Technical Challenges for Cognitive Radio in the TV White Space Spectrum

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***Abstract*— The FCC recently issued the regulatory rules for cognitive radio use of the TV white space spectrum. These new rules provide an opportunity but they also introduce a number of technical challenges. The challenges require development of cognitive radio technologies like spectrum sensing as well as new wireless PHY and MAC layer designs. These challenges include spectrum sensing of both TV signals and wireless microphone signals, frequency agile operation, geo-location, stringent spectral mask requirements, and of course the ability to provide reliable service in unlicensed and dynamically changing spectrum. After describing these various challenges we will describe some of the possible methods for meeting these challenges.**

I. INTRODUCTION

Recently the Federal Communications Commission (FCC) in the United States issued a report and order (R&O) which permits cognitive use of the TV white space spectrum. White space is the term used by the FCC for unused TV spectrum. These new regulatory rules open up an opportunity to develop new wireless networks to utilize this spectrum. This VHF and UHF spectrum provides superior propagation and building penetration compared to other unlicensed spectrum in other bands like the 2.4 and 5 GHz bands. However, access to this new spectrum also comes with some technical challenges. The FCC rules specify a number of requirements on these cognitive wireless network. The focus of this paper is to describe those challenges and discuss some possible methods of meeting those challenges.

A summary of the FCC rules is provided in Section II. One of the issues that comes up when considering the use of this spectrum is, ”How much spectrum is actually available?” This question is addressed in Section III. One of the cognitive radio technologies that is required to utilize this spectrum is *spectrum sensing*, where the cognitive radio makes observations of the RF spectrum and from those observations determines which of the TV channels is occupied and which is unoccupied. The unoccupied channels represent white space that can be used by the cognitive radio network. The challenges for spectrum sensing are covered in Section IV. Operating in a new frequency band with dynamic frequency access requirements has an impact on the RF architecture. These RF challenges are described in Section V. The second cognitive capability required to operate in this white space spectrum is location awareness, which is referred to as the geo-location capability, and is described in Section VI. To minimize any interference to licensed transmission on adjacent channels and channels beyond the adjacent channel, the FCC rules provide limits on out-of-band (OOB) emissions which impact the spectral mask of any cognitive radio network using this spectrum. The challenges of this strict spectral mask are described in Section VII. Finally, though not a strict FCC rule, it is important to provide reliable operation in these channels given the unlicensed nature of these cognitive radio devices. The ability to provide reliable operation is critical to the success of any wireless network. The challenges of providing reliable operation in this dynamic spectrum is described in Section VIII.

II. FCC RULES

In November 2008 the United States FCC issued a R&O on the unlicensed use of TV white space spectrum [1]. A number of the requirements to operate in TV white space are based on cognitive radio technology including location awareness and spectrum sensing. There are a number of other requirements also, that are intended to provide protection for the licensed services that operate in the TV bands. These requirements impose technical challenges for the design of devices operating in TV white space spectrum.

The devices operating according to these rules are referred to as TV band devices (TVBDs) by the FCC. There are two classes of TV band devices: fixed and personal/portable. To simplify the terminology we will use the shorter term *portable* for the personal/portable devices. The portable devices are further divided into Mode I and Mode II devices.

Fixed devices are permitted to transmit up to 30 dBm (1 watt) with up to 6 dBi antenna gain, while portable devices are permitted to transmit up to 20 dBm (100 mw) with no antenna gain. Fixed devices are permitted to use a higher gain antenna as long as the transmit power is decreased dB-for-dB for any antenna gain above 6 dBi.

The TV channels include the very high frequency (VHF) channels 2-13 and the ultra high frequency (UHF) channels 14-51. However, there are restrictions on which channels are permissable for use by TVBDs. Fixed devices are permitted in the VHF channels except channels 3-4 and on the UHF channels except channels 36-38. Portable devices are not permitted in the VHF band. Portable devices are permitted on the UHF channels except 14-20 and channel 37. The exclusion for channels 3-4 is to prevent interference with external devices (e.g. DVD players) which are often connected to a TV utilizing either channel 3 or 4. Portable devices are not permitted on channels 14-20 since in 13 metropolitan areas some of those channels are used for public safety applications. Finally, Channel 37 is a protected channel, used for radio astronomy measurements.

Television broadcast signals are protected with a *protection contour*. The FCC rules provide distances that a TVBD must be outside the protected contour for it to transmit. Within the protected contour there are special rules for operation on a TV channel adjacent to the TV broadcast channel. Fixed TVBDs are not permitted to operate on channels adjacent to the TV broadcast channel. Portable devices are permitted to operate on an adjacent TV channel; however, when operating on an adjacent TV channel, the maximum allowed transmission power is 16 dBm (4 dB lower than on non-adjacent channels).

There are also requirements on antenna height for fixed devices. The sensing antenna must be mounted outside and must be at least 10 meters above ground. The transmit antenna must be outdoors and be mounted no more than 30 meters above ground. So if the same antenna is used for both sensing, receiving and transmitting, then that antenna must be between 10 and 30 meters above ground.

The FCC has strict out-of-band emission requirements to prevent interference with licensed transmissions in other channels. A detailed description of these out-of-band emission requirements and their impact on the transmission spectral mask for TVBDs is provided in Section VII.

There are several interference avoidance mechanisms that must be supported in these TVBDs. These mechanisms are the *cognitive radio* capabilities provided in these devices. The first requirement is that these TVBDs must be location aware, which in the FCC document is referred to as having a geo-location capability. This location awareness is a cognitive radio capability frequently mentioned in the literature. This location awareness is coupled with Internet access capability for both fixed TVBDs and Mode II portable devices, and must be accurate to within 50 meters. This Internet access is utilized to obtain access to a database containing information about licensed transmission in the various TV channels. These licensed transmissions include ATSC (Digital TV) high-power broadcasts, ATSC and NTSC (Analog TV) low-power transmitter, and wireless microphones used by the broadcast industry. The second interference avoidance mechanism is *spectrum sensing* in which the TVBD must observe the various TV channels and determine if these channels are occupied by any licensed transmission. More will be said about the challenges of spectrum sensing in Section IV.

III. White Space Availability

Fixed and portable devices have different requirements among which is the separation distance from digital and analog TV protected contours. In particular, fixed devices are not allowed to operate on first adjacent channels to a TV station. On the other hand, portable devices are allowed to operate on first adjacent channels subject to lower maximum transmit power constraints (cf. Section II). This translates to different white space availability for fixed and portable devices.

Both fixed and Mode II TVBDs are required to access a TV band database in order to determine the permissible set of operating channels. This step is followed by spectrum sensing to confirm the emptiness of these channels. According to the FCC rules, the TV database should contain the following information on full-power television stations, digital and analog Class A stations, low-power television stations (LPTV), television translator stations, and television booster stations

- transmitter coordinates (latitude and longitude),
- effective radiated power (ERP),
- height above average terrain of the transmitter (HAAT),
- horizontal transmit antenna pattern (if the antenna is directional),
- channel number,
- station call sign.

In this paper, white space availability is characterized based on the information available on the Media Bureaus Consolidated Data Base System (CDBS)[1] for post-DTV transition full-power television stations. The white space availability in the fifty most populous cities in the United States[2] is characterized. In particular the following are calculated:

- the histogram for the number of white space channels available for fixed device operation in the UHF band, Figure 1, and
- the histogram for the number of white space channels available for portable device operation, Figure 2.

From Figures 1 and 2, the average number of channels available for fixed devices is ten, while the average number of channels available for portable devices is twenty. On the low side, there are four cities with only two channels available for fixed device operation while there are three cities with six channels available for portable device operation. We note that the calculation of white space availability in this paper is based only on full-service TV stations database. In general the presence of other primary incumbents such as LPTV or wireless microphones can reduce the available spectrum. The white space availability is different from one location to another and hence frequency agile operation is desired to efficiently utilize the white space. Frequency agile operation and the impact of different RF architectures on the available spectrum is discussed in more details in Section V.

IV. Spectrum Sensing

A. Single-Node Sensing

In the FCC rules, the main requirement on spectrum sensing is that a TVBD should be able to detect the presence of (digital and analog) TV signals and wireless microphone signals at a received power level -114 dBm. To understand this sensitivity requirement, we note that the noise power level of a 6 MHz TV channel is typically around -100 dBm (including a 6 dB noise figure), and therefore the -114 dBm received power level translates into a SNR of around -15 dB. Furthermore, since for lower UHF TV band the effective antenna size is reduced compared with higher RF frequencies, a phone-form factor receive antenna will have a low antenna gain, say, $-5 \sim -3$ dB. Consequently, the spectrum sensing problem for each

[1] http://www.fcc.gov/mb/cdbs.html

[2] http://en.wikipedia.org/wiki/List_of_United_States_cities_by_population

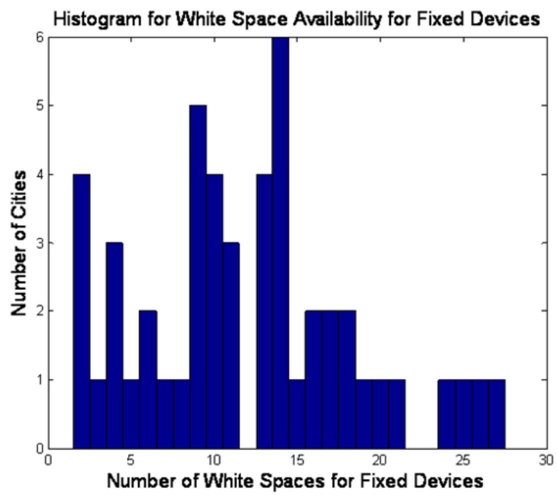


Fig. 1. White Space availability for fixed devices.

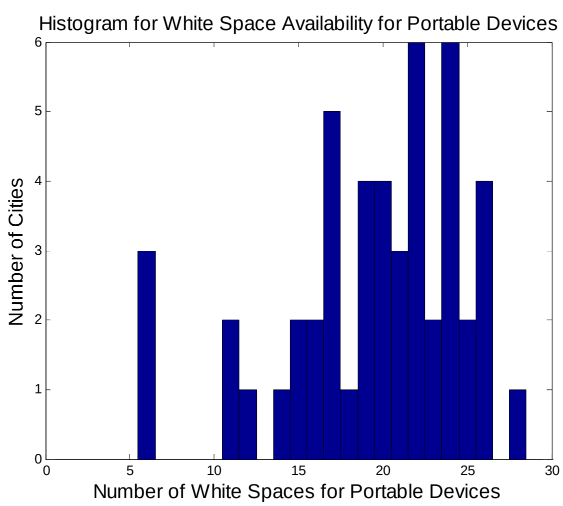


Fig. 2. White Space availability for portable devices.

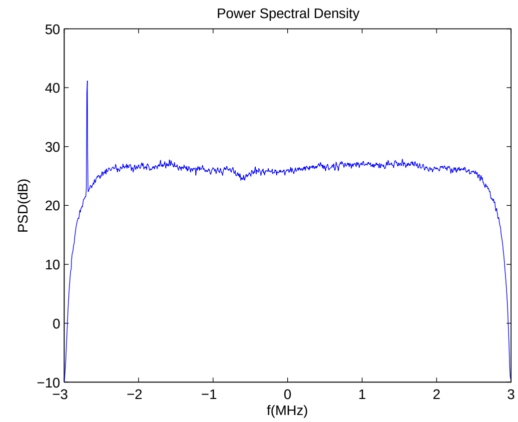


Fig. 3. Received PSD of a typical ATSC signal. The scale of the y-axis is not normalized. The pilot carrier exhibits like a narrow spike near the lower edge of the TV channel.

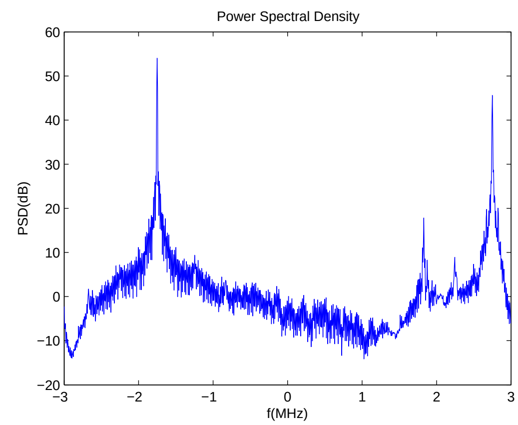


Fig. 4. Received PSD of a typical NTSC signal. The scale of the y-axis is not normalized. The video, color, and audio carriers are evidently noticeable at their corresponding frequency locations.

single TVBD becomes detecting the presence or absence of certain target signals (digital/analog TV, wireless microphone) across a bandwidth of 6 MHz, and at a SNR of $-20 \sim -18$ dB.

Before describing the challenges with spectrum sensing, it is useful to briefly introduce the three signal types to be sensed, namely, digital TV, analog TV, and wireless microphone. The digital TV in the United States follows the ATSC standard. TV programs are modulated using 8-level vestigial sideband modulation (8VSB) and the modulated signal occupies almost the entire 6 MHz TV channel uniformly, with a pilot carrier which contains approximately 7% of the total signal power and is located at approximately 310 kHz above the lower edge of the channel. Figure 3 displays the received power spectral density (PSD) of a typical ATSC signal. The analog TV in the United States follows the NTSC standard, and may still be used for low-power local broadcasting after the DTV transition. The luminance part of signal is amplitude-modulated, and its (video) carrier, containing more than half of the total signal power, is located at 1.25 MHz above the lower edge of the channel. The color part of signal is quadrature-amplitude-modulated with suppressed carrier, and its subcarrier is approximately 3.58 MHz above the video carrier. The audio part of signal is frequency-modulated, and its subcarrier is 4.5 MHz above the video carrier. Figure 4 displays the received PSD of a typical NTSC signal.

Wireless microphones, as the most common Part 74 devices, are allowed by the FCC [2] to transmit in TV channels which are not occupied by ATSC/NTSC signals, provided that their transmit power and bandwidth meet certain requirements. The maximum bandwidth of a wireless microphone is 200 kHz. Therefore, multiple such devices may operate within a single TV channel, and their carrier frequency locations are not *a priori* fixed, unlike carriers of ATSC/NTSC signals as described in the previous paragraph. There is no specific requirement on the modulation scheme for wireless microphones, whereas in the TV band, analog frequency modulation (FM) is the most common practice. Figure 5 displays the received PSD of a typical wireless microphone signal within a TV channel.

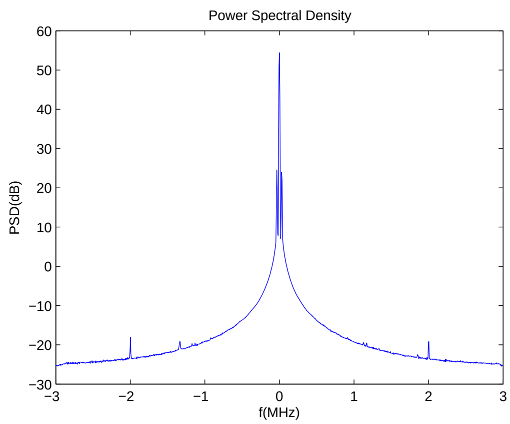


Fig. 5. Received PSD of a typical wireless microphone signal. The scale of the y-axis is not normalized. Note that the carrier frequency location may change within the 6 MHz TV channel.

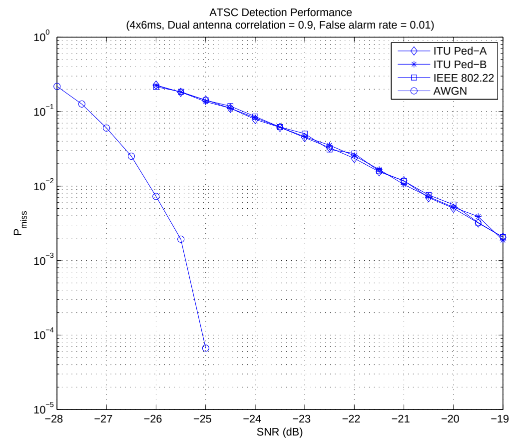


Fig. 6. Spectrum sensing performance of ATSC signals.

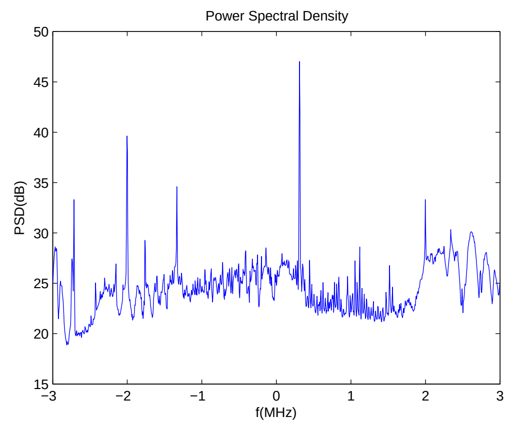


Fig. 7. Received PSD of a typical TV channel with wireless microphone signal and narrowband interference signals. The scale of the y-axis is not normalized. The wireless microphone signal is at 1 MHz above the lower edge of the TV channel, and the other spikes are from unknown sources.

Now return to the spectrum sensing challenges. At SNR as low as -20 dB, a number of challenges emerge. On the one hand, it becomes unreliable and even impractical to utilize coherent reception techniques and implement signature sequence acquisition. On the other hand, energy detection, which seeks to detect signal presence through comparing the received power against a certain threshold, is known to be fundamentally flawed at low SNR, under uncertainty with noise power level and distribution [3]. Alternative techniques based on spectral correlation analysis [4] also have limited applicability here. First, their performance rapidly degrades as SNR decreases. Second, for FM wireless microphone signals, the cyclostationarity is actually too weak to be exploited.

For ATSC/NTSC signals, spectrum sensing is a simpler task compared with wireless microphone signals, which will be elaborated shortly. The key observation is that, such signals statistically do not resemble white Gaussian noise, rather they exhibit narrowband features through the ATSC pilot, the NTSC video carrier, *etc*. Furthermore, the frequency locations of those narrowband features are fixed, and the "local" SNR in their vicinity can be boosted through appropriate filtering. The spectrum sensing problem hence can be posed as a binary hypothesis test between pure noise and a carrier with unknown phase in noise; or, specifically for NTSC, as a binary hypothesis test between pure noise and a stochastic signal in noise. Both of the two hypothesis test problems have been well understood (see, *e.g.*, [5]), and have been demonstrated as effective using real signals collected in laboratory. As an example, Figure 6 displays the performance of ATSC sensing, using laboratory collected ATSC signal (as "clean") from dual antennas and passing through different channel models as indicated in the figure. The false alarm rate (1%) is obtained with respect to pure white Gaussian noise.

The main challenge in spectrum sensing is for wireless microphone signals. Theoretically speaking, even though the carrier frequency location of a wireless microphone signal is unknown in advance, it is still possible to distinguish between such a signal and pure noise, because as illustrated in Figure 5 the PSD of wireless microphone signals exhibits a narrow spike which, with high probability, would not be produced by white Gaussian noise. Indeed, laboratory tests have shown that sensing techniques based on this idea can reliably detect the presence of wireless microphone signals even as low as -20 dB SNR. This fact is not entirely surprising, because a wireless microphone signal can at most occupy 200 kHz within a 6 MHz TV channel, and therefore within the 200 kHz bandwidth the SNR can at least be boosted by $\frac{6\times 10^6}{200\times 10^3} \approx 15$ dB. The challenge, however, is that such narrowband spikes are also observed in received signals *without* the presence of wireless microphones. In other words, the spectrum sensing problem is *not* the binary hypothesis between pure noise and wireless microphone signal in noise, because the "pure noise" hypothesis indeed contains narrowband interference. To illustrate this, Figure 7 displays the received PSD of a TV channel, which contains one wireless microphone signal (located at 1 MHz above the lower edge, and with power level approximately -105 dBm) and a number of narrowband interference signals from unknown sources.

There are different possible sources of narrowband interference. Spurious emissions and unintentional transmissions are universal from all types of electronic devices, and some reside within the TV band. The FCC rules do pose stringent limits on spurious emissions and unintentional transmissions [6] such that they would not interfere communications. For spectrum sensing, however, these interference signals turn out to have strengths similar to the signals to be sensed, say, wireless microphone signals below the noise floor. In addition, other sources of narrowband interference include leakages from adjacent TV channels, quantization noise from analog-to-digital conversion (ADC), and RF impairments like nonlinear inter-modulation (see, *e.g.*, [7]).

From the preceding discussion, it is evident that spectrum sensing of wireless microphone signals mandates a classification procedure, in order to expurgate narrowband interference. Without doing so, it is likely that most of TV channels would be decided to be occupied and consequently no TVBD would be allowed to operate. There are two main technical hurdles in the classification problem. First, there lacks a technical standard among different wireless microphone manufacturers. All design parameters (*e.g.*, operational frequencies, FM frequency deviation, side-tone placement, *etc.*) can drastically vary among manufacturers and device models. Therefore, it is difficult to abstract features that are stable and common for all wireless microphones. Second, analog FM signals, in their general form, is nothing but a carrier wave (CW) with a gradually changing phase. If the phase changes too slowly with time, say, when the input to a wireless microphone is silent, then the resulting wireless microphone signal would not be much different than CW-like spurious emissions.

Addressing the technical hurdles outlined in the previous paragraph is both interesting and useful research. The spectrum sensing problem may be most effectively solved from a pattern recognition perspective; alternatively, the theory of robust detection [8] may prove to be another useful tool. It is still unclear how the challenge will be settled eventually, or if there exist any fundamental performance limits. Nevertheless, the bottom line is that, for spectrum sensing at low SNR, the problem need be posed carefully in a way that does not over-simplify the reality.

B. Networking Issues

In the previous subsection, we considered spectrum sensing for individual TVBDs. When multiple TVBDs are connected to form a network or several networks, networking issues of spectrum sensing arise. One such issue, collaborative sensing, has already received heightened interest recently; see, *e.g.*, [9]. Roughly speaking, collaborative sensing seeks to apply ideas from distributed detection and data fusion to jointly process the spectrum sensing statistics from multiple TVBDs. The inherent diversity stemming from distributed observations, when exploited appropriately, leads to more efficient spectrum sensing schemes compared with single-node sensing.

We briefly outline another networking issue in the following. Recall from the previous subsection that the sensitivity requirement of spectrum sensing is -114 dBm, or, $-20 \sim -18$ dB SNR for typical phone-form factor TVBDs. Such a demanding performance specification thus can only be met when the co-channel interference from peer TVBDs is minimal. As we have seen from the previous subsection, narrowband, spike-like interferences pose the fundamental challenge for identifying unoccupied TV channels. Furthermore, even if TVBDs' signals all have AWGN-like PSD, their existence may still noticeably raise the effective noise floor. For a sensing TVBD, if its co-channel peer TVBDs transmit thus producing an interference power level comparable with the thermal noise floor, then the overall interference-plus-noise would be raised by approximately 3 dB, which in turn would degrade the sensing sensitivity accordingly.

One possible way of handling the aforementioned issue is a network quieting protocol, that mandates all the TVBDs in a geographic area to simultaneously turn off their transmit circuitry, so as to "quiet" the TV channel for a certain time period to sense the TV/wireless microphone signals. This idea bears some similarity with the well-known request-to-send/clear-to-send (RTS/CTS) mechanism in 802.11 networks, whereas the purpose of RTS/CTS is to avoid interference-induced collision in transmission. Since the tolerable interference power level (received by sensing TVBDs) for ensuring reliable spectrum sensing may need to be even lower than the noise floor, as discussed in the previous paragraph, the cleared geographic area provided by RTS/CTS may not be large enough.

The idea of quieting a geographic area further leads to an important question, that is, how to define a "geographic area". If a large number of TVBDs extend hop-by-hop to cover a long strip of area (for example, Manhattan Island) such that all TVBDs are connected, do we still need to quiet all of them simultaneously? Quieting a large geographic area containing many TVBDs possibly belonging to different heterogeneous networks also requires a standardized protocol to enable interoperability among heterogeneous networks, as well as efficient and robust techniques for distributed network synchronization.

V. RF Architecture Challenges

One of the challenging features of the white space is its variation across space and time. More specifically the available channels are not contiguous and vary from one location to another. In addition the white space available in a given location can vary with time if one or more of the TV band primary users start/stop operation. This requires frequency agile architectures to map to the available white space spectrum, retune to a new operating channel, or tune-away to perform sensing measurements. The requirements are more challenging for frequency division duplex (FDD) networks that need two separate channels for operation. In particular, some of the RF challenges that need to be solved for FDD networks include

- independent tuning of transmitter and receiver,
- providing RF isolation (in the order of 50dB) between transmitter and receiver for variable transmitter and receiver frequencies,
- developing highly linear receivers over a wide dynamic range to handle in-band high power TV broadcasts.

Among the possible approaches to implement the RF front end for a frequency agile transceiver are: duplexers, switching

RF filter banks, and tunable filters. It is important to note that white space availability may change according to the duplexing method used: time division duplexing (TDD) or FDD. In addition, different FDD RF architectures can result in different white space availability. In the following we present white space availability results for some case studies. Three white space availability metrics are analyzed.

- Maximum number of independent networks that can utilize the white space without requiring co-channel sharing.
- The minimum number of TV channels occupied by other networks before co-channel sharing is required.
- The average number of TV channels occupied by other networks before co-channel sharing is required. The randomness here is generated by assuming that any channel of the white space can be lost with equal probability.

A. Time Division Duplexing

The computations for TDD is straightforward because each white space represents an opportunity. Therefore, the three metrics defined above can be actually reduced to only one metric which is the number of available channels. This is not true however for FDD networks as discussed in the following sections.

B. Frequency Division Duplexing

Three different RF architectures for the FDD network are considered.

- The single duplexer approach in which the whole band is divided into two subbands.
- The dual duplexer approach in which the whole band is divided into four subbands.
- The tunable filter approach.

1) Single Duplexer Approach: FDD systems commonly use a duplexer to isolate the transmitter band and the receiver band. A typical single duplexer will divide the UHF spectrum equally into two bands with few channels left as a band gap. For example, band A contains channels from 14 to 31, band B contains channels from 34 to 51 and channels 32 and 33 are left to serve as a duplexer band gap. If the white space distribution in the UHF band was uniform, this design would be optimal in terms of white space availability.

However, the white space distribution is in general nonuniform. For example, in the Bay area most of the white space is in the lower part of the spectrum. Accordingly a uniform single duplexer which divides the UHF band into two equal bands will in general result in limited white space availability especially in highly congested areas as the Bay area. In general, an optimal single duplexer should divide the *white space* equally in the two bands. Since the distribution of white space differs from one location to another, it is not possible to find one optimal design that leads to the best results in all locations. To overcome this problem, we study the tradeoff that different duplexer designs present. A good design should increase the white space availability in areas with very few white spaces as the Bay area while not reducing white space availability in other locations significantly. To capture this tradeoff, the generalized average of the number of independent networks in the fifty largest cities in the United States is used as a metric to compare different single duplexer designs. The generalized average can be defined as follows

$$GA_p = \left(\frac{1}{n} \sum_{i=1}^{n} x_i^p \right)^{\frac{1}{p}}. \tag{1}$$

SD_0	Band A (14 to 31) and Band B (34 to 51)
SD_1	Band A (14 to 30) and Band B (33 to 51)
SD_2	Band A (14 to 29) and Band B (32 to 51)
SD_3	Band A (14 to 28) and Band B (31 to 51)
SD_4	Band A (14 to 27) and Band B (30 to 51)
SD_5	Band A (14 to 26) and Band B (29 to 51)
SD_6	Band A (14 to 25) and Band B (28 to 51)

TABLE I
DIFFERENT SINGLE DUPLEXER DESIGNS.

Design	Mean: $p = 1$	$p = -3$	Minimum: $p \to -\infty$
SD_0	10.2	2.53	1
SD_1	10.3	2.54	1
SD_2	10.3	4.86	2
$\mathbf{SD_3}$	**10.1**	**6.66**	**3**
SD_4	9.56	6.64	3
SD_5	9.12	6.54	3
SD_6	8.52	7.28	4

TABLE II
ANALYTICAL RESULTS FOR DIFFERENT SINGLE DUPLEXER DESIGNS.

Negative values of p in (1) assigns more weight to smaller values of x_i. Different single duplexer designs are described in Table I. The white space availability results for these designs averaged over the largest fifty cities in the Unites States are shown in the Table II. From these results, SD_3 (Band A (14 to 28) and Band B (31 to 51)) captures a good tradeoff between the minimum number of available channels and the average white space availability.

2) Dual Duplexer Approach: A dual duplexer can be used to increase white space availability for FDD networks. The dual duplexer approach divides the whole band into four sub-bands which results in a more flexible RF architecture compared to the single duplexer. One of the disadvantages of the dual duplexer design is the increased band gaps required to separate the four bands, therefore reducing the total white space available. The design of the dual duplexer can be optimized to increase white space availability and overcome this disadvantage. One possible approach is to switch between a set of single duplexers.

3) Tunable Filter Approach: Tunable filters are the most flexible RF architecture for an FDD network since the transmitter and receiver can be independency tuned to different channels. In order to achieve the required RF isolation between the transmitter and receiver, a tunable LC filter with a high inductor Q factor is required. High inductor Q factors can be achieved, for example, through Q-enhancement techniques

[11]. For this case study, we assume a tunable filter with Q equals 400 which represents an ideal scenario. To achieve the required RF isolation between the transmitter and receiver, the selected channels should be separated by at least 5 channels.

C. White Space Availability for Different RF Architectures

We analyzed the white space availability for three different locations: San Diego, Dallas and the Bay area. Figure 8 compares the number of networks that can be constructed using the different approaches. Figures 9 and 10 compare the worst case and average white space availability results for the different duplexing and RF architecture approaches.

The results show that TDD provides the most flexible duplexing approach in terms of utilizing the available white spaces especially in congested areas as in the Bay area. For areas with plenty of white spaces as in San Diego, the performance of the single duplexer, dual duplexer and tunable filter FDD designs are comparable. For such cases the single duplexer would strike a good tradeoff between performance and complexity.

VI. GEO-LOCATION

The FCC rules require both fixed TVBDs and personal/portable TVBDs in operating Mode II be directly connected through the Internet to incumbent databases. The principal purpose of this requirement is to provide a mechanism to inform TVBDs about their neighboring TV/wireless microphone signals and peer TVBDs. Indeed, all TV broadcasting stations (including low-power TV, translators, boosters, *etc.*) are required to be archived in incumbent databases, and such information essentially overrides the outcomes of spectrum sensing for TV signals. That is, for a TVBD located within the contour of a TV station as indicated in the geo-location database, even if spectrum sensing reports that the TV channel is unoccupied (say, due to shadowing), the TVBD still needs to view this channel as occupied by TV.

Providing incumbent databases requires knowledge of the locations of TVBDs themselves. The FCC rules specify a precision of ± 50 meters for TVBDs' locations. For fixed TVBDs, their locations are manually set when they are installed. Since their installation is thoroughly planned and performed by professionals, obtaining their locations is by no means a technical challenge. For personal/portable TVBDs, if global positioning service (GPS) is equipped and TVBDs are outdoor, obtaining their geo-locations may still be less a technical challenge. If no GPS is available or if TVBDs are indoor, then obtaining geo-locations becomes a challenging task. Reference anchors, *e.g.*, peer TVBDs with known geo-locations, may not be accessible. Even if reference anchors are accessible, distance ranging using physical-layer measurements may be inaccurate, due to inaccuracy in anchors' geo-locations as well as channel effects such as shadowing and multipath fading, and may be insecure, due to spoofing and other possible attacks.

VII. SPECTRAL MASK REQUIREMENTS

In [1] the FCC has provided a number of out-of-band emission requirements that impact the spectral mask of a

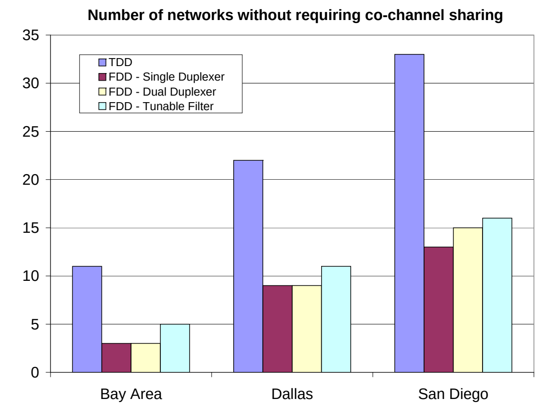


Fig. 8. Number of networks without requiring co-channel sharing.

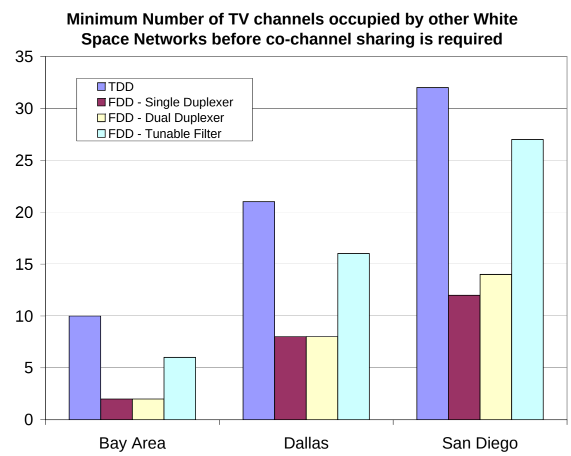


Fig. 9. Minimum number of TV channels occupied by other networks before co-channel sharing is required.

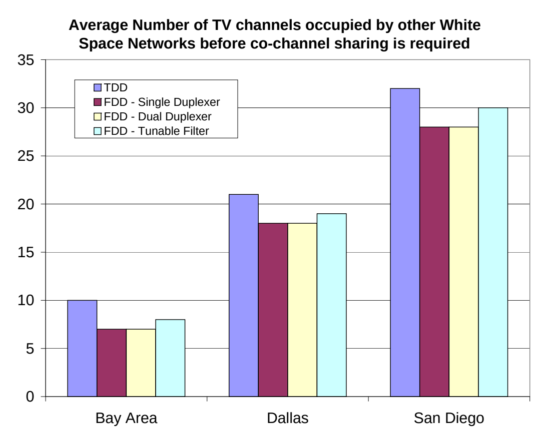


Fig. 10. Average number of TV channels occupied by other networks before co-channel sharing is required.

TVBD. There are three sets of rules that impact the spectral mask: adjacent channel rules, beyond adjacent channel rules, and rules for Channels 36-38. Some of these rules are stated in terms of spectral masks and other are in terms of the electromagnetic field strength measured at a specified distance within a specified bandwidth. These field strength rules must be translated into spectral mask requirements.

The FCC rules state that "In the 6 MHz channels adjacent to the operating channel, emissions from TVBD devices shall be at least 55 dB below the highest average power in the band." These measurements are made using a minimum resolution bandwidth of 100 kHz. This indicates that a spectral mask in the adjacent TV channel is required to be at least 55 dB below the maximum in-band signal.

The out-of-band emission requirements for beyond the adjacent channel must satisfy FCC Section 15.209. In that section of Part 15 it states that in the UHF frequency band the electromagnetic field strength measured in 120 kHz bandwidth at a distance of 3 meters from the transmitter must be below 200 microvolts/meter. Since this is a fixed field strength measurement in order to translate this into a spectral mask requirement we will need to consider the transmission power and antenna gain of the TVBD. First we must be able to convert between electromagnetic field strength and transmit power.

To do this we begin with the formula for the field strength in terms of the transmit power. The field strength at d meters from transmitter, assuming free space path loss, is given by [10],

$$FS = P + G + 104.77 - 20\log(d) \tag{2}$$

The field strength (FS) is in dB microvolts/meter (dBu), the transmit power (P) is in dBm, the antenna gain (G) is in dB and the distance (d) is in meters. Once we calculate the out-of-band transmit power in 120 kHz we must relate that to the total transmit power to determine a spectral mask requirement. If we let P_{TX} be the total transmit power and BW the bandwidth which captures the majority of the signal power, then the spectral mask requirement can be written as,

$$\Delta = \left(P_{TX} - 10\log\left(\frac{BW}{0.12}\right)\right) - P_{oob} \tag{3}$$

Now let us apply these equations to determine the spectral mask beyond the first adjacent channel. For $d = 3$ meters, the 200 microvolts/meter give the following maximum out-of-band transmission power, measured in 120 kHz, beyond the first adjacent channel,

$$\begin{aligned} P &= 20\log(200) - G - 104.77 + 20\log(3) && (4) \\ &= -(G + 49.21) && (5) \end{aligned}$$

To determine the spectral mask beyond the first adjacent channel we need to know the total transmit power, the antenna gain, and the signal bandwidth. The transmit power and the antenna gain are different for fixed and portable devices. We will use the maximum values allowed by the FCC. For fixed we will use a maximum transmit power of 30 dBm and an antenna gain of 6 dBi. For portable devices we will use maximum transmit power of 20 dBm and a 0 dBi antenna gain. In both cases we will use a signal bandwidth of 5 MHz, which is a reasonable choice since it uses the majority of the 6 MHz channel bandwidth but allows for some guard band.

	Adjacent Channel	Beyond Adjacent	Channel 37
Fixed	55 dB	69 dB	95 dB
Portable	55 dB	53 dB	79 dB

TABLE III
SPECTRAL MASK REQUIREMENTS

For fixed we have the out-of-band emissions are $P_{oob} = -(6 + 49.21) = -55.21$dBm. Therefore, for a fixed device the spectral mask beyond the first adjacent channel is,

$$\Delta = \left(30 - 10\log\left(\frac{5}{0.12}\right)\right) - (-55.21) = 69 \text{ dB} \tag{6}$$

If we do the same calculation for portable devices we get that,

$$\Delta = \left(20 - 10\log\left(\frac{5}{0.12}\right)\right) - (-49.21) = 53 \text{ dB} \tag{7}$$

The third requirement is for the field strength in Channel 37 and also the two channels adjacent to that channel, Channels 36 and 38. The field strength limit is lowered from the boundary between Channels 35 and 36 from 120 dBu measured at 1 meter, down to 30 dBu within Channel 37.

It is possible for a portable device to transmit in Channels 36 and 38 as long as they meet these field strength requirements. No matter which channel you operate in, the field strength from the out-of-band emissions in Channel 37 must be below 30 dBu, as measured in 120 kHz. The out-of-band transmit power in Channel 37 is then,

$$P = 30 - G - 104.77 + 20\log(1) = -(G + 74.77) \tag{8}$$

For a fixed device the spectral mask in Channel 37 is,

$$\Delta = \left(30 - 10\log\left(\frac{5}{0.12}\right)\right) + (6 + 74.77) = 94.6 \text{ dB} \tag{9}$$

For a portable device the spectral mask in Channel 37 is,

$$\Delta = \left(20 - 10\log\left(\frac{5}{0.12}\right)\right) + (74.77) = 78.6 \text{ dB} \tag{10}$$

We can summarize these spectral mask requirements in Table VII.

To appreciate these spectral mask numbers one must consider the typical spectral mask for an unlicensed system like Wi-Fi. The OFDM PHY in 802.11 has a spectral mask that is 20 dB down at the edge of the channel. It linearly decreases to 28 dB down at the middle of the adjacent channel, and then reaches 40 dB down at the edge between the first and second adjacent channel. This is dramatically different than the spectral mask required for even a portable TVBD. Figure 11 illustrates the portable TVBD spectral mask and the IEEE 802.11 OFDM PHY which has been scaled from 20 MHz to 5 MHz. In this figure we only show the upper portion of the spectral mask, above the carrier frequency. The mask is

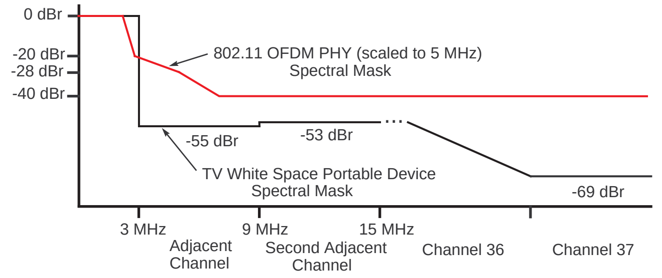


Fig. 11. Comparison of Spectral Mask for portable TVBD and 5 MHz version of IEEE 802.11

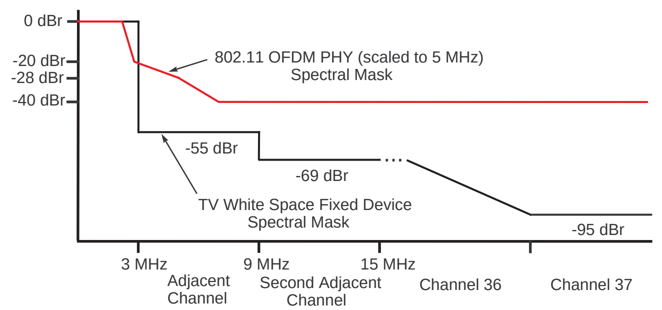


Fig. 12. Comparison of Spectral Mask for fixed TVBD and 5 MHz version of IEEE 802.11

symmetric about the carrier frequency. This type of scaling can be accomplished in an OFDM system by reducing the clocking rate by a factor of 4. We see that the 802.11 spectral mask is not close to attaining the required TVBD spectral mask. Similarly, in Figure 12 we show the spectral mask for a fixed TVBD along with the frequency scaled version of the 802.11 OFDM PHY. We see that the discrepancy in two spectral masks is even more pronounced in the case of fixed TVBDs.

There are number of straightforward techniques that can be used to improve the spectral mask, like increasing the power amplifier (PA) back-off, which will improve the OFDM spectral mask, but that alone will not meet these spectral mask requirements. Also, since this is a frequency agile system if one were to apply RF filtering to the signal after the PA, that filtering would need to be both frequency agile but also very linear.

VIII. Spectrum Sharing and Interference Management

Beside satisfying the FCC requirements for cognitive operation in the TV band, it is desirable to achieve reliable communications and acceptable performance levels in the white space and efficiently utilize the available spectrum. One of the major challenges that face reliable operation in the white space is interference among peer TVBDs given the unlicensed nature of operation in this band. Managing interference between nodes in the same network is generally a difficult problem, and the problem becomes more challenging when these TVBDs belong to heterogeneous networks using different air interfaces.

A. Spectrum Sharing Approaches

Spectrum sharing techniques can be divided into three main categories as follows.

- Non-cooperative techniques
- Rule-based techniques
- Message-based techniques

1) Non-cooperative Techniques: In non-cooperative spectrum sharing techniques each system tries to maximize its own utilization of the spectrum while mitigating the effects of interference from other networks. Examples for non-cooperative techniques include

- Dynamic frequency selection (DFS) in which nodes select channels with least interference.
- Multichannel-DFS (M-DFS): In case of a one-to-many system, the access-point can select a subset of the available channels to minimize the overall outage probability and improve system throughput. DFS is a special case of M-DFS when the access-point is restricted to use one channel.
- Interference cancellation via multiple antenna receivers. If the receiver is equipped with multiple-antennas, interference cancellation algorithms can be utilized. For example, an MMSE receiver can help canceling the incoming interference signal through estimating the interference covariance matrix and nulling out the dominant interference signal.
- Successive interference cancellation (SIC) in which the access-point decodes the dominant interference signal generated by other networks and cancels it out from the received signal. There are several technical challenges in order to implement such a technique. First it requires a complex receiver capable of decoding different waveforms and signals received from different technologies. Second the networks sharing the channel are in general asynchronous. Some of these networks can be frame based as in cellular air interfaces while others can be packet based as in Wi-Fi. The packet sizes can be varying as in Wi-Fi for example. Channel estimation is required to enable SIC and this requires the ability to estimate timing and frequency offsets and capture the pilot signals from other networks using different air interfaces.

2) Rule-based Techniques: In rule-based techniques the TVBDs agree on a set of rules to implement, and do not use a control channel to exchange information. Although there is no explicit coordination between the nodes, the set of rules should be designed to ensure fairness, efficiency and interference avoidance. Examples for rule-based techniques are listen-before-talk and transmit power control.

3) Message-based Techniques: In message-based sharing techniques, the TVBDs operating in the unlicensed band exchange messages (over-the-air or backhaul) to enable efficient and fair spectrum sharing and limit the interference among them. A message-based sharing technique should specify how to implement the control channel required for coexistence

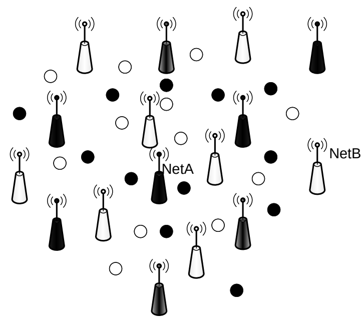


Fig. 13. Example of a coexistence scenario in which NetA and NetB are deployed as micro-cellular networks.

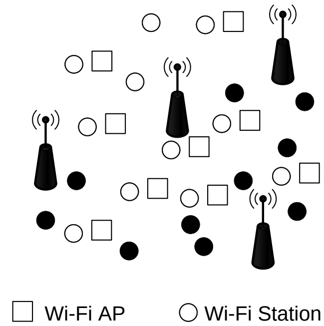


Fig. 14. Example of a coexistence scenario in which NetA is deployed as a micro-cellular while NetB is deployed as a WLAN.

message exchange, and what information to share with other TVBDs. Among the techniques proposed in the literature for message-based sharing are [12], [13] and [14]. In [12] a common spectrum coordination channel (CSCC) is proposed in which a common channel at the edge of the used band is reserved for sending coexistence information such as the node ID, center frequency, bandwidth, transmit power, data rate, interference margin etc., which can be used by neighboring nodes to coordinate and adapt their transmission for better sharing. A regional spectrum broker (spectrum clearing house) is proposed in [13], [14] in which a spectrum clearing house coordinates spectrum allocation to the existing service providers based on the bandwidth required by each one of them.

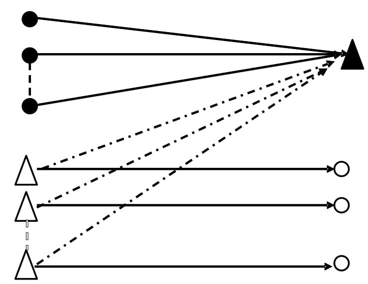
The downside with message-based protocols is that they require the systems to have a common air-interface capable of decoding the common control message. Moreover, some of the above protocols require synchronization between different systems. This might not be feasible for heterogeneous TVBDs.

B. Coexistence Scenarios

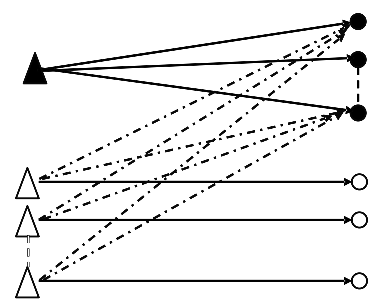
Different network deployment models can occur in the white space. One can generally divide the deployment models into planned deployment and unplanned deployment. Planned deployments may include fixed nodes that represent access-points, basestations or fixed customer premise equipment (CPE) and portable/personal devices. Examples for planned deployment networks include micro-cellular networks and IEEE 802.22 wireless regional area networks (WRANS). Unplanned deployments generally consist of user deployed networks as wireless local area networks (WLANs) and Femto cells.

Figures 13 and 14 depict two possible coexistence scenarios where two micro-cellular networks are sharing the spectrum in Figure 13, and a micro-cellular network is sharing the spectrum with a WLAN in Figure 14. Other coexistence scenarios are also possible.

Next we present some simulation results for non-cooperative sharing techniques applied to the coexistence scenario depicted in Figure 13. NetA is assumed to use an FDD cellular air-interface and NetB is using Wi-Fi. The interference channel model for Net A uplink and downlink are shown in Figures 15(a) and 15(b), respectively.



(a) UL Interference Channel



(b) DL Interference Channel

Fig. 15. Interference channel model for NetA.

Figure 16 depicts the cumulative distribution function (CDF) of the DL throughput achieved by NetA assuming 5 channels are available. From the results, it is clear that both DFS and M-DFS can achieve a performance that is very close to the scenario when NetA exists alone, i.e. no interference from NetB. The rationale for this good performance is the low interference regime that can be achieved in a low frequency reuse system, which is achieved here by the distributed DFS and M-DFS techniques.

The problem is more challenging in the uplink since the link gain between the interfering access-points from NetB to NetA access points can be higher compared to the uplink gain in NetA. This is due to the following. Fixed access points can transmit at higher power levels compared to portable devices as discussed before in Section II. The antenna heights for the access-points are larger than those for portable devices resulting in lower RF propagation losses. Finally portable

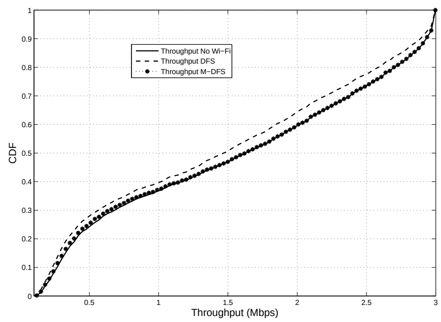


Fig. 16. DL Throughput for Network A. 5 channels available.

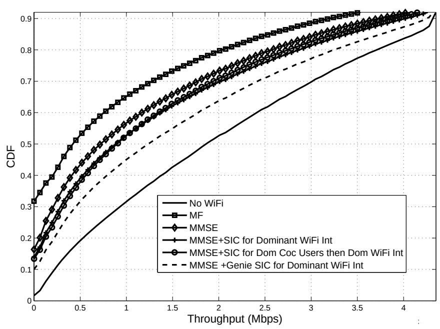


Fig. 17. UL Throughput for Network A. 5 channels available, 2Rx antennas.

devices can be indoor which results in additional building penetration losses.

The uplink throughput performance for several interference mitigation techniques are depicted in Figure 17 where two receive antennas are assumed at the access-point: a matched filter receiver, an MMSE receiver, a SIC receiver which tries to decode dominant NetB interference first then decode NetA users, a receiver that first decodes some of the NetA users with good link qualities followed by decoding dominant NetB interferer. To be able to decode dominant interference from NetB the channel capacity between the interferer and NetA's receiver must be higher than the rate transmitted by the interferer which depends on the link quality of the interference source to its intended receiver. The probability of satisfying this condition is generally low and therefore almost no gain is seen from such technique. An upper bound on the performance of the SIC receiver is depicted in which the dominant interference signal is cancelled out from the NetA receiver path by a genie. The gain that can be seen from such genie scheme confirms that the minor gain achieved by SIC is because of the low probability of the event that the NetB signal is decodable.

IX. Conclusions

The new FCC rules allowing the use of the TV white space spectrum will become one of the key drivers in the development of dynamic spectrum access, fostering revolutionary wireless applications, and meanwhile driving novel technical solutions. As we have seen in this paper, many of the technical challenges are unconventional and interdisciplinary in nature. For example, the development of spectrum sensing techniques involves RF design, robust signal processing, pattern recognition, networking protocols, *etc.*. The choice of RF architecture is no longer merely a hardware issue, but will directly affect the upper layer performance. To meet the stringent spectral mask requirements, novel signal processing designs such as transmit precoding and receive equalization become possibly indispensable tools. Spectrum sharing raises new challenges in applying techniques from information theory to heterogeneous networks. We expect that recognizing those challenges will lead to a fruitful interaction among academia, industry, and policy makers, and finally lead to the success of cognitive radio in the TV white space spectrum.

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