Limits on Fixed Broadband Devices for Interference-free Operation in the DTV Spectrum

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***Abstract*--This paper examines the limits that must be imposed on single and multiple fixed cognitive broadband devices (BDs) transmitting simultaneously on multiple unused TV channels in order to avoid interference with the reception of licensed TV channels. Single and multiple fixed BDs are assumed to radiate 4W peak power relative to an isotropic source and transmit within 10 meters of the nearest digital television (DTV) set antenna. The power and separation limits are shown to depend on whether BDs are licensed, on whether mandated minimum front-end performance specifications for DTV sets are in place, and on the definition of an "unused channel." Short and long-term general conclusions are drawn regarding the maximum allowable directional power and regarding taboo channels for interference-free coexistence with DTV sets. It is shown that unlicensed BDs would result in the least efficient use of the available DTV spectrum because the "worst case" interference limits must be imposed in an unlicensed environment. The most efficient utilization of the DTV spectrum would be achieved if BDs were licensed and then allowed to migrate, together with DTV channels, into two blocks of contiguous channels, one for DTV and one for BDs.**

***Index Terms*—Broadband devices, interference to DTV, unused TV spectrum.**

I. INTRODUCTION

The importance of efficient spectrum utilization cannot be overstated. In rural areas the DTV spectrum is sparsely populated while in urban areas it has been inefficiently allocated. Were the allocated DTV channels packed contiguously, first into channels 7-13 and then into the lower UHF band, a broad swath of spectrum would have been made available for unlicensed fixed and portable transmissions without interference to DTV reception. This paper shows that the interspersing of unlicensed BDs among temporarily or permanently unused TV channels would create a most inefficient use of the spectrum. This paper also shows that unless BD systems are licensed in metropolitan areas, interference by fixed BDs to DTV reception would be unavoidable. A BD license would specify the allowable channels, directional power, geographic location and height of fixed devices.

In the U.S., the Federal Communications Commission (FCC) has issued the First Report and Order regarding BDs in the TV spectrum[1]. Working group IEEE 802.22 is developing a draft of a recommended standard[2] intended for the deployment of BD networks intended primarily for rural areas.

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The FCC proceeding and the IEEE 802.22 draft are based on future cognitive radios with a presumably modulation-neutral[a] spectrum sensor and a GPS device to reliably map the spectrum available for transmissions on multiple channels by multiple BDs. There is no clear definition of what constitutes an "unused channel" from the regulatory or cognitive radio points of view. For example, if a DTV station uses a highly directional antenna, will the DTV channel be defined as "unused" outside the geographic service area bounded by the station's azimuth pattern? Will new BD and analog TV translators have equal access to the "unused" channels? In this paper, any channel not licensed to a full-power DTV station, regardless of the station's directional radiation pattern, is defined as an "unused" channel. By this definition, TV channels now assigned to Class-A stations and to analog TV translators whose future DTV status is still undecided, are regarded as "unused."

The FCC is required by statute to protect licensed DTV stations from harmful interference. There is no explicit definition of harmful interference within the FCC rules and regulations except for a set of fixed-value interference protection ratios from DTV into DTV and that set neither applies to BDs nor was it derived to cover the required dynamic range of consumer-grade receivers.

If BDs are permitted unlicensed operation in the TV spectrum with the expectation of no harmful interference to DTV broadcasting, the maximum allowable received BD power must pass "worst-case" analysis. A byproduct of complying with such analysis would be the inefficient use of the DTV spectrum, especially in populated areas. The limits that would have to be imposed on unlicensed BDs are in contradiction of the proclaimed goal of efficient use of the TV spectrum. In contrast, licensed BDs need not be subjected to "worst-case" interference analysis. In populated areas, licensed BDs could operate on more unused channels and at a higher power, unlike the limited power and fewer channels that unlicensed interference-free operation must sustain to avoid harmful interference to DTV reception.

The most critical of issues, the expected *aggregate interference from multiple BDs transmitting simultaneously on some or all of the TV channels which their cognitive radios deem "unused,"* has been ignored by the FCC and by IEEE 802.22[b]. The 3rd and possibly 5th order interference generated at a DTV set by strong signals received from multiple BDs transmitting simultaneously on two or more vacant channels,

[a] DTV broadcasting should be allowed to take advantage of future improvements in digital technologies including software-based cognitive radios that can adapt to any modulation format on the fly.

[b] IEEE 802.22-06/0242r3 draft proposes polarization discrimination as a means to reduce strong BD signals that would otherwise enter the DTV tuner. IEEE 802.22 draft also proposes that the front-to-back ratio of directional rooftop TV antennas be factored as a further reduction of BD interference on channels DTV N±1 but not on channels DTV≥N±2.

neither immediately adjacent to nor co-channel to the desired TV channel, is well known and has been demonstrated[3,4]. In this paper the interference levels by *virtual* BDs, created by multiple actual BDs, not on first adjacent channels, will be quantified. The virtual BDs are generated at the receiver from 3rd order intermodulation products of the actual BDs.

We quantify the maximum allowable power for a single device and for the aggregate of broadband devices on multiple channels in licensed and in unlicensed environments. The power depends on the transmission mask of the device, the number of devices, the number of channels and the DTV set's tracking filter bandwidth and dynamic range[c]. The upper limit of the dynamic range should be sufficiently high to minimize the degradation to the SNR of the desired DTV channel by strong BD signals entering the DTV tuner. Unfortunately, DTV sets are not designed to minimize the distortion that would be created by the very strong signals expected from nearby BDs. Nor are the tracking filters of DTV sets designed to reject the channels occupied by undesired BD signals. While wide-band automatic gain control (AGC) could provide relief for strong DTV and BD signals, such AGC cannot provide relief when the desired DTV signal is weak and the interfering BD signal is strong. Strong BD interference could be expected everywhere where fixed BDs with EIRP=4W are installed as close to as 10 meters away from a DTV antenna and where the DTV signal is weak. Weak DTV signals can be found everywhere, not just near the protected DTV contour. In urban areas, consumer A may operate a fixed BD 10 meters away from the DTV antenna of an unaware consumer B.

II. THE NATURE OF INTERFERENCE BY BD TRANSMISSION ON MULTIPLE CHANNELS

It has been demonstrated[5] that interference by a single BD transmitting EIRP=4W on the first adjacent channel would generate intolerable interference into DTV. This would be true in areas where the DTV signal is either weak or strong. In the area where the DTV signal is weak (not necessarily the fringe area) the spectral regrowth of a strong BD signal at the DTV set would lower the SNR of the DTV signal, possibly to below threshold. In the area where the DTV signal is strong, depending on how broadband the AGC is, a strong BD signal would overload the DTV tuner.

The interference by BDs transmitting on multiple channels is far more insidious. For example, in New York City[d] five BD could transmit simultaneously on channels N+2 to N+6 (excluding N+1) 10 meters away from a rooftop antenna[e] of a

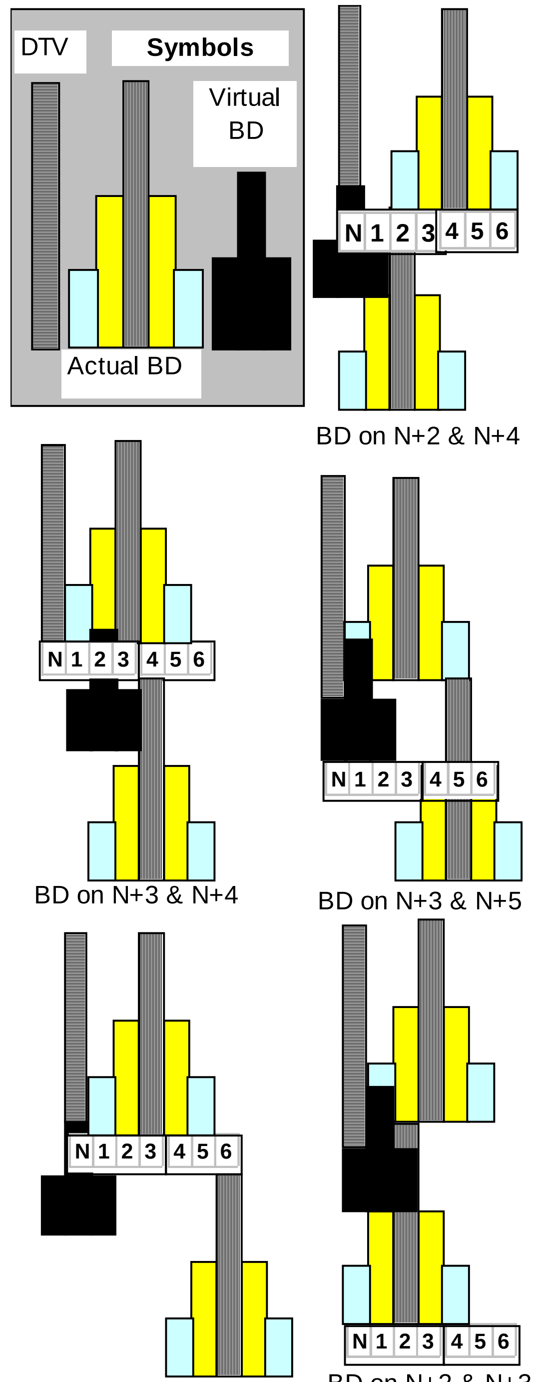

Figure 1: Pairs of BD on N+2 to N+6

DTV set tuned to channel N=44. Five channels would provide for 75 upload or 20 download sub-channels, not an unreasonable capacity for an apartment building in NYC. As shown in Figure 1 and Table 1, the five pairs of actual BDs on channels N+2 to N+6 would create new virtual BDs. In the example depicted in Figure 1 and tabulated in Table 1, the pairs of BDs would generate four of five co-channel and nine of eleven adjacent channel interference components, CCI and ACI, respectively.

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[c] There are three different "dynamic range" definitions based on compression, desensitization and spur-free ranges that apply to narrow band systems. In DTV, "dynamic range" without knowledge of the in-channel IM_3 + XM and the SNR margin as a function of input power would be misleading.

[d] IN NYC, channel 49 is now assigned to a translator and channel 46 to a Class A station. Each with highly directional azimuth pattern.

[e] The analysis is based on rooftop DTV antennas as specified by the FCC. In an unlicensed environment consumers could install UHF set-top and wall-hung picture frame antennas with sufficient gain (6-7dBi) for indoor DTV reception and for fixed BD transmission. Moreover, in an unlicensed environment, the BD transmitted power and its distance from the nearest DTV set can be modified at will by consumers, in effect interfering with DTV reception *and* cable reception of unsuspecting neighbors who would have neither the knowledge nor the ability to control their neighbors' BD.

BD on Channel	CCI	ACI	Total
N+1	1	1	2
N+2	0	1	1
N+2 & N+3	1	2	3
N+2 & N+4	1	3	4
N+3 & N+4	0	1	1
N+3 & N+5	1	1	2
N+3 & N+6	1	2	3
Total=	**5**	**11**	**16**

Table 1: Number of 3rd-order Interference Components into DTV on Channel N from Actual BD Singles and Pairs on N+1 to N+6

The complexity of interference created by channel pairs raises the question of how cognitive BD radios, owned by different operators, will dynamically decide which (if any) pairs of unused TV channels would be permitted and at what power level.

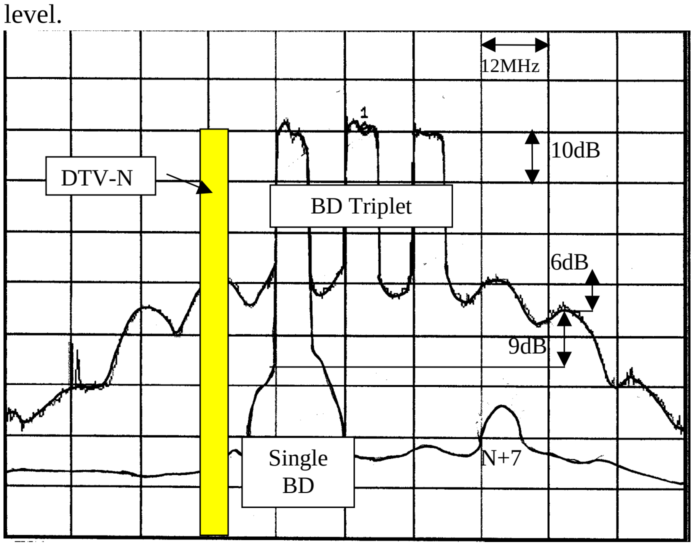

Figure 2: Triplet BDs on [N+2;N+4;N+6] and a Single BD on N+2. Each BD ≈ 0dBm input to an amplifier with IP3 ≈ 14dBm. Retrace of measurement.

In addition to the creation of new virtual BDs by certain pairs of actual BD, some triplets of actual BDs would also create new virtual BDs at the receiver. These additional virtual BDs may fall on the same desired DTV channels created by the BD pairs. In the NYC example cited above, the triplet generated by BDs on channel 46, 48, and 50 would generate additional virtual BD on channel 44. The virtual triplet adds to the virtual pair generated by channels 46 and 48 at the DTV channel. Figure 2 is a measurement of such UHF triplet[f] where the input level of each BD is ≈0dBm in accordance with the received power mask of Table 2. The triplet's sideband amplitude is twice that of a pair's sideband amplitude and so its RMS power is 6dB higher. When a virtual channel by a triplet lands on the virtual channel by a pair, their combined interference power is 5.12dB higher than that of the power due to the pair alone. A general solution of BD pairs and of clusters on contiguous channels is given in Appendix C.

In section III, the power received at the DTV antenna terminals from a single BD, 10m away, will be calculated for all TV bands based on the most restricted composite of the proposed RF masks.

III. RECEIVED BD POWER BEFORE REGROWTH AT THE DTV SET

Rational BD system planning must begin with knowledge of the transmission spectrum spread of actual, frequency-agile and power-controllable 6MHz BDs. This is a necessary condition but not a sufficient requirement to design systems that would not victimize viewers of over-the-air television. At present, the actual spectrum spread of a frequency-agile fixed BD operating at full power in the VHF and UHF DTV bands is unknown.

In this paper, a composite mask, which incorporates the more restricted elements of each of the masks proposed by the FCC and by IEEE 802.22(WG) will serve as a template for estimating the expected level of interference by single and multiple BDs. This composite mask is described in Table 2.

	Channel	
	BD ± 1	**BD ± >1**
Lo-VHF (ch. 5)	100 (40)	4.8 (13.6)
Hi-VHF (ch. 10)	150 (43.5)	
UHF (ch.38)	200 (46)	

Table 2: Composite of FCC/802.22 BD Masks Maximum uV/m (dBu) at 3 meters

Assuming free-space propagation, the BD mask described in Table 2 and the DTV antenna gains and protection ratios specified by the FCC[6], the power received at the terminals of a DTV set spaced 10m away from a BD transmitting EIRP=4W is shown in Figure 3. Even with the most restricted composite mask and prior to spectral regrowth at the DTV set, the CCI margin in DTV channels BD±2 is already negative relative to the allowable -103dB=-84dBm (at the noise-limited contour) -23dB (FCC protection ratio). The results of Figure 3 are based on co-polarization and boresighting the BD antenna with the DTV antenna. They show that the power from a single BD received at the terminals of the DTV antenna would exceed the most powerful DTV signal that would be received a mile or more away from full-power DTV transmitter[g] by from 8dB at UHF channel 38 to 20dB at Lo-VHF channel 5. In the next section it will be shown that the expected levels on a first adjacent DTV channel would create severe spectral regrowth at the DTV set in the form of CCI. Therefore, BD transmission with EIRP=4W 10m away from a DTV set on a first adjacent DTV channel will cause harmful and irreparable interference to DTV reception. In the next section it also will be shown that once spectral regrowth at the DTV set is included, one empty channel separation is not enough to protect DTV reception from

[f] Provided by C.W. Rhodes

[g] Based on a typical transmitting antenna at 1200 feet above average terrain.

a single unlicensed fixed BD 10m away from the DTV antenna and transmitting EIRP=4W spread over 6MHz.

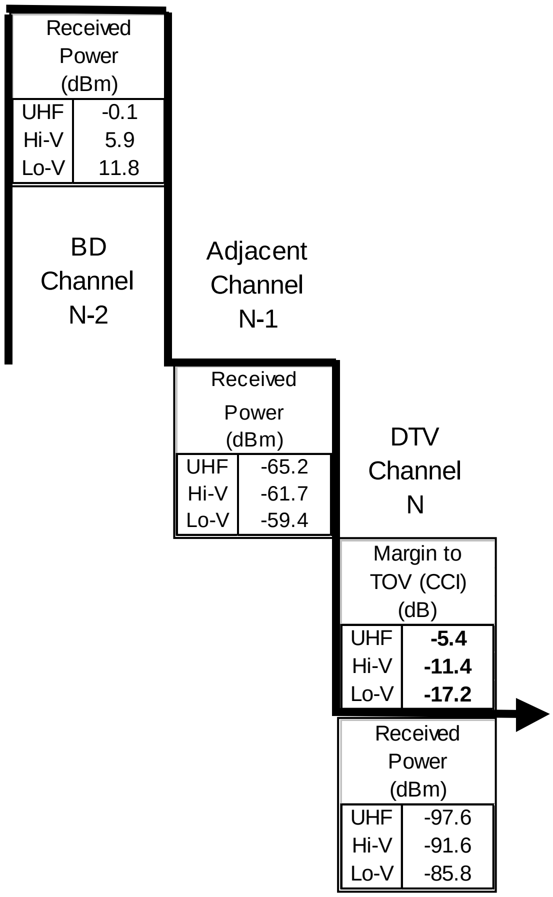

Figure 3: Received Power and Margin to TOV at the terminals of a rooftop DTV antenna 10m from EIRP=4W BD transmitter

IV. SPECTRAL REGROWTH AT THE DTV SET

The received power in each of the BD±1 and BD±2 channels is shown in Figure 3. At the DTV set, the additional undesired 3rd and 5th order intermodulation power generated into the BD±1 and BD±2 channels is given by:

$$IM_n(dBm) = nP_0(dBm) - (n-1)IP_n(dBm) \qquad (1)$$

where:

n=Order of intermodulation generated. n=3 for BD±1 and n=5 for BD±2.

IM_n=Spectral Regrowth power

P_0=Received BD power

IP_n=System Intercept Point of the DTV set.

Note that equation (1), developed for a single DTV channel (see ref.3 eq.10), is identical to the expression of the intermodulation produced by two equal-power tones.

The total power in each of the BD±1 and BD±2 channels, the sum of the received power and the newly generated IM_n power at the DTV set, is shown in Tables 3(a) and 3(b). That power constitutes the CCI into DTV channel N by a single BD on channel on N±1 or N±2. Implicit in equation (1) is a 3:1 linear slope for IM_3 and a 5:1 linear slope for IM_5 as a function of P_0.

The actual IP_n of DTV sets are not publicly available. They can be determined by independent laboratory tests. The DTV set used during the tests leading to the establishment of the ATSC standard in the U.S is believed to have had IP_3=3.5dBm (ref.3). From (1) it can be shown that for the condition that IM_3 in the BD±1 channels>IM_5 in the BD±2 channels within the linear slope of IM_n vs. P_0, the condition $P_0<IP_5 \leq IP_3$ must be satisfied. Therefore, the least IM_5 will be generated if $IP_5=IP_3$, and that condition is adopted for the least coverage loss shown in Figures 4-8.

	IP_3 (dBm) of DTV set		
	4	**8**	**16**
UHF (ch.38)	-20.2	-28.2	-44.2
Hi-V (ch.10)	■	-4.2	-20.2
Lo-V (ch.5)	■	■	0.3

(a) Total CCI Interference Power (dBm) by BD on N±1 into DTV N

	IP_5 (dBm) of DTV set		
	4	**8**	**16**
UHF (ch.38)	-36.4	-52.4	-84.2
Hi-V (ch.10)	■	-12.4	-44.4
Lo-V (ch.5)	■	■	-10.1

(b) Total CCI Interference Power (dBm) by BD on N±2 into DTV N

Table 3: CCI Interference at the DTV Tuner Single 4W BD 10m Away

■ :Interference Power=>IP

The expected coverage loss is based on the equivalent power penalty on the DTV transmitter as formulated in Appendix A less the penalty allowable by the FCC's CCI protection penalty of D/U=23dB.

Figures 4-8 show the loss of hypothetical UHF and Hi-V DTV stations transmitting from the future Freedom Tower in NYC and optimistically assuming 4dBm< IP_n<16dBm for the DTV sets. Figure 4 shows the coverage loss due to a single BD on the first adjacent channel to UHF DTV and Figure 5 shows the coverage loss due to a single BD on the first adjacent channel to Hi-V DTV. To restore the lost coverage shown in Figures 4-5, the BD power toward the DTV antenna must be reduced by 1/3 of the shown power penalty. For example, Figure 6 shows the improvement in UHF coverage relative to Figure 1 for a reduction of 15dB, from 4W to .128W of the BD power in the direction of the DTV antenna.

Figure 7 shows the coverage loss due to a single BD on the second adjacent channel to Hi-V DTV and Figure 8 shows the coverage loss due to a single BD on second adjacent channel to UHF DTV. To restore the lost coverage shown in Figures 7-8, the BD power toward the DTV antenna must be reduced by 1/5 of the shown power penalty. This penalty is much lower than that incurred when the BD is on the first adjacent channel.

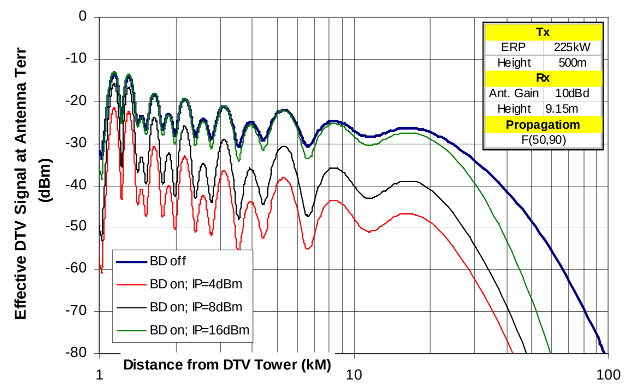

Figure 4: Loss of Coverage due to a 4W BD on UHF First Adjacent Channel 10m Away from the DTV Receive Antenna

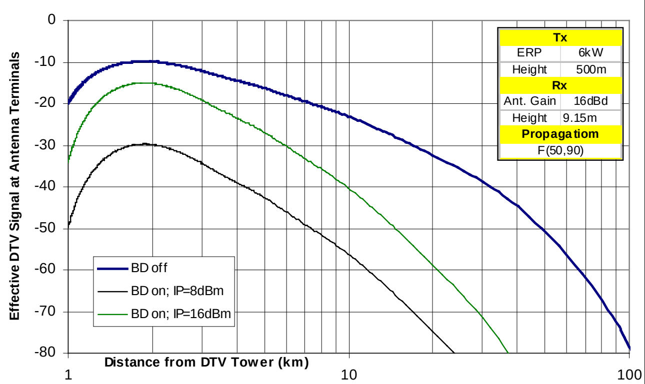

Figure 5: Loss of Coverage due to a 4W BD on Hi-V First Adjacent Channel 10m Away from the DTV Receive Antenna

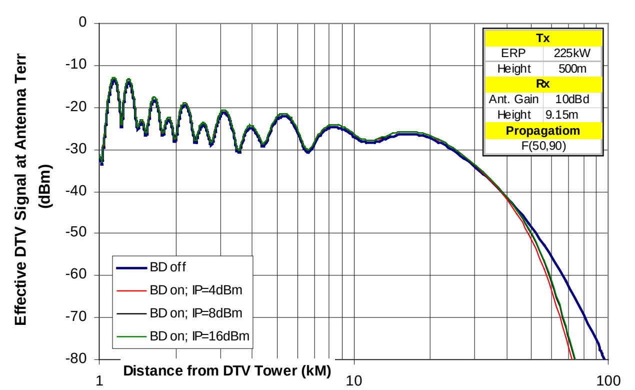

Figure 6: Loss of Coverage due to a .128W (-15dB) BD on UHF First Adjacent Channel 10m Away from the DTV Receive Antenna

For licensed BDs the power reduction could be implemented by attenuating the pattern of the 4W peak EIRP in the direction of the DTV set, or by separating the DTV set and the BD by more than 10m. The relationship between the required power reduction and the separation distance is given by:

$$R_{DTV}(m) = 10 * 10^{(|\Delta P|/20)} \qquad (2)$$

where:
$|\Delta P|$ = Desired reduction in BD power
R_{DTV} = Separation to produce equivalent power reduction.

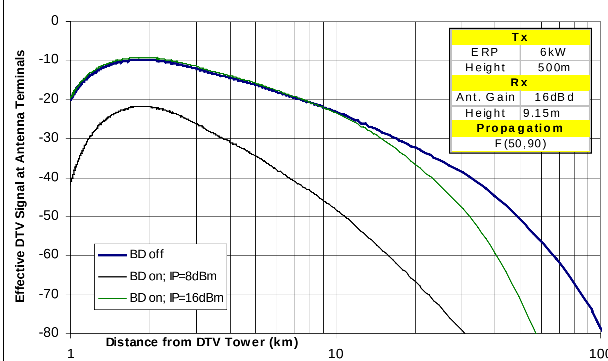

Figure 7: Loss of Coverage due to a 4W BD on Hi-V Second Adjacent Channel 10m Away from the DTV Receive Antenna

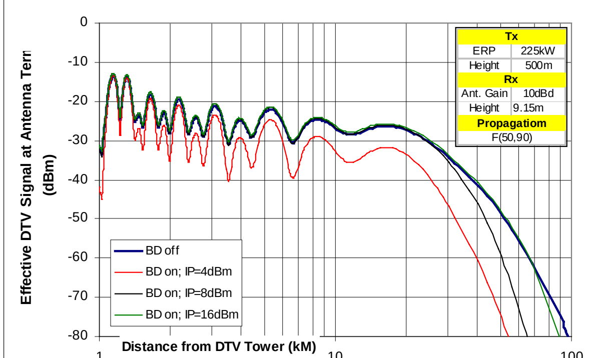

Figure 8: Loss of Coverage due to a 4W BD on UHF Second Adjacent Channel 10m Away from the DTV Receive Antenna

The required power reduction, whether through an antenna with directional pattern or through an increase in the separation between the BD and the DTV set cannot be effectively implemented in an unlicensed environment. Put another way, unlicensed BDs on DTV≤N±2 should be prohibited. Licensed operation on DTV≥N±2 is feasible because the power entering the DTV set can be controlled by verified separation between the BDs and the nearest DTV set and/or by assigning a directional azimuth pattern to the device. Better yet, mandated minimum IP_n would permit maximization of the BDs transmission power.

Power reduction using cross-polarization of BD antennas and directional DTV receive antennas should not be factored as a means to allow maximization of BD transmission power. Cross-polarization (and circular polarization) is permitted by FCC rules for FM and TV broadcasting. Practically all FM stations transmit in two planes of polarization to enhance mobile reception. Many NTSC stations are now transmitting elliptical or circular polarization and circular polarization would be an essential requirement for DTV stations targeting portable and mobile receivers. Further, the orientations of indoor and outdoor DTV receive antennas relative to BD antennas cannot be controlled by consumers or by regulatory bodies. The exception being in rural areas where the same consumer owns the BD's transmit antenna and the DTV's receive antenna.

Next, the results of sections II and IV will be applied to the example of section I, that of interference by pairs of multiple devices on five contiguous UHF channels in New York City. To simplify the analysis without effecting the conclusions the 5th order intermodulation and cross-modulation components will be excluded.

V. INTERFERENCE POWER BY MULTIPLE BDs ON MULTIPLE CHANNELS

In section III it was shown that a single BD on DTV channel N±1 with peak EIRP=4W 10m away from the DTV antenna should be prohibited. In section IV it was shown that the same BD on channel DTV N±2 would cause significant interference to DTV reception unless the BD power is reduced or the minimum separation distance to the nearest DTV set is increased to >>10m.

Multiple BDs on multiple channels would generate a far higher level of interference to DTV reception, especially if they occupy certain pairs and triplets of unused DTV channels. Figure 1 shows that five new virtual BDs created at the DTV set by the actual BD pairs would generate new ACI and CCI over and above the interference generated by an actual BD.

Figure 9 is an illustration of how the virtual BDs are generated at the DTV set by a pair of actual BDs (excluding 5th order interference). First there is a new spectral regrowth inside the actual BD channels and in their first adjacent channels. Second, two new virtual BDs are created. The virtual BD pairs generate ACI and/or CCI into the desired DTV channel.

The IM_3 power in each virtual BD channel, P_V, and the power in the IM_3 sideband of the virtual channel are (derived in Appendix C):

$$P_V\,(dBm) = 9 + [3P_0\,(dBm) - 2IP_3\,(dBm)]$$
$$Sideband\,(dBm) = P_V \text{ - } 6 \qquad (3)$$

The sum in parentheses represents the power in each sideband of the virtual channel. The P_V for a 6MHz BD radiating EIRP=4W 10m away from the DTV antenna is thus 9 dB higher. This level is consistent with the experimental data[7,8].

The aggregate CCI and ACI generated by pairs of five contiguous UHF channels on N+2 to N+6 at the DTV tuner is shown in Table 4 for DTV sets with $4dBm \le IP_3 \le 16dBm$. The data are referenced at the DTV tuner. As an example, for a DTV set with system IP_3=16dBm, the aggregate CCI=-31dBm and the aggregate ACI=-29dBm. How serious are these levels? They are 13dB higher than the CCI levels shown in Table 3 for a single BD[h] on N+1 and 55dB higher than the ACI level of a single BD on N+2. At present there is no recommended or mandated IP_3 for DTV sets. Nor do five contiguous channels (either above or below the DTV channel) constitute the "worst case." What Table 4 demonstrates is that even fixed BDs, with licensed directional ERP and minimum separation to the nearest DTV antenna (see Appendix B), must not be allowed to operate on certain taboo channels unless their aggregate power in the virtual channels is controlled by cognitive radios. In general, licensed operation of BDs should avoid taboo pairs and other single channel taboos that are yet to be determined. For example, licensed operation on N±2, N±5 and N±6 would be possible in locations where N±3 and N±4 are declared taboo. Alternatively, licensed operation on N±4, N±5 and N±6 would be possible in locations where N±2 or N±3 are declared taboo.

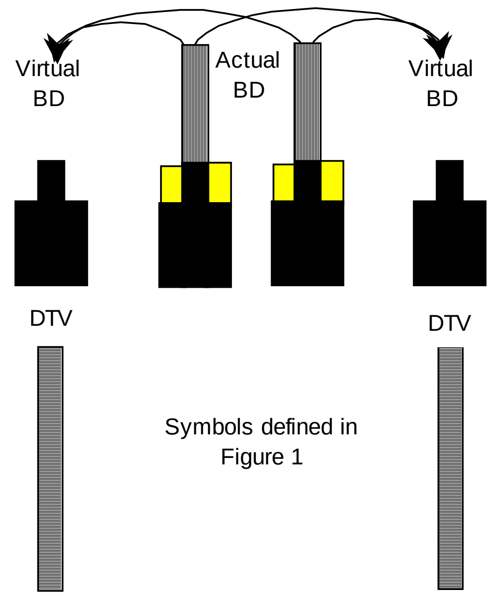

Figure 9: DTV Generated Interference by a Pair of Actual BD

	IP$_3$ of DTV set = 4				
BD on	**CCI (dBm)**	**ACI$_1$ (dBm)**	**ACI$_2$ (dBm)**	**ACI$_3$ (dBm)**	**Total ACI (dBm)**
N+2		-26.25			-26.25
N+2 & N+3	-17.25	-11.25	-17.25		-10.27
N+2 & N+4	-11.25	-17.25	-17.25	-17.25	-12.48
N+3 & N+4		-17.25			-17.25
N+3 & N+5	-17.25	-11.25			-11.25
N+3 & N+6	-11.25	-17.25	-17.25		-14.24
Total of Pairs=	**-7.3**				**-5**

	IP$_3$ of DTV set = 8				
BD on	**CCI (dBm)**	**ACI$_1$ (dBm)**	**ACI$_2$ (dBm)**	**ACI$_3$ (dBm)**	**Total ACI (dBm)**
N+2		-34.25			-34.25
N+2 & N+3	-25.25	-19.25	-25.25		-18.27
N+2 & N+4	-19.25	-25.25	-25.25	-25.25	-20.48
N+3 & N+4		-25.25			-25.25
N+3 & N+5	-25.25	-19.25			-19.25
N+3 & N+6	-19.25	-25.25	-25.25		-22.24
Total of Pairs=	**-15**				**-13**

	IP$_3$ of DTV set = 16				
BD on	**CCI (dBm)**	**ACI$_1$ (dBm)**	**ACI$_2$ (dBm)**	**ACI$_3$ (dBm)**	**Total ACI (dBm)**
N+2		-50.24			-50.24
N+2 & N+3	-41.25	-35.25	-41.24		-34.27
N+2 & N+4	-35.25	-41.25	-41.25	-41.24	-36.47
N+3 & N+4		-41.25			-41.25
N+3 & N+5	-41.25	-35.25			-35.25
N+3 & N+6	-35.25	-41.25	-41.25		-38.24
Total of Pairs=	**-31**				**-29**

Table 4:CCI and ACI by BD on 5 Contiguous UHF Channels above DTV N44 Each BD 10m Away; Each EIRP=4W

[h] If the 5.12dB interference by the [N+2;N+4;N+6] triplet identified in Section II were added to Table 4, the gain in CCI relative to single device would be 15.7dB. This is exactly as predicted by the cluster theory derived in Appendix C.

Table 4 shows the taboo BD channel pairs above DTV N=44 for integers K≤3. Below channel 44, the taboo BD channel pairs satisfying [N-K;N-2K] would be governed by K≤15. Clearly, the number of unused channels made available for BDs should depend on the IP_3 and tracking filter's passband of the DTV set.

VI. SPECTRUM EFFICIENCY OF LICENSED AND UNLICENSED DEVICES

Unlicensed transmission by cognitive fixed BD will cause significant interference to DTV reception unless the same consumer owns the DTV sets and the BDs and has the capability to point directional and to provide adequate separation between the BDs and the DTV sets. In rural areas, where unused channels are plentiful and propagation is easily predictable, unlicensed BDs would be possible, preferably by employing professional installers.

In metropolitan areas, protection from interference by unlicensed BDs would not be practical no matter how cognitive the BDs are. In apartment buildings and adjacent townhouses the minimum separation distance between the BDs and the nearest DTV set could be less than 10m, probably 3m. The base stations would have no knowledge of where one consumer's BDs would be relative to their neighbors' DTV sets and whether the consumer's BDs are indoor or outdoor. BDs installed indoors and radiating 4W would be able to reach a base station of one provider or another. All base stations would have to exclude all contiguous and non-contiguous BD clusters that could interfere with each DTV channel in the market. The alternative of significantly reducing the taboo channels' power in the UHF and VHF bands is not practical. In short, unlicensed BD operation in metropolitan areas, on non-taboo channels and excluding BDs from all DTV≤±N2 channels would be the most inefficient use of the available spectrum.

A far more efficient use of the spectrum in metropolitan areas can be achieved through end-to-end system licensing of base stations and consumer BDs. First, by excluding certain channels a priori the number of taboo channels can be substantially reduced. For the example of Section V, excluding 2 channels would free the remaining 3 channels for BD systems. Second, the location of all fixed BDs under license would be known and thus their power could be maximized as the cognitive capability of the BD could adjust the BD's pattern, polarization and power.

VII. SHORT-TERM CONCLUSIONS

1) BDs should not be permitted on DTV N±1.
2) DTV channels 4-6 should not be permitted for BDs in markets where one of the three channels is licensed to DTV.
3) For equally received UHF/Hi-VHF power 10m away, the peak EIRP of BD on VHF channels 7-13 should be scaled back from 4W by 6dB.
4) Unlicensed BDs on DTV≥N±2 should be prohibited in metropolitan areas where indoor installed consumer BDs would be arbitrarily located, possibly with booster/repeater or with additional amplifier, because they are likely to interfere with neighbors' reception of DTV and with cable programs. Licensed operation on DTV≥N±2, with reduced directional EIRP (below 4W) and/or with separation of >10m between the BD and the nearest DTV set is feasible except on certain taboo channels.
5) Efficient use of the DTV spectrum everywhere including metropolitan areas, being the proclaimed goal for allowing BDs to operate on vacant DTV channels, requires minimization of taboo channel pairs, attainable only through licensing. Further efficiency improvement can be realized with mandated minimum specification for the IP_3 and by mandated limit on the bandwidth of the tracking filter in DTV sets.
6) On consumers' premises, cross-polarization of BD antennas and orientation adjustment of DTV directional antennas relative to nearby BD antennas should not be considered as means of interference mitigation in licensing proceedings. Although such adjustments may be helpful, especially in rural areas, consumer DTV antennas, indoors and outdoors, may be hidden or pointing in various directions subject to consumers' preferences. Further, DTV and FM broadcasting will need to continue to use polarization diversity to maximize the throughput portable and mobile DTV sets.

VIII. LONG-TERM CONCLUSION

The best solution for spectrally efficient operation of unlicensed BDs in urban and suburban areas without mandated DTV receiver specifications and without harmful interference to DTV reception is to reallocate the spectrum into contiguous DTV and contiguous BD channels.

The "contiguous channels" approach for BD and DTV can be realized by first licensing fixed BDs with certain limits that would permit interference-free operation on channels interspersed with DTV channels. Subsequently BDs and DTV would be able to migrate, subject to mutually agreed compensation for DTV broadcasters, into two blocks of previously allocated contiguous channels, one for DTV and another for BDs. This migration need not be done simultaneously nationwide, but it may require simultaneous moves in more than one market at a time. Even if not all DTV markets agree to channel reallocation, those who do will enjoy interference-free operation as well as other benefits[9].

APPENDIX A

The FCC planning factors define the threshold DTV level that can be decoded for links limited by thermal noise. At UHF the level at the antenna terminal is -80dBm, at Hi-VHF it is -79dBm and at Lo-VHF it is -80dBm. The planning factors specify the maximum allowable interference in terms of Desired to Undesired protection ratios. At the edge of the noise-limited service area they are D/U=23 dB for CCI and D/U=-27dB for ACI.

The link power penalty due to the allowable interference at the thermal noise-limited contour can be derived from:

$$Penalty\,(dB) = 15.2 + 10\,Log\,[10^{-15.2/10} + 10^{-TxSNR/10} + 10^{-DU/10}] \tag{4}$$

where 15.2dB is the SNR at TOV of the U.S. DTV standard, TxSNR is the SNR in dB of the desired DTV channel at the output of the transmitter and DU is Desired to Undesired protection ratio against CCI or ACI.

Assuming typical TxSNR=27dB, the power penalty for CCI with DU=23dB is .90dB and for ACI with DU=19.5dB (see Figure A1) the power penalty is 1.57 dB.

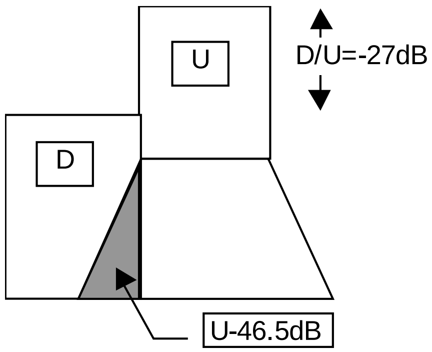

Figure A1: DU for ACI= D-(D+27-46.5)=19.5dB

APPENDIX B

Assuming free-space propagation, the maximum allowable EIRP of channel pairs can be determined from Equation (3) and from the power received at the DTV tuner:

$$P_{RT}(dBm) = EIRP(dBm) + G_{DTV}(dBi) - L(dB) + 20Log(\frac{\lambda}{4\pi d}) \quad (5)$$

where:
P_{RT} is the power at the tuner
G_{DTV} is the antenna gain.
L is the downlead loss at the DTV set.
d is the distance between the BD and the DTV set.

Substituting (3) in (5), the maximum allowable EIRP for channels [N±K] and [N±2K] is given by:

$$EIRP_{BD}^{MAX}(dBm) = \frac{1}{3}\left[P_{TOV}(dBm) + 2IP_3 - 9\right] - G_{DTV}(dBi) + L(\lambda) - 20Log\left[\frac{\lambda}{4\pi d}\right] \quad (6)$$

where P_{TOV} is the DTV threshold CCI power.

Assuming CCI protection ratio of D/U=23dB, Table B1 shows the EIRP limits for a BD pair at 10m and the minimum separation required for a BD pair radiating EIRP=4W. For example, at 10m the EIRP of each of UHF BD pair should be limited to 4dBm if the IP_3 of DTV sets is presumed to be 4dBm. That is a 32dB reduction toward the DTV set from the peak EIRP of the BD power (4W=36dBm).

	CCI TOV @ Tuner (dBm)	IP_3 (dBm) of DTV set: 4	8	16
UHF (ch.38) G_{DTV}=12.15dBi L=4dB	-107	4.1	6.8	12.1
Hi-V (ch.10) G_{DTV}=8.15dBi L=2dB	-104	-2.9	-0.2	5.1

(a) Maximum EIRP (dBm) of BD Pair 10m away @ TOV

	CCI TOV @ Tuner (dBm)	IP_3 (dBm) of DTV set: 4	8	16
UHF (ch.38) G_{DTV}=12.15dBi L=4dB	-107	393	289	157
Hi-V (ch.10) G_{DTV}=8.15dBi L=2dB	-104	881	648	351

(b) Minimum Separation (m) for BD Pair with EIRP=4W (36dBm)

Table B1: Maximum EIRP of BD Pair 10m away and Minimum Separation to DTV for EIRP=4W

Therefore, a combination of directional antenna and physical separation of ≤ 393m from the nearest DTV set would permit EIRP=4W toward the base station.

APPENDIX C

The general case of multiple BDs occupying a cluster of M contiguous DTV channels is shown in Figure C1. The cluster generates two IM_3 sidebands, each M channels wide. Thus each sideband can be divided into k channels and k=1,2…M where k=1 is adjacent to the cluster. A DTV channel may occupy each of the k channels.

The spectral power density of any segment in the sideband and the result of its integration have been shown to be[3]:

$$\int_{f_1}^{f_2} S(f)df = \quad (7)$$

$$IM_3 = \left(\frac{MP_0}{2B}\right)^3 10^{-IP_3/5}\left[(3B - |f_1 - f_0|)^3 - (3B - |f_2 - f_0|)^3\right]$$

$$0 < f_1 < f_2 \qquad |f_1 - f_0| > B \qquad |f_2 - f_0| \le 3B$$

The IM_3 power in the k^{th} channel of the sideband can be derived by repeated application of equation (7). The final result is:

$$IM_3(k,M) = P_0^3 10^{-IP_3/5}\left\{\left[M - (|k|-1)\right]^3 - \left[M - |k|\right]^3\right\} \quad (8)$$

$$|k| = 1,2...M$$

The quantity $P_0^3 10^{-(0.2IP_3)}$ can be recognized from equation (1) (after converting to dBm) as the IM_3 power in the sideband of a single BD.

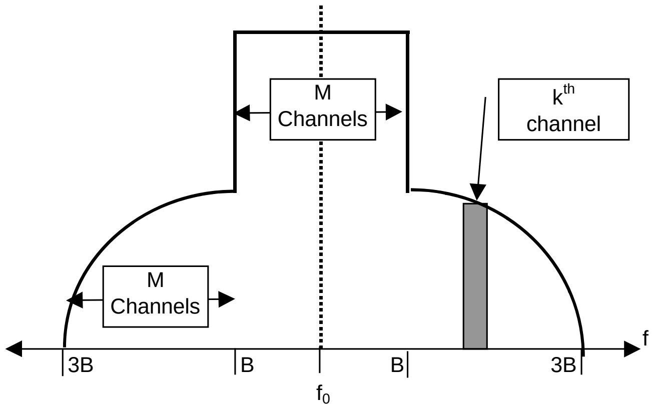

Figure C1: IM3 Sidebands of a Cluster of M channels
k=1,2….M k=1 is 1st adjacent to the cluster

Therefore, the quantity within the parentheses of equation (8) represents the power gain of IM_3 in the k^{th} channel relative to the sideband of a single BD. Figure C2 shows the IM_3 gain factor for an arbitrary TV channel separated by k-1 channels from the BD cluster.

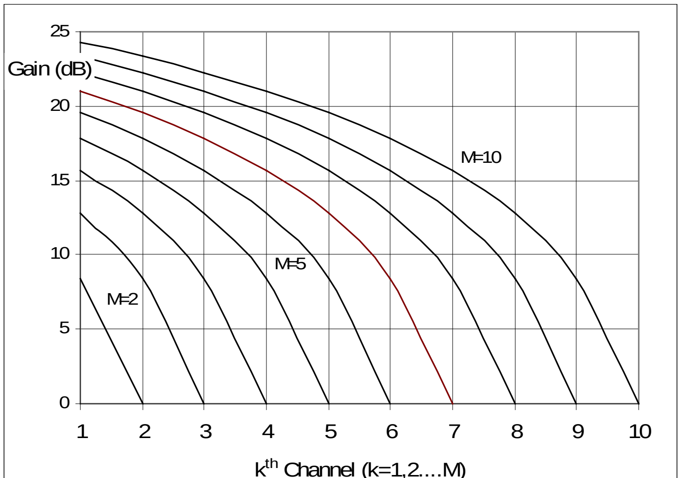

Figure C2: IM_3 Power Gain in the k^{th} Sideband Channel of a Cluster of M BDs Relative to the Sideband of a Single BD

For the NYC example of Figure 1, M=5. On channel k=2 (2^{nd} adjacent channel to the cluster) the IM_3 would be 15.7dB higher than on k=5 or 15.7dB higher than the IM_3 generated by a single BD in the 1^{st} adjacent channel. Thus, if the power of a single device must be reduced by 15dB relative to 4W (Figure 6) to avoid harmful interference then the power of each 4W device in a cluster of five would have to be reduced by additional 16dB.

Referring to Figure 9, the power in each of the two virtual channels created by two actual BDs can be derived by first assuming that the two actual channels overlap. It has been shown[3] that the IM_3 power in each sideband of the actual channel is given by equation (1). Since the input power is by the overlapping channels is twice that of a single channel, the sideband power would increase by 9dB:

$$IM_3(dBm) = 3[P_0(dBm) + 3] - 2IP_3(dBm) \qquad (9)$$

If the power in the overlapped channels is next spread into a new channel, twice the width of a single channel, it would be identical to the case of M=2 in equation (8) above. The total power will remain the same but will now be spread over two channels. Therefore from (9) the total IM_3 sideband power would be 9dB higher than that of a single channel. Comparing equation (7) and (3) of Reference 3 shows that the IM_3 power inside the channel is always higher by 6dB than the IM_3 power in each sideband so that the total in-channel IM_3 power would be (9+6)=15dB higher than the sideband power of a single channel. The sideband width doubles and in accordance with (8) the power in the sideband channel nearest to the actual channel is 8.4dB higher that the power in the second sideband channel.

When the two adjacent channels are further separated by at least one channel (no XM), two virtual channels are created and the total IM_3 power is divided equally into the two actual and two virtual channel (6dB reduction). The final result for each virtual channel by a pair of actual channels is (in dBm):

$$IM_3(in-channel) = 9 + 3P_0 - 2IP_3$$
$$IM_3(sideband) = 3 + 3P_0 - 2IP_3 \qquad (10)$$

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