Chapter

NOMA Transmission Systems: Overview of SIC Design and New Findings

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Abstract

Non-Orthogonal Multiple Access (NOMA) has been recently proposed as a good alternative to meet 5G and beyond requirements in terms of high spectral efficiency, massive connectivity, and low latency. It has been demonstrated that the use of NOMA in downlink has superior performance in terms of throughput, whereas the use in uplink outperforms OMA techniques in terms of fairness. A distinctive feature of NOMA is the presence of excessive multiple-access interference due to the case of usage of power domain to multiplex signals, thus the functional implementation of NOMA implies Successive Interference Cancelation (SIC) to combat this interference. Therefore, SIC design becomes the main point in the effectiveness of NOMA systems. On the other hand, hybrid schemes, NOMA/OMA, have been recently proposed to reduce the drawbacks of pure NOMA systems. However, in these schemes, it becomes necessary to distinguish NOMA and OMA users. Cognitive Radio techniques turn to be a good option to effectively separate NOMA/OMA users as well as to distinguish NOMA users. In this chapter, a brief overview of NOMA techniques related to Cognitive Radio technology (CR-NOMA) and SIC design reported in the literature is presented. Also, new findings about NOMA/OMA users' recognition are described.

Keywords: CR-NOMA, SIC algorithms, hybrid NOMA, user separation

1. Introduction

To cover 5G and Next Generation Networks (NGN) main requirements, such as better coverage, bandwidth, reliability, and spectrum efficiency, many techniques have been proposed. Non-Orthogonal Multiple Access (NOMA), concretely power NOMA has emerged as a promising trend to improve mobility, connectivity, and spectrum efficiency through spectrum sharing of OMA-user with other multiple users. Thus, multiuser interference cancelation techniques play a predominant role to successfully mitigate excessive Multiple Access Interference (MAI). The so-called Sequential Interference Cancelation (SIC) was considered through the last decades to be the most promising approach for MAI mitigation [1–3]. It is worth mentioning as well, that SIC algorithms are recently at the center of the attention for both the research community and the industry professionals to significantly reduce excessive interferences due to the spectrum sharing.

On the other hand, hybrid NOMA / OMA schemes have been proposed [4, 5] to overcome the drawbacks of pure NOMA systems and enhance pure OMA schemes in terms of total throughput. Hybrid NOMA schemes require an effective way to separate NOMA / OMA users. Promising techniques to successfully separate NOMA/OMA users are the ones used in Cognitive Radio: a few decades ago, Cognitive Radio (CR) technology was proposed to improve spectrum utilization by allowing a secondary user (SU) to access idle spectrum allocated to a primary user (PU) [6]. Lately, the usage of Cognitive Radio-based NOMA (CR-NOMA) for power domain NOMA has been suggested to allow the SU spectrum regardless of the presence of the primary user [7] and also to separate users in NOMA/OMA hybrid schemes [4, 5].

Hereafter, the main attention will be applied to the CR-NOMA principles to effectively separate NOMA/OMA users and implementing SIC algorithms for establishing the decoding order for the multiple users but for specific conditions of Doubly Selective channels, which naturally appears when information is transmitted from High -Speed -Vehicles (HSV): trains, cars, aircrafts, etc. to the nearest base station (BS). CR-NOMA principle should be used with several significant changes in 5G and beyond networks since meticulous analysis [6, 7] of existing SIC proposals shows that if it is applied to Doubly Selective channels, some significant changes and improvements are required due to:

- The usage of the Channel State Information (CSI) or its modifications [1, 2, 8, 9] is hardly possible, due to the strong selectivity of the channels in both time and frequency domains following with severe fading as well. Though CR-NOMA Transmission at Double Selective channels is mainly incoherent and channel conditions for users use to be significantly different. Moreover, as it was pointed at [4, 5], significant differences for channel conditions for OMA and NOMA users are necessary and sufficient conditions for effective decoding for both types of users.

- Decoding algorithms should be "as fast as possible" to avoid channel selectivity in time and frequency.

- Decoding algorithms must be also of high accuracy in a wide range of fluctuations of the user's Signal to Noise Ratio (SNR) values as the user's channel conditions need to be sufficiently different for NOMA effective application (see above).

- Relatively large values of Doppler shifts and Frequency Offsets are present in Double Selective Channels.

In this chapter, chaos filtering is proposed for decoding hybrid NOMA/OMA signals from the combined one (y (t) in **Figure 1**). Moreover, two original methods, illustrated in **Figures 2** and **3**, are proposed for separating users in the NOMA scheme. **Figure 1** shows the scenario of hybrid NOMA/OMA systems. Framework is defined as follows: OMA users are typical OFDMA users while NOMA users are generated as Non-OFDMA [10] shifting the central frequency by the factor of δ related to the original OMA signal.

As in conventional CR-NOMA, the primary user is decoded first (OMA signal) and then the set of "secondary users" (multiusers) are decoded, but contrary to conventional solutions, the OMA signal is first decoded by means of the chaos-based quasi-optimum Extended Kalman Filter (EKF) and multiusers are proposed to be decoded by one of the following methods:

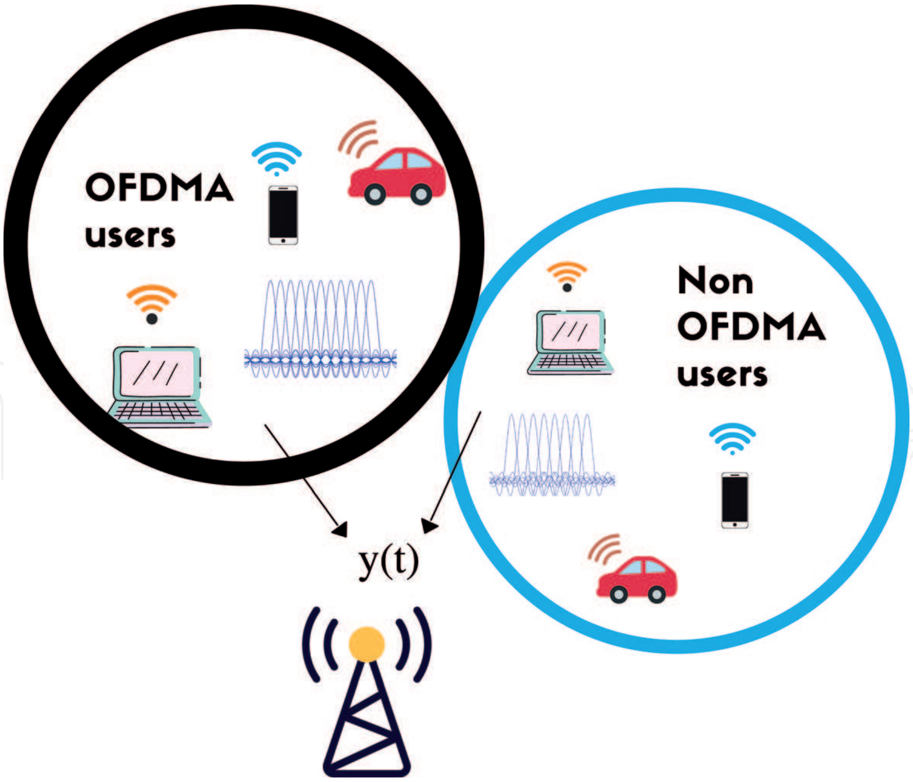

Figure 1.
A used framework of hybrid NOMA/OMA.

- Chaos-based EKF filters or

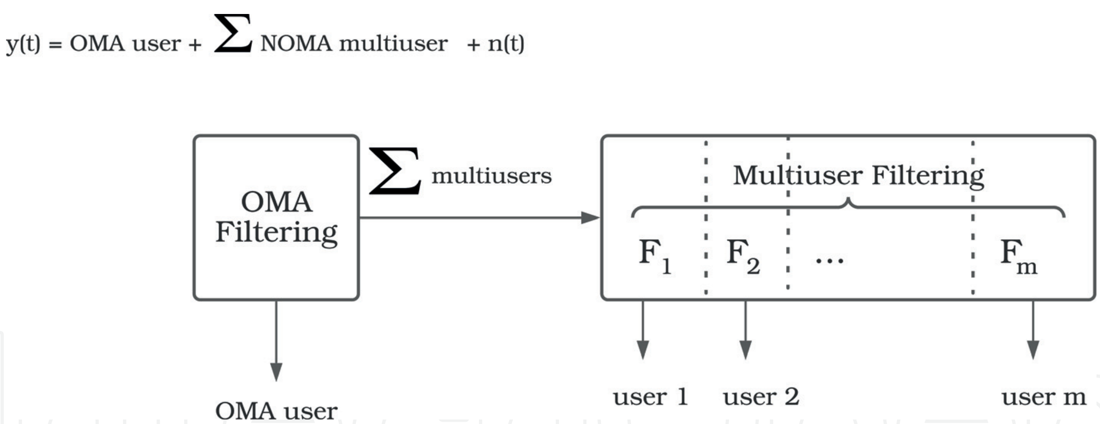

Figure 2.
Chaos-based filtering approach for NOMA users.

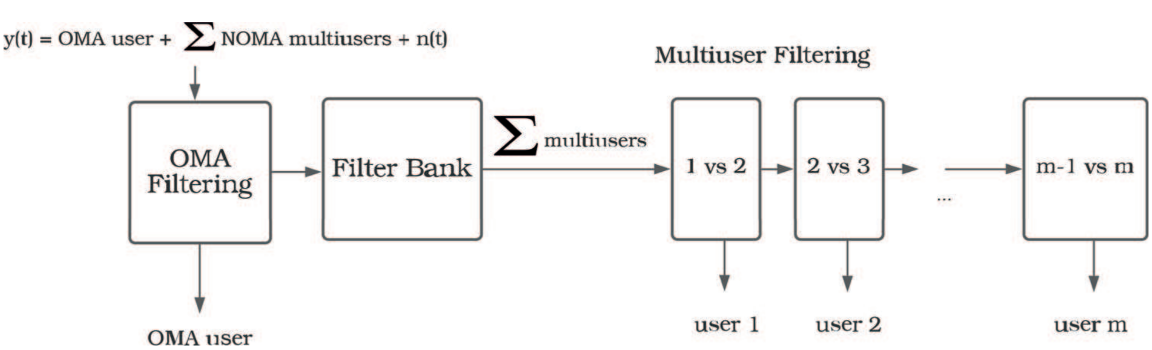

Figure 3.
Sequential m-hypothesis testing approach for NOMA users.

- Sequential m hypothesis testing.

After user's decoding, they are directed to corresponding demodulation blocks of the different services to whom they correspond. Both methods are shown to be essentially invariant to the CSI and their processing algorithms are fast and quasi-optimum Extended Kalman Filter (EKF) might give additional "benefits" for the Chaos-based filtering approach [11] (see below).

Moreover, according to [6, 7] and our own study, shown in Section 4, OMA signal and multiuser signals can be effectively approximated by means of a Gaussian random process model. Besides, the physical nature of the Doubly Selective Channels (high selectivity in both domains) shifts signals to an "almost" Gaussian random process, no matter what service they belong to. This matter gives additional "degrees of freedom" in choosing the concrete filtering algorithms for filtering: Standard Kalman Filtering (SKF), EKF, etc. for concrete conditions of NOMA transmission. This issue will be explained in the following.

The rest of the chapter is organized as follows: In Section 1 a brief overview of SIC-NOMA techniques reported in the literature is presented, Section 2 is entirely dedicated to explain Chaos-based filtering algorithms applied both to OMA signals and for the set of multiuser interferers. Section 3 demonstrates the visibility and high precision of the Chaos-based filtering. Section 4 presents simulation results for decoding the OMA signal and the rest of the multi-users. Section 5 is devoted to the Sequential Analysis testing of m hypothesis. For the hypothesis testing each signal of the multiusers will be considered in the form of time set samples of a Gaussian process with means and variances different for each of the multiusers (conditions for all users in power NOMA must be significantly different). The way of the calculus of the characteristics of the hypothesis testing is presented as well.

2. A brief overview about SIC algorithms in NOMA systems

In the last decade, NOMA methods have gained a lot of attention to increase spectral efficiency for 5G and beyond. The usage of NOMA techniques entails a lot of multiuser interference in the system; however, these methods increase the effective throughput in the system. Hybrid NOMA/OMA systems have been proposed [4, 5] to overcome the main disadvantages caused by the MAI. Several papers have dealt with SIC algorithms [1–3] and NOMA/OMA user selection [4, 5].

Authors of [4, 5, 12, 13] suggest the usage of combined (NOMA/OMA). In [12] partial-NOMA is introduced in a large two-user downlink network to provide throughput and reliability. The associated partial overlap controls interference while still offering spectrum reuse. The nature of the partial overlap also allows them to employ receive-filtering to further suppress interference. For signal, decoding was proposed, a flexible successive interference cancelation (FSIC) decoding and compared with OMA and NOMA performance.

In [12] a problem to maximize total throughput constrained to a minimum throughput requirement for each user was formulated and proposed an algorithm to find a feasible resource allocation efficiently. The results show that partial-NOMA allows greater flexibility in terms of performance. Partial-NOMA can also serve users that NOMA cannot. Different from the proposal made in this chapter, NOMA users in [14] cannot support high transmission rate requirements.

In [13] an iterative SIC receiver architecture with the pilot- and data-based channel estimation for efficient decoding of non-orthogonal superimposed signals was proposed. It was claimed that the non-orthogonal superposition concept on top of OFDMA is a promising technique to improve cell spectral efficiency. In the cellular case, the SIC multiuser receiver scheme is well adapted for user signal separation. However, authors in [13] do not work with high-mobility scenarios that entail Double Selective Channels.

Notice, that almost every proposed SIC technique in the literature strongly depends on the CSI. However, as it was stated before, the usage of the Channel State Information (CSI) or its modifications [14–16] is hardly possible, due to the Double Selective channels. Contrary to the previously published papers, new findings reported in this chapter consider the SIC impairments mitigation related to double selectivity troubles.

SIC methods for SISO channels have been extensively studied and reported in the literature. Nevertheless, in 5G and beyond networks MIMO techniques have been also proposed to increase capacity. Furthermore, with the employment of Massive MIMO techniques, as was mentioned before, the usage of CSI becomes challenging since the number of users goes large [17, 18]. At [17] a blind belief propagation (BP) detection for non-coherent NOMA with massive MIMO was proposed, where the transmitter of each user first performs differential modulation on PSK symbols, and then spreads its symbols using low-density spreading (LDS); the receiver of the base station (BS) employs differential demodulation and then detects all users' symbols using a blind BP detection without knowledge of CSI. Strictly speaking, this approach is not related to power domain NOMA, it rather belongs to CDMA-NOMA, but it was included here because of the idea of Incoherent transmission applications rarely considered in the NOMA design.

The new findings proposed hereafter use CR-NOMA principles and could be successfully applied to separate users in scenarios where the Channel State Information cannot be used, which corresponds to the incoherent ideology of NOMA transmission.

3. Chaos-based filtering algorithms outline

Real physical phenomena modeling through chaotic signals have been widely employed during the last decades and it has been recently used particularly for the purposes of interference mitigation [11, 19–21]. In this chapter OMA users, aggregated signal is modeled as a chaotic signal to efficiently separate NOMA/OMA users, as well as to differentiate between NOMA users.

Chaos modeling of physical phenomena has demonstrated to show very attractive characteristics regarding filtering precision and efficient interference suppression. As an example, in [20, 21] processing algorithms based on chaos filtering are used for mitigation of Radio Frequency Interference (RFI) produced by desktops and laptops. In this regard, the intention of the implementation of Chaos-based filtering for decoding OMA and multiusers looks almost natural. Considering that ideas of Chaos filtering were already widely published and discussed, hereafter only a brief outline will be presented, and details can be found at the cited references.

Continuous chaotic signals are generated by deterministic nonlinear systems (strange attractors) and are described generally by Ordinary Differential Equations (ODE) of the type:

$$\dot{x} = F(x, t) \tag{1}$$

Where x is an n-dimensional vector of the attractors output signals, $F(\bullet)$ is a known n-dimensional vector function and $\boldsymbol{x}(\boldsymbol{t_0}) = \boldsymbol{x_0}$ is the initial condition. Thanks to the fundamental ideas of A. N. Kolmogorov and M. Born (see references at [22–23] the statistical characterization of the deterministic systems (1) is well established.

In the following, three concrete types of attractors will be used: Lorenz, Chua, and Rössler; their statistical features are completely presented at [20]. Special cases for (1) applied hereafter (in discrete time) are:

Rössler attractor

$$x_{k+1} = x_k + T_s\left(-y_k - z_k\right)\, y_{k+1} = y_k + T_s\left(x_k + 0.2y_k\right)\, z_{k+1} \\ = z_k + T_s(0.2 - z_k(5.7 - x_k)) \tag{2}$$

Lorenz attractor

$$x_{k+1} = x_k + T_s\left(10\left(x_k - y_k\right)\right)\, y_{k+1} = y_k + T_s\left(28x_k - y_k + x_k z_k\right)\, z_{k+1} \\ = z_k + T_s\left(x_k y_k - \frac{8}{3} z_k\right) \tag{3}$$

Chua attractor

$$x_{k+1} = x_k + T_s\left(9.205\left(y_k - V(x_k)\right)\right)\, y_{k+1} = y_k + T_s\left(x_k - y_k + z_k\right)\, z_{k+1} \\ = z_k - T_s\left(14.3y_k\right) \tag{4}$$

Where $V(x_k) = m_1 x_k + \frac{1}{2}(m_0 - m_1)[|x_k + 1| - |x_k - 1|]$; $m_0 = -\frac{1}{7}$, $m_0 = \frac{2}{7}$. At (2)–(4) T_s is the sampling time.

Due to the lack of space, we take advantage that the theory and practice of Chaos-based filtering algorithms for different signals are exhaustively described and discussed at the cited references [20, 21], so there is no sense to repeat it here. Though only the concrete filtering algorithms for attractors (2)–(4) will be presented and some important conclusions are listed here [19–21]:

- Extended Kalman filter, implemented in the so-called “one-moment” (1MM EKF) and two-moment (2MM EKF) time fashion can be chosen as a “reasonable” option due to its balance between the filtering accuracy and computational complexity. Multi-moment implementations for more than two instants of time are still rather complex.

- The standard (optimum) Kalman filter (SKF) can be applied as well considering that both, OMA, and the set of multiusers can be well approximated via Gaussian models (see also Section 4), but the preference of the EKF for some scenarios will be explained below. One can suspect some “controversy” here, but it is not the case, and it does not have anything undermining of optimality of SKF for Gaussian scenarios. This issue must be explained more precisely.

- Linear SKF is strongly optimum for the linear Gaussian process models which are characterized by multidimensional Gaussian distributions with their dimensionality tending to infinity! As it will be illustrated in Section 4 it is not the case here! Hereafter, all the users are statistically described only by one-dimensional Gaussian distribution which can be approximately generated by nonlinear attractors.

- Though the above-mentioned controversy depends only on one side to the nonlinearity of Chaotic modeling of the signals and on the one-dimensional Gaussian approximation of its statistical characteristics on the other side.

- One-moment time instant (1MM) and two-moment time instants (2MM) algorithms [11, 19–21] differ in filtering accuracy, but they differ very lightly in terms of computational complexity. So, their implementation depends mainly on the concrete NOMA transmission system requirements.

- An analytical comparison of the accuracy between the EKF and the SKF in this regard is difficult to obtain but considering that models (1)–(4) are significantly nonlinear, the accuracy of the EKF might be sometimes better than the accuracy of SKF, for the Chaotic filtering. Reasons for this matter were "hinted" above and details can be found at [20].

EKF (1MM and 2MM) algorithms for chaotic attractors.

Let us present concrete algorithms of Chaos-based filtering which will be tested in the next section to choose the appropriate attractor model and the discrete-time algorithm for filtering OMA and multiuser interferences. The theory of 1MM SKF and EKF is well known and developed at [19–21], then only the corresponding results will be reproduced.

As it follows from [19–21] the SKF algorithm is optimum for a linear dynamic system, and it consists of two cycles:

Prediction:

$$\begin{cases} \hat{x}_{k+1}^{-} = f\left(\hat{x}_k^{+}\right) \\ P_k^{-} = A_k P_k^{+} A_k^T + Q_k \end{cases} \tag{5}$$

Correction

$$\begin{cases} G_k = P_k^{-} H_k^T \left[H_k P_k^{-} H_k^T + N_{0_k}\right]^{-1} \\ \hat{x}_k^{+} = \hat{x}_k^{-} + G_k \left[y_k - s\left(x_k^{-}\right)\right] \\ P_k^{+} = P_k^{-} + G_k H_k P_k^{-} \end{cases} \tag{6}$$

The algorithm for EKF 1MM is the same as (5) and (6) but with a small modification due to its quasi-linearity, as shown in the following. It must be stressed that the SKF is an optimum algorithm for the strongly Gaussian signals and the 1MM EKF algorithm is quasi-optimum for nonlinear Chaos models, so the accuracy of its filtering (in our case in terms of Normalized Mean Squared error MSE) is not the highest one for the Gaussian approximations of its statistics, but as it is shown at [19] it is practically acceptable for most applications. The 2MM EKF algorithm was proposed recently [19–21] and is totally heuristic; besides it is quasi-optimum as well.

It is time to stress that optimum (or quasi-optimum) filtering algorithms for Chaos Filtering demonstrate (with different grade) so-called **singular** features (see [19–21]) which practically belongs to the low dependence of the precision of filtering (in our case of MSE) to the input value of the Signal to Noise Ratio (SNR).

Meantime, the accuracy of the 1MM EKF and 2MM EKF does not demonstrate totally their "singular" properties as optimum ones (see [19–21]), but anyway those algorithms are accurate and highly recommended. Why it happens actually?

One must notice that Eqs. (1)–(4) and generally all attractors considered hereafter (see [19–21]) describe the deterministic system dynamics. In order to apply so-called statistical dynamics of the deterministic systems according to A. Kolmogorov and M. Born all dynamics of attractors (2)–(4) and the measurement of the state of the system are tied to the statistically independent noises with the a priori known covariance matrixes given by additive white noise with the intensity N_{0_k} and very small "process noise "for Eqs. (1)–(4) with the matrix Q_k[1] respectively. So, one can see that the ordinary differential Eqs. (OE) of attractors turn to the Stochastic Differential Equations (SDE), for which all the filtering theory is developed [22, 23].

In (5), (6) $G_k$is the so-called Kalman gain, $\hat{x}_k^-$ is the a priori state estimate in the k-th update cycle, $\hat{x}_k^+$ is the a posteriori state estimate in the k-th update cycle, P_k^-, P_k^+ are respectively the a priori and the a posteriori error covariance matrix estimate in the k-th cycle, A_k is the fix state transition Matrix (for SKF) or for the 1MM EKF the linearization matrix (Jacobian) $A_k = \frac{\partial f(x_k)}{\partial x_k}$ denotes "quasi-linearity" for 1MM EKF.

For 2MM EKF, P_k^- in (5), becomes [19]:

$$P_k^- = A_k P_k^+ \left(1 - \rho^2\right) A_k^T + Q_k \tag{7}$$

where ρ is the correlation coefficient of two adjacent samples.

Though if the intensity of the process noise (by definition) is always much less than intensities of the channel additive white noise (AWGN) influence of the "correction" part on the estimations of the signal is almost invariant to SNR (to which depends on a-priori an a-posteriori error matrixes) and practically follows the a-priori data. In other words, the filtered signals are "tuned" to the a-priori data or to processes generated by Eqs. (1)–(4). It is a brief "physical" explanation for the singularity of chaos filtering. For sure at [19–21] the interested reader might find more rigorous proof.

The rest of the equations in (5) and (6) remain unchanged and it can be easily seen that the filtering algorithm, in general, is the same [19–21]. Thus, the processing time (number of samples) for 1MM EKF and 2MM EKF are almost the same but filtering accuracy might differ significantly. The latter was illustrated for signals of different physical nature at [19–21] and at Section 4.

It is worth mentioning once more to conclude, that chaos-based algorithms (including certainly SKF and EKF) are based on Ordinary Differential Equations (ODE) of chaotic deterministic dynamics and they have a very important and spectacular property, the so-called "singularity" for their solutions. In other words, the filter's output signal is somehow "tuned" to its a-priori dynamics or to its mathematical model applied in the filtering algorithm, while the influence of the "correction" component of the algorithm is negligible for any reasonable value of the additive channel noise (AWGN) intensity. That is why the filtering accuracy is high, even for quasi-optimum algorithms and the filtering fidelity (in terms of the Normalized Mean Square Error, MSE) shows a rather low dependence on the input SNR. All those features will be illustrated in the next section.

4. Simulation results

Simulations presented in this section are dedicated to simulating a hybrid NOMA/OMA system using chaos-based filtering for recovery of the primary OMA signal. The process is simulated as indicated in **Figure 8**; the aggregated signal of OMA signal, NOMA signal, and AWGN noise. NOMA interference is the sum of non-orthogonal (NOMA) carriers [10][2]. EKF-1MM algorithm (5)–(6) is used to

[1] Once more: introducing the processing noise according to A. N. Kolmogorov and M. Born is fundamental for statistical characterization of the deterministic systems (see references at [22–24]).

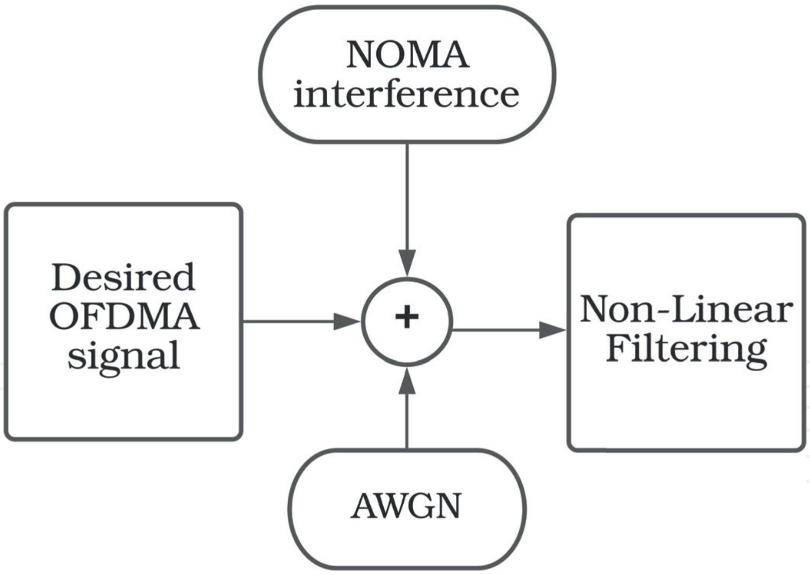

Figure 4.
Filtering scenario.

non-linear filtering OMA signal as indicated in **Figures 2, 3**, and **4**. As a reference, the IEEE 802.11a standard is considered here, where 52 carriers are used for modulated data, 4 pilot carriers, and 8 guard band carriers.

Generation of orthogonal and non-orthogonal signals.

Typical orthogonal signals are OFDMA symbols that are formed using IFFT as illustrated in the following figure.

In **Figure 5**, b_k is a set of binary pulses suitable for typical modulations such as BPSK, QPSK, etc. The pulses are passed from serial to parallel form and then multiplied by N orthogonal subcarriers using the IFFT, k is an integer number that goes from 0 to $N-1$, $\Delta f = 1/T$, $T$is the OFDMA symbol period which it can be set to 1 without loss of generality. The set of $N-1$ orthogonally modulated carriers are then summed to finally yield the orthogonal OFDMA signal $x(t)$.

In our case, the generation of the orthogonal signal was made by using the following scheme as is explained below.

The scheme of **Figure 5** uses IFFT and so the resulting signal $x(t)$ is complex, while in **Figure 6**, signals are real which makes the subsequent processing much simpler. Moreover, in the scheme of **Figure 6**, it is much easier to manipulate f_k to make it not to be an integer. This is useful for the next set of signals that would be part of the experimental setting. In our case, OFDMA and No-OFDMA multicarrier signals are simulated in the same way by using the scheme presented in **Figure 5**. Manipulating the carrier central frequencies with constant integers (OFDMA case) or non-integer constants δ (NOMA case).

The next set of signals that will be used are non-orthogonal (NOMA signals), and this is achieved using the scheme of **Figure 6** by multiply f_k by a non-integer constant, say $\delta = 0.8$.

As it was established previously, Doubly Selective Channels (high selectivity in both domains) shift signals to an “almost” Gaussian random process due to their physical nature, no matter what service they belong to. Thus, the set of corresponding signals that are considered in this chapter was processed to obtain

[2] The scenario in which multiuser signals are filtered by the bank of the Chaos-based filters and each element belongs to the specific multiuser could be also considered. This case might be treated in the same way, assuming that the OMA signal is extracted from the input.

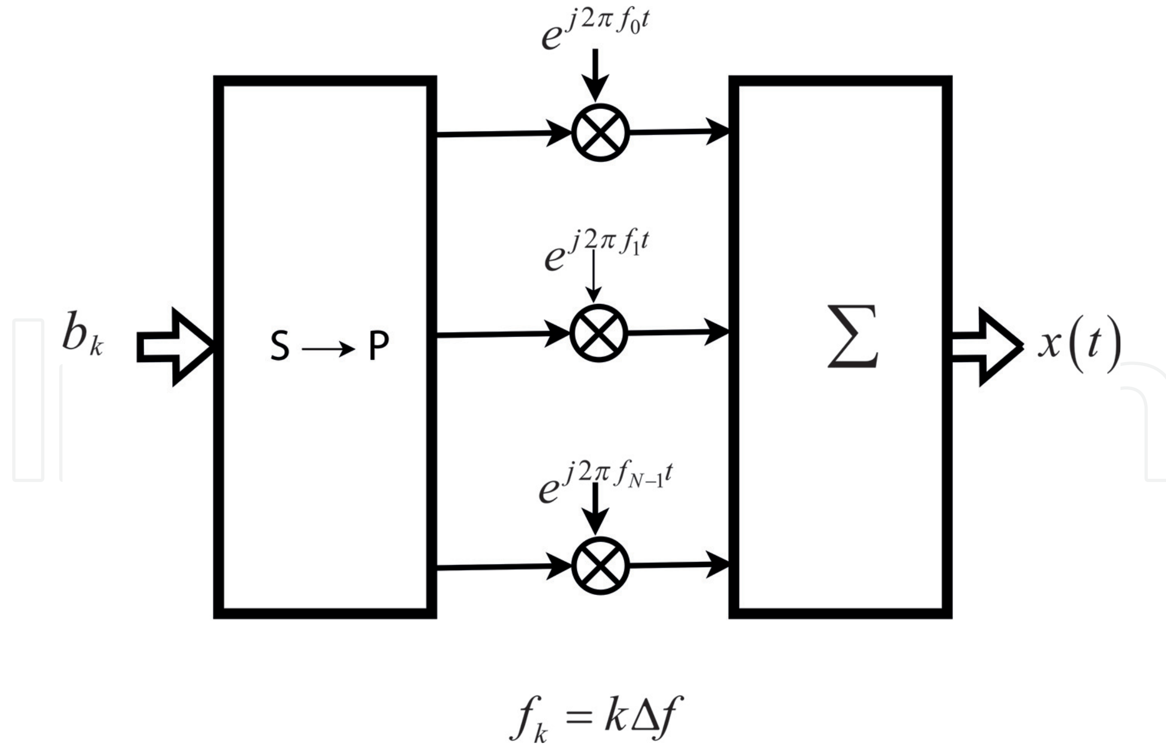

Figure 5.
OFDMA symbol forming.

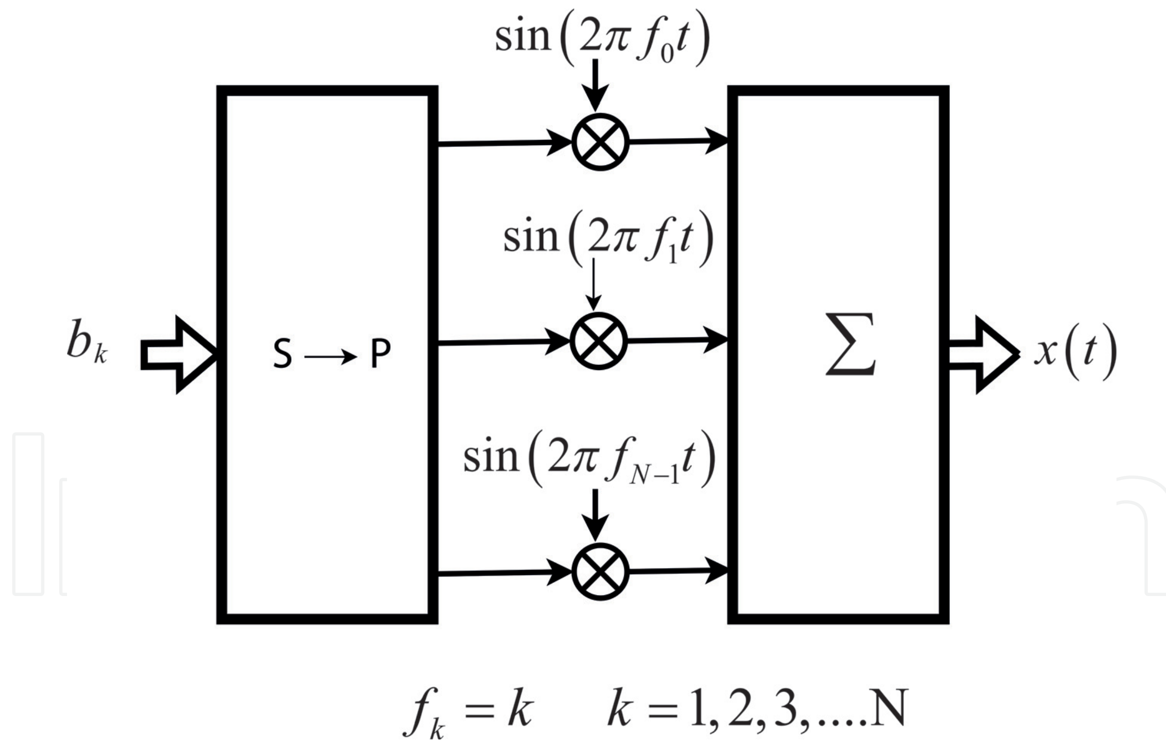

Figure 6.
OFDMA symbol forming used in simulations.

their statistical characteristics: PDF and autocorrelation function shown in **Figures** 7 and 8.

In the following, we explore how effective the EKF-based non-linear filtering (IMM and 2MM) can be, when it is applied to OFDMA(OMA) signals under the influence of AWGN and NOMA interference.

From now on, it will be considered, that the AWGN noise contributes with 50% of the total noise power and the ACGN contributes with the other 50% of the total

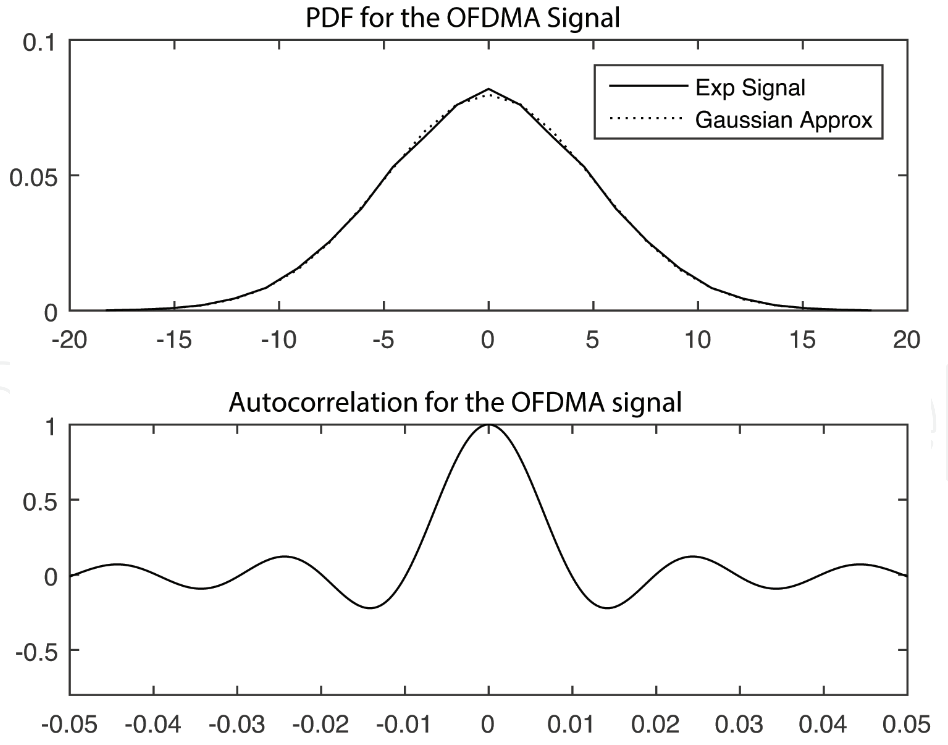

Figure 7.
PDF and autocorrelation for the OMA signal.

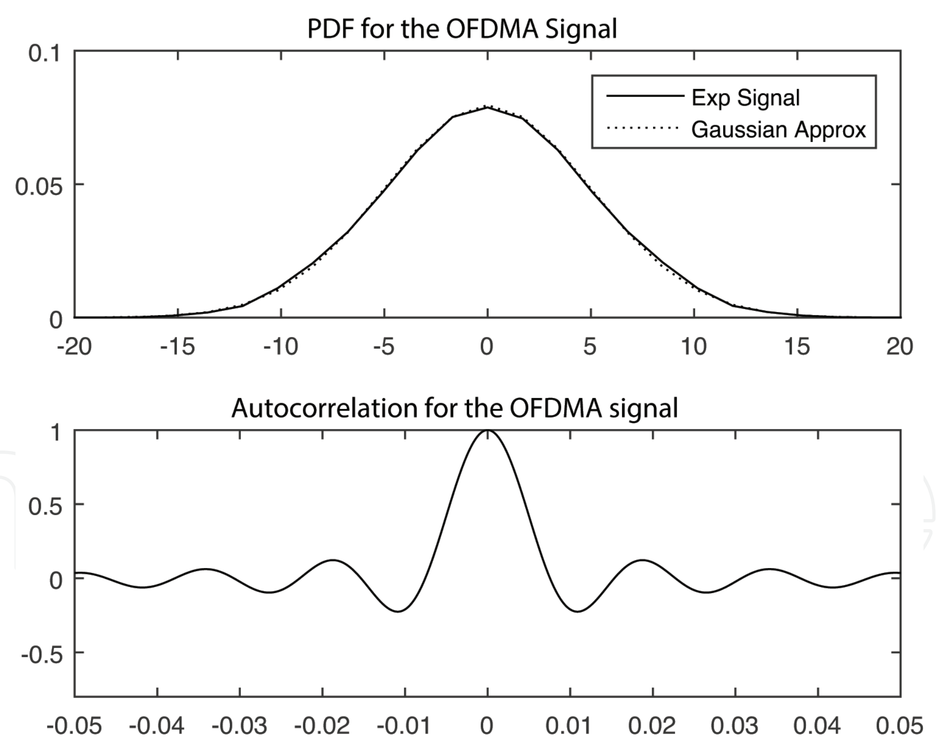

Figure 8.
PDF and autocorrelation for the NOMA signal.

noise power. Then, we will shape the SNIR (Signal to Noise to Interference Ratio) which is used in the EKF structure.

Two different experiments were conducted to test the Normalized Mean Square Error in terms of the SNIR. The experiments consider an OFDMA signal with 52 carriers as an OMA signal. The NOMA interferences were generated according to two proposed scenarios:

Scenario 1:

NOMA Signal: Non- Orthogonal FDMA with 52 carriers separated with $\delta = 0.8$ between carriers

OMA Signal: OFDMA with 52 carriers

Scenario 2:

Two OFDMA signal blocks with 52 carriers each, with a factor of 2.4 between central frequencies of each block.

The number of carriers was chosen rather high to guarantee the Gaussianity of the PDF of the signal, but one must notice, that it rather “arbitrary” and not critical.

After testing the x, y and $z$components of the Rössler, and Chua Attractors, it was found by comparing the correspondent statistical characteristics that only the x component of the Rössler and Chua attractors could be used for modeling and filtering.1MM and 2MM filtering was processed according to algorithms (5)–(7) and the results obtained are almost similar to the ones presented at [19].

Tables 1 and **2** show the results for experiments 1 and 2 respectively in terms of the SNIR vs. normalized MSE (Mean Square Error). Both tables also show the results in terms of the MSE for the filtering using Rössler’s and Chua’s $x$components. Note that the theoretical filtering according to (5)–(7) includes the influence of process noise Q. **Tables 1** and **2** also show the process noise values that allow adequate filtering (small MSE values) for the different SNIR values and the two attractors.

It must be noticed that Intensity Matrix for process noises Q is rather small (much less, than one) and even for very low SINR values (-10 dB) the MSE is much less than 10% and for SINR- 0 dB it was much less than 1%. Though, the accuracy of filtering is high enough for separating(classification) signals of OMA and multi-users. The explanation of the latter is simple: if the MSE is about of several percentages it means that close to 100% of the energy of the desired signal for its further demodulation is preserved and therefore bit-error-rate practically does not decrease. This “benefit” takes place because of the singular properties of Chaos-based algorithms for filtering (see above) which are somehow valid even for quasi-optimum EKF filtering in very hard interference scenarios.

It can be seen from **Figures 2** and **3** that the proposed SIC filtering algorithms are working not as a decoder but as a classifier for OMA and NOMA signals and when the OMA signal is well filtered (identified), then the multiuser interference

	EKF Rössler X		**EKF Chua X**	
SINR	**-3 dB (Q = 0.12521)**	**10 dB (Q = 0.2)**	**-3 dB (Q = 0. 0925)**	**−10 dB (Q = 0.25)**
1MM	0.0109	0.052	0.0139	0.0705
2MM	0.0103	0.047	0.0138	0.0672

Table 1.
MSE results for experiment 1.

	EKF Rössler X		**EKF Chua X**	
SINR	**-3 dB (Q = 0.25)**	**−10 dB (Q = 0.2)**	**-3 dB (Q = 0. 125)**	**−10 dB (Q = 0.325)**
1MM	0.0119	0.0504	0.0143	0.0730
2MM	0.0107	0.0487	0.0134	0.0677

Table 2.
MSE results for experiment 2.

separation or classification might be evaluated by the probability of classification error P_{cl}. The latter obviously affects the final bit-error-rate of the demodulation for all users (P_{err}).

One of the possible ways of evaluating P_{cl} for multiusers classification or for OMA-multiuser classification is applying the so-called DGL, or Chernoff upper bound in the way [24]:

$$P_{cl} \le 2m(m-1)^2 e^{-n\frac{\Delta^2}{2}} \tag{8}$$

where Δ is the minimum Kullback–Leibler distance between "closest" Gaussian distributions of the multiusers, n is the number of samples and m is the number of multiusers. For OMA-multiusers classification the total number of users is $m' = m + 1$.

If $\forall P_{err}, P_{cl} < < 1$ then it is easy to show that the resulting demodulation error P for each signal is:

$$P \approx P_{err} + P_{cl} \tag{9}$$

and if practically $P_{cl} \ge P_{err}$, then approximately $P_{cl} < P < 2P_{cl}$, i.e. it is defined mainly by errors of the multiuser classification. So, from (9) it follows that minimization of P_{cl} is crucial for the noise immunity of the NOMA transmission.

In this regard, the important question arises: what signal must be filtered first: OMA or multiusers? At the material presented above it wass stated that the OMA signal needs to be filtered first, however, this is an open question that must be thoroughly investigated in the future. In the meantime, some recent simulations show that filtering NOMA interferences first to "clean" the OMA signal (before its filtering) might be a rather complex issue, but it can give significant benefits in terms of reducing the MSE for the OMA signal decoding.

5. Multiuser classification by means of m sequential hypothesis testing algorithms

As it was established before, OMA signal is recovered through EKF filtering and then, NOMA users could be efficiently decoded by one of the following methods:

- Chaos-based EKF filters, using the same procedure as described before.
- Sequential m-hypothesis testing: due to the sequential character of multiuser decoding with SIC algorithms for the CR-NOMA it seems reasonable to apply here an adequate implementation of the decoding strategy, i.e. m-sequential hypothesis testing algorithms. To the best of our knowledge, this option for SIC design wasn't discussed before in the literature.

The advantages of these algorithms for binary testing are well known long ago from A. Wald [25], but the results of their generalizations for the case of m hypothesis testing are mainly addressed to its tiny mathematical problems [24–29] and very few to its implementation.

For practical implementation, their solutions seem rather complex except in a few special cases. Other options ("ad-hoc") so far are based on the heuristic extensions of the binary test to the case of the m hypothesis (see also below).

In this regard it was found reasonable to invoke the results from [29] together with the approach stated at [26] where the asymptotic approximates for the optimum Bayesian algorithms for testing are presented for the case of small probabilities of decoding errors and an expected rather long testing time, particularly for low SNR cases. Both those assumptions might be realistic for SIC design at Doubly Selective channels, applying the Gaussian statistics as well.

Here, it is time to remind, that NOMA transmission, as it was commented above, needs sufficiently different channel conditions for the users, including certainly multiusers as well. Though channel conditions for OMA and multiusers are assumed as significantly different, but between multiusers it is not always the case, i.e. hypothesis for multiusers might be "close", therefore testing time might be large!

The extractions from [26, 29] for the asymptotic characteristics of the algorithm are as following:

$$\langle N_k \rangle = -\frac{\log A_k}{\min\limits_{j:j\neq k} D\left(f_k, f_j\right)} \quad \alpha_k = \pi_k A_k \gamma_k \qquad \alpha = \sum_{k=0}^{m-1} \pi_k A_k \gamma_k \tag{10}$$

Where $D(f,g) = \int f(x) \log \frac{f(x)}{g(x)} dx$ is the Kullback-Liebler distance between the PDFs f(x) and g(x); $\langle N_A \rangle = \bar{N}_A$ is the average value of the first $n \geq 1$ when the decision for the hypothesis is taken; $\{\pi_k\}$ a priori probabilities of hypothesis.$(k = \overline{1, m})$, $\{\gamma_k\}$ and $\{A_k\}$ are detailed below.

In the usual case when the value of the probability α is predefined, from (10) it follows:

$$c = \frac{\alpha}{\sum_{k=0}^{m-1} \frac{\pi_\kappa}{\delta_k}}, \qquad \delta_k = \min_{j:j\neq k} D\left(f_k, f_j\right), \qquad A_k = \frac{c}{\delta_k \gamma_k} \tag{11}$$

where $0 < \gamma_k < 1$ is tabulated in Table 3.1 at [26, 29].

For concrete data, using (10)–(11), the asymptotic characteristics for m-testing can be calculated. It should be noticed that the essence and benefits of any sequential algorithm strongly depend on the choice of the threshold which defines the decision region for testing [26, 29]; the data processing algorithm can be: coherent (incoherent), energy detection, etc. which are well known [26].

For the concrete case of a Gaussian channel for all multiusers, where the decoding problem for multiusers depends on their SNR, QoS, amplitudes, average power, etc. the formal scenario is as follows: let $k = \overline{0, m-1}$ for hypothesis testing $\{H_k\}$and $x_1, x_2, \ldots$ is a sequence of independent Gaussian random variables with means $\{\theta_k\}$ and variances σ_k^2, which are known a priori (see also [21, 26]). If $\{x_k\}$ are multiuser amplitudes, the data processing algorithm is obvious: $\sum_{i=0}^{n} x_i$, and the results must be compared with the asymptotic thresholds for each "k" as follows [28]:

$$\frac{n(\theta_k + \theta_{k+1})}{2} + \frac{\log A_k}{\theta_{k+1} - \theta_k} \quad \frac{n(\theta_k + \theta_{k+1})}{2} - \frac{\log A_{k+1}}{\theta_{k+1} - \theta_k} \tag{12}$$

Where $k = \overline{0, m-1}$.

It is interesting to express here a remarkable issue: these asymptotic algorithms correspond exactly to the set of simple binary algorithms for testing: H0 vs. H1; H1 vs. H2 and so forth, i.e. are "ad hoc"(see above). This corresponds totally with the intuitive processing of the m-tests as a straightforward generalization of the binary sequential test (called "ad-hoc" [25, 28, 29]) that was known long ago and shown at [29] as an asymptotically optimum for m-hypothesis testing.

Therefore, in the Gaussian case the m-decoding asymptotic algorithm is nothing else but a "block" of cells each for the sequential testing of the different binary hypotheses of the multiusers, see **Figure 3**.

The examples of numerical results, for this testing can be found at [25], which show that for such kinds of algorithms the number of samples (time of analysis) can be reduced 2 or 3 times compared with the optimum algorithm for the fixed time testing. The latter follows exactly from the convergence of the m testing to the (m-1) set of "binary" algorithms well known several decades ago and rigorously presented first by A. Wald.

It is worth mentioning that robust features to the multiuser statistics follow due to the asymptotic character of the proposed algorithms. But the latter requires some further investigation.

6. Conclusion

It was shown earlier that because of the numerous impairments and distortions that take place in Double Selective channels, it is rather "hard" to obtain high values for characteristics, such as noise immunity and spectral efficiency in Doubly Selective Channels which usually appears in 5G and beyond networks for information transmission from HSV terminals.

The material presented above is devoted to two new options for users' separation in hybrid NOMA /OMA schemes related to the power CR-NOMA information transmission over-application of NOMA to improve the spectrum efficiency paradigm in SISO channels. It has been demonstrated that non-linear filtering is effective to separate OMA/NOMA users in hybrid schemes.

Moreover, two possible approaches for SISO channels were proposed for mitigation of the multiuser's interferences, namely a Chaos-based filtering approach and an approach based on the m sequential hypothesis testing. Both, show several attractive invariant features for application over Doubly Selective SISO channels such as high fidelity for multiuser decoding, robustness, and reduced decision time, which allows recommend them not only for Doubly Selective channels but also for the "conventional" channels as well, besides a large number of already reported algorithms for them (see [25–29] and references therein).

Previously published papers, where chaotic filtering is used for other applications [19–21], show that proposed algorithms here can be effectively implemented in hardware.

Proposals for future research

It is worth mentioning the existence of a solid number of unsolved problems for OMA/NOMA separating users, particularly for Doubly Selective channels. They are as follows:

- Both proposed methods need to be exhaustively compared for a broad range of impairment features that might exist at Doubly Selective channels.

- Generalizations of CR-NOMA for MIMO Doubly Selective channels and Massive MIMO. It seems, that besides the SIC is a pre-processor block before the main receiver unit (the latter is already well known [14, 15, 30]), for applications at MIMO over Doubly Selective channels, the before mentioned algorithms might require significant modifications.

- The power NOMA paradigm (see also CR-NOMA) must be sufficiently generalized by application of invariant methods of incoherent modulation and demodulation (see [15], etc.)

- It seems extremely promising to complete NOMA transmission for the Double-Selective Channels with block-chain access for application in Massive MIMO networks to improve the Spectrum Efficiency Algorithms for m-hypothesis of the transmission both from the physical channel and network access.
- Algorithms for m hypothesis testing (see Section 5) need to be precisely investigated for their invariant properties in Doubly Selective Channels.

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