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Outline

• Introduction
• Combining Hidden Markov Model with quickest detection
• Frequency sweeping based spectrum detection and recognition
• Experimental results
• Conclusion
Introduction

• Major contribution of this paper
  – Introducing the combination of Hidden Markov Model (HMM) and quickest detection to cognitive radio
• The proposed approach
  – An approach based on HMM and quickest detection for spectrum detection, by which the radio frequency spectrum is swept continuously and spectrum detection results are output as quickly as possible.
  – Outputs
    • A detection result
    • A recognition result with the category of the detected spectrum segment
    • The starting point and ending point of the detected spectrum segment in frequency domain
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HMM

• Defined by $\lambda = \{\pi, A, B\}$
  – $\pi$: initial state probability vector
  – $A$: state transition matrix
  – $B$: observation matrix
  – $M$: number of possible observation values
  – $N$: number of states

• Forward-Backward algorithm (part)
  – $\alpha_t(i)$: forward variable
  – $p_f(o|\lambda)$: likelihood function

\[
\begin{align*}
(\pi)_{i,1} &= \Pr(s_i \text{ at } t = 1) \\
(A)_{i,j} &= \Pr(s_j \text{ at } t+1 | s_i \text{ at } t) \\
&\quad i, j = 1, 2, \ldots, N \\
(B)_{i,j} &= \Pr(v_j \text{ at } t | s_i \text{ at } t) \\
&\quad i = 1, 2, \ldots, N \\
&\quad j = 1, 2, \ldots, M
\end{align*}
\]

1) Initialization.
\[
\alpha_1(i) = \pi_i b_i (o_1) \\
&\quad i = 1, 2, \ldots, N
\]

2) Iteration from $2 \leq t \leq T$ and $1 \leq j \leq N$.
\[
\alpha_t(j) = \left[ \sum_{i=1}^{N} \alpha_{t-1}(i)a_{ij} \right] b_j (o_t)
\]

3) Termination.
\[
p_f(o|\lambda) = \sum_{i=1}^{N} \alpha_T(i)
\]
Combining HMM with quickest detection (1)

• Now the question is that if the observation sequence $o$ to be recognized is embedded in a longer observation sequence $x = [x_1, x_2, \ldots, x_K]$, (1) how can we find the occurrence of a predefined pattern as quickly as possible? (2) And how can we determine the category of the pattern?

• Suppose the hypothesis testing problem
  – $n_k$ : additive white Gaussian noise
  – $k_0$ : starting position of $o$ in $x$

\[
H_0 : \begin{cases} 
  x_k = n_k & 1 \leq k \leq K \\
  x_k = n_k & 1 \leq k < k_0 \\
  x_k = o_{k-k_0+1} & k_0 \leq k < k_0 + T \\
  x_k = n_k & k_0 + T \leq k \leq K 
\end{cases}
\]
Combining HMM with quickest detection (2)

• Quickest detection is introduced to answer the first question, while HMM is exploited to answer the second question.

• This problem can be solved by using the following procedure.
  1) Initialization of variables. Set threshold $S_{th}$. Let $k = 0$ and $n = 1$.
  2) Initialize the Forward-Backward algorithm for HMM. And let $S_0 = 0$.
  3) Iteration. $k = k + 1$,

$$S_k = \max \{0, S_{k-1} + g(k; n)\}$$

where

$$g(k; n) = \ln \left( \frac{Pr_{H_1}(x_k | x_{k-1}, \ldots, x_n)}{Pr_{H_0}(x_k | x_{k-1}, \ldots, x_n)} \right)$$

If $S_k$ is forced to be zero by the max operation, then $n = k + 1$ and goto step 2).
Combining HMM with quickest detection (3)

4) Termination. If $S_k > S_{th}$, then the procedure is terminated and the occurrence of the pattern is announced. Otherwise, goto step 3).

where

$$\Pr (x_k | x_{k-1}, \ldots, x_1) = \frac{\Pr (x_k, x_{k-1}, \ldots, x_1)}{\Pr (x_{k-1}, \ldots, x_1)} = \frac{\sum_{i=1}^{N} \alpha_k (i)}{\sum_{i=1}^{N} \alpha_{k-1} (i)}$$

- In order to avoid numerical underflow as $k$ becomes larger, a scaling operation is applied to forward variables.

$$\hat{\alpha}_1 (i) = \alpha_1 (i) \quad i = 1, 2, \ldots, N$$

and for $2 \leq t \leq T$ and $1 \leq j \leq N$,

$$\hat{\alpha}_t (j) = \frac{\sum_{i=1}^{N} \hat{\alpha}_{t-1} (i) a_{ij} b_j (o_t)}{\sum_{i=1}^{N} \hat{\alpha}_{t-1} (i)}$$
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Frequency sweeping based spectrum detection and recognition

Received signals → Frequency Sweeping → Frequency samples → Quantification → Observations for HMM → HMM Training & Forward Variables Calculation → Forward variables → Quickest Detection & Recognition → Detection & recognition results

HMM Training & Forward Variables Calculation

HMM parameters (spectrum 1) → Forward Variables Calculation (spectrum 1) → S_x Calculation (1) → Arg Max → Index of kind of used spectrum segment

HMM parameters (spectrum 2) → Forward Variables Calculation (spectrum 2) → ... → S_x Calculation (Q) → Rising Detection → Starting point and ending point of used spectrum segment

HMM parameters (blank spectrum) → Forward Variables Calculation (blank spectrum) → S_x Calculation (Q) → Comparison with Threshold → Reference indicator for occupancy of spectrum segment

Threshold in Page’s Test
Summary of the process of spectrum detection and recognition in the proposed approach

1) Initialization. $k = 0$, $S_{i,0} = 0$, for $i = 1, 2, ..., Q$, where $Q$ is the number of kinds of known spectra, and $S_{i,k}$ represents the $k^{th}$ sample of $S$ for the $i^{th}$ kind of known spectrum. Initialize forward variables calculation submodules.

2) Iteration. $k = k + 1$. Calculate $S_{i,k}$, for $i = 1, 2, ..., Q$.
   If $S_{i,k}$ is forced to be set to zero by the max operation in 12, then goto step 1).

3) If $S_{i,k}$ is great than the threshold $S_{th}$, for any $i = 1, 2, ..., Q$, then the comparison submodule outputs a reference indicator for occupancy of spectrum segment and sends an enabling-signal to the rising detection submodule.

4) If the $S_{k}$ curve that later goes the highest begins to rise, the position of the starting point of rising is recorded by the rising detection submodule. If all of the $S_{k}$ curves begin to drop, the position of the ending point of rising is recorded.

5) If the rising detection submodule receives an enabling-signal and all of the $S_{k}$ curves begin to drop, then the positions of recorded starting point and ending point are output, and an enabling-signal is sent to the Arg Max submodule.

6) If the Arg Max submodule receives an enabling-signal, then it outputs the index of the $S_{k}$ curve that achieves the maximum value at the ending point, and goto step 1).

7) Goto step 2).
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The experiment

- Spectrum Analyzer (SA) has been used to sweep the spectrum and output the measured power spectrum densities (PSDs) of spectrum segments.
- Three categories of primary user’s spectrum are chosen for testing the proposed approach: CDMA, GSM, Wi-Fi.
- A blank spectrum is also measured for calculating $S_k$.
- The samples of these PSDs are quantified respectively with 64 levels.
- The HMMs are trained in advance with 5 states using the quantified PSDs.
- The whole quantified PSDs are regarded as observation sequences for HMM recognition.
Measured PSDs

CDMA

GSM

Wi-Fi

Blank
Experimental results – Wi-Fi (1)

Occupied spectrum detected!
Experimental results – Wi-Fi (2)

Wi-Fi spectrum recognized!
Experimental results – Wi-Fi (3)

Detected occupied frequency band matches to PSD!

Detected starting point and ending point
Experimental results - others

With input of CDMA

With input of GSM
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- An approach for quickest spectrum detection and recognition for cognitive radio has been proposed.
- The spectra of CDMA, GSM, Wi-Fi and blank spectrum have been measured and used for performance evaluation of the proposed approach.
- Experimental results have demonstrated that the proposed approach is effective.
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Reference

Thank you!