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On the Potential of TVWS Spectrum to Enable a Low Cost Middle Mile Network Infrastructure

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Abstract—The attractiveness of TV white space (TVWS) spectrum for last mile access in rural and developing regions has been recognized before. In this paper, we complement this existing work and draw attention to the potential of TVWS spectrum for enabling low cost middle mile connectivity to the Internet backbone. In particular, we examine the amount and nature of TVWS spectrum available towards this end, considering a representative rural setting in the UK, TV transmitter locations and their configuration, terrain information and antenna type. We introduce a new notion of receiver side usable spectrum that differs from the commonly considered available spectrum at transmitter side obtained from consulting a geolocation database. We find that cumulative interference from multiple nearby TV transmitters can severely reduce the amount of usable TVWS spectrum and also heavily fragments it. However, the use of directional antennas, as would be the case for TVWS backhaul links, negates this effect and suggests the possibility of high speed TVWS backhaul links via spectrum aggregation.

I. INTRODUCTION

Internet is widely acknowledged as a key infrastructure like other vital infrastructures and utilities (e.g., roads, electricity). Benefits of Internet access are wide ranging, easing information access and enabling applications in many areas including education and health. The ability of the Internet to foster economic growth has been well recognized. According to World Bank estimates, every 10% increase in broadband Internet access translates to 1-2% rise in gross domestic product (GDP). In low income and developing countries, Internet can be put to innovative uses, thereby serve as a developmental tool and lead to transformational impact.

Yet universal Internet access remains a challenge. 52% of the world's population does not have access to the Internet, per capita Internet users in very low income countries is even lower than 15 % and the major challenge lies in taking the Internet connectivity beyond the major urban centers to rural and remote areas [1]. This is significant given that in many developing countries majority of the population lives in rural areas. Even where Internet access is available, it is way too expensive for most people relative to their gross monthly income. It is important to note that the broadband access problem is not limited to developing countries alone. It is still an unresolved issue in rural areas of developed

countries including the UK. According to recent Ofcom analyses [2], while superfast broadband (download speeds 30Mbps or higher) is available at 89% of the UK premises, this percentage drops to 59% when considering only rural premises. Moreover, 25% of the premises in rural UK do not have access to 10Mbps broadband connections, now considered a basic level of broadband service.

The use of unlicensed wireless technologies (Wi-Fi and its variants) has proven to be a cost effective alternative for resolving the access issue in the last mile (few miles in several cases). However, the *middle mile or backhaul* (henceforth used interchangeably) network infrastructure — typically realized via fiber optic, licensed microwave or satellite links — connecting last mile networks with the Internet backbone (via an Internet point of presence) remains a challenge as it is the most expensive component of the network to connect users in non-urban and low income settings.

TV white space (TVWS) spectrum has the potential to be a significantly lower cost alternative for middle mile connectivity. TV white spaces at any given location and time refer to the portions of spectrum in the UHF TV bands (e.g., 470 - 790 MHz in the UK) which are not used by TV transmitters and wireless microphone users (the primary users of this spectrum). Led by the U.S. FCC in 2008, several countries including the UK have made the TVWS spectrum unlicensed (like with Wi-Fi devices) subject to interference protection for primary users (e.g., TV receivers) by consulting a geo-location database for available spectrum at a given location and time. TVWS spectrum is attractive for rural and middle mile connectivity for two reasons. First, it has superior propagation characteristics compared to other higher frequency bands in terms of range and non-line-of-sight (NLOS) propagation in presence of foliage and obstructions. For example, measurement studies confirm that it is possible to get 4 times greater range with TVWS spectrum compared to 2.4GHz unlicensed spectrum used by Wi-Fi [3]. This means lesser amount of infrastructure (fewer base stations) for connectivity over a given distance with TVWS spectrum and corresponding reduction in deployment costs. Second, there is a large amount of TVWS spectrum likely available in rural areas (in the region of 200+ MHz) with fewer TV transmitters and rare wireless microphone use. In developing countries, almost all of the UHF band is available as white space due to non-

existent or limited presence of over-the-air TV. This aspect is also beneficial for middle mile connectivity as it allows high bandwidth connections like the other expensive alternatives (e.g., fiber).

In this paper, we examine this potential for leveraging TVWS spectrum for middle mile connectivity through analysis of TVWS spectrum that could be used for this purpose, considering a representative rural region in the UK. Unlike the several previous studies on TVWS spectrum availability (e.g., [4]), we focus on the *quality* of the available TVWS spectrum to be able to enable middle mile links by accounting for not only the topography of the region but also the aggregate interference from nearby TV transmitters and relays. To this end, we introduce a novel TVWS receiver oriented notion of “usable” TVWS spectrum that differs from the commonly used TVWS transmitter side perspective on spectrum availability. Our analysis shows that aggregate interference from nearby TV transmitters can in fact have a significant negative impact on the usable TVWS spectrum for establishing middle mile links. Use of directional antennas, however, can counter much of this effect and thus is crucial for the TVWS backhaul case. Our analysis also sheds light on the nature of TVWS spectrum fragmentation for this use case and this in turn poses requirements for the design of spectrum aggregation systems for TVWS backhaul.

The rest of the paper is structured as follows. Next section discusses related work. Section III describes the methodology used for our analysis along with the newly introduced notion of “usable” TVWS spectrum. Sections IV-VI present the results from our analysis. Section IV highlights the negative impact of aggregate interference from multiple nearby TV transmitters. Section V shows the counteracting effect of using directional antennas while the nature of TVWS spectrum fragmentation for the backhaul use case is studied in Section VI. Section VII discusses the implications of the analysis results and identifies areas for future work. Section VIII concludes the paper.

II. RELATED WORK

TV White Spaces for Connectivity in Rural and Developing Regions. Rural broadband has been one of the key use cases for TVWS spectrum given its characteristics (see [5], for example). Similar arguments apply for exploiting this spectrum to address Internet connectivity challenges in developing regions [6]–[8]. Recent work in this area has started investigating how TVWS spectrum can be used in the context of current and future cellular network standards to enable rural coverage. CellFi [9] leverages TVWS and LTE standards to realize an unlicensed cellular network with some additional changes to standard LTE to handle the opportunistic nature of channel access in TVWS spectrum and unplanned interference experienced by TVWS secondary users. [10] consider the use of TVWS in the 5G architecture, supporting it with a cost analysis.

From the perspective of the particular use case of middle mile connectivity targeted in this paper, only one prior

work [8] from the literature considers TVWS based point-to-point (PTP) links and that too over short distances up to a few Kms. Other existing work largely focuses on the use of TVWS spectrum for last mile connectivity via point-to-multipoint (PTMP) links (e.g., [6]).

TVWS Spectrum Availability Studies and Measurements. Broadly speaking, TVWS spectrum can be accessed using either spectrum sensing or by consulting a geolocation database [11]. Early research and standards using TVWS spectrum employed the spectrum sensing approach (e.g., IEEE 802.22 [12], WhiteFi [13]). However, in view of the reliability and complexity concerns with the spectrum sensing approach, TV white space regulations in the US, UK and elsewhere have opted for the alternative geolocation database approach (e.g., [14]), which has also become the basis for newer TVWS standards (e.g., 802.11af [15]). Geolocation database systems in practice rely on mathematical propagation models along with the knowledge of primary user locations, similar to the several TVWS spectrum availability studies in the literature (e.g., [4], [16]–[18]). This has been argued to be too much in favor of incumbent protection, thus conservative and limit white space usage opportunities for secondary users [19]. These concerns along with increasing interest in using TV white spaces indoors have led to hybrid spectrum access techniques that augment geolocation databases with measurements [20]–[24].

Our work in this paper is novel compared to the above mentioned works in that it studies the following key aspects towards TVWS based middle mile connectivity for the first time: (i) considering the effect of interference from multiple TV transmitters; (ii) studying the benefit of directional antennas in mitigating this interference; and (iii) understanding the nature of spectrum fragmentation that is crucial from the perspective of aggregating spectrum to establish high-bandwidth middle mile links.

III. METHODOLOGY

This section describes the methodology we used for our analysis along with the newly introduced notion of usable TVWS spectrum. Regarding the TVWS spectrum, although it currently ranges from 490 – 790 MHz as per UK regulations [14], there is a plan to clear the 700 MHz band (694–790MHz) and allocate it to mobile operators [11]. Nevertheless, we consider the whole range as it is today.

Area and backhaul links considered. As noted at the outset, we are interested in examining the potential of TVWS spectrum for enabling middle mile connectivity in rural and developing regions. To this end, consulting the Urban-Rural Classification data [25], we select as a representative setting the rural region in the UK shown in Fig. 1 with dimensions 60 Kms \times 60 Kms. To guide the placement of TVWS backhaul transmitters and receivers in this large area, we divide it into smaller and equal sized pixels (0.67Km^2 for results in this paper). Each of these pixels is a potential location for TVWS transmitter/receiver.



Fig. 1: Representative rural region in the UK considered in our analysis.

While the placement of backhaul link transmitters and receivers¹ in practice need to also consider population distribution, access to grid power and other such factors, we take a general approach considering a wide range of backhaul links only taking into account the terrain/topography and its influence on radio signal propagation. To realistically model the radio wave propagation between a transmitter/interferer and receiver, we use the new Irregular Terrain With Obstructions (ITWOM v3.0) model implemented in the SPLAT! software package [26]. Concerning the length of a TVWS backhaul link, this could vary in practice from several Kms to few tens of Kms, we consider a fixed 10Kms length to limit the number of variables in our analysis. It is straightforward to repeat our analysis for other link lengths. Now to address the question of selecting the set of potential backhaul links considered in the selected area, we place a TVWS receiver in each pixel and pick a transmitter pixel location 10Kms away in the direction with least path loss (as determined by the above mentioned terrain based propagation model).

Interference calculation. At each pixel (i.e., TVWS receiver location) in Fig. 1, we calculate the signal-to-interference ratio (SINR) values as the ratio between the received power at the TVWS receiver (from its corresponding TVWS backhaul transmitter) and the sum of interfering power from all surrounding digital terrestrial TV (DTT) transmitters. We express the SINR value at a location κ as $\frac{P}{\sum_{i \in N} I_i + \text{noise}}$, where P is the received power from TVWS transmitter, N is number of DTT interferers. We obtained the information on location, transmission power, operating frequencies and antenna heights for all DTT stations from [27] maintained by Ofcom (the UK regulator). This information combined with

¹Depending on the deployment scenario and location of the Internet PoP, there could be a sequence of TVWS links with relays connecting them that make up the TVWS backhaul. But for the sake of simplicity, we focus on each such individual links in the backhaul path.

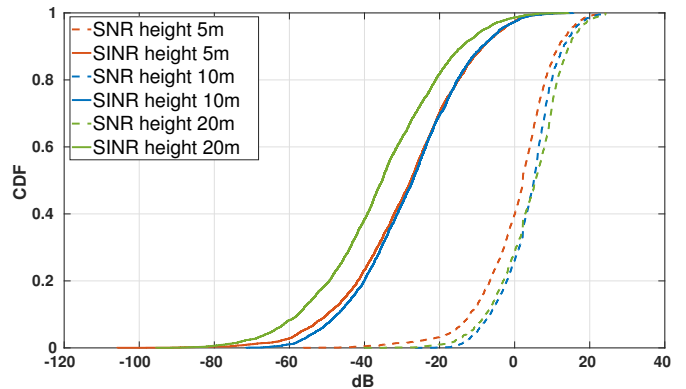


Fig. 2: Degradation in link quality (SINR) at TVWS backhaul receivers due to aggregate DTT interference for different TVWS device antenna heights.

the path loss calculated using the propagation model yields interference power from each DTT transmitter. To calculate the received power from the TVWS transmitter in question, we query the geolocation database with transmitter location to retrieve the list of available TV channels and their corresponding allowed transmission power in terms of Equivalent Isotropically Radiated Power (EIRP). As with interference power calculation, TVWS transmitter power discounted by the propagation related path loss gives the received power at TVWS receiver; we ignore cable related losses in our analysis. Note that as per Ofcom TVWS regulations, white space devices can fall in one of five classes, differing in their power leakage into adjacent channels [14]. We assume Class 1 devices with least power leakage in our analysis.

Usable TVWS channel. We now introduce the receiver oriented notion of a usable TVWS channel in the context of PTP TVWS backhaul links. Specifically, a TVWS channel at a location κ is considered usable if SINR exceeds a threshold ρ at that location. Denoting usability of a TVWS channel ch at location κ as $\Theta_{ch}(\kappa)$, we have:

$$\Theta_{ch}(\kappa) = \begin{cases} 1, & \text{if } SINR_{ch}(\kappa) \geq \rho \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Where $SINR_{ch}(\kappa)$ is the SINR value on channel ch at location κ and ρ is the usability threshold parameter. Depending on this threshold parameter, received power from TVWS transmitter and cumulative interference from nearby DTT transmitters, a channel that is considered available by the geolocation database at the transmitter may not be usable at the receiver. To study the impact of this parameter, we consider three different values for the threshold in our analysis: 5, 10, and 15 dB. Besides we also study the effect of TVWS transmitter/receiver antenna heights considering three different values: 5, 10 and 20 meters.

IV. NEGATIVE IMPACT OF AGGREGATE INTERFERENCE FROM DTT TRANSMITTERS

Contrary to common perception, the *effectively* available TVWS spectrum in rural areas can also be low just as in out-

door locations of urban areas due to the aggregate interference from multiple DTT transmitters. This would especially be the case when a TVWS receiver lies at the intersection coverage region of multiple surrounding DTT stations.

To better understand and quantify this effect, in Fig. 2 we compare the SNR and SINR at different TVWS receiver locations (pixels) in the area shown in Fig. 1, considering omnidirectional antennas and at different antenna heights. Note that SINR values here capture the effect of aggregate DTT interference while SNR values indicate the receiver perceived link quality ignoring this interference. Whereas median SNR is over 0dB, the median SINR values are lower than -30dB, more than 30dB drop in receiver signal quality solely due to DTT interference. Although increased antenna heights are expected to make this effect more pronounced and is the case for some antenna heights (e.g., 20m), it is not always the case (e.g., 5m). The reason is lowering the antenna height also increases the number of locations with non-line-of-sight (NLOS) links making the weak received power a bigger concern than DTT interference.

We now look at the question of how the degradation in receiver signal quality due to aggregate DTT interference manifests in terms of the number of channels that become unusable. To this end, Fig. 3 (a) presents the results for number of available/usable channels as CDFs considering different usability thresholds and a fixed TVWS device antenna height of 20m. As expected, given the rural region under consideration, the number of channels (the amount of TVWS spectrum) considered available at the transmitter side as per the geolocation database is quite high – above 20 channels (160 MHz in spectrum) in 90% of the locations and median number of available channels is around 30 (240MHz). However the number usable channels as per the TVWS receiver accounting for aggregate DTT interference drops significantly to less than 5 (40MHz) in 80% of the locations using any of the three reasonable link quality (SINR) thresholds considered. The difference in usable and available channels at different locations with different SINR thresholds is clearly shown in Fig. 3 (b). From this figure, we can observe that median drop in the number of usable channels (compared to available) is in the region of 25 (200MHz), a very significant reduction.

V. BENEFIT WITH DIRECTIONAL ANTENNAS

Results from the last section highlight the severe reduction in the number of usable channels due to aggregate DTT interference when TVWS backhaul link devices use omnidirectional antennas. In this section, we study the potential for mitigating this effect with directional antennas. Even without DTT interference, using directional antennas would clearly be a natural choice for P2P TVWS backhaul links as they have a signal amplification effect on both ends of the link due to gain of the antennas and this in turn results in range improvement for a given SINR threshold or improved SINR for a specified range due to higher received signal power. But our intention is to also consider the potential level of immunity to DTT interference that comes with the use of directional

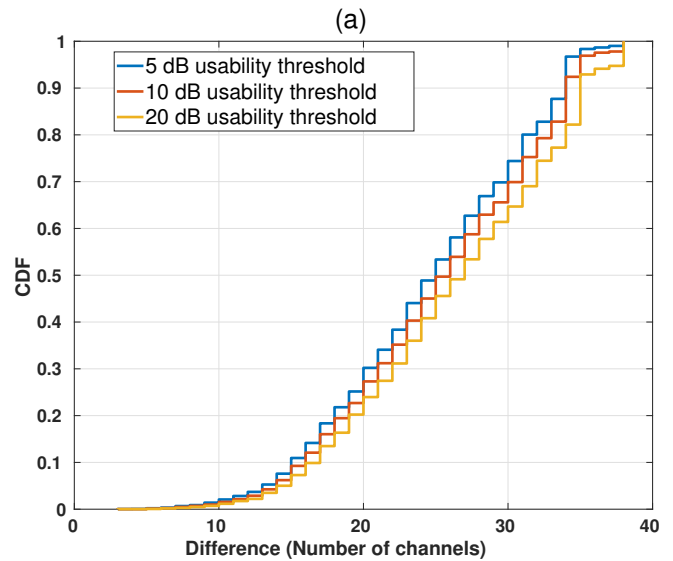
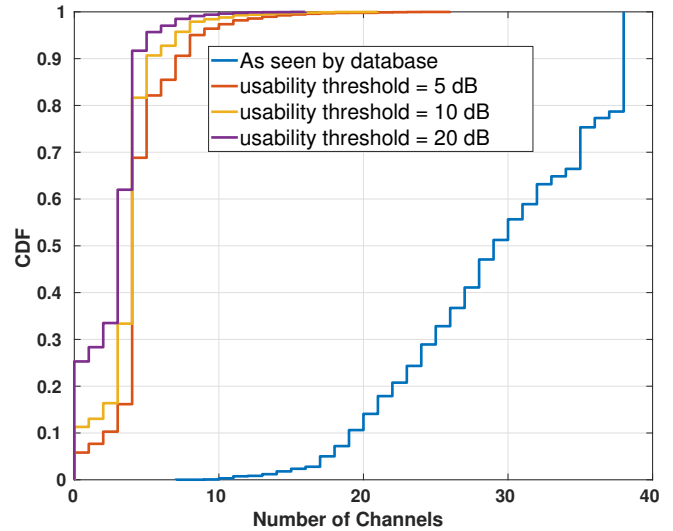


Fig. 3: (a) CDFs of the number of usable channels at the TVWS receiver with different usability thresholds in SINR levels compared to the number of available channels on the transmitter side as per the geolocation database for TVWS device antenna height of 20m. (b) Same results shown as CDFs of difference in number of usable and available channels with different thresholds.

antennas, i.e., suppression of interference from directions other than the main lobe of the antenna radiation pattern; this then would result in lowering the effective interference seen by the receiver and thus also contributes to a higher SINR.

To study the benefit from employing directional antennas at the TVWS devices, we consider a directional antenna with about 10 degree beam width and radiation pattern as shown in Fig. 4. To make a fair comparison with the previously considered omni-directional antenna case, we keep the EIRP level at transmitter side on every available TVWS channel identical in both cases, as prescribed by the geolocation

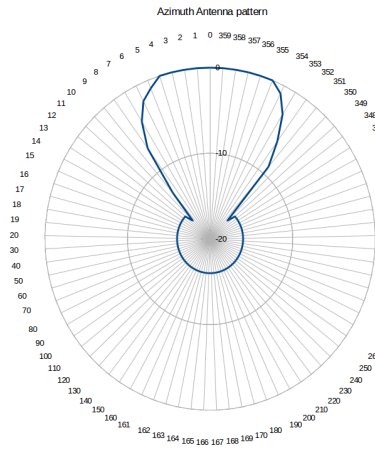


Fig. 4: Azimuthal antenna pattern for the directional antenna (with gain = 16 dBi) used in the analysis.

database; this essentially means the use of a lower transmit power in the directional antenna case.

Fig. 5 shows the results comparing the number of usable channels between omni-directional and directional antenna cases for different channel usability thresholds (ρ values) and at different TVWS device antenna heights. With all thresholds, there is a significant improvement in the number of usable channels with directional antennas. Whereas the median number of usable channels with omni-directional antennas is around 5 (40MHz) as seen before, this number increases with directional antennas to fall in the range of 15 – 25 (120 – 200MHz) depending on the ρ value. While this same conclusion across all different antenna heights considered, we can also observe that antenna directionality brings in a bigger advantage than lowering the antenna height. Overall these results clearly show that use of directional antennas at TVWS devices counter the negative effect of aggregate interference from nearby DTT transmitters to a large extent.

VI. NATURE OF TVWS SPECTRUM FRAGMENTATION

So far in our analysis, we focused only on the number of available/usable channels and the corresponding amount of spectrum without considering how this spectrum is distributed – contiguous versus highly fragmented. This is a key issue to understand in order to exploit the TVWS spectrum for enabling middle-mile connectivity by aggregating multiple TVWS channels; individual TVWS channels by themselves are small² and insufficient for this purpose. Generally speaking, non-contiguous spectrum in the same band is relatively harder to aggregate and fully exploit compared to the case where spectrum is available as a single chunk.

In order to better understand the nature of TVWS spectrum fragmentation for the rural middle mile use case, we consider

²Specific channel widths vary between regulatory regimes – 6MHz in the US, 8MHz in the UK and most African countries. But the fact that they are relatively much smaller compared to other bands (e.g., up to 160MHz in the 5GHz band) is clear.

three metrics: (i) number of TVWS spectrum fragments where each fragment is a contiguous chunk of usable spectrum that is at least the size of a single TVWS channel (i.e., minimum fragment size is 1); (ii) maximum fragment size (in terms of number of channels contiguously usable); (iii) percentage of fragmentation which is defined as $\Omega(\kappa)$ for a location κ :

$$\Omega(\kappa) = \left(1 - \frac{\text{Maximum fragment size}_{\kappa}}{\text{Total number of usable channels}_{\kappa}}\right) \times 100 \quad (2)$$

Note that $\Omega(\kappa) = 0\%$ is ideal as it means that all the usable spectrum is contiguous in one chunk. Higher values of this metric are less desirable and a value closer to 100 indicates a very high degree of fragmentation.

Figs. 6, 7, 8 show the results for the above three metrics, respectively, for different usability thresholds and antenna heights. Results for the omni-directional antenna case are included for completeness and as a baseline but our discussion of these results focuses on the directional antenna case based on the conclusion from the last section.

Starting with the results for the number of fragments metric (Fig. 6), we can observe that, regardless of the usability threshold and antenna height settings, the overall usable spectrum is divided into 8 or more fragments in half the locations. In over 90% of the locations, the number of fragments is at least 5. This indicates the aggregation of non-contiguous spectrum in the same band is inevitable in order to exploit all the usable TVWS spectrum.

Turning attention to the maximum fragment size (Fig. 7), the median value of this metric ranges from 3 to 10 channels depending on the usability threshold – higher the threshold, lower the maximum fragment size. Taken together with the above discussed number of fragments metric, these results suggest that exploiting all the usable spectrum at a typical location translates to aggregating 5 or more fragments, spanning over a wide range in size from 8MHz to around 160MHz.

Results on the percentage of fragmentation in Fig. 8 indicate that the level of fragmentation is quite high in general, consistent with the above observations – in 80% of the locations the overall usable amount of spectrum is 50% fragmented and the fragmentation level is above 70% in half the locations. In summary, these results suggest that TVWS spectrum is quite fragmented and using it for the rural middle mile case may in practice mean focusing on and aggregating the few biggest fragments.

VII. DISCUSSION

Our analysis results indicate that aggregated interference from multiple DTT stations can have a detrimental impact on the amount of usable TVWS spectrum in outdoor rural settings and also that this usable spectrum can be highly fragmented. To put these results into perspective, they reflect the situation in rural areas of developed countries with TVWS regulations like in the UK and substantial over-the-air TV use. In other regions with little or no terrestrial TV use, these effects would be relatively weaker and thus more amount of contiguous

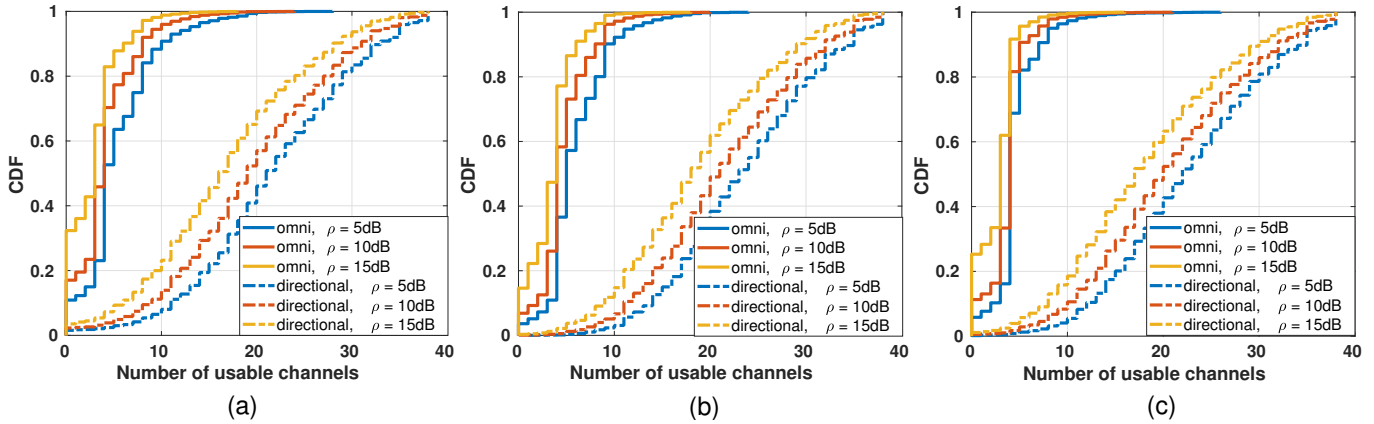


Fig. 5: Improvement in the number of usable TVWS channels using directional antennas compared to omni-directional antennas for different usability thresholds (5/10/15dB) and antenna heights: (a) 5m; (b) 10m; (c) 20m.

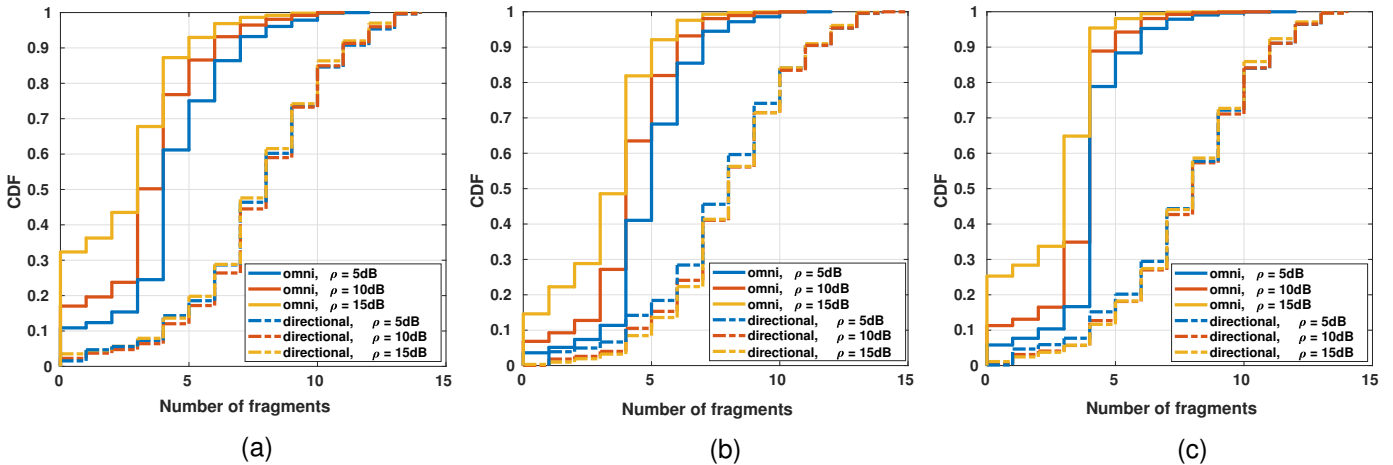


Fig. 6: Number of fragments of usable TVWS spectrum with different antenna types, usability thresholds (ρ) and TVWS device antenna heights: (a) 5m; (b) 10m; (c) 20m.

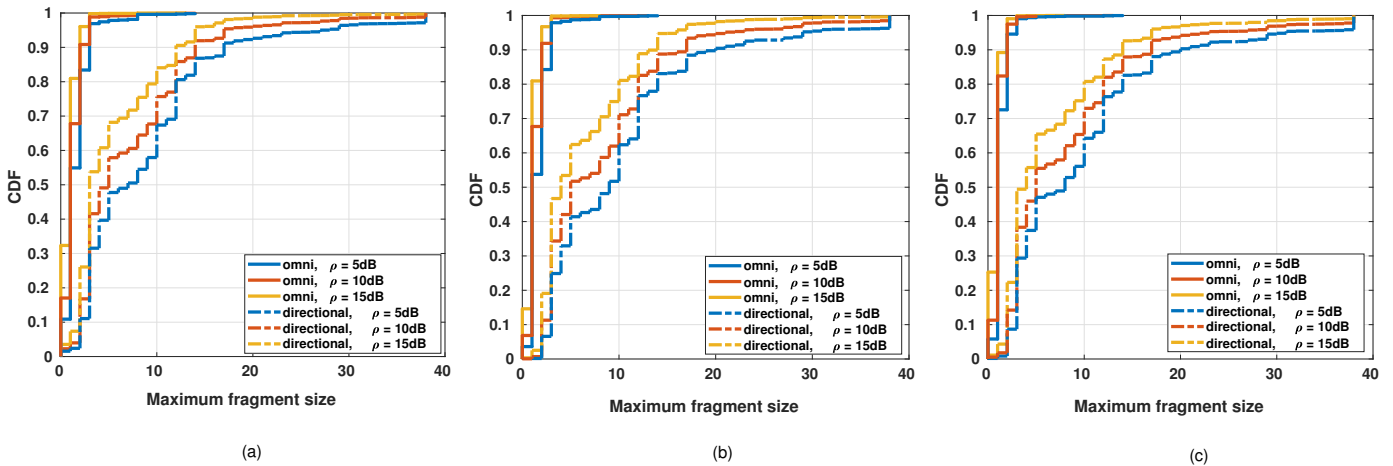


Fig. 7: Maximum fragment size of usable TVWS spectrum with different antenna types, usability thresholds (ρ) and TVWS device antenna heights: (a) 5m; (b) 10m; (c) 20m.

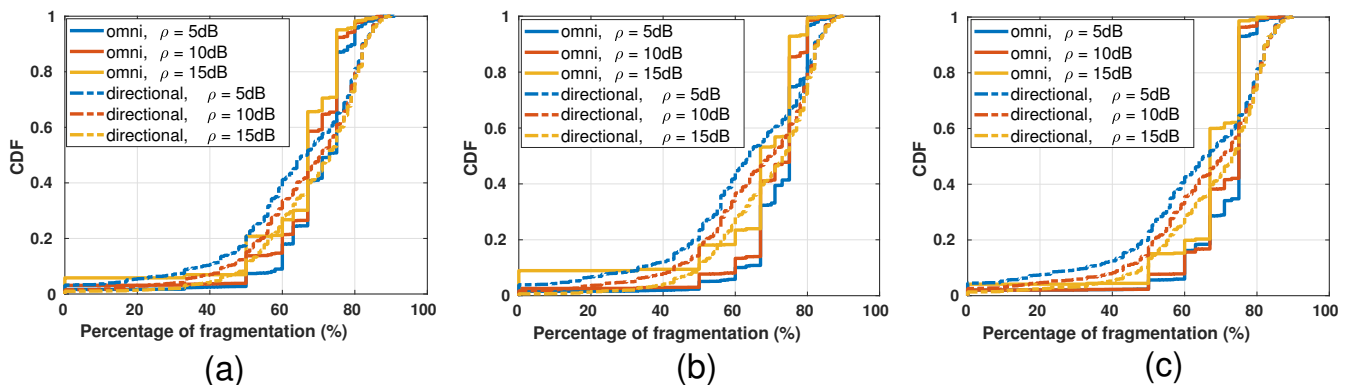


Fig. 8: Percentage of fragmentation of usable TVWS spectrum with different antenna types, usability thresholds (ρ) and TVWS device antenna heights: (a) 5m; (b) 10m; (c) 20m.

spectrum would be actually available to use for TVWS middle mile solutions. In that sense, the setting considered by the analysis in this paper is a relatively challenging one for TVWS based middle mile connectivity.

Concerning TVWS spectrum aggregation, which is shown to be essential to realize high-bandwidth backhaul links, there is no practical and low cost existing solution in the literature. Commercial solutions (e.g., newer generation of Carlson TVWS devices [28]) support limited aggregation to two 6MHz TVWS channels). Although in unlicensed 5GHz band used, more recent Wi-Fi standards support bonded contiguous channels up to 160MHz wide, such solutions are insufficient when spectrum is highly fragmented like our results show. LTE-Advanced carrier aggregation (CA) feature that in theory supports aggregation of intra-band non-contiguous spectrum is potentially a relevant approach although in practice only aggregation across different bands is currently supported. Aggregation of non-contiguous spectrum within a band requires the use of sophisticated and expensive filters to mitigate the interference among concurrent transmissions on adjacent chunks of the spectrum.

VIII. CONCLUSIONS

In recent years, TV white spaces have attracted the attention of the research and industrial communities to provide last mile solutions in rural and developing regions. In this paper, we instead examined the potential of exploiting TVWS spectrum for middle mile solutions. Different from the existing works in literature, we study the quality of available TVWS channels and how the available spectrum is fragmented. We show that the aggregated interference, observed at a TVWS receiver, coming from of multiple DTT stations is the main reason that risks making much of the available TVWS spectrum unusable even in rural outdoors. We have also shown that using directional antennas is key to mitigating this effect. Even though directional antennas can help recover some of unusable spectrum but TVWS spectrum is still quite fragmented. Thus, new cost-effective spectrum aggregation solutions are needed

to efficiently exploit the fragmented spectrum towards enabling high-speed TVWS middle mile infrastructure.

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