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A Cyclic Prefix Assisted Spectrum Sensing Method for Aeronautical Communication Systems

Libin.K. Mathew
School of Computer Science and
Engineering, Nanyang Technological
University, Singapore;
libin001@e.ntu.edu.sg

A.P. Vinod
Dept. of Electrical Engineering,
Indian Institute of Technology,
Palakkad, India;
vinod@iitpkd.ac.in

A.S. Madhukumar
School of Computer Science and
Engineering, Nanyang Technological
University, Singapore;
asmadhukumar@ntu.edu.sg

Abstract—Continuous growth of air-traffic demands new technologies for future aeronautical communication systems. L-band Digital Aeronautical Communications System (LDACS) is considered as a potential candidate for the future air-to-ground links. Spectrum utilization efficiency of LDACS can be improved by enabling dynamic spectrum access (DSA) in the system. In this context, the present paper proposes a novel cyclostationary feature detection scheme based on the periodicity of the auto-correlation of LDACS signals for spectrum sensing, which is key requirement in DSA. A wideband spectrum sensing simulation model is developed to evaluate the detection performance of the proposed scheme. To improve the adaptability of the spectrum sensing unit to variable wide bandwidth, the proposed system uses interpolation and masking based filters that can extract individual LDACS channels from the wide-band signals. Results of simulation studies show that the proposed scheme provides better detection accuracy against the conventional cyclostationary feature detection scheme and energy detection scheme, while maintaining the false alarm rates to an acceptable level which balances the overall throughput of the system.

I. INTRODUCTION

Air-traffic is experiencing continuous growth for the last two decades, and expansion in double is expected by 2035 in comparison with 2012 [1]. The current aeronautical communication systems still use analog voice communications for connecting the ground controllers to the pilots on board of the aircraft. Current technology uses the DSB-AM (Double-Sideband Amplitude Modulation), which is deployed in the VHF band from 118 to 137 MHz. The DSB-AM is capable of ensuring reliable communication between the aircraft and the ground controllers. However, this technology is highly spectrum inefficient, and voice communication is not able to satisfy most of the future needs.

To address these challenges, The International Civil Aviation Organisation has recommended Future Communications Infrastructure (FCI) that integrates the existing technologies and new optimal data link protocols for enhancing the air-to-air, air-to-ground and satellite-based links. For the air-to-ground links, the L-band Digital Aeronautical Communications System (LDACS) is gaining traction as the preferred model for final deployment. LDACS is proposed as an inlay approach with legacy L-band systems like Distance Measuring Equipment and hence has stringent requirements on transmission and reception [2], [3]. The LDACS system uses

spectrally efficient digital modulation schemes like Orthogonal Frequency Division Multiplexing (OFDM) for transmission. The LDACS is expected to operate on the lower half of the L-band from 960 MHz to 1164 MHz as an inlay system between the two neighboring Distance Measuring Equipment (DME) channels. The concept of dynamic spectrum access (DSA) can be applied to the LDACS for improving the spectrum efficiency. Use of cognitive radio (CR) technology is proposed to enable the DSA in LDACS [4]. Since aeronautical communications are very much safety critical, accurate sensing and estimation of spectral holes are mandatory for the deployment of DSA. The spectrum sensing in the aeronautical domain experiences unique challenges compared to the terrestrial cognitive radio (CR) based communication systems. The key challenges are:

- Reliable spectrum sensing techniques are required to cater to the mobility aspect of the aircraft and the related rapid changes in the channel.
- Comparing against terrestrial systems, there are stringent power limitations in onboard systems, which demand a low complexity spectrum sensing scheme..
- Most of the spectrum sensing require to estimate noise power. Any errors in the noise estimation degrade detection performance drastically. Removal of noise uncertainty with less sophisticated techniques is always a big challenge.

To the best of our knowledge, the spectrum sensing techniques for LDACS were not extensively discussed in the literature. Only two methods available as of now are: an energy-difference detection based technique [5] and multiplier-less correlator based detection technique [4]. The former one suffers from noise uncertainty problem [6] and needs two channels to be scanned for the decision making of one LDACS channel. The correlator based technique provides better detection accuracy compared to the energy detection (ED)-based techniques. This method uses the knowledge of preamble for detection of spectral hole. As it uses the knowledge of preamble at the starting of the LDACS multi-frame, the possible sensing time may be varied up to the maximum length of a multiframe. The cyclostationary properties of the LDACS signals (due to induced cyclic prefix) can be utilized for spectrum sensing. The various cyclostationary feature detection

(CFD) based spectrum sensing techniques are available in the literature [7], [8] are computationally intensive and demands long sensing duration for the decision making. Though the robustness towards noise uncertainty of these techniques is better compared to energy detection based techniques, they are still sensitive to noise estimation errors. The cyclostationary properties of the LDACS signals (due to induced cyclic prefix) can be utilized for spectrum sensing. The various cyclostationary feature detection (CFD) based spectrum sensing techniques are available in the literature [7], [8] are computationally intensive and demands long sensing duration for the decision making. Though the robustness towards noise uncertainty of these techniques is better compared to energy detection based techniques, it is still sensitive to noise estimation errors. In this paper, a low complexity cyclostationary spectrum sensing scheme is proposed to detect the LDACS spectral holes for better detection accuracy with less complexity. The main contributions of this paper are:

- A low complexity cyclostationary feature detection scheme is proposed to detect the LDACS spectrum holes.
- The test statistic is formulated in such a way that the decision threshold is independent of the noise variance.
- Theoretical formulations for the detection probability, false alarm probability, and decision threshold are done for the proposed scheme.
- A wide-band spectrum sensing simulation model is developed with an interpolation and masking based filters to extract the individual channels. This filter bank is adaptable to adjust with the number of subchannels by changing the interpolation factor and the masking filters.

II. SYSTEM MODEL

Two communication strategies are involved in the proposed LDACS based scheme: Primary communication and Secondary communication. Primary communication is similar to a traditional static channel allocation scheme, and in secondary communication, an aircraft can look for additional channels to transmit multimedia messages (mainly for aircraft health parameters). The additionally required secondary channels are identified through spectrum sensing.

The n^{th} sample of the baseband signal transmitted by the primary aircraft is given as,

$$s(n) = \sum_{m=-\infty}^{\infty} \sum_{k=0}^{N-1} d_m(k) g(n - mT_s) e^{\frac{j2\pi k(n - mT_s - T_{cp})}{N}}, \quad (1)$$

where N is the number of OFDM subcarriers, $d_m(k)$ is the data transmitted on the k^{th} subcarrier of the m^{th} OFDM symbol and $g(n)$ is the rectangular shaping window with a duration equal to T_s , the sum of useful symbol time T_u and the cyclic prefix (CP) time T_{cp} . A cyclostationarity property is present in the transmitted signal $s(n)$ due to the insertion of CP. The secondary aircraft has to detect the presence/absence of a primary signal on a given carrier by observing a noisy signal $x(n)$. A statistical hypothesis test has to perform to decide between the hypotheses $\mathcal{H}_0$ and the $\mathcal{H}_1$, i.e., the absence and

the presence of the signal $s(n)$ respectively. The system model for the statistical hypothesis test is given as,

$$x(n) = \begin{cases} w(n), & \mathcal{H}_0 \\ h(n)s(n) + w(n), & \mathcal{H}_1 \end{cases} \quad (2)$$

where $s(n)$ is the transmitted signal, $w(n)$ is the additive white Gaussian noise and $h(n)$ represents the channel.

III. PROPOSED SPECTRUM SENSING SCHEME

The normalized sub-optimal Fourier series coefficients of the time-varying auto-correlation of the received signal $x(n)$ are used in the detection process.

A. Test Statistic Definition

A sub-optimal Fourier series expansion of the autocorrelation of the received signal is given by [7], [8],

$$R_x^\alpha(\tau) = \frac{1}{M} \sum_{n=0}^{M-1} x(n)x^*(n + N_d) e^{-2\pi\alpha_k n}, \quad (3)$$

where $\alpha_k = \frac{k}{T_s}$ is the cyclic frequency, N_d is the time lag in samples which is equal to m times N , m is the oversampling factor, N is the length of each OFDM symbol before CP inclusion, M is the length of signal samples considered for the detection during the sensing interval and x^* denotes the complex conjugate of x . The term $x(n)x^*(n + N_d)$, which is a complex signal is given by

$$\begin{aligned} x(n)x^*(n + N_d) &= x_R(n)x_R(n + N_d) + x_I(n)x_I(n + N_d) \\ &\quad + j(x_I(n)x_R(n + N_d) - x_R(n)x_I(n + N_d)). \end{aligned} \quad (4)$$

It is to be noted that the imaginary parts of (4) do not contribute any correlation even if $x(n)$ and $x(n + N_d)$ is correlated due to cyclic prefix insertion under the hypothesis $\mathcal{H}_1$. The operation $\mathcal{R}[x(n)x^*(n + N_d)]$ removes the uncorrelated parts from $x(n)x^*(n)$. However, though this method provides better detection accuracy when compared to ED schemes, the noise uncertainty affects its detection performance. The influence of noise uncertainty in cyclostationary spectrum sensing is less in comparison with ED . In general, the decision threshold depends on the noise variance. Any errors in noise variance estimation lead to degradation of the detection probability. Considering these aspects, the proposed scheme uses a modified version of $R_x^\alpha(\tau)$ by considering only the real parts of the complex autocorrelation and it is normalized with respect to the signal power. The proposed single cycle detection (SCD) coefficient $\mathcal{D}_x^\alpha(\tau)$ is given by

$$\mathcal{D}_x^\alpha(N_d) = \frac{\frac{1}{M} \sum_{n=0}^{M-1} \mathcal{R}[x(n)x^*(n + N_d)] e^{-2\pi\alpha_k n}}{\sigma_x^2}. \quad (5)$$

Here, $x(n)$ is the complex-valued signal, $\mathcal{R}[\cdot]$ denotes the real part of a complex number, and $\sigma_x^2 = \frac{1}{M} \sum_{n=1}^M |x(n)|^2$ is the variance of the received signal. The proposed test statistic improves the correlation between the received signal samples under Hypothesis $\mathcal{H}_1$ through $\mathcal{R}[x(n)x(n + N_d)]$. The normalization with the estimated variance of $x(n)$ alleviates the

noise uncertainty problem and this makes the decision threshold independent of noise variance. The proposed hypothesis test $T(\alpha)$ is defined as

$$T(\alpha) = |\mathcal{D}_x^\alpha(N_d)|^2 \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\geq}} \mathcal{T}_h. \quad (6)$$

Here, $\mathcal{T}_h$ corresponds to the decision threshold. In the proposed method, $\mathcal{T}_h$ is a function of the number of signal samples M and the permitted false alarm rate (P_{fa}) makes the threshold fixed at different noise levels. The detector algorithm first estimates the cyclostationary feature and the energy values from the received signal and then square of the absolute value of their ratio is compared with the predefined threshold. The analysis of the distribution of $T(\alpha)$ under $\mathcal{H}_0$ indicates that the proposed test statistic follows the same mean and variance in different noise conditions.

B. Mathematical Analysis

The performance of the proposed spectrum sensing scheme is analysed in terms of probability of false alarm and probability of detection. Firstly, the distribution of $\mathcal{D}_x^\alpha$ is analysed, then the probability of false alarm, probability of detection and decision threshold are derived from the distributions. The derivations are not included due to limited space. The mean and variance of $\mathcal{D}_x^\alpha/\mathcal{H}_0$ are given as

$$E[\mathcal{D}_x^\alpha/\mathcal{H}_0] = 0 \quad (7)$$

$$\text{var}[\mathcal{D}_x^\alpha/\mathcal{H}_0] = \frac{1}{2M} \quad (8)$$

From (7) and (8), the distribution of $\mathcal{D}_x^\alpha/\mathcal{H}_0$ is obtained as

$$\mathcal{D}_x^\alpha/\mathcal{H}_0 \xrightarrow{d} \mathcal{N}(0, \frac{1}{2M}), \quad (9)$$

where $\xrightarrow{d}$ corresponds to the convergence of the distribution function. As $\mathcal{D}_x^\alpha$ follows the complex gaussian distribution, $T(\alpha) = |\mathcal{D}_x^\alpha|^2$ follows the chi-square distribution (χ^2) with two degrees of freedom with a probability density function (pdf) $f(x) = \lambda e^{-\lambda x}, \forall x \in R^+$ and $\lambda = 2M$. Hence the PDF of $T(\alpha)$ is obtained as, $f(T(\alpha)) = 2M e^{2MT(\alpha)}$ and the probability of false alarm P_{fa} is given by

$$\begin{aligned} P_{fa} &= P(T(\alpha) \geq \mathcal{T}_h/\mathcal{H}_0) \\ &= 2M \int_{\mathcal{T}_h}^{\infty} e^{-2MT(\alpha)} dT(\alpha) = e^{-\mathcal{T}_h M} \end{aligned} \quad (10)$$

From (10), the decision threshold $\mathcal{T}_h$ for a particular false alarm rate is given as

$$\mathcal{T}_h = \frac{1}{2M} \ln\left(\frac{1}{P_{fa}}\right), \quad (11)$$

where $\ln(\cdot)$ represents the natural logarithm. The decision threshold given in (11) is independent of noise variance. Thus, it is not required to estimate the noise variance in the proposed detection algorithm.

Similarly, for the Hypothesis $\mathcal{H}_1$, $E[\mathcal{D}_x^\alpha]$, which is denoted as D_s^α , is given by

$$D_s^\alpha = \frac{1}{M} \sum_{n=0}^{M-1} \mathcal{R}[s(n)s^*(n+N_d)]e^{-j2\pi\alpha_k n}. \quad (12)$$

Also, $E[|\mathcal{D}_x^\alpha|^2]$ under hypothesis $\mathcal{H}_1$ can be written as

$$\begin{aligned} E[|\mathcal{D}_x^\alpha|^2/\mathcal{H}_1] &= \frac{1}{M^2((\sigma_s^2 + \sigma_w^2)^2)} \cdot \sum_{n=0}^{M-1} \sum_{m=0}^{M-1} e^{-j2\pi\alpha_k(n-m)} \\ &\quad E[\mathcal{R}[x(n)x^*(n+N_d)x^*(m)x(m+N_d)]], \\ &= \frac{1}{2M} + |D_s^\alpha|^2. \end{aligned} \quad (13)$$

Let us define $\mathcal{V}^2 = \text{var}[\mathcal{D}_x^\alpha(N_d)/\mathcal{H}_1] = E[|\mathcal{D}_x^\alpha|^2/\mathcal{H}_1] - |E[\mathcal{D}_x^\alpha]|^2 = \frac{1}{2M}$ and $\gamma^2 = (E[|\mathcal{D}_x^\alpha|^2/\mathcal{H}_1])^2 = |D_s^\alpha|^2$. The pdf of the test statistic $T(\alpha)$ under hypothesis $\mathcal{H}_1$ is given as [7], [8]

$$f(T(\alpha))/\mathcal{H}_1 = \frac{1}{2\mathcal{V}^2} e^{-\frac{(\gamma^2 + T(\alpha))}{2\mathcal{V}^2}} I_0\left(\sqrt{T(\alpha)} \frac{\gamma}{\mathcal{V}^2}\right) \quad (14)$$

where I_0 is the zeroth order modified Bessel function of the first kind. From (14), the probability of detection over AWGN channel can be written as [9]

$$P_{d,AWGN} = \int_{\mathcal{T}_h}^{\infty} f(T(\alpha))/\mathcal{H}_1 dT(\alpha) = \mathcal{Q}_1\left(\frac{\gamma}{\mathcal{V}}, \frac{\sqrt{\mathcal{T}_h}}{\mathcal{V}}\right), \quad (15)$$

where $\mathcal{Q}_1(a, b)$ is the first degree marcum-Q function.

The deflection coefficient (DFC), which is denoted as ρ , is a metric to evaluate the performance tradeoff of the cyclostationary detector and is defined as [8]

$$\rho = \frac{|E[T(\alpha)/\mathcal{H}_1] - E[T(\alpha)/\mathcal{H}_0]|}{\sqrt{\text{var}[T(\alpha)/\mathcal{H}_0]}} \quad (16)$$

Since DFC is the measure of the separation between two hypotheses, the decision accuracy improves with increase in DFC.

C. Computational Complexity

The computational complexity of the proposed method is analyzed in terms of real multiplications. The complexity of the proposed method is $4M + 2(N_c + N_d)$, where M is the number of signal samples, N_c is the length of the cyclic prefix and N_d is the time lag in samples. Please note that $N_c + N_d$ is much smaller than M . This is considerably lower than the computational complexity of alternative methods ($= 8M$) suggested in [7] and [8].

IV. RESULTS OF SIMULATION STUDIES

This section presents the simulation set-up and the performance comparison of the proposed spectrum sensing scheme with the existing techniques.

A. Simulation Set-up

The performance of the proposed scheme is analyzed through simulation studies. A wide-band LDACS signal of bandwidth 5 MHz is generated according to the LDACS specifications. It consists of 5 LDACS channels with a bandwidth of 500 KHz each, and their central frequencies are separated by 1 MHz. The parameters used to generate the LDACS signals are available in [3]. The prototype filter parameters are fixed for the extraction of LDACS signals from a wide-band signal of

Fig. 1. Performance comparison of the proposed spectrum sensing scheme versus energy detection [5], autocorrelation [10] and cyclostationary feature detection (CFD) schemes [8].

Fig. 2. ROC curves (P_{fa} Vs P_d) of the proposed spectrum sensing scheme versus autocorrelation based spectrum sensing and cyclostationary feature detection with different noise uncertainty levels.

interest irrespective of the total bandwidth. The interpolation factor and the masking filter design need to be adjusted according to the number of channels. This design improves the reconfigurability feature of the detection hardware. Also, this optimization in the design topology reduces the complexity in hardware implementation. Once the individual channels are filtered, the proposed spectrum sensing scheme is applied for the decision making. For other signal processing aspects of the proposed spectrum sensing scheme, please refer the Section III-A.

B. Performance Analysis

The detection performance of the proposed spectrum sensing scheme is analyzed and the overall performance is benchmarked against existing methods. The probability of detection is plotted by fixing the probability of false alarms to a particular value ($P_{fa} = 0.1$).

The detection performance comparison of the proposed scheme against the conventional schemes is shown in Fig.1. The analysis also considers the effect of noise uncertainty and SNR. Results show that the proposed scheme gives better detection accuracy than conventional schemes [7], [8], [10]. The probability of detection of ED suddenly drops at SNR=-6

Fig. 3. Deflection coefficient analysis of the proposed scheme versus cyclostationary feature detection scheme [8].

dB with only 10% of noise uncertainty. Though conventional CFD scheme provides relatively better detection accuracy compared to ED scheme, its performance also degrades with errors in noise variance estimation. Fig. 6. presents the receiver operating characteristic (ROC) curves. The performance comparison of the proposed scheme against the conventional CFD scheme [8] and the autocorrelation based scheme [10] is shown in this figure. The effect of noise uncertainty in the detection performance has also been investigated. The trend shows that the performance is degrading when the noise uncertainty increases. The DFC analysis of the proposed scheme and the conventional CFD schemes is given in Fig. 3. It is noticed that the DFC increases with the increase in SNR. The rate in which the DFC of the proposed scheme increases is higher compared to the conventional CFD scheme. It indicates that the proposed scheme discriminates the hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$ more accurately than the conventional CFDs.

V. CONCLUSIONS

The spectral efficiency of the LDACS can be upheld by the dynamic access of the frequency bands in an opportunistic manner. The implementation of onboard systems with dynamic frequency access requires computationally intensive techniques. In this paper, a low complexity cyclostationary detection based spectrum sensing scheme is proposed for LDACS channels to find the spectral holes. Results show that the proposed scheme outperforms the existing spectrum sensing schemes. Results also indicate that the fading does not affect the detection performance due to the direct line of sight component. It is also observed that the proposed scheme could able to overcome the problem of noise uncertainty in wide SNR range. Finally, the simulation model substantiates the compliance of the proposed scheme for wideband spectrum sensing.

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