

A New Dynamic Spectrum Access Algorithm for TV White Space Cognitive Radio Networks

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Abstract: As more user applications emerge for wireless devices, the corresponding amount of traffic is rapidly expanding, with the corollary that ever-greater spectrum capacity is required. Service providers are experiencing deployment blockages due to insufficient bandwidth being available to accommodate such devices. *TV White Space* (TVWS) represents an opportunity to supplement existing licensed spectrum by exploiting unlicensed resources. TVWS spectrum has materialised from the unused TV channels in the switchover from analogue to digital platforms. The main obstacles to TVWS adoption are reliable detection of *primary users* (PU) i.e., TV operators and consumers, allied with specifically, the *hidden node* problem. This paper presents a new *Generalised Enhanced Detection Algorithm* (GEDA) that exploits the unique way *Digital Terrestrial TV* (DTT) channels are deployed in different geographical areas. GEDA effectively transforms an energy detector into a feature sensor to achieve significant improvements in detection probability of a DTT PU. Furthermore, by framing a novel margin strategy utilising a *keep out contour*, the hidden node issue is resolved and a viable secondary user sensing solution formulated. Experimental results for a cognitive radio TVWS model have formalised both the bandwidth and throughput gains secured by TVWS users with this new paradigm.

1. Introduction

A key driver for researching *Cognitive Radio* (CR) technology in a TVWS context is the omnipresent problem of the scarcity of available spectrum [1], [2]. This is reflected by the intense interest shown by telecommunication operators in deploying heterogeneous networks like *Long Term Evolution* (LTE) with Wi-Fi offload. The emergence of CR technology [1], [2] and the transference of TV channels from analogue to digital platforms [3], [4], [5], have combined to afford a unique opportunity to provide extra bandwidth for service providers. In a heterogeneous network example, LTE, Wi-Fi and unused TV channels offloading data, can successfully increase the available bandwidth to users, while still using the same backhaul infrastructure and existing LTE-based call set-up management channels.

TVWS is a prime candidate for exploiting CR behaviour because it is static spectrum so channels do not change in a particular location. This relaxes the requirement of efficient *primary user* (PU) updates since channels change only on a spatial rather than temporally basis [3], [4]. In order to exploit unused TVWS

spectrum, spectral *holes* [1, 2] must be identified using *dynamic spectrum access* (DSA) techniques [1], [4]. These can be broadly classified into three categories: beacons, sensing and static databases [3], [5].

Beacons are dedicated in-band signals that advertise whether a *secondary user* (SU) [3] can use a PU DTT channel. However, since the PU has to administer this process, it is not a viable option for DTT broadcasters due to the prohibitive overheads incurred.

Sensing techniques [3] in contrast, automatically update a PU database without human intervention so reducing operational costs while increasing accuracy by dynamically accommodating local variations in propagation. Traditional sensing approaches include matched filtering, cyclostationary, feature detection and energy detection, with a critique of the gamut of available sensing methods being given in [1].

Static databases require manual maintenance, and while system accuracy can be compromised because data is calculated from a theoretical algorithm rather than actually being measured, this option offers greater flexibility in accommodating special scenarios where sensing is not viable. Examples include *program making and special events* (PMSE) radio microphones [3], where a temporary licence is given for instance for a venue or auditorium.

This paper addresses the challenge of PU detection by introducing a new DSA technique called the *generalised enhanced detection algorithm* (GEDA) that exploits the unique deployment properties of DTT frequencies. GEDA uses a fuzzy logic inference model to convert a basic energy detector into a feature detector to resolve the uncertain nature of DTT signals. By employing a *keep-out contour* to protect the PU, an innovative solution to the hidden node issue is developed. GEDA also specifies SU transmit RF powers at call set-up, to ensure PU users do not experience interference, while concomitantly maximising the SU *Quality-of-Service* (QoS) experience. The available bandwidth for SU is framed as a QoS metric embodied by a *sterilisation index* (SI) which avoids recourse to using physical surveys. Importantly the SI considers the hidden node problem by incorporating the GEDA *keep-out contour* to determine available SU bandwidth on a channel and location basis.

The remainder of this paper is organised as follows: Section 2 reviews the relevant literature relating to CR and TVWS, while Section 3 presents details of the simulation models used. Section 4 provides an analysis of GEDA together with comparative results with existing sensing algorithms, while Section 5

critically investigates the pivotal role the *keep out contour* and SI play in resolving the *hidden node problem*. Finally, some concluding comments are provided in Section 6.

2. Literature Review

Both the UK *Office of Communications* (Ofcom) and the USA *Federal Communications Commission* (FCC) regulators have recently adopted standards allowing new CR broadband devices to operate in TVWS [3] [5] [6] [7]. The key TVWS engagement parameters specified by Ofcom, FCC and the IEEE 802.22 standard [5] are defined in Table 1. These include: the PU probabilities of detection and false detection; DTT sensing noise floor, SU transmit RF power for a *Base Station* (BS) node in the presence of PU adjacent channels; and SU transmit RF power for a mobile node in the presence of PU adjacent channel.

Table 1 Regulatory TVWS engagement parameters

Rule	Parameter	Ofcom	FCC	IEEE802.22
1	DTT Sensing Threshold	-120dBm	-114dBm	-114dBm
2	Wireless Microphone Threshold	-126dBm	-114dBm	-114dBm
3	SU Transmit Power Fixed Network Node 1st Adjacent Ch - $P_{BS(N+1)}$	4dBm	16dBm	-
4	SU Transmit Power Fixed Network Node 2nd Adjacent Ch - $P_{BS(N+2)}$	17dBm	36dBm	36dBm
5	SU Transmit Power Mobile Network Node 1st Adjacent Ch - $P_{M(N+1)}$	4dBm	16dBm	-
6	SU Transmit Power Mobile Network Node 2nd Adjacent Ch - $P_{M(N+2)}$	17dBm	20dBm	-
7	Out- of- Band powers	<-46dBm	-55dBc	-
8	DTT Bandwidth	8MHz	6MHz	6MHz
9	Probability of Detection	1	1	0.9
10	Probability of False Detection	-	-	0.1

Both the Ofcom and FCC parameter settings in Table 1 are dedicated to protecting PU in their respective countries. In contrast, IEEE802.22 is a SU-focused technology, with the specified parameters

being the maximum allowable transmit-power requirements, while corresponding PU protection is the responsibility of the respective country regulators.

The regularity framework in Table 1 has formed the basis for a variety of spectrum sensing proposals [6] [7] [8]. The co-operative spectrum sensing system in [8] for example, is an IEEE 802.22-based solution that uses the Rao test to measure the non-Gaussian noise level to improve the energy detection performance and includes a multi-user extension. A peak *false detection probability* (P_f) of 0.1 is defined, though a *detection probability* (P_d) of only 0.7 is achieved in the standalone configuration, rising to $P_d = 0.99$ in the co-operative mode. The former thus, does not uphold IEEE 802.22 requirements, while the latter marginally fails both Ofcom and FCC requirements, so giving impetus to investigate alternative sensing algorithms.

The two schemes in [6] and [7], respectively provide a Chinese and North American perspective to this sensing challenge. Both exploit the correlation between the frame headers and synchronisation blocks in a cyclostationary feature detection. $P_d = 0.9$ at -114dBm and $P_f = 0.1$ in [6], and while this conforms to the IEEE 802.22 standard (Table 1), it fails to meet the stricter requirements of Ofcom and FCC. In [7], P_d is also 0.9, but it has a much higher $P_f = 0.6$ at -22dB SNR so it fails to conform to any of the standards.

In contrast, [9] and [10] introduced an *Enhanced Detection Algorithm* (EDA) for PU detection to facilitate access to TVWS channels. EDA employs a *cross layer processing* (CLP) mechanism called the *cross-layer cognitive engine* which shares information between the *medium access control* (MAC) and physical layers, so energy sensing measurements dynamically influence DSA decisions [1], [10]. EDA innovatively exploits inherent patterns in the DTT frequency deployment to determine whether a PU occupies a particular DTT channel. By scanning adjacent frequencies on either side of the channel under investigation, this effectively turns the energy detector into a feature detector, with the *scan range* parameter B determining the number of channels to be sequentially scanned. Hence, if Ch_A is the DTT channel under review, EDA symmetrically scans $Ch_A \pm 1$, $Ch_A \pm 2 \dots$ up to $Ch_A \pm B$. Symmetrical scanning is used because the probability of a neighbouring DTT channel being below Ch_A or above is equal.

This affords a unique sensing option for DTT transmitters because regional DTT frequencies are deployed in clusters of 6 channels in the UK and due to DTT domestic receiver antennae groupings [11] and [12], these 6 channels can only lie within a possible bandwidth of 16 DTT channels. The corollary is that by scanning B channels either side of the channel of interest, the majority of occupied DTT channels in a region

are detected, with crucially, low false detection probabilities being achieved by maintaining a low B value. EDA [9] uses the sensed energy values in the scanned channels to resolve whether the DTT channel is occupied. This approach allied together with a geo-location database means EDA generates an accurate map of PU channel usage. The advantage of EDA, when coupled with a geo-location database, is that an accurate mapping of PU channel usage is obtained. PMSE devices can also be included in the database so reducing PU interference and increasing the available bandwidth for SU. While EDA conforms to the IEEE 802.22 standard with $P_d = 0.947$ and $P_f = 0.0641$, it does not uphold the stringent Ofcom requirements [3], [6], [10].

In 2011, a consortium of UK telecommunication operators and equipment vendors collaborated to test the feasibility of exploiting TVWS in locations in the city of Cambridge [4]. This trial enabled Ofcom to devise a standards framework proposal for license-exempt access to TVWS spectrum, which is assumed as the regulatory baseline for the new GEDA model presented in this paper. The trial undertook measurements to evaluate quantitatively the impact of allowing secondary access on PU. This helped to establish protection requirements to maintain the integrity of DTT PU, with the ancillary aim of stimulating wider industry exploitation of secondary access technologies in deploying user services.

While PU detection has been the principal focus, consideration must also be given to how the SU can be effectively deployed [13] and co-exist with the PU. In terms of SU deployment, these are generally classified according to the type of interference introduced to the PU, namely *co-channel* and *adjacent*. One approach is to institute an admissible *signal to interference noise ratio* (SINR) by defining a special *keep out contour* [13] governing the minimum distance between the PU protection contour i.e., maximum PU service distance, and any SU transmitter operating on the same frequency. This is the basis of the protection strategy adopted for GEDA, where a minimum SU distance is defined for a PU receiver.

One of the major considerations in any spectrum sensing strategy is the *hidden node* problem [1], [3] [5], [14], [15], [16]. This is where a SU sensing receiver shielded by an obstacle from a PU transmitter, falsely identifies a spectrum hole so potentially leading to major disruption of the PU network. This is especially critical at the PU cell edge where signal strength is low so this has to be factored into any PU sensing design, as in for example [14], [15], [16]. While various co-operative sensing solutions have been proposed to overcome the hidden node issue [8], this paper presents a novel algorithm that neither relies on co-operative mechanisms nor compromises the bandwidth available to the SU. The next section outlines the

model methodology in testing the GEDA effectiveness based on the outcome of the Cambridge trial [4] and subsequent regulatory decisions.

3. Test Models

Two CLP-based models are considered, namely a basic RF model [9], [10] and a fuzzy logic EDA model that uses a *Fast Fourier Transform* (FFT) energy detector [9] [10]. Both models encompass the regulatory requirements for the three TVWS standards, with Table 1 giving the corresponding TVWS engagement parameters.

The basic RF model comprises three constituent blocks: i) the DTT TVWS transmitter-receiver pair; ii) adjacent and co-channel noise generators; and iii) the sensing platform. The sensing platform comprises of an energy sensor and a fuzzy logic block [9], [17] which exploits *a priori* information concerning DTT frequency allocations [10], [11], [12] and shares information between the MAC and physical layers in making DSA decisions. The Egli propagation model [18] is used because this is specifically designed for TV distribution systems and includes a diffraction loss algorithm for obstacles, including beyond *Line of Sight* (LOS). Both CLP-based sensing models were implemented in Matlab®/Simulink [9], [10].

4. Generalised EDA (GEDA)

4.1 GEDA Design

EDA [9], [10] was designed for PU detection and to access TVWS channels by utilising energy sensing allied with a fuzzy logic decision block, which used information from both the MAC and physical layers to make the spectrum access decisions. The fuzzy block input was the sensor output for a reference channel and the maximum sensor output for either B channels up or down from the reference channel. For a specific DTT channel lying within the *uncertainty* range, and any other channel within B and also lying within the *uncertain* or *occupied* detection ranges, then the decision is weighted according to a set of fuzzy rules [10].

As highlighted in Section 2, while EDA upholds the $P_f=0.1$ requirement of IEEE 802.22 [7], it fails to achieve $P_d=1.0$ for the DTT sensing threshold [3], [5]. This provided the motivation for the development

of the GEDA paradigm, which uses certain EDA components, but importantly integrates a new refinement mechanism for selecting the B parameter to secure significant performance improvements.

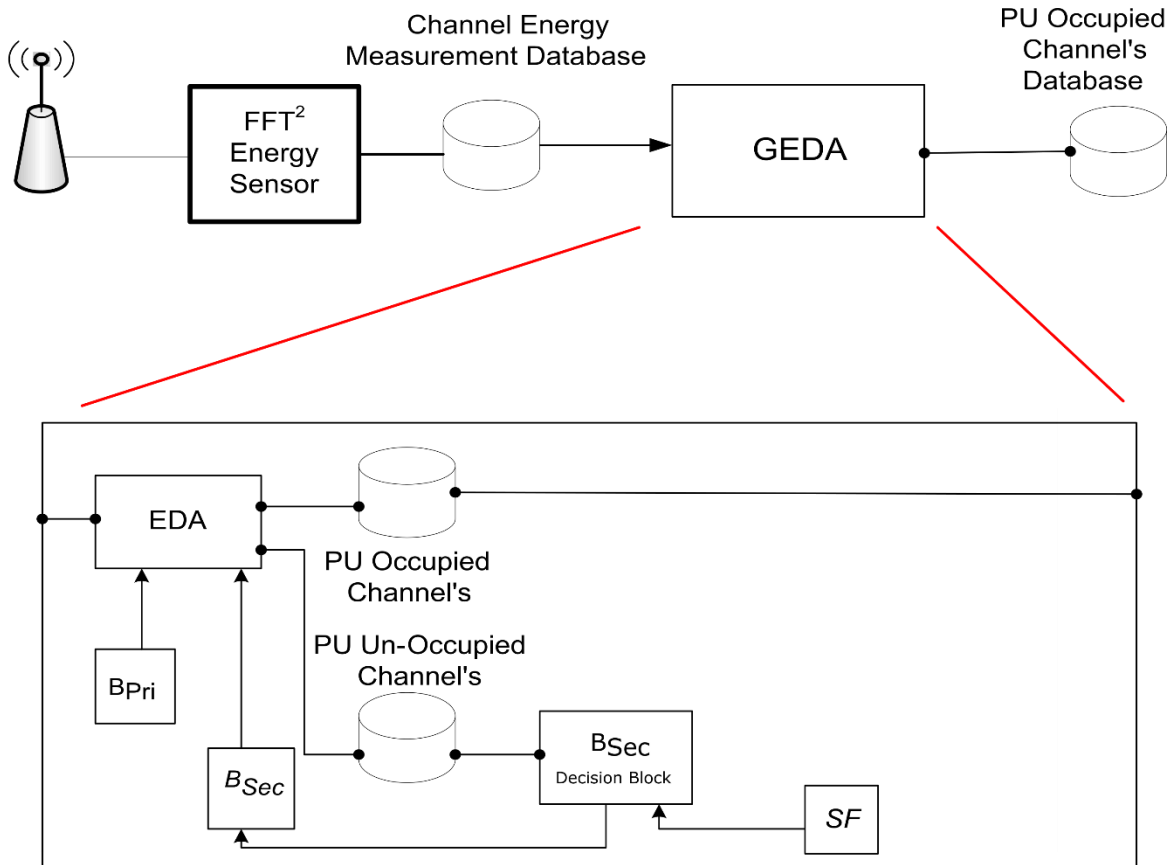


Fig. 1 The GEDA sensing model block diagram

Fig. 1 shows a block diagram of the GEDA model. In comparison with EDA [9], GEDA introduces three new system parameters, namely B_{Pri} , B_{Sec} and a *scaling factor* (SF). B_{Pri} is the initial scan range value of B used to evaluate channel occupancy in accordance with the IEEE 802.22 standard i.e., $P_d = 0.9$ and $P_f = 0.1$, while B_{Sec} is the higher B value, if required, which ensures an overall $P_d = 1$ once the first frequency scan using B_{Pri} has been completed. It is important to stress B_{Sec} cannot be directly used at the outset of sensing by GEDA because its higher value increases the likelihood of false detection which will compromise detection performance. It is thus, only used on occupied DTT channels that B_{Pri} cannot detect. Both B_{Pri} and B_{Sec} are country-specific and are determined from EDA using the corresponding B value that yields the respective P_d and P_f values.

GEDA detection can thus use either B_{Pri} or B_{Sec} for its DTT scanning range. The former is the initial scan range B value and in many cases, this is the only value required. In a few cases however, B_{Sec} has to be

used to achieve $P_d = 1$. Whether B_{Sec} is used is governed by the SF , which is the ratio of the highest to the lowest DTT frequency energy values, both of which are stipulated by the relevant regulatory authority [5]. Using this highest frequency (lowest RF energy) to the lowest frequency (highest RF energy) ratio enables a window of energy measurements to be defined within which it is feasible a PU DTT channel may trigger using B_{Sec} , provided the channel is in the unoccupied channel database. Thus, by scaling the lowest frequency energy measurement in the DTT channel occupied database obtained using B_{Pri} , a threshold for using B_{Sec} on an unoccupied DTT channel is established. SF is formally expressed as:

$$SF = \frac{|\mathcal{F}(RSS_{Hi_DTTFreq})|^2}{|\mathcal{F}(RSS_{Lo_DTTFreq})|^2} \quad (1)$$

where $RSS_{Hi_DTTFreq}$ and $RSS_{Lo_DTTFreq}$ are the respective *received signal strength* (RSS) measurements for the highest and lowest DTT frequencies for a preset distance between the DTT transmitter and receiver. The flowchart of the complete GEDA process is shown in Fig. 2.

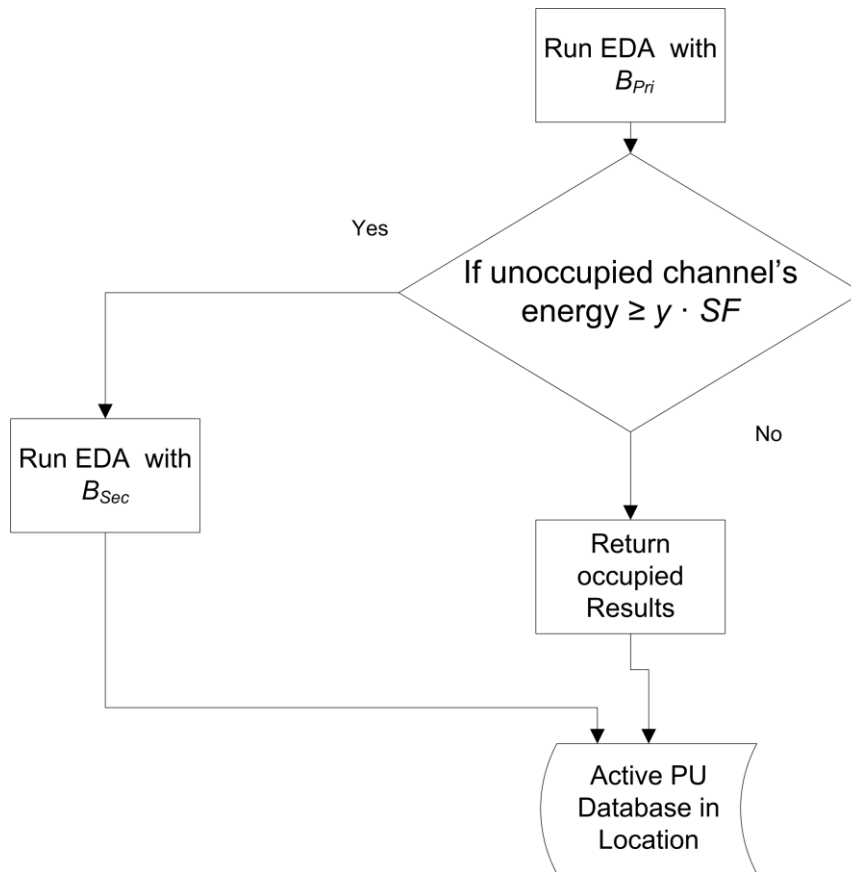


Fig. 2 Flowchart for the GEDA model with y being the energy measurement of the lowest occupied DTT channel

Using B_{Pri} , the initial PU sensing results are determined using EDA, from which a PU unoccupied list is compiled. If the criteria in (2) is upheld, EDA is reapplied but this time the DTT channel scanning is performed using B_{Sec} to assemble the final PU DTT channel occupied list (see Fig. 2).

$$IF \text{ unoccupied DTT channel energy} \geq \gamma \cdot SF \quad THEN \quad B = B_{Sec} \quad (2)$$

4.2 GEDA Results

To critically analyse the performance of the new GEDA model, the comparators in [6] and [7] were chosen as these correspond to sensing studies undertaken in China and USA respectively. Both sets of results were generated from a DTT deployment matrix of 22 sites. In [6], the same channel bandwidths and modulation schemes are used as in the UK DTT scenario, with $B_{Pri}=3$ and $B_{Sec}=7$. These B values were empirically determined according to the respective P_d and P_f values for the applicable channel deployment.

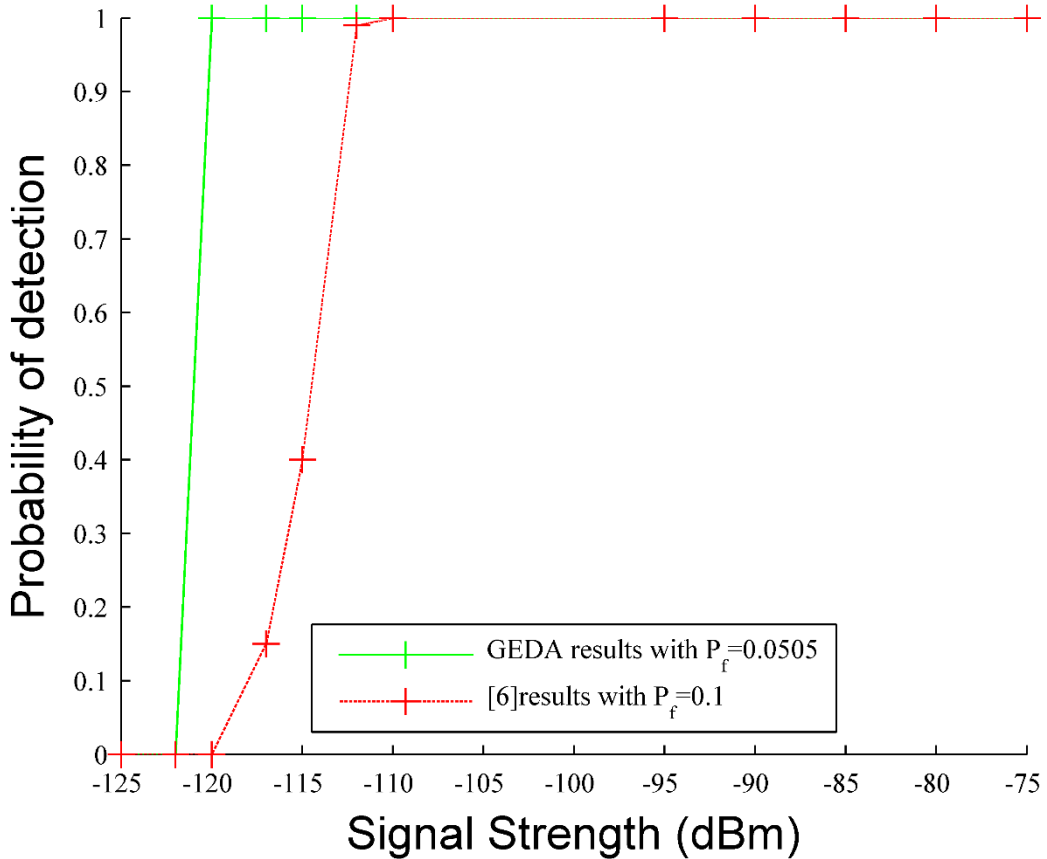


Fig. 3 The comparative detection probability performance of GEDA and [6] versus received signal strength (RSS)

Fig. 3 displays the respective performance of GEDA with [6] in achieving a $P_d=1$ at a signal strength of -120dBm. GEDA provides an improvement of 9dB in RSS, while the corresponding false detection rate is notably lower, i.e., $P_f=0.0505$ compared with $P_f=0.1$ [6].

The next set of results in Fig. 4 show how GEDA performs against the related American scenario [7]. For FCC channel deployment [7], $B_{Pri}=4$ and $B_{Sec}=9$, however to ensure an equitable comparison, both B_{Pri} and B_{Sec} values were varied between 1 and 9 so a wide range of P_f values were analysed.

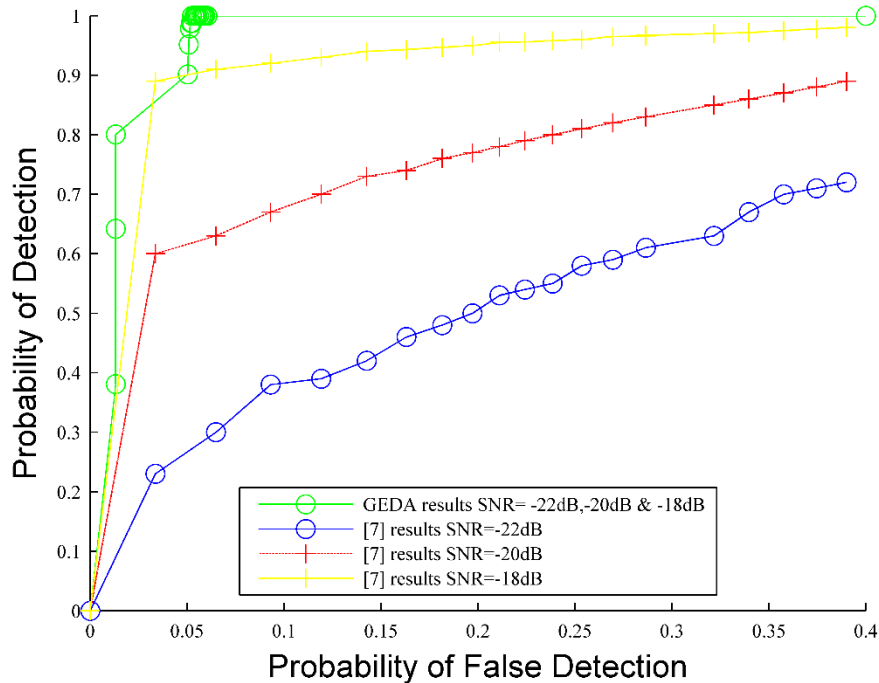


Fig. 4 The comparative detection probability performance of GEDA and [7] at various SNR values

These results demonstrate the superior robustness of GEDA at various SNR values. The reason for this improvement is that both comparator algorithms [6] and [7] depend on the detection of frame headers, which requires a certain SNR to exist. In contrast, the GEDA energy measurements are combined with the DTT channel deployment patterns, which effectively becomes a feature detector that is not dependent on demodulating the frame, and is thus autonomous of the prevailing noise environment.

5. Bandwidth available for TVWS devices

This section critically evaluates the potential of TVWS to make available extra bandwidth for SU cognitive devices. There are two key concepts to be analysed.

- i) The *Protection Contour* [13], which is a function of the DTT receiver being able to decode a DTT picture signal, even at the edge of a reception area, without incurring co-channel interference.
- ii) The *Keep Out Contour* which combines the protection contour and hidden node issue to establish a dedicated sterilisation zone for each specific DTT channel.

To assess how real DTT systems operate in the UK, both the average coverage distance from the transmitter for the Mendip area [10], [19], and the matching Egli terrain factor were calculated. Using the Mendip DTT area as the case study [19], without loss of generality, the Egli terrain value was empirically found =97%. It will now be shown how the above two concepts can be innovatively coupled to define how much bandwidth is available for SU TVWS cognitive devices. Each is now individually analysed.

5.1. *Protection Contour and Interference Management*

As highlighted above, the protection contour [13] depends upon the RSS at the edge of a DTT area, which is actually the worst-case scenario for a PU where no co-channel interference occurs. The related protection contour geometry is shown in Fig. 5.

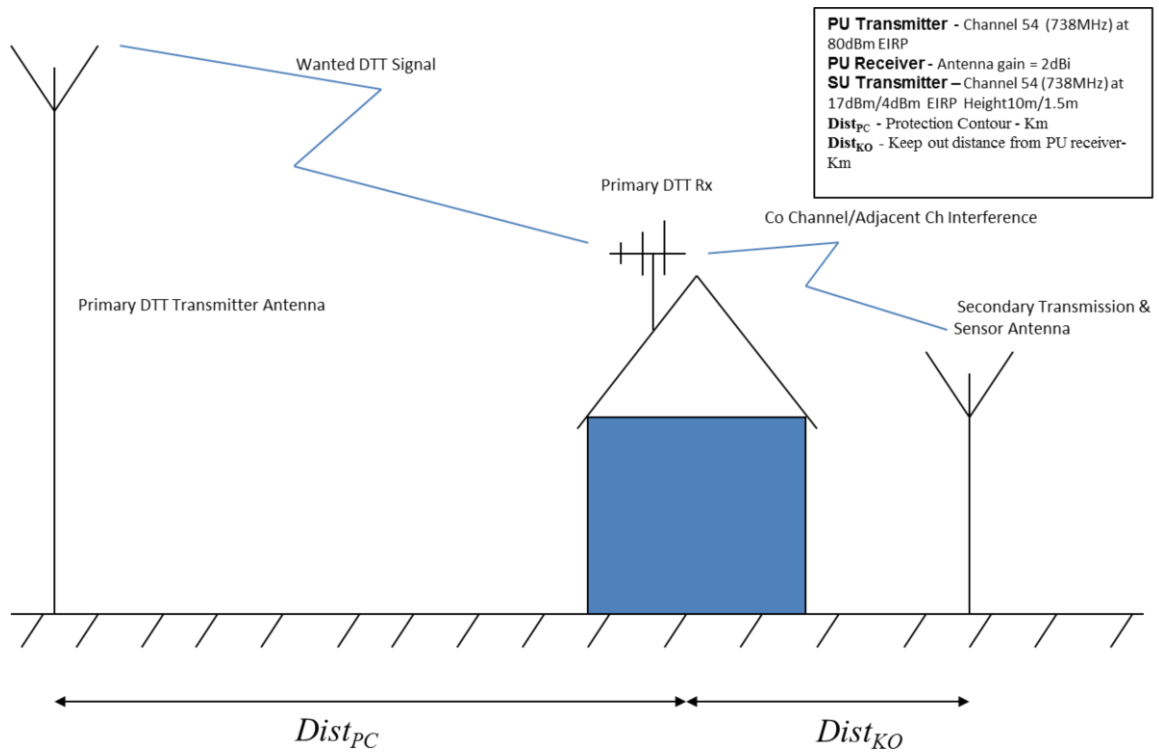


Fig. 5 Protection Contour Geometry for the Mendip DTT area

The *protection contour distance* ($Dist_{PC}$) [13] at the edge of the receivable DTT signal ($BER=2 \times 10^{-6}$) for the Mendip area is 63.101Km for Channel 54. This $Dist_{PC}$ value however, does not take into account two different sources of interference: i) *co-channel* – interferers on the same channel; ii) *adjacent channel* – interferers on channels adjacent to the PU [20].

For i), the DTT receiver is located on the protection contour, which for the Mendip model, means the $RSS_{PC} = -89.6dBm$. The co-channel interference signal is now increased until the BER exceeds the 2×10^{-6} threshold, which occurs at $RSS = -120.8dBm$. Using this value, a model was developed to determine the distance from the protection contour that would generate an interference of $-120.8dBm$ at the DTT receiver. It was assumed SU BS transmit *effective isotropic radiated powers* (EIRP) of 17dBm and 4dBm [3] were used, along with the TVWS parameters in Table 1, 16 QAM at 32Mbps raw data (user application data together with IP and MAC overheads), and an 8MHz DTT bandwidth. This equated to a minimum keep out distance ($Dist_{KO}$) of 3Km from the DTT receiver on the protection contour for the 17dBm SU, while $Dist_{KO}=1.4Km$ for the 4dBm SU. Both calculations crucially assume no margin for a hidden node.

For adjacent channel interference, the adjacent channel interference signal ($N+1$) was increased on the DTT receiver at the protection contour until the BER exceeded the 2×10^{-6} limit, which occurred when $RSS=16.56dBm$. This is the maximum allowable SU signal strength in this adjacent channel. Undertaking the same analysis for the ($N+2$) adjacent channel gave a maximum $RSS=189.57dBm$ for a SU.

To judge whether the Ofcom SU transmit powers of 4dBm for ($N+1$) and 17dBm for the ($N+2$) adjacent channel interference provide sufficient DTT PU defence against interference, the SU BS scenarios of RSS of both 4dBm and 17dBm on ($N+1$), and 17dBm on ($N+2$), 1m away from a DTT receiver were analysed. The respective ($N+1$) results were 4.84dBm and 17.84dBm, which endorses the Ofcom decision to limit the ($N+1$) transmit power to only 4dBm, as this is lower than 16.56dBm so it will not cause interference, unlike the 17dBm SU BS. In contrast, for the ($N+2$) channel case, the 17.84dBm RSS caused by a 17dBm SU BS is much lower than 189.57dBm, so no interference is generated.

While these co-channel results demonstrate the minimum distance away from the protection contour a SU can reliably transmit on the same channel, the hidden node issue [10], [14], [20] has not been reflected. From the above adjacent channel interference discussion, it is clear no interference is generated provided the Ofcom regulatory settings (Table 1) on the ($N+1$) and ($N+2$) SU power restrictions are upheld.

So far, the *hidden node* effect has been only considered in sensing a PU very close to an obstacle i.e. 10m and 20m away. The graph in Fig. 6 shows the sensor output at distances more than 65Km away from a DTT transmitter, for differing obstacle heights in the range 15m to 90m [21].

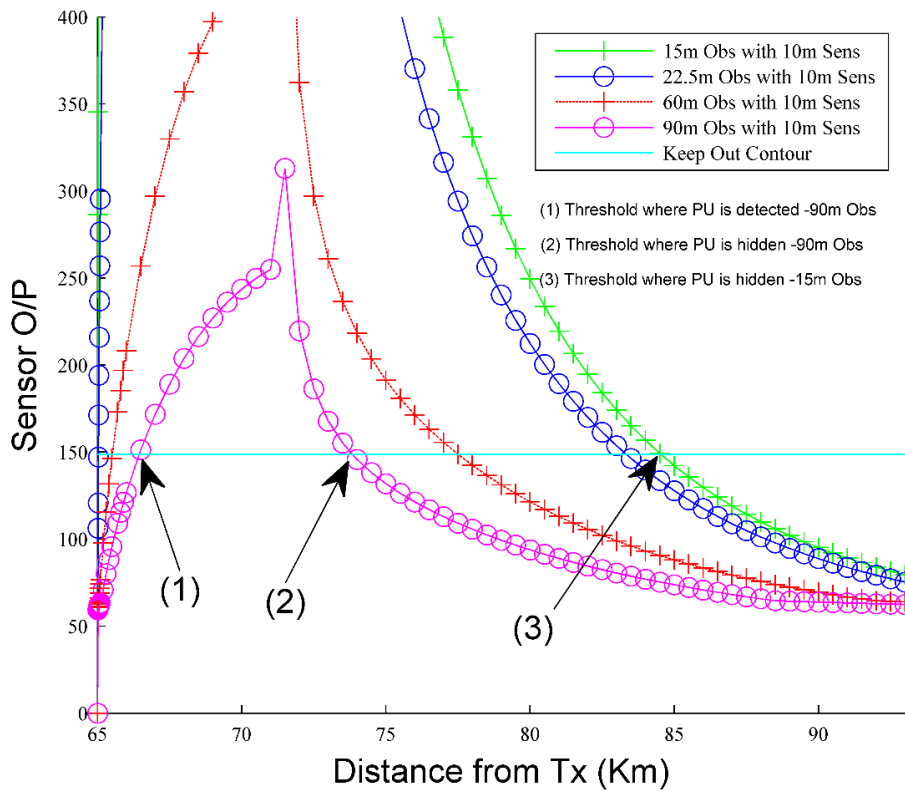


Fig. 6 Hidden node impact on the sensor output of varying height obstacles more than 65Km away from a DTT transmitter

These results confirm that devising a mechanism for extending the protection contour maximum co-channel interference RSS, to compensate for hidden nodes will be a pragmatic compromise involving the three highlighted points in Fig.6. Firstly, between reducing the detection threshold for the 90m obstacle close to the obstacle at (1), increasing the distance to (2), which is the threshold where the PU becomes hidden, and thirdly for the 15m obstacle, the far distance point (3) which effectively reduces the available bandwidth for a TVWS SU. The high spikes in Fig. 6 at 72Km, which is the RF horizon, are due to there being more even than odd Fresnel zones being cut by the horizon obstruction, hence increasing the RSS.

The next section examines the implications of obstacle diffraction due to hidden nodes, and introduces a *keep out contour* and *sterilisation index* that determines the amount of available bandwidth for TVWS SU devices, while resolving the hidden node problem.

5.2. Keep out contour

This is an exclusion zone around the DTT transmitter which offers protection to the PU receiver at the protection contour even when there is a hidden node present. It also provides sufficient bandwidth to TVWS devices to ensure their users receive the best QoS . The difference between the protection and keep out contours is that the latter includes a margin loss alongside the protection contour to permit prescribed interference RSS in the presence of hidden nodes as illustrated in Fig. 7.

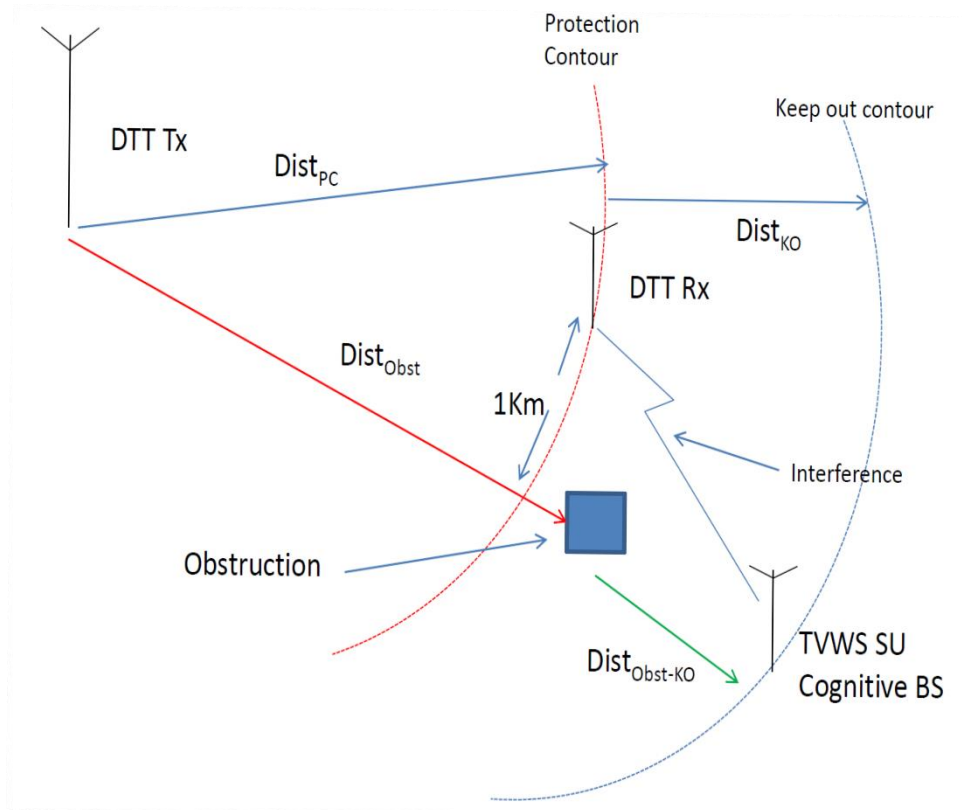


Fig.7 Keep out contour geometry

In the *keep out contour* geometry of Fig. 7, the main parameters are:

- i) $Dist_{PC}$ = protection contour for the lowest modulation scheme in the DTT deployment (see Section 5.1).
- ii) $Dist_{KO}$ = Distance from the *protection contour* to *keep out contour*
- iii) $Dist_{Obst}$ = Distance between an obstruction and DTT transmitter.

iv) $Dist_{Obst-KO}$ = Distance from an obstruction to the *keep out contour*.

To define the *keep out contour*, the distance from the protection contour in the worst-case scenario must be calculated, namely a 36dBm SU BS (maximum RF power see Table 1) producing an interference signal strength of -120.8dBm plus a margin for the hidden node. This margin is derived from the mid-variation point of the 90m obstacle diffraction loss at distances up to 400m away from an obstacle, where the most significant changes occur at 41.33dB. Using the interference models in Section 5.1, the corresponding distance $Dist_{KO}$ for this margin in the Mendip DTT region is 47Km. Distance $Dist_{KO} + Dist_{PC}$ now determines the minimum sensor threshold X_{KO} for the *keep out contour*. For the Mendip DTT area this is 148.7, which means any sensor output value lower than 148.7 will trigger the *keep out contour* to enable the SU to utilise that channel (see Fig. 6).

Fig. 7 reveals that while the distance to the *keep out contour* varies between highlighted points (2) and (3), depending on the obstacle height, X_{KO} remains constant. For the most typical residential scenario and a 15m obstruction, it can be assumed the maximum *keep out contour* distance is 84.53Km, which is the value used in channel re-use calculations. Note, the distance from the obstruction to point (1) is just 1.44Km which represents a special case where PU detection is only achievable using either a co-operative sensing strategy or special sensor heights [10].

The new GEDA model employs the *keep out contour* to determine active PU channels and to govern whether these channels can be used by a SU. The adjacent and co-channel interference management process is formally presented in pseudo-code form in Algorithm 1, with Table 2 defining the key parameters:

Table 2: Power control parameters

X_{KO}	Keep Out Contour energy (Section 5.2)
$P_{BS(N+1)}$	Regulatory definition for base station EIRP for adjacent channel (Table 1)
$P_{BS(N+2)}$	Regulatory definition for base station EIRP (Table 1)
$P_{M(N+1)}$	Regulatory definition for mobile EIRP for adjacent channel (Table 1)
$P_{M(N+2)}$	Regulatory definition for mobile EIRP (Table 1)
DB_{PU}	GEDA identified PU Channel database
DB_{DTT}	DTT Channel database containing channel numbers and energy measurements
$DB_{DTT}^{(Ch)}$	DTT Channel database channel number
$DB_{PU}^{(Ch)}$	GEDA identified PU Channel database channel number
$DB_{DTT}^{(E)}$	DTT Channel database energy measurement

Algorithm 1: Pseudo code for co-channel access and adjacent channel interference management using the *keep-out contour*

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1:      Inputs:  $X_{KO}, P_{BS(N+1)}, P_{BS(N+2)}, P_{M(N+1)}, P_{M(N+2)}, DB_{PU}, DB_{DTT}$ . Outputs:  $P_{BS}, P_M$ 
2:      Initialise:  $DB_{DTT}^{(Ch)} \in DB_{DTT}, DB_{PU}^{(Ch)} \in DB_{PU}, DB_{DTT}^{(E)} \in DB_{DTT}$ 
3:      FOR each channel  $DB_{DTT}^{(Ch)}$  DO
4:          FOR each channel  $DB_{PU}^{(Ch)}$  DO
5:              IF  $DB_{DTT}^{(Ch)} = DB_{PU}^{(Ch)}$  THEN
6:                  IF  $DB_{DTT}^{(E)} > X_{KO}$  THEN
7:                       $P_{BS} = 0$ 
8:                       $P_M = 0$ 
9:                  ELSE
10:                      $P_{BS} = P_{BS(N+2)}$ 
11:                      $P_M = P_{M(N+2)}$ 
12:                  END IF
13:              ELSE
14:                  IF  $DB_{DTT}^{(Ch)} = DB_{PU}^{(Ch)} + 1$  AND  $DB_{DTT}^{(E)} > X_{KO}$  THEN
15:                       $P_{BS} = P_{BS(N+1)}$ 
16:                       $P_M = P_{M(N+1)}$ 
17:                  ELSE
18:                       $P_{BS} = P_{BS(N+2)}$ 
19:                       $P_M = P_{M(N+2)}$ 
20:                  END IF
21:              END IF
22:          END FOR
23:      END FOR

```

Steps 5 to 13 allocate SU transmit RF powers when it is a co-channel interferer to a PU channel, while Steps 14 to 20 determine if the SU is an adjacent channel interferer ($N+1$) or ($N+2$) to a PU channel. If either $P_{BS}=0$ or $P_M=0$, then a SU is not allowed to transmit on the given channel.

In [4] and [22], the calculation of available TVWS bandwidth at any location was determined from physical RF surveys, which incurred considerable resources, so GEDA has adopted an alternative strategy to assess the amount of SU bandwidth available using the *keep out contour* and a *sterilisation index* (SI).

The UK DTT network consists of major regions, with each having minor transmitters operating within their boundaries to overcome local propagation issues so ensuring populated areas have service coverage. In contrast to this DTT deployment, America has distributed major transmitter sites covering a region, though the *SI* technique is still applicable. The *keep out contour* area of the adjacent main minor DTT transmitters transmitting within a major DTT area is $F \text{ Km}^2$ per DTT channel per transmitter.

If $Y \text{ Km}^2$ is the area covered by the furthest *keep out contour* of a major transmitter serving a UK DTT region, then for a distributed deployment like the US, this will represent the area covered by the radius of the furthest away transmitter *keep out contour*, added to the distance from the transmitter to the centre of the region under analysis. SI is thus formally defined as:

$$SI = \frac{F}{Y} \quad (3)$$

where the SI is calculated on per channel, per transmitter basis, with each individual si_{mn} value used to construct a primary area SI' matrix.

$$SI' = \begin{pmatrix} si_{11} & \cdots & si_{1n} \\ \vdots & \ddots & \vdots \\ si_{m1} & \cdots & si_{mn} \end{pmatrix} \quad (4)$$

where n is the number of DTT Channels i.e. 32 in the UK, and m is the number of transmitters radiating into area Y . If two different transmitters use the same channel, with one *keep out contour* area nested within another, then the lower si_{mn} value is set to zero.

The final step is to sum all columns and resulting rows in (4) to form a final SI value.

$$SI = \sum_{i=1}^n \sum_{j=1}^m SI'_{ij} \quad (5)$$

The SI determines the available bandwidth in the DTT area under investigation by $(N-SI) \times BW \text{ MHz}$, where N DTT channels of bandwidth of $BW \text{ MHz}$ area assumed in the country of interest. The next section investigates how the SI can be applied to determine the number of TVWS channels available in the specific case study area of the Mendip region.

5.3. UK Case Study for TVWS in the Mendip DTT transmitter area

All the major, adjacent and minor transmitters of either 50W or more [23] in the Mendip DTT transmitter area, together with their corresponding SI values are displayed in Table 3.

Table 3: Corresponding SI values for the DTT Major, Adjacent and Minor Transmitters of 50W or over

Transmitter Site	SI
Mendip	6
Wenvoe	3.495
Pontypool	0
Bristol Kings	0.36
Cirencester	0.12
Stroud	0.162
Bath	0.132
Hannington	0.942
Cerne Abbas	0.1584
Stocklands Hill	3.15
Salisbury	0.6
Bristol IC	0

Using the *SI* values in Table 3, the overall *SI* in (5) is 15.1194, which equates to an available bandwidth of 135MHz for TVWS SU devices, when considering all transmitters of either 50W or greater. However, there are 60 minor DTT transmitters operating below 50W that must also be taken into account. To do this efficiently, the average antennae heights and EIRP values are used to determine the *SI*. The *SI* for each channel was found to be 0.0133, and since 3 channels are allocated to each minor transmitter, $SI=2.4$. This is now added to (5) giving a total $SI=17.5194$, so the average available bandwidth for TVWS over the entire Mendip area is 115.85MHz. While this represents the average available bandwidth for the Mendip DTT region, it recognises this will vary according to locality. In heavily populated areas, it will reduce while in rural areas it will increase. This corroborates the findings in [5], which based on measured availability and geo-location database access, showed that in the largest city (Bristol) in the Mendip DTT region, 104MHz of bandwidth was available for TVWS devices.

Other Ofcom studies [22] suggest that over 90% of the population can access at least 100MHz, aggregated across the interleaved spectrum. They also estimated that $\approx 50\%$ of the population could have access to 150MHz or greater and some rural communities could enjoy more over 200MHz of this spare capacity [15]. These findings underscore the importance the *keep out contour* threshold and *SI* play in releasing valuable bandwidth for SU TVWS exploitation, while upholding the *QoS* provision for PU DTT users. As an illustration, the SU gains secured for the Mendip region using the *SI* is approximately 6 x 20MHz LTE RF bearers per location. This translates to an increase in the number of active data users in a LTE cell location from 800 to 4600, if a TVWS access node is used in conjunction with an LTE eNodeB, i.e., an improvement of more than a factor of 5.

6. Conclusion

TV White Space (TVWS) offers the prospect to enhance existing licensed spectrum by exploiting unlicensed resources. One of the principal hurdles to TVWS adoption is the reliable detection of *primary users* (PU) and the omnipresent *hidden node* problem. This paper has presented a new *Generalised Enhanced Detection Algorithm* (GEDA) that exploits the unique way *Digital Terrestrial TV* (DTT) channels are deployed in different geographical areas. GEDA transforms an energy detector into a feature sensor to achieve significant sensing improvements compared to existing solutions for DTT PU detection. By applying a *keep out contour* allied with a novel *sterilisation index*, the hidden node scenario has been resolved and a practical sensing solution for *secondary users* (SU) developed. Experimental results confirm the GEDA and *keep out contour* interference management paradigm leverages additional bandwidth for TVWS SU to secure notable *QoS* improvements, as demonstrated in the UK Mendip DTT transmitter region case study. Importantly, the GEDA model is transferable to alternative DTT deployments in other countries.

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