

Interference Cancellation Receivers in a Device-to-Device Network

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Abstract—Nowadays, the number of users and connected devices linked to a network is very large. For that reason, new technologies that do not need network support, such as Device-to-Device communication (D2D), have been explored. Due to the lack of support from the cellular network infrastructures, communications between devices occur randomly, uncoordinated and unscheduled, resulting in the appearance of interference. Hence, the purpose of this document is to study and create new procedures that allow the resolution of this problem.

To achieve this aim, a link level simulator and a system level simulator are designed with the purpose of evaluate, in terms of complexity and performance, several processes that take advantage of the Successive Interference Cancellation (SIC) technique. Particularly, the D2D network performance is assessed when there is no use of any kind of SIC, when intra-SIC is applied and when intra-SIC and inter-SIC are both used in a typical Slotted ALOHA scheme.

With the simulations and studies performed, it was proven that when there is no use of any type of SIC, the performance obtained is very low. However, with the increase of complexity, applying intra-SIC, the performance increases up to 50% and the increase reaches 70% when the two types of SIC, intra-SIC and inter-SIC, are applied.

Keywords—Device-to-Device communications, Successive Interference Cancellation, intra-SIC, inter-SIC.

I. INTRODUCTION

In the past years, due to larger improvements at engineering level and continuous development of technologies, smarter devices have reached the world. Their complexity exceeded the current network capabilities requiring the development of a new network standard, 5th Generation (5G).

One of the promising technologies, currently being study, to insert in 5G cellular networks is Device-to-Device (D2D) communications.

In conventional cellular systems, all communications must go through the base station (BS), even if both users are within a small distance. The BS is responsible for almost every aspect that enables the communication between multiple devices. However, in accordance with the 3GPP (3rd Generation Partnership Project) standard, in specific cases where user's equipment are in proximity, as commercial/social services, or even in case of cellular network infrastructure failure, with D2D technology there is

no need to pass the information through the cellular network infrastructure.

This project is focused on a D2D network (certain amount of devices in a specific area, communicating between each other using only D2D communication) working in unlicensed band and out-of-cellular coverage which implies that it does not have any support from cellular infrastructures. Notice that, the study will be for long range communications. The network setting is presented in Fig. 1.

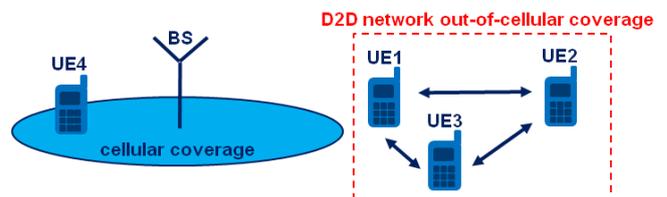


Fig. 1. D2D network setting.

Before a D2D link can be established, the following three processes need to be completed: Synchronization, Discovery and Communication. In this project, the emphasis is done in the discovery process which is when one device tries to find other nearby devices. Due to the lack of coordination in the proposed setting, since there is no support from the cellular network, one of the several challenges to be overcome in this process and the main focus of this project is the interference.

A. State of the Art

Many researchers and mobile companies are concentrated in interference between cellular networks and D2D devices because their current focus is in the introduction of D2D in 5G cellular networks. Hence, a significant amount of research papers present in the literature exposes interference cancellation techniques that take advantage of network support done by the infrastructures or the fact that D2D and cellular devices share the same licensed spectrum [1] [2].

However, in this project, the D2D devices do not have any support from the network infrastructures and work in unlicensed spectrum, the focus is then on methods to cope with the interference between these D2D devices. One solution proposed in the literature to deal with this kind of interference is to introduce interference cancellation at the receiver; this can be implemented into the receiver architecture of the D2D devices in the form of Successive Interference Cancellation (SIC) or Parallel Interference Cancellation (PIC) [3].

B. Objectives

The purpose of this project is to create an original solution that can take advantage of the two sides of a D2D communication – transmitter and receiver – and of a known existing technique – SIC – creating a new procedure that has benefits when comparing to existing techniques and can be used to mitigate interference in the specific setting in consideration.

First, to achieve this goal, the proposed solution is well-designed. Then, in order to evaluate it, a system is developed with the implementation of a Link Level Simulator (LLS) and a System Level Simulator (SLS) with the support of the software Matlab 2017a. Finally, an evaluation of the proposed solution, in terms of performance and complexity is performed.

Note that this project was done in collaboration with the company Intel Mobile Communications in Aalborg, Denmark and it allowed the creation of an Intel patent.

C. Document Structure

This document is structured as follow: in section 2, fundamental concepts to understand how the proposed solution is inserted in the technologies that already exist are presented; in section 3, the solution proposed to mitigate the problem in consideration is defined; in section 4, it is explained very briefly how the implementation of the system for evaluation of the proposed solution was done; in section 5, results are presented and analysed and different techniques are studied and discussed in terms of performance and complexity and finally; in section 6, conclusions and future work are drawn.

II. FUNDAMENTAL CONCEPTS

In this section, fundamental concepts required to understand and develop this project are briefly described.

A. Successive Interference Cancellation

In D2D communications, multiple users can send their information to a common receiver; multiple access techniques allow the division of the channel between the users. In the specific setting, defined in the previous section, since it is an uncoordinated network, the focus is on a multiple access scheme named slotted ALOHA. In this scheme, the time is divided in equal-duration slots, that allow the transmission of packets, and each user can start the packet transmission only at the beginning of a timeslot.

In a standard network, when multiple users transmit to the same device, this would result in a collision, as depicted in Fig. 2, and in most cases only the strongest signal would be decoded by the receiver.

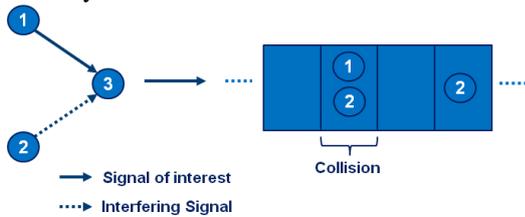


Fig. 2. Example of random access.

Successive Interference Cancellation (SIC) is a method that allows a receiver to decode multiple received signals, thus coping with the collided received signals.

Consider the example in Fig. 2 For this specific case, where there are two senders (user 1 and user 2) and one receiver (user 3), the received signal in the collision slot is

$$y = h_{13} \cdot x_1 + h_{23} \cdot x_2 + n \quad (1)$$

where x_1 and x_2 are, respectively, the zero-mean Gaussian complex signal transmitted by the devices 1 and 2, such that the respective variances are $E[|x_1|^2]=P_1$ and $E[|x_2|^2]=P_2$, where P_1 and P_2 represent the constant power levels used by the devices 1 and 2, respectively; n is a complex Gaussian variable that contains the noise such that the respective variance is $E[|n|^2]=N$, where N is its power level; h_{13} and h_{23} are the complex gains of the channels from device 1 to 3 and from device 2 to 3 respectively; and finally, y is the received signal in device 3 [4]. Note that for ease of exposition it is assumed that the channel between the devices, h_{13} and h_{23} , are constant and for simplification equal to 1.

When using SIC, the process starts with the decoding of the strongest signal (as an example it is assumed that the strongest signal is x_2). To decode x_2 , x_1 is treated as interference. Hence, if the signal-to-interference-plus-noise ratio of user 2 at 3 is higher than a certain threshold:

$$\text{SINR}_{23} = P_2/(P_1+N) > \tau \quad (2)$$

the signal from user 2 can be decoded. It is then subtracted from the received signal in the following manner:

$$\hat{y} = y - \hat{h}_{23} \cdot x_2 \sim h_{13} \cdot x_1 + n \quad (3)$$

where \hat{y} is the received signal without the contribution of the user 2 and \hat{h}_{23} is the user 2 channel estimation. After, from what is left, \hat{y} , if the signal-to-noise ratio of user 1 at 3 is higher than a certain threshold,

$$\text{SNR}_{13} = P_1/N > \tau \quad (4)$$

x_1 can be decoded. With this, it is shown that SIC can solve collisions.

B. Reference Signals and Channel Estimation

In order to enable the receiver to estimate the channel needed for the SIC process, reference signals (RS) or pilots, which are specific data placed in specific positions in the transmitted data, as depicted in Fig. 3, are used.



Fig. 3. Payload of messages.

Channel properties change as a function of place and time, so with the knowledge of the received pilots and the transmitted pilots, the receiver can estimate the channel at given positions. In the specific case of D2D, Demodulation Reference Signals (DM-RS) are used. To determine the channel in the rest of the positions (data positions), this project is based on the channel estimator Minimum Mean Square Error (MMSE). This is already a complex type of

channel estimation because it requires matrix inversion and the calculation of covariance matrixes,

$$\hat{H}_{\text{MMSE}i} = R_{h,hp} \cdot (R_{hp,hp} + R_{ri} \cdot I)^{-1} \cdot \hat{H}_{\text{LS}i,p} \quad (5)$$

$$\hat{H}_{\text{LS}i,p} = x_{i,p}^{-1} \cdot y_p \quad (6)$$

$$R_{n,n'} = J_0[2 \cdot \pi \cdot f_{D\max} \cdot (n-n')] \cdot T_{\text{sym}} \quad (7)$$

being $\hat{H}_{\text{MMSE}i}$ the MMSE channel estimation of signal i , $\hat{H}_{\text{LS}i,p}$ the least square (LS) channel estimation, with pilot symbols, of signal i , $R_{h,hp}$ the covariance matrix between pilots and data, $R_{hp,hp}$ the pilot's auto-covariance matrix, J_0 the zeroth-order Bessel function, $f_{D\max}$ the maximum Doppler shift, T_{sym} an SC-FDMA symbol period, $(n-n')$ the difference between index n and n' , R_{ri} the noise covariance matrix of signal i , I the identity matrix and $x_{i,p}$ and y_p the transmitted pilot symbols from signal i and received pilot symbols respectively. With this baseline it is possible to differentiate two types of channel estimation:

- MMSE-Maximum Ratio Combining (MRC), that treats the interference of other signals that may interfere as noise.
- MMSE-Interference Rejection Combining (IRC), that considers the effect of other interfering signals in the process.

Note that although MMSE-IRC requires more complexity, since it needs to know more information about the interfering signals, it is expected to have better performance due to the fact that takes its consideration in its process.

C. Types of SIC

In practice, the real process that is being considered in this project can be composed by two types of SIC: intra-SIC (realization of SIC within a slot) and inter-SIC (realization of SIC with data from a priori processing). Note that in this case, time is divided in equal duration slots, as in the slotted ALOHA, but also organized in frames; and each user can send a certain number of replicas of its packet in a frame. Let us analyse this process with the example in Fig. 4.

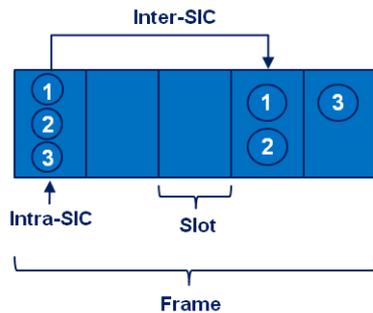


Fig. 4. Real process that includes two types of SIC.

Here, it is shown three users (1, 2 and 3) transmitting replicas of its packets in multiple slots of a frame. The receiver will process each slot of the frame starting by analysing slot 1. Exploiting decoding techniques, it tries to decode the strongest signal in this collision slot, even with

the presence of other interferers in it. Here it is considered that the signal from user 1 is the strongest. If this signal is decoded correctly, it is subtracted from the received signal in this slot and then, the receiver tries to decode the second strongest signal in this slot (for example, signal from user 2) and so one. At this stage the receiver tries to decode a maximum number of signals in this slot and the ones that are decoded correctly are subtracted from the received signal in that slot and kept its information in a memory buffer. This subtraction process is called intra-SIC. Imagine that the signal from user 1 was decoded correctly but the signals from user 2 and 3 were not. At this point, the decoded user packet from user 1 is stored in a memory buffer. Later, when the receiver is processing slot 4, it can use the information kept in the memory buffer to cancel/subtract (inter-SIC) the replica of the packet from user 1 and try to decode the packet from user 2 again without the presence of the packet from user 1.

III. PROPOSED SOLUTION

The purpose of this project is to mitigate the interference problem with a technique that includes both sides of the communication link:

- At the transmitter side, it is used a set of transmission patterns that are used in a random manner by the transmitter to send its packets and a set of multiple orthogonal pilot sequences from where a user randomly chooses one to insert in its message payload structure.
- At the receiver side, it is proposed an adaptive architecture that allows the use of two different types of Successive Interference Cancellation (SIC), inter and intra.

A. Key Concepts

As said before, this project is focused on the discovery process. In the discovery process, as shown in Fig. 5, a discover initiator (DI) device sends a message 1 (MSG1) to a discover replier (DR) device, so it can be discovered by it. If a DR receives its message, it sends a message 2 (MSG2) back to DI. If the DI successfully receives MSG2, a discovery session just occurred. In case the DI does not receive MSG2 when expected, it sends a retransmission of MSG1.

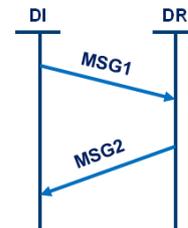


Fig. 5. Discovery protocol.

As introduced, a D2D link is divided into three phases: Synchronization (S), Discovery (D) and Communication (C). Hence, each frame has different resources available for each phase, as depicted in Fig. 6.



Fig. 6. Frame structure.

In order to have a flexible architecture at the receiver side and to take advantage of the use of inter-SIC, the concept of virtual frame is introduced. A virtual frame (VF) is a group of L consecutive discovery slots in which it is possible to exchange information between slots belonging to the same VF. As will be seen later, the number of discovery slots in a VF is one of the key design parameters of this method, which allows to satisfy latency and memory requirements. The way the VF is constructed is presented in Fig. 7.

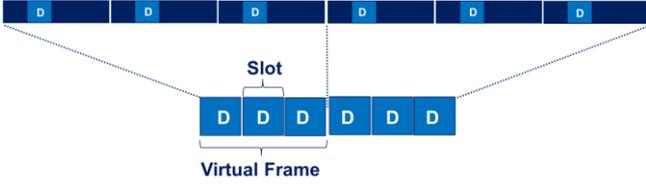


Fig. 7. Virtual Frame construction.

B. Transmitter Side

Now, the transmitter side of the proposed solution is described. At the transmitter side, the simultaneous transmission of MSG1 generates interference for the DRs that are waiting for their reception. Hence, our goal is to avoid this overlap between MSGs1. Taking as parameters the number of replicas per packet per virtual frame and the size of the virtual frame, a set of possible patterns from where the DI can choose from to send its message is created. Note that the devices are half-duplex, meaning that if MSG1 is transmitted in one slot by a DI, it expects the response to its message (MSG2) in the next slot. Hence, between MSG1 transmissions it has to exist at least one free slot.

So, in an example where it is considered a virtual frame of five discovery slots, and it is transmitted, in a virtual frame, two replicas of a MSG1, it is possible to observe that the total number of possible patterns that a DI can choose from to send its payload replicas is

$$C(L-r+1, r) = C(5-2+1, 2) = 6 \quad (8)$$

as shown in Fig. 8, with C being combinations, L the size of the virtual frame and r the number of replicas in consideration.

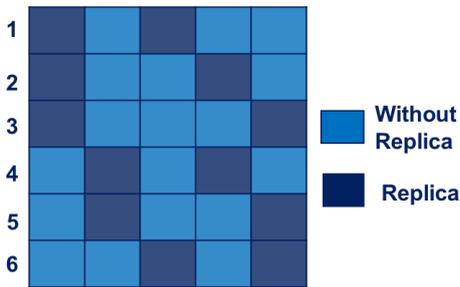


Fig. 8. Example of possible patterns that a DI can choose from.

Another parameter that will be taking in consideration is the size of the set of possible configurations for transmission. For example, in the example exposed where there is 6 possible patterns, it is possible to pre-define a set with 1, 2, 3, 4, 5 or 6 possible patterns. The size of the set is defined before simulation and then the DIs choose a pattern for transmission from this pre-defined set, in a random way.

To send a certain message, a respective packet is created following the transmitter chain presented in Fig. 9.

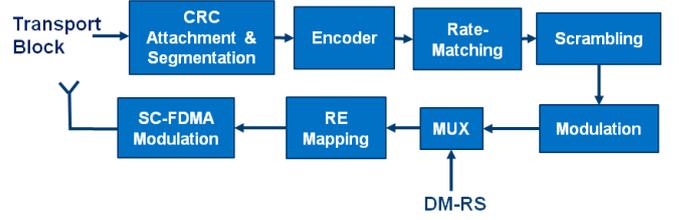


Fig. 9. Transmitter chain.

As it is possible to observe, this process follows a usual transmitter chain, starting with a sequence of information bits, called transport block, and finishing when a correspondent waveform is created. An important detail about this chain is the way the pilot symbols (DM-RS) that together form a pilot sequence, are chosen by the devices.

In the considered network, the devices establish communication links between each other through a random access scheme. As such, the number of contending devices is unknown to the receiver. To ensure that the receiver applies the appropriate decoding procedure (e.g. number of SIC rounds) knowledge of the number of contending devices is required. For that reason the use of multiple orthogonal pilot sequences is considered.

In a simpler LLS system, which is explained in more detail in [5], the comparison between the use of a single pilot sequence and multiple orthogonal pilot sequences in different types of channel estimation is performed. In this system, two signals (one of interest and one interferer) were transmitted through a wireless medium having into account a Rayleigh fading channel and white Gaussian noise. At the receiver side, the signal of interest was decoded without any SIC technique and the block error rate (BLER) was calculated. It is possible to observe from the simulations presented in Fig. 10 and Fig. 11 that in two different extremes of SIR (-15 dB and 15 dB), the best performances are obtained when the two signals use orthogonal pilot sequences. This is due to the fact that the receiver, with a pilot activity detection block which will be explained in the receiver side, can distinguish the two signals and so detect and decode the signal of interest more correctly. Also, it is possible to state that the use of MMSE-IRC improves the performance of the system.

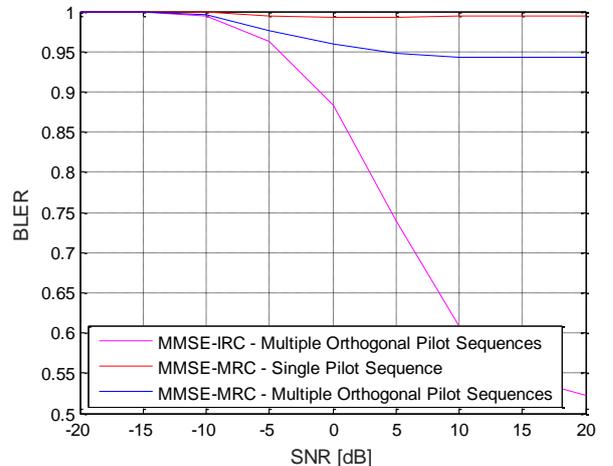


Fig. 10. Comparison between the use of one or multiple orthogonal pilot sequences for SIR=-15 dB.

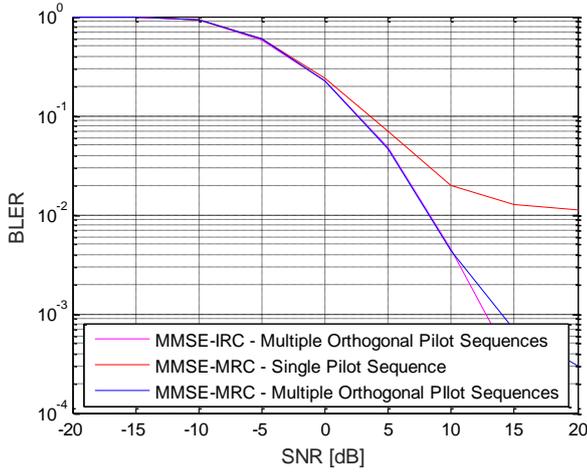


Fig. 11. Comparison between the use of one or multiple orthogonal pilot sequences for SIR=15 dB.

Hence, one of the innovations of this solution is the design of a set of multiple orthogonal pilot sequences from where a user can choose from for its payload. The number of available orthogonal pilot sequences is a system design parameter. The orthogonal pilot sequences with pilot symbols are generated according to the method described in the standard 3GPP TS 36.211 [6].

A more detailed presentation about the rest of the blocks belonging to the transmitter chain is presented in [5].

C. Receiver Side

In this section, the receiver side of the proposed solution is described. The receiver has the possibility of using diverse and advanced decoding techniques. Here it is proposed an adaptive architecture that allows the use of two types of SIC, as depicted in Fig. 12.

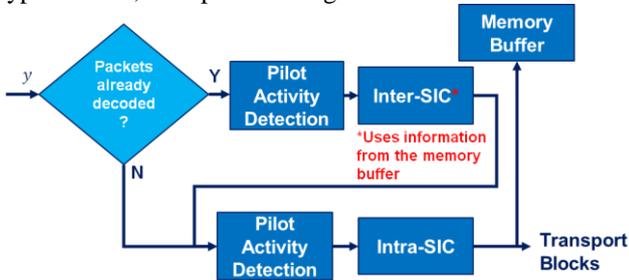


Fig. 12. Proposed adaptive architecture for the receiver side.

This architecture consists in the improvement of the decoding process in the following manner: when packets from the received signal that were not acquired yet, are decoded and the CRC checks, they are cancelled from the received signal (intra-SIC) and kept in a memory buffer. Later, if another signal comes with the same packet that was already decoded before, the receiver uses the information kept in the memory buffer to subtract its contribution from the received signal (inter-SIC) and try to decode the remaining packets. The information present in the memory buffer is deleted every time a VF starts since one of the reasons why the concept of VF arose is to keep both latency and memory constraints reasonable.

This architecture is considered adaptive since it is possible to choose between the use of only intra-SIC, or the

use of intra and inter-SIC. In this architecture there are three important blocks:

- Pilot Activity Detection.
- Intra-SIC process.
- Inter-SIC process.

In the next sections, these three processes will be described.

1) Pilot Activity Detection

The purpose of the pilot activity detection block is to derive the number of unique orthogonal pilot sequences activated by the transmitters, without any a priori information, based on the received signal. Remember that in the transmitter side each user selects independently and randomly a pilot sequence from a set of orthogonal pilot sequences. With this information, the receiver can then decide an appropriate receiver architecture. Not only the receiver can choose the correct channel estimation, but also it can decide if the use of SIC should be considered or not.

For means of simulation, the pilot activity detection is genie aided. However, during the development of this project, different types of pilot activity detection blocks were developed and tested. In the following, it will be described different types of pilot activity detection blocks architectures.

a) Parallel Matched Filter (baseline)

The baseline proposed is an architecture based on a matched filter as depicted in Fig. 13.

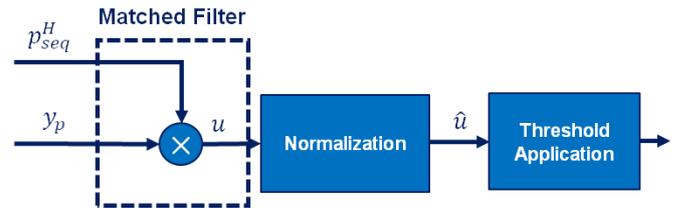


Fig. 13. Parallel matched filter baseline.

First, the receiver extracts the symbols that are located in the pilot positions from the received signal. Then, the extracted pilot sequence is multiplied with the conjugate transpose of all pilot sequences present in the set of multiple orthogonal pilot sequences, as follows:

$$u_i = |y_p \cdot p_{seq,i}^H| \quad (9)$$

where y_p is the received signal corresponding to the pilot symbol positions, $p_{seq,i}$ is the i -th pre-defined pilot sequence from the set of size P , u_i is the statistic element that form the vector u and H is the conjugate transpose operation. Then, the obtained values are normalized by the largest element of u as follows:

$$\hat{u}_i = u_i / u_{\max} \text{ s.t. } u_{\max} = \max_i u_i. \quad (10)$$

In the presence of multiple transmissions there is a need to put in place a mechanism to identify which of the pilot sequences are active. Hence, a hard decision mechanism is introduced based on a threshold. If a value \hat{u}_i is above this threshold, then the system detects the i -th pilot sequence as active. So, one way to improve the performance of this block is to improve the reliability of the \hat{u}_i values. For that reason, an improved architecture was developed.

b) Parallel Matched Filter with Adaptive Threshold via Common Neural Network

Now, another architecture, depicted in Fig. 14, where the outputs of the parallel matched filter are inserted into a feedforward neural network is considered. In this architecture two configurations for the inputs of the feedforward neural network are considered:

- The inputs of the feedforward neural network are the outputs of the matched filter (Fig. 14a).
- The inputs of the feedforward neural network are the outputs of the matched filter plus the original received signal in pilot positions (Fig. 14b).

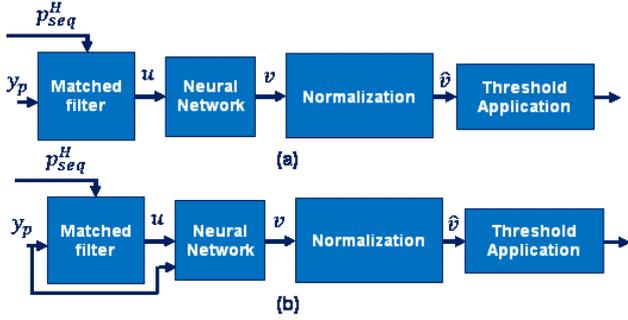


Fig. 14. Parallel matched filter with adaptive threshold via common neural network.

The main difference between this architecture and the previous one is the place where the normalization process and the threshold application are done. In this new case these operations are performed at the output of the feedforward neural network, and not at the output of the parallel matched filter. The addition of a neural network allows to refine the estimation of the activation probabilities. More details about the type of the neural network used can be found in [5].

c) Parallel Matched Filter with Adaptive Threshold via Individual Neural Network

Finally, a third architecture is proposed, where each pilot sequence is assigned to a dedicated neural network (NN) as depicted in Fig. 15.

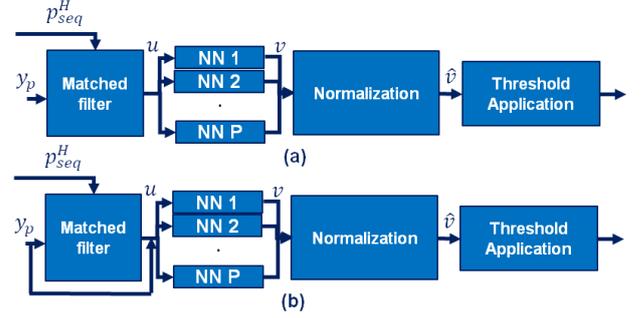


Fig. 15. Parallel matched filter with adaptive threshold via individual neural network.

This architecture is very similar to the previous one. The only difference is that instead of having only one neural network responsible for the soft values of all pilot sequences, it has P separate neural networks, each trained to detect the activity of a single pilot sequence.

2) Intra-SIC process

With the information of the number of pilot sequences active in the received signal given by the pilot activity detection block, the intra-SIC process consists in the application of a certain number of SIC loops, in order of decoding as many packets as possible. The packets that are decoded and the CRC checks are kept in a memory buffer for posterior use. In Fig. 16 is presented this process diagram.

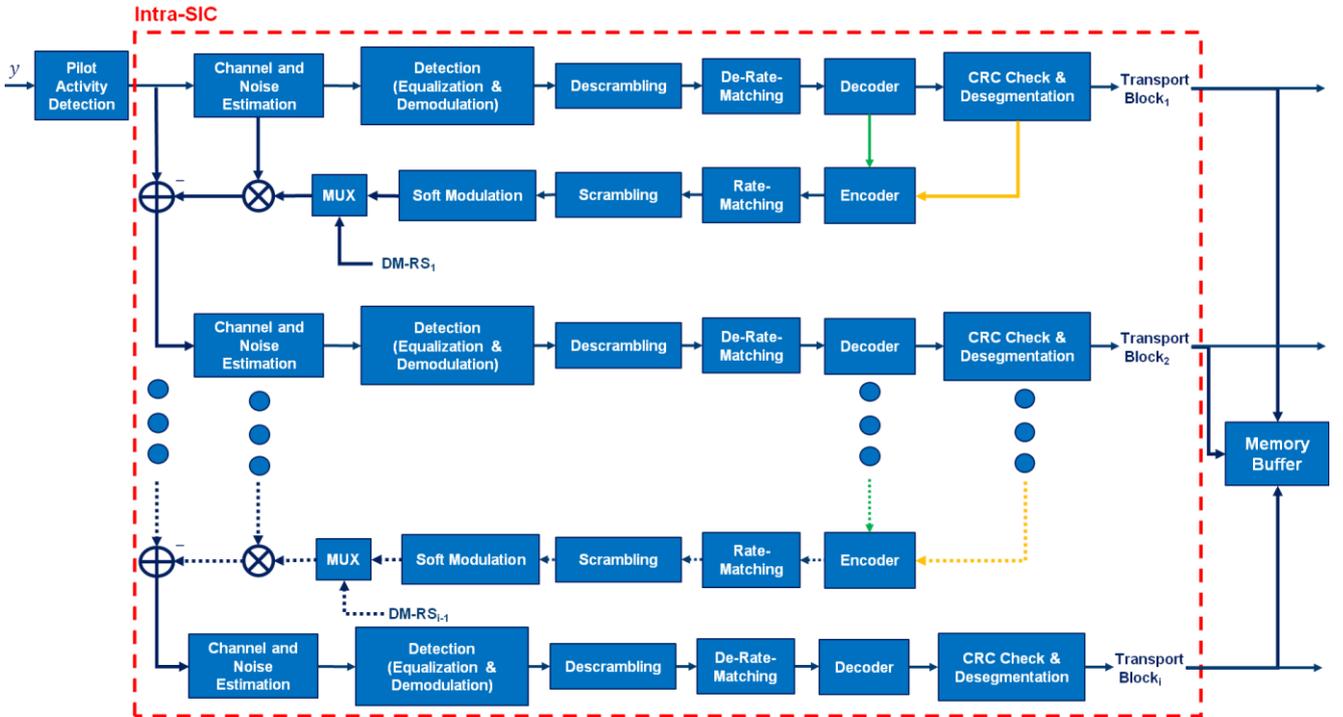


Fig. 16. Intra-SIC block diagram.

was affected by a multipath Rayleigh fading channel EPA 5Hz implemented with the `IteFadingChannel` from Matlab and a white Gaussian noise. There are a certain number of available orthogonal pilot sequences from which the two devices randomly choose one of them. Hence, they can transmit different orthogonal pilot sequences or the same one. In the reception, there is no need to apply the full chain since the output of the pilot activity detection block is what is being study here. The system parameters used in the simulations are presented in Table I.

TABLE I. SYSTEM PARAMETERS FOR PILOT ACTIVITY DETECTION ARCHITECTURES.

LLS parameters	Value
Size of Transport Block	40
Δf [Hz]	15 000
Modulation	QPSK
Turbo iterations	8
P_{noise} [dBm]	-133
P_{Signals} [dBm]	Random from -200 to 0
Available Orthogonal Pilot Sequences	16
Samples for network training	55 000
Samples for testing the architectures	10 000

To evaluate the performance of the proposed architectures, the received pilot sequences can be classified as follows:

- If a pilot sequence is detected but it was not transmitted by any of the devices, it is a false positive.
- If a pilot sequence is detected and was transmitted by at least one device, it is a true positive.
- If a pilot sequence is not detected but was transmitted by at least one device, it is a false negative.
- If a pilot sequence is not detected and it was not transmitted by any of the devices, it is a true negative.

The performance evaluation is done with the calculation of the false positive and true positive when different threshold values are applied. Fig. 18 shows the comparison between the three proposed solutions where:

- Case 1: Parallel Matched Filter (baseline).
- Case 2a: Parallel Matched Filter with Adaptive Threshold via Common Neural Network, with the outputs of the matched filter as input of the neural feedforward network.
- Case 2b: Parallel Matched Filter with Adaptive Threshold via Common Neural Network, with the outputs of the matched filter plus the original received signal as input of the neural feedforward network.
- Case 3a: Parallel Matched Filter with Adaptive Threshold via Individual Neural Network, with the outputs of the matched filter as input of the neural feedforward networks.
- Case 3b: Parallel Matched Filter with Adaptive Threshold via Individual Neural Network, with the outputs

of the matched filter plus the original received signal as input of the neural feedforward networks.

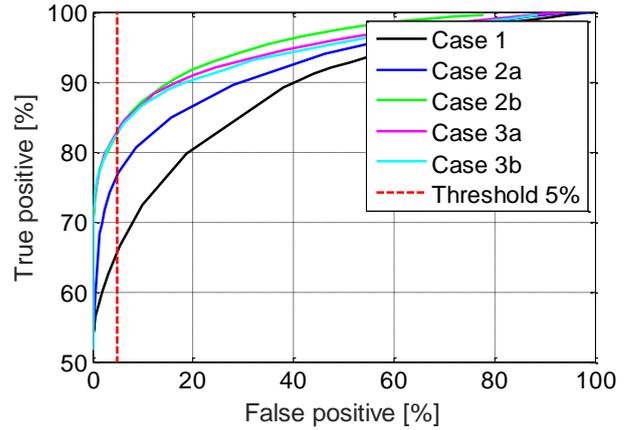


Fig. 18. Percentage of true positives for different pilot activity detection architectures.

As it is possible to see, when operating at a maximum value of false positives equal to 5%, introducing the neural network allows to significantly increase the number of true positives compared to the naïve (Parallel Matched Filter only) solution. A further gain in the performance is obtained by either providing extended input vectors (2a vs 2b) or by switching to separate neural networks.

Now, it will be shown the results obtained for different receiver architectures – no SIC, intra-SIC, and intra and inter-SIC – in the system proposed. Here it was used the SLS and LLS systems presented before. The general system parameters used are presented in Table II.

TABLE II. SYSTEM PARAMETERS FOR PROPOSED SOLUTION.

LLS parameters	Value
Size of Transport Block	40
Δf [Hz]	15 000
Modulation	QPSK
Turbo iterations	8
Channel	Rayleigh Fading EPA 5Hz
Noise	White Gaussian
Account for Cross Sub-Band Attenuation	Yes
Channel Estimation	MMSE-MRC/MMSE-IRC
SLS parameters	Value
Number of frames	4000
Time of a frame [ms]	1000
Number of DIs per km ²	200
Number of DRs per DI	1
Size of set with orthogonal pilot sequences	16

Note that parameters such as number of replicas per packet, size of the virtual frame and size of the set with the

possible transmission patterns will be defined next since they change depending on the receiver architecture in consideration. However, in the case of “no SIC” and “intra-SIC” there is no advantage of using replicas, since there is nothing helping the communication between them, so it is used slotted ALOHA which is equivalent to the use of one replica, a virtual frame of size one and a set with only one possible transmission pattern.

Hence, starting by considering a system with MMSE-MRC, the three types of architecture were simulated. Note that, here it is shown the option for the intra-SIC configuration that obtains better performance results. Also, for the case of inter and intra-SIC and using a virtual frame of size ten, it was found the number of replicas and the size of the set with the possible transmission patterns that maximizes the performance of this architecture. The parameters used in the simulations are presented in Table III and the respective results in Fig. 19.

TABLE III. SYSTEM PARAMETERS FOR MMSE-MRC.

	No SIC	Intra-SIC	Inter/Inter-SIC
Number of replicas	1	1	2
Size of the VF	1	1	10
Size of the set with the possible transmission patterns	1	1	30

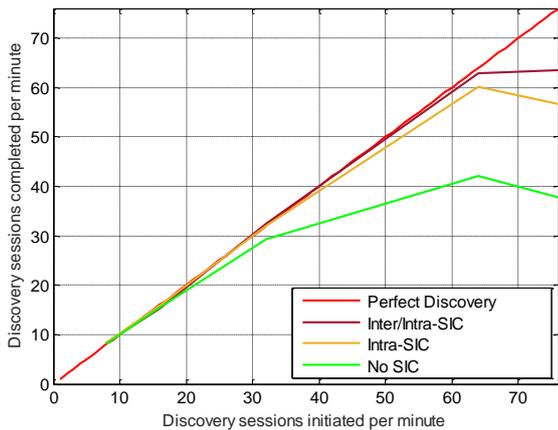


Fig. 19. Comparison between different architectures for MMSE-MRC.

As expected the system with lower performance is when no type of SIC is applied. The use of intra-SIC increases a lot the system performance but the one that, as expected, has the highest performance is when the two types of SIC are applied.

Then, the same process was done for channel estimation MMSE-IRC. In Table IV, the respective simulation parameters are presented and in Fig. 20, the performance results.

TABLE IV. SYSTEM PARAMETERS FOR MMSE-IRC.

	No SIC	Intra-SIC	Inter/Inter-SIC
Number of replicas	1	1	3
Size of the VF	1	1	10
Size of the set with the possible transmission patterns	1	1	50

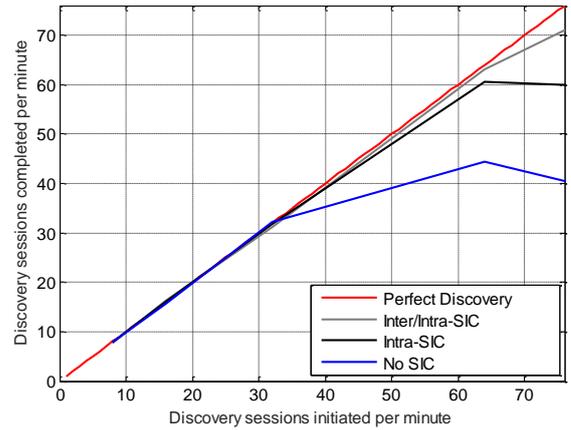


Fig. 20. Comparison between different architectures for MMSE-IRC.

The results were similar to the ones obtained for MMSE-MRC.

Finally, joining the two plots together, Fig. 21, it is possible to compare the results obtained by the two channel estimations.

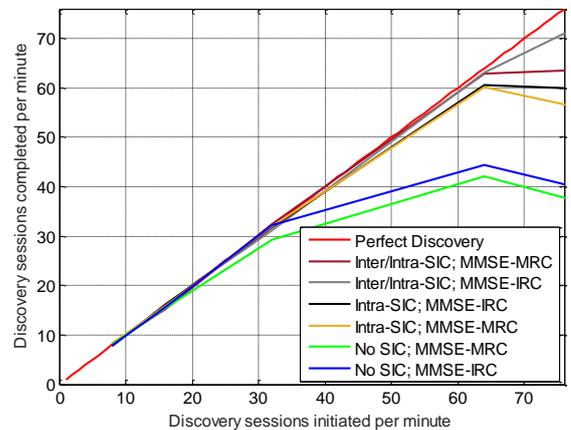


Fig. 21. Comparison between different architectures for MMSE-MRC and MMSE-IRC.

In each system, the use of MMSE-IRC has always performance benefits in respect to the less complex channel estimation MMSE-MRC.

These and other simulations are presented in [5] with a higher degree of detail.

B. Complexity

Due to time restrictions, it was done an upper bound of the complexity. To be possible to distinguish between the MMSE-MRC and MMSE-IRC block complexity, it was considered 100 for every block complexity except in the case where MMSE-IRC is used, because its complexity depends on the number of interferers. Meaning that, for example, when doing the channel estimation of a signal of interest with interfering signals present in the received signal, because this channel estimation also has to estimate the channel of all interfering signals, it is considered that

$$K_{ch-IRC} = (1+N_{interferers}) \cdot K_{ch-MRC} \quad (11)$$

where K_{ch-IRC} is the MMSE-IRC block complexity, K_{ch-MRC} is the MMSE-MRC block complexity (100) and $N_{interferers}$ is

the number of interferers in the received signal. Then, having the complexity for each block, it was considered the number of times that the system goes through each one of them in the simulations.

In Fig. 22 it is depicted the average complexity of the systems for different arrival rates. The parameters used in this simulation are the same as the ones used in the SLS and LLS in the performance results.

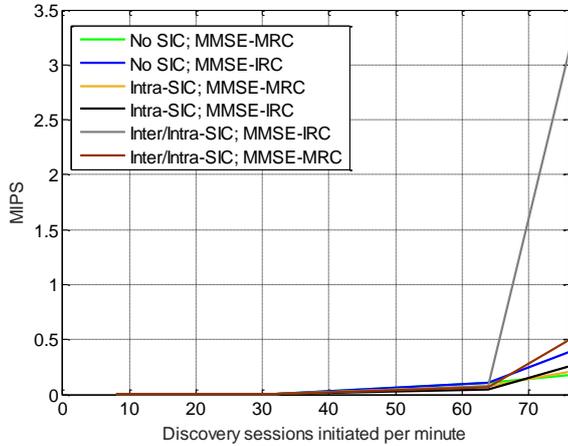


Fig. 22. Comparison between different architectures, in terms of complexity (MIPS – Millions of Instructions Per Second).

For lower rates the complexity is very similar and lower for all architectures. However, around 64 discovery sessions initiated per minute, which is the time where the system starts to have more than one transmission per slot, the complexity increases rapidly.

It is possible to see that in general as expected the use of two types of SIC is more complex than the use of only intra-SIC which is already more complex than the no use of SIC at all. However, there is one result that seems out of place – “No SIC; MMSE-IRC”. The reason why the complexity of this architecture appears higher than the architectures that use intra-SIC is because with the increase of the number of transmissions per slot, this architecture cannot handle the number of collisions that starts to appear and so these MSGs start to accumulate in the system. At the same time, because it is using MMSE-IRC, with the number of transmissions accumulating, the complexity of the channel estimation block will also increase its complexity due to all interferer channels that it has to estimate.

Also, for each architecture, it is possible to see that the use of MMSE-IRC requires more system complexity.

VI. CONCLUSIONS

Finally, this last section presents the conclusions that can be drawn from this project development and future work that can be done for further research.

A. Summary

A first conclusion that was taken during the development of this project was that the use of orthogonal pilot sequences by the devices increases the performance of the system. This is due to the fact that with the pilot activity detection block, the receiver can detect which orthogonal pilot sequences is

active and from that detect the signal that is associated with it.

Another conclusion taken from this project development is that the application of MMSE-IRC increases the performance in respect to MMSE-MRC no matter what receiver architecture is applied. This was expected because MMSE-IRC takes into consideration the interfering signals. Also, for that reason, if the number of interferers increases, the number of instructions executed in the MMSE-IRC block also increases, raising its complexity.

Finally, it was proven that the use of SIC although it increases the complexity of the system, it also boosts its performance. In higher channel loads, for example 75 discovery sessions initiated per minute, as expected the no use of any kind of SIC implies a low system performance. However, with the increase of complexity, applying only intra-SIC the performance of the system can increase up to 50%. And a receiver architecture that uses inter and intra-SIC, also increasing the complexity of the system, its performance increases up to 70%.

B. Future Work

The topic explored in this project is very broad and continues to be intensively discussed by researchers and telecommunication companies. Hence, although this project already made so many technical contributions, here are some aspects that can be further explored and researched:

- In the proposed solution, there are some parameters such as for example the size of the VF that depend on the load of the network. In here it is assumed that this load is known, however in a real system that does not happen. Hence, a good research path would be explore ways to detect what is the current load of a D2D network without infrastructure network support.
- Also, as seen before, the implementation of intra and inter-SIC implies the increasing of system complexity. One important path to follow in terms of research would be discover similar techniques, with the same purpose but requiring less complexity.
- Another possibility of research could be extend the proposed solution to work in other types of systems, e.g. cellular networks, or crossing different types of interference.

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