# MIMO Evaluation Platform for Fast Hardware Baseband Reconfiguration of Advanced Wireless Networks

**Abstract**: Communication systems will have to support an ever increasing number of transmission standards. In this context, the reconfiguration capability appears as a promising solution for designing multi-standard terminals with a limited impact on the size, cost and power consumption budgets. This paper describes a hardware real-time reconfigurable hardware platform, developed jointly by CEA-LETI and MERCE in the context of the CELTIC project WINNER+. This platform, implements a basic 3GPP/LTE system composed of a terminal and a base station, The terminal baseband architecture is based on the MAGALI ASIC developed by CEA-LETI, which implements a Network on Chip (NoC) technology, which allows the dynamic reconfiguration of the system. The base station relies on a more traditional FPGA prototyping platform. The reconfiguration is showcased by changing the transmission mode from a 3GPP/LTE SIMO (1x2) mode and a 3GPP/LTE compliant 2x2 MIMO mode. In addition to the evaluation and the demonstration of the hardware re-configurability, the platform is also used to measure the benefit of spatial transmission diversity scheme envisioned for the evolutions of the 3GPP/LTE, e.g. LTE-A, system in comparison to the basic transmission over a single antenna at a time as specified in the LTE standard.

**Keywords:** Reconfigurability, MIMO, 3GPP-LTE, 3GPP-LTE-A, SC-FDMA, SC-SFBC, Network-on-chip, FPGA

## 1-Introduction

Communication systems will have to support an ever increasing number of transmission standards (legacy 2G, 3G, LTE, LTE-A, WiFi,.WiMax..). In this context, the reconfiguration capability appears as a promising solution for designing multi-standard terminals with a limited impact on the size, cost and power consumption budgets: indeed, a reconfigurable terminal will be based on a single circuit, instead of one circuit per standard

This paper describes a hardware real-time reconfigurable hardware platform, developed jointly by CEA-LETI and MERCE in the context of the CELTIC project WINNER+ [1], and evolved from the one developed in the French ANR project APOGEE [2]. This platform, denoted in the sequel as CEA-LETI MERCE (CLM in short) platform implements a basic 3GPP/LTE system composed of a terminal and a base station,, supporting a real time over-the-air uplink (UL) transmission. The terminal baseband architecture is based on the MAGALI ASIC developed by CEA-LETI, which implements a Network on Chip (NoC) technology. It is made of dedicated nodes such as scalable OFDM modules and a number of programmable memory and computing units that along with the network architecture allow the dynamic reconfiguration of the system. The base station relies on a more traditional FPGA prototyping platform from Nallatech [3].

The main purpose of the CLM platform is to illustrate how future systems such as those targeted in the WINNER+ project could benefit from the use of re-configurable architectures. The re-configuration capabilities of the terminal is applied to change the transmission mode from a 3GPP/LTE SIMO mode (single antenna at the terminal, dual antenna at the base station) and a 3GPP/LTE compliant MIMO mode (dual antenna both at the terminal and at the base station). In addition to the evaluation and the demonstration of the hardware re-configurability, the CLM platform is also used to measure the benefit of spatial transmission diversity scheme envisioned for the evolutions of the 3GPP/LTE, e.g. LTE-A, system in comparison to the basic transmission over a single antenna at a time as specified in the LTE standard.

This paper is organized as follows. Section 2 describes MAGALI NoC architecture, Section 3 gives a detailed description of the platform,, Section 4 describes the reconfiguration scenario and the two spatial modes at stake. Section 5 gives performance results.

## 2-Reconfigurable Architecture Based on NoC

MAGALI is the second generation of Network-on-Chip (NoC) based System-on-Chip (SoC) designed by CEA-LETI. It implements a 500 MHz, 32-bits mesh NoC topology connecting 21 computing nodes running between 300 and 600 MHz The chip is semi-homogeneous, ie, composed of cores repeated many times in the chip. The cores are dedicated ones, such as scalable OFDM modules, or programmable ones, such as the memory management unit and specialized telecom DSP. Finally the network architecture (NoC + Network Interface) brings the support for dynamic reconfiguration of the system A general view of the MAGALI chip is presented in Figure 1. The main elements of the chip are a CPU controller (ARM1176 core) for chip control and MAC, memory managers (Smart Memory Egnines or SMEs), DSP cores called MEPHISTO, OFDM cores, two bit level cores (Tx_bit and Rx_bit: scrambling, interleaving, etc), and an Application Specific Instruction set Processor (ASIP, a programmable core for turbo-decoding functions). In addition there are two LDPC decoding cores dedicated to some special codes (UWB codes and WiFi/WiMax codes). The two aforementioned blocks are developed by an external partner of the consortium and will not be used within the WINNER+ project.

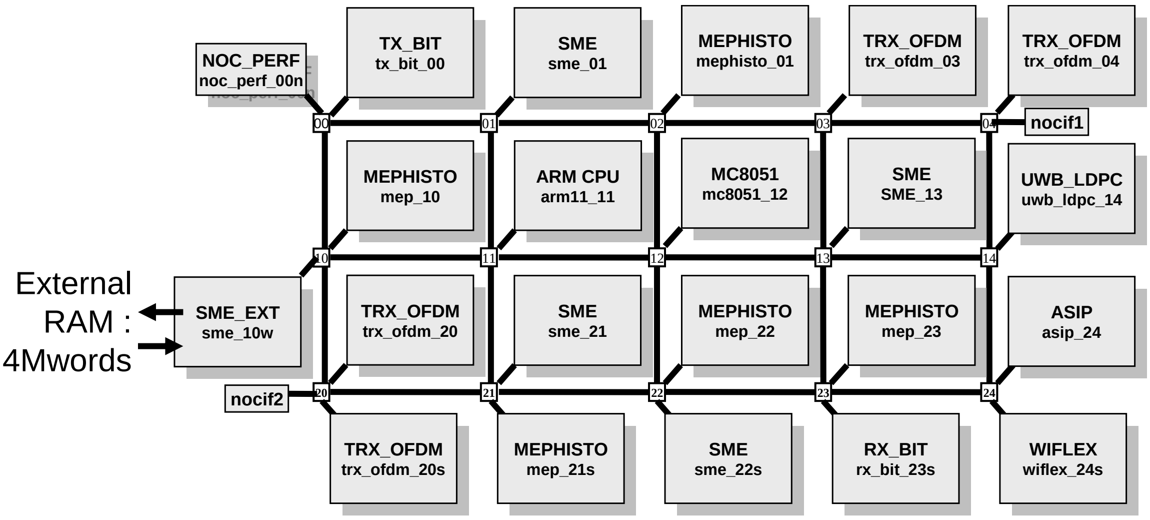

*Figure 1 General view of the MAGALI chip.*

## 3- Platform Description

The CLM platform is an evolution of a demonstrator developed outside the WINNER+ project (in the French ANR project APOGEE,). This platform focuses on the enhancement of the UL transmission of a 3GPP/LTE network. In order to emulate, the terminal is connected to the base station by means of wired digital interfaces. It is composed of two different entities, one implementing the transmitting functionalities of a user equipment

(UE) and another implementing the receiving functionalities of a base station (eNodeB). Both entities are dual antennas.

The platform implements with some simplifications the core specifications of the 3GPP Release 8 (LTE) system for transmissions in a 20 MHz bandwidth. The system relies on the Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation technique, where each user is allocated a number of contiguous sub-carriers of DFT-spread OFDM modulation. This modulation permits the reduction of the power consumption thanks to a lower peak to average power ratio (PAPR) in comparison to OFDMA as used in downlink. The system also supports some additional features such as MIMO DM pilots to enable the evaluation of innovations envisioned for the evolutions of the 3GPP/LTE system, i.e. the releases 9 and 10 (LTE-A). In that purpose, the terminal includes two RF transmitting chains. The simplest MIMO algorithm is the open loop Alamouti [4], applied in the frequency domain (SFBC: Spatial Frequency Block Coding). However, a straightforward application of SFBC changes the frequency structure of the signal: the frequency inversions between successive subcarriers break the single-carrier property of the signal, thus increasing the PAPR [5]. A modified SFBC scheme, coined SC-SFBC has been proposed in [5], in order to solve this problem. This algorithm is implemented in the CLM platform, The base station implements a MIMO decoder able to cope with the two transmission schemes supported by the terminal (MIMO 2x1 and 1x2). Other features of the platform include turbo-code and Chase combining HARQ. More details about the platform may be found in [6].

### *3.1 Hardware architecture of the terminal emulator*

The terminal transmitter comprises a transmit MIMO RF front-end enclosed in a separate cabinet and a digital board that hosts the physical and MAC layer functionalities and finally a host PC to run monitoring and end-user applications. The MIMO RF front-end supports 2 transmit antennas for operation in the 2.4-2.6 GHz frequency band. The UE baseband platform results from the UPPERMOST (Medea+) [7] and E2RII (FP6 IST) projects. As shown in Figure 2 it is basically composed of three main parts, the MAGALI ASIC, a Xilinx Virtex-5 FPGA and a set of versatile interfaces. The MAGALI chip is used to speed up performance of computationally intensive functions and to support the basic functions of a transmitting chain. The FPGA is used to implement the advanced functions which are not supported by the MAGALI chip. Three different output interfaces are available on the board. A host interface provides several different links to a PC, a simple RS232 link for FPGA control, two Ethernet interfaces for board configuration and debug, and a USB interface. The RocketIO interface can be used both for RF interface and connection of the board with another high-speed board. Analogue low-IF interfaces are also available.

A general view of the board is shown in Figure 2. The FPGA and MAGALI chip are linked by two “Network on Board” interfaces, which are extensions of the Network-on-Chip (NoC) of the MAGALI chip. The NoC architecture and functionalities are also implemented in the FPGA to extend the functionalities of the MAGALI chip.

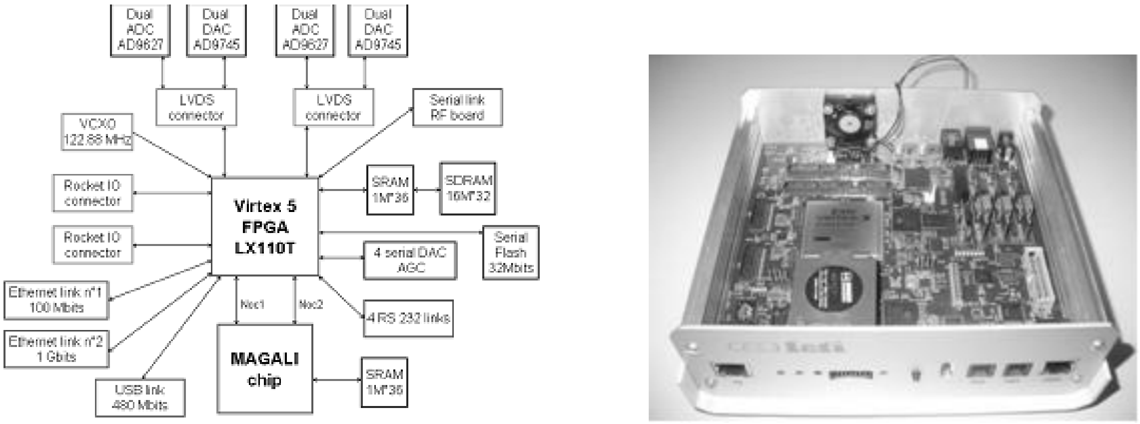


*Figure 2 CLM terminal BB board architecture*

### *3.2 Hardware architecture of the base station emulator*

The base station receiver comprises a receive MIMO RF front-end enclosed in a separate cabinet, a digital board that hosts the physical (PHY) and medium access control (MAC) layer functionalities and finally a host PC to run monitoring and end-user applications. The MIMO RF front-end supports 2 antennas for operation in the 2.4-2.6 GHz frequency band. The baseband part of the base station is implemented on a commercial FPGA prototyping platform namely the BenNUEY-PCI-4E PCI board from Nallatech [6]. The board embeds three daughter boards that provide computing resources (FPGAs) and acquisition capabilities (ADCs) to interconnect with the MIMO RF front-end.

An overview of the baseband sub-system is depicted on Figure 3 with the identification of the different interfaces and processing elements. As shown on Figure 3, the MAC layer is implemented on the IBM PowerPC 405 processor embedded within the Virtex-2 pro Xilinx FPGA of the Nallatech motherboard. In real systems, terminals synchronize with the base station through the downlink transmission. Without actual downlink RF, the terminal is connected to the base station through two wired digital interfaces. The base station transmits synchronization signals through a Xilinx RocketIO link operating at 2.5 Gbit/s over coaxial cables. As this link supports full-duplex operations, the RocketIO link can also be used to transmit the UL signal in digital mode for validation purposes. In addition, the base station forwards control signaling information to the terminal through an UDP over Ethernet connection.

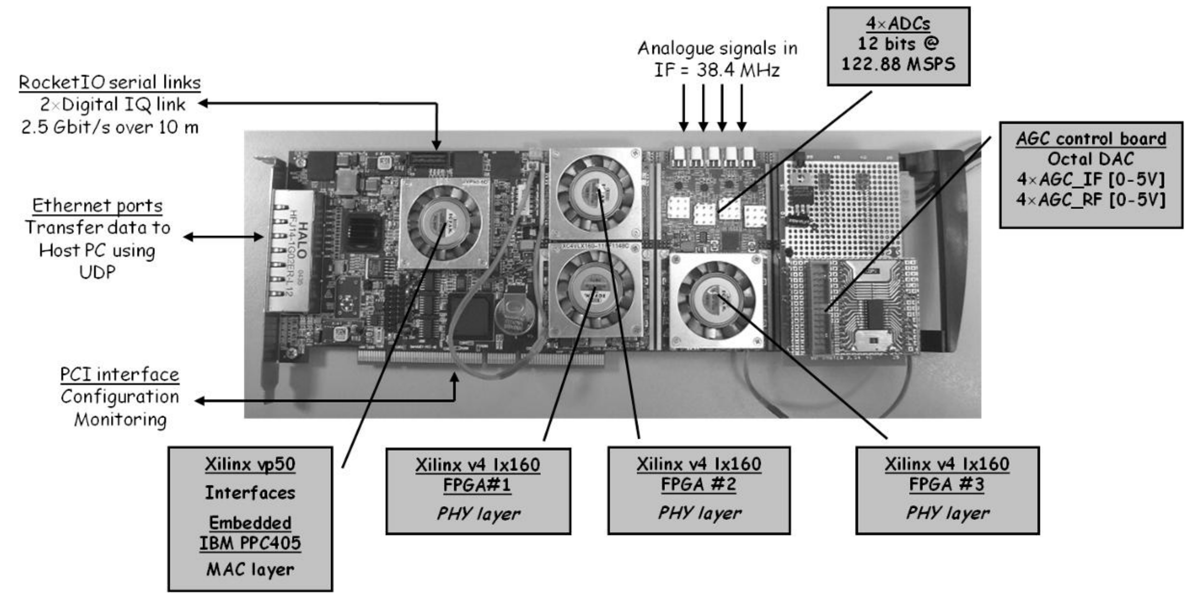

*Figure 3 General overview of the CLM baseband sub-system.*

## 4- Performance evaluation scenarios

As introduced above, the main purpose of the CLM platform is to illustrate how future systems such as those targeted in the WINNER+ project could benefit from the use of re-configurable architectures.

The MAGALI NoC technology is able to handle the complete reconfiguration of the system between two transmission standards (eg. a change from WiFi to 3GPP/LTE). It is not the case of the eNodeB emulator, which is implemented on an FPGA prototyping platform with few hardware resources left, i.e. without the possibility to implement simultaneously two different systems. As a result, the evaluation of the re-configurability potentialities of the MAGALI architecture can only be conducted within the scope of the original system, i.e. the 3GPP/LTE standard. Instead of switching between two different systems, the terminal is modified to re-configure a reduced part of its functionality, the one dealing with the support of multi-antenna schemes. More specifically, the terminal uses its re-configurability capabilities to switch between two modes:

- transmission over a single antenna,
- transmission over two antennas using the SC-SFBC code,

The re-configuration is carried out with a modification of both the network routing and nodes functionality, similar to what would happen in a scenario with full reconfiguration between two standards. Therefore, in spite of the fact this reconfiguration scenario is focused on a sub-part of the system, it is representative of a more general scenario.

*On the base station side, the signal is observed over two receive antennas in both modes. When the terminal transmits over one antenna, the base station recovers the transmitted symbol using a SIMO decoder (Maximum Ratio Combining and equalization). When the terminal transmits over two antennas, the base station implements a 2×2 MIMO Minimum Mean Square Error decoder to recover the transmitted stream. As a whole, the system switches between a 1×2 SIMO UL SC-FDMA system and a 2×2 SC-SFBC MIMO UL SC-FDMA system. This can be interpreted as a handover between a LTE eNodeB and a LTE-A eNodeB. Indeed, according to the LTE Release 8 standard, UEs can only transmit over a single antenna at a time (only antenna switching is permitted at the exception of any other SU-MIMO scheme). On the other hand, it is already agreed that next releases of the LTE system (i.e. LTE-Advanced) will support SU-MIMO UL schemes over at least two transmit antennas. The UE is supposed to be compliant with LTE-Advanced specifications. The principle of the demonstration scenario is depicted on*

Figure 4.

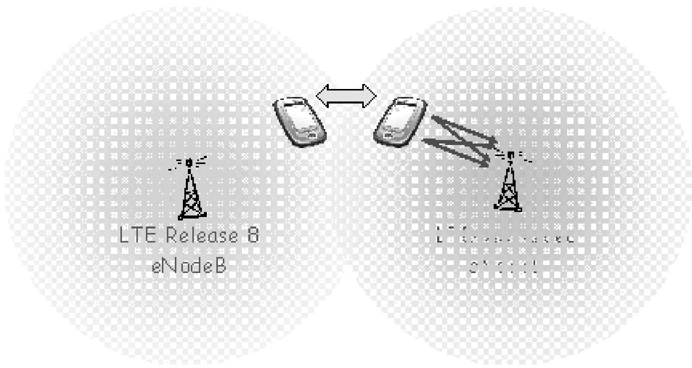


*Figure 4 Handover between LTE and LTE-A networks.*

On the UE side, the switch between the two schemes leads to a full reconfiguration. More precisely, both the general scheme and the algorithms performed by the different units are impacted. For the 1×2 SIMO uplink SC-FDMA mode, a single path is activated toward the antennas: no MIMO encoding is applied and the frame carries reference pilots for a single transmit antenna. For the 2×2 SC-SFBC MIMO uplink SC-FDMA system, both antenna paths are activated, MIMO encoding is applied and the frame structure is different with two reference pilots, one for each transmit antenna. As a consequence, the reconfiguration impact is high: the NoC programming of communications between the units must be modified. The program of the SME which is in charge of the frame modification, the OFDM which must perform part of the framing and MEPHISTO core which performs the MIMO encoding, must be modified to take into account the new schemes. Constraints on the reconfiguration time are high, as we want to perform this reconfiguration at the smallest possible level, i.e. the LTE sub-frame level (Transmission Time Interval at the MAC layer). Thus, we want to ensure that reconfiguration does not cause any specific delay in addition to those possibly coming from upper layers. Therefore, the reconfiguration time must not exceed 10 % of the total frame time (1 ms), which means 100 µs maximum for the reconfiguration time. The challenge of such a scheme showcases the reconfiguration capacity of the UT.

# 5-Performance Results

### *5.1 UE Reconfiguration time*

The NoC platform supports a full dynamic reconfiguration scheme, as shown in [8]. This scheme allows a reconfiguration without any interruption to host controller: the SME cores are used as configuration servers for the computing units. As a consequence, the whole reconfiguration time is roughly the sum of intrinsic units' reconfiguration time. Few cycles (typically 10) are required in addition for the reconfiguration request grant mechanism on the NoC. **Erreur ! Source du renvoi introuvable.** shows the raw figures of time needed for reconfiguring the whole baseband for 3GPP-LTE Tx used in WINNER+. A total of 3.45 µs is required for a full reconfiguration of the baseband. Compared to the 1 ms of frame duration, it can be considered as negligible.

| | | Operating Frequency (MHz) | Configuration Time (ns) | Instances | |
|---|---|---|---|---|---|
| | | | | Total | Used in LTE Tx |
| Processing cores | MEPHISTO | 400 | 2580 | 5 | 1 |
| | OFDM | 400 | 330 | 4 | 2 |
| | RX_BIT | 333 | 1560 | 1 | 0 |
| | TX_BIT | 400 | 213 | 1 | 1 |
| | UWB_LDPC | 400 | 8 | 1 | 0 |
| | WIFLEX | 400 | 3010 | 1 | 0 |
| | ASIP | 400 | 16675 | 1 | 0 |
| Other units | ARM11 | 313 | — | 1 | 1 |
| | DCM | 350 | — | 4 | 2 |
| | DCM_EXT | 350 | — | 1 | 0 |
| | NODE | 530 | — | 15 | 10 |
| | NOCIF | 200 | — | 2 | 1 |
| | I/O | 200 | — | 1 | 1 |
| **TOTAL (Tx instances)** | | | **3,45 µs** | | |

*Figure 5 Performance and Reconfiguration Time for MAGALI on Rx.*

### *5.2 Multi-antenna schemes*

Ultimately, the performance of the multi-antenna schemes shall be measured in terms of BER and BLER for both digitally simulated and real channels. The use of digital channel models is needed to allow the comparison and thus the validation of the platform with respect to theoretical results. As the CLM platform is currently being integrated, it is not yet possible to perform measurements using the whole platform (base station and terminal). On the other hand, the integration of the base station is merely achieved. The validation of the base station is conducted using a simplified terminal that only supports a few physical modes. This terminal implements two RF transmission paths thus allowing the evaluation of the 2×1 SC-SFBC MIMO scheme. Digital channel simulation is not yet available. Performances are presented here only in the case of the AWGN channel, where noise is digitally generated. The goal is here to validate the overall system more than truly evaluate its performance. Results are provided for both digital baseband and RF transmission at 2.4 GHz. In the latter case, transmission is achieved through a coaxial cable to enable the emulation of an ideal channel, though transmission over antennas would be already possible. As the 3GPP/LTE Turbo Code is under integration, performances are presented for the NASA convolutional code.

*Table 1 Main parameters for multi-antenna scheme evaluation.*

| | |
|---|---|
| Carrier frequency | Baseband / 2.4 GHz |
| Transmission medium | coaxial cable |
| Bandwidth | 20 MHz |
| Allocated resources | 100 resource blocks |
| Channel | AWGN (No spatial diversity) |
| Channel coding | NASA convolutional code |
| MCS | QPSK-1/2<br>16-QAM-2/3<br>64-QAM-3/4 |
| Nb of transmit antennas | 2 |
| Nb of receive antennas | 1 |
| Multi-antenna scheme | 1×1,<br>2×1 SC-SFBC |
| MIMO decoding | MMSE |

Figure 6 displays the BER performance measured respectively in the digital baseband and 2.4 GHz analogue RF modes. It can be seen that the MIMO scheme behaves slightly worse than in SISO while these two schemes should exhibit the same performance when no spatial diversity is available. This is simply due to the degradations that affect the channel estimation module when operating on a MIMO signal with reference pilots made orthogonal by circular time shifting. In addition to noise, the module must also remove the contribution of the other antenna path, thus leading to a degraded overall SNR. Evaluations performed with over the air transmission would show a significant improvement of the performance as soon as the channel brings enough diversity. Then, the gain obtained through exploitation of the diversity overrides the loss of the MIMO channel estimation.

Coming evaluations will be conducted using digitally emulated channels bringing some kind of spatial diversity, thus allowing the effective evaluation of the SC-SFBC MIMO scheme. Measurements will also be conducted with two receive antennas and the 3GPP Turbo Code instead of the NASA convolutional code.

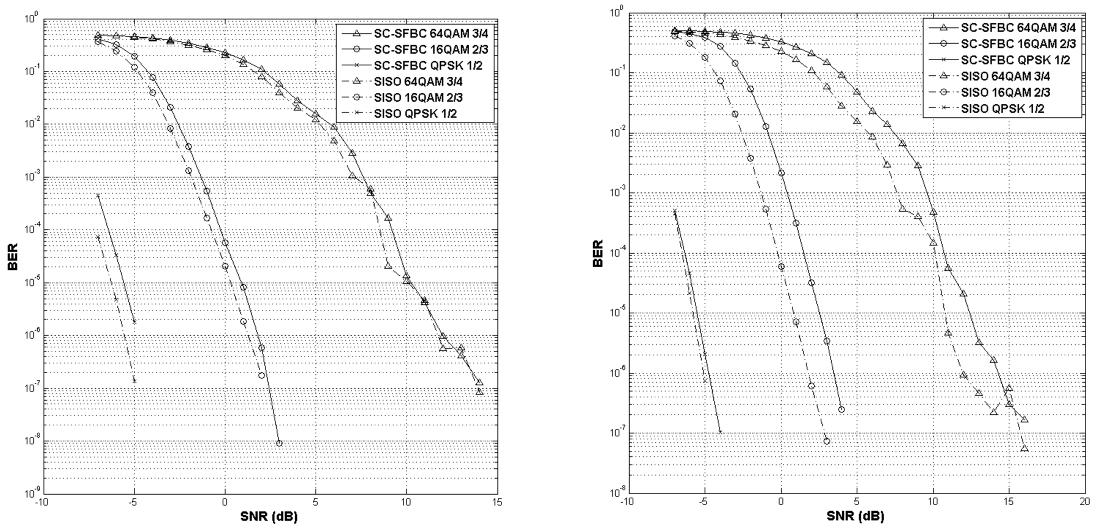


*Figure 6 Performance evaluation in digital baseband, (left) and analogue RF (right) AWGN channel*

## 6-Conclusions

The CLM platform showcases terminal reconfigurability between a 3GPP/LTE-A SIMO and MIMO UL transmission. This result is obtained thanks to the NoC architecture of the MAGALIi basenband chip. Reconfigurability between these two schemes is relevant to illustrate the more general reconfigurability between two standards.

In addition, this platform will allow performance comparison between these two spatial schemes, in over-the-air transmission.

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