WATCH: WiFi in Active TV Channels

by

Xu Zhang

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APPROVED, THESIS COMMITTEE:

Edward W. Knightly, Chair
Professor of Electrical and Computer Engineering

Behnaam Aazhang
J.S. Abercrombie Professor of Electrical and Computer Engineering

Lin Zhong
Associate Professor of Electrical and Computer Engineering

Houston, Texas
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ABSTRACT

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“White space” model allows TV channels that are not being used regionally by a TV broadcaster to be re-purposed for secondary access. Unfortunately, populated areas have few these unused channels. Nonetheless, Nielsen data show severe under-utilization with vast regions in range of TV transmitters having no active TV receivers even at peak TV viewing time. In this thesis, I present the design, implementation, and evaluation of WATCH (WiFi in Active TV CHannels), the first system to (i) enable secondary WiFi transmission in the presence of kilowatt-scale TV transmitters by employing WATCH-IC (Interference Cancellation) and CAT (Constructive Addition Transmission); (ii) protect active TV receivers by employing their spatial-spectral requirements. With FCC permission to test WATCH implementation, I show that WATCH can provide at least 6.0 times the total achievable rate to 4 watt secondary devices compared to white space model, while increasing the TV channel switching time by less than 5%.
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Chapter 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 to be primary transmitters (or primary users, PU) because they have the highest priority to access the spectrum as the protected incumbents. To accommodate the increasing demand for wireless network access, today’s regulatory frameworks (in the U.S. [1] and U.K. [2]) define that when a geographical region has no primary broadcaster on a particular channel, that channel is called “white space” and is available for transmission by secondary users (SU). Unfortunately, the large number of over-the-air TV broadcasters in many populated areas yields extremely limited white space availability [3]. However, 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 [4,5].

In this thesis, I 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. Nonetheless, 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. Consequently, WATCH comprises the following three contributions.

First, I propose a new spectrum sharing model and obtain an FCC experimental license for testing. To date, TV white space 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 [1]. In contrast, I propose a dynamically computed exclusion zone characterized as the union of locations where SU transmit power must be reduced in order to protect active primary TV receivers. By exploiting that the receiver-based exclusion zone has a much smaller footprint than the transmitter-based exclusion zone, WATCH enables vastly increasing secondary spectrum re-use.

Second, to protect active TV receivers from secondary transmissions, I introduce two mechanisms to dynamically control the exclusion zone. (i) By generalizing the functionality of spectrum database controller in standards such as IEEE 802.11af [6], I design WATCH spectrum database controller to collect information of active primary TV receivers and accordingly coordinate secondary transmissions. Namely, with active TV receiver channel usage and location information, WATCH controller dynamically determines the maximum transmit power for SU’s. (ii) I design a WATCH TV receiver that can inform the controller of TV viewing. I introduce two complimentary feedback mechanisms to allow the use with legacy TV systems: first, I propose to use a smart remote coupled with a legacy TV, e.g., via a smartphone. Upon switching the TV channel via infrared, the enhanced remote also informs WATCH controller of the new selection. Second, I propose to use a smart TV coupled with a legacy remote, where the Internet-connected TV informs WATCH controller of the new selection.

Third, I design a novel secondary transmit-receive architecture that enables sec-

\*FCC experimental license call sign WH9XHJ and file number 0121-EX-ST-2014.
ondary WiFi transmission even when the kilowatt-scale primary TV transmitters are broadcasting. For secondary reception, I design an interference cancellation (IC) technique, WATCH-IC, which exploits the fact that TV signals are always being broadcasted, in contrast to IC in non-streaming-broadcast systems such as cellular or WiFi. In particular, I design an IC algorithm to cancel TV signals without requiring their preambles to be known a priori. Therefore, WATCH is compatible with any broadcast technologies and is not specific to a regional TV coding scheme. For secondary transmission, I 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, I employ selective feedback to reduce CAT’s overhead. Compared to transmit beamforming in IEEE 802.11n, CAT adapts to continuous and strong interference.

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

*Protecting active TV receivers:* I emulate the feedback process of primary TV receivers and find that 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). I show that WATCH’s TV receiver feedback process adds no more than 5% (or 100 ms) to the above channel switching time.

*Secondary WiFi transmission in active TV channels:* I build two-antenna secondary transceivers using WARP and UHF-band radio boards [7] and implement both WATCH-IC and CAT. I provide the first demonstration of secondary transmis-
sion in active TV channels, including under interference of the strongest DTV signals in my lab location. With 16-QAM and no channel coding, WATCH-IC alone enables WATCH to achieve an average BER of $2.4 \times 10^{-3}$ 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. I also show that larger sub-carrier density is needed in WATCH for secondary transmission compared to current TV white space systems [6] in order to cancel long-distance TV interference.

Urban scale analysis: I provide a city-wide data-driven analysis of WATCH with UHF spectrum usage data of Houston [8], TV viewing data from Nielsen [5,9,10], and WATCH parameters from my implementation. I show that the existence of primary TV signals leads to very different qualities of re-usable frequencies for SU’s. With 1% active TV receivers (among all TV households) per UHF channel, WATCH can provide 6.0 times the total achievable rate to 4 watt secondary devices compared to current TV white space systems. This utilization represents 42% of the total achievable rate if all TV transmitters were turned off.

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

WATCH Architecture

2.1 Legacy Spectrum Sharing

Current TV white space regulations target exclusion of secondary re-use based on locations of TV transmitters. In particular, a typical scenario is shown in Fig. 2.1: Around the TV transmitter, a broadcast service area is determined by the TV signal propagation model. Within this area, secondary transmissions are prohibited. In other words, the secondary transmitter (SU-TX) and the secondary receiver (SU-RX) can only communicate outside the TV service area. Information of all TV transmitters and the pre-calculated exclusion zones are 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 [6].

Different methods are employed to compute the exclusion zone. According to FCC, the exclusion zone is the TV service area, plus an additional separation which is determined by SU’s antenna height and operating frequencies. Outside this area, fixed secondary devices are allowed to transmit at up to 4 W EIRP (Effective Isotropic Radiation Power, or 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 [1]. In comparison, Ofcom determines the exclusion zone implicitly, by dividing space into 100 m×100 m blocks with each one having a calculated maximum SU EIRP, so
that the broadcast reception quality of TV receivers are ensured [2]. Both FCC and Ofcom require a central spectrum database controller with optional spectrum sensing by SU’s.

![Diagram of TV service area with TV transmitter, SU-TX, SU-RX, Active TV, Exclusion zone, and Inactive TV]

Figure 2.1: The exclusion zone is calculated based on TV transmitters in current TV white space systems.

### 2.2 WATCH Spectrum Sharing

Legacy spectrum sharing models protect a region determined by the TV transmitter. However, because the percentage of active TV receivers relying on over-the-air UHF broadcasts is very small [4,5], we can re-purpose spectrum even within the TV service area:  
(i) *Spectrum in the spatial gaps:* In-between active TV receivers, we can allow secondary transmissions without interfering with TV receivers.  
(ii) *Spectrum in the temporal gaps:* When TV receivers are not tuned into a particular TV channel, we can allow secondary transmissions in that channel and in the region around the TV receivers.
Figure 2.2: The exclusion zone is calculated based on active TV receivers in WATCH.

While current TV white space systems cannot re-use both of the above spectrum opportunities, WATCH enables re-use by dynamically determining the per-channel exclusion zone based on protection of only active primary TV receivers. As illustrated in Fig. 2.2, 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 dynamic and adapted each time a primary TV receiver is tuned in or out of that channel.

To realize the new spectrum sharing model, WATCH comprises the following components as shown in Fig. 2.3: 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 the activeness 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 chapters.
Chapter 3

Protecting Active Primary TV Receivers

This chapter describes mechanisms to protect broadcast reception quality of active primary TV receivers. While wireless microphones are also incumbents according to FCC [1], they can be protected by similar mechanisms. In the following, I will present the design of WATCH spectrum database controller and the functions and realization of primary feedback.

3.1 Spectrum Database Controller

The WATCH spectrum database controller determines the operational parameters of SU’s based on active TV receivers coupled with implicitly determined exclusion zones with a method analogous to Ofcom calculation [2]. In particular, WATCH does not explicitly disallow secondary transmissions in certain areas. Instead, it divides 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. Since the database stores the transmit powers and locations of TV transmitters and the locations of active TV receivers, the maximum SU EIRP for each block can be computed.

Whenever TV receiver $i$ becomes active in channel $c$, WATCH controller updates the maximum SU EIRP $S_{c,j}^{SU}$ 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: WATCH limits the maximum SU EIRP to $S_{SU \ max}^{SU}$. Moreover, we can obtain
the minimum required TV signal strength $S_{\text{service}, \ min}^{PU}$ and TV signal SINR $\Delta_{TV, \ SINR}$
within the TV service area from legacy standards, e.g., the ATSC DTV standard.
Denote $h(\cdot)$ as the pathloss of secondary signals. Using the Extended-Hata and
Hata-SRD models [11], $d^c$ is selected to satisfy

$$\Delta_{TV, \ SINR} + \Delta_{\text{redundency}} = \frac{S_{\text{service}, \ min}^{PU}}{S_{SU \ max}^{SU}} \cdot h(d^c),$$  

where an additional $\Delta_{\text{redundency}}$ is added to $\Delta_{TV, \ SINR}$ to represent the aggregate
interference from multiple SU’s. When updating $S_{c,j}^{SU}$, WATCH ensures that

$$S_{c,j}^{SU} \leq \frac{S_{c,i}^{PU}}{(\Delta_{TV, \ SINR} + \Delta_{\text{redundency}}) \cdot h(d_{c,j}^c)},$$

where $S_{c,i}^{PU}$ denotes the mean TV signal strength at TV receiver $i$ in channel $c$, which
is computed by the Longley-Rice irregular terrain model currently used by FCC [12].

When TV receiver $i$ is turned off or switched to another channel, all $S_{c,j}^{SU}$ within $d^c$
distance are updated again by WATCH controller: either to a larger value restricted
by another active TV receiver $i'$ or to $S_{SU \ max}^{SU}$.

3.2 Primary TV Receiver Feedback

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

In WATCH, the allowed in-block maximum SU EIRP $S_{c,j}^{SU}$ is dynamically set with
different active primary TV receivers. For block $j$, if all the TV receivers within
$d^c$ are switched to channels other than $c$ or turned off, $S_{c,j}^{SU}$ is reset to $S_{SU \ max}^{SU}$ (it is
symmetric that for either a TV receiver $i$ or a block $j$, controller calculations are only 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, active TV receivers need to inform the database controller of the channel changes through primary feedback.

After the TV receiver informs the controller that it is tuned into a particular UHF channel $c$, the controller updates all $S_{c,j}^{SU}$ within $d^c$. However, if the active TV receiver is nonetheless incurring excessive interference due to the errors in either the collected data, e.g., the locations of SU’s, or the calculation of the exclusion zone, e.g., the pathloss model, WATCH employs the following fail-safe mechanism: If a TV receiver infers that there is excessive interference, WATCH controller will gradually increase $\Delta_{\text{redundancy}}$, grow the exclusion zone, and re-calculate $S_{c,j}^{SU}$, until that the TV receiver can successfully decode the TV programming. If $\Delta_{redundancy}$ exceeds a pre-defined threshold $\Delta_{\text{redundancy}}^{max}$ and the TV receiver still infers being interfered, WATCH controller will consider that the excessive interference is due to poor channel 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, the primary feedback can be transmitted out-of-band via WiFi or cellular networks or wired connections such as DSL, or in-band via a UHF feedback channel. I propose two methods to implement primary feedback with minimum modifications to legacy TV systems: (i) *Smart remote:* Smartphones can control TV’s via infrared, e.g., Samsung Galaxy S5 and HTC One M8.* Consequently, smartphones can be used as

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combined feedback and remote devices. (ii) Smart TV: Feedback can be sent via the TV’s Internet access.

The two functions of primary feedback determine the feedback amount. In the above discussion, all the channels (TV channels, UHF channels) are treated the same. However, in practice, channels are divided into two different types: a physical channel which occupies 6 MHz bandwidth and a virtual channel which contains a TV programming. Each physical channel comprises 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 [13], 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 $\Delta_{\text{redundancy}}$ determines how well the active primary TV receivers can be protected. A large initial $\Delta_{\text{redundancy}}$ reduces the amount of feedback to trigger the “fail-safe” mechanism, whereas in the meantime increases the possibility to excessively limit the SU EIRP.

I finally analyze the degradation of broadcast video reception quality that occurs immediately following a physical channel switch. Denote $t_{\text{legacy}}$ as the time a legacy TV receiver takes to switch between physical channels, which includes physical signal decode, transport stream demultiplexing and video data decode. WATCH increases $t_{\text{legacy}}$ to $t_{\text{WATCH}}$ by adding an additional delay at the beginning. This delay is used for the TV receiver to send the primary feedback and WATCH controller to update $S_{c,j}^{SU}$ and send to SU’s. A comparison between $t_{\text{legacy}}$ and $t_{\text{WATCH}}$ is given in Chap. 5.
Chapter 4

Secondary Networks in Range of TV Broadcasts

After a SU has been given the permission by the controller to transmit, it can freely access the channel. However, new mechanisms are needed in order 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 and a 200 m-high TV transmitter is 4 W and over 1000 kW, respectively. In this chapter, I show how WATCH exploits the unique properties of the continuous interference to precode secondary transmission and cancel TV signals at secondary receiver.

4.1 WATCH-IC: Cancellation of Primary 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 secondary receiver is shown in Fig. 4.1. WATCH does not require more than two antennas since there will only be a single TV transmitter per UHF channel requiring cancellation. Denote $X_{PU}$ and $X_{SU}$ as the primary and secondary signals, respectively. The two signals $Y_{1}$
Figure 4.1: WATCH employs two-antenna secondary receiver to cancel TV signals.

and $Y_2$ at the two receiving antennas are

$$Y_1 = H_{PU1}X_{PU} + H_{SU1}X_{SU},$$

$$Y_2 = H_{PU2}X_{PU} + H_{SU2}X_{SU}. \quad (4.1)$$

If the secondary receiver could receive a clean (uninterfered) preamble of the 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 standard [14] 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 primary DTV signals are sent only every 24.2 ms, which is inconvenient for SU to use.
As a result, WATCH cancels TV signals without estimating $H_{PU1}$ and $H_{PU2}$. Instead, it estimates $\frac{H_{PU1}}{H_{PU2}}$, 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, it exploits that the primary TV transmitter is always transmitting and that the secondary transmitter intermittently transmits. Consequently, when the secondary transmitter is not sending data and $X_{SU} = 0$, the secondary receiver can estimate

$$H'_{PU/SU-RX} = \frac{Y_1}{Y_2} = \frac{H_{PU1}}{H_{PU2}}.$$  \hspace{1cm} (4.2)

When the secondary transmitter is sending data, TV signals can be canceled at the secondary receiver 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. (4.2) in [15]. We can also use MMSE (minimum mean square error) IC by computing $H'_{PU/SU-RX} = C_{Y_1Y_2}C_{Y_2}^{-1}Y_2$ when $X_{SU} = 0$, where $C$ is the covariance matrix.

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 the TV transmitter. Consequently, I design CAT, a Constructive Addition Transmission scheme that maximizes secondary signal SINR at secondary receiver after accounting for the known channels from the TV transmitter to the secondary receiver.

Namely, without CAT, when WATCH cancels TV signals, secondary signals may be inadvertently canceled as well in some sub-carriers. This effect can be severe when
the sub-carrier density for secondary transmission becomes large and when the TV signals cannot be completely canceled. Indeed, my experiments in Chap. 5 show that most bit errors of secondary transmissions are focused in several sub-carriers. To address this problem, CAT leverages multiple antennas at the secondary transmitter to maximize $|H_{SU}'|$, where $H_{SU}'$ is the CSI of secondary signals including WATCH-IC.

Figure 4.2: WATCH employs CAT to improve the performance of WATCH-IC.

As shown in Fig. 4.2, $\alpha = \cos \theta$ and $\beta = e^{i\phi}\sin \theta$ are the two beam weights. Different from Eq. (4.1), the two receiving signals $Y_1$ and $Y_2$ now become

$$Y_1 = H_{PU1}X_{PU} + (\alpha H_{SU11} + \beta H_{SU12})X_{SU},$$

$$Y_2 = H_{PU2}X_{PU} + (\alpha H_{SU21} + \beta H_{SU22})X_{SU}. \tag{4.3}$$

After WATCH-IC, $H_{SU}'$ can be calculated as

$$H_{SU}' = (\alpha H_{SU11} + \beta H_{SU12}) - H'_{PU/SU-RX} (\alpha H_{SU21} + \beta H_{SU22}). \tag{4.4}$$

If all the CSI in Eq. (4.4) are known, we can calculate the optimal $\hat{\alpha}$ and $\hat{\beta}$ to maximize $|H_{SU}'|$. However, to estimate the CSI, the secondary receiver 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, I define

\[ H_1 = H_{SU11} - H'_{PU/SU-RX} H_{SU21}, \]
\[ H_2 = H_{SU12} - H'_{PU/SU-RX} H_{SU22}. \]  

(4.5)

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 \( \alpha \) and \( \beta \).

Figure 4.3: CAT’s timeline.

An illustrative timeline of CAT is shown in Fig. 4.3:

(i) First, a sounding packet which contains training sequences with two different \((\alpha, \beta)\) sets is sent from the secondary transmitter to the secondary receiver.

(ii) At the secondary receiver, after TV signals are canceled, WATCH 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

\[ \hat{\phi} = \arg H_1 - \arg H_2, \]
\[ \hat{\theta} = \frac{\pi}{2} - \arccos \frac{|H_2|}{\sqrt{|H_1|^2 + |H_2|^2}}. \]  

(4.6)

(iii) The values of \( \hat{\phi} \) and \( \hat{\theta} \) are sent from the secondary receiver to the secondary
transmitter. Similar to Eq. (4.2), at the secondary transmitter $H'_{PU/SU-TX}$ is estimated. TV signals are canceled before the secondary feedback data are decoded.

(iv) The secondary transmitter uses $\hat{\phi}$ and $\hat{\theta}$ for precoding. At the secondary receiver, 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. 4.3, explicit sounding and feedback packets need to be sent before CAT can be applied to SU data transmission.

One way to reduce overhead in obtaining the CSI at the transmitter is to use implicit sounding, which does not require the sounding and feedback packets [16]. Instead, the secondary transmitter overhears packets from the secondary receiver and employs channel reciprocity to estimate $\hat{\phi}$ and $\hat{\theta}$. Unfortunately, implicit sounding cannot be used in WATCH due to TV interference. Namely, the TV signals are different at the secondary receiver and the secondary transmitter. With different $H'_{PU/SU-RX}$ and $H'_{PU/SU-TX}$, the secondary transmitter cannot estimate $H_{SU}$ (at the secondary receiver), which is required by CAT.

Therefore, WATCH employs an alternative to reduce the overhead of collecting the 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 secondary transmitter. Since secondary signals are not inadvertently canceled in every sub-carrier, CAT can only send selective $\hat{\phi}$ and $\hat{\theta}$ of those sub-carriers where secondary signals are canceled, and bit errors of secondary transmissions can still be largely reduced. Evaluations of CAT with selective feedback are shown in Chap. 5.
Chapter 5

Implementation and Evaluation

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

5.1 Testbed Implementation

I implement the key components of WATCH and configure a testbed as follows: (i) The DTV systems are Houston-area DTV broadcasters and the DTV receivers are off-the-shelf TV tuners.∗† (ii) I implement all aforementioned SU functionality on the software-defined radio platform WARP [17]. To enable UHF transmission and reception, I replace the default 2.4/5 GHz radio boards with custom UHF-band radio boards [7].

**PU system.** As shown in Fig. 5.1a, I combine over-the-air DTV signals with secondary signals generated by WARP and feed them into the TV tuners, which output the TV programing to a laptop through the USB interface. To emulate the latency of primary feedback, I set a timer when the channel switching command is

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†Hauppauge WinTV-HVR-950Q tuner: http://www.hauppauge.com/site/products/data_hvr_950q.html
sent to the TV tuners, and stop WARP transmission by disabling the transmitting chain after the timer expires.

**SU system.** As shown in Fig. 5.1b, I synchronize two WARP boards to build a
two-antenna secondary transceiver, and construct secondary links between secondary transceivers with 10 m separation. To download/upload signal samples to/from WARP, I use the WARPLab 7 development framework. At the secondary transmitter, I generate secondary packets according to the IEEE 802.11a standard, including preambles, pilots and data. The secondary receiver collects signals in a special format as shown in Fig. 5.2. The first part only contain the primary TV signals with secondary transmitter not transmitting. I 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. I first cancel the TV signals with $H'_{PU/SU-RX}$. Then I correct the timing and frequency offset of the secondary packet before decode. Secondary signal SINR before WATCH-IC is calculated as

$$\text{SINR} = \frac{E\{S_{PUSU}\} - E\{S_{PU}\}}{E\{S_{PU}\}}.$$  \hspace{1cm} (5.1)

5.2 Timing Requirement of Primary Feedback

Experiment Setup. To evaluate the interaction between the primary and the secondary system in WATCH, I 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. My 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 secondary transmitter is sending data?

To characterize the degradation of broadcast video reception quality, I define $\Delta = (t_{WATCH} - t_{legacy})/t_{legacy}$, with $t_{legacy}$ and $t_{WATCH}$ defined in Chap. 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, I find that there is a very narrow transition zone of the TV signal SINR between perfect TV programming displaying without errors and undecodable TV signals. I set the WARP transmit power sufficiently high to create strong SU interference, so that TV signals cannot be decoded if a SU is transmitting.

![Figure 5.3: Measured channel switching time with different primary feedback latencies.](image)

**Experiment Results.** I vary the control-loop latency of feedback between the TV remote channel change indication and notification to the SU to vacate the corresponding channel. For each latency, repeated experiments are performed with both TV tuners and different channel pairs and the corresponding channel switching time for the TV tuner are measured. The results are depicted in Fig. 5.3: 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. I only display average channel switching time because results are close for different TV tuners and channel pairs.

We can make several observations: First, channel switch alone is quite lengthy at 1.86 seconds even without WATCH. This is because that the 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 primary feedback with a smartphone-based remote, I consider the LTE network: According to [18, 19], 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 delay to a large database server report about 80 ms average RTT. Finding: Thus, I expect that in a full-scale system, the primary feedback latency of WATCH will be less than 100 ms, which leads to an additional channel switching time of TV’s with $\Delta < 5\%$. The use of a wire-connected Smart TV can lead to an even smaller $\Delta$ due to the smaller RTT.

\[\text{http://www.fiercewireless.com/special-reports/3g4g-wireless-network-latency-how-did-verizon-att-sprint-and-t-mobile-compa-3}\]
5.3 Cancellation of Primary TV Signals

To evaluate WATCH under the most adversarial conditions, I sweep all UHF channels and select the one with the strongest DTV signals, which is channel 26 (545 MHz). According to [8], the TV transmitter of channel 26 is approximately 17 km away from my lab and it can broadcast at a maximum of 1300 kW EIRP. In TV white space systems, this channel is clearly excluded from secondary transmission. Consequently, I received an experimental license from FCC to conduct the first experiments of secondary transmission in active TV channels. Since channel 26 contains the strongest DTV signals, my analysis shows the lower-bound performance of WATCH in our lab. For evaluation, I separately evaluate WATCH-IC and CAT, with this section considering WATCH-IC without CAT.

(i) Sub-carrier density for diverse primary/secondary channels: 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 my experiments use 5 MHz bandwidth, 16-QAM and no channel coding. For different secondary signal SINR, I vary the transmit power at the secondary transmitter. I also change the sub-carrier density of SU transmission from 64 to 512. The sampling rate and buffer size of WARP limit that at most 512 sub-carriers can be used for 5 MHz bandwidth.

Experiment Results. The results are shown in Fig. 5.4. The x-axis is the maximum SINR of secondary signals at the two receiving antennas before WATCH-IC (I 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
Without WATCH-IC, the BER is near 0.5 (random guessing) indicating a complete failure if legacy systems are used. 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 $1.9 \times 10^{-2}$ and $2.4 \times 10^{-3}$ respectively. In the experiments, while the increase of secondary signal strength after WATCH-IC is similar, the cancellation degree of primary 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 the channel fading can be considered flat over an OFDM sub-carrier. However, in WATCH, the required sub-carrier density of the secondary signals is dominated by the delay spread of the primary TV signals. In the experiments, the distance from the secondary transmitter to the secondary receiver
is only 10 m, whereas the distance from the TV transmitter to the secondary receiver is 17 km. According to [20], 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 the primary TV signals, a large sub-carrier density is required. This sharply contrasts with the TV white space standard: In IEEE 802.11af, SU’s only use 144 sub-carriers for 6 MHz bandwidth, which is equivalent to 120 sub-carriers for 5 MHz bandwidth [6]. Finding: To sufficiently cancel the primary TV signals with large delay spread, WATCH requires high sub-carrier density even for short range secondary transmission.

(ii) Secondary receiver dynamic range: Experiment Setup. Since WATCH cancels TV signals in the digital domain, it is important to characterize the impact of receiver ADC dynamic range on the performance of TV signal cancellation. An ADC with a greater number of bits provides higher resolution when digitalizing the signals, whereas it also increases the system cost and power consumption.

The experiment setup is the same as above. For a fair comparison, I keep the receiver gain settings unchanged (by disabling AGC) with different secondary signal SINR. All 12 bits of the WARP ADC are used when I collect the data. However, I modify the receiving signals in MATLAB before WATCH-IC in order to emulate the different ADC dynamic ranges.

Experiment Results. The results of 512-sub-carrier secondary transmission are shown in Fig. 5.5. The x-axis is the maximum secondary signal SINR at the two receiving antennas before WATCH-IC. The y-axis is the average BER of secondary signals. In the experiments, the average BER of secondary signals are very close when the ADC bit number reduces from 12 to 8. Therefore, in Fig. 5.5, I only plot
the results when the ADC bit number is 12, 7, 6, and 5. At 2 dB secondary signal SINR, the corresponding average BER is $2.4 \times 10^{-3}$, $4.9 \times 10^{-3}$, $2.2 \times 10^{-2}$, and $1.5 \times 10^{-1}$, respectively. The increase of BER is mainly due to the reduction of TV signal cancellation degree, which is 14.72 dB for 12-bit ADC and 9.30 dB for 5-bit ADC. Therefore, WATCH requires at least an 8-bit ADC at the secondary receiver to sufficiently cancel the TV signals. **Finding: A standard 8-bit ADC is sufficient for WATCH to cancel TV signals, despite the diversity in reception signal strength of the PU and SU.**

*(iii) Noise impact on WATCH-IC: Experiment Setup.* Finally, I analyze the impact of noise on WATCH-IC. Compared to MMSE WATCH-IC, ZF WATCH-IC may amplify the noises at the secondary receiver. However, MMSE WATCH-IC consumes more hardware resources. I use the same experiment setup to compare the performance of MMSE and ZF WATCH-IC.

**Experiment Results.** The results of 512-sub-carrier secondary transmission are
shown in Fig. 5.6. The x-axis is the maximum secondary signal SINR at the two receiving antennas before WATCH-IC. The y-axis is the average BER of secondary signals. Observe that the average BER of MMSE WATCH-IC is only slightly smaller than that of ZF WATCH-IC. There is fewer than 0.2 dB difference when they cancel the TV signals. The reason of the similar performance is because I select one of the UHF channels with the strongest TV signals. Therefore, the noises introduced by the channel and the receiver are much weaker than the TV signals. Note that for the noises/harmonics generated by the TV transmitter, WATCH-IC will try to cancel them at the secondary receiver. Nonetheless, the noises introduced by the channel and the receiver still limit WATCH performance, because they will be accumulated during WATCH-IC. Finding: With strong TV signals, the performance of ZF and MMSE WATCH-IC is sufficiently close that simpler-to-implement ZF WATCH-IC is sufficient for the secondary receiver.
5.4 Constructive Addition Transmission of Secondary Signals

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

**Experiment Setup.** For repeatable experiments, I collect over-the-air channel traces and evaluate CAT with TV signals received in channel 26. I use channel 29 (563 MHz) to collect the CSI between secondary transmitter and secondary receiver. According to Google Spectrum Database, there are no co-channel TV signals in channel 29 in my lab, so that I 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 the TV signals.

Out of the 512 sub-carriers, only 396 are used to transmit data/pilots (non-silent sub-carriers). To evaluate selective feedback, I only send ˆφ and ˆθ of N% of the 396 non-silent sub-carriers to the secondary transmitter. As shown in Chap. 4.2, the secondary receiver can estimate the current value of |H′SU|, which is |H′SU−current|. It can also calculate the optimal beam weights for the secondary transmitter and thereby the maximum value of |H′SU|, which is |H′SU−max|. Therefore, at the secondary receiver, WATCH can compute

\[ \gamma = \frac{|H'_{SU\text{-max}}|}{|H'_{SU\text{-current}}|} \]  

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 decode. I 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. 5.7. For Fig. 5.7a, 5.7b, and 5.7c, the secondary signal SINR is 2 dB, -2 dB, and -6 dB, respectively. There is a vertical line of \( 2 \times 10^{-3} \) BER in each figure. In practical systems, forward error correction coding can reduce \( 2 \times 10^{-3} \) BER to below \( 2 \times 10^{-16} \) [21]. Therefore, I approximately view all the secondary packets with BER smaller than \( 2 \times 10^{-3} \) as largely error-free packets.

In Fig. 5.7, 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. 5.7a, 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. (4.5), 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, I 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
Figure 5.7: Cumulative distribution functions of the BER of secondary packets at (a) 2 dB, (b) -2 dB, and (c) -6 dB 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 5.1. \( M \) denotes the percentage of data sub-carriers with highest BER (different from \( N \) in Fig. 5.7 which 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 5.1: Percentage of bit errors of the top \( M \% \) data sub-carriers with highest BER.

<table>
<thead>
<tr>
<th>SINR</th>
<th>2 dB</th>
<th>-2 dB</th>
<th>-6 dB</th>
<th>-10 dB</th>
<th>-14 dB</th>
<th>-18 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M = 1 )</td>
<td>50.0%</td>
<td>40.8%</td>
<td>19.2%</td>
<td>9.5%</td>
<td>5.5%</td>
<td>4.0%</td>
</tr>
<tr>
<td>( M = 10 )</td>
<td>99.4%</td>
<td>98.9%</td>
<td>91.1%</td>
<td>58.2%</td>
<td>38.4%</td>
<td>28.8%</td>
</tr>
<tr>
<td>( M = 50 )</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>99.6%</td>
<td>87.9%</td>
</tr>
</tbody>
</table>

**Finding:** (i) CAT significantly improves the performance of secondary transmission even after WATCH-IC. (ii) For cases of 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, I couple the in-lab measurements with UHF spectrum usage and TV viewing data to estimate the performance of an urban scale deployment.

**Setup.** The data for the estimation are from both online database and my experiments. I collect TV signal strength of 20 strong UHF channels in Houston from TVFool [8]. Moreover, I use data of the total TV households in Houston [9], the percentage of TV households that rely on broadcasts in the U.S. [5], and the percentage of TV households that are watching a certain TV programming among all the TV households at peak TV viewing time in the U.S. [10].

In the data-driven simulation, I first divide Houston into blocks of 10 m $\times$ 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 the 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, I assume that there is a SU-PU reference distance between them. I also assume that the secondary transmitter and the secondary receiver are separated by a SU-SU reference distance. For the secondary signal pathloss, I employ the Extended-Hata and Hata-SRD models [11]. The achievable rates of secondary links in all the blocks are calculated with Shannon equation, which are then averaged over the whole Houston area yielding spatial-spectral efficiency results with unit $\text{bits/sec/Hz/m}^2$. Table 5.2 summarizes the parameters.

**Results.** Fig. 5.8 depicts the average spatial-spectral efficiency for all SU’s in one UHF channel. In particular, I compute average $\text{bits/sec/Hz/m}^2$ 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,
Table 5.2: Parameters for urban scale analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX SU EIRP $S_{SU}^{max}$</td>
<td>4 W</td>
</tr>
<tr>
<td>SU-TX, SU-RX/PU-RX Antenna Height</td>
<td>3/10 m</td>
</tr>
<tr>
<td>TV SINR Threshold $\Delta_{TV,SINR}^{[1]}+\Delta_{redundency}$</td>
<td>23 + 10 dB</td>
</tr>
<tr>
<td>TV Service Threshold $S_{PU}_{service,min}$</td>
<td>-84 dBm / 6 MHz</td>
</tr>
<tr>
<td>Noise Floor $[1,22]$</td>
<td>-114 dBm / 6 MHz</td>
</tr>
<tr>
<td>SU-SU/SU-PU Reference Distance</td>
<td>10/5 m</td>
</tr>
</tbody>
</table>

![Normalized average achievable rate in a channel](image)

Figure 5.8: Normalized average achievable rates that WATCH provides to SU’s in one UHF channel

the normalization baseline, 1, is the average achievable rate for SU’s in an unused UHF channel by current TV white space regulatory model. There are two groups of bars in Fig. 5.8: 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 the experiments, combined WATCH-IC and CAT can lead to about 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 such case, the secondary system is only constrained by the primary TV interference and not by the need to avoid interfering with active primary 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 TV’s 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% TV’s active in each UHF channel. Therefore, the operational limit of WATCH is primarily from the strong TV signals (interference) rather than protecting active primary TV receivers. Moreover, because the TV signal strength are different in different UHF channels, the corresponding per channel achievable rate for SU’s are also different.

Considering the case of 1% TV active rate, the corresponding average achievable rate for SU’s is 0.37 per UHF channel. According to Google Spectrum Database, in
Houston there are only 3.26 out of the 47 UHF channels that can be used by TV white space systems (spatially averaged over Houston), 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 TV white space systems, which is also over 42% of the maximum value if all TV transmitters were turned off.

Finding: (i) In Houston, WATCH can provide at least 6.0 times the total achievable rate to SU’s compared to current TV white space systems. (ii) The operational limit of WATCH is dominated by the strong primary TV signals, and not by the need to protect active primary TV receivers.
Chapter 6

Related work

Re-use of UHF channels. Most prior work on secondary re-use of the UHF band employed the TV white space model. As mentioned in Chap. 2, FCC determines the exclusion zones with locations of TV transmitters and propagation model of TV signals [1]. Under this concept, Murty et al. proposed a system design called SenseLess in [12], where a central database controller is also employed to coordinate between PU’s and SU’s. Yuan et al. and Bahl et al. proposed methods for SU’s to efficiently re-use the TV white space in [23] and [24], respectively. Recent work by Zhang et al. proposed to use extensive spectrum measurements to calibrate the TV signal propagation model and also to characterize the white space quality [22]. In comparison, WATCH does not build on the white space model. It determines the exclusion zones only with locations of active TV receivers.

To reduce the exclusion zone and increase secondary re-use, Ying et al. and Bedogni et al. focused on indoor environments where the thick wall largely decreases the interference both from the primary TV system to SU’s and from the secondary system to primary TV receivers in [25] and [26], respectively. Ellingsaeter et al. proposed to use TV receiver information and estimated the resulting increase in re-usable spectrum (in Hz) for several Norwegian cities [13]. In contrast, I realize the design, implementation, and experimental evaluation of a new system, WATCH. It cancels TV signals at secondary receivers and protects dynamically active TV receivers from secondary transmissions. Moreover, WATCH targets both indoor and outdoor
environments.

**Interference cancellation.** Previous IC work focused on 2.4/5 GHz ISM bands [15, 27, 28]. Tan et al. decoded overlapping WiFi packets [27]. Gollakota et al. proposed to cancel interference without the help of preambles [15]. Based on that, Yan et al. decoded a WiFi packet and an overlapping ZigBee packet [28]. In comparison, I design IC mechanisms under the constraint of a streaming kilowatt-scale interferer for 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 [29–31]. However, such techniques require coordination among different access points/clients. In contrast, TV transmitters are non-adaptive to the secondary system in WATCH. CAT also operates under continuous and strong interfering TV signals instead of intermittent WiFi transmission.

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 [32]. However, this technique requires multiple-antenna primary and secondary users, 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.
Chapter 7

Conclusion

In this thesis, I propose WATCH, the first system to enable secondary WiFi transmission during active TV broadcasts. WATCH utilizes primary receiver feedback to protect incumbent TV reception. I also design WATCH-IC and CAT to enable secondary WiFi transmission under interference from streaming kilowatt-scale TV transmitters. I build a testbed and evaluate WATCH with FCC permission and show that in a typical U.S. city like Houston, WATCH can provide at least 6.0 times the total achievable rate to SU’s compared to current TV white space regulatory models, while at the same time only increasing the TV channel switching time by less than 5%.
Bibliography


