Investigating Dependability of Short-Range Wireless Embedded Systems through Hardware Platform based Design

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***Abstract*— Most of the links in future wireless communication networks will be established over relatively short distances. This new direction in wireless communication is adopted and being developed by embedded multimedia applications leaders. Moreover, these short range communications are introduced into critical applications, where the dependability/reliability is mandatory. Thus, dependability concerns around reliability evaluation becomes an essential question to answer, and poses several challenges. Obviously, it's particularly difficult to investigate the reliability of such mixed HW/SW IPs based systems. Therefore, dependability has to be investigated at different abstractions levels, and for all components integrated into the system being designed. In this paper, we discuss the investigation of dependability in wireless short range systems. Firstly we show how a HW platform based dependability investigation can be a very interactive approach; secondly, we describe a real experience in building a wireless hardware platform for short range systems dependability analysis, and finally, based on this wireless network platform, we propose a dependability flow that takes care of the heterogeneous parts of the wireless embedded systems**.

Keywords- Dependability; Reliability; Embedded System; Wireless Short-Range radio applications; HW/SW co-design/verification; Platform based design; COTS

I. INTRODUCTION

In the past few years, wireless computing has strongly increased because of the mobility it provides; in addition the cost of deployment has dropped dramatically. Wireless networking has revolutionized the way we communicate, the way we monitor resources and the way we control personal/and professional equipments. We would expect, one day, that everything will be wirelessly connected.

Wireless networks allow the client application or a device to move without a physical connection. It saves the cost of cabling, and is very convenient for moving robotic engines, where a physical wired connection can be difficult to use or even impossible. Wireless networks also provide flexibility; devices can be reprogrammed or reconfigured without the need to completely re-wire the network.

Typically, wireless communications are divided into two broad ranges of different standards, long range wireless communication and short range wireless communication.

Mobile communication usually consists of technologies that can cover a wide range more then 100m (e.g. GSM, WiMAX). Short-range wireless communication typically covers short distances less then 100m (e.g. Bluetooth, 802.11, Zigbee, W-USB, and FireWire).

They are more and more used nowadays. Future wireless systems will not only connect users and their personal equipment but also access to indoor stand-alone equipment will be provided. This vision places short-range communications in a position of reputation, as one could argue that most of the wireless links in future wireless communication networks will be established over relatively short distances.

II. SHORT RANGE WIRELESS SYSTEMS DEPENDABILITY CHALLENGES

On one hand, we might think that would be a limit to the used of short range wireless application, but the big progress in circuit miniaturization (antennas compact size such as planar antenna) augmented by the new digital modulation techniques (based on CPU/SW embedded in these systems), tend to be pushed as more and more make use, especially in very critical systems, where an incorrect behaviour may have dramatic effects.

Therefore the dependability/reliability requirements become increasingly important in these wireless short range applications (Table I) [4].

Thus, the dependability has to be mastered in these systems, and may be considered as the major challenge to reach [3].

Table I: Dependability Requirement Short Range Applications (examples)

Short Range Application	Frequencies MHz	Dependability Requirment
Security Systems	300-900	++++
Emergency Alarms	300-800	+++
Computer (mouse, keyboard)	UHF	++
Wireless Microphone	VHF	++
Garage Door Opener	UHF	+++

In compliance with the generic definition given in [2], if one summarizes the definition of the dependability/reliability as the correct functioning of the system during the whole operating process, taking into account the presence of exceptional inputs or stressful environmental conditions, one can say that nowadays wireless electronic systems are less and less reliable. This is due to the heterogeneity and the density of the current systems which also contain a huge amount of software and deal with a set of mixed hardware components. The sources of derivation of such systems are various:

- Unanticipated communication between the digital data source and the analog Tr/Rr,
- Agressions from outsider environnemental conditions.
- Faults within the complex software embedded in these systems,
- Improve Electromagnetic compatibility effect on the wireless data link
- In the case of using a predesigned COTS (Commercial off-the-shelf), how to improve their dependability inside the system being designed
- Design must meet FCC (Federal Communications Commission) requirements?

Hence, behind these short range radio applications a real complex HW/SW architecture is built (Figure 1), usually referred to wireless a SoC (System on Chip).

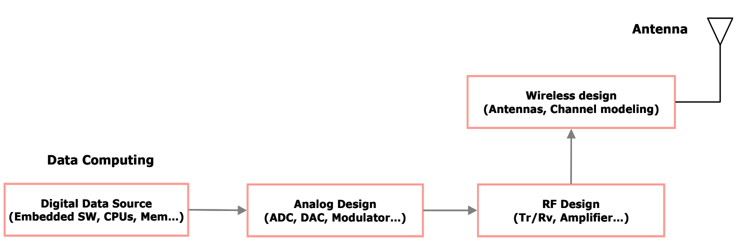

Figure 1: Wireless System based heterogeneous components

Therefore, dependability investigation and fault tolerance of the whole embedded wireless system becomes a multifaceted equation, which involves several dependability stages (digital, analog, wireless), and it will be difficult to talk about the wireless part dependability without taking into account the other architectural parts:

$$D_{WS} = f\,(D_{DP}, D_{AP}, D_{WL})$$

D_{WS}: Dependability of whole wireless embedded system
D_{DP}: Dependability of digital part
D_{AP}: Dependability of the analog/RF part
D_{WL}: Dependability of the wireless links

One of the major challenges addressed in this paper is to answer the following question: **can one really built such a dependable HW/SW wireless system or prove that an embedded short range wireless system is dependable?**

To meet this big challenge, it is mandatory to analyze the integrated circuit as a set of sub-systems described at different levels, and then one requires:

- An effective dependability design methodology/flow and tools to assume the system verification of the heterogeneous components at the different level of the design
- New electronic dependability automation tools flow analyzing processes,
- And, a real teamwork effort between embedded SW designers, HW designers, mixed signal designers, wireless networking, and power management experts

The paper is organized as fellows; first short range wireless system dependability challenges are presented. Section 3 presents the state of the art and some related work. Section 4 presents a hardware platform-based concept as the best solution for wireless system dependability investigation. Also, it gives an insight with regard to the wireless hardware platform built for dependability purposes and details the implementation. Section 5 describes the dependability/design flow for embedded wireless systems. Some results and analysis are provided in section 6, while section 7 concludes the paper.

III. Related Work

Currently, there is no scientific method capable to estimate the dependability of the whole complex wireless HW/SW embedded system at the different abstraction levels. This paper is the first step in this direction although there have been several works suggesting such a requirement in general [9] [8] [13]. In [14] authors present a dependability-explicit development model. The proposed approach relies on the identification of basic activities for the system creation process and for the dependability processes, and then on the analysis of the interactions among the activities of each process and with the other processes.

In related works and to our knowledge, the known methods for dependability investigation (e.g. FMEA) present a lack of automation, fullness and specification respecting the full wireless HW/SW embedded systems analysis. Very few research studies have been reported in this subject.

The work reported in [4] concerns the COTS dependability, but focuses further on the dependability characterizing of open source operating system (Linux) drivers, based on the software simulation practice. The authors propose a practical approach to benchmarking the robustness of the embedded operating systems with respect to faulty device drivers.

In [5] the authors present architecture to evaluate the reliability of a HW/SW system (SoC: System on Chip). They propose to integrate an autonomic layer into the SoC to detect the chip's current condition and instruct appropriate countermeasures. This approach is performed at one specific abstraction level.

Overall, most of the techniques used for HW/SW wireless embedded system dependability study is based on co-simulation practice using software components models and mathematical equations for channel modulation (e.g. SRD Design Studio, Matlab/Simulink based model…). In such techniques many hypotheses on the reliability of the system are made early in the design process and have to be verified in a tardy stage of the design process (prototyping phase in real environment). If one or more of the assumptions is incorrect, it results in a significant re-design and debug overtime as compared to the initial expected design time. Another ignored factor is there is a risk that these shortcomings will be missed the time-to-market of the product, and lead to displeased customers. Simulation-based techniques raise at least three or four inconveniences:

- A time consuming technique (very slow)
- Very hard to enable a co-simulation in the case of heterogeneous components (ex: RF components with digital ones),
- Presents a real bottleneck for environmental threats examination, there is no existing tool to study the effect of the environment threats on the wireless embedded system/application being designed
- Furthermore, it can be very difficult or even impossible (e.g. in the case of Electromagnetic Compatibility perspective)

IV. WIRELESS HARDWARE PLATFORM FOR DEPENDABILITY ANALYSIS

One of the questions which should be raised is why there is a real need for this wireless hardware platform for dependability investigation? If one analyzes the trend for the dependability investigation of wireless embedded applications in the embedded market, especially in short range radio applications, it is clear that dependability/reliability analysis process using simulation models for digital, analog and wireless parts will not be able to support the required overall investigation. Particularly in terms of environment threats examination, and electromagnetic compatibility perspective. Besides, simulation-based dependability study is time consuming technique.

In classic simulation-based dependability investigation techniques (e.g. the FMEA, Failure Mode and Effects Analysis method), system designers investigate the dependability of each part (HW part, SW part, wireless …) alone, it is only at the end of this long process that a global reliability analysis of the entire system is performed, generally involving simulation model of the environment and outside threats (Figure 2).

Therefore, the best option for dependability/reliability investigation of such systems seems to rely on the hardware platform (physical architecture) concept to analysis, verify, and check the reliability of wireless embedded systems. Such hardware platforms make it possible to test the dependability of a system in an environment very close to the real (final) setting where the system will be used.

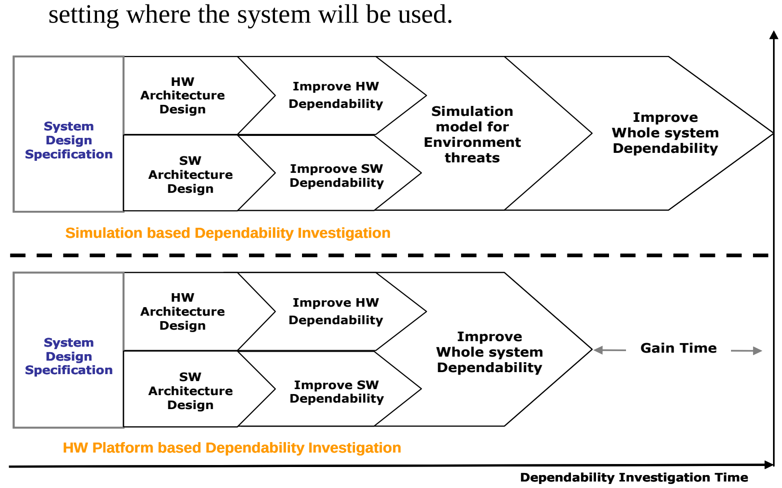

Figure 2: Platform based & Co-Simulation for dependability investigation

A. Main Approach

In the wireless HW/SW systems dependability investigation, one can discuss all of details of performance, such as HW/SW security, availability…etc. It is necessary to adopt a global top-down methodology that investigates the dependability of the different parts of the wireless embedded system as sub systems/components as well as the interfacing between these components. The system architecture has to be divided into sub-systems and then probably a roadmap should first be roll out. Also, previously mentioned, working on dependability issues of short range wireless application should be a coordinated effort between a numbers of experts (embedded SW designers, HW designers, mixed signal …etc)

FPGA fabrics with heterogeneous components (digital, analog, HW IPs, connectors…) are emerging in the industry, either for data processing applications design/validation such as (audio codec, video encoder) or for communication applications such as client-server. The Xilinx Virtex family [15], and Microsemi (Actel) SmartFusion [16] devices are examples of these FPGA fabrics. These HW devices are considered to be the future and the best solution for design, validation, checking, and dependability studies of embedded systems.

Our methodology described in this paper is a process for performing and analyzing dependability of the whole embedded wireless system. It is based on a hardware platform approach [1]. Two main steps are defined in our methodology:

1. ***Building the wireless platform***: The first and most crucial one is to build the wireless platform. For that purpose, several instances were used of the new SmartFusion devices provided by MicroSemi (Actel). Our wireless hardware platform is defined as a several reconfigurable instances connected with each other wirelessly. Subsequently the designers select a set of these components to build their wireless embedded system. Two main structural designs are defined in our wireless platform, on-chip structural design and off-chip structural design. Details about the two parts are given below. Such hardware platform enables the investigating of the reliability of the wireless application by analyzing the different components of the system separately, and at different abstraction level. It is now also possible to test the circuit/application in an environment very close to the final one, taking into account the operational conditions (where the system is being used). This wireless platform is the best alternative for the time-consuming co-simulation approach.

2. ***Defining a global Dependability approach based on this Platform:*** The methodology described in this paper is a method for performing and analyzing dependability of the whole embedded wireless system. It is based on a hardware platform approach. The basic idea of our dependability framework is to have several tightly coupled hardware and software peripherals (dependability mechanism) to manage and verify SoC based components at the functional level. At OS level, for example, these dependability mechanisms implemented in SW and will check and supervise the booting of the OS, the context switch and the interrupt controller.

B. Wireless Platform Overview: SmartFusion FPGA

SmartFusion device is a mixed-signal FPGA, and so far the only, device that integrates on the same chip programmable analog blocks (for mixed signal development), a set of logic gates (for HW IPs development), CPU-ARM Cortex-M3 processor (for embedded SW control development), and a set of connectors in order to communicate with outside [16].

These characteristics make this device very appropriate for wireless applications development. Figure 3 shows a global view of our wireless platform.

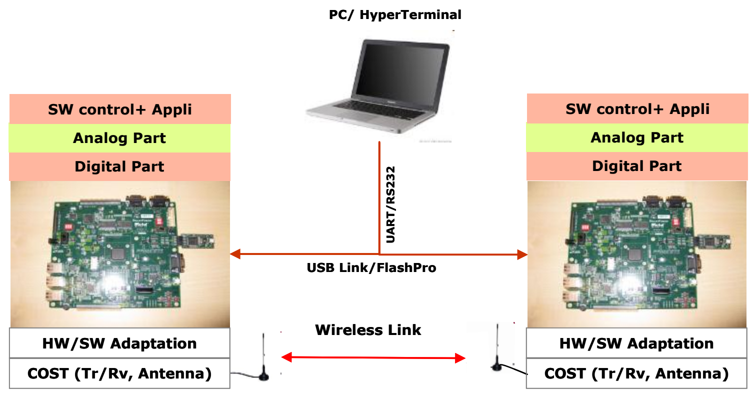

Figure 3: Wireless Platform based on SmartFusion Mixed Signal Device

C. On-chip structural design

As mentioned earlier, the wireless platform is composed of two main parts: an embedded architecture fully built inside the FPGA device, software control running on the ARM CortexM3 based architecture, and the analog modules.

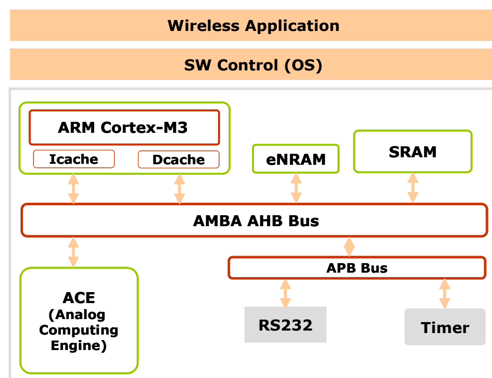

Figure 4: CortexM3 based architecture

- Using this device, a HW/SW digital architecture was built based on the ARM-CortexM3 CPU (Figure 4). The CortexM3 CPU is connected to a local booting memory (eNVM: embedded Non Volatile Memory) and a high speed data memory (SRAM) via an AMBA high performance system bus (AHB) [16].

- The analog part is designed around the Analog Computing Engine (ACE) and Analog Frontend (AFE) block. The analog block is connected directly to the rest of the system via a 32-bit wide connection. The block has also its own CPU, called Analog Computing Engine (ACE). It is almost a co-processor, which can perform functions such as automatically adjusting the resolution of the ADC (Analog to Digital Converter), initiate an digital-to-analog conversion (or vice versa) basing on an active FPGA signal, and stop the Cortex-M3 when a particular event occurs.

- The software part is mainly built around a software control part (tiny embedded operating system) in order to manage the execution of the software application on the target digital architecture. It sends the computing data off-chip via the analog mixed signal architecture.

D. *On-chip structural design flow*

The on-chip design flow assures the requirements of the embedded software design, the processor sub-system configuration and the analog components configuration by providing parallel design steps. A hardware adaptation step is required in order to adjust the connexion between the On-chip architecture and the COTS (off-chip). A specific HW IP care this adaptation. Figure 5 shows the on-chip design flow steps.

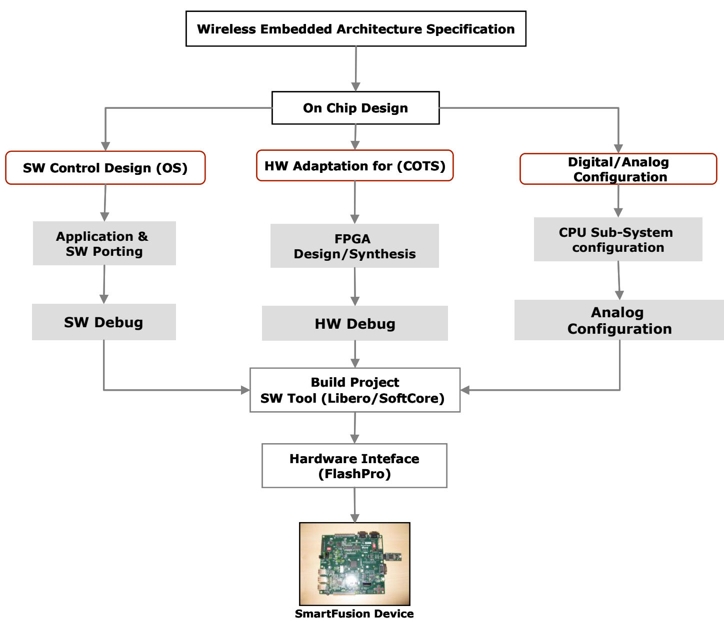

Figure 5: On-Chip Design Flow

For the hardware digital part, the ARM CortexM3 subsystem and other design component blocks are configured and connected together to complete a full processor-based architecture using the Libero IDE/SoftConsole tool. The software application and the software control are created and debugged using the same tool. During the construction of the system, the memory mapping and drivers are provided by the same tool for the selected configuration. When the design development is complete, the FPGA device is programmed using the hardware interface (FlashPro4) and an USB link.

E. Off-chip Hardware Architecture

Commercial off-the-shelf (COTS) components are designed to be used as black boxes. If one integrates such COTS components into a short range wireless application, that involves high dependability requirements; there may be mismatches between the failure assumptions of these components and the rest of the system. For resolving these mismatches, system integrators must rely on methodologies that allow for the COTS hardware or software components. Even if the COTS blocks are delivered with deeper knowledge about their failure modes, dependability degree, and its behaviour in the presence of faults, it still presents a real bottleneck.

The SmartFusion instances are connected via wireless links using antennas. This antenna is adapted via a USB connection in order to send data from one platform device (on chip architecture) to another one. In this stage of the wireless platform design, we used a COTS (Commercial off the Shelf) predesigned component. A task adaptation between the integrated COTS and the other parts of the architecture design (on-chip architecture) will be performed. COTS dependability is a research subject by it self [6], we are focusing on the dependability of the adaptation interface between it and the rest of the architecture.

V. HARDWARE PLATFORM BASED DEPENDABILITY APPROACH

The methodology described in this paper is a method for performing and analyzing dependability of the whole embedded wireless system (Figure 6). It is based on a mixed HW/SW approach. There are a number of factors that need to be considered to determine the best process.

It is considered that the most important feature is the investigation of the whole system dependability at different abstraction levels of the design, SW, digital, analog, and wireless.

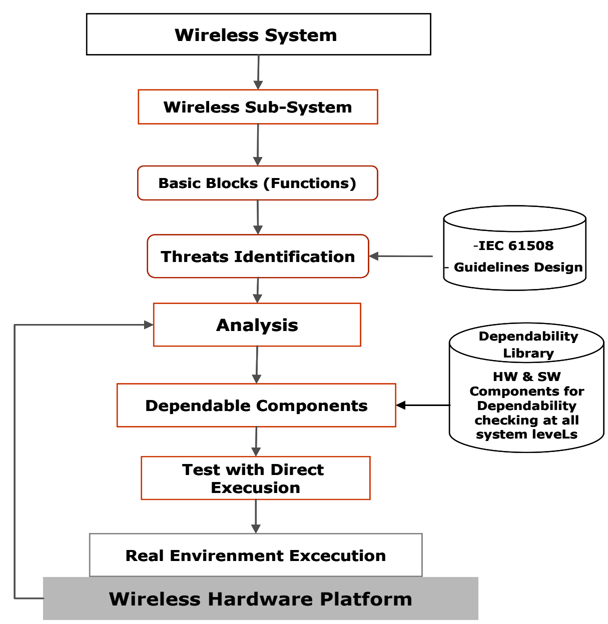

Figure 6: Dependability flow

In such dependability a paradigm, the components of the system at hand are defined separately, at different abstraction levels (transactional, RTL or transistor level) and with different specification languages (C, HDL…). Then, the proposed methodology takes care of this issue by investigating the dependability at several levels of the design by the use of dependability components described at the same level of abstraction as each component of the design.

One can defines these dependable components (or dependability mechanism) as tightly coupled hardware and software peripherals run during the run time execution of the wireless system on the hardware wireless platform, in order to manage and verify the system's components at functional level. Hence, the following three main stages of dependability investigation are planned in our methodology:

- Dependability exploration within the HW/SW digital part
- Dependability exploration within the analog/RF part
- Dependability exploration within the Wireless part

As a result of that, the dependability flow covers the different sub-systems: wireless, digital, and analog part (block diagrams, RTL level, channel link level and transistor level)
One can also add one more stages of dependability concerning the integrated COTS in the system being designed.
After partitioning the embedded wireless system to three sub-systems (digital, analog/RF, and wireless parts), in the first stage one extract information from each sub-system by partitioning each sub-system into several basic blocks (HW or SW blocks). Partitioning means that these basic blocks shall be maintained with respect to the abstraction level, and description language.

The next step in the methodology consists of extracting the usage profile and information of such basic blocks under a given specification. In a third stage, the information and usage profile are used to prepare a dependability components (mechanism) library database. This library database is constructed by entering information related to both to the wireless safety specifications of the IEC 61508 norm, and to some of the design guidelines available in the market.

A. Digital dependability level:

In this dependability level, on one side there is the hardware digital components, mainly represented by the processor-based architecture (ARM CortexM3 in our case). On the other side, the software architecture which is built around a small software control (operating system, OS) which involves real-time computations, and management of the execution of the tasks-wireless application, it also handle all exceptions during the execution run-time.

As the software control (OS) is considered as one of the important parts of the circuit, we have developed a generic software dependability component running at the same time as the software on the hardware platform. During a real execution, the different SW functions of the OS are verified, starting with the scheduler until the low level functions, booting system, synchronization, and context switch.

B. Analog dependability level:

At this level, dependability library components are written in another level of abstraction (transistor). At present it is assumed that verifying analogue components is carried out separately on another platform (software one) since we used pre-designed hardware blocks provided from the market as a component in which the transmitter/receiver and the wireless antenna are integrated. Hence, at this moment not much effort will be spend at this level.

C. Wireless link level:

Several layers are defined in the known OSI (Open System Interconnect) standard for a communication system. Here, as well, investigation of the dependability will be done on two layers which are crucial for us. The functional and procedural data transfer between network mobile notes (SmartFusion FPGA entities) are explored and this will detect possible errors that may occur at the low level layers media and data layers of the OSI communication model.

At this dependability level, one gives special attention to the EMC (Electromagnetic Compatibility) of the environment with the wireless system being designed. The wireless hardware platform facilitate the investigation of the EMC on the wireless link by providing the possibilities to understand how the EMC field can affect the wireless communication link inside a reverberation chamber which is available within our laboratory.

D. Functional safety and IEC 61508

The IEC 61508 international norms define requirements for dependability/safety of electrical/electronic/programmable electronic related systems [7] [10].

Even if these norms not really refer to complete wireless HW/SW embedded systems, they contain some accurate rules and requirements for the system subcomponents. They include CPUs, memory systems, bus network and so on. An extension of such a norm to SoC systems will be appearing soon. The basic concepts of IEC61508 is the definition of safety integrity level (SIL), i.e. the discrete level (one out of a possible four) for specifying the safety integrity requirements of the safety functions to be allocated to the safety-related systems. Safety integrity level 4 has the highest level of safety integrity and safety integrity level 1 has the lowest. This factor concept is taken into account when specifying the different components of the dependability library.

VI. RESULTS, ANALYSIS AND FUTURE WORK

The effort required for this first step to set up wireless platform based on the SmartFusion device is three person/months, and this is only for a particular digital/analog configuration. In the case of reuse of the same processor based architecture, this effort could be reduced.

This work allows the investigation of the dependability/reliability in mixed wireless systems context, as the first step in understanding the complexity to approve the dependability of such systems, which is a multifaceted problem. Our current research has shown that the usage of hardware platform for embedded wireless short-range radio application reliability study is the most attractive approach in comparison with the time-consuming co-simulation approach. It allows the analysis of the heterogeneous parts of the wireless systems (digital data source, wireless and analog part) by verifying the system at the different design levels.

This wireless hardware platform is an important step toward a seamless dependability study of complex embedded wireless systems/applications. The goal behind the proposed approach is to build a dependability library database of reusable components on the road to add the designers to verify and approve the dependability of the system being designed, in an environment close to the real operational conditions.

One of the most difficult steps in building the wireless platform is the bridging between the instances of the SmartFusion devices, which bring us to bridge the digital and analog part (which is on the same chip in this case) with the off-chip architecture (transmitter/receiver, antenna).

Building this wireless platform in the context of the design, re-configuration and reuse, allows the validation and verification of the dependability of several wireless applications on the same hardware platform. This flexible platform provides also the possibility in the near future to investigate the EM (Electromagnetic field failure) on these short-range radio applications by investigating the behaviour of the entire platform. Our basic motivation is to build pre-designed HW and SW components that can check the reliability of the different basic blocks of the system, and give us numeric information to improve the dependability of the system at functional level. These dependability components are build up according to the international safety/reliability standards (IEC 61508) and the guidelines usually used in circuit design. In fact to reach and built these library components for all the abstraction levels and for the general case is very hard and may be not a realistic goal, in proportion to the large heterogeneity of the applications.

In particular, the wireless communication between mobile robots will be used as vehicle.

VII. CONCLUSION

In this paper, experiences are presented in investigating the dependability of wireless embedded systems for short range-radio application (indoor applications). A hardware approach for dependability study is presented. We successfully built a hardware wireless platform for this purpose. The goal behind the construction of the wireless hardware platform is to help the designers to verify and approve the reliability of the system being designed in an environment very close to the real application settings.

Based on the platform a new dependability flow/methodology was introduced to facilitate the reliability verification in complex short-range wireless systems, taking into account the different parts of the system, embedded SW, digital part, analog/RF part, and wireless link part).

Acknowledgement

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