The Transponder Data Recorder: first implementation and applications

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***Abstract*—The Transponder Data Recorder is an experimental 1090 MHz signal acquisition system designed by the Radar and Navigation group at Tor Vergata University to record the signals in the Secondary Surveillance Radar band, centered at 1090 MHz. The peculiarity of the receiver is that it is based on five receiving chains (4 linear chains with large dynamic range and one with a logarithmic receiver) connected to a wideband linear array antenna. The TDR was developed in order to analyze the channel traffic and to test the new signal processing algorithms, in the research frame on multilateration (MLAT) and Automatic Dependent Surveillance (ADS-B), with real signals.**

Keywords- Mode S, Multilateration, signal processing

I. INTRODUCTION

Today the 1090 MHz channel, exploited first by the military IFF (Identification Friend or Foe) systems and then by the secondary surveillance radar (SSR) [1], is widely used for air traffic (but also in airport for vehicular traffic) surveillance. In this context there are many applications that use the 1090 MHz signals. Some of these, such as ADS-B and Multilateration, are becoming increasingly important within the air traffic control, and may integrate or, in some cases, replace the SSR radar stations. For these reasons the integrity and the efficiency of these systems have become very important. In a typical high-density airspace, an increasing number of transponders (airborne or vehicular) transmit signals at 1090 MHz, either as replies to the SSR stations (conventional and Mode S), or spontaneously ('Squitter'). Also in the future the burden of the channel may be increased by the TIS-B stations, which provide information on non-ADS-B aircraft using Mode S signals. In order to reduce the effects of receiving superimposed signals from different sources, we studied signal processing algorithms, useful to discriminate and separate overlapping sources; some of these algorithms need a multichannel receiver and an antenna array [2]. Hence the need for a 1090 MHz signals acquisition system with appropriate characteristics, useful to evaluate the efficiency of the separation algorithms using the received signals, and also to compute traffic analysis and statistics. This paper presents a description of this system, called TDR (Transponder Data Recorder), complying with ICAO and RTCA requirements [3],[4]. It has been designed and developed by the Radar and Navigation group, RadarLab, at Tor Vergata University. Based on the RadarLab requirements, the array antenna has been designed, realized and tested by the Microwave Laboratory at the University of Calabria, Rende (CS), Italy. The design of the antenna, the analogue front-end and the digital section as well as the results from the first use of TDR, with the analysis of the 1090 MHz channel around the experimental area (i.e. the Tor Vergata University area) are presented. Moreover we analyze the signals density and present the statistics of each signals type (conventional, Mode S), and finally the statistics of overlapping signals. Finally, we present the results of tests of the preliminary application of the separation algorithms on the recorded signals and the proposal for future work and conclusions.

II. TDR DESIGN

The research requirements have driven the design of the TDR. In order to use decoding algorithms based on array processing [6], the selected type of the antenna is a uniform linear array, with 6 elements. The analog part is composed by four receiving chains, connected to the four central elements of the array, and one logarithmic receiver connected to a side element of the array (the other side element is connected to a 50 Ohm load). The logarithmic channel is to be used for (a) Reply detection, (b) Evaluation of compliance of the pulse. The digital section must sample the channels with a shared clock, and it has to reach high sampling rate (up to 100 MS/s) to perform the better phase estimation between the channels.

A. *Antenna*

Figure 1. Photograph of the six elements array

The antenna was developed by Università della Calabria, Microwave Lab [5]. It is a six patch elements on a stratified dielectric support. A half wavelength spacing between the elements and a linear vertical polarization have been chosen. The antenna has a pattern of each array element wide enough in both directions in order to cover the air traffic and the surface traffic, and it is possible to obtain a bandwidth of 30 MHz, needed to maintain the fidelity in signal analysis.

B. *Analog front-end*

The analog section has a dynamic range of 70 dB , figure 3 shows a schematic of the TDR analog section with the four linear receiving chains and the logarithmic receiver. The low-noise amplifier (LNA) permits a good noise figure (0,8 dB) and a total gain of 60 dB. The RF filters are Surface Acoustic Wave type (SAW), with a bandpass of 50 MHz. The IF (Intermediate Frequency) is 21.5 MHz and the output of the IF section is filtered with a band-pass filter and a DC-block. The variable attenuator (in steps from 0 dB to 16 dB) is useful to shift the dynamic range in order to use the TDR in an aeroportual area, or in a wide area.

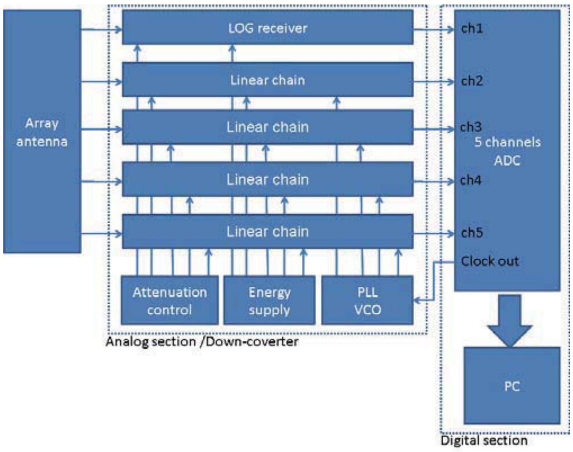


Figure 2. TDR blcok scheme

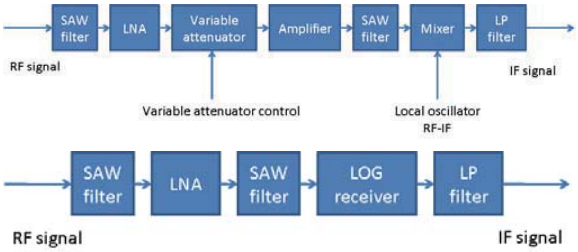


Figure 3. linear and LOG channel - analog section

The signal at 1065 MHz, used for the frequency down-conversion in the mixer, is generated by a PLL that use a 10 MHz clock as a reference. The reference clock is obtained by an internal quartz oscillator, otherwise it should be taken by the digital section, obtaining a clock sharing between the analog and digital section. The logarithmic receiver has an RF input linear dynamic range of 60 dB, and it is preceded, as for the linear chains, by the filtering and LNA stage and by the variable attenuator. The analog section also provides a 1090 MHz signal for test and calibration purpose.

C. *Digital section*

The digital section for the whole system provides a high sampling rate, up to 100 Msamples/s with a 14 bit resolution. To acquire the linear channel directly at IF the sampling frequency is set at 100 Msamples/s. It is based on the NI PXI 1082 controller. There are three acquisition cards by National Instruments (NI PXI 5122), with two analog input channels each. Figure 3 shows the NI digital section front view: on the left there is the input/output controller, on the right there are the three acquisition devices, each with two analog input and the trigger input.

Figure 4. NI PXI digital section

The digital section share a common clock reference that should be used as phase locked loop (PLL) reference for the analog section. The embedded work suite permits the development of acquisition software.

III. 1090 MHz CHANNEL ANALISYS

The first TDR implementation is a prototype version composed by a one channel receiver. The receiving chain is splitted before the IF down-conversion to get the LOG channel. Figure 5 shows the front panel of the TDR prototype, figure 6 shows the receiver block scheme.

Figure 5. TDR prototype front panel view

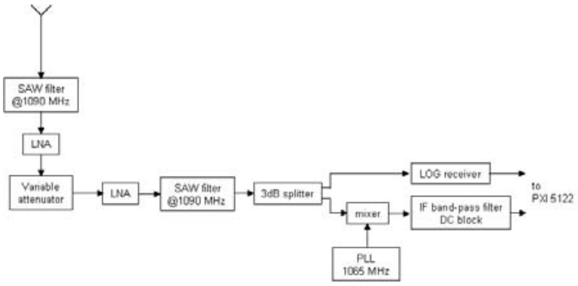


Figure 6. TDR prototype block scheme

Using the TDR prototype, connected to one element of the antenna, it was possible to record the data stream (at 10 Msamples/s) to perform a channel traffic analysis. The results allow traffic statistics related to the area around the installation site. The antenna was positioned in Tor Vergata University on the Engineering Faculty building roof, as shown in figure 7. The location is near Rome, close to Ciampino airport and 30 Km away from the International airport of Fiumicino.

Figure 7. TDR antenna location

The recording session was developed on Thursday 14th April 2011 at 01 p.m.. Up to 10 data streams of 1 *s* was recorded time continuously. The starting time of each acquisition was chosen random in order to avoid a synchronization with the traffic due to ground radar interrogations. An analysis of the received signals power, considering the receiving chain gain, the antenna gain and the transmitting power, permits to obtain the range distribution of aircraft, which transmitted the received signals. Figure 8 show that a large part of the received signals was transmitted from a range between 40 – 80 km.

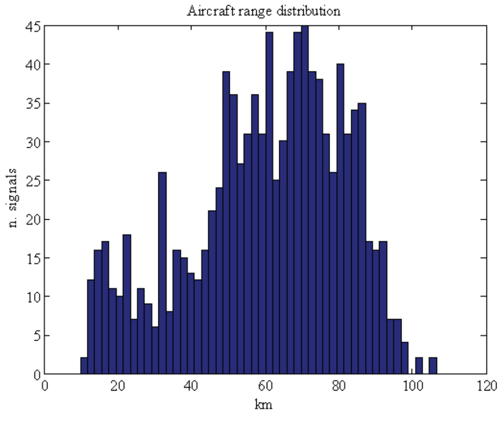


Figure 8. Aircraft range distribution

Besides a traffic analysis was done, using a software developed at RadarLab, capable to detect and decode SSR replies using ICAO and RTCA compliance algorithms. The analysis was useful to count the number of conventional and mode S messages for each data stream, and also to compute the number of overlapping signals.

Table I shows the result of this analysis on the recorded signal segments:

TABLE I. SIGNALS SEGMENTS STATISTICS

Stream No.	**Received SSR replies**		
	# conventional	***# Mode S***	***# garbled Mode S***
1	859	128	5
2	1155	130	12
3	717	62	6
4	790	99	7
5	1143	92	8
6	990	95	13
7	1236	76	7
8	1695	116	16
9	921	86	4
10	756	57	3
mean	1026	94 (8%)	8 (8.5%) of Mode S

From table I, the percentage of Mode S signals over all the received signals is 8%. A percentage of 8.5% of the Mode S replies are affected by interference with other signals. To better understand these results, it is possible to note that the probability to receive a 1090 squitter (ES) free of interferences using an omni-directional receiver, is estimated by a poissonian model with λ (FRUIT rate) equal to the inverse of the average number of received messages per time [6]:

$$P_{ES}(0) = \exp\left(-\lambda t_{ES}\right) = 0.93$$

where t_{ES} = 120 μs, λ= 1026 s^{-1}. Hence the estimated probability to receive garbled Mode S signals is 7%, the value being close to the experimental rate. An exhaustive measurements campaign, at different time each day, permits to evaluate the channel traffic density near Rome. This earlier result shows that although the FRUIT rate is low, the probability to receive interfered mode S signals is not negligible.

IV. PASA APPLICATION WITH TDR DATA

Using the TDR prototype it is also possible also to test the processing algorithm for overlapping signals discrimination described in [6], where PASA algorithm is proposed for a blind source separation using one channel data. Figure 9 shows a recorded signal with two overlapping Mode S short signals (IF signal by linear channel), with different amplitude: a typical input for PASA algorithm. The signals used for PASA evaluation were sampled at 100 Msamples/s, in order to have more samples to be used for the de-garbling algorithm. PASA method permits to perform overlapping sources separation exploiting the signals diversity. The array processing methods PA and EPA presented in [2], permits the sources separation exploiting the signals direction of arrival as signals diversity, using an array antenna and a multi-channel receiver. PASA method is based on a signal vector reshaping useful to reorganize the acquired signal samples into a matrix. The idea is to apply PA or EPA onto the reshaped matrix exploiting as signals diversity, not the direction of arrival (that is not recoverable using a single antenna), but the signals frequency. Applying PA or EPA to the data matrix, the mixing matrix and its mixing vectors are estimated. The beamformers of each source is obtained by the pseudo-inverse of the mixing matrix. Applying the data matrix on the beamformers two sub-matrix are computed: one containing the first source, the other containing the second source. To recover the separated signals an inverse re-shaping is applied on the two sub-matrix obtaining the signal vectors.

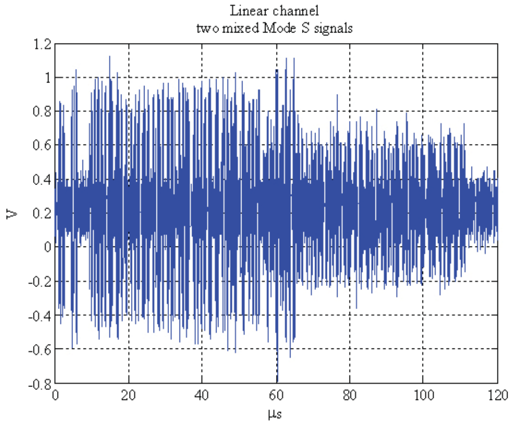


Figure 9. Two Mode S signals mixing (IF linear channel signal)

Figure 10 shows the results of the application of PASA on the signal shown in figure 9. In this case two overlapping Mode S signals was received, the time delay between the signals is approximately of 46 μs, and the power of the second source is less than the first (i.e. it was emitted by a further aircraft than the other). The application of PASA permitted to recover the original two signals, as shown in figure 10 where the envelope of the signals is depicted. The blue line is the first mode S signal, the red one is the second mode S signal. The separated signals are affected by an irregular pulses power behaviors.

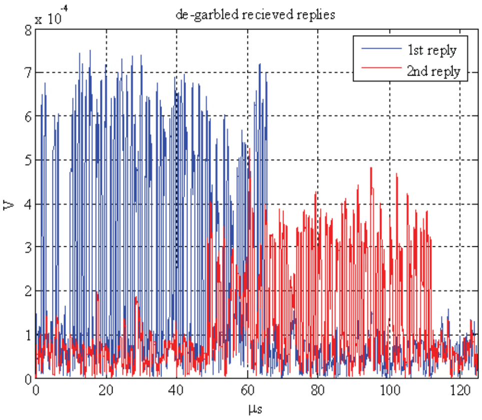


Figure 10. Sources signals de-garbled (Envelope signal)

In order to reconstruct the replies, a final stage with a bandpass filter (B=10 MHz) centered at the TDR IF frequency (21.5 MHz), followed by a threshold comparator with 2 levels quantization is used. Figure 11 shows the output of the final stage delivering the reconstructed replies.

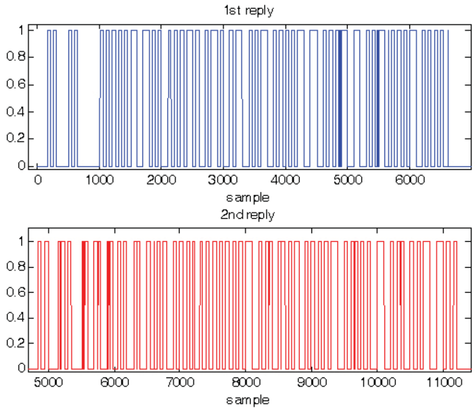


Figure 11. Reconstructed replies

These preliminary results are also confirmed by an application of PASA algorithm with another overlapping signal recorded by TDR. In figure 12 it is possible to see the IF sampled signal and in figure 13 and 14 the degarbled and reconstructed signals respectively.

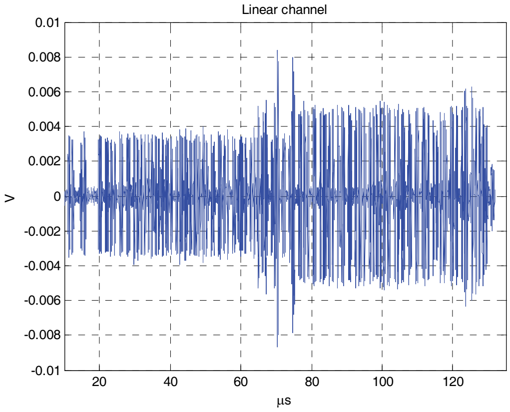


Figure 12. Two Mode S signals mixing (IF linear channel signal)

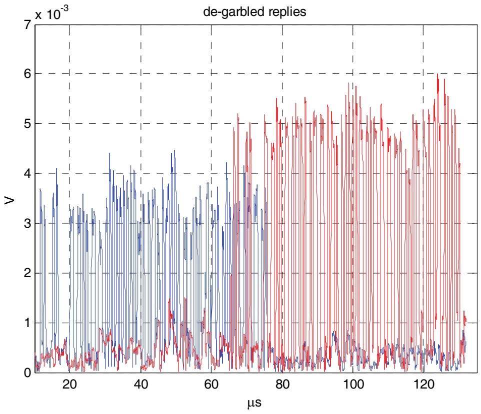
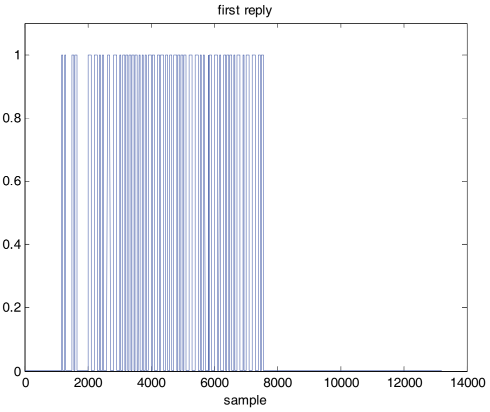


Figure 13. Sources signals de-garbled (Envelope signal)



These results with real data confirms the trials done in [6] and puts the basis for an extensive acquisition campaign useful to measure the effective performance of the algorithm in a real environment.

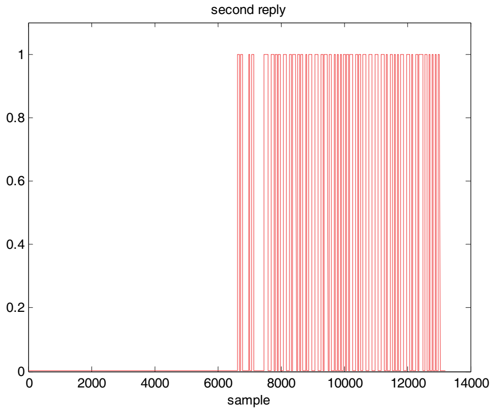


Figure 14. Reconstructed replies

V. CONCLUSIONS AND FUTURE WORK

The transponder data receiver (TDR) is a multi-channel system useful to receive, record and process 1090 MHz signals from airborne and vehicular transponders (Mode S and conventional). It is composed by a six patch elements array antenna, connected to the 4 linear channel and to a logarithmic receiver. The digital section is based on NI technologies. The TDR system was designed in the research frame on the ADS-B/MLAT to develop and test new signal processing algorithm, and to analyze the 1090 MHz channel traffic. Actually a prototype system based on a single channel receiver is operative at Tor Vergata University. The prototype is composed by a single RF channel divided into a linear channel, directly sampled at the IF of 21.5 MHz, and into a logarithmic channel used as signal detector. The prototype permits to obtain a first channel traffic analysis and the evaluation of PASA algorithm, useful for mixed signal separation using a mono-channel receiver. The first results are encouraging to continue the studies and are helpful for the final TDR version design and implementation.

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