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1090 MHz channel capacity improvement in the air traffic control context

EMILIO G. PIRACCI[1], GASPARE GALATI[1], NICOLAS PETROCHILOS[2] AND FABRIZIO FIORI[1,*]

The aim of this study is to increase the capacity of the 1090 MHz secondary surveillance radar (SSR) channel by novel transmission and decoding techniques. In particular, multilateration stations have omni-directional antennae; hence considering aircraft traffic and including the extension of surveillance to cooperating vehicles, the reception of superimposed signals is more and more probable. We propose mitigating this problem by combining frequency agility and source separation techniques; we analyze the pertaining channel capacity improvement, and then evaluate the detection and timing estimation for frequency-shifted and separated signals.

Keywords: Secondary surveillance radar, Multilateration, Airport surveillance

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I. INTRODUCTION

Today, air traffic control systems make immense use of the 1090 MHz channel: secondary surveillance radar (SSR), multilateration and its wide area version (MLAT/WAM), automatic dependent surveillance (with its broadcast and retransmit functions: ADS-B and ADS-R), traffic information system (TIS-B), and flight information system (FIS-B).

An MLAT system can identify and localize airborne and ground vehicles in an airport-centered volume. This system measures the time of arrival (TOA) at many stations and uses the time difference of arrival (TDOA) of the signals of the 1090 MHz transponders at the various receiving stations. By TDOA the transponder position is found through intersection of three or more hyperboloids. The system may operate in a passive way, i.e. without eliciting 1090 MHz transmissions from the transponders (and exploiting spontaneous "squitter" transmission from the vehicle), or in an active way, allowing some stations (e.g. one-third of the total number) to use their interrogation capability. In order to extend the surveillance also to airport service vehicles (and to the apron), it is necessary to equip the vehicles with a 1090 MHz signal (squitter) transmitter (a transponder without airborne requirements often referred to as non-transponder device (NTD)) with a 1–2 s^{-1} squitter rate according to ICAO/EUROCAE standards and recommendations [1, 2]. This surveillance extension will strongly increase the 1090 MHz channel traffic when a significant number of vehicles will be equipped [3–5]. In MLAT applications, the use of omni-directional (or wide beam) antennae and the presence of both SSR Mode S replies and squitters make the superposition of 1090 MHz signals rather probable, not to mention the presence of Mode A/C signals [1, 2] on the same band as well as the above-mentioned emerging surveillance applications [6, 7]. Consequently, the superposed signal may be garbled and the related replies cannot be detected or localized; their information is basically lost.

These limitations in SSR signal analysis and decoding can be mitigated by the implementation of new agility techniques [3] and source separation techniques [4, 5]. In particular:

(a) By using the ICAO tolerance, the method of [3] is based on a downlink channel allocation: a 1090 MHz centered band to avionic transponders, while the adjacent channels are for the vehicles (see Fig. 1).

To estimate the 1090 MHz channel capacity, we model traffic by the Poisson probability for the reception of transponder transmissions. This is the standard technique for estimating the probability of the arrival of randomly generated events in a listening window. The implementation of the frequency division transmission results in new channel capacity values, since channel capacity depends on channel allocation.

(b) After the use of frequency agility, the signals-subspace projection, projection algorithm single antenna (PASA) [5], separates overlapping received signals in the remaining cases (see Fig. 2).

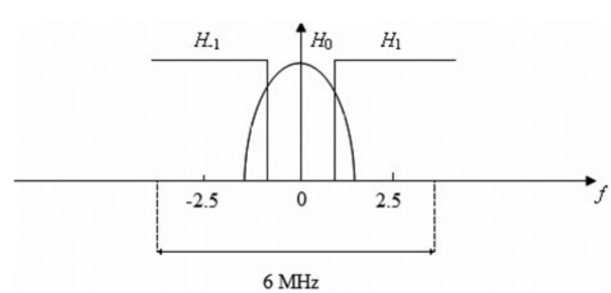

Fig. 1. Downlink channel frequency separation. Three dedicated bands from 1087–1093 MHz, by low-, high- and band-pass filtering, are depicted and the abscissa is the shift from the nominal value 1090 MHz.

*Now with TechnoSky srl, Roma.
[1]DISP/CVV, University of Rome Tor Vergata, V. d. Politecnico, 1 00133 Roma, Italy
[2]JABSOM, University of Hawai'I, 1356 Lusitana Street, 7th Floor, Honolulu, HI 96813, USA.
Corresponding author:
Emilio G. Piracci
Email: piracci@disp.uniroma2.it

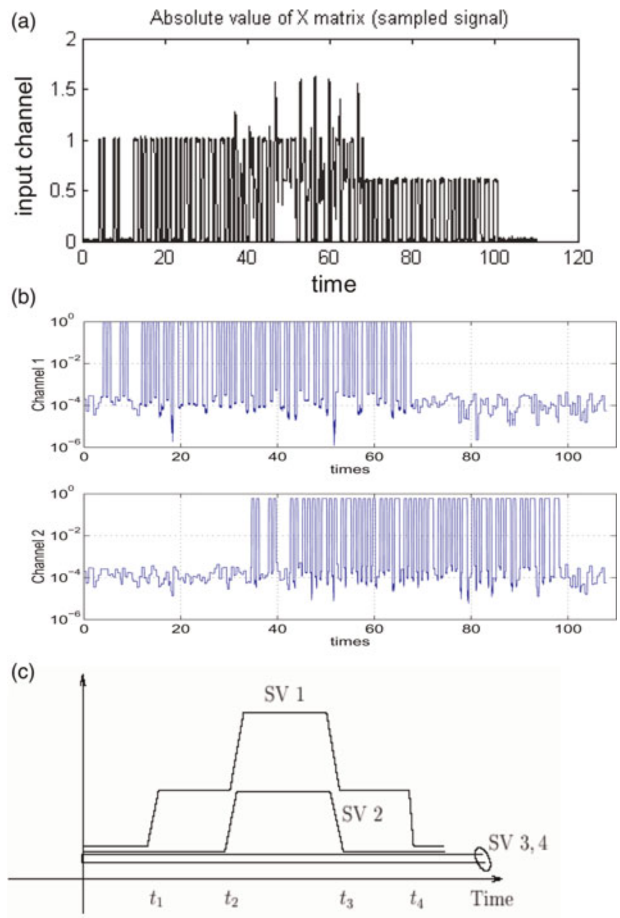

Fig. 2. (a) Received superimposed SSR sources. (b) Sources separation by PASA [5] (log. scale). (c) Timing for estimation of the mixing matrix, by time analysis of the singular values (SV) associated to signal data matrix [9].

To separate superimposed signals (as needed in high traffic density airports and in apron vehicles surveillance), several signal processing algorithms have been developed or adapted from the literature (see [8] for a bibliographical review). Among them, there are a few based on signal-subspace projection techniques: PA (projection algorithm) [4], EPA (extended PA) [4], and PASA [5, 8]. The latter does not require array processing, it only needs a single antenna.

The sole limitation of the PAs is that they are not robust when replies are fully superimposed, i.e. they have the same TOA. Although this is a rare case, it has been discussed in [10, 11].

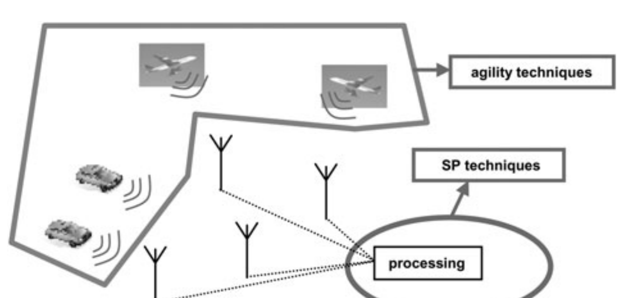

Fig. 3. Application of the proposed techniques in the MLAT scenario.

To enhance MLAT performance, several studies have been made from different points of view: signal processing, estimation algorithms, data processing, data fusion, system integrity, system requirements, system management, etc. The aim of this paper is to begin to consider the integration of these sparse add-ons. We chose, as a first step, the analysis of channel capacity improvement by using the aforementioned techniques. Frequency channel division and separation algorithms are involved in the scenario as shown in Fig. 3.

Section II presents the frequency agility, while Section III presents the PAs. In Section IV we show the channel capacity improvement, and compliance with the detection and TOA estimation requirements, before concluding.

II. FREQUENCY AGILITY: DOWNLINK CHANNEL DIVISION

The aim of the invention [3] is to increase the capacity of the SSR Mode S downlink channel and, thereby, the number of mobiles that may be identified, located, and tracked in the operating zone, e.g. in a large airport, by an MLAT system. The pertaining idea, while leaving unchanged the airborne transponders, is based on a new way of generating SSR-like signals emitted by the NTD. The new features are:

1) a variable carrier frequency and
2) a time division scheme for the transmission.

In this work we focus attention on the improvement by the implementation of item (a) only.

In this respect, ICAO [2] standardized the nominal carrier frequency of 1090 MHz, with an initial tolerance of ± 3 MHz (reduced to ± 1 MHz later). Due to the ICAO tolerance of the transponder transmission carrier frequency, the receiver frequency band is greater than the frequency band associated to the information content of the Mode S reply signal. However, from the analysis of over 600 recorded replies/squitters acquired at Delft University, we recognized that about 90% of the Mode S replies has its central frequency in the interval 1090 MHz $\pm$ 200 kHz. Therefore, the exploitation of the large bandwidth in the receiving Mode S channel is possible by a properly designed, non-flyable, cheap transponder (the "non-transponder device") that may operate in a bank of frequency channels within the 1090 $\pm$ 3 MHz band, as shown in Fig. 1, where a three-band system is shown: the central (pass band) one H_0 for aircraft, and the side (low and high pass with respect to the nominal carrier frequency) H_1 and H_{-1} for vehicles. Using a digital filter in the receiving station, it is possible to create several downlink channels and to increase the system capacity. This "frequency agile" transponder allows us to vary the central transmitted frequency according to a scheduling, for the whole set of airport applications (MLAT, ADS, and TIS) on the 1090 MHz band, without affecting the operation of standard airborne devices.

III. PROJECTION ALGORITHMS

The PA [4, 5] separates SSR sources by exploiting the diversity of the signals, i.e. (a) the different DOAs ("directions of arrivals") of the incoming signals on the *array antenna* and (b) the different carrier frequencies of the incoming signals on the *omni-directional antenna* (i.e. the PASA case).

(a) For an m-element array case, the received data are modeled by the matrix $\mathbf{X} = \mathbf{MS} + \mathbf{N}$, whose rows are the N signal samples for each array channel; $\mathbf{M}$ contains the array *signature* (i.e. the response of each array element and receiver; non-calibrated arrays are considered in this work), $\mathbf{S}$ is the sources matrix, and $\mathbf{N}$ is the noise matrix. The algorithm goes on with (i) estimation of the timing (i.e. of the TOA of the signals), (ii) estimation of $\mathbf{M}$ and beam forming (i.e. derivation of the spatial filters by a projection technique), and (iii) source separation by applying beam formers. A typical result is depicted in Fig. 2. Note that timing estimation (Fig. 2(c)) is performed by analysis of the singular values of the data matrix $\mathbf{X}$ [4]; this is a critical point, as discussed in more detail ("effect of sources timing errors") in Section IV.

(b) At present, MLAT stations use an omni-directional antenna and a one-channel receiver. We did adapt the PA algorithm to the case of a single-antenna receiver (PASA). As this receiver cannot exploit the spatial diversity, our modified algorithm uses the residual carrier frequency of the signals, and the resulting phase accumulation – sample by sample – as a "time diversity".

The adaptation of the PA to the single-antenna case is achieved by a rearrangement of the received data: from a time series originating from a single antenna/receiver consisting of N samples, we construct a matrix of size $m \times l$, where the first column of this matrix (first slot) contains the first m data samples, the second column the next m samples, and so forth, l being the integer part of N/m; see Fig. 4. The accumulation of the phase shift along the data samples is exploited in a way similar to the phase difference along the antenna elements in the PA case. The effectiveness of the PASA method increases as the frequency deviation (from the nominal 1090 MHz) of the involved transponders increases; therefore, this method is suited to "frequency agile" NTDs.

IV. PERFORMANCE: DETECTION, TOA ESTIMATION, AND CHANNEL CAPACITY

This section is dedicated to performance evaluation. To test the replies detection probability and the sources timing errors, real Mode S signals are used, as recorded in Delft University, as well as the combinations needed to generate different situations (e.g. different degrees of overlapping): we call such methods "semi-simulation". In particular, to estimate PA performance the test signal was generated by a coherent sum of two recorded Mode S replies, in order to obtain a two replies garbled signal.

By means of an "ad hoc" semi-simulator [12], variable frequency shifts and time delays were attributed to real Mode S replies/squitter from the Delft data set. The signal-to-noise ratio (SNR) was also varied (i.e. reduced by noise addition) to generate a set of scenarios with overlapped replies. In all of the semi-simulations, the sampling frequency is equal to 50 MHz, i.e. 50 Msamples/s.

A) Detection of replies

We show in the following the garbled replies detection probability versus the frequency shift between overlapping signals. Using the PASA separation method, it is possible to also detect the trailing reply that is undetectable by current receivers when garbled. Figure 5 shows the trailing reply detection probability as a function of the frequency shift between overlapped replies, in the interval 0–0.1 MHz with 10 steps by 10 kHz each. The detection strategy considered here is based on matched filtering to the four pulses Mode S preamble and CFAR threshold [13]. The time delay of the trailing reply was set to 30 µs, and the SNR is in the interval 22–26 B. The figure shows the effect of m (reshaping parameter). Including the PASA in the signal processing chain it is possible to increase the replies rate detection capacity, since in the absence of source separation the trailing garbled reply is undetectable because its preamble is garbled (superimposed with the leading reply). The overlapped replies, when separated by PASA, were correctly decoded (both leading and trailing) in 100% of cases.

B) Effect of sources timing errors

Table 1 shows the TOA (timing) estimation results (Fig. 2(c)) using the real recorded signals, with the same basic methodology as in the previous paragraph; time delay is simulated by a uniform distribution in 10–30 µs, and the replies

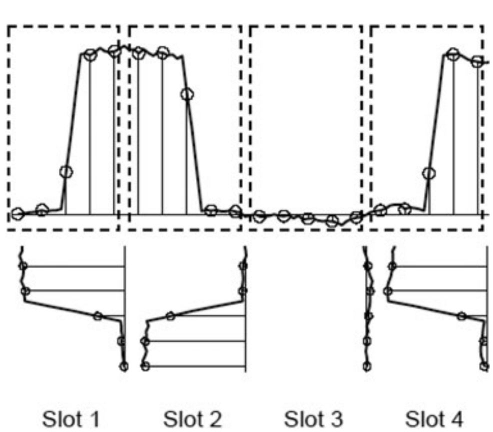

Fig. 4. Receiving data rearrangement (re-shaping).

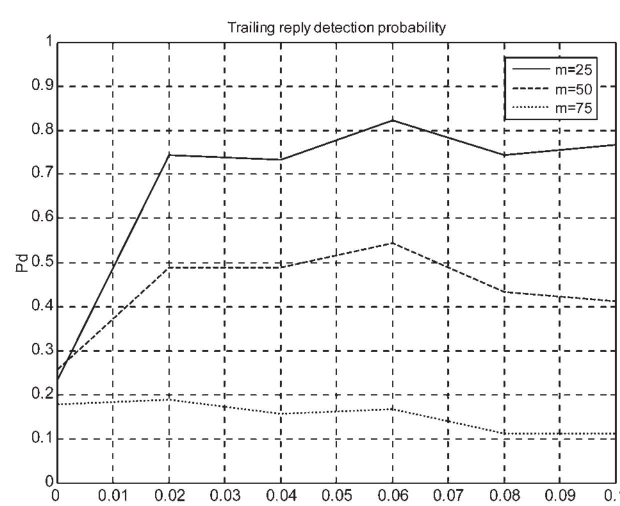

Fig. 5. Trailing reply detection probability versus replies frequency shift (delay between leading and trailing reply: 30 µs).

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Table 1. Real recorded signals, trailing reply TOA estimation.

SNR	22–26 dB
Time delay	10–30 μs
Mean timing (bias)	65 samples
Std. dev. of timing	59 samples
Failure rate	4.5%

carrier frequency and the SNR are maintained as the original. Using an appropriate noise threshold it is possible to obtain a timing estimation ($\hat{\Theta}$) less than the real value (Θ), $\hat{\Theta} \leq \Theta$. The timing estimation error $\Theta - \hat{\Theta}$ is biased at 65 samples, with a standard deviation equal to 59 samples. An underestimation of the timing is suitable for avoiding the presence of the sources mixing in the data block used to estimate the first beam former. A failure (last line of Table 1) is declared when the trailing reply is undetected.

Since the pulses shape is not modified after the projection, the PA does not affect the replies timing at the multilateration receiving stations. Rather, because it is equivalent to a spatial filter that eliminates a part of the noise, the PA improves the matched filter–differentiator processing for timing estimation [14].

C) Channel capacity

In this section, we show how PASA implementation and frequency agility management can provide significant channel capacity improvement for the whole set of airport applications on the 1090 MHz carrier (MLAT, ADS, TIS, and SSR surveillance and data link). In this study, interference on the 1090 MHz channel by Mode A/C replies has not been taken into account, so that the operating capacity of the proposed simulated scenario is supposed to be limited by interference due to the Mode S replies and squitters of type *SLM* ("standard length message", delivering 56 bits and 64 μs long) and *ELM* (112-bit "extended length message", 120 μs long) [2].

The 1090 MHz channel capacity has been evaluated by the analysis of the "no garbling" chance ($P(0)$), which is the probability of receiving a Mode S reply without any interfering signal, since a reply might not be correctly received if any part of it is overlapped with a Mode S interfering reply.

We assumed the signals arrival to be distributed according to the Poisson probability model for the reception of randomly generated transmissions. This model is characterized by the intensity (or "rate") λ, which depends on the fruit emission rate and on the number of emitting transponders. Moreover, the interference effect of an individual reply is a function of its length; thus the analysis treated the effect of each reply separately through the use of different *vulnerability intervals (T)*, which are the listening windows where no interference is permitted in order to allow correct and successful decoding.

Then, according to the Poisson traffic model, the probability of receiving n overlapping replies in an interval of duration T is

$$P(n) = \frac{(\lambda T)^n}{n!} e^{-\lambda T}. \qquad (1)$$

Since the received replies can be successfully decoded if no interference – neither *ELM* nor *SLM* – has occurred in the vulnerability interval, the "no garbling" probability is

$$P(0) = P_{SLM}(0) P_{ELM}(0). \qquad (2)$$

The Poisson model is applied separately to each reply type to calculate the probability of receiving zero interfering replies in the 64 μs listening window needed to receive an *SLM* reply, taken as a reference.

For the 56-bit Mode S reply, the probability of receiving zero *SLM* interfering replies is calculated by assuming the vulnerability interval equal to $t_{SLM} = 64 + 64\ \mu s = 128\ \mu s$, which is the listening window duration plus the *SLM* reply duration (64 μs).

The calculation for the 112-bit case is similar, except that an interval of $t_{ELM} = 64 + 120\ \mu s = 184\ \mu s$ is used to account for the long Mode S reply (120 μs).

In this study, the transmission rates have been assumed as

– eight short signals (i.e. *SLM*) per second plus
– six extended signals (i.e. *ELM*) per second

for both airborne and vehicular transponders.

The PASA [5, 9], described in Section III, allows us to discriminate up to two overlapping replies, with a probability of detection for the leading and trailing replies that depends on the time delay between them. When the time delay between two overlapping replies is less than $t_p = 8\ \mu s$, the discrimination and sources separation by PASA is impossible, due to the replies preambles garbling.

For each interference case, the aforementioned vulnerability interval $[o - T]$ is divided into two sub-intervals: the first and shorter one – $2t_p = 16\ \mu s$ long, twice the preamble duration – where no interfering signals are permitted, since the preambles garbling does not allow the PASA algorithm to correctly discriminate and decode the overlapped replies.

In the remaining vulnerable time – 112 or 168 μs long, depending on the interference type: either *SLM* or *ELM* – one interfering signal is permitted, thanks to the PASA algorithm separation and decoding capabilities.

Figure 6 depicts the above-defined vulnerability intervals for an *SLM*.

In order to evaluate the 1090 MHz channel capacity improvement due to the PASA algorithm implementation, we calculate the probability (P_{free}) of receiving a Mode S reply

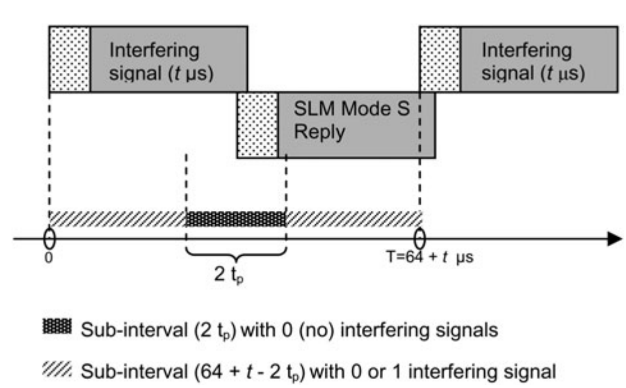

Fig. 6. Vulnerability intervals for an *SLM*.

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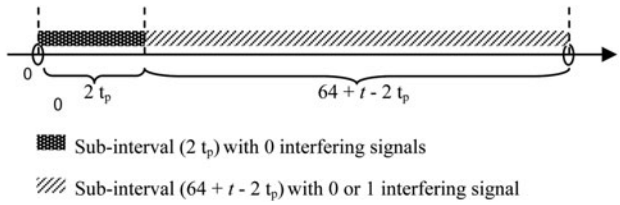

Fig. 7. Rearranged vulnerability intervals for an *SLM*.

with an un-garbled (interference-free) preamble and affected by up to one interfering signal in the data block. In Fig. 8 this probability is compared to the previously calculated $P(0)$.

For the sake of simplicity, in order to compute P_{free}, it is possible to rearrange the aforementioned vulnerability intervals as shown in Fig. 7, and to define the following events in order to describe the interference occurrences:

$$A: \{0 \text{ signals in } [0 - 2t_p]\}$$
$$B: \{0 \text{ signals in } [2t_p - T]\}$$
$$C: \{1 \text{ signal in } [2t_p - T]\}$$
$$D: \{0 \text{ signals in } [0 - T]\}$$

Considering the given definitions and considering the disjoint and statistically independent events, this probability can be expressed as

$$\begin{aligned} P_{free} &= P(B \cup C|A) = \frac{P((B \cup C)A)}{P(A)} = \frac{P(BA \cup CA)}{P(A)} \\ &= \frac{P(BA) + P(CA)}{P(A)} = \frac{P(D) + P(C)P(A)}{P(A)} = \frac{P(D)}{P(A)} + P(C). \end{aligned} \tag{3}$$

By applying the Poisson traffic model, this expression can be simplified as follows:

$$\begin{aligned} P_{free} &= \frac{P(D)}{P(A)} + P(C) \\ &= \frac{e^{-\lambda T}}{e^{-\lambda 2t_p}} + e^{-\lambda(T-2t_p)}(\lambda(T - 2t_p)) \\ &= e^{-\lambda(T-2t_p)} + e^{-\lambda(T-2t_p)}\lambda(T - 2t_p) \\ &= e^{-\lambda(T-2t_p)}(\lambda(T - 2t_{p,}) + 1), \end{aligned} \tag{4}$$

λ being the FRUIT rate; T the whole vulnerability interval length, equal to 112 or 168 μs, in the *SLM* or *ELM* interference cases, respectively, and t_p the preamble duration.

The model is applied separately to each reply type (*SLM*, *ELM*) to calculate the probability (P_{free}) of receiving up to one interfering reply in the data block (B and C events), given the un-garbled reception of the preamble (event A):

$$P_{free} = P_{free}(SLM)P_{free}(ELM). \tag{5}$$

For the 56-bit Mode S reply, the $P_{free}(SLM)$ is calculated by assuming the vulnerability interval equal to $t_{SLM} = 64 + 64\ \mu s = 128\ \mu s$, and the *SLM* fruit rate λ_{SLM}.

The calculation for the 112-bit case is similar, except that an interval of $t_{ELM} = 64 + 120\ \mu s = 184\ \mu s$ and the λ_{ELM} parameter are used.

In the considered scenario, it has been hypothesized that 30% of transponders are assigned to vehicular applications and transmit on the lateral frequency channels thanks to frequency agility, while the remaining 70% is constituted by "traditional" airborne transponders that transmit on the central channel, as depicted in Fig. 1.

Figure 8 shows the improvement of surveillance capacity when PAs are adopted in the receiver, as the number of transponders increases: the dashed line refers to the actual (no PASA) 1090 MHz band use, with traditional transponders and receivers, in this case $P_{free} = P(D)$; the solid line refers to the analyzed system that exploits the frequency agility for vehicular transponders (30% of the total) and PAs. The probability curves shown in Fig. 8 represent the chance of receiving a decodable signal that is an interference-free reply with the presently used detection algorithm or a reply affected by up to one interference in the data block in the case of PASA algorithm implementation. The traffic capacity (Fig. 8) is about four times greater when PASA is used.

In the "agile transponder + PASA" case, the probability of detection is more than 98% for the leading reply and 50% for the trailing reply. It has been (safety) assumed that PASA does not work at all with more than two superimposed replies – anyway this kind of situation is made less and less likely by frequency agility applied to the NTD and filtering upstream the digital processing.

When a bank of filters is implemented in order to separate adjacent frequency channels, the superposition of vehicles-originated replies or squitters with the aircraft ones can be minimized, with a significant increase of system capacity.

Figure 9 shows such capacity improvement versus the total number of operating transponders, by using two frequency channels: one for avionic transponders and the other for vehicular traffic. The curves refer to the case of complete separation of airborne replies/squitters from vehicular replies/squitters by means of filtering upstream the PASA algorithm.

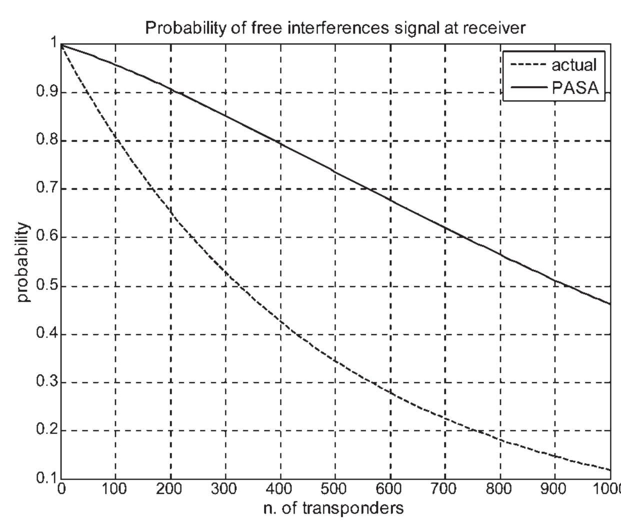

Fig. 8. Probability of interference-free signal at receiver, with and without PASA.

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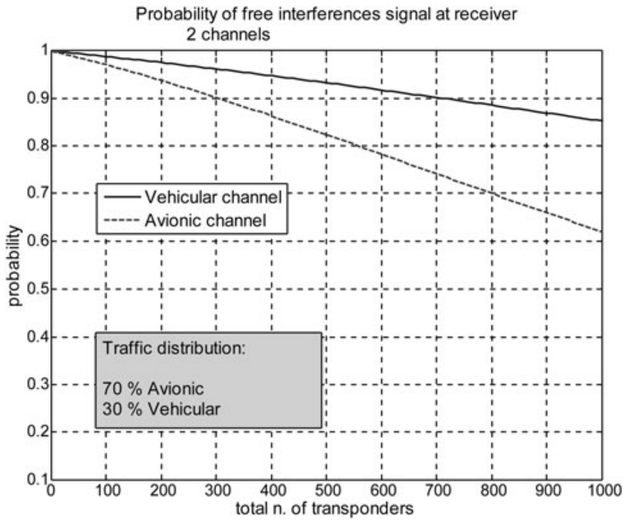

Fig. 9. Probability of interference-free signal reception with multichannel receiver (2 channels).

An outstanding improvement can be noticed, and, unlike the case of Fig. 8, a very large number of transponders (i.e. order of many hundreds) may simultaneously operate in the airport area. Such high figures will be realistic, in a future scenario with all service vehicles equipped with NTD, for large airports, where the number of service vehicles may be as large as a few thousands (although not all simultaneously operating).

V. CONCLUSIONS AND PERSPECTIVES

The 1090 MHz downlink channel is being used for many applications including, surveillance (Modes A/C, Mode S) and data link. The collision of 1090 MHz signals, due to random access to the channel, may be critical when many sources operate, as in an airport environment when many hundreds of vehicles may use it. Novel solutions to this problem, based on source separation enhanced by frequency diversity for NTD, have been described and evaluated by simulations that have shown an important capacity improvement over the state of the art.

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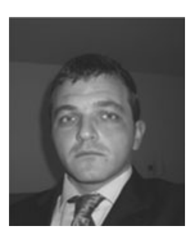
Gaspare Galati is a full professor of Radar Theory and Techniques at the Tor Vergata University of Rome. He received the Dr. Ing. degree (Laurea) in 1970 at the University of Rome "La Sapienza". His main interests are in radar theory and techniques, detection and estimation, navigation, and air traffic management. He is the author/co-author of over 200 papers, 16 patents, and two international books on these topics.



Emilio G. Piracci received an M.S. degree in telecommunication engineering in 2005 and an M.S. degree in network systems engineering in 2007 from the University of Rome "Tor Vergata". Now he is a Ph.D. student at the same university; his main research interests are in radar techniques and radar signal processing. He is the author/co-author of over 20 papers and 1 patent.

Nicolas Petrochilos received his bachelor's degree in 1994 at "EcoleNormale Superieure de Lyon", and an M.S. in signal and image processing of E.N.S.E.A in Cergy-Pontoise in 1996. In 2002, he obtained a Ph.D. from University Delft. At present, he is an assistant professor at the University of Reims, on sabbatical leave at the Queen's

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Hospital, HI. His research interests are algebraic methods for array signal processing, and biomedical application of signal processing. He has co-authored 40 articles, and is a reviewer for several journals.

Fabrizio Fiori received an M.Sc. degree in telecommunication engineering cum laude from the University of Rome "Tor Vergata" in 2007. He is currently pursuing a Ph.D. degree at the same university; his main research activity is focused on radar techniques for Air Traffic Control. Since March 2008 he has been working on ATM and airport systems at TechnoSky Srl as a systems engineer.

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