

Dynamic spectrum access in terrestrial TV band: assessment of prospects in Kenya

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Abstract

Wireless connectivity has become a significant part of human life all over the world, both in developing and developed countries. In order to provide sufficient coverage without the densification of cellular networks, relatively low carrier frequencies should be used. This paper considers the reuse of the digital terrestrial television (DTT) band for cellular system operation in Kenya, while protecting incumbent TV signal reception according to the Dynamic Spectrum Alliance (DSAL) rules. A state of the art model for DTT coverage and allowed cellular system power calculation is tested using real data for Kenya. Suggestions regarding future DSAL rules amendments are provided. Moreover, the amount of spectrum resources available for cellular system operation in the DTT band in Kenya is estimated against varying system parameters.

Keywords Dynamic spectrum access · Dynamic spectrum alliance · TV white spaces

1 Introduction

Internet connectivity has become a driving factor in the development of countries and people's well-being. According to a Cisco forecast [13], the global IP (Internet Protocol) traffic will increase by 26% annually from 2017 to 2022. Even more significant are the numbers for specific regions, e.g., for Africa, the annual IP traffic increase is expected to be 41%. Differences between regions are visible in other statistics as well. The number of Internet-connected devices per capita spans from 1.1 in the case of Africa to 8 for North America (as for 2017). This shows that faster development in this market can be expected in some parts of the world, for example, in Africa. Such a rapid growth requires proper infrastructure to be developed. While the provisioning of fixed access, e.g., through fibers, requires significant time and money, wireless connectivity can fill this infrastructure gap faster. 5G networks will provide a number of features to support users with high-speed Internet access, for instance, Massive Multiple Input Multiple Output (MIMO), New Radio (NR),

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network densification and mmWave transmission [23]. However, some of these techniques are not suitable for developing countries with sparse populations, as, e.g., the cost of building a dense network that supports mmWave transmission is unacceptable. If only sparse infrastructure is provided, relatively high User Equipment (UE) - Base Station (BS) distance is anticipated. As pathloss typically increases with the utilized carrier frequency, the lowest possible frequency should be used in the considered scenario.

While 5G has a lot of frequency resources in the high frequency range, namely, around 1 GHz of bandwidth per operator in the 26 GHz band [5], in the lower bands, limited spectrum resources will be available, that is, around 60 MHz in the 700 MHz band [21]. Therefore, in order to provide high data rate to users, more spectrum is to be allocated, or existing spectrum resources have to be managed more efficiently. There are some novel spectrum access schemes, like sharing using License Assisted Access (LAA), Licensed Shared Access (LSA) or Citizen Broadband Radio Service (CBRS) [7,14,15,21]. High potential lies in the reuse of the Ultra High Frequency (UHF) band from 470 to 790 MHz that is used by Digital Terrestrial Television (DTT) as a primary service. It has been considered to support cellular access both by researchers [24] and spectrum regulators [19]. The potential of this band comes from its relatively high width, nearly fixed parameters of DTT transmitters (TXs) and propagation conditions that are favorable for a wide area cellular network.

As the DTT network typically utilizes just a few frequency channels at a given location there are many locally unused channels, so-called TV White Spaces (TVWS). However, in order to utilize these white spaces while protecting DTT transmission, some technical problems have to be solved. One of these is the typically unknown location of a DTT receiver. This is usually solved by ensuring that in each location where a given DTT reception was possible before TVWS transmission, it is available with parallel TVWS transmission as well. Therefore, worst-case DTT receiver (RX) location is considered, requiring a significant protection margin for the inaccuracy of pathloss estimation. Additional margin has to be used if the assessment of DTT reception quality is based on local sensing at a TVWS device. This results in very stringent requirements on stand-alone TVWS operation, i.e., high sensitivity (to detect DTT transmission much weaker than thermal noise power) and low transmission power. Therefore, stand-alone TVWS device operation is a method less promoted than the database-driven Dynamic Spectrum Access (DSA), e.g., [7,15].

The database driven DSA relies on Radio Environment Maps (REMs). These contain an estimated (using some propagation models or measurements) coverage area of the incumbent systems and the maximum allowed power to be emitted by a DSA device at a given location, in a given frequency channel for the considered spectrum emission masks. Such a dataset has been prepared by the Office of Communications (OFCOM), the radio communications regulator of the United Kingdom, for TVWS with a discussion on the utilized approach/assumptions presented in [20]. While these rules are specifically designed for the UK, there is a general set of rules proposed for DSA in TVWS by the Dynamic Spectrum Alliance (DSAL) [4]. DSAL is a global organization promoting more efficient spectrum utilization that was joined by many global companies, for instance, Amazon, Facebook, Google, Microsoft. The rules provide a methodology to calculate DTT coverage (knowing the location, height and transmit power of DTT transmitters), and based on it, the allowed power of a TVWS device at a given location.

It is important that LTE or a similar wideband wireless communications system can work effectively at frequencies close to the TVWS band, e.g., consider LTE Band 31 (around 450 MHz) or LTE band 28 (around 700 MHz). Therefore, the throughput of such systems in TVWS is expected to be similar as in their ordinary bands, for example, 2600 MHz, for the same bandwidth and SNR. The highest advantage of a TVWS-based network in comparison to ordinary broadband access networks is its range. Let us compare the coverage area of an LTE-like BS operating at 474 MHz (TVWS) to a BS utilizing an ordinary 2.6 GHz band. Let us assume that both BSs transmit with the same power, the same gain antennas are used and the receivers have the same sensitivity. For simplicity, the range of these systems can be compared using the Friis formula. The range of a TVWS-based cell is about 5.5 times wider than for a 2.6 GHz-based cell. For a circle-like cell area the TVWS-based BS covers about 30 times wider area than the BS operating at 2.6 GHz. This shows that provisioning of coverage using TVWS will be much more efficient than utilizing ordinary bands.

The first purpose of this paper is to show the potential of DSA in TVWS, using Kenya as an example. Because of the large area to be covered by the broadband Internet access service and relatively sparse terrestrial TV deployment, Kenya is an excellent candidate to deploy TVWS-based services. The Communications Authority of Kenya has reported a high number of TVWS trials carried out from 2013 to 2019 [2]. In none of these trials was there any harmful interference to DTT receivers observed. Kenya is one of many countries in Africa that are interested in the TVWS technology and have carried out trials [18], including South Africa [16], [17], Malawi [3], Tanzania, Ghana and Namibia [22]. The DSAL rules will be used to assess the TVWS device transmit power allowed at a given location, frequency and for a given device class (specifying the spectrum emission mask). In addition, the work on the implementation of these rules allows us to present some suggestions regarding the best implementation practices and some issues to be solved. The numerical results for varying system parameters show the sensitivity of the solution. In summary, the main contributions of this paper are:

- A quantitative assessment of the amount of TVWS in Kenya;
- Recommendations regarding efficient DSAL rules implementation;
- A proposal of DSAL rules amendments;
- A quantitative assessment of the influence of the main DSAL rules parameters on the resultant TVWS availability.

This paper is organized as follows: Section II describes the main steps and assumptions used in the DSAL rules, Section III presents the assumptions/proposed amendments to the standard. The results of the numerical assessment of TVWS availability in the case of Kenya is provided in Section IV with a discussion on the influence of some DSAL rules parameters on the results. The paper is concluded in Section V.

2 Dynamic spectrum alliance rules

Dynamic Spectrum Alliance rules [4] are specified to allow dynamic access to TVWS, while protecting the existing systems. However, it is mentioned that it can be applied to any spectrum band based on a decision of a local electromagnetic spectrum regulator. The rules allow for TVWS access



Fig. 1 Diagram of DTT RX protection from TVWS device transmission

using DTT transmission sensing at a TVWS device or using a geolocation database. The first method requires a given vendor to propose a sensing scheme and a local regulator to propose testing rules, leaving the whole methodology practically unspecified by DSAL. Moreover, while sensing-based access allows for the maximal Effective Isotropic Radiated Power (EIRP) density of -0.4 dBm/100 kHz, database-driven access allows for the maximum of 21 dBm/100 kHz EIRP (see page 9-10 in [4]). As database-driven access allows in the best case more than 100 times higher emitted power and is well defined in the rules, it will be the main focus of this discussion.

Database-driven access requires a given TVWS device to contact a database with its accurate location (in WGS84 coordinates), height and spectrum emission mask, that is, one of 5 emission classes specified by the European Telecommunications Standards Institute (ETSI). The database can be managed by a public or many private companies. It should respond with the allowed power for a given frequency channel. A transmitting TVWS device is obliged to regularly contact the database for the confirmation of utilized transmission parameters or when it changes its location. The maximum EIRP allowed for a given TVWS is constrained by the following factors:

2.1 DTT receiver protection

If at a given location DTT signal reception in a given channel is possible, TVWS transmission should not deteriorate this reception. The utilized approach is graphically presented in Fig. 1 with main values/parameters denoted. This issue requires first to assess if at a given location, without TVWS device transmission, DTT reception is possible. The default maximum DTT TX-RX distance is set in the rules to 200 km, limiting the required calculations range. The pathloss between the wanted TX and DTT RX has to be calculated using a terrain-based propagation model, e.g., Longley-Rice or ITU-R P.1812 [12], assuming the receiver's antenna (DTT RX in Fig. 1) is located 10 m above the ground. The received wanted signal power depends on this pathloss, transmitter EIRP and DTT RX installation gain of 9.15 dB. The reception quality is limited by both thermal noise and interference originating from other DTT transmissions (denoted as $I_{DTT} + N$ in Fig. 1). While the same pathloss model is considered for all DTT signals, the interference can be attenuated at DTT RX by an antenna installation by up to 16 dB (by RX antennas azimuth for co-polar transmission) or 15 dB (reverse polarity). Additionally, DTT transmission at a different frequency channel than the wanted signal has an additional attenuation of minimum 61 dB. However, the noise and interference is increased at the receiver by the noise figure of 7 dB. Finally, a given DTT signal can be successfully received if signal (S in Fig. 1) to noise and interference power ratio is greater than 27.1 dB. This number can be factorized into 19.5 dB, resulting from the required block error rate of the considered modulation and coding scheme, and 7.6 dB being an additional receiver link margin.

A location with DTT reception possible at a given channel requires to be protected from harmful, TVWS deviceoriginated interference (I_{TVWS} in Fig. 1). The minimum distance from the DTT RX location and TVWS TX location is defined to be 60 m (to prevent propagation model anomalies for short links and consider that, for instance, TVWS base stations will not be collocated with a DTT RX antenna as a requirement given to the system installer). The pathloss between TVWS TX and DTT RX should be calculated using a terrain-based model. Although the utilization of, e.g., ITU-R P.1812 is possible, considering its high computational complexity, and possible low propagation range (result of much lower typical antenna height and transmit power than DTT TX), it is reasonable to utilize a simplified model, for instance, extended Hata as proposed in [19]. The calculations aim at obtaining the maximal TVWS TX power in the neighboring locations that will cause the interference power at the DTT RX location to be significantly below the wanted signal power, considering the directivity of the DTT RX antenna, polarization, and distance in frequency (by means of a protection ratio parameter). The proposed protection ratios are based on OFCOM measurements for all TVWS TX classes, depending on the wanted DTT signal power and distance in frequency of TVWS transmission. For a DTT RX collocated in frequency with a TVWS TX, the protection ratio equals 39.5 dB, i.e., the TVWS TX-origination interference at the protected DTT RX antenna has to be at least 39.5 dB weaker than the wanted DTT signal. A TVWS TX power is constrained theoretically by all DTT RX locations over all protected DTT frequency channels. However, the rules propose to neglect for a given TVWS TX location 0.1% of the most constraining DTT RX locations, potentially increasing the transmission power.

2.2 Protection of incumbents other than DTT in the TVWS band

The regulations assume that in a specific country, some wireless systems, other than DTT, can operate, e.g., wireless microphones. The document suggests limiting the received interference at each protected location, for instance, by keeping it below a constant value specific for a given system or thermal noise power. The final specification of this protection is left to the local regulators.

2.3 Protection of systems operating outside the TVWS band

The regulations foresee that some bands, not considered to be used by TVWS devices, should still be protected from TVWS-originating interference as a result of imperfect TX/RX characteristics in frequency, that is, non-zero Out-of-Band radiation or imperfect receiver selectivity. The power emitted from a given TVWS TX reduced by Adjacent Channel Leakage Ratio (ACLR) specific for a given DTT TX class and a given frequency shift should be below a given constant. This value is proposed to be -25 dBm, although it can be different and varying in frequency, depending on local regulator decisions.

2.4 Protection of country borders

The emitted TVWS TX power should be such that at each point of a country border it should not exceed -74 dBm/ 8 MHz of received power. This has to consider pathloss from each TVWS TX location to each country border point, considering the RX antenna is located 10 m above the ground.

The minimum allowed TVWS power at a given location at a given frequency channel from the above described constraints should be additionally upper-limited by the maximum emitted power per channel equal to 40 dBm. This terminates the calculations.

The computational complexity of deriving TVWS device transmit power can be significant. Therefore, the rules allow some data to be precomputed, computed with lower spatial resolution or even to be omitted if no significant change in the results is guaranteed. While the DTT TX configuration rarely changes, it always causes a significant number of calculations to be repeated. The change of a single DTT TX configuration results in the need to recalculate many DTT channels in many reception locations as a result of interference that has to be considered between nearby DTT transmitters, both in frequency and in space. This, in turn, results in the need for TVWS TX power recalculation. On the other hand, DSAL rules do not require recalculations after any TVWS TX turns on/off. The second reason for the requirement of computational complexity reduction is the number of calculations rapidly increasing with the resolution of the space grid, as will be shown in the next section.

3 Implementation issues

The above described computations can be divided into two parts: DTT coverage calculations and TVWS device allowed power calculation. The proposed implementation approach, observed problems and suggested modifications can be discussed separately.

3.1 DTT coverage calculation

The calculations have to be carried out in a grid, most typically a square one. The size of the grid has direct influence on the calculation time. Considering that all pixels ¹ within 200 km from a DTT transmitter have to be checked for DTT coverage, the decrease of a pixel side by half results in 4 times more pixels, i.e., computational complexity rises quadratically. On the other hand, a finer grid can result in a more accurate solution. However, the accuracy is partially limited by the granularity of input maps required for pathloss estimation in ITU-R P.1812 [12], namely, the map of terrain height above mean sea level, the map of the country border, the map of clutter type (e.g., water, urban, trees), the map of radio-climatic zones (i.e., sea, inland or coastal land) and the map of refractivity parameters. As the considered path can have several kilometers, earth curvature should be considered, while specifying the shortest path between two coordinates, including equally-distanced path-profile points. This is done using Vincenty's algorithm.

In order to reduce the Carrier to Interference and Noise power Ratio (CINR) calculation complexity, the interference power from other DTT transmitters is calculated only if the carrier-to-noise-power ratio is above the required threshold. This is one of the many heuristics that can increase the calculation speed.

The calculated interference power depends on the angle between the azimuth and elevation of the maximal DTT RX antenna gain and the interference source azimuth and elevation. Such a *cone* angle can be calculated using formula (37b) from [9].

The result of this stage can be a list of locations (latitudes and longitudes) for which a given DTT signal can be received. Each location should be accompanied by the wanted signal power and the direction of DTT RX antenna (azimuth and

¹ A *pixel* is a square (of a given side length) whose central point is used for the calculation of wanted power or interference. It is assumed that the values calculated for the central point are close to the results of these calculations for other locations within this square.

elevation). These data will be required for TVWS power calculation.

The DSAL rules seem to omit some important issues. The most important one is the consideration of many DTT transmitters operating as a Single Frequency Network (SFN). This is an important feature of OFDM-based DTT standards. Many transmitters can operate on the same frequency, transmitting synchronously the same data stream. As long as the signals arrive at the DTT receiver with an acceptable delay spread (shorter than the cyclic prefix duration), the wanted signal power is increased and the probability of fading is decreased in comparison to a single DTT transmitter case. However, this feature, used in many DTT networks, is not considered in the rules, that is, any DTT signal transmitted from another DTT location is treated as interference. This will significantly reduce DTT coverage. We have proposed to simply add the wanted signal powers from various SFN transmitters as suggested in [8]. As the DTT RX is assumed to use a directional antenna, its antenna is assumed to point at the strongest source of the wanted signal.

The second observed problem is linked to the DTT RX antenna gain and the interfering signal from DTT transmitters. As both the wanted and unwanted DTT signals go through the same RF chain in the receiver, both should be increased by the antenna installation gain, i.e., G_{RX:inst} of 9.15 dB in [4]. This is performed for the wanted signal but omitted for DTT-originating interference, namely, in equation (4.3), attenuation caused by the considered antenna pattern $G_{ant@X \rightarrow T'}$ should be modified by the maximal antenna gain $G_{RX:inst}$. While this part of calculations seems to underestimate interference power, another observed problem increases it. In equation (4.8), the noise figure $L_{RX:noisefig}$ of 7 dB increases the total interference plus noise power $P_{noise:T@X}^{i}$. The noise figure should probably only increase the thermal noise $P_{thermal}$ of -105.2 dBm. This value equals Johnson-Nyquist thermal noise at $20^{\circ}C$ over the useful bandwidth of the DVB-T signal, i.e., 7.61 MHz. The influence of these two parameters on the total DTT coverage will be assessed in the next section.

The last problem observed in this part of regulations is interference caused by other DTT transmissions occurring at the same location at different frequencies. According to the rules, a given transmitter T can utilize many frequency channels *i*. While considering an interfering transmitter T', it has to be different than T. As such, the interference from channel $i' \neq i$ from transmitter T is not considered in calculations. This is not a problem if both the *i*-th and *i'*-th channels are transmitted with similar power, as the ACLR will cause the interference to decrease by at least 61 dB. However, if a high transmit power difference is observed, this source of interference can be crucial.

3.2 TVWS transmitter maximal power calculation

The second phase is the calculation of the maximal transmit power of a TVWS device located at a given height, characterized by a given emission class in a given frequency channel. The implementation is carried out with a grid size the same as in DTT coverage calculations. While all the TVWS device power constraints listed in Sec. 2 are implemented, the most problematic one from the point of view of computational complexity is DTT RX protection. If in a given position, at a given channel DTT signal reception is possible, TVWS transmitters' power is to be limited in the neighborhood. Observe that for a pixel of side x, typically longer than 60 m, for the DTT RX pixel and potential TVWS TX pixel overlapping, the distance considered for interference calculations is 60 m, as explained in Sec. 2. On the other hand, for the closest adjacent TVWS TX pixel, the distance equals x. The lower the DTT wanted power (obtained from the previous calculations stage), the wider the range to be considered for TVWS power limitation. Consider that the grid size is decreased in half, giving an about 4 times increase in the number of DTT protected positions. For each of these locations the number of TVWS locations for which TX power reduction is to be considered is 4 times higher as well. As such, the grid size decreased two times results in about 16 times more calculations to be done. This shows the optimization of this calculation phase is even more important than in the case of DTT coverage calculations.

First of all, pathloss calculations between DTT RX and TVWS TX can be simplified. The reason for this is typically much lower power (below 40 dBm) and antenna height of TVWS TX in comparison to DTT TX. This allows us to use the extended Hata model, as proposed in [20]. Analysis in the UK has shown that this model typically underestimates pathloss in the considered use-case, thus providing an additional degree of protection for DTT RX (see page 9 in [20]).

As both the DTT RX antenna height and TVWS TX antenna height are fixed for a given TVWS allowed power map, it is possible to tabulate pathloss as a function of distance and environment, namely, rural, suburban and urban. This allows us to get the correct pathloss value by using a quantized distance to address the correct element in the precalculated array.

In order to limit the computational complexity of distance calculation, it can be observed that the relatively low distance between TVWS TX and DTT RX allows us to use the *locally flat earth* approximation. The computationally complex Vincenty's algorithm is replaced by a simple calculation using the Pythagoras theorem. Another way to reduce computational complexity is to limit the number of TVWS TX locations that, for a given DTT reception point, have to be considered for TVWS TX power limitation, e.g., a TVWS device located 800 km from the DTT reception point is not causing any significant interference to this DTT receiver. This approach suggests looping over all protected DTT RX locations first, and for each of these points, specifying the maximum distance to TVWS location that has to be considered for TVWS TX power reduction. This requires using a reverse Hata model that provides a distance for a given pathloss. Additionally, DTT RX antenna directivity can be considered in this range limitation. Most interestingly, this loop order is useful from the point of view of choosing the correct environment type in the Hata model as well. According to [20], the link environment to be considered is to be defined by the environment at the DTT RX position, i.e., for a given DTT RX position, the Hata model parameters are fixed.

The main problem observed while implementing this part of the rules are protection ratio values. Protection ratio is the ratio of the wanted signal power to interfering signal power at the interfered RX antenna at the point of reception failure. In the regulations it is defined between the wanted, DTT signal and interfering, TVWS device signal. These values, as suggested in the rules, are taken from [20] for adjacent channels and discrete values of the wanted signal power at the DTT RX input. As the wanted signal power obtained in calculations typically is not aligned with tabulated values, interpolation is required (following the rules) for a value in between the available entries, and extrapolation is required (as proposed here) for a value lower or higher than the available entries. The linear interpolation or extrapolation of the protection ratio in logarithmic scale is done using two entries of the closest wanted signal power for a given channel separation. What is interesting is the co-channel protection ratio, that is, protection ratio for a TVWS device and DTT RX operating in the same channel. According to the rules, it equals 39.5 dB, being the sum of the minimum DTT carrier to noise ratio (19.5 dB), and 20 dB of additional margin. In the case of [20], the source of adjacent channel protection ratios, the co-channel protection ratio is suggested to be the required minimal Carrier-to-Interference power ratio (19.5 dB in the rules) increased by a margin of 9 dB. This should result in the co-channel protection ratio of 28.5 dB. The impact of this parameter on TVWS availability will be tested numerically in the next section.

The last proposal in the DSAL rules to be mentioned is the omission of some, mostly constraining DTT RX locations, while calculating the TVWS device TX power. This is specified in the DSAL rules [4], Annex A by formula (4.16). For a given TVWS TX location there is a set of locations Y in which at least one DTT channel is to be protected. As such, each element of Y results in a constraint on TVWS device TX power. The rules suggest discarding some of the most constraining values. The number of these elements is proposed to be 0.1% of the total number of positions in a map (set X). There is no justification for discarding any constraints mentioned in the rules. Moreover, if the size of X is used, the number of discarded points depends on the country size, not the coverage area of DTT signals. For these reasons this feature has been neglected, resulting in more stringent DTT RX protection.

4 Numerical results for Kenya

4.1 Input data and numerical model parameters

The rules and their implementations will be tested for the whole Kenya area, considering real DTT transmitter locations and their parameters. In total, 327 DTT emissions are considered, utilizing 28 unique DTT frequency channels with the carrier frequency ranging from 474 MHz to 690 MHz. The DTT transmitters utilize antennas located 33 to 90 m above the ground level, emitting signals ranging from 1.64 kW to 16.4 kW EIRP. The simulator was implemented in Matlab, requiring a set of maps, for example, for pathloss estimation according to the ITU-R P.1812 model. While the map of terrain height above the mean sea level was obtained from National Aeronautics and Space Administration (NASA) with a 30 m resolution $[1]^2$, the map of country borders can be downloaded from [10]. The landcover required both by the P.1812 model and the Hata model can be found at [11]. This map is additionally used, after post-processing, to specify the radio-climatic zone (i.e., sea, inland or coastal land) required by the P.1812 model. The last required inputs were refractivity parameters specific for a given location. This is found in a source file attached to [12].

4.2 Results

First, the influence of various design factors on DTT coverage was tested. The main factor is grid density. The smaller *pixel* is considered, the higher computational complexity is expected. On the other hand, a denser grid should result in a more accurate pathloss estimate, e.g., because of more path profile points. The numerical comparison of DTT coverage was performed for a grid of 1000 m, 2000 m and 4000 m. The calculations were carried out according to DSAL rules, as explained in Sec. 2. In Fig. 2, the Cumulative Density Function (CDF) of the number of DTT channels available for reception for all locations in Kenya is presented. There are some locations (around 10% of Kenya area) where the reception of 6 or more DTT channels is possible. However, in 33%, 42% and 49% of locations the reception of any DTT channel is impossible for 4000 m, 2000 m and 1000 m grids,

² ASTER GDEM is a product of Japan's Ministry of Economy, Trade, and Industry (METI) and NASA.



Fig. 2 CDF of the number of DTT signals available for reception over all locations in Kenya vs grid size

respectively. It shows that the utilization of a more accurate grid decreases the calculated DTT coverage in the considered numerical model. As such, a coarse grid, for instance, 4000 m, can be used for TVWS device power calculation, as it provides DTT reception protection in a wider area than a more accurate but computationally complex denser grid.

This observation is confirmed by the wanted DTT power distribution at the frequency of 474 MHz in Fig. 3. For locations where this DTT signal cannot be received successfully (CINR below threshold), $-\infty$ is assumed. It is visible that for all grid sizes the minimum wanted DTT power that, in favorable interference conditions, allows for DTT signal reception, equals about -78.7 dBm. The coverage area increases with the increasing grid size from 13.3% for a 1000 m grid to 18.5% for a 4000 m grid. The most limiting factor for TVWS devices' TX power is the percentage of locations where the DTT signal has low power, that is, close to the reception threshold, as these are the locations mostly constraining TVWS transmission. Considering a weak DTT signal of power lower than -60 dBm, there are 5.9%, 6.2% and 6.6% of locations where a weak DTT signal at 474 MHz has to be protected for 1000 m, 2000 m and 4000 m grids, respectively. As such, DTT protection calculated with a coarse grid should guarantee DTT protection with a finer grid as well.

These results allow us to use a grid of 1000 m in further studies, guaranteeing DTT protection (even for a finer grid), reasonable computation time and a relatively high amount of TVWSs.

Next, an important feature of DTT networks is Multi Frequency Network (MFN) or SFN design that is not taken into account in the original rules [4], as explained in Sec. 3. In Fig. 4, the distribution of the number of DTT channels available for reception in the whole Kenya area is presented. In the MFN case, transmission from a single DTT TX is interfered by all other transmitters. On the other hand, in the SFN case, all transmitters operating on a given frequency



Fig.3 CDF of wanted DTT signal power for locations with DTT reception possible (CINR > 27.1 dB) for UHF channel of frequency 474 MHz vs grid size



Fig. 4 CDF of the number of DTT signals available for reception over all locations in Kenya assuming MFN or SFN configuration

increase the wanted DTT signal power. Interference is created only by DTT transmissions on other frequencies. As expected, the SFN case provides higher coverage, e.g., the percent of locations not covered by any DTT signal drops from 49.3% in the MFN case to 45.4%. This is even more visible when analyzing the DTT coverage map in both cases, as it is visible in Fig. 5 for the 474 MHz channel. While the white color denotes a location with DTT signal reception impossible, the other locations are color-coded with colors varying from blue to yellow proportionally to the wanted DTT signal power. The chosen area has many transmitters (black stars in Fig. 5) that interfere with each other in the MFN case, reducing DTT coverage. The SFN assumption significantly increases DTT coverage. As such, the reference scenario will use full SFN assumption in further studies. We are aware that this approach overestimates DTT coverage, as SFN can work only for relatively closely located transmitters (for instance, to guarantee signals from various transmitters arrive at the DTT RX antenna with relative delay smaller than cyclic prefix duration used by the DTT system). How-



Fig. 5 Part of Kenya map of wanted DTT signal power for locations with DTT reception possible for MFN or SFN configuration. Channel frequency: 474 MHz. Transmitter locations marked with black stars



Fig. 6 CDF of the number of DTT signals available for reception over all locations in Kenya while changing the method of DTT-originated interference calculation

ever, the assumption that all transmitters operating on a given frequency create a single SFN guarantees that all DTT signal reception points are protected at the cost of a potentially reduced amount of TVWSs.

Finally, two additional changes are tested as suggested in Sec. 3, i.e., DTT-originated interference gain correction and the addition of DTT interference coming from the same transmission site. The distribution of the number of DTT channels available in each location over the whole Kenya area is shown in these cases in Fig. 6. The difference introduced by the two mentioned modifications to DTT coverage is negligible for the considered area and DTT network plan.

Based on the obtained DTT coverage maps, considering the numerical algorithm presented in Sects. 2 and 3, the maximum TVWS EIRP power in each location for each frequency channel can be calculated considering TVWS device class and its antenna height. Without the loss of generality, a device of class 1 will be considered with the antenna height of 10 m



Fig. 7 CDF of bandwidth available for TVWS transmission assuming EIRP density of 0 dBm/8 MHz, 20 dBm/8 MHz or 40 dBm/8 MHz over all locations in Kenya. Original and modified protection ratios considered

transmitting with vertical polarization. The considered UHF channels start from the center frequency of 474 MHz and end at the channel of center frequency 794 MHz, giving a total bandwidth of 328 MHz, that is, between channel edge frequencies of 470 MHz and 798 MHz.

An important parameter mentioned in Sect. 3 is the cochannel protection ratio (PR) that in the rules [4] equals 39.5 dB (original PR) but according to [20] can be equal to 28.5 dB (modified PR). A comparison of the amount of TVWSs (bandwidth) available across Kenya, assuming fixed TVWS TX EIRP densities is shown in Fig. 7 for the original and modified protection ratios. It is visible that the maximum EIRP density of 40 dBm/8 MHz is not available in about 6% of locations even for single channel utilization, no matter which co-channel protection ratio value is used (line with circles). Please keep in mind that most of these locations are limited by border protection (around 4% of all considered locations). The same curve shows that in 90% of locations more than 100 MHz of TVWS bandwidth is available, assuming full power transmission. If the required EIRP density decreases to 20 dBm/8 MHz or less, at least 104 MHz of bandwidth is available in any location (black lines: solid and dashed).

The modification of co-channel PR usually increases the available bandwidth. For EIRP density of 40 dBm/8 MHz the bandwidth increases by about 12 % for 50% of locations. For lower power densities this gain equals about 3% and 6% for 20 dBm/8 MHz and 0 dBm/8 MHz, respectively. As such, the proposed modification, if accepted by DSAL, can increase the availability of TVWSs.

Finally, for the original co-channel protection ratio, the influence of grid size on TVWS availability has been tested. The resultant CDF of TVWS bandwidth available over all locations in Kenya is shown in Fig. 8. Most interestingly, for all grid sizes the TVWS availability distribution looks similar, even though DTT coverage varies significantly with



Fig. 8 CDF of bandwidth available for TVWS transmission assuming EIRP density of 0 dBm/8 MHz, 20 dBm/8 MHz or 40 dBm/8 MHz over all locations in Kenya. Varying grid size considered

grid size, as shown in Fig. 2. Even though it is observed in the TVWS allowed power map that in certain locations on certain channels the maximum TVWS TX power varies, the total TVWS availability in a given area can be quite reliably estimated using a coarser grid.

4.3 Comparison of TVWS availability in Kenya and in other countries

It is difficult to find a reference paper that utilizes the same calculation methods and presents results for a whole country. Therefore, the comparison of TVWS availability between countries will be somehow biased by the chosen methodology. An interesting paper comparing TVWS availability in many European countries is [25]. It shows that the mean number of available TVWS channels averaged over the whole country area varies from 13.4 for the Czech Republic, to 23.1 for the United Kingdom, to 26.1 for Slovakia. However, this study presents an "upper bound" of TVWS availability, assuming 0 W power TVWS transmission. This can be compared to a median of 36 channels available for TVWS transmission with 0 dBm EIRP, according to Fig. 7. As the methodology used by us follows OFCOM rules, it is natural to compare our results with the ones obtained by "Ofcom TV White Spaces Pilot" [6]. It is reported that in the London M25 area for class 1 devices (the same as considered in our paper) there are, on average, 15.6 channels available, assuming EIRP of 30 dBm and TVWS TX height of 30 m (in our case, the results are presented for 10 m). The closest of our results is for 40 dBm EIRP, providing a median of 26 DTT channels available over the whole Kenya area. These two examples show that there are many more TVWSs in Kenya than in any European country investigated in these studies.

5 Conclusion

The DSAL rules facilitate dynamic access to the spectrum utilized by terrestrial television. The study has revealed a high amount of TVWSs that can be used for Internet access, e.g., in the case of Kenya, in 90% of locations TVWS transmitters can operate with EIRP of 40 dBm/8 MHz and bandwidth of at least 100 MHz. This result can be probably extended to many developing countries. The DSAL rules analysis and numerical comparison shows that while the grid size has a significant impact on the computational complexity and DTT coverage, the amount of available TVWSs is independent of this parameter. While implementing the rules special care should be given to the problem of SFN network configuration (it significantly increases DTT transmitter coverage but is not considered by the DSAL rules) and the co-channel protection ratio from TVWS TX to DTT RX (in 50% of locations the available bandwidth increased by 12% for the maximum transmit power while applying the co-channel protection ratio based on OFCOM rules [20]).

The authors see a few potential extensions of this work. First, the presented calculations framework can be used for other countries. This should allow for fair comparison and provisioning of recommendations regarding regions that can gain mostly from TVWS utilization. Secondly, if there is a large-scale TVWS trial in one of the modeled countries, it will provide a possibility to verify the accuracy of the DSAL rules and the proposal for their modification. Finally, while the manuscript recommends solutions to the reduce computational complexity of the calculations, there is still room for further improvements.

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Declarations

Conflict of interest Authors declare no conflicts of interests.

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