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Spectrum Sensing Aided Long-Term Spectrum Management in Cognitive Radio Networks

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***Abstract*—Wireless microphones operating in the TV white spaces often appear at specific venues such as schools or churches, and at specific times. Hence, their location and appearance pattern can be predicted from spectrum sensing statistics. In this paper we propose and evaluate three spectrum selection functions that utilize sensing results to provide long-term spectrum usage statistics as basis for channel selection to enhance performance by reducing interference and increasing throughput. To evaluate performance of the spectrum selection functions, these are implemented in a detailed system level simulator for the IEEE 802.22 standard. We find that the spectrum selection function that uses statistics about channel idle and busy periods performs best when primary user activity is high, and that the spectrum selection function that uses predictions about location and distance to primary users performs best when IEEE 802.22 radio users are mobile and the primary user activity is low.**

I. INTRODUCTION

The IEEE 802.22 [1] standard is the first technical standard to provide a broadband service by operating in the TV white spaces [2]. IEEE 802.22 devices use geo-location and communicate with a database to obtain information about available frequencies and allowed transmit power levels at their locations. In addition IEEE 802.22 devices can use sensing techniques to detect sudden appearances of primary users, such as TV transmitters and wireless microphones (WMs). TV broadcasters update the database with their frequency usage and transmit power levels at all locations. Other low power devices operating in these bands, such as WMs, might update the database, but might also appear suddenly without notification. Detection and protection of these WMs are considered to be a great challenge that can be handled by using sensing techniques to detect WMs and then switch to a vacant channel.

The spectrum management, which aims at exploiting white space channels while protecting the primary users, is usually executed on short time scales according to standards, such as IEEE 802.22. In this paper, however, we propose and evaluate three different spectrum selection (SSE) functions executed on longer time scales, based on the historical record of existing short-term measurements. This new spectrum management approach is not specified in the IEEE 802.22 standard. The new SSE functions reduce interference and increase throughput by working complementary to the existing short-term spectrum management functions, instead of replacing them. To evaluate performance of the SSE functions we extend our comprehensive implementation of the IEEE 802.22 stack in the NS-2 simulator [3]–[6].

II. SYSTEM MODEL

The reader is referred to [3]–[6] for a detailed description of our IEEE 802.22 NS-2 simulation model. For consistency we recapitulate some of the fundamental assumptions here.

We consider a wireless system based on the IEEE 802.22 standard. It is limited to one Base Station (BS) and N mobile Opportunistic Users (OUs). It is assumed that M channels with frequencies $F_1, \cdots, F_M$ are available for use by the IEEE 802.22 system after consulting the spectrum database. Furthermore, there are M unregistered WM Tx-Rx pairs, so that there is exactly one pair appearing in each of the M available channels. A computer connected to the BS establishes links to the OUs and runs the traffic model.

Traffic to the IEEE 802.22 OUs is modeled as constant bit rate (CBR) in the IEEE 802.22 system. CBR runs over UDP. Different traffic rates are simulated by constantly transmitting UDP packets of size 1500 Bytes to each OU. The CBR traffic uses the best effort (BE) QoS traffic profile in IEEE 802.22.

A WM pair in the simulator are two WMs communicating with a distance of 100 m. When a WM is turned on and becomes active, its traffic pattern is characterized by a 100% duty cycle until the WM is turned off again and disappears. Since WMs typically are present in venues such as churches, schools and concert halls, and since WMs thus often appear on a channel at specific times (e.g. each evening), we model their appearance pattern according to an ON-OFF model. It is assumed that all WMs generate new connections according to the negative exponential distribution for the average inter-arrival time $1/\lambda_w$ and average on time $1/\mu_w$.

In the simulations, the 6 MHz bandwidth profile as specified in the IEEE 802.22 standard is used. The WM activity will be detected by sensing techniques only in the simulator. For in-band sensing the two-stage spectrum sensing approach is used. At the coarse sensing stage (first stage) a simple

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energy detection is used for frequent and short sensing periods $T_c = 1\,\text{ms}$ during allocated time periods every $T_p = 2\,\text{s}$. If coarse sensing detects a WM signal, it switches to the fine sensing stage (second stage), which uses a more detailed WM detection process for a longer period $T_s = 30\,\text{ms}$. If a WM signal is detected by fine sensing then the operating channel is switched to one of the backup channels.

III. SPECTRUM SELECTION FUNCTIONS

Three SSE functions are proposed. These will not replace the spectrum management functionality specified in the IEEE 802.22 standard, but will be complementary and coexist to enhance performance by considering statistics calculated over longer time periods. The first function *SSE-Power* is a basic algorithm used to benchmark the proposed SSE functions.

A. SSE-Power (Reference Function)

The *SSE-Power* function selects the channel where the spectrum sensor has detected the lowest total signal power from WMs. No historical measurements are used.

The *SSE-Power* function uses sensing results $\{r_{i,j}\}$ in dBm from OU_i on channel j, and selects the optimal channel ch_{Opt}^{Power} based on the following criteria:

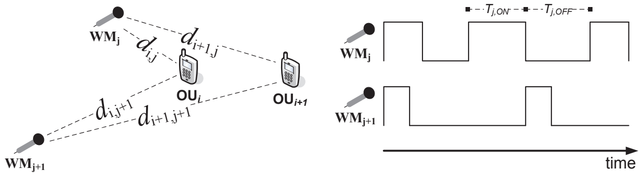
$$ch_{Opt}^{Power} = \min_j\{\max_i\{r_{i,j}\}\}, \tag{1}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M], i \in [0, N],$$

where N is the total number of OUs connected to the BS, M the total number of channels to be sensed and η the sensing detection threshold (–107 dBm over 200 kHz in the simulator).

B. SSE-Distance

The *SSE-Distance* function enhances QoS when the IEEE 802.22 terminals are mobile. It is motivated by the fact that primary users, such as WMs, are located and often appear at the same geographical locations. The goal is to predict the WM location on each channel and select the channel with farthest distance from the BS and OUs to the WM.

It is assumed that the BS and OUs know their geo-location and that WM transmit power is known. First, *SSE-Distance* uses historical measurements from the BS and OUs to predict the distance to the WM on each channel, using the Okumura-Hata propagation model. Then, *SSE-Distance* selects the shortest distances to the WM. These distances and the geo-location coordinates of the measuring BS and OUs are then used to predict the WM location using trilateration. Having predicted the WM location on all channels, *SSE-Distance* is able to find the current shortest distance from the BS and OUs to the WM on each channel. Finally, the channel with current farthest distance from the BS and OUs to the nearest WM is then selected for use. *SSE-Distance* as well as *SSE-OnOff* and *SSE-Hybrid* are proactive in that the SSE function runs automatically if no WM activity is detected within 5 seconds after the SSE function was run.



(a) Illustration of *SSE-Dist* policy (b) Illustration of *SSE-OnOff* policy

Fig. 1. Illustration of SSE functions.

Mathematically, *SSE-Distance* finds the distances $\{d_{i,j}\}$ from the BS and each OU_i to the closest WM on each channel j based on sensing measurements, and then selects the optimal channel $ch_{Opt}^{Distance}$ based on the following criteria:

$$ch_{Opt}^{Distance} = \max_j\{\min_i\{d_{i,j}\}\}, \tag{2}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M], i \in [0, N].$$

In the example scenario for *SSE-Distance* illustrated in Fig. 1(a), $d_{i,j}$ and $d_{i,j+1}$ are the shortest distances on channel j and $j+1$ respectively. Since $d_{i,j}$ is shorter than $d_{i,j+1}$, channel $j+1$ will be selected.

C. SSE-OnOff

The *SSE-OnOff* function aims to enhance QoS and performance of the mobile OUs in scenarios where the WM density and activity level is high. This function is motivated by the fact that WMs often use the channel at specific time intervals. *SSE-OnOff* uses sensing to predict the probability that a channel will not be occupied by a WM. To do this, sensing measurements from the BS and OUs are used to calculate the mean values for the channel ON (busy) and OFF (idle) periods for the WM for each channel j, denoted $\mathbb{E}[T_{j,ON}]$ and $\mathbb{E}[T_{j,OFF}]$ respectively. Note that other approximations than taking the mean could be used [7]. These statistics are then used to select the optimal channel ch_{Opt}^{OnOff} based on the following criteria:

$$ch_{Opt}^{OnOff} = \max_j \frac{\mathbb{E}[T_{j,OFF}]}{\mathbb{E}[T_{j,OFF}] + \mathbb{E}[T_{j,ON}]}, \tag{3}$$
$$\text{subject to: } r_{i,j} < \eta, j \in [0, M].$$

The sensing sampling rate for determining $T_{j,ON}$ and $T_{j,OFF}$ in the operating channel equals the coarse sensing period $T_p = 2\,\text{s}$. In backup channels, the BS and OUs sense during idle periods no longer than T_p.

In the example scenario for *SSE-OnOff* illustrated in Fig. 1(b), since WM_j has higher activity pattern than WM_{j+1}, channel $j+1$ will be selected.

D. SSE-Hybrid

SSE-Hybrid combines *SSE-Distance* and *SSE-OnOff* to use the optimal function depending on spectrum usage statistics. The goal is to enhance QoS and performance both when the OUs are mobile and the density of WMs and/or OUs is high.

We want to use *SSE-Distance* when the distance $d_{i,j}$ between OU_i and WM_j on channel j is high, and *SSE-OnOff* when $d_{i,j}$ is low for all backup channels. A distance threshold d_{th} is defined as criteria for deciding which SSE function to use during system run-time. Different distance thresholds are

TABLE I
PARAMETERS USED IN THE SIMULATION SCENARIO

Parameter	Value
IEEE 802.22 BS cell radius	1.2 km
IEEE 802.22 OU traffic load	200 kbit/s
IEEE 802.22 OU speed	1 . . . 20 m/s (random), random waypoint
IEEE 802.22 height	BS: 15 m, OU: 1.5 m
IEEE 802.22 EIRP	BS: 4 W, OU: 0.1 W
Modulation and Coding	16-QAM 1/2
WM height	1.5 m
WM EIRP	0.05 W (17 dBm)
WM bandwidth	200 kHz
WM pairs distance	100 m
Available channels	4 (600 MHz band, channels with center frequencies 605, 611, 617, 623)
Traffic direction	Downlink

used for the BS and OUs referred to as d_{th}^{bs} and d_{th}^{ou}. The *SSE-Hybrid* function is configured to select the optimal channel ch_{Opt}^{Hybrid} based on the following criteria:

$$ch_{Opt}^{Hybrid} = \begin{cases} ch_{Opt}^{Distance}, & d_{i,j} > d_{th}^{ou}, d_{bs,j} > d_{th}^{bs} \\ ch_{Opt}^{OnOff}, & \text{else} \end{cases} \tag{4}$$

subject to: $r_{i,j} < \eta, j \in [0, M], i \in [0, N]$.

Our strategy for selecting the distance threshold is to have it equal to the WM detection range:

$$\eta > TX_{wm} - PL(d_{th}). \tag{5}$$

where TX_{wm} dBm is the WM transmit power and $PL(d_{th})$ is the path loss found by using the Okumura-Hata model. We can then find d_{th} from (5) for use in (4).

IV. PERFORMANCE EVALUATION

A. Scenario Description

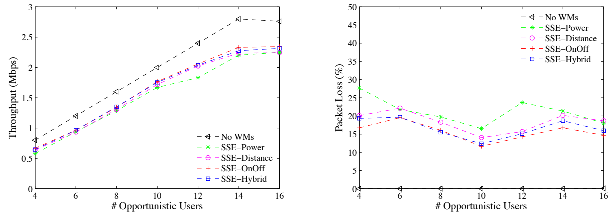
The scenario considered is a mobile cellular network in a light urban area. Each mobile OU moves following a random waypoint model with a random speed. Their initial location is randomly selected within the BS cell radius. The basic parameters used in the simulation scenario are given in Table I.

The number of available TV white space channels after consulting the geo-location database is assumed to be $M = 4$. Four unregistered WM pairs will appear on these channels, each one appearing separately on one of the 4 channels. Their location is randomly selected within the area of 1.4 km radius from the BS. Their average inter-arrival and on time will be selected randomly following a uniform distribution $1/\lambda_w = 20 \pm 10$ and $1/\mu_w = 5 \pm 2.5$ seconds respectively (i.e. in the intervals $[10, 30]$ and $[2.5, 7.5]$). Note that during simulation, both the WM inter-arrival and on times vary according to the negative exponential distribution.

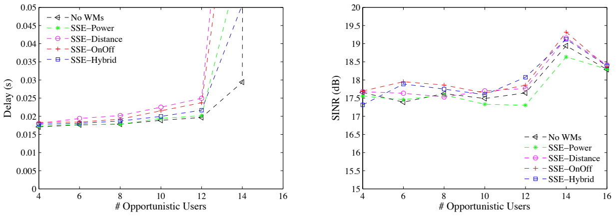
About 80 simulations are run for each of the results presented, each with a duration of 550 s. The results are averaged. A warm up time of 50 s is used.

B. Evaluation of SSE Functions for Increasing Number of Opportunistic Users

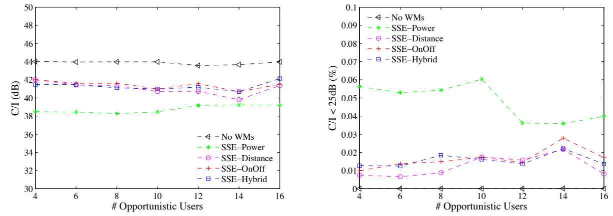
Simulation results for increasing number of OUs for *SSE-Power*, *SSE-Distance*, *SSE-OnOff* and *SSE-Hybrid* are presented in Fig. 2, in addition to the case without presence of WMs, referred to as “No WMs”.



(a) Average IEEE 802.22 Throughput (b) Average Packet Loss for OU



(c) Average Delay for OU (d) Average SINR for OU



(e) Average C/I for WM (f) Average percentage of time WM C/I<25 dB

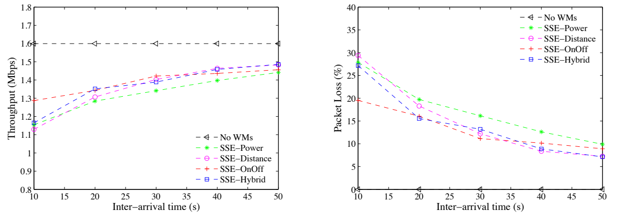
Fig. 2. Performance for the SSE functions for increasing number of OUs.

From the average system throughput for all OUs given in Fig. 2(a) it is first observed that the three proposed SSE functions achieve higher throughput than *SSE-Power*. (95% confidence intervals, not included in the plots due to visibility, are in the range 0.04 to 0.14 for *SSE-Power* and 0.02 to 0.08 for the proposed SSE functions.). It is also seen that *SSE-OnOff* achieves highest throughput. This is because when the WM activity is quite high as in the considered scenario, *SSE-OnOff* will more often select the channel that stays idle for the longest period. Hence, the number of channel switches and the average interference is reduced (see average WM C/I in Fig. 2(e)). Average packet loss given in Fig. 2(b) is generally highest for *SSE-Power* and lowest for *SSE-OnOff*, which complies with the observation in Fig. 2(a).

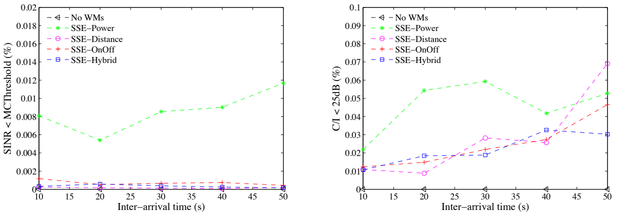
SSE-Distance achieves higher throughput than *SSE-Power*. Since *SSE-Power* selects channel without knowledge about where the WM might appear, both the OU and WM will often experience harmful interference. It was observed especially for *SSE-Power* that this resulted in the OU losing synchronization with the BS. This reduces throughput dramatically (and explains the dip in throughput for 12 OUs). This was also observed for the other SSE functions, but less frequently.

SSE-Hybrid does not achieve maximum throughput all the time as desired, which means that the optimal SSE function is not selected all the time in this scenario. Hence, other threshold values in (4) or another selection criteria should be used.

Average delay given in Fig. 2(c) is around 18 milliseconds when the number of OUs and traffic load is low, and increases



(a) Average IEEE 802.22 Throughput (b) Average Packet Loss for OU



(c) Average percentage of SINR < Modulation and coding threshold (d) Average percentage of time WM C/I<25 dB

Fig. 3. Performance of the SSE functions for various WM activity levels.

as load increases. It can be seen that delay increases dramatically when the IEEE 802.22 OFDMA frame is full.

Average SINR measured at the OUs given in Fig. 2(d) show a notable increase in SINR for 14 OUs. It also observed that interference from OUs to WMs increases at this point for *SSE-Distance*, *SSE-OnOff* and *SSE-Hybrid* (see average WM C/I in Fig. 2(e)). The reason for the increase in SINR at this point has not yet been identified and is left for further work.

Average C/I for the WMs given in Fig. 2(e) is quite high in general. Thus, interference does not impact much WM performance. It is seen that *SSE-Power* causes most interference to the WMs, which is because it selects channel without historical knowledge about where and how often the WMs appear. One observation is that interference to the WMs seems to increase slightly for *SSE-Distance* when the number of OUs increases, which is because the average distance to the nearest WM decreases as the number of OUs increases.

A better measure of harmful interference is the percentage of time the WM experience C/I below 25 dB given in Fig. 2(f), which also is highest for *SSE-Power*. Impact on the WM is found to be lower for the three proposed SSE functions, and is observed to occur only for a short period when the WM appears between sensing periods. Interestingly, *SSE-OnOff* generally gives more harmful interference than *SSE-Distance* despite the higher average interference for *SSE-Distance* in Fig. 2(e). This is because the OUs select channel without knowledge about WM location. Hence, harmful interference occurs more often since the WM appears close to an OU.

C. Evaluation of SSE Functions for Various WM Activity

The simulation results for increasing WM inter-arrival time (i.e. for lower WM activity) when there are 8 OUs for the different SSE functions are presented in Fig. 3.

From the average throughput and packet loss for all OUs in Fig. 3(a) and 3(b), it is seen that *SSE-OnOff* achieves best performance for high WM activity with inter-arrival time 10, 20 and 30 s and that *SSE-Distance* achieves best performance as the WM activity reduces. It is evident that the effect of *SSE-OnOff* reduces as WM activity reduces. However, *SSE-Hybrid* does not achieve highest performance all the time. This means that the threshold values in (4) are not optimal or that a new selection criteria must be used.

Average percentage of received packets that obtain SINR value less than the modulation and coding rate threshold given in Fig. 3(c) is highest for *SSE-Power*, which often selects channel without knowledge of how often or where WMs are located. *SSE-Power* generally causes more harmful interference to the WMs as illustrated in Fig. 3(d). It can also be seen that harmful interference generally increases as WM activity reduces. Similarly, it was also found that average WM C/I (not shown here) reduces as WM activity reduces, which is because the probability that the IEEE 802.22 system has started using a channel between the WM inter-arrival times increases as the WM activity reduces. Another reason for this observation is that the number of useful statistical data samples (sensor measurements) for use by the SSE functions during the simulation time reduces as WM activity reduces.

V. CONCLUSIONS

Three SSE functions that utilize sensing results to provide long-term spectrum usage statistics were evaluated through system level simulations, using a detailed implementation of the IEEE 802.22 standard in NS-2. It was found that these SSE functions can complement existing spectrum management functions to enhance performance in the IEEE 802.22 network. Harmful interference was reduced for both the IEEE 802.22 network and the WM. This resulted in a more stable network with higher system throughput.

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