Preventing Interference to DTV Broadcasting in Every Market from Unlicensed or Uncontrolled Clusters of Broadband Devices on Unoccupied DTV Channels

O. Bendov

***Abstract* – The threat of interference to licensed DTV by clusters of unlicensed and uncontrolled broadband devices (BDs) transmitting simultaneously on unoccupied DTV channels remains. DTV channels in major U.S. cities could be victimized by interference from unlicensed or uncontrollable clusters. This paper shows how and why interference by clusters of broadband devices would be significantly higher than interference by individual broadband devices or by interference from clusters of single-tone devices. This paper also provides a real-world assessment of the maximum interference that consumer-grade receivers can accept from clusters of broadband devices operating on unoccupied DTV channels. To prevent interference to DTV and to maximize spectral efficiency individual base stations would have to be licensed as part of a network, and portable unlicensed devices would have to be equipped with dual DTV tuners with GPS chips.**

***Index Terms* – Broadband devices, licensed, unlicensed, clusters and interference.**

I. INTRODUCTION

The conflict and consequences of unfettered use of scarce public resources to accommodate individual interests are analyzed in a well-known essay [1]. Unfettered access to the unoccupied[1] DTV channels poses a threat to the public in its reliance on free television. In hindsight, this threat can be attributed, at least in part, to the inefficient packaging of the DTV spectrum [2], the failure to designate a comprehensive table of DTV taboo channels, and to the lack of mandated minimum performance standards for consumer-grade DTV tuners. The Federal Communications Commission's (FCC) mandated minimum tuner performance specifications [3] in order to encourage the development of UHF analog television, but they were not extended to DTV tuners. Moreover, DTV tuners are integrated on a chip and thus are not capable of the in-band selectivity of the best analog TV tuners.

There is no way for BDs to know how close is the nearest TV set that they might interfere with. Yet, that distance must be estimated so that the BD interference power is under control. To estimate their allowable transmission power, BDs must also acquire their own coordinates and estimate the received power of all DTV channels (with known transmitter's coordinates and transmission power) that must be protected.

The author is with TV Transmission Antenna Group, Inc., Cherry Hill, NJ 08003 USA (e-mail: oded@tvantenna.tv).

[1] There is more than one way to define "unoccupied" or "unused" channel. See [5].

That can be accomplished with global positioning system (GPS) and TV tuner chips that are already ubiquitous in consumer hand-held devices and could be inexpensively incorporated into all BDs.

A quantitative description of interference by clusters and the maximum allowable interference into consumer-grade DTV tuners is covered in Sections II-IV. Sections V-VI present a solution that would permit unlicensed but controlled portable BDs to coexist with DTV broadcasting free of interference by clusters.

II. DEFINITION AND PROPERTIES OF 3RD ORDER INTERFERENCE BY SYMMETRICAL AND EQUAL-POWER BDs CLUSTERS

Clusters are defined here as undesired devices transmitting on contiguous or equally spaced DTV channels. The channels are spaced by NΔ where Δ is the bandwidth of a single DTV channel.

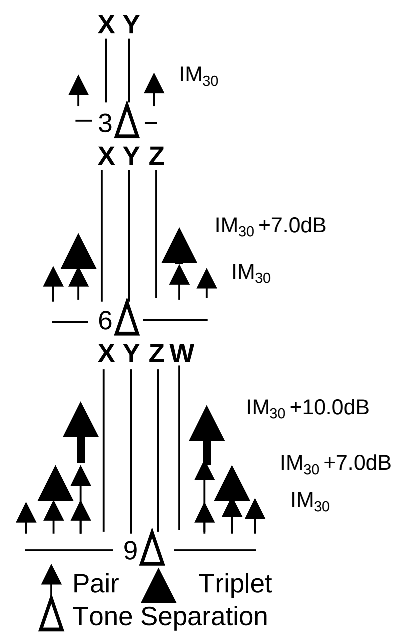

Figure 1: 3rd Order Intermodulation Products of Single-Tone Devices X,Y,Z,W

Figure 1 shows the 3rd order intermodulation components outside clusters of two (XY) to four (XYZW) single-tone devices separated by Δ. Regardless of how many devices constitute the cluster, the IM_3 sidebands are made only of triplet and pair combinations of the single tones. This is proven in Appendix A.

As will be shown next, clusters of BDs do not exhibit the IM_3 bandwidth and interference power properties that define clusters of single-tone devices. For example, two contiguous BDs occupy twice the bandwidth of two single-tone devices and their IM_3 on 1^{st} adjacent channels is higher by 8.5 dB than that due to two single-tone devices.

In Appendix B it is shown that failure to recognize the differences between BDs and single-tone devices has resulted in publishing an erroneous analysis.

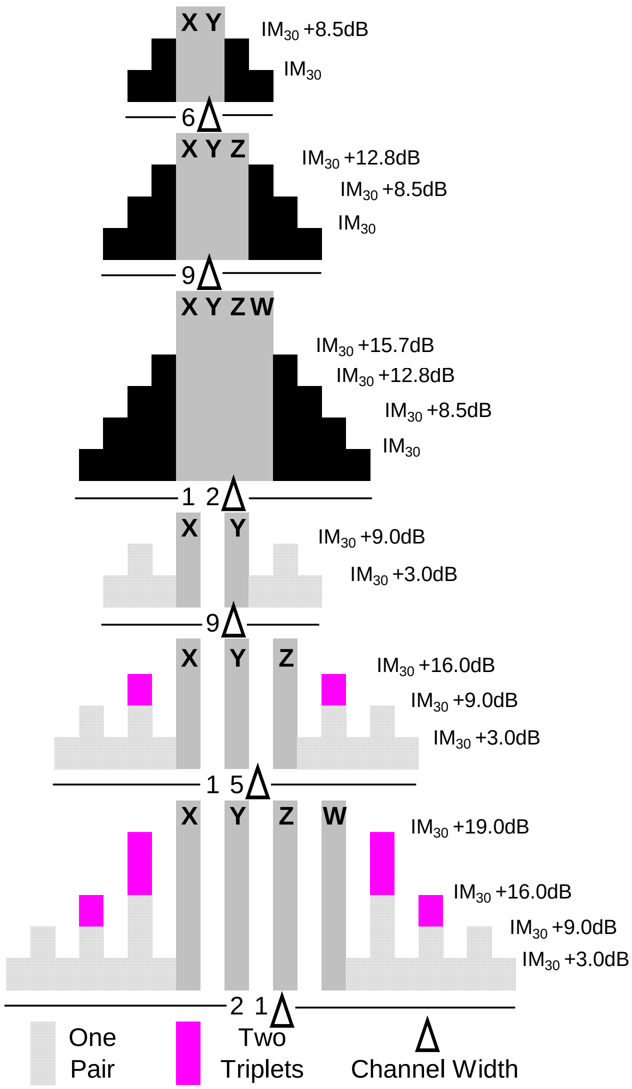

Figure 2: Virtual IM_3 Channels Generated at the DTV Receiver by Actual Broadband Devices X,Y,Z,W

Figure 2 shows the virtual IM3 channels generated outside clusters of two (XY) to four (XYZW) actual BDs. The IM_3 of contiguous N BDs, separated by one channel from each other, spreads over 3N channels whereas the IM_3 of non-contiguous BDs separated by two channels from each other spreads over 3(2N-1) channels.

It takes at least two single-tone devices to generate IM_3 sidebands in the output of a non-linear mixer or amplifier but a single BD already generates IM_3 power in its 1^{st} adjacent channels [4]. That power, equal in each of the 1^{st} adjacent channels, is given by:

$$IM_{30}(dBm) = 3U(dBm) - 2IP_3(dBm) \qquad (1)$$

where U is the power of a *single* BD and IP_3 is the 3^{rd} order intercept point at the input of the non-linear system of amplifiers and mixers.

As shown in Figure 2, when multiple BDs transmit simultaneously, the sideband power and its bandwidth are increased to magnitudes that are significantly different from those of single-tone devices shown in Figure 1. The theory of equal-power BDs, contiguous or separated by 2Δ, can be found elsewhere [5]. In Figure 2, Δ equals the width of one BD channel and 2Δ spacing was chosen to be the minimum spacing between non-contiguous channels so as to avoid the complexity of cross modulation. The IM_3 in the unused spacing between the non-contiguous BDs is not shown in Figure 2 because it is assumed that BD operation on 1^{st} adjacent channel to DTV will not be permitted and thus the victimized DTV channels will be outside the shown BD clusters.

A DTV channel anywhere inside the entire bandwidth of a cluster will be victimized by cochannel interference (CCI). Assuming that BDs on the 1^{st} adjacent channels to DTV are prohibited, the highest level of CCI will be experienced by DTV on 2^{nd} adjacent channel to the BD cluster. *In an unlicensed or uncontrolled environment any user could rig portable devices to simultaneously transmit on clusters of unused DTV channels in order to increase his data throughput. Herein lies the worse threat to terrestrial DTV broadcasting.* In the next section it is shown just how susceptible DTV stations in major U.S. cities are to interference by clusters.

III. CLUSTERS IN MAJOR U.S. CITIES

As shown in Table I[2], the potential for severe interference by BD clusters such as those described in Section II exists in every community, including the top five DTV markets in the U.S. That interference would materialize unless the transmission power of clusters of BDs, none cochannel or adjacent channel to licensed DTV channels, is significantly curtailed.

For example consider DTV channel 34 in Philadelphia. A cluster of four BDs on channels 37-40 would have its lower IM_3 sideband on channels 33-36 and as shown in Figure 2, the CCI power from this cluster into channel 34 would be IM_{30}+8.5 dB. The three BD pairs on channels 39+44 [n+5; n+10], 29+24 [n-5; n-10] and 40+46 [n+6; n+12], each with CCI power is IM_{30}+9.0 dB, could also add CCI into DTV 34. Of the 50 licensed UHF DTV channels in Table I, only 3 are not subject to

[2] Base on the August 2007 Final Assignment of Digital Television Channels in the U.S.

interference by BDs that are off-channel and off-1st adjacent channels to DTV.

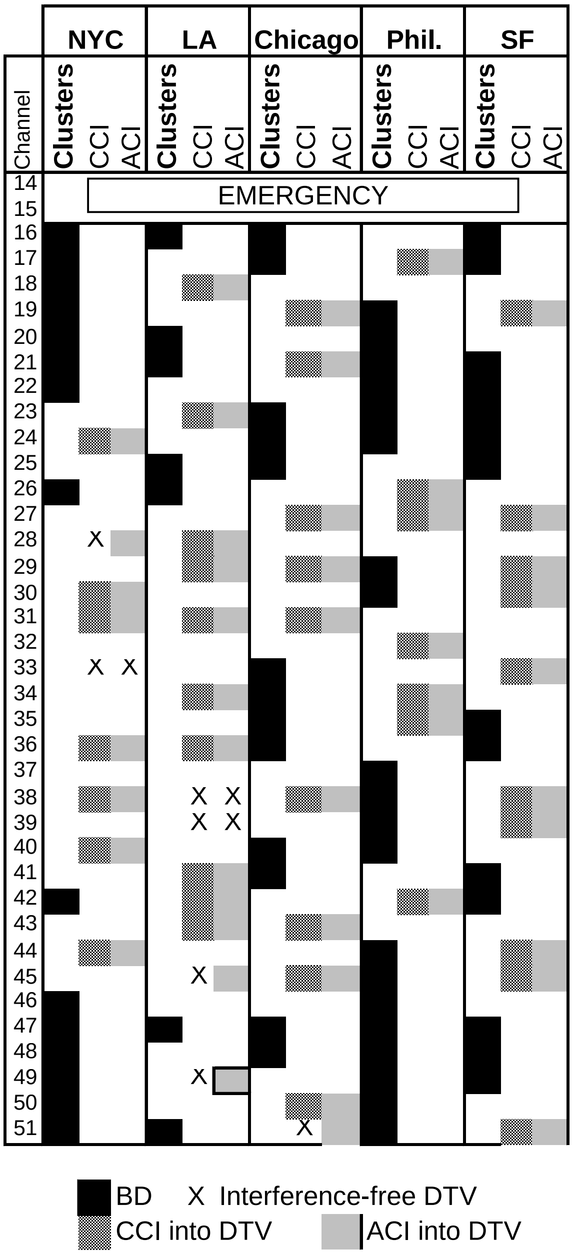

Table I: Potential Interference by Clusters to DTV in Major U.S. Cities

The insidious nature of interference by such clusters to licensed DTV channels is rooted in the integrated chip tuner of modern DTV sets because a tuner-on-a-chip does not allow for channel selectivity within a band[3].

The maximum allowable aggregate undesired power at the tuner from BD clusters is first quantified in Section IV and then translated into the allowable cluster power by portable BDs in Section V.

IV. DTV RECEIVER THRESHOLD TO INTERFERENCE BY CLUSTERS

The theoretical threshold of visibility (TOV) of 8-VSB modulation occurs when the signal-noise ratio (SNR) at the tuner's input is 15.2 dB. When the DTV receiver is subject to interference by off channel BDs, four noise components (excluding phase noise) constitute the total noise in the DTV channel. These components, shown in Figure 3, are defined as follows:

- **Thermal Noise = N_T** (dBm) **= NF** (dB) **- 106.2**

The noise figure (NF) is presumed to include the true NF at the tuner with the antenna connected.

- **Transmitter Noise = N_{Tx} = Desired Signal** (dBm)–**SNR_{Tx}** (dB)

The SNR at the DTV transmitter is known from measurement. It typically varies between 24 dB and 30 dB with ≥27 dB considered acceptable.

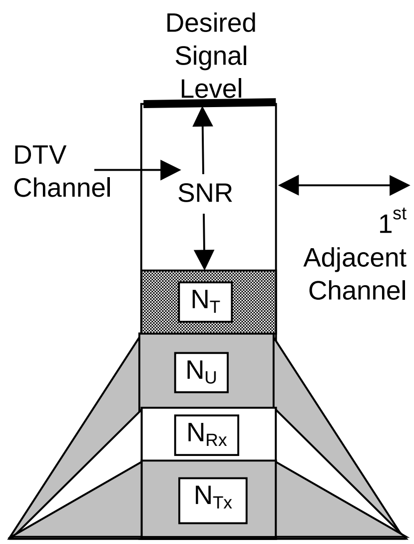

Figure 3: The Noise Components of the Receiver's Signal-Noise Ratio

- **Undesired BD Interference[4] = N_U (dBm) $=10Log(IM_{30}*G+N_{BD})$**

Two components constitute the interference by BDs into the DTV channel. One, leaked by the BD transmitter's RF mask on channels ≥N+2, is N_{BD}.

The second, a function of the received undesired power level, is generated at the DTV receiver and is given by $IM_{30}+G$ for each cluster. IM_{30}, the sideband power of a single BD, is defined by equation (1) and values for G, the gain in IM_{30} due to clusters of BDs are shown in Figure 2. Unless the DTV channel

[3] As shown by the FCC tests [9].

[4] Assuming no transmission on cochannel and first adjacent channels is prohibited inside the DTV protected service area.

is at the edge of the spectral spread shown in Figure 2, the interference to a DTV channel inside the spectral spread of the cluster would be the sum of one CCI component and two ACI components. Figure 3 illustrates the CCI and ACI spectral growth over three channels.

- **DTV Generated XM+IM = N_{Rx}** (dBm)

At the tuner, intermodulation and cross-modulation (XM) products are generated inside the DTV channel by the desired DTV signal. These undesired products appear as noise whose magnitude, N_{Rx}, depends on the DTV signal level and is given by [4][5]:

$$N_{Rx}(dBm) = 10Log(6*10^{0.2D}*10^{-0.1IP_3} + 13*10^{0.3D}*10^{-0.2IP_3}) \qquad (2)$$

where IP_3, the receiver's 3rd order intercept point and D, the desired signal level, are in dBm. The desired DTV signal also generates IM_3 on its first adjacent channels given by equation (1) for U=D.

With the noise components at the DTV tuner defined, it is possible to calculate the maximum allowable interference, the D/U ratio, and the SNR margin at TOV over the dynamic range of five DTV sets as shown in Figures 4-6.

Figure 4 shows how the SNR margin (0 dB margin is SNR at TOV=15.2 dB), varies across the dynamic range of each DTV set where the source, be it the actual transmitter or test generator, is essentially noiseless (SNR_{Tx}=57 dB). The five DTV sets are graded "poor" (IP_3 = -4 dBm), to "good" (IP_3 = +16 dBm) at 4 dBm intervals. Note that from low to moderate desired signal, "good" to "poor" sets would allow the same level of undesired signal because the thermal noise N_T is the dominant noise level in that portion of the dynamic range. At high desired levels, depending on the AGC design, TOV is reached with no external interference and the SNR margin shrinks to zero again.

From the lower edge of the dynamic range the SNR margin above TOV and the allowable undesired interference first increase as the desired level increases. That is so because at low desired levels the rate of increase in the receiver's generated IM+XM due to the desired channel is negligible. As the desired level increases the receiver's generated IM+XM predominates and the allowable undesired interference decreases.

With a realistic SNR_{Tx}=27 dB for the transmitter's noise the "sweet spot" of the SNR margin is flattened down to 12 dB for all sets. This is shown in Figure 5.

Figure 6 clearly demonstrates that the D/U ratio at TOV of the five sets and for SNR_{Tx}=27 dB varies over the dynamic range of the receiver. The minimum D/U, including the degradation due SNR_{Tx}=27 dB, is shown to be 15.5 dB, or .3dB above the theoretical TOV, which is based on $SNR_{Tx}=\infty$ dB. The FCC's protection ratio against cochannel interference is presently a constant 23 dB regardless of the desired signal level, approximately 8 dB above the theoretical SNR at TOV. Presumably, the 8 dB margin over TOV would reliably protect DTV sets from CCI during short and long-term signal fading.

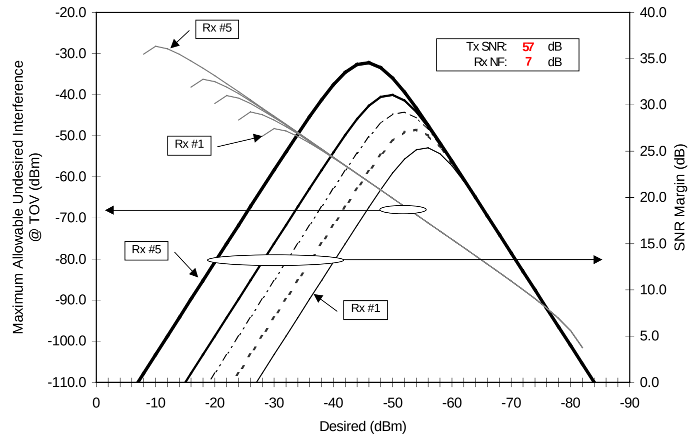

Figure 4: SNR Margin above TOV=15.3dB, Dynamic Range and Allowable Cochannel Interference for Poor (Rx#1) to Good (Rx#5)DTV Receivers without AGC/Attenuation

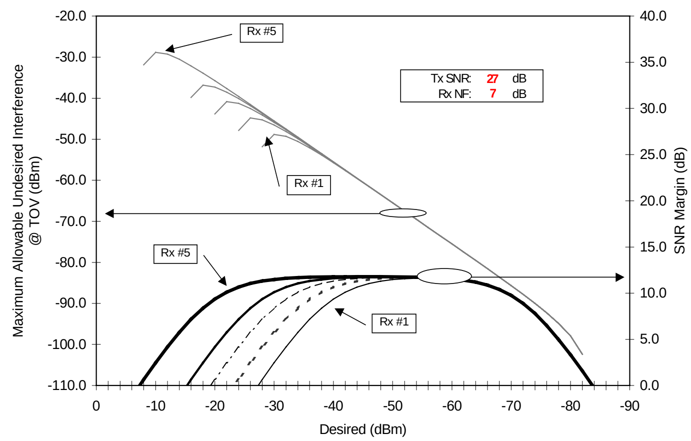

Figure 5: SNR Margin above TOV=15.3dB, Dynamic Range and Allowable Cochannel Interference for Poor (Rx#1) to Good (Rx#5)DTV Receivers without AGC/Attenuation

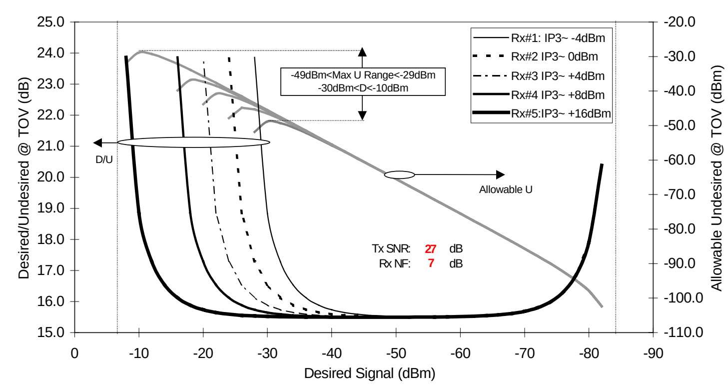

Figure 6: Desired/Undesired vs D and U @ TOV for DTV Receivers without AGC/Attenuation

Based on Figure 6, and assuming equal protection across the dynamic range, the FCC's protection ratio for very weak and very strong DTV signals should be increased to 24+8=32 dB. The variable D/U shown in Figure 6, with the

[5] There is a typo in equation (8) of reference [4]. The constant 13.5 should read 13.0.

additional 8 dB margin, will next be applied to system implementation of an interference-free DTV in the presence of BD clusters.

Although the emphasis here is on BD-only clusters, where strong DTV signals exist, usually within 10 km of the DTV transmitter, and where the SNR margin is low, interference could be formed by certain combinations of undesired DTV channels or in combination with undesired BD signals.

V. POWER TEMPLATE FOR COEXISTENCE WITH CLUSTERS OF PORTABLE BDs

The International Telecommunications Union's (ITU) protection criterion recommendation [6] is that the aggregate interference, regardless of the desired signal level, not exceed 1% (-20 db) of the total receiving system noise power. Applying the ITU's criterion to the FCC's planning factors [7] for UHF channels, the allowable aggregate interference should not exceed -119.2 dBm.

The ITU's recommendation is inexplicably independent of the desired signal's level. Maximum aggregate interference of -119.2 dBm may be applicable if the desired signal is very weak or very strong but, as shown in Figures 4-6, it is far too severe for moderate desired levels. The ITU's recommendation is further compromised by the fact that the receiver system noise power to which the 1% is to be applied was left unspecified.

In contrast, the protection criterion derived in Section IV is based on a D/U ratio that varies from 23 dB to 32 dB across the dynamic range of the receiver. The FCC's D/U=23 dB is 7.5 dB above TOV and D/U=32 dB maintains the same 7.5 dB margin for very weak and very strong DTV signals.

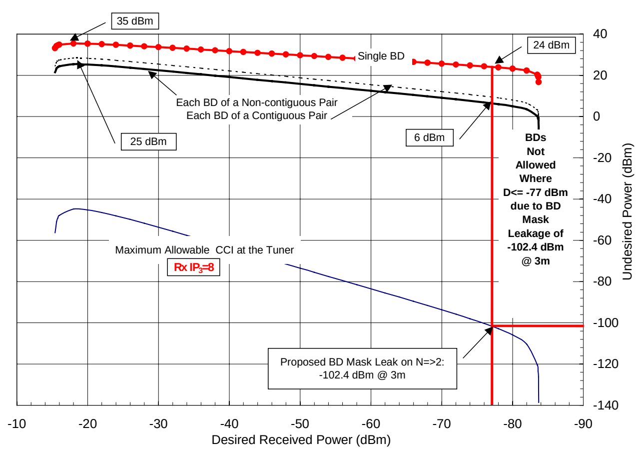

Figure 7: Allowable EIRP for BDs 3m from a DTV Set Tuned to 2nd Adjacent Channel

Knowledge of cluster interference levels (Section II) and the maximum allowable CCI at the receiver by such clusters (Section IV) has been incorporated into the EIRP template for a single BD and a pair of BDs shown in Figure 7.

The plots of Figure 7 are based on Rx#4 in Figure 6 and the proposed RF mask for BD transmitters [8]. This RF mask specifies a maximum of 4.8 μV/m at 3m in 120 kHz bandwidth for channels ≥N±2. It translates into EIRP = -64.6 dBm and received power of -102.4 dBm in 6 MHz bandwidth at a portable DTV set 3m away. The antenna of the portable DTV set is assumed to have 0 dB gain and the 3m free-space path loss is 37.8 dB.

The intersection of the received leak of -102.4 dBm on channels ≥N±2 due to the RF mask with the maximum allowable undesired signal at the receiver defines the range beyond which portable BD transmission should not be permitted. That range is shown in Figure 7 to be the –77 dBm contour of the DTV channel. Depending on the AGC performance of the receiver, additional range restriction may apply for very strong DTV signals.

As an example of how the EIRP templates shown in Figure 7 were derived, consider a cluster of two, equal-power ~~and~~ non-contiguous, BDs. Following Figure 2, the allowable power by each BD at the DTV tuner is:

$$U_{BD}(dBm) = \frac{1}{3}[U_{Rx}(dBm) + 2IP_3(dbm) - 9] \quad (3)$$

where U_{Rx} is the maximum allowable undesired signal at the receiver with added 7.5dB margin to the TOV values of Figure 6. The lowest plot in Figure 7 represents U_{Rx} for Rx#4 with IP_3=8dBm.

The EIRP of each BD is then given by:

$$P_U(dBm) = L_{3m}(dB) + 10Log[10^{U_{BD}/10} - 10^{-99.2/10}] \quad (5)$$

where L_{3m} represents the path loss in 3m and the quantity -99.2 dBm represents the RF mask leak by two BDs 3m away.

From Figure 7 it is seen that the power of each BD in the cluster of two, 3m away from the DTV set and with one channel spacing from the nearest DTV channel, should not exceed 6dBm unless the actual DTV level is known with certainty to be above –77 dBm. There is however no way for the BD to ascertain the level at the channel the DTV is tuned to, and further, the choice of 3m separation between the BD and the DTV set is arbitrary. In apartment buildings, the separation between the BD in one apartment and the DTV set in another could be less than 3m.

A similar analysis of a single BD assuming conservatively that $IP_3 \approx IP_5$ shows that it could operate on a second adjacent channel to DTV with EIRP = 24 dBm, provided it is located inside the –77 dBm contour of the DTV station.

VI. PREVENTING INTERFERENCE TO DTV SERVICE BY OFF-CHANNEL AND OFF-1st ADJACENT CHANNEL CLUSTERS OF BDs

In order to avoid harmful cluster interference to DTV, GPS-equipped fixed devices must be part of a licensed network that uses three databases to supervise and manage GPS-equipped unlicensed portable devices. One database provides the transmission parameters of all DTV stations whose noise-limited contour (NLC) overlaps the licensed contour of each base station ("The Controller") within the network. A second database provides the mapping for each DTV station within the

DTV database, of all possible clusters as shown in Table I. A third database provides the continuously updated transmission parameters of all portable devices that are registered to the network. The supervision and control of the portables would be either via omnidirectional beacons transmitted by the Controller or through the Internet. Each portable device must comply through a secured "handshake" certificate[6] with the instructions transmitted by its assigned Controller.

Each portable device must be located inside a licensed service area of a Controller. A portable device will have a dual DTV tuner chip in addition to the GPS chip. One tuner will continuously store the received signal level of each DTV station in the database and report that information to the Controller upon request. The portable need not report DTV levels below -84 dBm. If a portable cannot detect a DTV signal >-84 dBm and its GPS indicates it to be inside that licensed DTV station's NLC, such portable will be classified as hidden[7] node. The Controller's algorithm will not permit BD operation on unused channels that, if used by a combination of uncontrolled multiple BDs and/or DTV, would create cluster interference into DTV sets in proximity to hidden and unhidden nodes.

The second DTV tuner within the portable monitors all non-DTV channels during its idle time and reports their received levels to the Controller. With the knowledge of the transmitted power and location of each portable under its supervision the Controller can construct a complete propagation path loss algorithm between itself and each portable and from portable to portable.

For interference into DTV channels with received level >-84 dBm, the Controller will apply an EIRP template, such as Figure 7, in determining the allowable aggregate interference. That determination will be based on the location of the various portables as reported by their GPS, the nature of the cluster if exists and assuming 3m to the nearest DTV.

Unlicensed portables on first adjacent channel to DTV and in locations outside the DTV station's –77 dBm contour must be prohibited. The maximum power of a single BD on a second adjacent channel to DTV would be based on IP_3=8 dBm and ≤ 3m separation.

VII. CONCLUSIONS

Coexistence of BDs among licensed DTV channels in areas other than rural is possible and would require a carrier-grade (>99.999% of time availability) and secured data networks of licensed base stations within which unlicensed portable BDs, each registered to a base station, are supervised and controlled. Such networks should employ open architecture and standardized algorithms for interference protection of DTV.

[6] For example, ITU-T recommendation X.509 could be used.

[7] A "hidden node" describes a BD in a shielded environment and with insufficient sensitivity to detect the very low DTV signals. The BD might then cause interference by erroneously declaring a used DTV channel and/or the first two adjacent channels as "unused."

Unlicensed BDs would have GPS and DTV tuner chips and would not be allowed to operate on first adjacent channels to DTV and in areas bounded by the –77 dBm and –84 dBm contours of each DTV station that are in the database of the controlling base station.

Portable BDs Inside the –77 dBm contours will report to the controller base station their location and also the received power levels in the unoccupied channels. The base station, using path loss algorithm, the database of potential interference into each DTV station by clusters of BDs and the templates of the maximum allowable power for each BD, will then communicate to the BDs the power and channel on which each portable device will transmit.

APPENDIX A: 3RD ORDER INTERMODULATION COMPONENTS BY DEVICES ON MULTIPLE CHANNELS

Third-order intermodulation components are combinations of only pairs and triplets of the multiple frequencies that generate such components. To see this consider the third order polynomial expansion of two to four devices XYZW whose carrier frequencies are xyzw.

As shown in Equation A1, two devices generate two new frequencies, the result of the product xy, and two new XM components (x,y) that modulate the carriers.

$$(\mathrm{x}+\mathrm{y})^3 = \left(x^3 + y^3\right) + \left[3x^2 y + 3xy^2\right] \quad \text{(A1)}$$

$$(\mathrm{x}+\mathrm{y}+\mathrm{z})^3 = \left(x^3 + y^3 + z^3\right) + \left[3x^2 y + 3xy^2 + 3x^2 z + 3y^2 z + 3xz^2 + 3yz^2\right] \left\{6xyz\right\} \quad \text{(A2)}$$

$$(\mathrm{x}+\mathrm{y}+\mathrm{z}+\mathrm{w})^3 = \left(x^3 + y^3 + z^3 + w^2\right) + \left[\begin{array}{l} 3x^2 y + 3xy^2 + 3x^2 z + 3y^2 z + 3xz^2 + 3yz^2 \\ + 3xw^2 + 3yw^2 + 3zw^2 + 3x^2 w + 3y^2 w + 3z^2 w \end{array}\right] \left\{6xyz + 6xyw + 6xzw + 6yzw\right\} \quad \text{(A3)}$$

When three channels are present, the nonlinear system generates six pairs, each of two carriers and one triplet as shown in Equation A2.

When four channels are present, twelve pairs and four triplets would be generated as shown in Equation (A3).

Therefore, regardless of the number of channels involved, the power in each IM_3 component is limited to a combination of pair or triple frequencies. The addition of pairs and triplets that fall on the same frequency would be peak instantaneous power of the voltages if added in phase and RMS power if the individual powers are summed.

APPENDIX B: THE FCC's THEORY OF INTERFERENCE BY A PAIR OF BDs

The FCC's analysis [9] of BD pairs [U_{N+K}; U_{N+2K}] and K=integer, is wrong and has resulted in misleading assessment of the IP_3 level of modern receivers. For example, Table 9-3 in the cited document provides the range of [$IP_3/(SNR)^{1/2}$] values for eight receivers tuned to channel 30 at the desired signal levels of –53 dBm and –68 dbm (no AGC). According to the FCC's theory, the IP_3 range of the eight tested receivers is:

$$-17\,dBm \le IP_3 = \left[\frac{IP_3}{\sqrt{SNR_R}}\right] - 7.6\,dB \le +16\,dBm \qquad (B1)$$

The FCC theory is centered on the expression:

$$IP_3 / \sqrt{SNR_R} = (U^3 / D)^{1/2} \qquad (B2)$$

which, when converted to dB/dBm is:

$$D(dBm) - SNR_R(dB) = 3U(dBm) - 2IP_3(dBm) \qquad (B3)$$

where D is the desired signal level, $U=U_{N+K}=U_{N+2K}$ is the undesired interference of each of the pair [U_{N+K}; U_{N+2K}], and SNR_R is the TOV signal to noise ratio at the tuner.

The improbable range of IP_3 in equation (B1) is due to the invalidity of each side of equation (B3). Consider first the right side of equation (B3). As shown in equation (1), it represents the IM_3 level by a *single BD* or by a pair of equal-power single tones, each half the power of a single BD, but not the IM_3 power generated by a pair of BDs. As show in Figure 2 and in [5], the IM_3 level for the case analyzed by the FCC is 9 dB higher than that of two-tones. The left side of equation (B3) is also incorrect because the interference by the pair of BDs is not the only noise at the tuner. The total noise at the tuner, in addition to the cochannel interference by the off-channel BDs, includes the thermal noise at the receiver, the transmitter (or test generator) noise, and the intermodulation/cross-modulation noise generated by the desired signal at the receiver as shown in Figure 3. Equation (B3) also implies that the ratio D/U is a constant over the dynamic range of the DTV set, but as shown in Figure 6, that is not true.

Using the correct level of IM_3 and excluding the pair K=1 to avoid the cross-modulation factor, the estimated IP_3 of the receivers tested at the FCC is 10.8 dBm ± 4.2 dB.

REFERENCES

[1] G. Hardin, "The Tragedy of the Commons," Science 162, 1243-1248, 1968.
[2] O. Bendov, "A Framework for Software-Defined Digital Terrestrial Television (DTTV)," IEEE Transactions on Broadcasting, Vol. 52, No. 3, September 2005.
[3] Code of Federal Regulations 47 CFR §15.117
[4] O. Bendov, "Interference to DTTV Reception by First Adjacent Channels," IEEE Transactions on Broadcasting, Vol. 51, No. 1, March 2005.
[5] O. Bendov, "Limits on Fixed Broadband Devices for Interference-free Operation in the DTV Spectrum," IEEE Transactions on Broadcasting, Vol. 53, No. 4, December 2007.
[6] Recommendation ITU-R BT.1786, International Communications Union, April 2007.
[7] FCC/OET Bulletin No.69, February 6, 2004.
[8] RF Mask for the 802.22 WRAN Standard, document IEEE 802.22-07/0518r0, October 2007.
[9] S. Martin, "Interference Rejection Thresholds of Consumer Digital Television Receivers Available in 2005 and 2006," OET Report FCC/OET 07-TR-1003, March 30, 2007.