishing protection criteria. On the other hand, tropospheric interfering signals are short-term interfering signals at levels exceeded for no more than 1% to 10% of the time. Both are independently calculated and the one causing the highest interference level is considered, while the other source is discarded for planning purposes [191].

The geographical area where the broadcast service is protected by guaranteeing a certain protection ratio is key for network planning and international coordination. Its definition is not straightforward and there are different approaches for this. A first choice is based on the concept of the protected region. This region is the combination of the noise-limited area around the transmitter (protected contour set by FCC) plus a region defined by a minimum distance (dMS) from the protected contour where the operation on the same channel is forbidden. The value of dMS is calculated to guarantee the protection ratios of each specific case [251]. This procedure is the typical operation approach in North America. In regions where the density of different networks is higher (Europe is the paradigmatic example), the coordination between many countries within a short distance range makes the service area calculation a challenging process. In this case, the service region definition can be accomplished in two ways: assignments or allotments. An assignment is the allocation of a frequency resource to a single transmitter with specific geographical features (location, height above sea level) that will be protected within the associated service area. In this case, the service area is defined first using the noise limited contour (set by the EIRP restriction imposed by each national regulatory authorities) and forcing the interference limited contour (using the applicable PRs) to match the noise limited contour at certain test points [239]le transmitter. An allotment is the coordination procedure to grant protection to single frequency networks (SFN) [240] that will provide coverage to the service area using several transmitters. In this case, the PR ratio applies to the allotment area contour and not to the one associated with each individual transmitter.

Guaranteeing protection ratios over the service area involves a geographical separation between transmitters, with a minimum frequency reuse distance within the range of 3 to 4 times the protected contour of radius R around each transmitter. This reuse distance creates the so-called Television White Spaces (TVWS), where the channel in use cannot be used for primary services. The problem and opportunities provided by TVWS have been widely analyzed in the literature [252]–[255]. The size of TVWS depends strongly on the geographical features of the planning scenario (a reference value of 2R from the protected contour is a good rule of thumb) [256]. The use of the TVWS involves spectrum sensing [257], spectrum management resource allocation techniques [258] and system architectures based on a geolocation frequency use database to support unlicensed operation without disturbing the primary broadcast service [259]. The prediction on the interfering field strength levels will depend on the nature of the interference. If the nuisance field is regarded as continuous, the prediction is usually accomplished by versions of the point to area methods evaluated at certain points (test points of the contour of the service area, for example). If the interference is tropospheric, then it will be driven by unsteady and occasional phenomena that occur during small percentages of time. ITU-R P. 452 is the most widely used model [133] for tropospheric interference prediction. This recommendation provides the "worst month" calculation method and it contains a description of all the propagation mechanisms involved: (line of sight, scattering, ducting, upper layer refraction and diffraction, and meteor scattering). The recommendation proposes calculation formulae to evaluate the losses associated with each one of the propagation phenomena. Some of the calculations require radiometeorological data also included in ITU-R P.452. The "tropospheric scatter" model adopted in ITU-R P.452 accounts also for secondary propagation phenomena which give rise to similar propagation effects [160]. The approach is empirical as a function of refractivity, antenna characteristics and gaseous absorption (the latter not applicable to UHF). The method differentiates "clear-air" and "hydrometeor-scatter" interferences. The clear-air method consists of separate models for diffraction, ducting and layer-reflection. The diffraction calculations are similar to other models, with specific corrections associated with small percentages of time. The ducting and upper layer effects component is calculated as an empirical formulation of the total of fixed coupling losses between the antennas and the anomalous propagation structure within the atmosphere. The expression is a function of the frequency, horizon distance and a series of correction factors that depend on site-shielding, over-sea surface duct coupling corrections as well as time percentage and angular-distance dependent losses within the anomalous propagation mechanism. The hydrometeor scattering is based on the application of the bistatic radar equation and involves meteorology statistics, antenna pattern geometries as well as rain cell volume models.

VII. LESSONS LEARNED

This survey has shown that modelling the point-to-area propagation is a challenging research area. A few prediction algorithms such as the ITU-R P.1546 and the NTIA Longley Rice family have concentrated a significant amount of engineering effort. The current version in force of ITU-R P.1546 is version 6, updated in 2019 [119] and the Longley Rice method has evolved into a family of different estimation procedures [11], [36], [134], [135], [141], [240], [243]. There are different factors that motivate model updates: better database resolution [260], stringent requirements for efficient network planning [261], and more computational power on current servers, will continue pushing for better and more accurate predictions. In addition, especially in urban and sub-urban environments, the materials and shape of artificial buildings and other structures will require model updates. To this end, work on field strength spatial distribution statistics is key, as well as having updated building attenuation empirical data. Moreover, the typical size of service areas of a broadcast transmitter will reduce because of the convergence with 5G networks. This fact will reduce the accuracy expected from prediction methods, optimized for estimating the field strength values over several dozens of kilometres around the transmitter. Additionally, in some regions (e.g. North America [262]), significant portions of the UHF band are being allocated to mobile broadband services so broadcast services will have the choice (or mandate) to migrate to channels on the upper VHF, which will require updates and more accuracy in the range from 300 to 400 MHz. Another aspect that will move propagation studies forward is the slow but steady incorporation of MIMO techniques into the broadcast standards. So far, MIMO is optional in the latest systems, but it will be definitely the only solution if 8K services will be deployed on terrestrial broadcast networks [48]. MIMO channels are available for the upper mobile bands, but further work is required at lower frequencies (UHF below 700 MHz). Closely related to the challenges of including MIMO into the broadcasting site infrastructure, the antenna system and transmitting site infrastructure are also evolving in the next decade. The traditional broadcast site is elevated over the average height of the coverage area. This parameter, referred as effective height, will tend to reduce if the convergence with 5G and mobile TV becomes a successful business case. Most of the methods are based on transmitter antenna heights of a few hundreds of meters (typically from 300 m to 3000 m) [263]. If networks evolve to LPLT and mixed HPHT – LPLT architectures [53], [146], the effective height will reduce significantly and the point to area calculations will have to be refined accordingly. A typical case already proposed in the literature is the so-called overlay architecture, where two networks cooperate to provide a mix of broadcast and broadband interactive services [264]. An additional challenge related to convergence is the definition of coverage, radically different in cellular and broadcast systems. In this regard, again, the statistics of spatial distribution and time distribution are a fundamental target for new research activities.

Mobility is another challenge for point to area broadcasting. The broadcast mobile coverage definition by regulatory bodies [265] is based on the area coverage definition for fixed reception that does not ensure continuous QoE along the trajectory of the mobile receiver [266]. Models might need to be complemented with mobility layers that could take into account the dynamics of the propagation along the movement

TABLE 17. Frequency bands allocated to terrestrial TV broadcasting.

Broadcast Bands as ITU- R	Europe			USA/Canada/S. Korea			Japan			China		
	f_{start}	f_{end}	BW	f_{start}	f_{end}	BW	f_{start}	f_{end}	BW	f_{start}	f_{end}	BW
VHF	48.5	230	7	54	216	6	90	222	6	48.5	223	8
Band I	48.5	66		54	88					48.5	72.5	
Band II							90	108		76	92	
Band III	174	230		174	216		170	222		167	223	
UHF	470	694	8	470	512	6	470	512	6	470	694	8
Band IV	470	614		470	608		470	608		470	566	
Band V	614	694		614	698		614	698		606	702	
Former DTTB Frequencies Band V: 2nd Digital Dividend	694	790		602	698		602	698		702	798	
Former DTTB Frequencies Band V: 1st Digital Dividend	790	862		698	806		698	806		798	862	

route: path loss evolution, slow fading dynamics, and fast fading statistics. Another research area in terrestrial broadcasting is related to propagation channel modelling. Broadcast and multicast have not been included in the first releases of 5G [267] and it is expected in future Rel. 18 or Rel. 19. The propagation channel model involved will need to consider the new network architecture and expected reception modes. To that end, either modifications of existing ones and new wideband channel models referred to the new reception scenarios are necessary. New reception modes are also envisaged for HPHT networks. These new modes will be associated with the delivery of services embedded in the broadcast signal ensemble but targeting other devices that TV sets (i.e IoT devices, vehicular applications, etc) [268]. Finally, new technologies incorporated into the waveform and network architectures of future broadcast standards will require research on coverage prediction methods and channel modelling. This requirement is illustrated with recent examples [269], [270], where the gain of including complex but theoretically very advantageous technologies was under strong discussion. The controversy came from assumptions on propagation models (i.e. time and space distribution statistics) that depending on the model choice calculations could lead to outstanding gains or minimal advantages. The soundness of the propagation assumptions has been key in the adoption/rejection of those technologies. In conclusion, propagation remains a timely and relevant field of research that is strongly tied to the future advances in broadcast technologies, services, and networks.

APPENDIX

Broadcasting TV services around the world have been divided in regions, for which various frequency allocations have been made. Table 17 shows how these frequencies have been distributed. Note that most European countries do not have plans in VHF for DTT. The situation of the use of VHF changes significantly from country to country in Europe. On the other hand, for Asia, high VHF will be partially used for disaster prevention communications in Japan.

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