A Hardware Platform for Utilizing TV Bands With a Wi-Fi Radio

(Invited Paper)

Srihari Narlanka, Ranveer Chandra, Paramvir Bahl, John Ian Ferrell
Microsoft Research
Microsoft Corporation
Redmond, USA 98052

Abstract— **The Federal Communications Commission (FCC) is currently exploring the use of TV bands for unlicensed communication. This step has sparked significant interest in the research and corporate community as it opens up new possibilities for high speed and long range wireless communication. In this paper, we present the design and implementation of a complete system that can detect the presence of TV signals, and perform high-speed data communication in an available TV band without interfering with neighboring TV bands. To the best of our knowledge, this is the first known system with all the above capabilities.**

I. Introduction

Recent measurements have shown that a large portion of the spectrum licensed to TV bands is unutilized [1]. For example, the average utilization of TV broadcast bands in the US was as low as 14% in 2004 [2]. This is in sharp contrast to the overcrowding of wireless communications in the unlicensed ISM bands. To alleviate this disparity, the Federal Communications Commission (FCC) is exploring the possibility of allowing unlicensed wireless communication in *white spaces*, i.e. portions of the TV bands that are not actively being used by the TV operators. Compared to the higher frequency ISM bands, the lower frequency TV bands have certain radio frequency (RF) propagation properties, such as, longer range, better penetration, and lower interference, that make them extremely desirable for data communication.

The above initiatives by the FCC has captured the imagination of researchers and engineers who have been thinking about building high-speed data communication systems that can operate in the white spaces, without interfering with existing TV signals. Despite the high level of interest, we are not aware of any existing system that achieves this goal. More specifically, while there is some work in high-end scanner systems for detecting the presence of a TV signal, there is no complete system that dynamically integrates the results of the scanner output with a radio that is capable of performing high-speed data communication in the TV bands.

In this paper, we describe a hardware prototype that meets the objectives outlined above. Our hardware couples a high resolution TV scanner with a off-the-shelf commercial IEEE 802.11bg [3] (Wi-Fi) radio. We process the scanner's results in software to determine the white spaces. We add an up and down converter to the front end of the Wi-Fi radio to translate the ISM band signals to the appropriate TV band and vice versa. To ensure that the transmissions from our device stays within one TV band, we shape the 22 MHz Wi-Fi OFDM waveform to operate within one TV channel by passing it through an appropriate filter. With this arrangement we achieve more than 10 Mbps data rate in a 6 MHz TV band and we avoid the bands with TV signals allowing the TV receivers to operate without interference.

In designing our hardware we had to be careful that we were compliant with the FCC requirement, i.e. data transmissions from our hardware must not interfere with existing TV signals. This meant that our hardware must only operate in frequencies where there is no active TV transmission. Furthermore, to the extent possible, we designed our system to avoid hidden terminal interference, even for the case where our scanner did not "hear" a TV signal. Our objective was that a transmission from our system must not interfere with any close-by TV receiver.

To manage cost, we used a commodity Wi-Fi device and converted the 2.4 GHz 22 MHz wide-band signal to a 6 MHz narrow-band signal. The IEEE 802.11b/g standard [3] specifies that the peak signal across +/- 11 MHz of the Wi-Fi signal to be attenuated by 30 dB from the center frequency. If this signal is transmitted without modifications on the TV band, where a channel width is 6 MHz (in the US), the transmission will interfere with TV signals in the neighboring bands. Therefore, we needed a mechanism to prevent the leakage of transmitted signals outside the unoccupied TV band, i.e. 6 MHz in the US, 8 MHz in Europe and Asia.

We have built a hardware prototype of the system in collaboration with Metric Systems [4]. Through this system we show that it is possible to perform opportunistic data communication in the TV white spaces without interfering with a TV receiver, and we show how an off-the shelf Wi-Fi card can be made to operate in narrow band TV channels. We describe the design and implementation of our system in detail in the rest of this paper.

II. Our Approach

We use a two radio approach to enable high speed data communication in the TV bands. We use a scanner that monitors the spectrum for TV signals, and outputs the available white spaces. The second radio is the Wi-Fi radio, which operates in a vacant TV band.

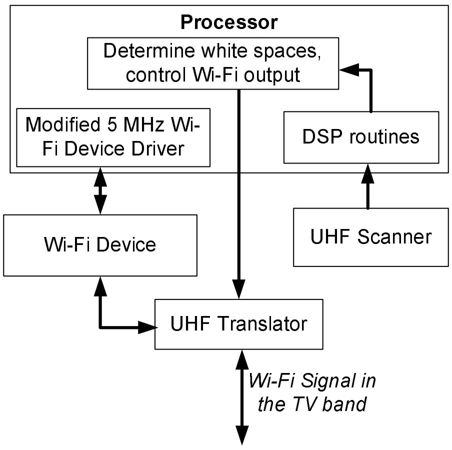

Fig. 1. The main components of our system that enables Wi-Fi devices to operate in the TV bands.

The primary components of our system are illustrated in Figure 1. The spectrum scanner is attached to the same computer to which the Wi-Fi device is attached. The scanner samples the TV bands and passes the scan information to a user-level network analyzer, where the signals are processed by Digital Signal Processing (DSP) routines. These routines compute the latest set of white spaces and pass it up to the Wi-Fi controller. The Wi-Fi controller determines the best available white space and sets the UHF translator to operate in the appropriate TV band. The function of the UHF translator is to down-convert the Wi-Fi signal in the 2.4 GHz band to the appropriate TV band. The Wi-Fi controller also sets the transmit power of the Wi-Fi radio, such that the emitted signals do not interfere with existing transmissions in the TV band. Another important component of our system is the Wi-Fi device driver, which sets an appropriate register in the Wi-Fi device in order to send the Wi-Fi signals using a 5 MHz bandwidth instead of the default 20 MHz Wi-Fi bandwidth. This ensures that the transmissions from the Wi-Fi device stay within the TV band, and do not interfere with transmissions by licensed operators in the neighboring bands.

This design has several advantages. First, we do not require any changes to the Wi-Fi radio. We only need changes to the Wi-Fi driver. Second, our system is sensitive to changes in the TV bands. When there is a transmission in the TV band by a licensed operator, our scanner routines detect this transmission, and shift the signals from the Wi-Fi radio to a different TV band. Furthermore, the Wi-Fi radio uses CSMA, and hence does not interfere with any ongoing transmissions. Finally, since the Wi-Fi radio uses OFDM, we are able to achieve high speed data transfers.

III. Implementation

In Figure 2, we present components of the hardware platform that enable Wi-Fi radios to operate in the TV bands. It consists of three core components:

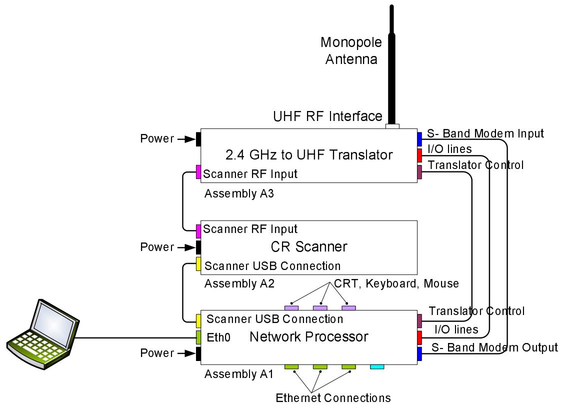

Fig. 2. System Interconnection Diagram

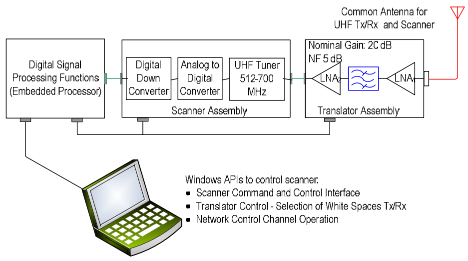

Fig. 3. Functional Flow of the Scanner Component

- **Wide-band Spectrum Scanner:** The primary function of the scanner is to discover the TV white spaces. It consists of a wide-band digital tuner in TV band and a high speed A/D converter .
- **Tunable UHF Half-Duplex Transceiver:** The UHF transceiver consist of a 2.4 GHz 802.11g Wi-Fi radio as the primary signal generator in the 2.4 GHz band, and a UHF translator which does down and up-conversion to convert the 2.4 GHz signal to the TV bands (470-700MHz) and vice versa.
- **Network Processor:** This is an x386 based processor, which controls the scanner and the UHF radio. It processes the scanner information and applies DSP routines for feature detection, i.e. identify the presence of incumbent operators, such as ATSC, NTSC and FM wireless microphones, by matching their signal characteristics. The processor also controls the transmit power and operating frequency of the UHF radio.

We describe each of these components in detail in the rest of this section.

A. *Scanner*

The functional components of the scanner are shown in Figure 3. To increase the sensitivity of the scanner to even weak TV signals, we use front end low-noise amplifiers (LNAs) with a nominal gain of 20 dB. The LNAs feed the signal to a frequency scanner, which is capable of scanning the TV bands (channels 21 through 51) in 6 MHz segments (the size of a TV band). The scanner sends the digitized time-domain scan

Frequency range	512 to 698 MHz
Scan frame bandwidth	8 MHz
Samples per scan	100
Scan frame FFT size	2048 points
FFT bin size	3.9 KHz
Min. DTV pilot tone sensitivity	-114 dBm
Min. wireless microphone detection sensitivity	-114 dBm

TABLE I

FEATURES AND SPECIFICATIONS OF THE SCANNER MODULE

information to the network processor, which performs a 2048 Fast Fourier Transform (FFT) on the received data. The signal feature templates for the Digital TV (DTV) and analog NTSC signals are sequentially applied to identify the presence of these channels. The network processor declares the unoccupied channels as potential white spaces, and subsequently checks for the presence of possible narrow band incumbents, such as wireless microphones.

The scanner is capable of scanning a large range of frequencies covering most of the TV bands, i.e. 512 to 698 MHz. In each iteration it scans 8 MHz of bandwidth. Processing 8 MHz of bandwidth allows us to operate in other parts of the world, such as Europe, where the TV bands are 8 MHz wide. We use a 2048 point FFT to get more samples and good accuracy in incumbent signal detection, which implies that the FFT bin size is 3.9 KHz (= 8 MHz/2048). Using this setup, our scanner achieves a minimum discernible DTV pilot tone, and wireless microphone sensitivity of -114 dBm. This threshold is much lower than the TV signal reception threshold of -85 dBm, and helps in alleviating the hidden terminal problem. We summarize these specifications and features of the scanner in Table I.

To show the effectiveness of our scanning module, we present its ability to detect the DTV and NTSC signals, which are popular mechanisms used by TV broadcasters in the US. Figures 4 and 5 show the signal strength of the DTV and NTSC signals respectively as captured by our scanner when placed in a building in the San Diego metropolitan area. The top-most line (in red) shows the maximum signal strength of all samples, the next line (in blue) shows the signal strength of the last sample, while the bottom most line (in green) represents the minimum signal strength over all the samples. As can be seen from the figure, our scanner is capable of detecting DTV signals using a prominent pilot tone at the beginning of start of its frequency spectrum. It detects the analog NTSC signal, using the 6 MHz energy of the transmitted signal (in the US), and also applying signatures of the 4.5 MHz video and 1.5 MHz audio carrier. Note that the scanner does not decode the signals, and is therefore able to detect the TV signals at -114 dBm, which is much lower than the TV signal reception threshold of -85 dBm.

B. UHF Translator

The other important part of our system is the UHF Translator. Its function is to transmit the signals sent by the Wi-Fi radio in the appropriate TV band, and convert the received

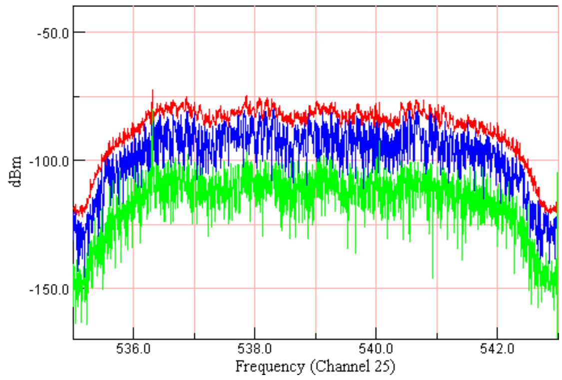

Fig. 4. DTV signal detection.

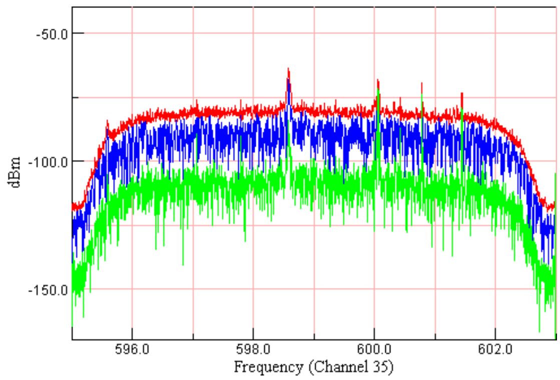

Fig. 5. NTSC signal detection.

signals in the TV bands to the S-band (2.4 GHz for an IEEE 802.11g radio). The functional components of the translator are illustrated in Figure 6.

In our system, we use an IEEE 802.11g Wi-Fi radio, which we set to a static frequency channel, for example channel 6, in which case the center frequency is 2437 MHz. To convert the signal in the S-band to the TV band, we use a UHF block converter. This converter consists of a wide-band synthesizer, using a Phase Locked Loop (PLL). The frequency range of the PLL's Voltage Control Oscillator (VCO) is between 1400 and 2100 MHz, which covers the difference between the S-band and TV band frequencies. The UHF block converter uses a mixer to combine the signal of the Wi-Fi radio with the synthesizer so that the output frequency is in the appropriate TV band.

The UHF translator also provides a linear power amplifier to provide a 12 dB backoff from the Wi-Fi radio's OFDM transmit power of 100 mW. The power amplifier uses a 0 to 30 dB digitally controlled attenuator for transmit power control (TPC).

Furthermore, we have optimized our system to use the same antenna and front end LNAs for the scanner and the receive path of the UHF converter, as shown in Figure 6. We accomplish this using low loss switches, which implement separate transmit and receive switches in the UHF converter. These

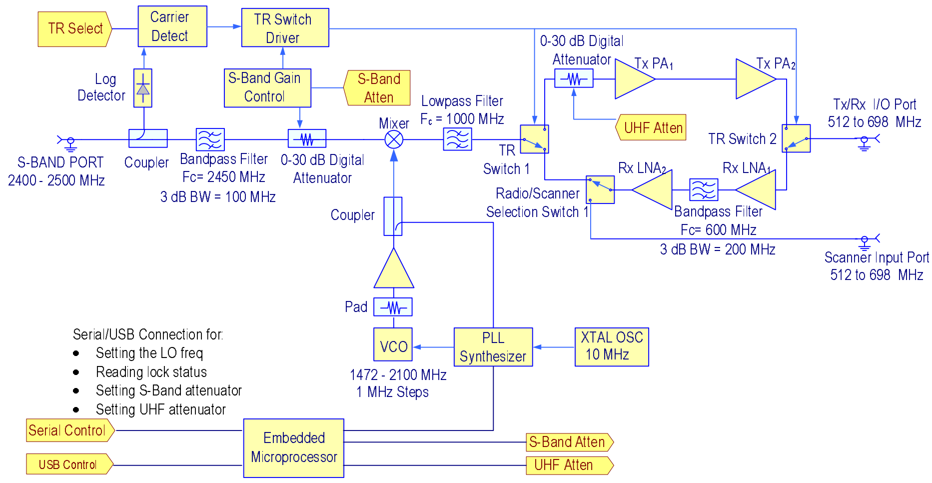

Fig. 6. Block Diagram of S-Band to UHF Translator

switches are also used to provide half-duplex functionality of the UHF converter. The specifications of the UHF radio are presented in Table III-B

2.4GHz Band Modem frequency	2400 to 2500 MHz
2.4GHz modem output Power Level	-10 to +20 dBm
UHF Tx Output	521 to 698 MHz
Tx 1 dB Compression	+28dBm
UHF Tx Tuning Increments	1 MHz
UHF Rx frequency band	521-698MHz
UHF Rx power level	-90dBm to -20dBm
UHF Rx tuning increments	1MHz
UHF Rx 1dB compression	-20dBm(max)
3dB signal BW	4.25MHz
UHF Rx NF	5dB
UHF Rx Gain	16dB
2.4GHz Rx level	-75dBm to -10dBm
UHF LO integrated phase noise	5 degrees RMS

TABLE II

FEATURES AND SPECIFICATIONS OF THE UHF TRANSLATOR

We now present two results to show the effectiveness of the UHF translator. In Figure 7, we present a sample waveform transmitted by the UHF translator *without* an RF filter. The figure is a screenshot from a spectrum analyzer with a span of 20 MHz bandwidth. As we can see in the figure, the UHF translator transforms the 2.4 GHz Wi-Fi signal and sends it in the TV band with a 3 dB bandwidth of 4.25 MHz. This result also demonstrates the need for additional mechanisms to prevent interference in adjacent TV channels. In particular, we need a mask that resembles ATSC, which is a Digital TV standard.

We now show how our RF filter achieves the desired adjacent channel interference properties. In Figure 8, we plot the waveform generated by the UHF translator with the RF filer. We see that using our filter, the transmitted signal has around 60 dB rejection in adjacent bands and more than 60 dB rejection in farther channels. This feature of our system prevents the transmitted signals from interfering with other TV bands, and therefore makes our system a practical approach for using the Wi-Fi radio in the TV bands.

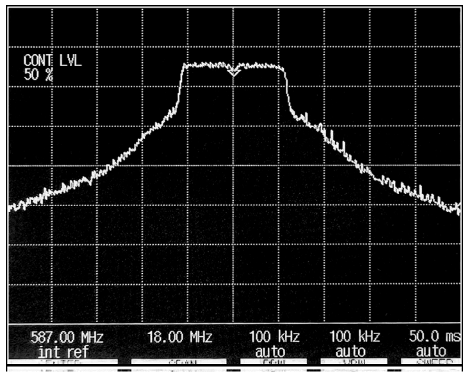

Fig. 7. Sample transmitted waveform in the TV band captured by a spectrum analyzer.

C. Network Processor

The network processor integrates the scanner and the UHF translator with two user-level processes. The first process performs feature detection on the scanner results to determine the presence of TV or microphone transmissions. It computes a list of vacant TV bands, and passes them to the second process, which controls various parameters of the Wi-Fi radio and the UHF translator. It computes the best band for transmission, the appropriate transmit power level and UHF attenuation, and sets these parameters.

We have kept the software structure modular, so that it is easy to add new functionality. For example, to support collaborative sensing [5], one would only need one more process to aggregate results from nearby scanners, and send its own scanning results to the neighbors. This process would then interact with the second process from above to set the appropriate parameters of the Wi-Fi radio and the UHF transla-

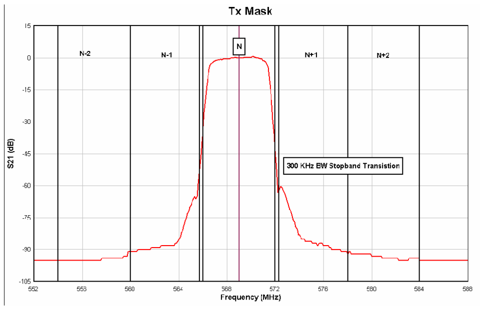

Fig. 8. Out of Band emissions from the radio after passing the signal through and RF filter.

tor. There are several other challenges in collaborative sensing, such as the need for a control channel and coordination among nodes. We address these issues in another piece of work [6].

IV. Related Work

A number of recent studies [1] have focussed on the availability of TV bands for unlicensed communication. Other related work have studied the impact of communication by unlicensed devices on interference at nearby TV receivers, including the impact of the hidden node problem [7]–[9]. These results show that it is possible to perform data communication in the TV bands without interfering with the TV receivers. We take these results further in this paper, and build a complete system for scanning and sending and receiving data.

Another recent work [7] has designed an alternative OFDM waveform (different from Wi-Fi), which fits within a 6 MHz TV band. Their signal also does not interfere with neighboring TV channels. Our scheme is different from this work, since it uses a scanner to detect incumbent TV operators, and uses an off-the-shelf Wi-Fi radio for high speed data communication. Motorola [10] has designed a software designed radio platform that integrates a scanner with a radio, but which operates in the 2.4 GHz spectrum. On the other hand, our system handles all the challenges of operating in the TV bands, such as feature detection and interference avoidance.

V. Conclusions and Future Work

In summary, we have presented the design and implementation of a real system that is capable of operating in the TV bands. It complies with the FCC specifications of non-interference with licensed users of the TV band, and is able to achieve high data rates by using an off-the-shelf Wi-Fi radio. To the best of our knowledge, this is the first publically available system to demonstrate this functionality. In the future, we plan to use this system for further research on high speed data networking in the TV bands. We are working on the design of a MAC for cooperative sensing and utilizing contiguous free bands [6]. We are also exploring alternative waveforms, similar to prior work [7], for high speed data communication in the narrow TV bands.

References

[1] "Shared Spectrum Company, www.sharedspectrum.com."

[2] "Federal Communications Commission (FCC), www.fcc.gov."

[3] "IEEE 802.11b/D3.0, Wireless LAN Medium Access Control(MAC) and Physical (PHY) Layer Specification: High Speed Physical Layer Extensions in the 2.4 GHz Band," 1999.

[4] "Metric Systems Corporation," http://www.metricsystems.com/.

[5] S. M. Mishra, A. Sahai, and R. W. Brodersen, "Cooperative Sensing Among Cognitive Radios," in *ICC 2006*.

[6] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. I. Ferrell, T. Moscibroda, S. Narlanka, and Y. Wu, "KNOWS: Kognitive Networking Over White Spaces," in *IEEE Dyspan 2007*.

[7] D. DePardo, J. B. Evans, J. A. Roberts, V. R. Petty, A. M. Wyglinski, P. J. Kolodzy, and M. J. Marcus, "Quantifying the Impact of Unlicensed Devices on Digital TV Receivers," *The University of Kansas: Technical Report ITTC-FY2007-44910-01*, January 2008.

[8] R. Brodersen, A. Wolisz, D. Cabric, S. Mishra, and D. Willkomm, "Corvus: a cognitive radio approach for usage of virtual unlicensed spectrum," Berkeley Wireless Research Center (BWRC) White paper, 2004.

[9] R. Mukhopadhyay, Y. Park, P. Sen, N. Srirattana, J. Lee, C. Lee, S. Nuttinck, A. Joseph, J.D. Cressler, and J. Laskar, "Reconfigurable RFICs in Silicon-based technologies for a compact intelligent RF front-end," *IEEE Transactions on Microwave Theory and Techniques,*, vol. 53, no. 1, pp. 81–93, Jan. 2005.

[10] "Cognitive Networks: A Paradigm for Wireless Communication in which networks adapt, in a self-aware manner, their topology and operational parameters to fulfill specific tasks," Position Paper: http://www.motorola.com/.