PERFORMANCE EVALUATION OF A SPECTRUM-SENSING TECHNIQUE FOR LDACS AND JTIDS COEXISTENCE IN L-BAND

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ABSTRACT

This paper deals with a cognitive approach able to guarantee the coexistence of new data link for air-ground aeronautical communications LDACS and military JTIDS systems. Future LDACS shall coexist with current systems operating in the same frequency band for this reason coexistence issues must be carefully investigated. In particular JTIDS transmissions can affect the LDACS performance acting as disruptive impulse noise. JTIDS exploits frequency hopping to protect information, hence its interference on LDACS system cannot be foreseen and avoided. In addition the bandwidth of the two signals results to be completely overlapped in case of collision. The disruptive effects of JTIDS interference on LDACS can be mitigated if the collisions can be detected and hence suitable processing techniques can be activated. This paper proposes a method to detect the presence of JTIDS interference exploiting an energy detection spectrum sensing technique based on sliding windows and packets retransmission. The performance of the proposed method is presented in terms of missed detection probability of the JTIDS interference and error rate of the LDACS system showing a significant capability to counteract JTIDS interference.

1. INTRODUCTION

The increasing demand for advanced communication services in civil aviation leads to the need for a new management and communication framework able to support the capacity and security requirements of the air transportation system [1]. The European project SESAR (Single European Sky ATM Research) aims to develop and validate a new communication system capable of satisfy the requirements specified in Communication Operating Concept and Requirements (COCR) document [2].

Since the COCR operational requirements cannot be fulfilled by a single technology, the Future Communication Infrastructure (FCI), constituting the communication part of the framework, will be implemented as a system of systems, integrating existing as well as new communication technologies. The FCI should support both digital voice and data communications. Particular emphasis is given to the data, since in case of failure, voice would not be able to maintain the operations with the same reliability.

Since the VHF frequencies are congested, the communication system in charge of supporting the air/ground data link will operate on the aeronautical L-Band (960-1213 MHz) and it will be named L-Band Digital Communication System (LDACS). This technology is currently under development and, at the present time, two options have been identified. LDACS1 is the former option. It is a Frequency Division Duplex (FDD) system exploiting the OFDM (Orthogonal Frequency Division Multiplex) technique, that is very effective against the inter symbols interference. The latter option, LDACS2, is a Time Division Duplex (TDD) system utilizing the CPFSK (Continuous-Phase Frequency-Shift Keying) modulation, that allows to reduce the out-of-band emissions. At the end of the SESAR program studies one of them will be selected as the key technology for air/ground communications. This work focuses on LDACS1.

LDACS will operate in the L-Band where several legacy systems are already present (e.g., DME, SSR, UAT, JTIDS/MIDS), hence the spectral compatibility is an important issue that needs to be addressed. In particular in this paper we consider the coexistence between LDACS1 and the Joint Tactical Information Distribution System (JTIDS), also known as Multi-functional Information Distribution System in the NATO implementation.

JTIDS is military system used for several purposes, like identification in surveillance and mission management. It exploits an impulsive signal and frequency hopping, in order to make the system interference-tolerant.

Unfortunately the frequency hopping is performed on a large range of frequencies spanning almost the whole L-Band, hence the probability to have collisions between the LDACS and the JTIDS signals is very high.

Since LDACS is an OFDM system and the decoding is performed in the frequency domain, the impulsive noise affects all the bits carried by the interfered OFDM symbol. This represents an advantage until the power of the interference does not exceed a certain threshold [3], but it becomes very disruptive since leads to high error probability on each OFDM subcarrier. The problem of impulsive interference in OFDM system is a known problem in Power Line Communication (PLC), where the man-made noise, as the turning on/off of an electrical switch, can deteriorate the performance. This topic has only recently been investigated in wireless networks context, where the co-channel interference can assume an impulsive nature. The solutions available in the literature deal with non-linear elaborations of the interfered signal through clipping or blanking schemes [4]-[6]: when the received signal amplitude exceeds a certain threshold the signal level is set to the threshold value or to zero, respectively. Another interesting solution relies on a close loop scheme based on data detection and successive noise estimation and reduction [7]. Unfortunately this scheme has a high computational cost. However, none of these methods takes under consideration any advanced technique to distinguish which samples are affected by interference.

Coexistence between systems through spectrum sensing is a typical topic of the Cognitive Radio networks, where an unlicensed (Secondary) system coexists with a licensed (Primary) system in a transparent manner: the Secondary user's radio identifies the free frequency channels for secondary usage and transmits in these frequencies in a non-interfering manner. The scenario considered in this paper is different: sensing operation is used to detect the presence of the JTIDS signal and then to perform suitable operations at the receiver side. In particular the proposed scheme is based on energy detection and packets retransmission. The energy detector is a well-known sensing algorithm that allows the detection of interfering signals with low complexity and works well when the interference features are not known. In our scheme sensing operation is combined with packets retransmission and is performed by exploiting two signal replicas in order to have a more efficient detection. Furthermore the replicas are combined to improve the signal detection after an interference blanking.

The paper is organized as follow: Section 2 presents the system model and Section 3 provides an analytical evaluation of the impact of JTIDS system on LDACS performance. Section 4 presents the proposed scheme while in Section 5 the numerical results are shown and in Section 6 the conclusions are drawn.

2. SYSTEM MODEL

In the scenario under consideration the LDACS and JTIDS systems operate in the same area and LDACS frequency band is part of one of the hopping bands used by JTIDS.

We considered a system where LDACS operates within one of the band used by JTIDS, so, due to the frequency hopping technique adopted by the latter, occasionally the two systems interfere each other. In particular, LDACS exploit OFDM modulation technique, where the data stream is divided in many orthogonal sub-streams, referred as sub-carriers, each one with reduced rate. This allows to reduce the negative effects of Inter Symbol Interference (ISI) without decreasing the total data rate. According to the latest specification in [8], the total LDACS available band is equal to B_{LDACS}=498.05 kHz, that is oversampled with sampling rate f_s=625 kHz. This spectrum is divided in N=64 subcarriers, of which only 50 are active. In addition, a cyclic prefix (CP) with duration equal to 11 samples is inserted in order to avoid ISI. In the considered system each active subcarrier is modulated following a QPSK scheme. The LDACS main parameters are outlined in Table 1, where t_s is the sampling period, Δf is the frequency spacing between two contiguous subcarriers and T_u, T_g and T_{TOT} are the useful symbol time, the guard interval duration and the total OFDM symbol duration, respectively.

B_{LDACS}	498.05 kHz	**N**	64	**T_u**	102.4 µs
f_s	625.00 kHz	**CP**	11	**T_g**	17.6 µs
Δf	9.76 kHz	**t_s**	1.6 µs	**T_{TOT}**	120.0 µs

Table 1: LDACS system parameters

JTIDS exploits the TDMA (Time Division Multiple Access) technique [9]. The transmission in each time slot is composed by a minimum of 258 pulses of duration T_p=6.4µs and spaced by T_i=6.6µs. The active part of each pulse is multiplied for a spreading sequence containing 32 chips modulated through a CPFSK scheme and representing a combination of 5 informative bits: in particular, JTIDS specifies only one spreading sequence and the particular combination of informative bits introduces a circular offset in that. The chip duration is equal to T_{chip}=200 ns and hence the signal bandwidth is equal to 5MHz. However, since the JTIDS system operates in a large range of frequencies, [960 - 1215] MHz, divided in bands of 3 MHz, the signal is filtered to fit the bands. Each pulse is transmitted on a different frequency according to a certain hopping sequence. In particular there are N_{ch}=51 possible carriers. Since the hopping sequence is a classified information, in our model we assume every carrier has the same probability to be selected, hence we consider a hopping pattern randomly generated with uniform probability on all frequencies. Considering that the LDACS spectrum is

significantly smaller than the JTIDS bands, for the sake of simplicity we can assume it is completely contained in one of the these bands. This means that only one hopping frequency affects the LDACS signal but on the whole spectrum. Finally, since the JTIDS sampling rate is much higher of that of LDACS, the JTIDS signal is down-sampled. This makes the interference even harder to be detected, since the signal power is spread on a longer period.
We assume both the signals (LDACS and JTIDS) are transmitted on fading channels and AWGN noise is added at the receiver. Fading coefficients are modeled as random variables with Ricean distribution, with Ricean factor equal to K=4 dB and normalized power.

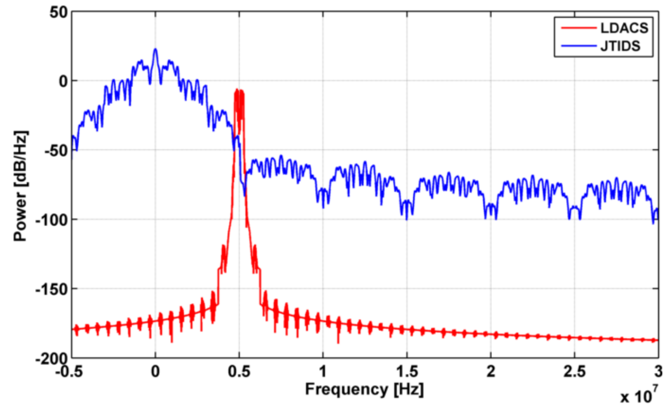

Figure 1 JTIDS and LDACS spectra with a frequency offset equal to 5 MHz

3. ANALYTICAL INTERFERENC EVALUATION

The development of a new system operating in a frequency band densely populated by legacy systems introduces the need of a careful evaluation of coexistence issue. The joint representation of the frequency domain signals of different systems operating on the same band gives a qualitative evaluation of the mutual interference permits to put in evidence potentially critical scenarios. For this reason we give a joint representation of JTIDS and LDACS spectrum in nominal band and in Out of Band and Spurious Domain. The signals have been generated in Time Domain (TD) taking into account the standards mandatory features [8],[9] that directly affect the spectrum shape. For LDACS1, an OFDM signal with 64 subcarriers has been generated in FD and transformed in TD by means of a IDFT (Inverse Discrete Fourier Transform). Then a raised cosine window that aims to reduce out-of-band radiations has been applied. Later, the signal has been transformed in FD and filtered with the spectral mask. For JTIDS an impulse of 6.4µs duration has been produced and modulated with a spreading sequence of 32 chips each of 200ns duration and CPFSK modulated. Once transformed the signal to FD, the spectrum mask has been applied. Figure 1 shows LDACS and JTIDS power spectra when an offset (*Δf*) of 5 MHz is assumed between the central frequencies of the two systems. It is evident that the JTIDS spectrum heavy interferers with the LDACS due to its high transmission power. It can be noted that the results are similar even with higher frequency offsets (i.e. translating the LDACS spectrum).
To quantify the effect of the interference a numerical analysis can be performed. The aim is to identify the conditions that permit to LDACS to operate in presence of JTIDS interference. The analysis consists of the computation of the interference power level at the victim receiver and on its comparison with the maximum tolerable interference power level obtained from a protection criteria typically the minimum Carrier to Interference ratio (C/I).

The analysis follows the procedure defined in the CEPT MCL (Minimum Coupling Loss) method [10]. The interference level is obtained by means of a link budget (1) that depends on different parameters, as frequency separation and distance:

$$I(d, \Delta f) = EIRP - PL(d) + Grx - Lrx + OCR(\Delta f) + DC \quad (1)$$

where:

- *EIRP* is the JTIDS Equivalent Isotropically Radiated Power;
- *PL(d)* is the free space path loss;
- *Grx* e *Lrx* are the LDACS receiver antenna gain and cable loss, respectively;
- *OCR(Δf)* (Off Channel Rejection) is a term that takes into account the ability of the victim receiver to reject the interferer signal. It depends on the power spectral density of the interferer and on the frequency separation between interferer and victim [11].
- DC is a term that takes into account the interferer duty cycle. For JTIDS, it depends on the Time Slot Duty Factor (TSDF) that represents the maxim number of slots assigned to an user in a frame.

From this analysis it is possible to determine the minimum distance between the interferer and victim equipment at which the interference results to be tolerable. The coexistence between the two systems is guaranteed if this distance is lower than the minimum operational distance: in a rough evaluation we can consider the minimum operational distance equal to the minimum vertical separation of the aircrafts: 300mt (on the ground this distance is lower).
The results of the analytical analysis are shown in Table 2 in a worst case assuming the following working hypothesis:

- Parameters of the link budget as antenna gains and cable losses are varied according to the scenario taking into account typical values for ground or aircraft installations;

- The ratio C/I is fixed to 10 dB, in according to B-AMC (Broadband Aeronautical Multi-carrier Communication) specifications, from which LDACS has been derived, since this value is not available in the current LDACS specification.
- The value of maximum interference power acceptable is obtained from C/I ratio assuming the carrier power equal to receiver sensitivity.
- The JTIDS transmission power is fixed to 1000 W.
- TSDF is set to 50% and 5% that represent the maximum and minimum values.

	Scenario	**Non Interfering Distance**	
		TSDF=50%	**TSDF=5%**
1	Ground Station to Airborne Aircraft	d > 500km	d > 157km
2	Airborne Aircraft to Airborne Aircraft to	d > 500km	d > 500km
3	Airborne Aircraft to Ground Station	d > 500km	d > 260km
4	Ground Station to Ground Station	d > 500km	d > 500km
5	Aircraft on the Ground to Aircraft on the Ground	d > 26.6km	d > 18.5km
6	Ground Station to Aircraft on the Ground	d > 500km	d > 162km
7	Aircraft on the Ground to Ground Station	d > 46.5km	d > 25.5km

Table 2: Analytical Evaluation Results

These results show that minimum distance that allow the spectral compatibility is considerably higher than the minimum operational distance in all scenarios, therefore the problem of the interference of JTIDS transmission on LDACS1 requires the application of some countermeasures to ensure the coexistence between the two systems.

4. INTERFERENCE SENSING AND MITIGATION

In this Section the proposed sensing and mitigation scheme is explained. The basic idea is the retransmission of the Packet Data Unit (PDU) when the presence of JTIDS system is detected (it can be done through a first sensing phase).

The first copy of the packet is stored and combined with its retransmission: since JTIDS and LDACS transmissions are independent processes, even if both the copies of the PDU are affected by JTIDS interference with high probability different portions of the PDU are corrupted. Packet combining is used either to improve interference detection and signal decoding.

Interference detection aims to detect with significant reliability which samples of the PDU are affected by interference. This is done through the energy detector, that is a particular spectrum sensing algorithm which computes the energy of the received samples during a time interval called sensing period. This detector is well-known in the Cognitive Radio networks, where a secondary unlicensed user (SU) looks for spectrum holes that are not used by the primary licensed user (PU). Free spectrum portions can be used by the SU for transmission. Energy detector provides the test statistic (i.e., the energy of the signal coming from the sampler) used to decide between two binary hypothesis: the channel is free and only thermal noise is present or primary user signal plus noise is present. Accuracy of energy detector is proportional to the duration of the sensing period: increasing the number of collected samples is possible to improve the performance. The interference detection proposed here is slightly different: in our system the goal is to detect which samples are corrupted and not only if the interference is present. It means that the sensing period must be limited: differently from traditional approach increasing the sensing period does not leads to a performance improvement, since the energy of the pulse is spread on a longer interval making more difficult to discriminate which samples are affected.

For this reason we introduce a modified energy detector that exploits a sliding window which collects the energy of a part of the received signal.

In addition the interference detection is not performed on the received signal but on a sample by sample difference between the two copies of the signal that have been previously equalized to remove the channel effect.

This permits to reduce the false alarm probability due to by the a high peak to average ratio (PAPR) that characterizes the LDACS (i.e. OFDM) signal: the difference between the two replicas depends only on the JTIDS interference and noise power; the LDACS signal fluctuation does not affect the detection procedure.

Assuming a perfect channel equalization, the received signals difference on the *i*-th sample is:

$$\Delta r[i] = r_1[i] - r_2[i] \tag{2}$$

where $r_k[i]$ is the *i*-th received sample of the *k*-th PDU transmission (k=1,2).

The *n*-th output of the sliding window energy detector is the test statistic T_n:

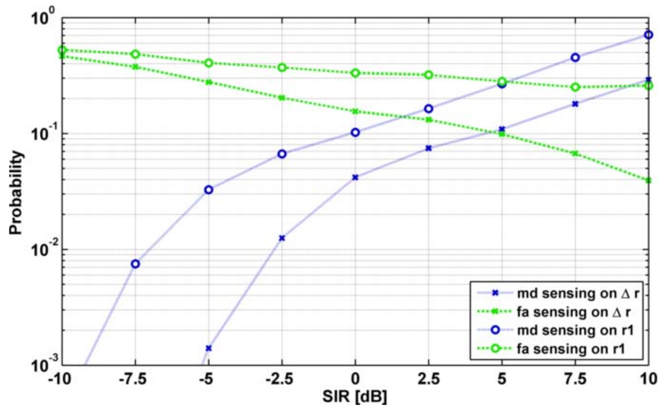

Figure 2 False alarm and miss detection probability for the proposed method and traditional sensing

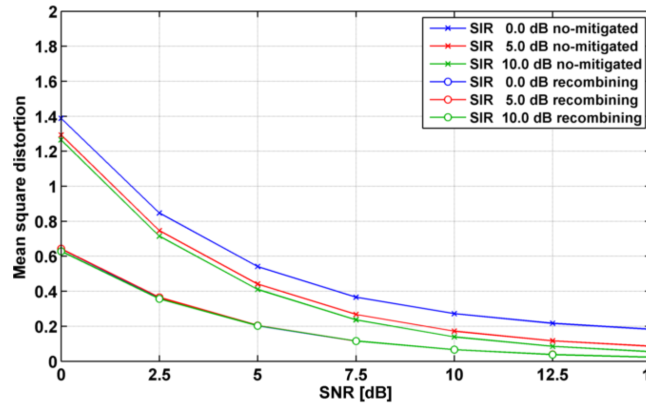

Figure 3 Mean square distortion of the received signal and the signal after the interference mitigation

$$T_n = \sum_{i=n-\frac{W}{2}}^{n+\frac{W}{2}} a_i \left\| \Delta r[i] \right\|^2 \tag{3}$$

where W is the window width and a_i are the window weights (weights are selected in order to give more importance to central samples).

If T_n exceeds a certain threshold interference is supposed to be present in the sample n-th.

The window length depends on the duration of the interfering signal that cannot be exactly known because the pulse is filtered by the receiver, however a rough estimation of the JTIDS signal duration can be calculated as $L = T_p/f_s = 4$ samples, where f_s is the sampling frequency and T_p the pulse duration. We adopt a windowing size, W, equal to $L + 1$ samples. A further improvement to reduce the false alarm probability is obtained by observing M consecutive test statistics: if at least $M=L-1$ consecutive samples are over the threshold we assume the interference is present.

Observing the retransmissions difference is possible to know which samples are affected by interference but it is not known if the interference is introduced by the first, $r_1[n]$, or the second $r_2[n]$ copy of the received signal.

Indicating as n_i, with $i = 0,\ldots, I-1$ the samples affected by the interference, for each n_i the values of $r_1[n_i]$ and $r_2[n_i]$ are compared: the maximum is blanked while the minimum is doubled. The resulting signals are summed together, and the final signal can be expressed as:

$$r'[n] = \begin{cases} r_1[n] + r_2[n] & \text{if} \quad n \neq n_i \quad \forall i \\ 2r_1[n] & \text{if} \quad r_1[n] < r_2[n] \quad \text{and} \quad n = n_i \\ 2r_2[n] & \text{if} \quad r_2[n] < r_1[n] \quad \text{and} \quad n = n_i \end{cases} \tag{4}$$

Demodulation and decision are taken on r' signal.

5. NUMERICAL RESULTS

This section shows the numerical results obtained to validate the proposed scheme by resorting to computer simulations.

We start our analysis by evaluating the performance of our interference detection method. The main drawback of this method is the higher noise power, since by considering the difference between two signal copies the noise power is doubled. On the other hand, it does not suffer the presence of the LDACS signal as traditional method. Figure 2 shows the comparison of the false alarm (*fa*) and miss detection probabilities (*md*) between our detection technique based on difference between two signal replicas (Δr) and the same sensing technique performed on one signal (r_1) when the SIR (Signal to Inference Ratio) varies. Looking at this figure we can see that by exploiting the two signal replicas it is possible to get a significant improvement for both false alarm and miss detection probabilities.

In order to evaluate the behavior of the mitigation scheme, we define the performance index D as the mean square distortion of the signal.

$$D = \frac{1}{P} \sum_{p=0}^{P-1} \left| r'[p] - s[p] \right|^2 \tag{5}$$

Figure 3 presents the distortion of the received signal and the reconstructed one, when the SNR varies and for different SIR values. From this figure we can see that the proposed scheme is able to significantly decrease the distortion of the signal for the considered SIR values. In particular, the residual distortion is due to the AWGN noise.

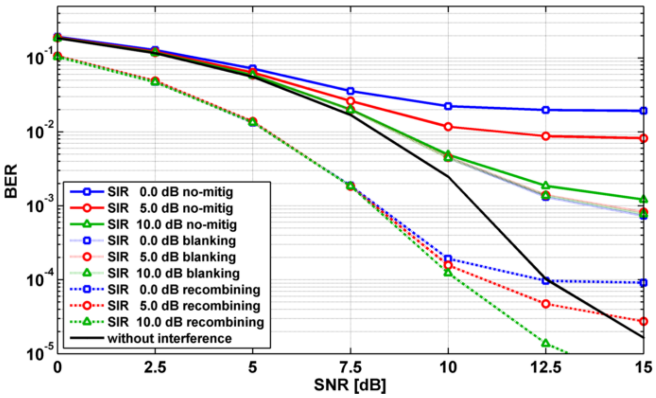

Figure 4 BER performance of the system without channel coding when interference is not mitigated and when blanking and the proposed technique are applied

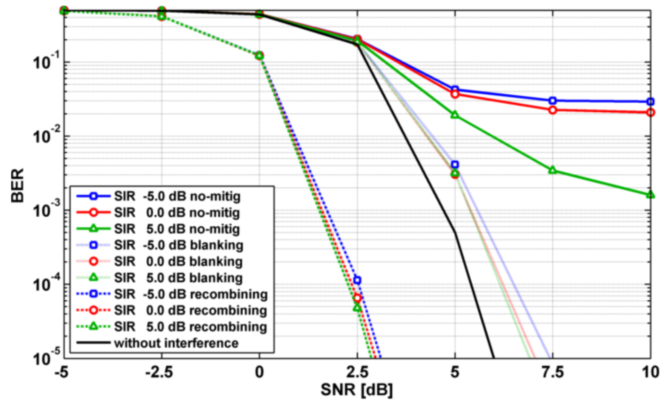

Figure 5 BER performance of the system with channel coding when interference is not mitigated and when blanking and the proposed technique are applied

This means that the presented mitigation scheme is able to reject the interference made by JTIDS and to bring an additional gain of 3 dB due to the soft combining of the packet's replicas.

The good behavior of the proposed scheme is even more evident in terms of BER (Bit Error Rate). When the interference is high the BER gain permits to counteract the reduction of throughput introduced by the retransmission assuring more reliable communications. Figure 4 represents the BER when the QPSK modulation is used for different SIR values and when the SNR varies. In this figure the proposed scheme is compared with traditional blanking method and the case without any elaboration. We can see that interference leads to a floor of the BER: this means that the performance does not improve even when the SNR gets higher. Even traditional blanking does not allow to reach satisfying performance. On the other hand, when the proposed scheme is applied we have excellent results: the performance shows the interference is almost completely removed and we have an additional gain of about 3 dB due to the soft combining of the packets. For high signal to noise ratio even the performance of the proposed method reaches a floor, due to those samples affected by interference in both the signal replicas. However this drawback is overcome when the channel coding is considered: Figure 5 shows the same performance of the previous case but considering the channel coding envisaged in LDACS specifications. In particular we considered an inner convolutional coder with coding rate equal to 1/2, an interleaver and an outer Reed-Solomon coder. We can observe that the floor concerns only the performance of the system when mitigation is not applied. Here the performance of the proposed scheme clearly overcome the traditional blanking solution. We can note from the previous results that performance does not depends on the considered SIR: when the interference power is very high it is easy to be detected and removed, while when the JTIDS signal strength is low it becomes more difficult to detect but it has also a lower impact on performance.

6. CONCLUSIONS

In this paper we proposed a novel scheme for impulsive interference detection and mitigation in the new LDACS system. The proposed method is based on interference detection and packet retransmission: by exploiting the difference between the signal replicas affected by two independent interference realizations it is possible to improve the interference detection, since it does not depend on the useful signal. Furthermore, the two signal copies can be used to reconstruct the useful signal, decreasing the distortion and the system bit error rate.

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