Detection and Combining Techniques for Asynchronous Random Access with Time Diversity

Federico Clazzer, Francisco Lázaro, Gianluigi Liva and Mario Marchese

Abstract—Asynchronous random access (RA) protocols are particularly attractive for their simplicity and avoidance of tight synchronization requirements. Recent enhancements have shown that the use of successive interference cancellation (SIC) can largely boost the performance of these schemes. A further step forward in the performance can be attained when diversity combining techniques are applied. In order to enable combining, the detection and association of the packets to their transmitters has to be done prior to decoding. We present a solution to this problem, that articulates into two phases. Non-coherent soft-correlation as well as interference-aware soft-correlation are used for packet detection. We evaluate the detection capabilities of both solutions via numerical simulations. We also evaluate numerically the spectral efficiency achieved by the proposed approach, highlighting its benefits.

I. Introduction

Sharing efficiently the resources among users that are required to access a common medium is of utmost importance in today's systems where bandwidth is scarce. Random access (RA) was proposed first [1], [2] to allow users to share a common medium without coordination. Recent advances in RA show that high efficiency can be achieved [3]–[6]. In these solutions, the transmitters send multiple copies of their packets (called replicas). Each replica contains information about the position of all its copies within a time slotted frame. At the receiver side, via successive interference cancellation (SIC), potential collisions are resolved taking advantage of the replicas position information. In [7] it has been shown that joint decoding on the collided packets can be attempted, resorting to multiuser detection (MUD) techniques. The authors of [8], [9] elaborate the concept of *frameless* slotted scheme, i.e. the duration of a frame is not a-priori fixed but the contention ends when the throughput is maximized. Further evolutions of RA include the extension to multiple receiver scenarios [10] and to all-to-all broadcast transmission [11]. Identification of replicas for slot synchronous RA schemes has been addressed in the works [12], [13], where a simple autocorrelation method has been adopted for identifying replicas of the same user.

Most of these schemes, although less complex at the transmitter side with respect to orthogonal schemes, still require synchronization at time slot level. It was recently observed that time synchronicity can be abandoned while keeping similar protocol operations. A first attempt in this direction has been done with the contention resolution ALOHA (CRA) protocol [14]. As in its slotted counterpart, contention resolution diversity slotted ALOHA (CRDSA) [3], the transmitters send replicas of their packets. However, while in CRDSA the replica transmission needs to comply with a slotted frame structure, in CRA the slot alignment is abandoned. The replicas are transmitted with arbitrary delays within a window of fixed duration, and the relative delay among replicas is signaled in the replicas headers. The receiver seeks for decodable packets. Every time it is successful, the decoded packet is re-encoded, re-modulated and removed from all positions in the received signal, thanks to the position information stored in the replica header. Interference cancellation possibly allows further packets to be decoded. A similar scheme to CRA is proposed by the authors in [15], where the virtual frame (VF) concept is introduced. Users are synchronized to their local VF and are allowed to send their replicas only in discrete positions within the VF. The VFs of different users are asynchronous.

An evolution of CRA called enhanced contention resolution ALOHA (ECRA) has been presented first in [16]. Combining techniques are exploited in order to boost the performance. At the receiver, after SIC is carried out in a similar way as in CRA, the received signal samples associated with the replicas that cannot be decoded are combined and a new decoding attempt is performed. Selection combining (SC), equal gain combining (EGC) and maximal-ratio combining (MRC) can be used as combining technique. As shown in [16], remarkable gains can be obtained. The main drawback of ECRA is the requirement of perfect knowledge of the replicas position prior to decoding. A possible solution presented in [17] is to replicate this information in both header and trailer. Error protection can also be added increasing the probability of retrieving the replicas position information even in presence of collisions, but although viable, this solution increases the overhead.

In this paper with propose an alternative solution to the problem of localizing the replicas position that does not need any reserved field in the header.

The rest of the paper is organized as follows. Section II reviews the ECRA protocol and its features. In Section III we present the system model, the two phase detection technique and we derive the interference-aware soft-correlation detection rule. Section IV investigates ECRA adopting the derived detection techniques via Monte Carlo simulations and is followed by the conclusions in Section V.

Federico Clazzer, Francisco Lázaro and Gianluigi Liva are with the Institute of Communications and Navigation of the Deutsches Zentrum für Luft- und Raumfahrt (DLR), D-82234 Wessling, Germany (e-mail: {federico.clazzer, francisco.lazaroblasco, gianluigi.liva}@dlr.de).

Mario Marchese is with the Department of Electrical, Electronic, and Telecommunications Engineering, and Naval Architecture (DITEN), Via Opera Pia 13, 16145 Genova, Italy (e-mail: mario.marchese@unige.it).
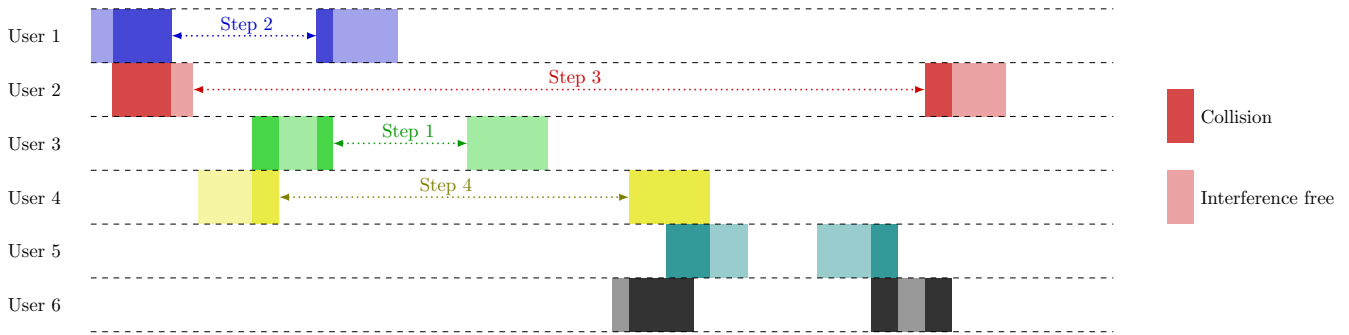
Fig. 1. Example of collision pattern at the receiver in ECRA, and of the corresponding SIC steps. During the first step, user 3 second replica - the only one free from interference - is decoded and the information content as well as the pointer to its replica are retrieved. Users 1 and 4 replicas are now free from interference. In the second step second replica of user 1 can be decoded. Its interference contribution together with the one of its twin can be now removed from the received signal and first replica of user 2 is now freed from interference. In step 3, user 2 replicas can be decoded and removed from the received signal. Finally in step 4 user 4 replicas are decoded and removed from the received signal.
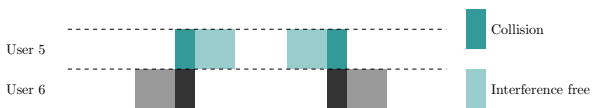

Fig. 2. Residual collision pattern after SIC decoding for the example in Figure 1.

II. ENHANCED CONTENTION RESOLUTION ALOHA

We review next the ECRA [16] access protocol. For the sake of simplicity, in the following we assume each user attempting the transmission of one packet only. At the transmitter side each user sends 2 (or more) replicas of its packet within its local VF of duration T_f seconds. We recall here that the concept of VF has been first introduced in [15] and was not present in the first version of ECRA [16]. The delay between replicas of the same user is chosen at random. An example of a possible received medium access control (MAC) signal is shown in Figure 1.

At the receiver side, the SIC procedure starts looking for decodable packets. In our example, the first to be found is the second replica of user 3. Once correctly decoded, all replica positions of the decoded user are retrieved from the pointer field in the header. The packet is re-encoded, re-modulated and his waveform is removed from all the identified positions. In this way, the interference caused on the second replica of user 1 is removed and this replica can be successfully decoded. Similarly, we are able to decode the packets of users 1 to 4, while users 5 and 6 cannot be decoded.

User 5 and 6 have both their replicas colliding with each other and SIC alone cannot resolve the collision, as emphasized in Figure 2. The approach proposed in [16] would use in this example, SC combining for choosing the interference-free samples from the replicas of user 6, creating an enhanced observation of user 6 packet. On it, decoding is attempted and if successful, its interference contribution is removed from the received signal. This would allow the recovery of user 5 too.

Other combining techniques, such MRC and EGC can also be applied, leading to remarkable gains in terms of throughput as shown in [18]. There, it has been shown that ECRA with MRC is able to reach up to 1.8 b/s/Hz. A main challenge in the implementation of combining techniques is the need of performing the detection of the replicas and the identification of the user which they belong to, prior to decoding. A way to achieve this is to exploit the pointer field of the replicas, as proposed in [17], i.e. by

- Duplicating the pointer field in the header and trailer of a replica;
- Protecting the pointer field with a specific low rate forward error correction (FEC) code.

Although viable, both options imply an increase in the protocol overhead, which can be particularly critical in applications where the message length is short. In the next Section, we propose a novel approach that allows detection and localization of replicas avoiding any protocol overhead.

III. SYSTEM MODEL

Each user arranges his transmission within a VF of duration T_f seconds. Virtual frames are asynchronous among users. Each VF is divided in N_s slots of duration ΔT, so that $T_f = N_s \Delta T$. Users transmit d replicas of duration T_p seconds within the VF. Each replica is transmitted over n_p consecutive slots within the VF and we have that a replica duration is a multiple of the slot duration, $T_p = n_p \Delta T$. Each replica is composed by n_s modulated symbols and the symbol duration is T_s. We have $nT_s = n_p \Delta T = T_p$. Each replica is transmitted starting from a slot index chosen uniformly at random in $[0, N_s - n_p - 1]$, rejecting starting slot indexes which lead to self-interference among replicas of a user's packet.

We assume an infinite user population generating traffic following a Poisson process of intensity G. The channel load[1] G is measured in packet arrivals per packet duration or per T_p seconds. In contrast to CRDSA [3], CRA [14] and the first version of ECRA [16], no pointer field is required in the header for localizing the replicas position. The first section of each replica is a sync word composed by n_{sw} binary symbols $\mathbf{s} = (s_0, ..., s_{n_{sw}-1})$ common to all users, with

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[1]The channel load G takes into consideration the net information transmitted, depurated from the number of replicas per user d.
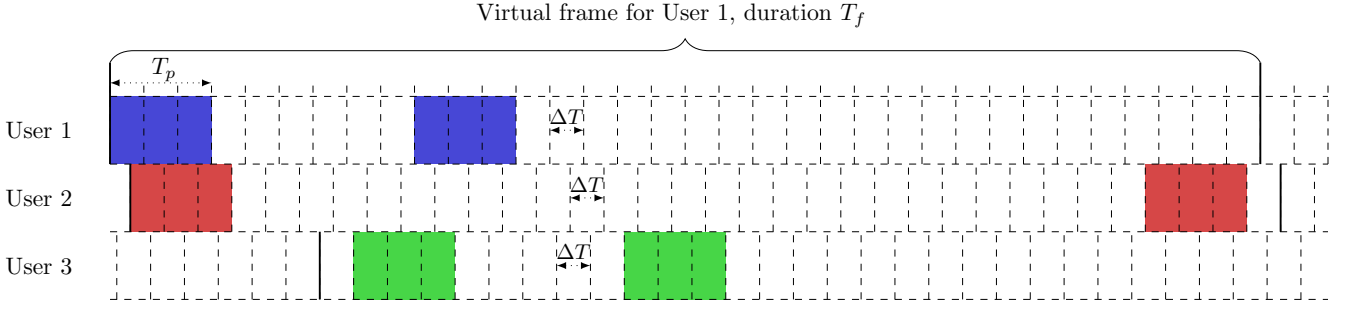
Fig. 3. Transmitted signals. Each user sends two replicas of duration T_p seconds that occupy 3 time slots in the example.

$s_i \in \{-1, +1\}$ for $i = 0, ..., n_{\mathrm{sw}} - 1$. The sync word is then appended to the BPSK modulated data part and sent through an additive white gaussian noise (AWGN) channel. The focus of this work is on satellite communication links where AWGN is a typical channel model extensively used. Extensions to other channel models that include fading are out of scope for the present contribution, although being a valuable future research direction. We assume the data part to carry the actual information and the redundancy introduced by a forward error correction code.

We will assume perfect power control, so that all packets are received with the same power. For a generic user's signal both frequency offset f and epoch ϵ are modeled as uniform random variables with $f \sim \mathcal{U}[-f_{\max}; f_{\max}]$ and $\epsilon \sim \mathcal{U}[0; T_s)$. The frequency offset and epoch are common to a user's packet, while they are independent across users. The random phase offset is uniformly distributed between 0 and 2π, i.e. $\varphi \sim \mathcal{U}[0; 2\pi)$, and it is assumed to independent replica by replica. Under the assumption that $f_{\max} T_s \ll 1$, the received signal $y(t)$ after matched filtering can be approximated as

$$y(t) \cong \sum_{u=1}^{m} \sum_{r=1}^{d} x^{(u)}(t - \epsilon^{(u)} - T^{(u,r)} - t_0^{(u)}) e^{j(2\pi f^{(u)} t + \varphi^{(u,r)})} + n(t)$$

where,
- $\epsilon^{(u)}$ is the user u epoch;
- $T^{(u,r)}$ is the u-th user r-th replica delay w.r.t. the associated VF start;
- $t_0^{(u)}$ is the user u delay w.r.t. the common reference time;
- $f^{(u)}$ is the frequency offset for user u;
- $\varphi^{(u,r)}$ is the phase offset for the r-th replica of user u's packet.

The signal for the u-th user $x^{(u)}$ is given by

$$x^{(u)}(t) = \sum_{i=0}^{n_s - 1} a_i^{(u)} g(t - i T_s).$$

Here, $\left\{ a_i^{(u)} \right\}$ is the symbol sequence forming user u's packet and $g(t) = \mathcal{F}^{-1}\{\mathrm{CR}(f)\}$ is the pulse shape, where $\mathrm{CR}(f)$ is the frequency response of the raised cosine filter. The noise $n(t)$ is given by $n(t) \triangleq \nu(t) * h(t)$, being $\nu(t)$ a white Gaussian process with single-sided power spectral

density N_0 and $h(t)$ the matched filter (MF) impulse response, $h(t) = \mathcal{F}^{-1}\left\{ \sqrt{\mathrm{CR}(f)} \right\}$.

A. Detection and Decoding

At the receiver side, the incoming signal $y(t)$ is sampled and input to the frame start detector. The receiver will operate with a sliding window, similarly to [15], [19]. The decoder starts operating on the first W samples, with W the designed window size. First it detects candidate replicas. Then, for the candidate replicas, a subsequent processing is performed with the scope of matching the replicas transmitted by the same user. For the matched replicas, combining is performed and decoding via the channel decoder is attempted. The channel decoder is assumed to be capable of identifying unrecoverable errors with high probability.[2] If decoding is successful, SIC is performed: the interference contribution of all the replicas of the decoded packet is removed from the received signal. Once no more packets can be decoded within the window, the receiver window is shifted forward by ΔW samples and the procedure starts again. We detail now how candidate replicas are detected and matched. The procedure is performed in two phases, that we dub detection phase and matching phase.
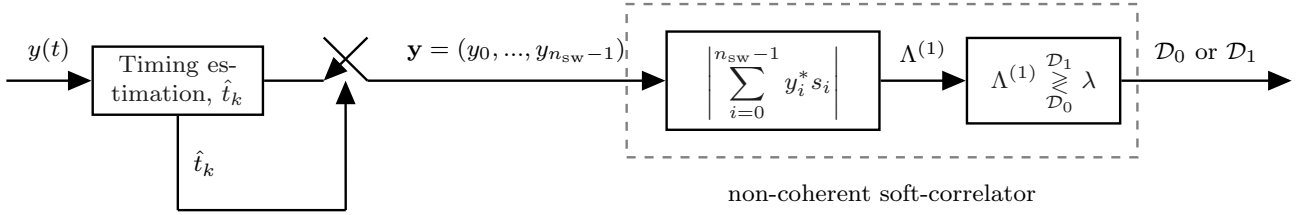
1) Detection Phase: In the first phase we use the non-coherent soft-correlation metric [20] for identifying candidates replicas (see Figure 4(a)). Within a receiver window, a threshold-based test is applied to each of the $W - n_{\mathrm{sw}}$ sequences of n_{sw} consecutive samples (referred in the following as test intervals) to detect the presence of a sync word. We denote in the following
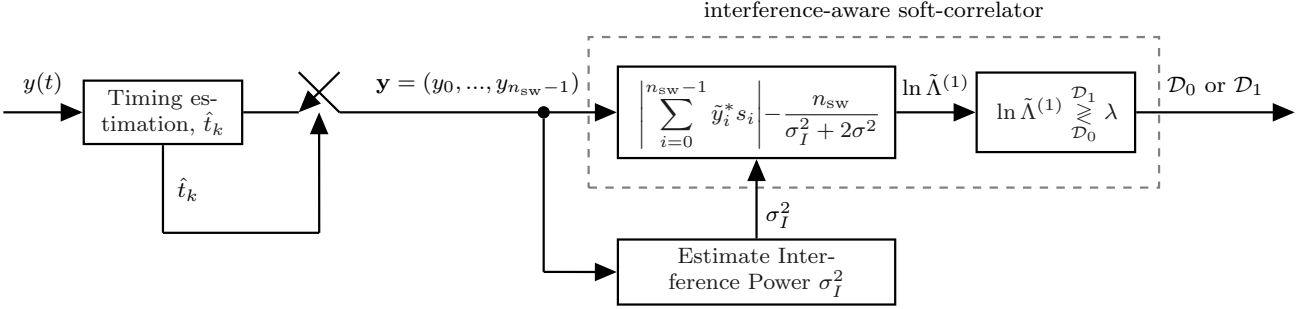
$$\mathbf{y} = (y_0, ..., y_{n_{\mathrm{sw}}-1})$$

the sequence of n_{sw} samples on which the threshold test is applied. Here, we are implicitly assuming that the epoch is estimated prior to frame synchronization. Under the hypothesis that the test interval is actually aligned to a sync word, the epoch estimation can be reliably performed using pilot-aided[3] techniques mutated from code synchronization algorithms used in spread-spectrum communications (see e.g. [21] and

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[2]Error detection can be implemented either by using an incomplete channel decoder or by concatenating an outer error detection code with the inner channel code.

[3]Observe that the sync word can be effectively used as pilot field for timing estimation.

(a) Non-coherent soft-correlator used for the detection of candidates replicas.

(b) Interference-aware soft-correlator used for the detection of candidates replicas.

Fig. 4. The non-coherent soft-correlator and the interference-aware soft-correlator used for the detection of candidate replicas.

references therein). If the test window is not aligned with the sync word of any user, we assume the epoch estimator returning a random sampling offset, uniformly-distributed in $(0, T_s]$. For each test interval, similarly to [20], the frame synchronizer has to decide among two hypothesis, i.e.

$$\mathcal{H}_0 : \mathbf{y} = \mathbf{z} + \mathbf{n}$$
$$\mathcal{H}_1 : \mathbf{y} = \mathbf{s}\, e^{j\varphi^{(u,r)}} + \mathbf{z} + \mathbf{n}$$

where the first hypothesis refers to the case of no sync word, while the second one refers to the case of sync word present. Here $\mathbf{n} = (n_0, ..., n_{n_{\mathrm{sw}}-1})$ are samples of a discrete white Gaussian process with $n_i \sim \mathcal{CN}(0, 2\sigma^2)$ and $\mathbf{z}$ is the interference contribution over the n_{sw} observed samples.

We adopt the threshold test

$$\Lambda^{(1)}(\mathbf{y}) = \left| \sum_{i=0}^{n_{\mathrm{sw}}-1} y_i^* s_i \right| \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \lambda. \qquad (1)$$

Where decision $\mathcal{D}_1$ corresponds to hypothesis $\mathcal{H}_1$ and decision $\mathcal{D}_0$ corresponds to hypothesis $\mathcal{H}_0$. The threshold λ is the discriminant between the two decision regions. We call $\mathcal{S} = \{\tau_1, \tau_2, ...\}$ the set of candidate replica starting positions, i.e. the set containing the positions within the receiver window for which the test provided by (1) outputs $\mathcal{D}_1$. The set of candidate replica positions is the outcome of the first phase.

2) Replica Matching Phase: The second phase works as follows. Let us consider the first candidate replica identified in the first phase. We denote its starting position as τ_1, with $\tau_1 \in \mathcal{S}$. We are interested now in finding a subset $\mathcal{S}_1 \subseteq \mathcal{S}$ containing the initial positions of bursts that are likely replicas of the (hypothetical) burst starting in position τ_1. To do so, we define the following compatibility criterion:

Definition 1 (Compatibility Criterion). *A start position $\tau_i \in \mathcal{S}$ is said to be compatible with τ_1 iff*

$$\tau_i = \tau_1 + k\Delta T \qquad (2)$$

for some positive integer k, $\tau_1 < \tau_i < WT_s - \Delta T$.

The set $\mathcal{S}_1$ is hence formally defined as

$$\mathcal{S}_1 \triangleq \left\{ \tau_i \in \mathcal{S} | \tau_i = \tau_1 + k\Delta T, k \in \mathbb{Z}^+ \right\}. \qquad (3)$$

The subset $\mathcal{S}_1$ contains the starting positions that are compatible (given the VF structure) with τ_1, i.e., their associated burst are likely replicas of the burst starting at position τ_1.

Denote next $\mathbf{y}^{(i)} = (y_0^{(i)}, ..., y_{n_s-1}^{(i)})$ as the n_s samples of the received signal starting with sample in position τ_i within the window. For each $\tau_i \in \mathcal{S}_1$, we compute the non-coherent correlation

$$\Lambda_{1,i}^{(2)}(\mathbf{y}) \triangleq \left| \sum_{j=0}^{n_s-1} y_j^{(1)} \left[y_j^{(i)} \right]^* \right|. \qquad (4)$$

We order the $\Lambda_{1,i}^{(2)}$ in descending order and we mark the first $d-1$ as replicas of the same user.

On these replicas we apply combining techniques as selection combining (SC), MRC or EGC. If decoding is successful, all the replicas are removed from the received signal. Accordingly, $\mathcal{S}$ is updated by removing the starting positions of the cancelled replicas. The process is iterated until $\mathcal{S}$ is empty, or if decoding fails for all remaining candidates in $\mathcal{S}$.

In the next Subsection, a refinement of the detection rule, when an estimate of the interference power is available at the receiver is presented.

B. Hypothesis Testing, Interference-Aware Rule

We derive here an advanced correlation rule, named $\tilde{\Lambda}^{(1)}$, which takes into consideration the presence of interference. To do so, we resort to a Gaussian approximation of the interference contribution. We hence model the interference term ν_i as $\nu_i \sim \mathcal{CN}(0, \sigma_I^2)$. Furthermore, we assume σ_I^2 to be constant for the entire test interval. The joint noise plus interference contribution is given by $n_i' = \nu_i + n_i$, so that $n_i' \sim \mathcal{CN}(0, \sigma_I^2 + 2\sigma^2)$. The approximate likelihood ratio test (LRT) is then obtained by evaluating,

$$\tilde{\Lambda}^{(1)}(\mathbf{y}) = \frac{f_{\mathbf{Y}|\mathcal{H}_1}(\mathbf{y}|\mathcal{H}_1)}{f_{\mathbf{Y}|\mathcal{H}_0}(\mathbf{y}|\mathcal{H}_0)} \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \lambda' \qquad (5)$$

where $f_{\mathbf{Y}|\mathcal{H}_i}(\mathbf{y}|\mathcal{H}_i)$ is the approximate distribution of the random vector $\mathbf{Y} = (Y_0, ..., Y_{n_{\mathrm{sw}}-1})$ under the hypothesis $\mathcal{H}_i$. For the $\mathcal{H}_0$ hypothesis we can write

$$f_{\mathbf{Y}|\mathcal{H}_0}(\mathbf{y}|\mathcal{H}_0) = \prod_{i=0}^{n_{\mathrm{sw}}-1} \frac{1}{\pi\left(\sigma_I^2 + 2\sigma^2\right)} e^{-\frac{|y_i|^2}{\sigma_I^2 + 2\sigma^2}}. \qquad (6)$$

For the $\mathcal{H}_1$ hypothesis we can write

$$f_{\mathbf{Y}|\mathcal{H}_1,\varphi}(\mathbf{y}|\mathcal{H}_1,\varphi) = \prod_{i=0}^{n_{\mathrm{sw}}-1} \frac{1}{\pi\left(\sigma_I^2 + 2\sigma^2\right)} e^{-\frac{|y_i - s_i e^{j\varphi}|^2}{\sigma_I^2 + 2\sigma^2}} \qquad (7)$$

We define $\tilde{y}_i = y_i / \left(\sigma_I^2 + 2\sigma^2\right)$. Averaging (7) over φ we find,

$$f_{\mathbf{Y}|\mathcal{H}_1}(\mathbf{y}|\mathcal{H}_1) = \left[\prod_{i=0}^{n_{\mathrm{sw}}-1} \frac{1}{\pi\left(\sigma_I^2 + 2\sigma^2\right)} e^{-\frac{|y_i|^2 + 1}{\sigma_I^2 + 2\sigma^2}} \right] \\ \cdot I_0\left(\left| \sum_{i=0}^{n_{\mathrm{sw}}-1} \tilde{y}_i^* s_i \right| \right). \qquad (8)$$

Substituting equations (8) and (6) in the expression of equation (5) we get

$$\tilde{\Lambda}^{(1)}(\mathbf{y}) = e^{-\frac{n_{\mathrm{sw}}}{\sigma_I^2 + 2\sigma^2}} I_0\left(\left| \sum_{i=0}^{n_{\mathrm{sw}}-1} \tilde{y}_i^* s_i \right| \right) \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \lambda'$$

Taking the natural logarithm of both sides we can write

$$\ln \tilde{\Lambda}^{(1)}(\mathbf{y}) = \ln\left[I_0\left(\left| \sum_{i=0}^{n_{\mathrm{sw}}-1} \tilde{y}_i^* s_i \right| \right) \right] - \frac{n_{\mathrm{sw}}}{\sigma_I^2 + 2\sigma^2} \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \lambda \quad (9)$$

where $\lambda = \ln\left(\lambda'\right)$. Making the use of the approximation $\ln(I_0(x)) \cong |x| - \ln\sqrt{2\pi|x|} \cong |x|$ [20], we can further rework equation (9) as

$$\ln \tilde{\Lambda}^{(1)}(\mathbf{y}) \cong \left| \sum_{i=0}^{n_{\mathrm{sw}}-1} \tilde{y}_i^* s_i \right| - \frac{n_{\mathrm{sw}}}{\sigma_I^2 + 2\sigma^2} \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \lambda. \qquad (10)$$

With respect to the non-coherent soft-correlation rule of equation (1), we can observe that in (10) the correlation term is followed by a correction term that depends on the sync word length and on the interference level. See Figure 4(b) for the block diagram of the presented synchronizer. Observe that the interference-aware rule requires an estimate of the interference power.

IV. Numerical Results

In this section we present numerical results for the proposed approach. We first compare the two non-coherent soft-correlation rules presented in Sections III-A and III-B in terms of receiver operating characteristics (ROC). In the second part we show the performance of the ECRA receiver in terms of probability of correct detection of the replicas and probability of correct combining of replicas from the same user.

A. ROC Comparison

The performance of the two correlation rules $\Lambda^{(1)}$ and $\tilde{\Lambda}^{(1)}$ that can be adopted in the detection phase of the receiver operations are compared via Monte Carlo simulations. The comparison is done in terms of ROC. The false alarm probability P_F is defined as $P_F = \Pr\{\Lambda > \lambda|\mathcal{H}_0\}$. The detection probability P_D is defined as $P_D = \Pr\{\Lambda > \lambda|\mathcal{H}_1\}$. We assume $f_{\max} = 0.01/T_s$. The aggregate signal is then summed with Gaussian noise. The selected E_s/N_0 is $E_s/N_0 = 10$ dB. A sync word of 32 bits of hexadecimal representation $\{1ACFFC1D\}$ has been adopted, which results in $n_{\mathrm{sw}} = 32$ symbols.

Results for channel traffic values $\mathsf{G} = \{0.5, 1.0, 1.5\}$ are presented in Figure 5. As we can expect, the knowledge on the interference level exploited in the rule $\tilde{\Lambda}^{(1)}$ leads to better ROC performance, regardless form the channel traffic conditions. Nevertheless, the gain compared to the non-coherent correlation rule $\Lambda^{(1)}$ is rather limited. In general, both rules show good performance, with $P_D > 0.99$ for $P_F > 0.02$ in the worst case (channel traffic $\mathsf{G} = 1.5$) and for $\Lambda^{(1)}$.

B. ECRA Detection and Replicas Coupling Performance

We present here the results for the detection and correct combining probabilities. We focus in the particular setting where $d = 2$ (i.e., users transmit 2 replicas of their packets). The detection probability P_D has been defined in the previous subsection. We define the correct combining probability P_{CC} as the probability that two replicas of a burst are correctly selected for combining after the two-phase procedure. Obviously, $P_{CC} \leq P_D^2$, i.e., a necessary condition for correct combination is the actual detection of the sync words associated with the two replicas, during the first phase. We select a fixed threshold λ^* equal for all the channel traffic values and we use the non-coherent soft-correlation rule $\Lambda^{(1)}$. The threshold λ^* has been selected through numerical simulations. We show the results in Figure 6, for a signal-to-noise ratio (SNR) of $E_s/N_0 = 10$ dB. The discretization interval equals to one physical layer packet duration, i.e. $\Delta T = T_p$. Each packet is composed by a sync word of $n_{\mathrm{sw}} = 32$ symbols (as the one already presented) and a total of $n_s = 1000$ BPSK antipodal modulated symbols (including the sync word symbols), the VF duration as well as the window duration WT_s are 100 times the packet duration, $T_f = WT_s = 100T_p$.

Observe that the detection probability remains above 95% for all the channel traffic G values, up to $\mathsf{G} = 1.5$. The non-coherent soft-correlation rule $\Lambda^{(1)}$ is particularly robust to variations in the channel traffic, since the presented results are obtained for a single threshold value λ^* which has been
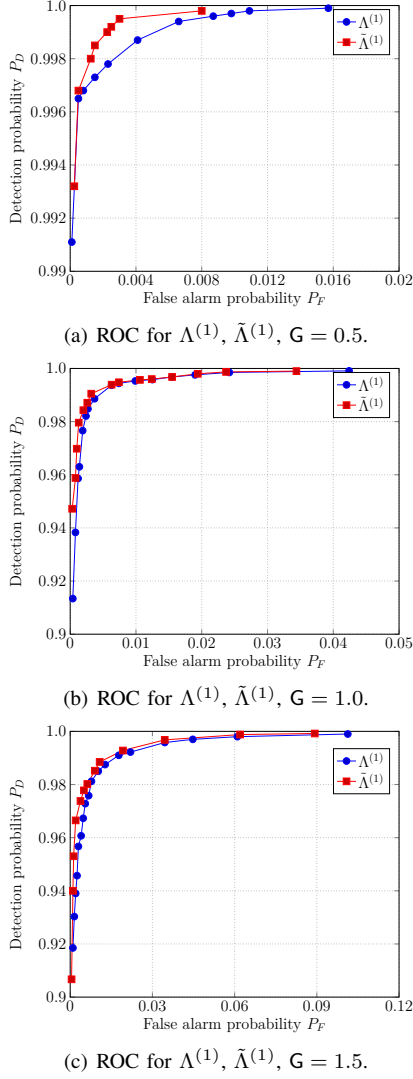
(a) ROC for $\Lambda^{(1)}$, $\tilde{\Lambda}^{(1)}$, G = 0.5.

(b) ROC for $\Lambda^{(1)}$, $\tilde{\Lambda}^{(1)}$, G = 1.0.

(c) ROC for $\Lambda^{(1)}$, $\tilde{\Lambda}^{(1)}$, G = 1.5.

Fig. 5. ROC for the non-coherent and interference-aware soft-correlation synchronization rules, with G = $\{0.5, 1.0, 1.5\}$, equal received power, $E_s/N_0 = 10$ dB and $n_{\text{sw}} = 32$ symbols.
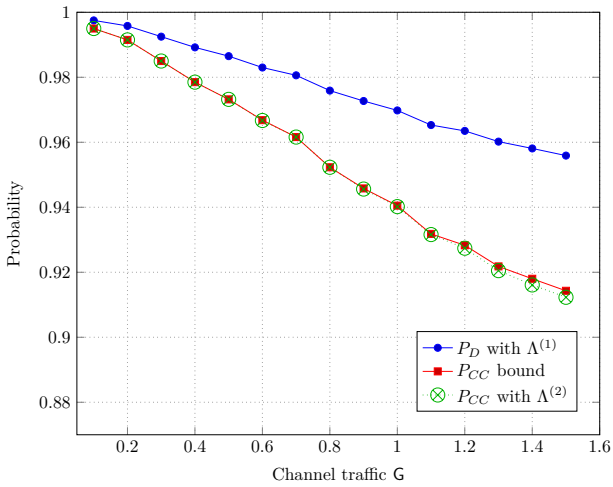

Fig. 6. Detection probability P_D for a fixed threshold λ^* independent from the channel traffic using $\Lambda^{(1)}$ and correct combining probability P_{CC} with $\Lambda^{(2)}$.
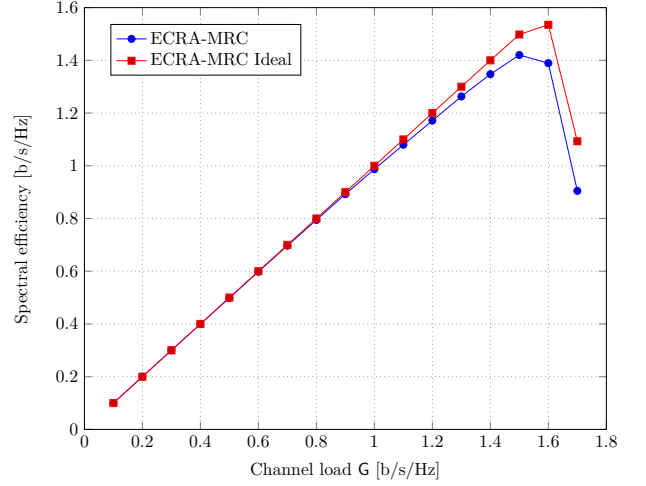

Fig. 7. Spectral efficiency of ECRA-MRC with the proposed two phase detection and combining technique compared to the ideal ECRA-MRC.

kept constant for all the channel traffic values. For all values of channel traffic simulated, the correct combining probability is very close to the bound P_D^2.

C. Spectral Efficiency

We compare the simulation results in terms of both spectral efficiency achieved by ECRA with MRC, after the two-phase detection process described in Section III-A. The proposed two phase detection technique is compared against the idealized case in which all replicas positions are known to the receiver prior to decoding. We select $\Delta T = T_p$ and again the window duration is $T_f = WT_s = 100T_p$. Perfect channel state information (CSI) at the receiver is assumed for enabling MRC.

As before, we use the non-coherent soft-correlation rule $\Lambda^{(1)}$ and a fixed threshold has been selected and kept constant, regardless the channel load G. All replicas are received with equal power $E_S/N_0 = 2$ dB. A capacity achieving code adopting a Gaussian codebook with rate $R = 1$ is assumed, so that if the mutual information at the output of the combiner exceeds the rate R, then the packet is considered to be successfully decoded. Further refinements of the decoding model can be adopted following a realistic packet loss rate (PLR) performance of a specific code for example. Nonetheless, for the present work such a model is sufficient to show the goodness of the detection and identification approach. The maximum number of SIC iterations is set to 10. SIC is assumed ideal. That is, if the position of both replicas of one user is known at the receiver, MRC is applied and if the packet can be decoded its interference contribution is completely removed from the received signal applying SIC.

In Figure 7, the spectral efficiency results for the proposed two phase detection and combining technique (called ECRA-MRC in the legend) and the ideal ECRA-MRC where all the replica positions is known at the receiver are presented. The proposed technique is close to the performance of the ideal case. The maximum spectral efficiency exceeds 1.4 b/s/Hz,

which is only 8% less than the maximum spectral efficiency of the ideal case.

V. CONCLUSION

In this work we presented a solution for localizing candidate replicas and combine them prior to decoding, in the asynchronous random access protocol ECRA, enabling the exploitation of combining techniques as MRC. A two phase approach is proposed. First candidate replicas are identified using the known sync word. Non-coherent soft-correlation is adopted as baseline metric and an interference-aware soft-correlation rule is derived. The latter can be adopted when the interference power on the sync word can be estimated. Numerical results have shown that already the simple non-coherent soft-correlation metric is sufficient to guarantee the detection of most replicas. For example, up to 99.5% of replicas can be detected for a hannel load of $\mathsf{G} = 1$ b/s/Hz. In the second phase, the entire candidate replica signal is exploited to compute the non-coherent soft-correlation metric against the other candidates.

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