A Spatial Reuse Media Access Protocol for Cooperative Spectrum Sensing

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Overview

Introduction

Provide the background knowledge of cooperative spectrum sensing, and WSN MAC design.

System Model of the DetF WSN

(DetF: Detect-and-Forward)

Depict the network architecture, and system setup assumptions. Moreover, the time-invariant fading channel model including the effects of *path loss* and *additive interference* is presented.

Spatial Reuse MAC protocol based on Hybrid TDMA/OFDMA

Discuss the design and implementation of the spatial reuse MAC protocol in detail.

Performance Numerical Results

Present the performance numerical results of the MAC protocol in a specific scenario.

Introduction

1. Cooperative Spectrum Sensing
2. WSN MAC Protocol Design

Introduction

Cooperative Spectrum Sensing

- Cognitive Radio

  Cognitive Radio (CR) is a paradigm for a more flexible and efficient usage of radio spectrum. In a CR system, a secondary user (SU) can access spectrum holes without introducing harmful interference to the primary user (PU).

- Cooperative Spectrum Sensing

  Spectrum sensing is an essential function of CR to identify such spectrum holes, and the sensing process can be improved by employing several sensing nodes.

- External Option based on Wireless Sensor Networks

  External Sensing separates the spectrum sensing function from SU devices and relies on a dedicated wireless sensor network (WSN) to perform spectrum sensing.

Introduction

WSN MAC Protocol Design

- Conventional MAC Design

  MAC is part of the Data Link Layer in the OSI model, and the primary role is coordinating transmissions so as to efficiently utilize the resources and resolve contention.

- Constrains on WSN MAC Design

  Limited energy budget of a sensor with the requirement of longevity of the network is usually the largest constraint.

- Particularities of our DetF WSN

  Sensors are assumed to be fixed and don’t depend on limited battery power. Spectrum efficiency and interference become the primary issues.

System Model of the DetF Distributed WSN

1. Network Architecture
2. System Setup Assumptions
3. Channel Model

System Model

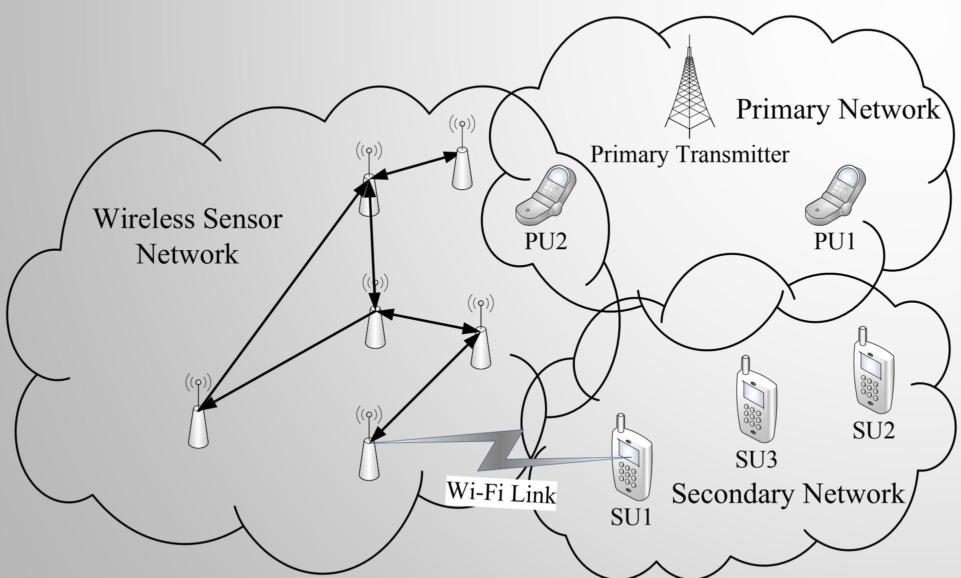
Network Architecture

- Intra-WSN Sensing

Measurement → Local Decision → Communication → Final Decision

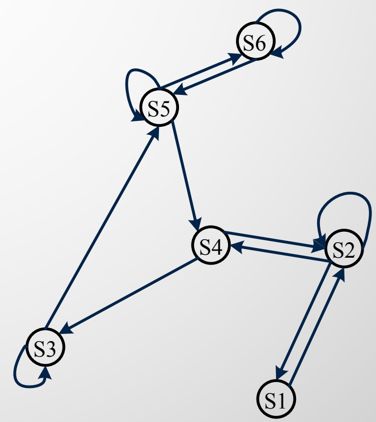
(This stage involves *Partner Selection* and *Decision Fusion*.)

- WSN-SU Handshaking



- Representation of Cooperation

Directed Graph or Adjacency Matrix:



$$\mathbf{R} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

System Model

System Setup Assumptions

- The sensors are static after deployed, with locations determined to optimize the spectrum sensing performance.
- A certain *partner selection* scheme has been utilized to generate the adjacency matrix of cooperation, and each sensor is in direct transmission range of its partners.
- The sensors communicate by broadcasting packets, and can dynamically switch to different sub-carriers.
- The sensors can transmit and receive at the same time on different sub-carriers.
- The sensors are synchronized with reference to a global clock.

System Model

Channel Model

Time-invariant fading channel model including the effects of path loss and additive interference.

- Multi-path Fading: Rayleigh, Rician, Nakagami, …
- Path-loss Model: Simplified Model [1, p.47]

$$P_L = \frac{P_t}{P_r} = \frac{1}{A} d^{\mu} \qquad (1)$$

where A is a unitless constant, d is the distance, and μ is the path-loss exponent.

- Interference Model: Additive Interference Model [2]

$$\gamma_{i,j} = \frac{G_{i,j} P_{tra}^{(i)}}{P_{noi} + \sum_{k \in \mathcal{K} \setminus \{i\}} G_{k,j} P_{tra}^{(k)}}$$

where $\gamma_{i,j}$ is the SINR of the transmission from s_i at s_j, $G_{i,j}$ is the channel gain, $P_{tra}^{(i)}$ is the transmit power of s_i, P_{noi} the thermal noise power, and $\mathcal{K} \setminus \{\mathrm{i}\}$ denotes the set of nodes that are transmitting simultaneously on the same channel other than s_i.

[1] A. Goldsmith, *Wireless Communications*. New York, NY: Cambridge University Press, 2005.

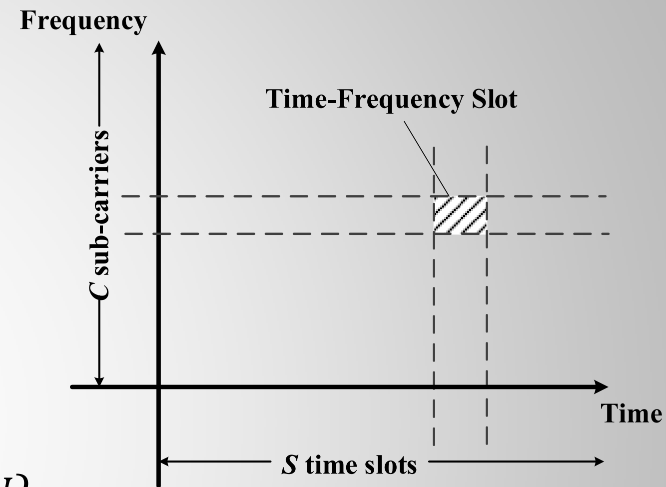
[2] A. Iyer, C. Rosenberg, and A. Karnik, “What is the right model for wireless channel interference,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2662–2671, May 2009.

Spatial Reuse MAC based on Hybrid TDMA/OFDMA

1. Basic Concept
2. Candidate Set of Each Sensor
3. Scheduling as a Vertex Coloring Problem
4. Complete Scheduling Process

Spatial Reuse MAC

Basic Concept



- Hybrid TDMA/OFDMA

  Collision-free and reservation-based.

- Spatial Reuse

  Divide N sensors into M separate sets, and assign one slot to the sensors in the same set. Denote these sets as $\mathcal{P}_1$, $\mathcal{P}_2$, ..., $\mathcal{P}_M$, with

  $$\mathcal{P}_m = \{i \in \mathbb{Z}^+ | s_i' \mathrm{s\ T-F\ slot\ ID\ is}\ m, 1 \le i \le N\}$$

  We use $COLOR(i) \in \mathbb{Z}^+$ to represent s_i's slot ID, and thus $i \in \mathcal{P}_{COLOR(i)}$.

- Requirement for Each Link: $\boxed{\gamma_{i,j} \ge \beta_{i,j}}$

  $\gamma_{i,j}$ is the received SINR of $s_i \to s_j$

  $$\gamma_{i,j} = \frac{A d_{i,j}^{-\mu} P_{tra}^{(i)}}{P_{noi} + \sum_{k \in \mathcal{P}_{COLOR(i)} \setminus \{i\}} A d_{k,j}^{-\mu} P_{tra}^{(k)}} \qquad (2)$$

  $\beta_{i,j}$ is the received SINR threshold of $\mathbf{r}_{i,j}$.

Spatial Reuse MAC

Candidate Set of Each Sensor

- A sufficient condition

$$A d_{i,j}^{-\mu} P_{tra}^{(k)} \leq \frac{1}{c}\left[\frac{A d_{i,j}^{-\mu} P_{tra}^{(i)}}{\beta_{i,j}} - P_{noi}\right], \forall k \in \mathcal{P}_{COLOR(i)} \setminus \{i\} \qquad (3)$$

where c is defined as the *reuse* degree, and the size of $\mathcal{P}_{COLOR(i)}$ is $c+1$.

- Forming the Candidate Set

a) Form an $N \times N$ adjacency matrix $\mathbf{R}$.

b) Find the sensors satisfying (3) for any link starting from s_i, and form a set $\mathcal{A}_{i,c}$.

c) For each member s_k in $\mathcal{A}_{i,c}$, if $R_{k,i} = 1$, delete s_k from $\mathcal{A}_{i,c}$; otherwise, keep it. As a result, we get a subset $\mathcal{B}_{i,c}$.

d) Create a relation matrix $\mathbf{F}^{(c)}$ with the element $F_{i,k}^{(c)} = \begin{cases} 1 & \text{if} \quad s_k \in \mathcal{B}_{i,c} \\ 0 & \text{if} \quad s_k \notin \mathcal{B}_{i,c} \end{cases}$.

e) Form the *Candidate Set* of s_i at the reuse degree c, denoted by $\mathcal{G}_{i,c}$, composed of the element s_k satisfying $F_{i,k}^{(c)} = 1$ and $F_{k,i}^{(c)} = 1$.

Spatial Reuse MAC

Scheduling as Vertex Coloring

- Construct a simple undirected graph

  Consider sensors as vertices, and if $s_j \notin \mathcal{G}_{i,c}$, draw an edge between s_i and s_j.

- Equivalent vertex coloring problem under two conditions

  1) No two adjacent vertices share the same color;
  2) No color is used more than $c + 1$ times.

- DSATUR Algorithm [3]

  Degree: Number of edges incident to a vertex;
  Saturation Degree: Number of different colors in the neighbors of a vertex.

  Vertex Coloring in a Dynamic Order:

  a) Always select the uncolored vertex with the highest *saturation degree*.
  b) Colors are numbered sequentially first. Search the colors in the ascending order, and choose the first available color satisfying the following two conditions:
    1) It hasn't been assigned to any neighbor of the current vertex;
    2) It hasn't been used more than c times by other vertices.

[3] D. Brelaz, "New methods to color the vertices of a graph," *Communications of the ACM*, vol. 22, no. 4, pp. 251–256, 1979.

Spatial Reuse MAC

Complete Scheduling Process

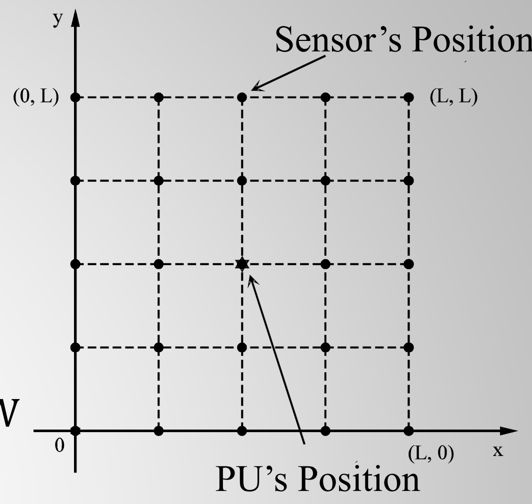
- a) Create the *unassigned sensor set* $\mathcal{S}$, and initialize it to
$$\mathcal{S} = \{s_1, s_2, \dots, s_N\}.$$
b) Estimate the highest possible reuse degree according to (3).
c) Start from $c = c_{max}$.
d) Obtain the *candidate set* $\mathcal{G}_{i,c}$ of each sensor s_i in $\mathcal{S}$.
e) Utilize *DSATUR* algorithm to assign colors to the sensors, and schedule s_i to $\mathcal{P}_{COLOR(i)}$ with other sensors having the same color.
f) Remove the colors which don't reach the current reuse degree, i.e. $\left|\mathcal{P}_{COLOR(i)}\right| < c + 1$. Reset these sensors to *unassigned*, and mark the rest as *assigned*.
g) Schedule the *assigned* sensors with the same color into the same slot, and update $\mathcal{S}$ for the next loop with $c \leftarrow c - 1$.
h) Repeat d) – g) until all the sensors are scheduled, i.e. until $\mathcal{S}$ is empty.

Performance Numerical Results

1. Scenario Setup
2. Spectrum Sensing based on Energy Detection
3. Performance Results

Numerical Results

Scenario Setup



- **Deployment of Sensors**
  Region: Square ($L = 1000\text{m}$); PU: Center
  Sensors: On the grid; Number of Sensors: $N = 225$
- **Transmit Power**
  Total: $P_{tot} = 50\text{W}$; Sensor: $P_{tra} = P_{tot}/N$; PU: $P_{pu} = 50\text{W}$
- **Partner Selection**
  Identical communication range: $d_{comm} = \frac{bL}{a-1}, b \in \{0, 1, \sqrt{2}, 2, \sqrt{5}, \sqrt{8}, \ldots\}$
  Each sensor selects all the sensors within d_{comm} as receivers.
- **Empirical Path-loss Model**
  COST-WI model with parameters set for Urban Macro scenario [4].

$$P_L = 10^{3.018}\, d^{2.6}, 20\text{m} \le d \le 5\text{km}. \text{ i.e. } A = 10^{-3.018}, \mu = 2.6$$

- **Multi-path Fading Model**
  Rician fading model with parameter $K = 7$, and the PDF of the SNR γ is

$$f_{Ric}(\gamma) = \frac{K+1}{\bar{\gamma}} \exp\left[-K - \frac{(K+1)\gamma}{\bar{\gamma}}\right] I_0\left(2\sqrt{\frac{(K+1)\gamma}{\bar{\gamma}}}\right), \gamma \ge 0$$

[4] D.S. Baum, J. Hansen, and J. Salo, "An interim channel model for beyond-3G systems: extending the 3GPP spatial channel model (SCM)," in *VTC 2005-Spring. 2005 IEEE 61st.*, vol. 5, pp. 3132–3136.

Numerical Results

Spectrum Sensing based on Energy Detection

- Energy Detection under Rician Fading

  The average probabilities of detection and false alarm :

$$P_{d,i} = \int_{all\ \gamma_i} Q_u\left(\sqrt{2\gamma_i}, \sqrt{\lambda}\right) f_{Ric}(\gamma_i) d\gamma_i\,, \qquad P_{f,i} = \frac{\Gamma(u, \lambda/2)}{\Gamma(u)}. \qquad (u = TW_D)$$

- Cooperation between Sensors

  i.i.d. Rician fading, identical threshold λ, OR rule for fusion

$$Q_{d,i} = 1 - \prod_{j \in \{j \mid R_{j,i}=1\}} \left(P_{d,j}\varepsilon_{j,i} + (1 - P_{d,j})(1 - \varepsilon_{j,i})\right)$$

$$Q_{f,i} = 1 - \prod_{j \in \{j \mid R_{j,i}=1\}} \left(P_{f,j}\varepsilon_{j,i} + (1 - P_{f,j})(1 - \varepsilon_{j,i})\right)$$

- Bit Error Probability ε

  Modulation Scheme: BPSK

  Average bit error probability for BPSK in Rician fading [5, p. 126]:

$$\varepsilon = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \frac{(1+K)\sin^2\phi}{(1+K)\sin^2\phi + \bar{\gamma}} \exp\left[\frac{K\bar{\gamma}}{(1+K)\sin^2\phi + \bar{\gamma}}\right] d\phi \qquad (5)$$

  In our system, the noise includes both AWGN and additive interference.

[5] M.K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels,* 2nd ed. John Wiley & Sons, 2005.

Numerical Results

Performance Results

- Other Parameters

  Noise Power Spectral Density: $N_0/2 = 5 \times 10^{-16}\,\mathrm{W/Hz}$

  Communication Subcarrier Bandwidth: $W_c = 20\mathrm{kHz}$

  Detection Bandwidth: $W_D = 1\mathrm{MHz}$; Identical SINR threshold: β_0

- The performance is analyzed through the complementary receiver operating characteristic (ROC), which is a curve of $Q_m = 1 - Q_d$ versus Q_f.
- Q_d and Q_f are the network probabilities of detection and false alarm averaged over sensor locations.
- We also consider the number of T-F slots needed for intra-WSN communications.
- The *Simple MAC* protocol, in which each sensor is scheduled in a private slot, serves as a comparison, and provides an upper bound of spectrum sensing performance with the largest number of T-F slots.

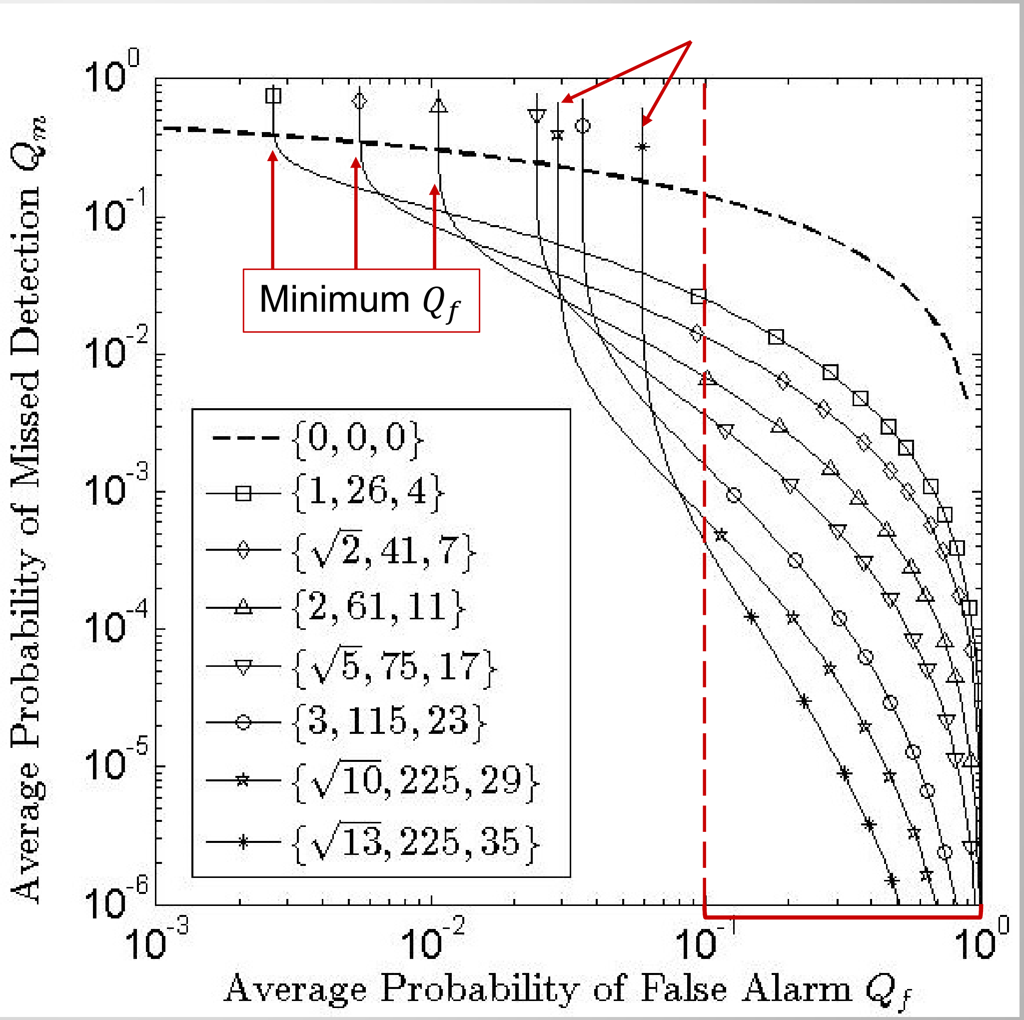
Numerical Results

Performance Results

- Performance at different cooperation levels.
- $d_{comm} = bL/(a-1)$. $\beta_0 = 4.3652$ ($\varepsilon_0 = 0.01$). The values in the legend are $\{b, N_{slo}, N_{par}\}$.

$$N_{par} = \left\lfloor \frac{\sum_i^N \sum_j^N R_{i,j} - N}{N} + 0.5 \right\rfloor$$

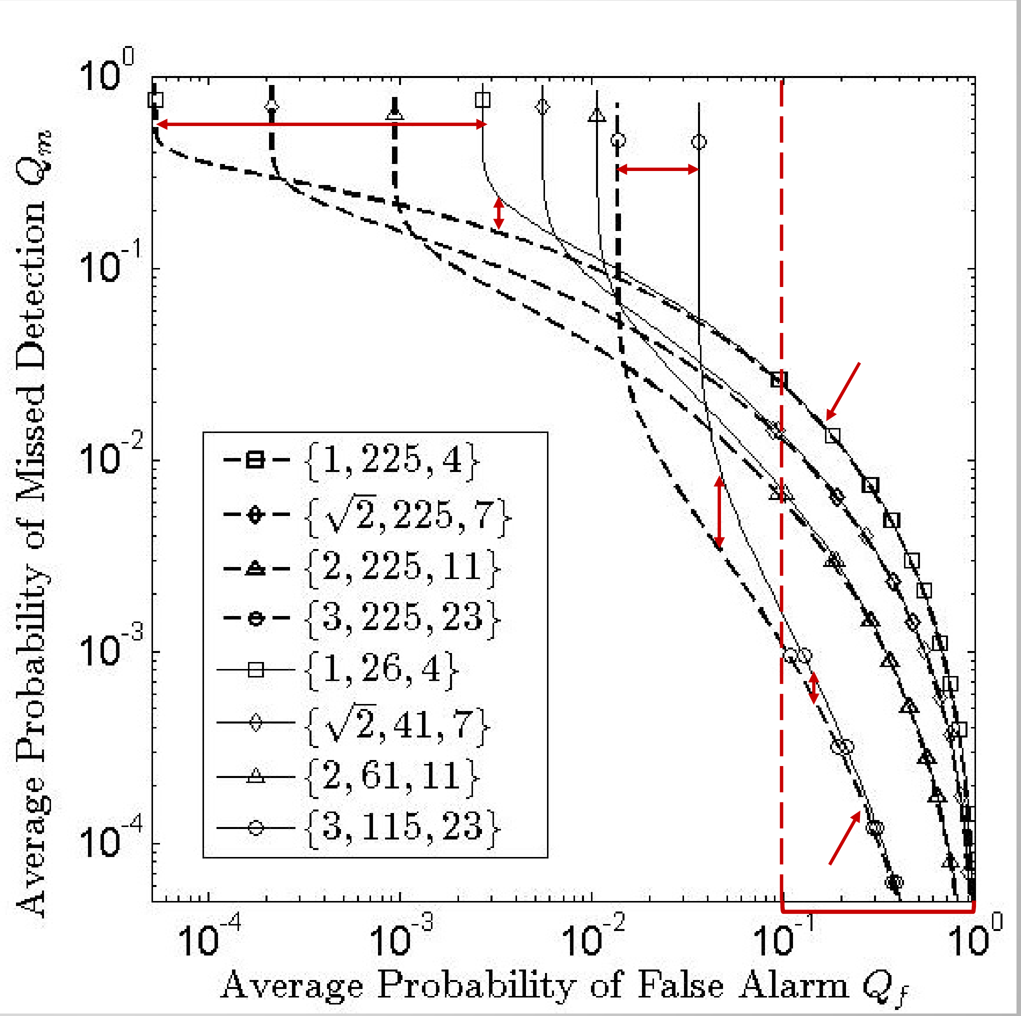
is the average number of each sensor's partners.



Numerical Results

Performance Results

- Effect of the interference caused by slot-reuse.
- $d_{comm} = bL/(a-1)$. $\beta_0 = 4.3652$ ($\varepsilon_0 = 0.01$). The values in the legend are $\{b, N_{slo}, N_{par}\}$.



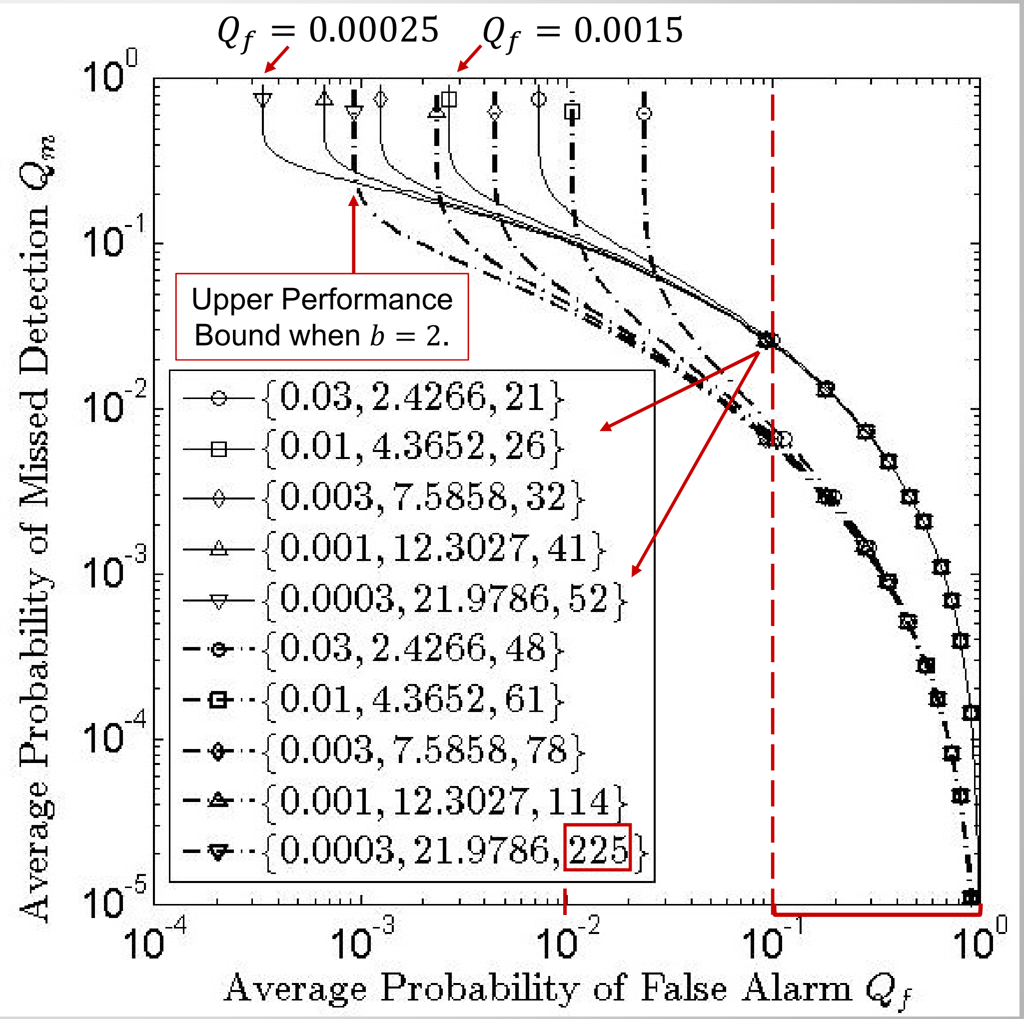
Numerical Results

Performance Results

- Results with different SINR thresholds.
- $d_{comm} = bL/(a-1)$.

  The solid lines represent $b = 1$, and the dash-dot lines represent $b = 2$.

  The values in the legend are $\{\varepsilon_0, \beta_0,\ N_{slo}\}$, where ε_0 and β_0 are the BER and SINR threshold. For a given ε_0, the corresponding β_0 is calculated through (5).



Conclusions

- We introduced a DetF distributed WSN for cooperative spectrum sensing, and proposed a spatial reuse MAC protocol based on TDMA/OFDMA. Numerical results show the trade-off between the number of T-F slots and the spectrum sensing performance.
- If the communication range is fixed, the differences between the complementary ROC curves with different SINR thresholds are very small in the high Q_f range, e.g. $0.1 \leq Q_f < 1$.
- We can save 49% to 88% of T-F slots with different cooperation levels ($\beta_0 = 4.3652$), and when N_{par} reaches a certain level ($N_{par} = 29$ in our scenario), no spatial reuse is possible.
- In the lower Q_f range, e.g. Q_f<0.1, when the cooperation level is fixed, we can increase the SINR threshold to expand the range of applicable Q_f at a cost of more T-F slots.
- The future research efforts may include associating the MAC protocol with partner selection schemes and decision fusion rules.

Thank you.

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