WATCH: WiFi in Active TV Channels

Xu Zhang and Edward W. Knightly
Rice University, Houston, Texas, USA
{Xu.Zhang,knightly}@rice.edu

Abstract

Today's "white space" model of spectrum sharing applied in the UHF TV band allows channels that are not being used regionally by a TV broadcaster to be re-purposed for unlicensed-style secondary access in 24 hour increments. Unfortunately, populated areas have few unused channels for white space usage. Nonetheless, from the UHF TV viewer's perspective, Nielsen data show severe *under-utilization* of this spectrum, with vast regions that are in range of TV transmitters having no active TV receivers on multiple channels even at peak TV viewing times. In this paper, we present the design, implementation, and experimental evaluation of WATCH (WiFi in Active TV CHannels), the first system to enable secondary WiFi transmission even in the presence of kilowatt-scale TV transmitters, while simultaneously protecting TV receivers when they are active. To protect active TV receivers, WATCH includes a smartphone-based TV remote or an Internet-connected TV to inform the WATCH controller of TV receivers' spatial-spectral requirements. To enable WiFi transmission in UHF bands, we design WATCH-IC (Interference Cancellation) and CAT (Constructive Addition Transmission) to *(i)* exploit the unique environment of asynchronous WiFi transmission in the presence of a strong streaming interferer, and *(ii)* require no coordination with legacy TV transmitters. With FCC permission to test our implementation, we show that WATCH can provide at least 6 times the total achievable rate to 4 watt secondary devices compared to current TV white space systems, while limiting the increase in TV channel switching time to less than 5%.

Categories and Subject Descriptors

C.2.1 [**COMPUTER-COMMUNICATION NETWORKS**]: Network Architecture and Design—*Wireless communication*

General Terms

Design, Experimentation, Performance, Reliability

MobiHoc'15, June 22–25, 2015, Hangzhou, China.

http://dx.doi.org/10.1145/2746285.2746313.

Keywords

Spectrum Re-use; TV White Space; Database Controller; TV Receiver Feedback; Interference Cancellation; Transmit Beamforming

1. INTRODUCTION

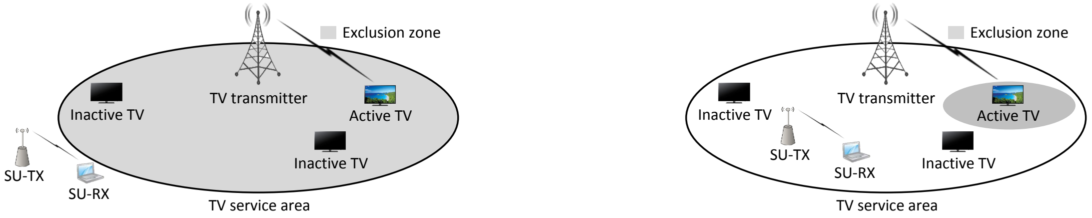
The UHF band of 400 MHz to 700 MHz is often termed the "beach front property" of spectrum due to its superior range and penetration compared to higher frequency bands. Globally, this band is typically licensed to TV broadcasters, which can be considered as primary transmitters (or primary users, PU) because they have the highest priority to access the spectrum as protected incumbents. When a geographical region has no primary broadcaster on a particular channel, that channel is said to be "TV white space (TVWS)," which is available for transmission by secondary users (SU) under today's regulatory frameworks, e.g., in the U.S. [9] and U.K. [15]. Unfortunately, the large number of over-the-air TV broadcasters in many populated areas yields extremely limited white space availability [13]. Nonetheless, in practice, the number of viewers watching TV via UHF is dwarfed by those watching via satellite or cable. For example, in the U.S., only 7% to 10% of all TV households rely on over-the-air UHF broadcast for TV programming [5, 20].

In this paper, we design, implement and evaluate WATCH, the first system that enables secondary WiFi transmission in *active* TV channels. WATCH exploits the property that few households are *receiving* UHF-band TV programming in a given channel, time, and location. Because TV transmitters cannot be rapidly power-cycled even if they temporarily have no receivers (due to high transmit power associated capacitance), nor can they direct their energy only towards active TV receivers, WATCH comprises the following three contributions.

First, we propose a new spectrum sharing model and obtain an FCC license for its testing.[1] To date, TVWS models calculate exclusion zones (areas where secondary transmissions are not allowed/transmit power is set to zero) based on transmitting TV channels and their corresponding tower locations [9]. In contrast, we propose a dynamically computed exclusion zone characterized as the union of locations where secondary user transmit power must be reduced in order to protect *active TV receivers*. By exploiting that the receiver-based exclusion zone has a much smaller footprint

---

[1] FCC experimental license call sign WH9XHJ and file number 0121-EX-ST-2014.



(a) (b)

Figure 1: The exclusion zone is computed with (a) TV transmitters in TVWS systems and (b) active TV receivers in WATCH.

than the transmitter-based exclusion zone, WATCH enables vastly increasing secondary spectrum re-use.

Second, to protect *active TV receivers* from secondary transmissions, we introduce two mechanisms to dynamically control the exclusion zone: *(i)* By generalizing the functionality of the spectrum database controller in standards such as IEEE 802.11af [10], we design the WATCH spectrum database controller to collect information of active TV receivers and accordingly coordinate secondary transmissions. Namely, with active TV receiver channel usage and location information, the WATCH controller dynamically determines the maximum transmit power for SU's. *(ii)* We design a WATCH TV receiver that can inform the controller of TV viewing. We introduce two complimentary feedback mechanisms to allow use with legacy TV systems: first, we propose a smart remote control coupled with a legacy TV, e.g., via a smartphone. Upon switching the TV channel via infrared, the enhanced remote also informs the WATCH controller of the new selection. Second, we propose a smart TV coupled with a legacy remote, in which the Internet-connected TV informs the WATCH controller of the new selection.

Third, we design a novel secondary transmit-receive architecture that enables secondary WiFi transmission even when the kilowatt-scale TV transmitters are broadcasting. For secondary *reception*, we design an interference cancellation (IC) technique, WATCH-IC, which exploits the fact that TV signals are always being broadcasted, unlike IC in non-streaming-broadcast systems such as cellular or WiFi. In particular, our design cancels TV signals without requiring their preambles to be known a priori such that WATCH is compatible with any broadcast technology and is not specific to a regional TV coding scheme. For secondary *transmission*, we design CAT, a Constructive Addition Transmission scheme for secondary WiFi transmitters. CAT precodes transmissions and computes beam weights of the secondary transmitting antenna array to ensure that secondary signals add constructively *after WATCH-IC*. It addresses the problem of inadvertent cancellation of secondary signals without coordination with legacy TV systems. Moreover, we employ selective feedback to reduce CAT's overhead. Compared to transmit beamforming in IEEE 802.11n, CAT adapts to continuous and strong interference.

Finally, we implement the key components of WATCH and experimentally evaluate their performance with FCC permission and have the following outcomes.

Protecting active TV receivers: Without WATCH, off-the-shelf TV tuners incur an average delay of 1.86 seconds to switch between UHF channels (the time between receiving the command from the remote and displaying the new channel content on the screen). We show that WATCH's TV receiver feedback process adds no more than 5% to the above channel switching time.

Secondary WiFi transmission in active TV channels: We build two-antenna secondary transceivers using WARP [25] and its UHF-band radio boards [1] and implement both WATCH-IC and CAT. We provide the first demonstration of secondary transmission in active TV channels, including under interference of the strongest DTV signals in our lab location in Houston. With 16-QAM and no channel coding, WATCH-IC alone enables an average BER of 2.4×10^{-3} for secondary transmission at 2 dB secondary signal SINR in a typical indoor environment. CAT further doubles the percentage of zero-BER packets from fewer than 40% to more than 90%. In the same setup, legacy IEEE 802.11af techniques cannot decode *any* secondary packets. We also show that larger sub-carrier density is needed in WATCH for secondary transmission compared to current TVWS systems [10] in order to cancel long-distance TV interference.

Urban scale analysis: We provide an urban-scale data-driven analysis of WATCH with UHF spectrum usage data of a U.S. major city (Houston) [24], TV viewing data from Nielsen [19–21], and WATCH parameters from our implementation. We find that with 1% active TV receivers (among all TV households) per UHF channel, WATCH can provide 6 times the total achievable rate to 4 watt secondary devices compared to current TVWS systems. This represents 42% of the total achievable rate if all TV transmitters were turned off.

The remainder of this paper is organized as follows. Sec. 2 compares legacy spectrum sharing with WATCH spectrum sharing. Sec. 3 and Sec. 4 introduce how active TV receivers are protected and how secondary transmissions are enabled, respectively. Our implementation and evaluations are in Sec. 5. Sec. 6 discusses the related work. Finally, Sec. 7 concludes the paper.

2. WATCH ARCHITECTURE

2.1 Legacy Spectrum Sharing

Current TVWS regulations target exclusion of secondary re-use based on locations where TV broadcast services are available. A typical scenario is shown in Fig. 1a: the secondary transmitter (SU-TX) and the secondary receiver (SU-RX) can only communicate outside the TV service area. In order to calculate the exclusion zone, information of all TV transmitters is stored in a database. SU's are required to query the database periodically for updated information of their operational parameters, e.g., per location re-usable frequencies [10].

Different methods are employed to compute the exclusion zone. According to the FCC, the exclusion zone is an area where the TV signal strength exceeds a pre-defined value, which is calculated by the TV service threshold, SU antenna height, etc. Outside this area, fixed secondary devices are allowed to transmit at up to 4 W EIRP (Effective Isotropic Radiation Power/transmit power including antenna gains), while personal/portable secondary devices are restricted to 100 mW EIRP, or 40 mW EIRP if there are TV transmitters occupying at least one of the two adjacent UHF channels [9]. In comparison, Ofcom divides space into 100 m×100 m blocks with each one having a calculated maximum SU EIRP [15].

2.2 WATCH Spectrum Sharing

Legacy spectrum sharing models (e.g., TVWS) protect a region determined by TV transmitter. However, because the percentage of active TV receivers relying on over-the-air UHF broadcasts is very small [5,20], we can re-purpose spectrum even within the TV service area: *(i) Spectrum in the spatial gaps:* In-between active TV receivers, we allow secondary transmissions without interfering with TV receivers. *(ii) Spectrum in the temporal gaps:* When a TV receiver is not tuned into a particular TV channel, we allow secondary transmissions in that channel and in the region around the TV receiver.

While current TVWS systems cannot re-use both of the above spectrum opportunities, WATCH enables re-use by dynamically deciding the per-channel exclusion zone based on protection of only *active TV receivers*. As illustrated in Fig. 1b, the TV transmitter location is now irrelevant to WATCH, because only *active TV receivers* can trigger secondary exclusion. The exclusion zone for each channel is also dynamic and adapted each time a TV *receiver* is tuned in or out of that channel.

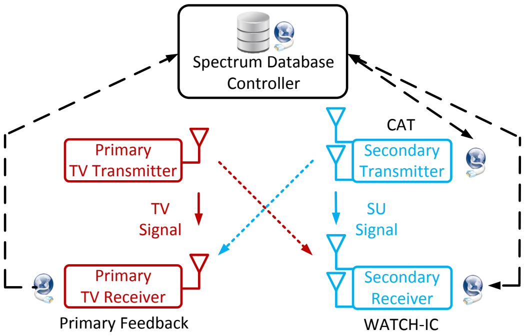


Figure 2: WATCH system overview.

To realize the new spectrum sharing model, WATCH comprises the following components as shown in Fig. 2: a spectrum database controller adapted to receive primary receiver feedback and compute active-TV-receiver-based exclusion zones, legacy TV receivers enhanced with the capability to provide feedback to the database controller, and multiple-antenna SU's. For the PU part, because spectrum sensing cannot detect activity of TV *receivers*, WATCH employs primary feedback to collect information (current channel reception and location) when a TV receiver is tuned into a UHF channel and accordingly triggers secondary exclusion. For the SU part, WATCH multiple-antenna SU's employ WATCH-IC and CAT to enable secondary transmission under TV interference. These subsystems are described separately in the following sections.

3. PROTECTING ACTIVE TV RECEIVERS

In this section, we describe mechanisms to protect broadcast reception quality of active TV receivers. We present the design of the WATCH spectrum database controller, and the functions and realization of primary feedback.

3.1 Spectrum Database Controller

The WATCH database controller computes the operational parameters of SU's based on *active TV receivers* coupled with implicitly determined exclusion zones. In particular, WATCH does not explicitly disallow secondary transmissions in certain areas. Instead, we divide the region into blocks and compute the maximum SU EIRP for each block. Secondary transmission requests are disallowed only in blocks where the maximum SU EIRP is zero. Current TVWS database already has the information of transmit power and location of TV transmitters. We further require that WATCH database also collects the location and channel reception of active TV receivers. Therefore, the maximum SU EIRP for each block can be computed with various pathloss models.

Whenever a TV receiver i becomes active in channel c, the WATCH controller updates the maximum SU EIRP $S^{SU}_{c,j}$ for channel c and each block j that is within distance d^c from TV receiver i. d^c is only related to the channel and can be computed as follows: In WATCH, we limit the maximum SU EIRP to S^{SU}_{max}. We also obtain the minimum required TV signal strength $S^{PU}_{service\_min}$ and TV signal SINR Δ_{TV_SINR} within the TV service area from legacy standards, e.g., the ATSC DTV standard. Denote $h(\cdot)$ as the pathloss of secondary signals, which does not need to be isotropical. $h_{max}(\cdot)$ is the maximum pathloss over a certain distance. d^c is selected to satisfy

$$\Delta_{TV\_SINR} + \Delta_{redundency} = \frac{S^{PU}_{service\_min}}{S^{SU}_{max} \cdot h_{max}(d^c)}, \tag{1}$$

where an additional $\Delta_{redundency}$ is added to represent the aggregate interference from multiple SU's. When updating $S^{SU}_{c,j}$, WATCH ensures that

$$S^{SU}_{c,j} \le \frac{S^{PU}_{c,i}}{(\Delta_{TV\_SINR} + \Delta_{redundency}) \cdot h(d^c_{i,j})}, \tag{2}$$

where $S^{PU}_{c,i}$ denotes the mean TV signal strength at TV receiver i in channel c, which can be computed by the Longley-Rice irregular terrain model (currently used by FCC [18]). When TV receiver i is turned off or switched to another channel, all $S^{SU}_{c,j}$ within d^c distance are updated again by the WATCH controller: either to a larger value restricted by another active TV receiver i' or to S^{SU}_{max}.

All SU's are required to provide their infomation to the spectrum database controller in order to acquire the transmission parameters, exactly as in current TVWS systems.

3.2 Primary Receiver Feedback

WATCH employs primary feedback to connect active TV receivers to the spectrum database controller and dynamically determine the exclusion zone. The main functions of primary feedback are to inform the controller of TV channel changes and to act as a fail-safe mechanism.

In WATCH, the in-block maximum SU EIRP $S^{SU}_{c,j}$ is dynamically set with different active TV receivers. For block j, if all TV receivers within d^c are switched to channels other than c or turned off, $S^{SU}_{c,j}$ is reset to S^{SU}_{max} (for either a TV receiver i or a block j, calculations are limited to SU's or PU's within distance d^c). However, channel changes of TV receivers cannot be detected by external techniques such as spectrum sensing. Therefore, we require active TV receivers to inform the database controller of the channel changes through primary feedback.

After a TV receiver informs the controller that it is tuned into a particular UHF channel c, the controller updates all $S^{SU}_{c,j}$ within d^c. However, if the active TV receiver is nonetheless incurring excessive interference due to the errors in either the collected data, (errors in locations of PU's/SU's, errors in pathloss estimates, etc.), WATCH employs the following fail-safe mechanism: If a TV receiver infers that there is excessive interference, the WATCH controller will gradually increase $\Delta_{redundency}$, grow the exclusion zone, and recalculate $S^{SU}_{c,j}$, until that the TV receiver can successfully decode the TV programming. If $\Delta_{redundency}$ exceeds a predefined threshold $\Delta^{max}_{redundancy}$ and the TV receiver still infers being interfered, WATCH controller will consider that the excessive interference is due to poor channel quality of TV signals instead of SU interference.

3.3 Primary Feedback Subsystem

While the broadcasting TV signals and the secondary data are sent in the UHF band, primary feedback can be transmitted out-of-band via WiFi, cellular, or wired connections such as DSL, or in-band via a UHF feedback channel. We propose two methods to implement primary feedback with minimum modifications to legacy TV systems: *(i) Smart remote:* Smartphones can control TVs via infrared, e.g., Samsung Galaxy S5 and HTC One M8.[2] Consequently, smartphones can be used as combined feedback and remote devices. *(ii) Smart TV:* Feedback can be sent via the TV's Internet access.

The required feedback in the previous discussion considers all channels (TV channels, UHF channels) as identical. However, in practice, channels are divided into two types: a physical channel which occupies 6 MHz bandwidth and a virtual channel which contains TV programming. Each physical channel can comprise several virtual channels. Therefore, when an active TV receiver is switched between virtual channels but stays in the same physical channel, it does not need to contact the controller. Feedback is required only when the TV receiver is switched between physical channels. According to [8], TV viewers switch among virtual channels with an average of 2.3-2.7 times per hour. The rate of physical channel switch cannot be larger, which indicates that the primary feedback of channel switch will not be sent very frequently. For the fail-safe mechanism, the value of $\Delta_{redundency}$ determines how well active TV receivers can be protected. A large initial $\Delta_{redundency}$ reduces the amount of feedback to trigger the fail-safe mechanism, whereas in the meantime increases the possibility to excessively limit the SU EIRP.

In order to analyze the quality degradation of broadcast video reception that occurs immediately following a physical channel switch, we denote t_{legacy} as the time that a legacy TV receiver takes to switch between physical channels, which includes physical signal decode, transport stream demultiplexing and video data decode. WATCH increases t_{legacy} to t_{WATCH} by adding an additional delay used by the TV receiver to send the primary feedback and the WATCH controller to update $S^{SU}_{c,j}$ and contact SU's. A comparison between t_{legacy} and t_{WATCH} will be given in Sec. 5.

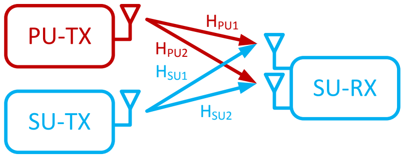


Figure 3: WATCH employs two-antenna SU-RX to cancel TV signals.

One concern of this subsystem is that some TVs lack the ability to locate themselves. However, since a TV receiver usually has a fixed location, we can register that location once and use it for subsequent primary feedback. Registration of TV location is already required in some countries, e.g., in Norway [8]. Moreover, even if a TV receiver cannot use the above two methods to provide real-time feedback, we can use its previously stored location to determine a quasi-static protection zone and only update it occasionally. Another concern is the privacy of TV receivers. One solution is to use data with larger granularity at the controller, e.g. grouping nearby TV receivers and using larger time slot when updating activeness.

4. SECONDARY NETWORKS IN RANGE OF TV BROADCASTS

After a SU is given permission by the WATCH controller to transmit, it can freely access the channel. However, new mechanisms are needed to enable communication in the presence of TV transmitters, since TV transmitters cannot be rapidly power cycled or adapt their energy footprint. Moreover, the maximum EIRP of a 30 m-high secondary device is 4 W over 1000 kW for a 200 m-high TV transmitter. In this section, we show how WATCH exploits the unique properties of continuous TV interference to cancel TV signals at the SU-RX and precode secondary transmission at SU-TX.

4.1 WATCH-IC: Cancellation of TV Signals

Receive beamforming uses multiple antennas to project received signals onto the direction that is orthogonal to the interference. When the interference is relatively strong, receive beamforming can lead to large SINR increase after canceling most of the interfering signals.

A typical scenario of receive beamforming with a two-antenna SU-RX is shown in Fig. 3. WATCH does not require more than two antennas since there will only be signals from a single TV transmitter per UHF channel requiring cancellation. Denote X_{PU} and X_{SU} to be the primary and secondary signals, respectively. The two signals Y_1 and Y_2 at the two receiving antennas are

$$\begin{aligned} Y_1 &= H_{PU1}X_{PU} + H_{SU1}X_{SU}, \\ Y_2 &= H_{PU2}X_{PU} + H_{SU2}X_{SU}. \end{aligned} \tag{3}$$

If the SU-RX could receive a clean (uninterfered) preamble of TV signals, it could estimate the primary channel state information (CSI) H_{PU1} and H_{PU2}, and therefore cancel X_{PU}. However, this method cannot be applied to WATCH due to the vast system-level heterogeneity between the primary and the secondary system (while the analysis hereafter is focused on DTV signals, WATCH techniques can also be applied to analog TV signals): *(i)* The ATSC DTV stan-

---

[2] `http://en.wikipedia.org/wiki/Infrared_blaster`

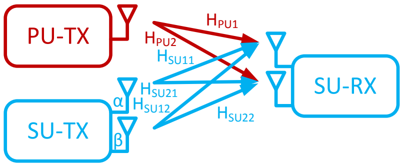


Figure 4: WATCH employs CAT to improve the performance of WATCH-IC.

dard [2] uses single-carrier transmission. Its preambles (field synchronized signals) are only defined for in-phase components. In contrast, the secondary system uses multi-carrier OFDM transmission, for which preambles are defined for in-phase/quadrature components. Moreover, for some sub-carriers, there may be no preambles for estimating the CSI of TV signals. *(ii)* Secondary signals may use different bandwidth from the 6 MHz DTV signals, e.g., a wider bandwidth through channel bonding or occupying only part of the 6 MHz channel. *(iii)* Preambles of DTV signals are sent only every 24.2 ms, which is inconvenient for the SU to use.

As a result, WATCH cancels TV signals without estimating H_{PU1} and H_{PU2}. Instead, we estimate $\frac{H_{PU1}}{H_{PU2}}$, which does not need to use preambles of TV signals and therefore does not require synchronization between the primary and the secondary system. That is, the SU network operates fully asynchronously. In particular, we exploit that *the TV transmitter is always transmitting whereas SU-TX transmits intermittently*. Consequently, when SU-TX is not sending data and $X_{SU} = 0$, SU-RX can estimate

$$H'_{PU/SU-RX} = \frac{Y_1}{Y_2} = \frac{H_{PU1}}{H_{PU2}}. \tag{4}$$

When SU-TX is sending data, TV signals can be canceled at SU-RX by computing $Y = Y_1 - H'_{PU/SU-RX}Y_2$. To realize the receiver signal processing, we can use ZF (zero-forcing) IC by Eq. (4) [11]. We can also use MMSE (minimum mean square error) IC by computing $H'_{PU/SU-RX} = C_{Y_1Y_2}C^{-1}_{Y_2Y_2}$ when $X_{SU} = 0$, where C is the covariance matrix.

To generalize, M antennas at SU-RX can cancel N_1 TV signals and support N_2 secondary data streams as long as $N_1 + N_2 \leq M$. In practice, N_1 usually equals 1 due to the deployment of broadcasting TV systems.

4.2 CAT: Constructive Addition Transmission of Secondary Signals

Transmit beamforming is a method that adapts transmitter antennas' gains and phases to focus signal energy onto the receiver. Unfortunately, this technique alone would provide little benefit to WATCH due to the strong interference from TV transmitters. Consequently, we design CAT, a Constructive Addition Transmission scheme that maximizes secondary signal SINR at SU-RX after accounting for the channels from the TV transmitter to SU-RX.

Namely, without CAT, when WATCH cancels TV signals, secondary signals may be inadvertently canceled as well in some sub-carriers. This effect can be severer when the sub-carrier density for secondary transmission becomes large and when TV signals cannot be completely canceled. Indeed, our experiments in Sec. 5 show that most bit errors of secondary transmissions are focused in several sub-carriers. To address this problem, CAT leverages multiple antennas at SU-TX to rotate the secondary signals at SU-RX to maximize the strength of its effective channel, which is $|H'_{SU}|$ and it includes the WATCH-IC process.

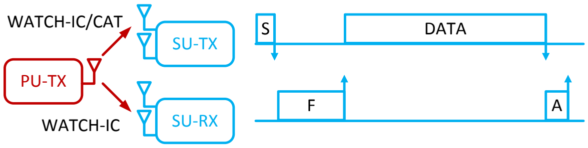


Figure 5: CAT's timeline.

As shown in Fig. 4, $\alpha = \cos\theta$ and $\beta = e^{j\phi}\sin\theta$ are the two beam weights. Different from Eq. (3), the two receiving signals Y_1 and Y_2 now become

$$\begin{aligned} Y_1 &= H_{PU1}X_{PU} + (\alpha H_{SU11} + \beta H_{SU12})X_{SU}, \\ Y_2 &= H_{PU2}X_{PU} + (\alpha H_{SU21} + \beta H_{SU22})X_{SU}. \end{aligned} \tag{5}$$

After WATCH-IC, H'_{SU} can be calculated as

$$\begin{aligned} H'_{SU} = \;& (\alpha H_{SU11} + \beta H_{SU12}) - \\ & H'_{PU/SU-RX}\,(\alpha H_{SU21} + \beta H_{SU22}). \end{aligned} \tag{6}$$

If all the CSI in Eq. (6) are known, we can calculate the optimal $\hat{\alpha}$ and $\hat{\beta}$ to maximize $|H'_{SU}|$. However, to estimate the CSI, SU-RX needs to receive clean preambles of secondary signals, which is impossible in WATCH due to the continuous and strong TV signals.

To solve this problem, we define

$$\begin{aligned} H_1 &= H_{SU11} - H'_{PU/SU-RX}H_{SU21}, \\ H_2 &= H_{SU12} - H'_{PU/SU-RX}H_{SU22}. \end{aligned} \tag{7}$$

Observe that $H'_{SU} = \alpha H_1 + \beta H_2$. Since there are only two unknowns H_1 and H_2, we can obtain their values by using two sets of α and β.

An illustrative timeline of CAT is shown in Fig. 5:

(i) First, a sounding packet which contains training sequences with two different (α, β) sets is sent from SU-TX to SU-RX.

(ii) At SU-RX, after TV signals are canceled, we can estimate H'_{SU} and compute H_1 and H_2. Then the optimal $\hat{\phi}$ and $\hat{\theta}$ for $\hat{\alpha}$ and $\hat{\beta}$ can be calculated as

$$\begin{aligned} \hat{\phi} &= \arg H_1 - \arg H_2, \\ \hat{\theta} &= \frac{\pi}{2} - \arccos \frac{|H_2|}{\sqrt{|H_1|^2 + |H_2|^2}}. \end{aligned} \tag{8}$$

(iii) The values of $\hat{\phi}$ and $\hat{\theta}$ are sent from SU-RX to SU-TX. Similar to Eq. (4), at SU-TX $H'_{PU/SU-TX}$ is estimated. TV signals are canceled before the secondary feedback data are decoded.

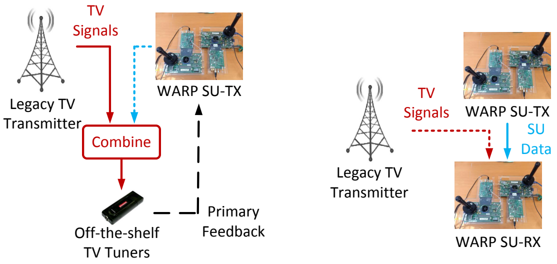
(iv) SU-TX uses $\hat{\phi}$ and $\hat{\theta}$ for precoding. At SU-RX, WATCH-IC is used to cancel the TV signals.

4.3 Selective Sub-carrier Feedback

While CAT reduces BER, it also requires overhead. As shown in Fig. 5, explicit sounding and feedback packets need to be sent before CAT SU data transmission.

One way to reduce overhead in obtaining the CSI at the transmitter is to use implicit sounding, which does not require feedback packets: Instead, SU-TX overhears packets from SU-RX and employs channel reciprocity to estimate $\hat{\phi}$ and $\hat{\theta}$. Unfortunately, implicit sounding cannot be used in WATCH due to TV interference. Namely, TV signals are different at SU-RX and SU-TX. With different $H'_{PU/SU-RX}$ and $H'_{PU/SU-TX}$, SU-TX cannot estimate H'_{SU} (at SU-RX), which is required by CAT.

Therefore, WATCH employs an alternative to reduce the overhead of collecting CSI. Generally, the feedback packets account for most of the additional overhead, because the coded information of $\hat{\phi}$ and $\hat{\theta}$ of every sub-carrier need to be sent to the SU-TX. Since secondary signals are not inadver-



(a) PU sub-system (b) SU sub-system

Figure 6: Implementation of WATCH.

tently canceled in every sub-carrier, CAT need only send selective $\hat{\phi}$ and $\hat{\theta}$ of those sub-carriers where secondary signals are canceled, after which bit errors of secondary transmissions can still be largely reduced. Evaluations of CAT with selective feedback are shown in Sec. 5.

5. IMPLEMENTATION AND EVALUATION

To evaluate the performance of WATCH, we build a small scale indoor testbed and perform over-the-air experiments with FCC permission. Moreover, with UHF spectrum usage and TV viewing data, we characterize WATCH's performance on an urban scale.

5.1 Testbed Implementation

We implement the key components of WATCH and configure a testbed as follows: *(i)* The DTV systems are urban scale DTV broadcasters and the DTV receivers are off-the-shelf TV tuners.[3,4] *(ii)* We implement all aforementioned SU functionality on the software-defined radio platform WARP [25]. To enable UHF transmission and reception, we replace the default 2.4/5 GHz radio boards with UHF-band radio boards designed by [1].

PU system. As shown in Fig. 6a, we combine over-the-air DTV signals with secondary signals generated by WARP and feed them into the TV tuners, which output TV programing to a laptop through the USB interface. To emulate the latency of primary feedback, we set a timer when the channel switching command is sent to the TV tuners, and stop WARP transmission by disabling the transmitting chain after the timer expires.

SU system. As shown in Fig. 6b, we synchronize two WARP boards to build a two-antenna secondary transceiver, and construct a secondary link between secondary transceivers with 10 m separation. To download/upload signal samples to/from WARP, we use the WARPLab 7 framework. At SU-TX, we generate secondary packets according to the IEEE 802.11a standard, including preambles, pilots and data. The SU-RX collects signals in a special format as shown in Fig. 7. The first part only contain TV signals with SU-TX not transmitting. We employ them to calculate $H'_{PU/SU-RX}$ for WATCH-IC. The second part contain both TV signals and header and payload of the secondary packet. We first cancel TV signals with $H'_{PU/SU-RX}$. Then we correct the timing and frequency offset of the secondary packet before decode. Secondary signal SINR before WATCH-IC is calculated as

$$SINR = \frac{E\{S_{PUSU}\} - E\{S_{PU}\}}{E\{S_{PU}\}}. \qquad (9)$$

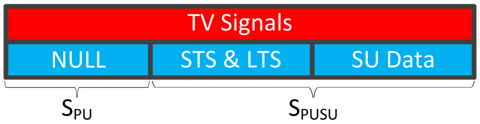


Figure 7: Collected data format at SU-RX.

5.2 Timing Requirement of Primary Feedback

Experiment Setup. To evaluate the interaction between the primary and the secondary system in WATCH, we measure the channel switching time of off-the-shelf TV tuners with different latencies of primary feedback. The channel switching time is defined as the duration between when the channel switching command is sent and when the new TV programming is displayed. Our experiments address two issues: *(i)* How much latency can primary feedback have so that WATCH's increase in channel switching time is overwhelmed by the inherent TV tuner's channel switching time? *(ii)* Can TV receivers begin the tuning process even when the SU-TX is sending data?

To characterize the degradation of broadcast video reception quality, we define $\Delta = (t_{WATCH} - t_{legacy})/t_{legacy}$, with t_{legacy} and t_{WATCH} defined in Sec. 3. Three channels with strong DTV signals are used in the experiments: 19 (503 MHz), 35 (599 MHz), and 42 (641 MHz). For the TV tuners, we find that there is a very narrow transition zone of TV signal SINR between perfect TV programming displaying without errors and undecodable TV signals. We set the WARP transmit power sufficiently high to create strong SU interference, so that TV signals cannot be decoded if a SU is transmitting.

Experiment Results. We vary the control-loop latency of feedback between TV remote channel change indication and notification to SU to vacate the corresponding channel. For each latency, we perform repeated experiments with both TV tuners and different channel pairs and measure the corresponding channel switching time for the TV tuner. The results are depicted in Fig. 8: the x-axis shows the feedback latency and the blue bars depict the measured average channel switching time, e.g., for zero feedback latency it is 1.86 s. The red line shows the sum of the zero-latency case result and the feedback latency as depicted on the x-axis (i.e. 1.86 + x) to provide a baseline for comparison. We only display *average* channel switching time since results are close for different TV tuners and channel pairs.

We make several observations: First, channel switch alone is quite lengthy at 1.86 seconds even without WATCH. This is because highly compressed TV programming results in long initial decoding delay. Moreover, the TV tuner must adapt to the new frequency and a potentially new TV signal SINR. Second, the measured channel switching time with WATCH (the blue bars) is smaller than the calculated sum with feedback latency (the red line). This indicates that even if the secondary signals are initially too strong to prevent the decode of TV signals, the TV tuner can begin the tuning process while the SU is still transmitting.

To estimate the latency of the primary feedback with a smartphone-based remote, we consider an LTE scenario: According to [16, 26], the round-trip delay time (RTT) including both the access and core networks is approximately 35 ms. Such time can be divided into the uplink delay from the smart remote to the database controller and the downlink delay from the database controller to SU's. Further measurements over LTE including end-to-end server response

---

[3] DIAMOND ATI Theater HD 750 tuner

[4] Hauppauge WinTV-HVR-950Q tuner

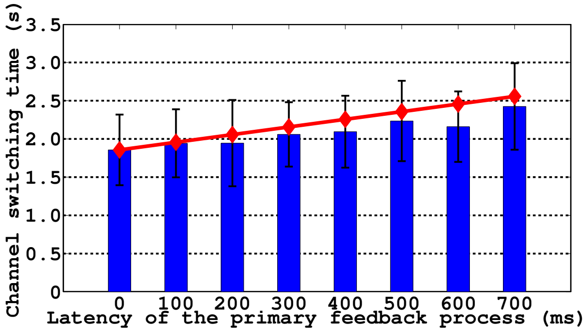


Figure 8: Measured channel switching time with different primary feedback latencies.

delay to a large database server report about 80 ms average RTT.[5] *Finding: In a full-scale system, the expected primary feedback latency of WATCH will be less than 100 ms, which leads to an additional channel switching time of TV's with* $\Delta < 5\%$. *Use of a wire-connected Smart TV can further reduce* Δ *due to smaller RTT.*

5.3 Cancellation of TV Signals

To evaluate WATCH under the most adversarial conditions, we sweep all UHF channels and select the one with the strongest DTV signal, which is channel 26 (545 MHz) in our lab location at Rice University. According to [24], the TV transmitter of channel 26 is approximately 17 km away from our lab and it can broadcast at a maximum of 1300 kW EIRP. In TVWS systems, this channel is clearly excluded from secondary transmission. Consequently, we received an experimental license from the FCC to conduct the first experiments of secondary transmission in active TV channels. Since channel 26 contains the strongest DTV signals, our analysis shows the lower-bound performance of WATCH in our lab. For evaluation, we separately evaluate WATCH-IC and CAT, with this sub-section considering WATCH-IC without CAT.

Experiment Setup. Because the primary (single-carrier) and the secondary (multi-carrier) system use different modulation, it is important to determine the sub-carrier density (number of sub-carriers in certain bandwidth) for secondary transmission required by WATCH in diverse primary/secondary environments. SU transmissions in our experiments use 5 MHz bandwidth, 16-QAM and no channel coding. For different secondary signal SINR, we vary the transmit power at SU-TX. We also change the sub-carrier density of SU transmission from 64 to 512. The sampling rate and buffer size of WARP limit that we can use at most 512 sub-carriers for 5 MHz bandwidth.

Experiment Results. The results are shown in Fig. 9. The x-axis is the maximum SINR of secondary signals at the two receiving antennas before WATCH-IC (we do not use average SINR since BER is more related to one of the two receiving signals that has larger SINR). The y-axis is the average BER of secondary signals. There are five curves in the figure: The upper dashed curve shows the BER before WATCH-IC, whereas the bottom four solid curves show the BER after WATCH-IC.

Without WATCH-IC, the BER is near 0.5 (random guessing) indicating a complete failure if legacy systems are used.

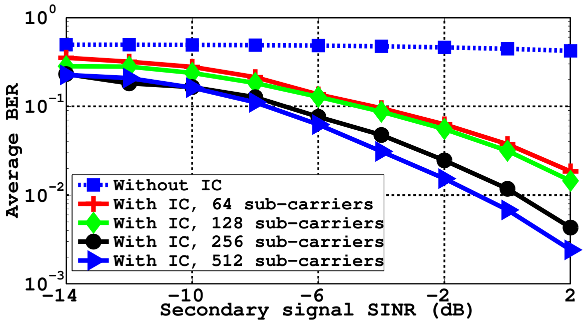


Figure 9: Impact of sub-carrier density on MMSE WATCH-IC.

However, after WATCH cancels the TV signals, the BER decreases, with larger sub-carrier density having a more rapid decreasing rate (indicating better cancellation). At 2 dB secondary signal SINR, the BER for 64 and 512 sub-carriers is 1.9×10^{-2} and 2.4×10^{-3} respectively. In the experiments, while the increase of secondary signal strength after WATCH-IC is similar, the cancellation degree of TV signals vary significantly with different sub-carrier densities.

Generally, the required sub-carrier density is governed by the delay spread (coherence bandwidth) of the signals, so that channel fading can be considered flat over an OFDM sub-carrier. However, in WATCH, the required sub-carrier density of secondary signals is dominated by the delay spread of *TV signals*. In our experiments, the distance from the SU-TX to the SU-RX is only 10 m, whereas the distance from the TV transmitter to the SU-RX is 17 km. According to [17], the delay spread of the UHF band for indoor WLANs is smaller than 1 μs, while that for tower-to-home environments with tens of kilometers of distance is 11 to 25 μs. Therefore, even for short range secondary transmission, in order to sufficiently cancel TV signals, a large sub-carrier density is required. This sharply contrasts with the TVWS standard: In IEEE 802.11af, SU's only use 144 sub-carriers for 6 MHz bandwidth (equivalent to 120 sub-carriers for 5 MHz bandwidth) [10]. *Finding: To sufficiently cancel TV signals with large delay spread, WATCH requires high sub-carrier density even for short range secondary transmission.*

We analyze the impact of other operational parameters of the secondary system in [32] due to space limitations.

5.4 Constructive Addition Transmission of Secondary Signals

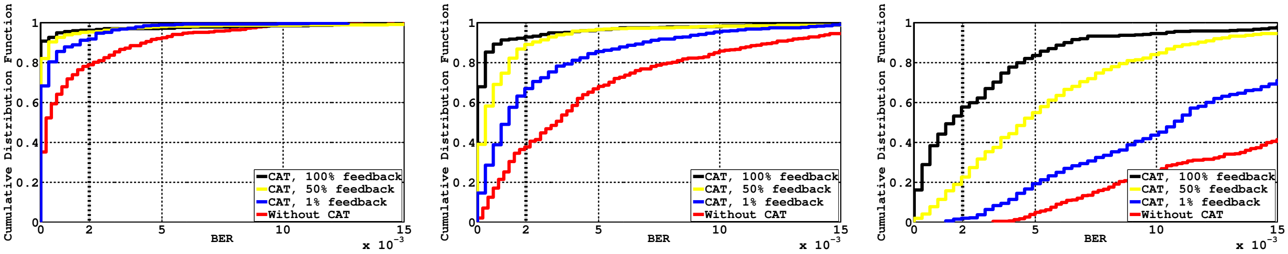
In the following, we evaluate the performance of CAT coupled with WATCH-IC.

Experiment Setup. For repeatable experiments, we collect over-the-air channel traces and evaluate CAT with TV signals received in channel 26. We use channel 29 (563 MHz) to collect the CSI between SU-TX and SU-RX. According to Google Spectrum Database, there are no co-channel TV signals in channel 29 in our lab, so that we can collect the secondary CSI without TV interference. For trace post-processing, 5 MHz secondary signals are generated with 512 sub-carriers, 16-QAM and no channel coding. The signals are transmitted through secondary channels first and then mixed with TV signals.

Out of the 512 sub-carriers, only 396 are used to transmit data/pilots (non-silent sub-carriers). To evaluate selective feedback, we only send $\hat{\phi}$ and $\hat{\theta}$ of $N\%$ of the 396 non-silent sub-carriers to the SU-TX. As shown in Sec. 4.2,

---

[5] `http://www.fiercewireless.com/special-reports/3g4g-wireless-network-latency-how-did-verizon-att-sprint-and-t-mobile-compa-3`



(a)

(b)

(c)

Figure 10: Cumulative distribution functions of the BER of secondary packets at (a) 2 dB, (b) -2 dB, and (c) -6 dB secondary signal SINR.

the SU-RX can estimate the current value of $|H'_{SU}|$, which is $|H'_{SU-current}|$. It can also calculate the optimal beam weights for the SU-TX and thereby the maximum value of $|H'_{SU}|$, which is $|H'_{SU-max}|$. Therefore, SU-RX, we can compute

$$\gamma = \frac{|H'_{SU-max}|}{|H'_{SU-current}|} \tag{10}$$

for each non-silent sub-carrier. These γ's are sorted and the top N% sub-carriers with the largest γ are selected. Because feedback accounts for most of the overhead, N% feedback can be coarsely regarded as reducing the overhead to N%. Note that both data and pilot sub-carriers are considered for selective feedback. This is because pilots help to correct phase offset. Therefore, inadvertently canceled pilots have significant impact on signal decoding. We consider values of N including 100 (all non-silent sub-carriers), 50 (the top half), and 1 (top 1%).

Experiment Results. The cumulative distribution functions of secondary packet BER at different secondary signal SINR are shown in Fig. 10. For Fig. 10a, 10b, and 10c, the secondary signal SINR is 2 dB, -2 dB, and -6 dB, respectively. There is a vertical line of 2×10^{-3} BER in each figure. In practical systems, forward error correction coding can reduce 2×10^{-3} BER to below 2×10^{-16} [14]. Therefore, we approximately view all the secondary packets with BER smaller than 2×10^{-3} as largely error-free packets.

In Fig. 10, the red curves show the results when CAT is not applied, while the black curves show the results when CAT is applied with feedback of all sub-carriers. The results indicate that CAT significantly increases the percentage of error-free secondary packets. At 2 dB, -2 dB, and -6 dB secondary signal SINR, it is increased from 79.0% to 96.2%, 37.7% to 92.9%, and 0.0% to 57.8%, respectively. In Fig. 10a, the percentage of packets with zero BER also increases from 35.2% to 90.8%. However, even with CAT, some SU packets still have relative large BER. There are mainly two reasons: *(i)* When the residual TV signals are relatively strong compared to both $|H_1|$ and $|H_2|$ in Eq. (7), CAT cannot provide significant gain. This is because even if the secondary signals add constructively, the increase of the secondary signal SINR is small. *(ii)* When channels vary rapidly, the calculation of CAT may be stale.

There are two other curves showing the performance of CAT with 50% (yellow curve) and 1% (blue curve) feedback. Note that with 1% feedback, we only send the beam weights of 4 sub-carriers. At 2 dB secondary signal SINR, 50% feedback leads to 95.4% error-free packets, which is very close to that of 100% feedback. Even with 1% feedback, 91.9% packets are error free. However, when the secondary signal SINR decreases, the improvement by selective feedback also decreases. At -6 dB secondary signal SINR, the percentage of error-free packets with 50% and 1% feedback is only 22.6% and 2.0%, respectively. Both of them have a large difference from the 57.8% error-free rate with 100% feedback. The reason is shown in Table 1. M denotes the percentage of data sub-carriers with highest BER (which is different from N in Fig. 10 that considers data/pilot sub-carriers). When the secondary signal SINR increases, bit errors are more focused on the several sub-carriers. This is because when the secondary signal SINR is large, most bit errors are caused by inadvertent cancellation of secondary signals in certain sub-carriers. However, when the secondary signal SINR becomes smaller, more bit errors are caused by residual TV signals.

Table 1: Percentage of bit errors of the top M% data sub-carriers with highest BER.

SINR (dB)	2	-2	-6	-10	-14	-18
$M = 1$	50.0%	40.8%	19.2%	9.5%	5.5%	4.0%
$M = 10$	99.4%	98.9%	91.1%	58.2%	38.4%	28.8%
$M = 50$	100%	100%	100%	100%	99.6%	87.9%

Finding: (i) *CAT significantly improves the performance of secondary transmission even after WATCH-IC.* (ii) *For cases of relatively high secondary signal SINR, CAT requires feedback of only 1% non-silent sub-carriers.* (iii) *The improvement of CAT's selective feedback is diminished when the secondary signal SINR decreases, mainly because more bit errors are caused by residual TV signals instead of inadvertent cancellation of secondary signals.*

5.5 Urban Scale Analysis

Finally, we couple the in-lab measurements with UHF spectrum usage and TV viewing data to estimate the performance of an urban scale deployment.

Setup. We collect TV signal strength of 20 strong UHF channels in Houston (4th largest U.S. city) from TVFool [24]. Moreover, we use data of the total TV households in that city [21], the percentage of TV households that rely on broadcasts in the U.S. [20], and the percentage of TV households that are watching a certain TV programming among all TV households at peak TV viewing time in the U.S. [19].

In the data-driven simulation, we first divide the city into blocks of 10 m×10 m. Active TV receivers are randomly placed according to the calculated density. The maximum EIRP of SU's in each block is computed so that for all TV receivers that can originally decode the TV programming (TV signal strength larger than the TV service threshold), the TV signal SINR is still above the TV SINR threshold. If a PU and a SU are in the same block, we assume that

Table 2: Parameters for urban scale analysis.

MAX SU EIRP [9] – S^{SU}_{max}	4 W
SU-TX, SU-RX/PU-RX Antenna Height	3/10 m
TV SINR Threshold – Δ_{TV_SINR} [9]+$\Delta_{redundency}$	23+10 dB
TV Service Threshold [9] – $S^{PU}_{service\_min}$	-84 dBm/6 MHz
Noise Floor [9,31]	-114 dBm/6 MHz
SU-SU/SU-PU Reference Distance	10/5 m

there is a SU-PU reference distance between them. We also assume that SU-TX and SU-RX are separated by a SU-SU reference distance. For the secondary signal pathloss, we employ the Extended-Hata and Hata-SRD model [7]. Even though here the coverage of each SU-TX is a sphere, in practice WATCH can be used with any non-isotropical pathloss models. The achievable rates of secondary links in all the blocks are calculated with Shannon equation, which are then averaged over the whole urban area yielding spatial-spectral efficiency results with unit $bits/sec/Hz/m^2$. Table 2 summarizes the parameters.

Results. Fig. 11 depicts the average spatial-spectral efficiency for all SU's in one UHF channel. In particular, we compute average $bits/sec/Hz/m^2$ for each UHF channel and present average values of the 20 channels normalized to the achievable rate of a UHF channel that has no TV transmitters nor TV receivers. In other words, the normalization baseline, 1, is the average achievable rate for SU's in an unused UHF channel by current TV white space regulations. There are two groups of bars in Fig. 11: the left one shows the results when WATCH-IC and CAT are not applied, while the right one shows the results when WATCH-IC and CAT are both applied. According to our experiments, combined WATCH-IC and CAT can lead to approximately 20 dB increase of secondary signal SINR (for 512-sub-carrier SU transmission). Within each group, the three bars from left to right represent 0%, 1%, and 5% TV active (among all TV households) in each UHF channel, respectively. The case of 0% provides a baseline in which only the TV transmitter is on but no TV receivers are viewing the channel. In this case, the secondary system is only constrained by TV interference and not by the need to avoid interfering with active TV receivers.

When WATCH-IC and CAT are not employed, the average achievable rate for SU's is only 0.23 per UHF channel in the case of 0% TV active rate. WATCH-IC and CAT can almost double the achievable rate to 0.42 by increasing the SINR of secondary signals. When there are TVs viewing the channel, the spatial-spectral efficiency of the secondary system decreases due to the protection of active TV receivers. When WATCH-IC and CAT are not applied (applied), compared to 0% TV active rate, 1% TV active rate results in 22.2% (12.7%) decrease of SU achievable rate, while 5% TV active rate results in 46.6% (28.2%) decrease of SU achievable rate. However, while the number of active TV receivers has a large influence on WATCH's performance, in practice, there cannot be an average of 5% TVs active in each UHF channel since each household can view only a single channel at a time. Therefore, the operational limit of WATCH is primarily from strong TV signals (interference) rather than protecting active TV receivers. Moreover, because TV signal strengths are different in different UHF channels, the corresponding per channel achievable rate for SU's are also different.

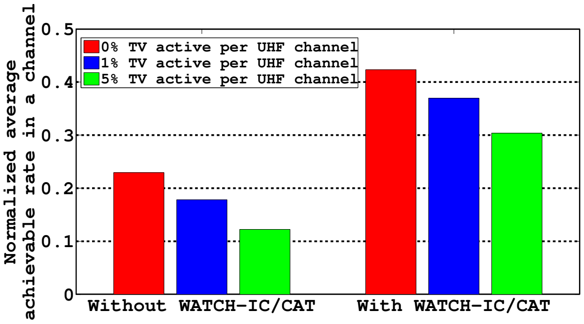


Figure 11: Normalized average achievable rates that WATCH provides to SU's in one UHF channel

Considering the case of 1% TV per-channel activity, the corresponding average achievable rate for SU's is 0.37 per UHF channel. According to Google Spectrum Database, Houston has only 3.26 out of the 47 UHF channels that can be used by TVWS systems (spatially averaged), which leads to a total normalized average achievable rate for SU's of 3.26. Compared to that, WATCH provides $0.37 \times (47 - 3.26) + 3.26 = 19.44$ total achievable rate of all the 47 UHF channels. As an upper bound, if all TV transmitters were turned off, the total achievable rate for SU's would be 47 (1 per channel). Therefore, WATCH provides at least 6.0 times the total achievable rate to SU's compared to current TVWS systems, which is also over 42% of the maximum value if all TV transmitters were turned off.

Finding: (i) *WATCH can provide at least 6.0 times the total achievable rate to SU's compared to current TV white space systems in Houston (typical of a large U.S. city).* (ii) *The operational limit of WATCH is dominated by strong TV signals, and not by the need to protect active TV receivers as TV viewers have low viewing rates and only view one channel at a time when active.*

6. RELATED WORK

Re-use of UHF channels. Most prior work on secondary re-use of UHF band employed the TVWS model, in which TV transmitters determine the exclusion zone and only "idle" channels can be re-purposed [3, 18, 30, 31]. Other work attempts to reduce the exclusion zone by excluding indoor environments where thick walls can largely attenuate interference both from TV system to SU's and from secondary system to TV receivers [4, 28]. Ellingsaeter et al. proposed to use TV receiver information to increase SU spectrum re-use and estimated the resulting increase in spectrum availability (in Hz) for several Norwegian cities [8]. In contrast, we realize the design, implementation, and experimental evaluation of WATCH to cancel TV signals at SU-RX's and protect dynamically active TV receivers from secondary transmissions. Therefore, WATCH targets both indoor and outdoor environments.

Interference cancellation. Previous IC work focused on 2.4/5 GHz ISM bands [11, 23, 27]. Tan et al. decoded overlapping WiFi packets [23]. Gollakota et al. proposed to cancel interference without the help of preambles [11]. Based on that, Yan et al. decode a WiFi packet and an overlapping ZigBee packet [27]. In comparison, we design IC mechanisms under the constraint of a streaming kilowatt-scale interferer in the UHF band.

Constructive addition transmission. Transmit beamforming is employed in IEEE 802.11n and combined transmit beamforming (interference alignment) and receive beamforming (interference cancellation) have been proposed for WiFi bands [6, 12, 29]. However, such techniques require coordination among different access points/clients. In contrast, TV transmitters are non-adaptive to the secondary system in our scenario. CAT also operates under continuous and strong interfering TV signals.

Noam et al. proposed to send secondary signals in the null-space of the interference channel of primary signals at the primary receiver, so that interference to the primary receiver is minimized [22]. However, this technique requires multiple-antenna PU and SU, with the primary transmitter adaptively beamforming to the primary receiver according to interference and channel conditions. In comparison, CAT is compatible with legacy single-antenna broadcast TV systems. The purpose of CAT is also different, which is to avoid inadvertent cancellation of secondary signals.

7. CONCLUSION

In this paper, we propose WATCH, the first system to enable secondary WiFi transmission during active TV broadcasts. WATCH utilizes primary receiver feedback to protect incumbent TV reception. We also design WATCH-IC and CAT to enable secondary WiFi transmission under interference from streaming kilowatt-scale TV transmitters. We build a testbed and evaluate WATCH with FCC permission and show that in a typical U.S. major city, WATCH can provide at least 6 times the total achievable rate to SU's compared to current TVWS regulatory models, while at the same time only increasing TV channel switching time by less than 5%.

8. ACKNOWLEDGMENTS

The authors would like to thank Narendra Anand and Ryan Guerra for their assistance in performing the experiments. This research was supported by Cisco Systems, Intel, the Keck Foundation, and by NSF grants CNS-1444056, CNS-1126478 and CNS-1012831.

9. REFERENCES

[1] N. Anand, R. Guerra, and E. Knightly. The Case for UHF-Band MU-MIMO. In *Proc. of ACM MobiCom*, 2014.

[2] ATSC. ATSC Digital Television Standard – Part 2: RF/Transmission System Characteristics, 2011.

[3] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh. White Space Networking with Wi-Fi Like Connectivity. In *Proc. of ACM SIGCOMM*, 2009.

[4] L. Bedogni, A. Achtzehn, M. Petrova, and P. Mähönen. Smart Meters with TV Gray Spaces Connectivity: A Feasibility Study for Two Reference Network Topologies. In *Proc. of IEEE SECON*, 2014.

[5] CEA. U.S. Household Television Usage Update. `http://store.ce.org/Default.aspx?TabID=251&productId=328850`, 2013.

[6] L. Ching-Ju, S. Gollakota, and D. Katabi. Random Access Heterogeneous MIMO Networks. In *Proc. of ACM SIGCOMM*, 2011.

[7] CPTE. Extended Hata and Hata-SRD Models. `http://tractool.seamcat.org/wiki/Manual/PropagationModels/ExtendedHata`.

[8] B. Ellingsaeter, H. Bezabih, J. Noll, and T. Maseng. Using TV Receiver Information to Increase Cognitive White Space Spectrum. In *Proc. of IEEE DYSPAN*, 2012.

[9] FCC. Second Report and Order and Memorandum Opinion and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands Additional Spectrum for Unlicensed Devices below 900 MHz and in the 3 GHz Band, 2008.

[10] A. Flores, R. Guerra, E. Knightly, P. Ecclesine, and S. Pandey. IEEE 802.11af: A Standard for TV White Space Spectrum Sharing. *IEEE Communications Magazine*, 51(10):92–100, 2013.

[11] S. Gollakota, F. Adib, D. Katabi, and S. Seshan. Clearing the RF Smog: Making 802.11n Robust to Cross-Technology Interference. In *Proc. of ACM SIGCOMM*, 2011.

[12] S. Gollakota, S. Perli, and D. Katabi. Interference Alignment and Cancellation. In *Proc. of ACM SIGCOMM*, 2009.

[13] K. Harrison, S. Mishra, and A. Sahai. How Much White-Space Capacity Is There? In *Proc. of IEEE DYSPAN*, 2010.

[14] ITU. ITU-T Recommendation G.975.1. `http://www.itu.int/rec/T-REC-G.975.1`, 2004.

[15] H. Karimi. A Framework for Calculation of TV White Space Availability Subject to the Protection of DTT and PMSE. In *Proc. of IEEE PIMRC*, 2013.

[16] M. Laner, P. Svoboda, P. Romirer-Maierhofer, N. Nikaein, F. Ricciato, and M. Rupp. A Comparison between One-Way Delays in Operating HSPA and LTE Networks. In *Proc. of IEEE WiOpt*, 2012.

[17] D. Lekomtcev and R. Maršálek. Comparison of 802.11 af and 802.22 Standards – Physical Layer and Cognitive Functionality. *Elektro Revue*, 3(2):12–18, 2012.

[18] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl. Senseless: A Database-Driven White Spaces Network. In *Proc. of IEEE DYSPAN*, 2011.

[19] Nielsen. Nielsen Top 10 List. `http://www.nielsen.com/content/corporate/us/en/top10s.html`.

[20] Nielsen. Cross-Platform Report. `http://www.nielsen.com/us/en/insights/reports/2014/shifts-in-viewing-the-cross-platform-report-q2-2014.html`, 2014.

[21] Nielsen. Local Television Market Universe Estimates. `http://www.nielsen.com/content/dam/corporate/us/en/docs/solutions/measurement/television/2013-2014-DMA-Ranks.pdf`, 2014.

[22] Y. Noam and A. Goldsmith. Blind Null-Space Learning for MIMO Underlay Cognitive Radio with Primary User Interference Adaptation. *IEEE Transactions on Wireless Communications*, 12(4):1722–1734, 2013.

[23] K. Tan, H. Liu, J. Fang, W. Wang, J. Zhang, M. Chen, and G. Voelker. SAM: Enabling Practical Spatial Multiple Access in Wireless LAN. In *Proc. of ACM MobiCom*, 2009.

[24] TVFOOL. `http://www.tvfool.com/`.

[25] WARP. `http://mangocomm.com/`.

[26] M. Wylie-Green and T. Svensson. Throughput, Capacity, Handover and Latency Performance in a 3GPP LTE FDD Field Trial. In *Proc. of IEEE GLOBECOM*, 2010.

[27] Y. Yan, P. Yang, X. Li, Y. Tao, L. Zhang, and L. You. ZIMO: Building Cross-technology MIMO to Harmonize ZigBee Smog with WiFi Flash Without Intervention. In *Proc. of ACM MobiCom*, 2013.

[28] X. Ying, J. Zhang, L. Yan, G. Zhang, M. Chen, and R. Chandra. Exploring Indoor White Spaces in Metropolises. In *Proc. of ACM MobiCom*, 2013.

[29] H. Yu, O. Bejarano, and L. Zhong. Combating Inter-cell Interference in 802.11ac-based Multi-user MIMO Networks. In *Proc. of ACM MobiCom*, 2014.

[30] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, I. Ferrell, T. Moscibroda, S. Narlanka, and Y. Wu. KNOWS: Kognitiv Networking Over White Spaces. In *Proc. of IEEE DYSPAN*, 2007.

[31] T. Zhang, N. Leng, and S. Banerjee. A Vehicle-based Measurement Framework for Enhancing Whitespace Spectrum Databases. In *Proc. of ACM MobiCom*, 2014.

[32] X. Zhang. WATCH: WiFi in Active TV Channels (Master Thesis), Rice University, Houston, Texas.