Ratings for Spectrum: Impacts of TV Viewership on TV Whitespace

Zhongyuan Zhao* Mehmet C. Vuran* Demet Batur† Eylem Ekici‡
*Department of Computer Science and Engineering
†Department of Management
University of Nebraska-Lincoln, Lincoln, Nebraska 68588-0405
Email: {zhzhao,mcvuran}@cse.unl.edu, dbatur@unl.edu
‡Department of Electrical and Computer Engineering
The Ohio State University, Columbus, Ohio 43210
Email: ekici@ece.osu.edu

***Abstract*—Current TV whitespace regulations mainly benefit rural areas where large amounts of TV whitespace exist. Thus, the spectrum scarcity problem is yet to be addressed in urban locations, where it is most experienced. To further improve the spectrum efficiency, a new framework for cognitive radio network operation is presented, which can co-exist with current broadcast TV networks. Through geographical evaluations based on distribution of TV towers and population dynamics, it is shown that by leveraging the TV viewership statistics, 5.6-7.7-fold increase in available channels can be provided to mobile users in populated areas such as New York City. Furthermore, daily dynamics of TV viewership can be exploited to provide up to 96 MHz additional bandwidth during prime time and 162-228 MHz additional bandwidth during non-peak hours. The additional TV spectrum can provide additional channel capacities in both rural and urban areas. To the best of our knowledge, this is the first work that analyzes TV whitespace availability based on TV viewership statistics in space and time.**

***Index Terms*—TV Whitespace, Cognitive Radio Networks, Dynamic Spectrum Access, TV ratings**

I. INTRODUCTION

Today's wireless networks are characterized by a fixed spectrum assignment policy. However, it is well known that a large portion of the assigned spectrum is used sporadically, and geographical variations in the utilization of assigned spectrum range from 15% to 85% [5]. On the other hand, by 2018, the cellular data traffic is estimated to grow 11-fold while WiFi traffic is estimated to reach 5 times the cellular data traffic [7], challenging the available wireless resources within this fixed assignment. As a first step towards addressing the emerging *spectrum crisis*, unlicensed Television Band Devices (TVBDs) are allowed to operate in the TV spectrum band in the US (channels 2-51) under regulations set forth by the FCC [13], [14]. Accordingly, TVBDs can operate on available TV bands based on TV spectrum databases or local spectrum sensing.

A major challenge in TV whitespace operation is that current regulations mainly benefit rural areas [17], e.g., there is only one available channel for mobile TVBDs in Manhattan, New York. Other initiatives of FCC, such as imposing spectrum fees, encouraging channel sharing, and enabling incentive auctions of spectrum, however, are facing strong opposition from incumbent licensees [22]. Accordingly, the spectrum scarcity problem is yet to be addressed in locations, where it is most experienced.

While the existing policy aims to avoid interference to *potential* TV sets, it does not consider their actual operations and can significantly constrain the utilization of available spectrum. More specifically, in US, only 9.5% of the households have broadcast TV [3]. Moreover, as shown in Fig. 1, TV viewership fluctuates significantly within a day between only 3% during the night to 83% in prime time. Furthermore, within a household, a limited number of channels are viewed at a given time. Accordingly, spectrum availability can be significantly improved even in high density areas by high-granularity spectrum *usage* information of primary users.

In this paper, we consider Cog-TV, a new framework for cognitive radio networks for local wireless access on TV spectrum in residential and commercial places. Cog-TV leverages TV viewership to exploit available spectrum without interfering TV viewers. Within this framework, we analyze the availability and capacity of TV whitespace in typical rural and urban environments. A large-scale geographical analysis is conducted based on existing broadcast TV tower databases, population distributions, and TV ratings. Accordingly, the spatial and temporal characteristics of these additional TV whitespaces are described. The results motivate further research to realize the potential advantages of this framework.

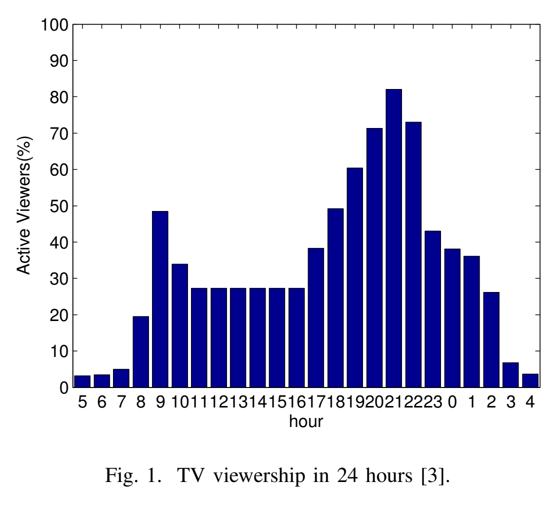

Fig. 1. TV viewership in 24 hours [3].

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The remainder of the paper is organized as follows: Related work is discussed in Section II. The Cog-TV framework and methodology are introduced in Section III. In Section IV, the analysis results of geographical distribution of TV whitespace availability and corresponding channel capacity are presented. Moreover, the impacts of TV viewership across channels and time on available spectrum are discussed in Section V. The paper is concluded in Section VI with a discussion on future directions.

II. Related Work

A. TV Whitespace Availability

A quantitative analysis of TV whitespace in continental US is presented in [17], [18]. The analysis is based on the TV tower registration information, population distribution, FCC's propagation models and a single antenna system model. The TV whitespace is evaluated based on the number of TV channels and the Shannon channel capacity. The availability of UHF band TV whitespace in Europe is estimated in [24] with the same methodology, and it is shown that propagation models can significantly influence the obtained estimates between nearby regions. In this paper, we follow similar methodologies to illustrate the influence of TV viewership on additional available channels.

TV whitespace in urban areas has also been studied based on measurements in Chicago [20], [23], Singapore [19], Guangzhou [28], and Hong Kong [29], where abundant TV whitespace is illustrated in urban areas, which contradicts with the results of [17], [24]. The contradictory results are explained by mismatch of the statistical propagation models used by FCC [17], [24] and the influence of terrain and buildings in the field [29]. More importantly, existing work on modeling, simulation, and measurement of TV whitespace focus on the spatial and temporal dynamics of the primary *transmitters*. However, impacts of primary *receiver* activity on the secondary interference have not been analyzed in these work. To the best of our knowledge, this is the first work that analyzes TV whitespace availability based on TV viewership statistics in space and time.

B. Dynamic Spectrum Access

The Cog-TV network accesses TV spectrum as a secondary user and shall not interfere with the primary users (TV viewers). Under such an hierarchical spectrum access model, spectrum sharing approaches for secondary users include underlay, overlay, interleave, and their combinations [15].

In this paper, we consider a combination of underlay and interleave techniques. Within a communication area, Cog-TV users exploit the spectrum holes through spectrum management functionalities [5], [6]; whereas Cog-TV access points perform power control [12] to the secondary terminals to prevent interference to the primary users outside the communication area [15].

To mitigate interference to TV viewers, overlay-based black space communication can also be employed such that the primary user experience can be enhanced by rebroadcasting TV signals while hiding the secondary signal [9].

C. Primary Receiver Sensing

To leverage the TV viewership, information about the activities of TV viewers including channel selection and locations is required. A TV receiver detection method is developed in [26] by exploiting the local oscillator (LO) leakage power emitted by the RF front-end of the primary receiver. However, this method may suffer from the very low leaked LO power for detection. Collaborative spectrum sensing such as multi-dimensional correlation (spatial, temporal, and spectral) based spectrum sensing can be employed to improve the accuracy of spectrum availability information and reduce the complexity and overhead [27].

A more straightforward and mature approach to obtain TV viewer activity is to use additional devices installed on TV sets for rating statistics. For example, in US, Nielsen installs electronic devices in roughly 10,000 sample households to collect various TV using activities under contracts [11]. Such functionality can be directly integrated in next generation interactive TV sets but further discussions are required within policy and privacy aspects. Nevertheless, these successful technology and business models are valuable examples for the validity of the Cog-TV approach.

III. Cog-TV Architecture and Methodology

In Cog-TV framework, the secondary users in an small area operate on unwatched TV channels obtained from real-time local TV viewership information with strict power control. Its technical feasibility is yet to be fully developed but the developments discussed in Section II and potential directions in Section VI provide pathways towards its realization. This paper emphasis on the potential opportunities of the Cog-TV framework in terms of spectrum availability and capacity, which, we believe will motivate the research community to address the technical challenges in integrating TV viewership information into network operation.

In the rest of the paper, we present analysis results of the TV whitespace availability in typical urban (New York City, NY) and rural (Lincoln, Nebraska) cities in the United States through large-scale geographical simulations. The methodology, models, data sources, and assumptions of the analysis are described next.

A. TV Whitespace Availability

The additional TV whitespace provided by the Cog-TV architecture can be illustrated by an example in Fig. 2, where we consider an area with three TV channels (e.g., channels 3, 27, 45), several secondary users (SUs) and primary users (PUs), where the channels watched by PUs are also indicated. Two squares A and B are defined as the communication regions, in which the SUs can communicate with each other without interfering with any outside PU(s) or SU(s).

According to the FCC rules, SUs are forbidden to operate on any of the three channels in region B (i.e., no-talk zone), but can freely operate in region A on all three channels. Thus, under FCC rules, the TV whitespace availability (in terms of

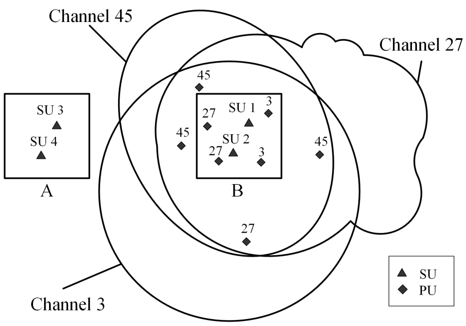


Fig. 2. Cog-TV model.

number of channels) in a given region X is defined as:

$$N_{FCC}(X) = N_c - N_{tx}(X) \ , \quad (1)$$

where N_c is the total number of TV channels and $N_{tx}(X)$ is the number of channels broadcasted in region X.

In the Cog-TV architecture, the channel availability is defined based on the *usage* of these channels by the TV viewers. In our example, channel 45 is not watched by any PU in region B. Accordingly, SU1 and SU2 may talk on channel 45 without interfering with any PUs. Accordingly, TV whitespace availability of Cog-TV in region X is defined as:

$$N_{Cog}(X) = N_c - N_{rx}(X) \ , \quad (2)$$

where $N_{rx}(X)$ is the number of locally watched channels. In US, the total number of channels N_c for fixed and mobile TVBDs are 47 and 30, respectively [13], and locally watched channels are estimated based on TV rating statistics and population density information in our evaluations.

The main premise of the Cog-TV architecture is as follows: As each PU can independently choose one of the covered channels or shutdown the TV set, there is a non-zero probability that some of the channel(s) in a region are not watched by any PU. Since N_{rx} is statistically smaller than N_{tx}, additional TV whitespace channels are available with Cog-TV compared to existing FCC rules.

B. Channel Capacity

Based on the Cog-TV model described in Section III and the TV whitespace availability in Section III-A, we use a similar method as in [17] to calculate the channel capacity. The channel capacity of a single channel is calculated according to Shannon, $C = B\log_2(1+SNR)$, where $B = 6MHz$, and SNR is the signal to noise ratio at the secondary receiver. The secondary transmitter uses a single antenna with basic transmit power control. At the secondary receiver, co-channel TV signal is either viewed as interference as in [17] or canceled based on interference cancellation (IC) techniques [9], [21]. An interference-free scheduling is assumed among SUs such that at a given time there is only a single secondary link pair on one TV channel in a cell. This assumption is reasonable since we consider the overall available capacity and in a WLAN setting, it can be realized through existing solutions, e.g., CSMA/CA, at the cost of capacity loss due to overhead.

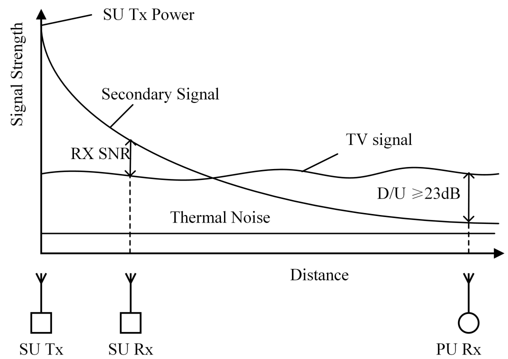


Fig. 3. Cog-TV: Secondary user transmit power control model.

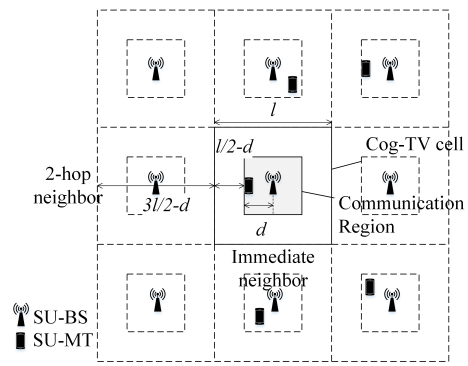
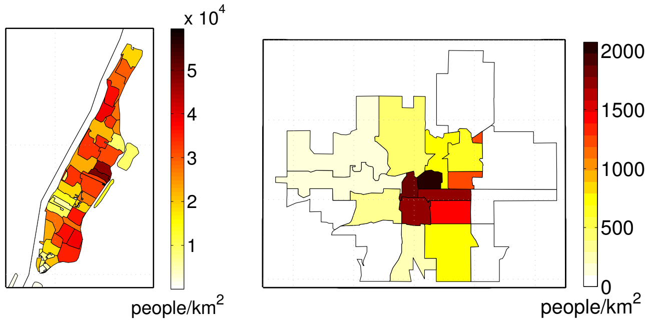


Fig. 4. Cog-TV analysis model.

The basic power control scheme is illustrated in Fig. 3. To protect the active primary receiver, the secondary transmit power is constrained such that the desired signal to undesired signal power ratio (DUR) at the primary receiver is greater than 23dB [14]. Since TV towers are usually far from cities, the variance of TV signal strength in a cell is negligible. Thus, the TV signal strength measured at the secondary access point can be used to represent the TV signal strength in the whole cell. The thermal noise is -106.2dB on a single channel. The path loss of the secondary signal is calculated from the propagation model TM91 and Longley-Rice methodology [14], where the TX and RX antenna height are both 1 m. The secondary transmit power is obtained by adding the maximum undesired signal power to path loss between secondary transmitter and primary receiver. The noise at the secondary receiver is either the TV signal strength in this cell or the TV signal strength suppressed by 20dB when interference cancellation technique is considered. For a whitespace channel with no TV signal, the secondary signal strength at the primary receiver is limited to -103.2dBm so that it does not interfere with secondary communications on nearby cells.

When considering the minimum distance between secondary transmitter and primary receiver, d_{sp}, two scenarios are considered. **Individual SU (IS):** In this scenario, we assume that the analyzed link pair is the only secondary communication in this area. In this scenario, interference to other SUs or aggregate interference to a nearby co-channel primary receiver are not considered. As illustrated in Fig. 4, if there is a co-channel primary receiver in the immediate



(a) NYC (b) Lincoln, Nebraska

Fig. 5. Population density by ZIP code [10].

neighboring cells, $d_{sp} = \frac{l}{2} - d$ and $d_{sp} = \frac{3l}{2} - d$ if no primary receiver exists in the immediate neighboring cells. **SU network (SN):** In this scenario, the secondary network is heavily utilized so that there is either co-channel primary receiver(s) or co-channel secondary communication in any immediate neighboring cell. Hence $d_{sp} = \frac{l}{2} - d$. Furthermore, aggregate interference from nearby cells has to be considered in the SU network scenario such that:

$$I_{agg} = 4I_{edge} + 4I_{corner} = 5P_{su}PL(d) \qquad (3)$$

Accordingly, the aggregate interference is 5 times ($\sim$ 7 dB) higher than the basic case and hence, the transmit power of secondary signal needs to be 7dB lower than the basic power control model in the most conservative scenario. The IS and SN scenarios can be considered as two extreme cases of Cog-TV operation that constitute the upper and lower bounds for expected channel capacity, respectively[1]. Finally, the overall channel capacity of a cell is defined the sum of the channel capacities for each available TV channel.

C. Primary Network

The signal coverage of TV towers are found based on their geolocation and the transmission contour at each TV channel [16]. Signal propagation models in [14] are used to calculate TV signal strength[2].

The precise geolocation information of each PU (TV set) is unavailable but can be approximated by known statistics of population [10] and TV households [3]. We choose NYC and Lincoln as representative urban and rural environments for the analysis, respectively. Based on the Census database [10] and simulation tools provided by [18], the population density by ZIP code district are illustrated in Figs. 5(a) and 5(b).

Since most TV sets are fixed devices, their distribution is generally dependent on the population density. Considering there are $10,947,000$ broadcast only TV Households [3], 2.24 TV sets per TV Household on the average [1], and US population of $312,471,327$ [10], the ratio of broadcast TV sets to population is 7.84%. The geolocations of PUs can then be approximated based on local population density and the broadcast TV set ratio. In the simulations, we use a slightly higher ratio of 8% with a uniform distribution of broadcast TV sets, which provides a lower bound for channel availability. We consider that people are uniformly distributed in the zip code district. These assumptions provide a fine trade off between tractable large-scale simulations and realistic analyses.

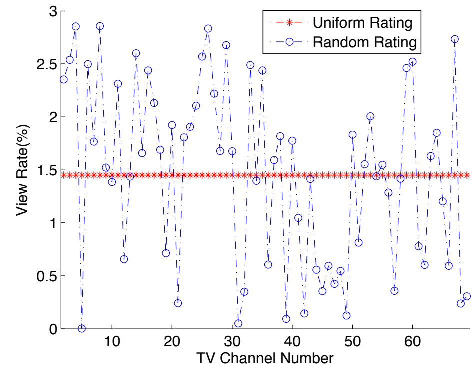
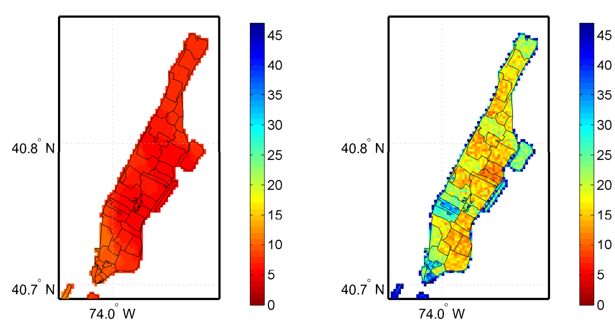


Fig. 6. Ratings: TV viewership rates on channels $2 \sim 69$

D. TV Viewership

Currently there is no available information for each TV viewer channel selection. However, such information can be inferred from existing TV rating data which is a representative statistic of choices of TV channels in certain periods from large number of TV viewer samples [25]. As detailed TV rating data is not publicly available, we consider two rating models as shown in Fig. 6. Uniform rating assumes that each channel is watched with the same probability, which is the worst case for Cog-TV operation. The random rating model provides a random rating for each channel, which is closer to realistic rating distributions, where a limited number of channels have high ratings[3].



(a) FCC rule (b) Cog-TV

Fig. 7. Available channels in NYC for a $200m \times 200m$ cell size.

[1]Adjacent channel interference (ACI) is not considered because of the low ERP of the secondary signal. Adjacent emission can be suppressed down to thermal noise by highly linear power amplifiers with output power less than 10dBm to prevent ACI.

[2]Field strength is calculated by the F(50,10) curve for propagation distance $\geq 15km$, and TM91-1 model for distance $< 15km$, Longley-Rice methodology OET69 is used to convert the field strength to signal strength.

[3]We define viewership rate of a channel as the probability of being watched. In each area, viewership rate of locally available channels are normalized based on the set of broadcasted channels in that area

TABLE I
AVERAGE CHANNEL AVAILABILITY WITH $200m \times 200m$ CELL SIZE, UNIT: NUMBER OF CHANNELS

Rules	Rating	NYC		Lincoln	
		Fixed	Mobile	Fixed	Mobile
FCC	-	6.43	1.35	40.08	25.08
Cog-TV	Random	20.91	11.73	46.21	29.48
	Uniform	17.22	8.98	46.23	29.44

In addition to ratings, one should also consider the activity of TV sets with the time of the day. TV usage exhibits a high peak-to-average ratio such that the prime time usage (e.g. 82% at 8pm) is several times higher than that non-peak time usage (e.g. 3.2% at 3am) as shown in Fig. 1, which is translated from limited publicly available data [2][4].

Based on the model in Section III-A and the assumptions in Section III-D, the expected spectrum availability in cell X under Cog-TV rule is expressed as:

$$\overline{N_{Cog}(X)} = N_c - \sum_{i \in \Psi(X)} u(\lfloor P(i)\eta\varphi(t)D(X)l^2 \rfloor) , \quad (4)$$

where, $\Psi(X)$ is the set of available TV channels, $P(i)$ is the channel rating, η is broadcast TV set per population, $\varphi(t)$ is the TV usage at time t, $D(X)$ is the population density, $u()$ is the unit step function, and l is the cell edge length.

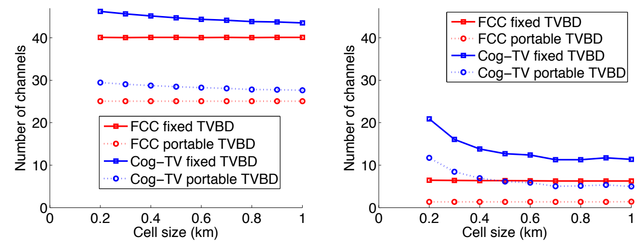
IV. STATIC GEOGRAPHICAL SIMULATION RESULTS

In this section, the TV usage is assumed to be 100% such that all broadcast TV sets are on. This is clearly the worst case, and the results represent a lower bound for the Cog-TV performance.

A. Spectrum Availability

We first analyze the spectrum availability of both FCC and Cog-TV rules with different cell sizes. The spatial distributions of available spectrum under different rules in NYC with a cell size of $200m \times 200m$ are shown in Fig. 7, and the average available spectrum in NYC and Lincoln are shown in Table I. The spatial availability of channels is mainly dependent on TV towers for FCC, whereas with Cog-TV, a larger spatial variability is observed based on population density. On the average, Cog-TV approach provides 1.6-2.2-fold increase in available channels for fixed TVBDs and 5.6-7.7-fold increase for mobile TVBDs in NYC. Improvements in rural areas are limited to 15%-17%. In Fig. 8, the distribution of available spectrum over cells is shown, where it can be observed that 40.1% of the cells can be provided with 20 or more available channels compared to less than 7 channels for 86% of the cells with FCC rules for fixed TVBDs. In both urban and rural environments, Cog-TV can improve the spectrum availability by at least 5 channels in most of the areas compared to the current FCC rule.

[4]This data reflects the habits of general TV viewers. Since there is no evidence to show that broadcast TV viewers have different TV viewership habits, we use the general TV usage statistics.



(a) Lincoln (b) NYC

Fig. 9. Available channels as a function of cell size.

TABLE II
AVERAGE CHANNEL CAPACITY, UNIT: MBIT/S

Rules, rating	d (m)	NYC			Lincoln		
		IS	SN	SN-IC	IS	SN	SN-IC
FCC	10	126.2	69.6	-	1,397	744.0	-
	20	97.0	37.8	-	1,094	409.0	-
Cog-TV, random	10	512.4	244.2	644.6	2597	1,045	1725
	20	238.8	56.7	322.9	1,851	442.2	901.1
Cog-TV, uniform	10	383.7	200.5	496.7	2,560	1,042	1,714
	20	173.9	53.1	248.1	1,821	441.9	895.5

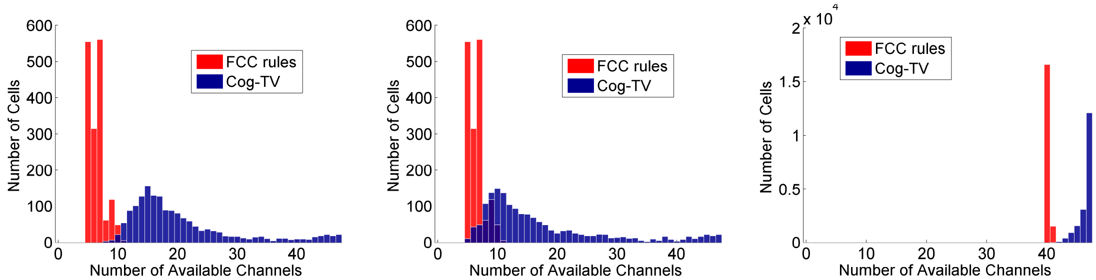
The average channel availability as a function of the cell size is shown in Fig. 9. Intuitively, for a larger cell size, more PUs reside inside a cell and the probability of available channels is lower. It can be observed that the available spectrum for Cog-TV decreases as the cell size increases in both urban and rural environments. In rural environments, larger cell sizes can be used without significantly impacting performance, whereas in urban environments, small cell sizes are needed such that significant channel capacity improvement can be achieved.

B. Channel Capacity

We next present the results for channel capacity of a household application in a 200m by 200m cell with communication distances of 10m and 20m according to (4). The average channel capacity results are listed in Table II for three scenarios: individual SU (IS), SU network (SN), and SU network with interference cancellation (SN-IC)[5]. It can be observed that Cog-TV approach provides capacity improvements of 79%-306% for IS, 40%-251% for SN, and 5.6-8.3-fold increase for SN-IC in NYC depending on the communication distance and rating model. Lower but still significant improvements are observed for rural areas (40%-132%). An important observation is that as expected, SN scenario provides lower capacity enhancements compared to single SU communication, whereas interference cancellation techniques can be employed to significantly improve secondary network capacity.

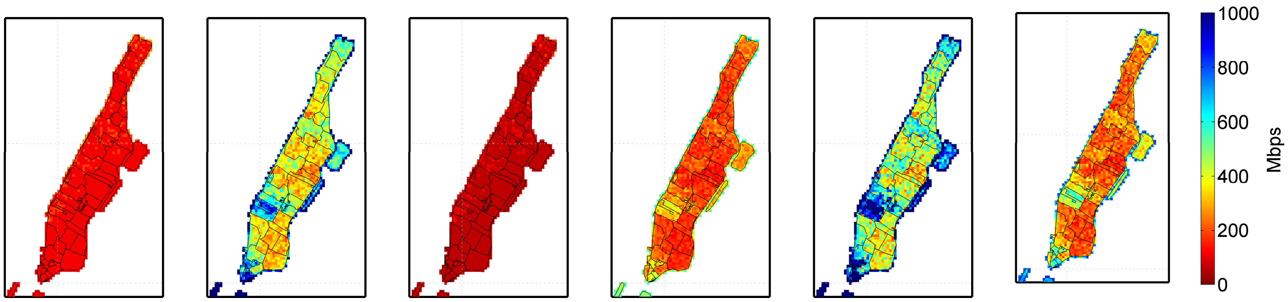
Similar dynamics can be observed in the spatially distributed capacity in NYC as shown in Fig. 10. We can observe that Cog-TV can effectively increase the spectrum efficiency by utilizing spatial distributed spectrum holes in urban area.

[5]Since we use different transmit power levels, communication distances, and total number of channels than [17], our channel capacity for FCC rule is also different from [17].



(a) NYC, Random (b) NYC, Uniform (c) Lincoln, Random

Fig. 8. Available channel distributions for a $200m \times 200m$ cell size with random and uniform rating models.



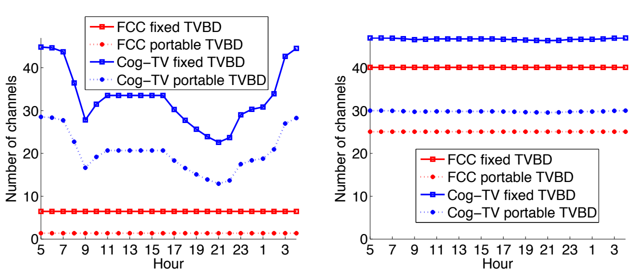
(a) FCC, IS (b) Cog-TV, IS (c) FCC, SN (d) Cog-TV, SN (e) Cog-TV, SN-IC (f) Cog-TV, SN-IC, 20m

Fig. 10. Channel capacity for a $200m \times 200m$ cell size in NYC, Random Rating. Dark blue color is used to represent capacities larger than 1 Gbps.

V. Impacts of TV Viewership

A. Types of Ratings

The distribution of ratings among channels impacts available spectrum. Large peak-to-average ratio results in a large number of channels being available as few people watch a large number of channels and their spatial distribution can be exploited as spectrum holes. The impacts of rating models can be observed in Figs. 8(a) and 8(b), where channel availability distribution is shifted to larger values with random ratings compared to uniform. The impact of rating distribution also depends on the population density. As can be observed from Table I and II, differences due to rating models are limited in rural areas (e.g., Lincoln). While uniform rating is unrealistic, it provides a lower bound for the potential of Cog-TV framework. Even in this worst case, Cog-TV still greatly outperforms current FCC rules.

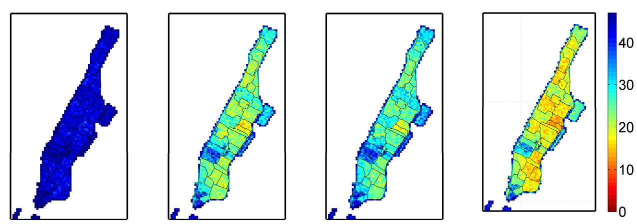


(a) 0.2km Cell, Manhattan, NY (b) 0.2km Cell Lincoln, NE

Fig. 11. Average available channels in a day (random rating)

B. Temporal Dynamics

So far, we assumed TV usage rate of 100%, i.e., every TV set is turned on at all times, which is rarely observed. Actual TV usage is strongly related to the lifestyle and daily schedule of most people. The TV usage, as illustrated in Fig. 1, is highly dynamic and does not reach to 100% rate even at prime time. Next, we capture the daily variations of TV whitespace availability based on daily statistics [3]. The impacts of daily TV viewership variations on the average channel availability is shown in Figs. 11. First, note that as less than 100% of the TV sets are assumed active, the average number of channels provided by Cog-TV further increases. During non-prime time, up to 27 and 38 additional channels can be provided to mobile and fixed TVBDs, respectively, leading to additional 162-228 MHz bandwidth. During prime time, the additional channels drops down to 11 and 16, respectively, resulting in a significant enhancement even at the worst case. It can be observed in Fig. 11(b), daily variations in TV viewership does not impact spectrum availability when population density is low. The spatio-temporal variations of spectrum availability in NYC can be observed in Figs. 12.



(a) 3:00 (b) 8:00 (c) 14:00 (d) 20:00

Fig. 12. Daily channel availability in NYC.

VI. Conclusion and Future Directions

In this paper, we provide a holistic view of the available TV spectrum when TV viewers are considered as the primary users instead of their TV sets. When TV viewership is accommodated, our analysis shows the significant potential in secondary usage of TV spectrum for opportunistic access. This potential is highly dynamic over time due to temporal variation of TV usage. While we acknowledge that the Cog-TV framework may not be currently possible, its significant potential for available spectrum would motivate further discussions and improvements in technical, business, and policy aspects. Next, we discuss potential future directions.

Technically, operation within no-talk zones faces two major challenges: (1) interference from TV towers to SUs and (2) interference from SUs to TV viewers. Recent advances in interference cancellation techniques developed for black space operation [30] can be applied to address the first challenge such that SUs can operate within relatively short distances with the interference from TV towers. Similarly, advancements in inter-cell interference cancellation (ICIC) in femto-cell architectures are also applicable to Cog-TV scenarios [4], [8].

The second challenge of protecting TV viewers requires integration of TV viewership information into spectrum management. To this end, three different approaches can be considered. The most feasible approach is to use Cog-TV approaches within houses by addressing self-interference to the TV sets within the same house. The second approach is to use statistical channel access methods with interference cancellation approaches based on TV ratings and collaborative sensing approaches. A more holistic but more effective approach is to undergo a TV set revolution similar to the transition from analog to digital TV such that TV sets are upgraded to provide viewership information to nearby cognitive radio devices. While this approach will help reach the significant potential of TV whitespaces, it requires further discussions in policy, business, and privacy aspects. We believe that the results in this paper will facilitate such discussions.

VII. Acknowledgment

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