Cooperative Spectrum Sensing in TV White Space Scenarios with Fading and Impulsive Noise

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Introduction

- Currently, there is a scenario of spectral scarcity, mainly below 1GHz, which comes from spectrum limitation but also due to underutilization.
- In the UHF and VHF TV bands, the underutilization is more evident. Idle spaces in this frequency range are called TV White Spaces (TVWS).
- Regulatory bodies such as the FCC (USA) and ANATEL (Brazil) have already begun regulating TVWS for secondary use.
- To enable the opportunistic use of TVWS, cognitive radios (CRs) with spectrum sensing (SS) functionality will be required.

Introduction

- Non-Cooperative Spectrum Sensing (Non-CSS): Each cognitive radio (CR) independently monitors the spectrum, potentially leading to unreliable decisions.
- Cooperative Spectrum Sensing (CSS): Multiple CRs gather information about a channel and send it to a fusion center (FC), enabling a more reliable global decision on channel occupancy.
- Research Gap: Despite extensive studies, there is a lack of works addressing realistic challenges and practical applications of SS techniques.

Main objective

Evaluate the performance of CSS in TVWS under realistic conditions, including AWGN, multipath fading, and impulsive noise considering OFDM signals from the ISDB-T/TB standard as the primary user (PU) and using two fusion rules in CSS: sample fusion (SF) and decision fusion (DF).

System Model

The model consists of two hypotheses:

$$y(t) = \begin{cases} w(t) + r(t), & \text{if } \mathcal{H}_0 \\ x(t)h(t) + w(t) + r(t), & \text{if } \mathcal{H}_1 \end{cases}, \qquad (1)$$

- $y(t)$ is the received signal.
- $w(t)$ thermal noise at receiver.
- $r(t)$ impulsive noise at receiver.
- $x(t)$ PU transmitted signal.
- $h(t)$ channel gain.

Decision on spectral occupancy

- A decision variable, T, is generated by processing $y(t)$.
- if $T > \lambda$, decides for H_1, otherwise for H_0.

Energy Detection

- Energy detection is one of the most widely used techniques owing to its low implementation complexity.
- The decision statistic (variable), T, is calculated according to

$$T = \sum_{i=1}^{n} |y(i)|^2. \tag{2}$$

- Considering a sufficiently large number of samples, n, and using the central limit theorem, $T = \mathcal{N}(n\sigma_{\mathsf{w}}^2, n\sigma_{\mathsf{w}}^4)$ under hypothesis H_0 and $T = \mathcal{N}(n(\sigma_{\mathsf{s}}^2 + \sigma_{\mathsf{w}}^2), n(\sigma_{\mathsf{s}}^2 + \sigma_{\mathsf{w}}^2)^2)$ under hypothesis H_1.

$$P_{\mathsf{fa}} = Q\left(\frac{\lambda - n\sigma_{\mathsf{w}}^2}{\sqrt{n\sigma_{\mathsf{w}}^4}}\right), \qquad P_{\mathsf{d}} = Q\left(\frac{\lambda - n(\sigma_{\mathsf{s}}^2 + \sigma_{\mathsf{w}}^2)}{\sqrt{n(\sigma_{\mathsf{s}}^2 + \sigma_{\mathsf{w}}^2)^2}}\right), \qquad \lambda = \sigma_{\mathsf{w}}^2(Q^{-1}(P_{\mathsf{fa}})\sqrt{n} + n).$$

CSS Approaches (m CRs)

Decision Fusion (DF)

- Each CR sends its individual decision (1 bit) about spectrum occupancy to the FC.
- The FC applies the **majority rule**: - If most CRs indicate the spectrum is occupied $\implies$ final decision is occupied. - Otherwise, it is considered free.
- **Advantage:** Low complexity, requiring only the transmission of 1 bit per CR.
- **Balanced Approach:** Maj rule reduces false positives compared to the OR rule while being less strict than the AND rule, allowing a higher probability of detection.

Sample Fusion (SF)

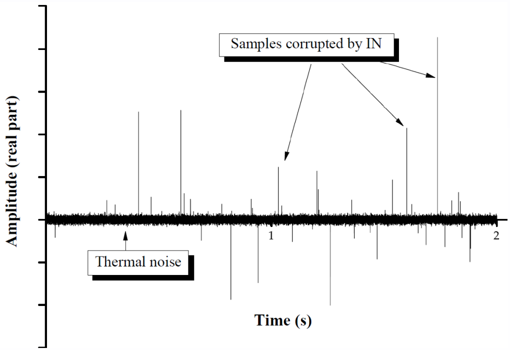
- Each of the m CRs sends its n collected samples to the FC.
- The FC computes a joint decision statistic using all $m \times n$ samples:

$$T_{\text{EDSF}} = \sum_{l=1}^{m} \sum_{i=1}^{n} |y_l(i)|^2$$

- Decision: $T_{\text{EDSF}} > \lambda \implies$ spectrum is occupied.
- **Disadvantage:** High implementation complexity due to the need for transmitting samples at a high rate.

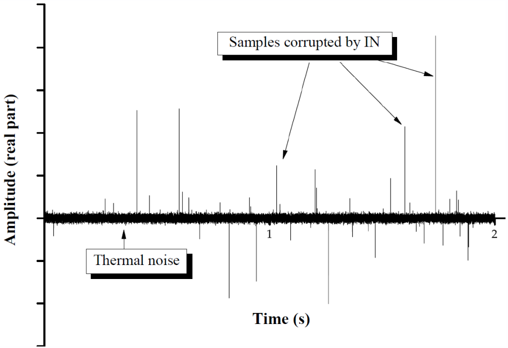
Impulsive Noise Modeling

- IN can significantly degrade telecommunications and spectrum sensing systems.
- It introduces high-amplitude disturbances caused by sources like electrical switching, lightning, and engine ignitions.
- The number of IN pulses in a sensing period follows a **Poisson distribution**.
- The interval between pulses is modeled as an **exponential distribution** with a mean value of β.



Impulsive Noise Modeling

- The IN pulse amplitude (Z) follows a **log-normal distribution** (amplitude A [dBμV] and standard deviation B [dB]).
- The IN phase is modeled as a **uniform** random variable $\theta \in (0, 2\pi]$.



- Parameters for adapting IN to CSS:
  - K: Ratio of IN power to thermal noise power ($K = \sigma_{\text{r}}^2/\sigma_{\text{w}}^2$)
  - P_{IN}: Probability of IN occurrence (Bernoulli RV).
  - P_{CR}: Percentage of CRs affected (Binomial RV - parameters m and P_{CR}).

Primary User Signal in TVWS

- The PU signal considered in the SS simulations is OFDM fully compliant with the transmission signal of the ISDB-T$_B$ standard.

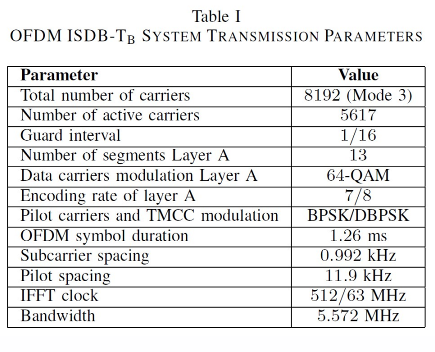
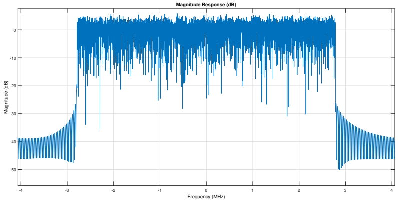


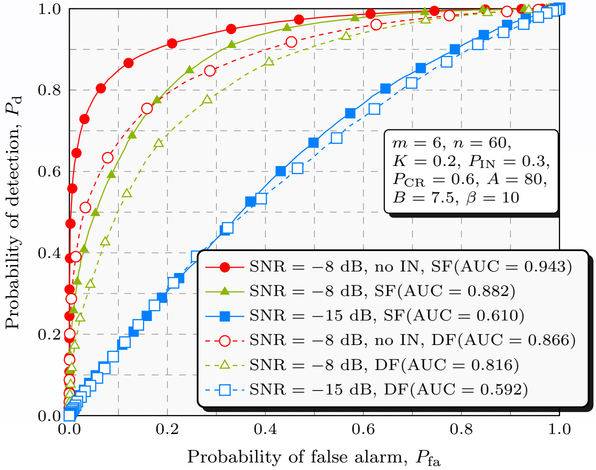
Table I
OFDM ISDB-T$_B$ SYSTEM TRANSMISSION PARAMETERS

Parameter	**Value**
Total number of carriers	8192 (Mode 3)
Number of active carriers	5617
Guard interval	1/16
Number of segments Layer A	13
Data carriers modulation Layer A	64-QAM
Encoding rate of layer A	7/8
Pilot carriers and TMCC modulation	BPSK/DBPSK
OFDM symbol duration	1.26 ms
Subcarrier spacing	0.992 kHz
Pilot spacing	11.9 kHz
IFFT clock	512/63 MHz
Bandwidth	5.572 MHz



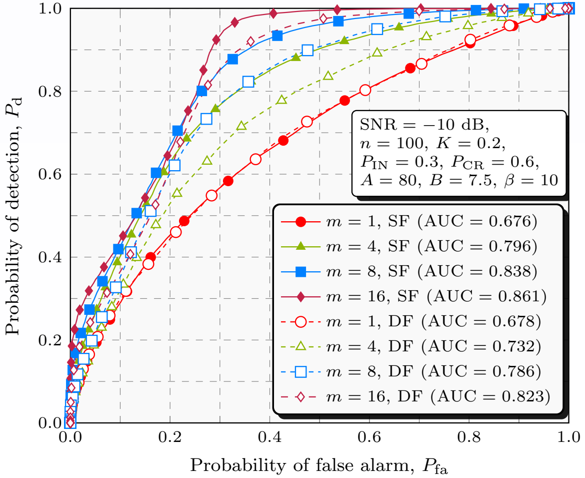
$$s(t) = \sum_{s=0}^{\infty} \sum_{k=0}^{K-1} c_{s,k} \psi(s,k,t) \qquad (3)$$

Numerical Results (varying SNR)



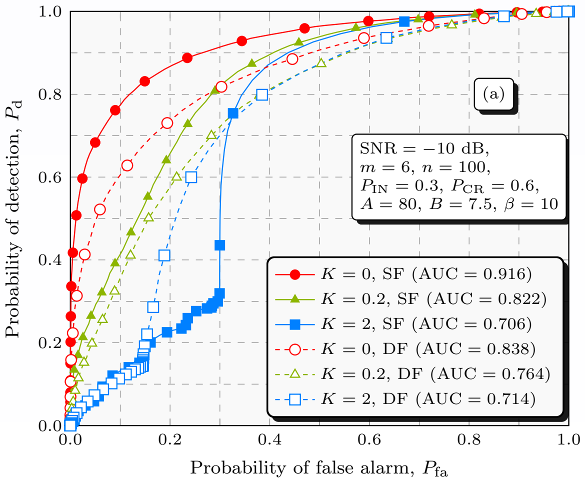
- MATLAB software, taking into account 20000 Monte Carlo events
- ROC curves deviate from the optimal point, and the AUC metric decreases in the presence of IN.
- The SF method outperforms DF in all evaluated cases.
- The performance gap between SF and DF is less pronounced with IN.

Numerical Results (varying m)



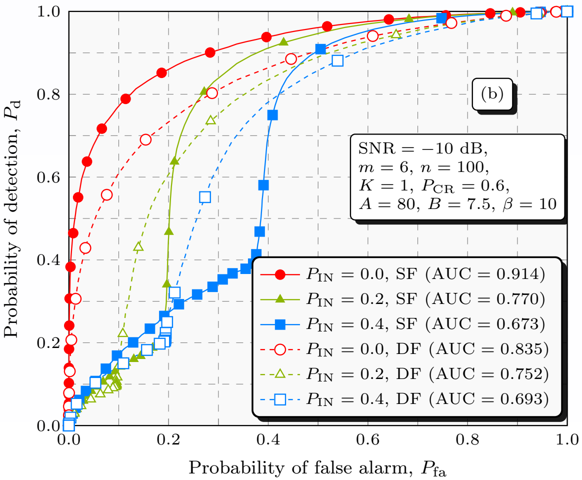
- The cooperative approach mitigates IN compared to a non-CSS system ($m = 1$) for both SF and DF methods.
- Performance improvements diminish as the number of CRs increases, especially at low P_fa values.

Numerical Results (varying K)



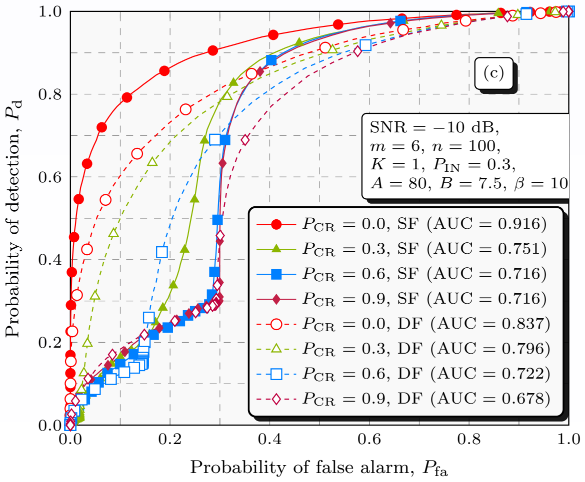
- K: Ratio of IN power to thermal noise power ($K = \sigma_\mathrm{r}^2/\sigma_\mathrm{w}^2$)
- Increasing K reduces SS performance due to higher IN, leading to more false alarms.
- Without IN ($K = 0$), SF (AUC $= 0.916$) outperforms DF (AUC $= 0.838$)
- At high K ($K = 2$), DF (AUC $= 0.714$) surpasses SF (AUC $= 0.706$) despite its simpler implementation.

Numerical Results (varying P_{IN})



- Without IN ($P_{\text{IN}} = 0$), SF outperforms DF, but DF becomes superior as P_{IN} increases.
- Intense IN causes SF ROC curves to exhibit a sharp vertical drop near $P_{\text{fa}} = P_{\text{IN}}$, indicating operational infeasibility.
- DF shows smoother degradation under high IN, outperforming SF for $P_{\text{IN}} = 0.4$ (AUC $= 0.693$ vs. AUC $= 0.673$).

Numerical Results (varying P_{CR})



- In scenarios with $P_{\text{CR}} \neq 0$, DF outperforms SF when fewer CRs are affected by IN, e.g., for $P_{\text{CR}} = 0.3$, DF achieves AUC $= 0.796$ compared to SF's AUC $= 0.751$.
- DF is more robust to high-intensity IN due to majority decision-making, while SF is compromised as all samples are used in the final decision.

Conclusion

- This study analyzed CSS in TVWS scenarios using the ISDB-T$_B$ signal under realistic disturbances, including Rayleigh fading, thermal noise, and IN, comparing SF and DF cooperation methods.
- The analyses highlighted the negative impact of IN on SS performance and showed diminishing performance gains as the number of CRs increases.
- DF was found to outperform SF in scenarios with high IN power intensity but a low percentage of affected CRs, despite its lower implementation complexity.
- These findings provide critical insights for optimizing SS strategies, improving the robustness and reliability of CSS in TVWS environments.

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