Universidade de Aveiro
2008

Departamento de Electrónica, Telecomunicações e Informática

Emanuel Filipe Cunha Miranda

Gerenciador de Recursos

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Electrónica e Telecomunicações (300-9365), realizada sob a orientação científica do Dr. Paulo Pedreiras, Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática (DETI) da Universidade de Aveiro (UA).

o júri

agradecimentos

Gostaria de agradecer aos meus pais e irmã, Emanuel, Ana e Anita, que me ajudaram na minha estadia na Holanda e sempre seguiram de perto os meus passos académicos.

Aos meus amigos na Holanda, João, Rodrigo e Bibiana, que sempre me apoiaram em todo o processo de adaptação.

Ao Orlando Moreira (NXP) e ao Prof. Paulo Pedreiras (UA), pela oportunidade e auxílio.

Por último, mas não menos importante, ao meu amigo Luis Silva que me ajudou na revisão da tese.

acknowledgements

I would like to thank my parents and sister, Emanuel, Ana and Anita, who made my journey to the Netherlands possible and followed my life and my studies closely.

To my friends in the Netherlands, João, Rodrigo and Bibiana, who supported me in several milestones during my stay.

To Orlando Moreira (NXP) and Prof. Paulo Pedreiras (UA), who gave me the opportunity and guidance to help me succeed.

Last but not least, to Luis Silva who reviewed my thesis. No one could hope for a better friend.

palavras-chave Gerenciador de recursos, Rádio definido por Software, Sistema heterogéneo de Multi-processadores.

resumo

Esta tese reporta a implementação de um módulo gerenciador de recursos para uma plataforma heterogénea multi-processador de rádio para equipamento movel. Nessa plataforma os rádios são definidos como *data flows* e são dinamicamente alocados, ou libertados consuante a necessidade da aplicação.

Os rádios são alocados em *runtime* e requerem vários recursos que podem ou não estar livres na plataforma. Quando uma tentativa de alocação de um rádio falha, todos os recursos até ai reservados têm que ser libertados. Esta metodologia requer tempo e não é eficiente. O objectivo desta dissertação é investigar diferentes metodologias e algoritmos para tornar o processo de alocação mais eficiente. A abordagem escolhida foi baseada na modelação dos recursos, opção que permite controle de admissão e é independente da plataforma. Este trabalho foi desenvolvido o mais genericamente possível para abranger a maior variedade de aplicações.

No estado actual do projecto são suportados até 5 standards de rádio simultaneamente, cada um com diferentes taxas de entrada/saída e com requisitos *real-time*. Em conclusão, este projecto contrói o caminho para a quarta geração (4G) de tecnologia de comunicação.

keywords Resource Manager, Software-Defined Radio, Heterogeneous Multi-processor system.

abstract

This dissertation addresses the project and implementation of a Resource Manager module for heterogeneous multi-processor radio platforms. In the target platform the radios are defined as data flows and are dynamically allocated and released, according to the application needs.

Radios are allocated at runtime and require the sequential allocation of several resources that may or may not be available. Whenever the allocation of any necessary resource fails, the radio allocation procedure has to be aborted and the eventually allocated resources released. Allocating and de-allocating resources is costly and thus this methodology is not efficient. In the scope of this dissertation are investigated different methods and algorithms to make the radio allocation process more efficient. Four different possibilities are considered and assessed. The chosen approach is based in the use of a resource model, which permits fast admission control and is platform-independent, since it does not require any modification on the platform-specific modules. This application is being developed as generically as possible to be able to embrace the largest possible group of applications.

In its current status this project supports up to 5 different radio standards concurrently, each one exhibiting specific input/output rates and real-time requirements. In conclusion, it is the path to fourth generation (4G) communication technology.

Contents

Abbreviations

0G	-	Zero Generation
1G	-	First Generation
2G	-	Second Generation
3G	-	Third Generation
3GPP	-	Third Generation Partnership Project
4G	-	Fourth Generation
ADC	-	Analog-to-Digital Converter
AHB	-	Advanced High-performance Bus
API	-	Application Programmer's Interface
ARM	-	Advanced RISC Machine
AXI	-	Advanced eXtensible Interface
BB-RM	-	Baseband Resource Manager
BF	-	Best Fit
CM	-	Configuration Manager
CPU	-	Central Processor Unit
DAC	-	Digital-to-Analog Converter
DSP	-	Digital Signal Processing
EVP	-	Embedded Vector Processor
F-ARM	-	FPGA ARM
FF	-	First Fit
FIFO	-	First In First Out
FPGA	-	Field-Programmable Gate Array
G-RM	-	Global Resource Manager
GSM	-	Groupe Special Mobile
J-ARM	-	JEOME ARM
J-ARM	-	JEOME ARM
J-EVP	-	JEOME EVP
J-EVP	-	JEOME EVP
J-Tile	-	JEOME tile
LTE	-	Long Term Evolution
MPS	-	Multi-Processor System
MW	-	Module Weights
NM	-	Network Manager
OS	-	Operating System
PC	-	Personal Computer
RAP	-	Resource Allocation Problem
RISC	-	Reduced Instruction Set Computer
RM	-	Resource manager

RR	-	Round Robin
RT	-	Real-Time
RTOS	-	Real-Time Operating System
RTS	-	Real-Time System
RW	-	Relative Weights
RX	-	Receive
SDR	-	Software-Defined Radio
SK	-	Streaming Kernel
SoC	-	System On Chip
SoD	-	Sea of DSP
SRDF	-	Single Rate Dataflow
TX	-	Transmit
UART	-	Universal Asynchronous Receiver/Transmitter
uC/OS	-	Micro-Controller Operating System
USB	-	Universal Serial Protocol
VBP	-	Vector Bin-Packing
WLAN	-	Wireless Local Area Network

List of tables

List of figures

(This page was left blank delivered)

1. Introduction

The way to the future is built on knowledge from the past, so a brief description of the cellular mobile radio history will be given next.

As early as 1921 the first communications were done via the mobile radios rigs and used in vehicles such as taxicabs, police cruisers and ambulances. These devices were not considered as mobile phones because they were not normally connected to the telephone network (1).

During the early 1940s, Motorola developed a backpacked two-way radio, the Walkie-Talkie and later developed a large hand-held two-way radio for the US military. It was in 1945 when the zero generation (0G) of mobiles phones was invented. There the mobile phone just worked in one station, so the cellular concept did not exist. At this time several prototypes were invented (2).

Firstly in Tokyo, Japan (1979) and two year latter in Denmark, Finland, Norway and Sweden, the first commercial cellular phone networks, called as first generation (1G), were launched.

In 1982 the *Groupe Spécial Mobile* (GSM) (3) created the first standard for mobile phones, and in 1990 the first GSM mobile communication infrastructure was deployed. This new release was called second generation (2G). This new variant brought the SMS service, which permits sending text messages in addition to the voice calls.

Not long after and with the introduction of 2G networks, third generation *(3G)* systems began to develop. There were many different standards created by different contenders. The meaning of 3G was the standardization of the requirements (maximum data rate indoors/outdoors) instead of technology standards. At this point, several different standards were introduced.

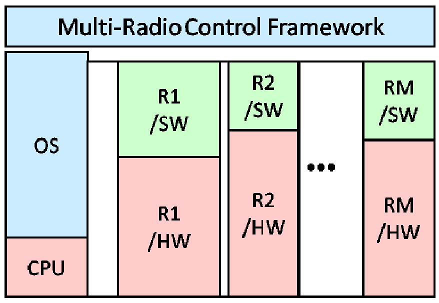


Figure 1 : Ordinary radio archittecture from [14]

Current ordinary radio devices have a similar architecture to the one depicted in Figure 1. The control element is the Operating System (OS) that runs on a Central Processor Unit (CPU). It manages all the device activities on the platform. It should be

remarked that each radio has specific hardware to support it and, consequently, each radio standard is supported by dedicated hardware. Figure 1 depicts a radio architecture example that supports M radio standards with M dedicated hardware modules.
The number of applications supported by mobile devices is growing day by day. Most of them use remote databases and/or services. The need to make an efficient use of the communication bandwidth led to the development of different standards.

Nowadays, mobile cell systems support more than ten radio standards. Furthermore, some of them (e.g. GSM) have several versions. This imposes a constraint on the radio devices. If a radio device aims at supporting the majority of these radio standards it would need dedicated hardware for each one and so it becomes big and complex. Another drawback of this radio architecture is that it is not upgradeable, and thus cannot evolve to support radio standards than are created after its development.
Finally, it should be noted that the "classical" architecture depicted in Figure 1 is used in mobile devices, and thus subject to strict size limitations, which can also constraint the number of dedicated HW radios and, consequently, the number of standards supported.
In face of all of these trends, the ordinary phone platform is starting to become obsolete. Following the personal computer (PC) innovation, mobile phone platforms are going heading to Multi-Processor Systems (MPS), called 4G (4).

Multiprocessor systems present several advantages in terms of flexibility, power efficiency and cost (5).
In conclusion, the balance between installed uni and multi-processors will change in the upcoming years.

A. *Software-Defined Radio*

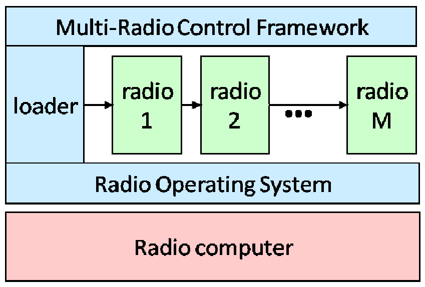


Figure 2 : SDR radio systematic from [14]

The negative aspects pointed out to the current radio platforms can be traced to the dedicated hardware implementation of the radio components. This observation led to the development of the Software-Defined Radio (SDR) (6) concept. This concept was a small revolution in the field of hardware devices. The use of SDR is completely compatible with the existing network infrastructure and standards, however changes significantly the internal architecture of the mobile devices.

The major difference between the conventional and SDR radio platforms is the fact that instead of having dedicated hardware for each radio standard, the radios are programmable software entities, similar to application programs in a personal computer.

Thus, provided that enough resources are available, it becomes possible running multiple radios simultaneously as well as replacing radios dynamically, according to the needs.

As depicted in Figure 2, the SDR architecture comprises an OS that manages the platform resources, namely supporting run-time reconfiguration by installing, loading and activating new radios.

In this approach, the radios are now engineered in software, easily allowing platform updates with the objective of supporting new radios and standards. Thus, the platforms become flexible and evolutive.

B. *This project*

In SDR architectures, the instantiation of radios requires resources such as CPU, memory and communication channels. These services are provided by the so-called Base-Band Resource Manager (BB-RM) module. The main target of this master's dissertation is to develop a BB-RM module able to manage efficiently the different resources.

The platform used in this work is based in a multi-processor system. Furthermore, each CPU board has local memory, which is partially used by the local processes and partially shared, for communication. Hence, the BB-RM has to take in account the available computational and memory resources available in each processor.

In addition, the platform is heterogeneous, meaning that it uses diverse processor types. Specifically, the platform has Reduced Instruction Set Computer (RISC) processors and Embedded Vector Processors (EVP). In this type of systems some functions can be executed more efficiently in one particular type of processors than in others. Hence, the BB-RM must also be aware of these possibilities and permit allocating the computation to the best suited execution platforms. The main purpose of this platform is infotainment applications. Many of these applications have soft real-time (RT) requirements, and thus the BB-RM must also guarantee that radio applications meet the associated deadlines.

C. *Base-Band Resource Manager*

Embedded platforms for media streaming have to handle several streams at the same time, each one with its own properties (7). Typically the radio can be divided in minimal groups of components, called processing components that are controlled independently by an external source. These processing components that form the radio communicate through First-in-First-out (FIFO) buffers.

Working on the radio operating system layer, the BB-RM has the responsibility to allocate these radios on the platform. It uses a strong policy to ensure:

- Strict admission control - a radio is just allowed to run on the platform if the system can support the resource budget and RT requirements of each radio component.
- Strict resource reservation - each radio can only use the resources that have been allocated to it.

To provide these policies the BB-RM copes with several issues like:

- Heterogeneous multi-processor platform - several processors of different types.
- Multiple radios simultaneously active - the platform should provide different radios and radios standards at the same type.
    - Different rates of operation - each component in the radio has its own rate.
    - Unpredictable start/stop times - the start/stop of the radios are independent among them.
- Must provide RT guarantees - radio functions require real-time guarantees.

D. Thesis overview

This master's thesis is split into six main chapters. The "Background" chapter introduces basic concepts associated with the work developed. The "Software-Defined Radio framework and radio description" chapter presents a detailed description of the platform hardware and software architecture. In the "Design space, problems and solutions" chapter it is shown the workspace of BB-RM, its problems and possible solutions. The core chapter of this thesis is "Implementation of the BB-RM", in which it is explained the BB-RM implementation, functions and API. The implemented solution to solve the resource allocation problem and the file structure is also described. The tests and analysis of the BB-RM implementation are presented in chapter "Experimental results and analysis". Finally, an overview and global assessment of the work developed is presented in chapter "Conclusions and future work".

2. Background

This chapter reviews some fundamental concepts that are associated with the work developed in this dissertation.

A. Real-Time Systems

Real-Time Systems (RTS) are systems with time constraints. This means that the system activities have associated temporal constraints. The most common temporal constraint is called deadline, and indicates an upper bound to the conclusion of a task. Deadlines can be classified according to the relevance and potential consequences of failing to meet them. A deadline is classified as **Firm** if, when violated, the results obtained are useless to the system. Conversely, deadlines are classified as **Soft** when computations obtained after the deadline keep some level utility. A firm deadline is classified as **Hard** when its violation can result in catastrophic consequences, e.g. by threatening human lives or causing significant economical impact. Systems may also be classified according to the deadlines of the associated tasks. **Soft Real-Time Systems** contain only non real-time or real-time tasks having soft or firm deadlines. **Hard Real-Time Systems** contain at least one task having a hard deadline (8).

B. Multi-Processor System

MPS is a computational system which has at least two processors, also designated by cores (9).
The advantage of such system is to increase the computational power, but it doesn't mean that two processors running the same code as one processor will run in half the time!
One MPS can be composed of several cores of the same type, being designated in this case by homogeneous system or composed of different core types, in which case is called heterogeneous system.

C. Multi skills systems

Nowadays almost all real-time applications, i.e., applications where the time response is required are supported by RTOS. These systems became trivial in such a way that even simple applications where the time response is not hard are frequently based on RTOS.

On the industry field there are some systems which contain RT behavior running on a uni-processor system. On a uni-processor system the OS does not need to handle shared resources or duplicated resources. Early on, most of these platforms were migrated to MPS. Due to the shared resources and duplicated resources required, a RM was used to handle them. The MPS can have all processors of a same type, or processors of a different type (10). To the system which gives RT guaranties and running on a MPS it's called multi skill systems.

In summary, to handle the multi skills systems it is necessary to add an additional background software to manage the shared and duplicated resources in the platform. This additional software is pretty important. If the resources are not properly handled, a heterogeneous MPS can be worst than a uni-processor platform in performance terms.

D. Single-Rate Dataflow

Single rate dataflow (SRDF) is a computational model that can be used for the specification and implementation of Digital Signal Processing (DSP) applications. Its main advantage over other computational models is that it uses a strict data-driven rule to decide when each computation can be performed. This allows for rigorous RT analysis, and the computation of static schedules and buffer sizes that are guaranteed to meet the RT requirements of the application. As represented in Figure 3, an SRDF graph is a directed graph where the nodes (normally referred to as actors in the context of SRDF) represent a block of computation, and edges represent FIFO queues used by actors to communicate amongst themselves. Each actor has a strict rule for activation; whenever a pre-specified amount of data – referred to as a token - is available at each of its inputs, it can be activated. In dataflow jargon this activation is frequently referred to as a firing. When an SRDF actor fires, it consumes a token from each one of its inputs, and produces a token on each one of its outputs. The model allows the specification of an arbitrary number of tokens which have to be stored in the queues prior to the beginning of execution. This initial number of tokens per edge is often referred to as the delay of that edge. By default, actors hold no internal state from one firing to another. An edge from an actor to itself, with a delay of one is frequently used to represent the passage of state between consecutive firings. For more details see (11).

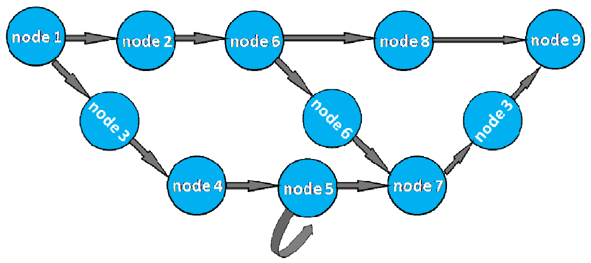


Figure 3 : Single-Rate dataflow

(This page was left blank delivered)

3. Software-Defined Radio Framework and Radio description

This section presents a general overview of the platform hardware, from the smallest conceptual unit, called tile, crossing over the JEOME hardware and arriving to the global platform. An explanation about the physical connections and the logical relations between each component will be given further ahead.

A. Hardware Framework

Tile

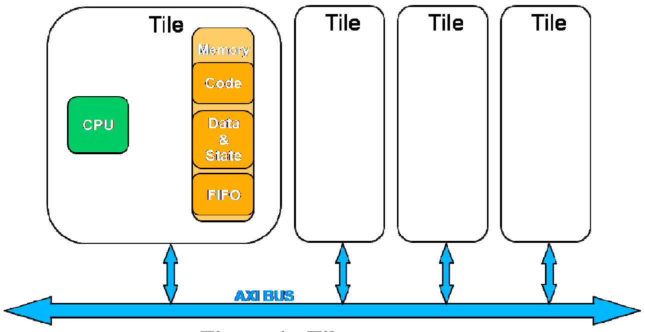


Figure 4 : Tile strucure

The smallest conceptual unit defined in the system is designated by tile, being composed by a core and dedicated local memory. The core can be an Advanced RISC Machine (ARM) or an EVP. The dedicated memory is split in to three parts: code memory, data/state memory and FIFO memory. The function of each one of these memory blocks will be detailed in section C of this chapter. The platform used in this work is composed by four tiles, two of them having ARM processors and the other two with EVPs.

The communication among processes can be either, local when the processes reside in the same tile, or remote, when the processes reside in different tiles. Local communications are carried directly over the tile's own FIFO memory block, which is directly addressable by both processes. When the two processes are executed in different tiles the communication is carried out via the Advanced eXtensible Interface (AXI) (Figure 4). In this case the FIFO memory is allocated only in the tile of one of the processes. Consider for instance a process A running on tile #1 that needs to transfer data to a process B that will execute in tile #2. In the example the FIFO memory is allocated in tile B and, consequently, when process A issues a write operation the data is actually written in FIFO memory of the tile #2. Process B reads the data it from its own local memory. Remote operations are more costly than local operations, a factor that has to be taken into account during the system design. Therefore, communicating processes should, whenever possible, be allocated to the same tile to minimize the communication latency.

For the sake of performance, the FIFO memory is preferably allocated to the tile of the consumer process. As stated above, remote operations, carried out via that AXI bus, are more costly than local operations, issued on local memory. Writing operations always succeed, provided that the buffers are properly dimensioned. On the other hand, the reader process has to pool the memory to detect the arrival of new data. Thus, a single data transaction typically involves a single write operation and several reading operations and, consequently, the complexity of the reading operation end up having a higher impact on the system performance than the complexity of the write operation.

JEOME

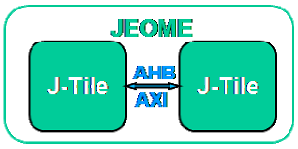


Figure 5 : JEOME structure

JEOME is a NXP's System On Chip (SoC) specifically developed for SDR. Its internal structure is depicted in Figure 5.

JEOME contains two tiles, one based on an ARM processor and the other based on an EVP. The communication between JEOME Tiles (J-Tiles) is carried out via the Advanced High-performance Bus (AHB) and AXI protocol.

Platform

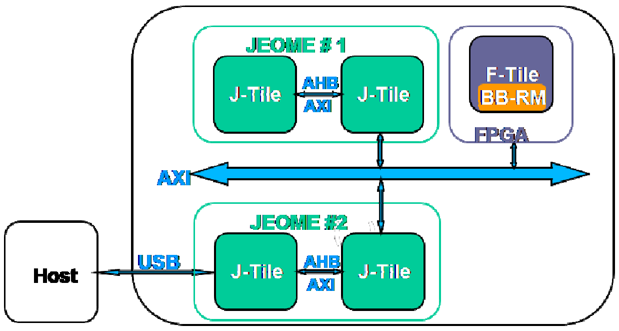


Figure 6 : Platform structure

The SDR platform is composed by two JEOME chips, one Field-Programmable Gate Array (FPGA) and the external connections. There is a clear separation between the hardware devoted to the system management and the hardware dedicated to support the actual radio system. The hardware dedicated to manage the system, identified by the purple color in Figure 6, is based on an FPGA. The FPGA integrates an ARM processor core which supports the Data Communication Dispatcher, BB-RM and Sea of Digital Signal Processor (SoD) software modules. The purpose and structure of these modules will be detailed in the section B.

The two JEOME chips, identified by the green color in Figure 6, form the radio system, which is the hardware where the SoD Streaming Kernel (SK) and radio functions are executed. These services can be executed either in the ARM or the EVP processor, depending on several reasons that will be detailed in section C.

To make the distinction among the different ARM processors, the FPGA ARM is called F-ARM while J-ARM refers to the ARM processors in the JEOME SoC.

The block identified as “Host” in Figure 6, also called PC, is a general purpose computer where the configuration modules are executed. More specifically, this hardware executes the configuration manager and the Global Resource Manager (G-RM). The purpose of these software modules is detailed in section B as well.

These different modules form a distributed system. The communication between the JEOME tiles and the FPGA tiles is based on the AXI bus, while the communication with the host is made through Universal Serial Bus (USB) link. This path is used to upload the manager software system on the platform.

In terms of visibility, the F-ARM is the manager of all others tiles and thus can communicate (send and receive data) with all the other tiles. The J-Tiles with EVP processors have the same view of the platform. However, the J-Tiles with ARM processors just see the EVP within the same JEOME. That is, within the JEOME board the tile with an EVP processor sees everyone in platform and the tile with an ARM just sees the other tile in JEOME board. This constrain limits the number of possibilities to allocate radio components in the platform. On the next board generation this problem is fixed.

Hardware description

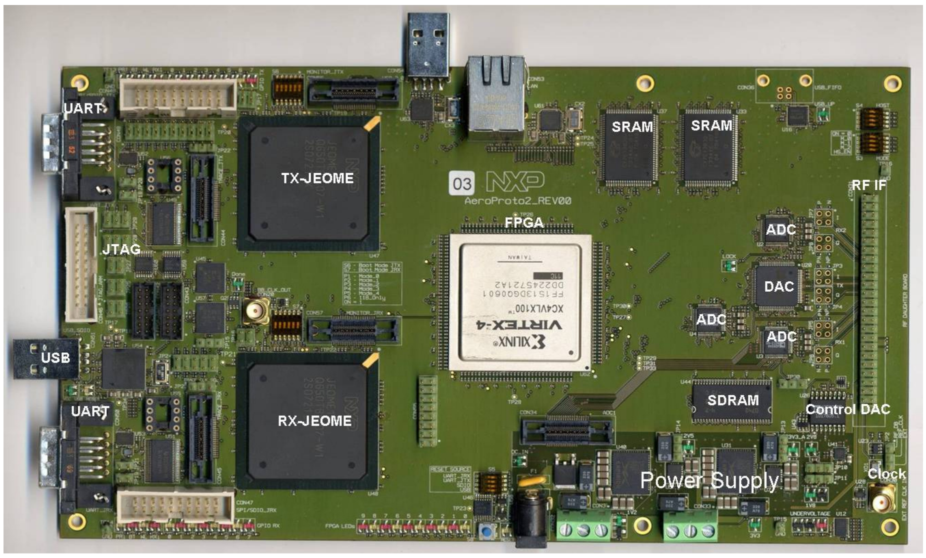


Figure 7 : AeroProto2 board

Figure 7 depicts an AeroProto2. This is a NXP's board built for development with the third Generation Partnership Project in Long Term Evolution (3GPP LTE) and other communication standards.

In addition to the two JEOME and FPGA tiles, this board integrates interfaces such as Digital-to-Analog Converters (DACs) and Analog-to-Digital Converters (ADCs). Additionally it incorporates several hosts and a debug interface. As stated above, each JEOME SoC has one ARM and one EVP (12).

External connections

The AeroProto2 provides several external connections. The most important ones are the following:

- Ethernet (Fast) - RJ45
- USB connector - USB B-type jack
- Debug UART RX JEOME - DSUB9 male
- Debug UART TX JEOME - DSUB9 male
- USB host controller - USB A-Type plug
- External reference clock input - SMA jack
- Base band clock output - SMA jack

B. Software Framework

With respect to the radio signal frequency, the software is split into two major groups, one dealing with the radio band and the other with the baseband processing. Associated with the radio band can be seen all radio systems, the G-RM and the configuration manager. On the baseband side there are the BB-RM, SoD, and RTOS. These modules are described below.

Compile-Time environment

LIME As started in section C, a radio application is described by a set of software radio components written in "C" language, and a radio graph description, in XML. The software components, although written in C, conform to the LIME dataflow-based programming model, and correspond to dataflow actors. LIME prescribes certain rules that the prototype of the head function in each software radio component must adhere to. This function prototype informs the LIME compiler about the input and output ports, and the data-availability dependent activation patterns of the actor. The Radio Graph Description file describes how the Software Components are connected with others to form a radio. This information can be used by the LIME compiler to generate code for the underlying platform. This includes the automatic generation of task wrappers, and automatic generation of communication between tasks, using the communication primitives of the underlying multi-processor operating system, which, in the current setup is SoD. The LIME compiler also generates a dataflow analysis model, that can be used to compute the amount of platform resources (processor cycles per period, buffer sizes) that are required for the application to meet its real-time requirements. The LIME language has been open-sourced by NXP. The code and documentation detailing the usage of the language can be found in (13).Furthermore, there is not a one-to-one correspondence between LIME software components and tasks in the platform-specific generated code. This is because the compiler may decide –if possible- to take groups of actors, schedule them in static order relative to each other, and merge them onto a single task, as described in (14). This has the disadvantage that it reduce the run-time mapping options of the Resource Manager, but it also reduces the number of tasks in the radio, the task-switching overheads, and tightens the bounds of worst-case timing analysis, which in turn allows the computation of smaller resource requirements. This is described in detail in (14).

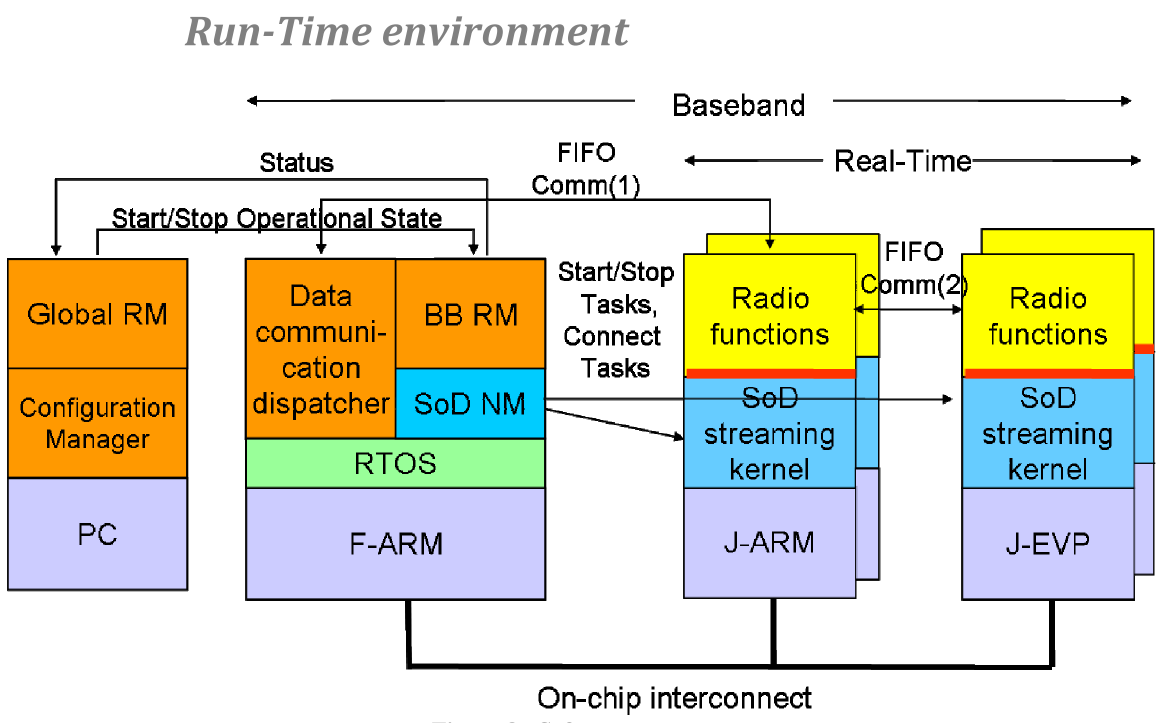


Figure 8 : Software structure

The mapping between the hardware structure, depicted in Figure 6, and the software layer, represented in Figure 8, is listed as follows (walking from the left to the right):

- The Configuration Manager (CM) and G-RM blocks are executed in a PC and are mapped on the host block on the Figure 6. The host establishes a connection with the SoC via the USB link. The second vertical block, composed by BB-RM, SoD NM, and RTOS are executed on the F-ARM processor (FPGA tile)
- The RT blocks (last two vertical blocks), are in one of the two JEOMEs running on J-ARM or J-EVP. For the sake of simplicity the software figure represents only one JEOME; both have the same structure

The remaining of this section presents an overview of the functionality of each one of the software components that compose the system software architecture.

Global RM The G-RM is the component responsible for controlling the BB-RM. It was designed to manage multiple platforms, each with one BB-RM responsible for managing the resources of its own platform. Thus the BB-RMs provide, for each platform, admission control and resource reservation that are used by the G-RM. Furthermore, the G-RM also interacts with the CM, where the radio definitions are stored.

As illustrated in orange in Figure 8, the G-RM is executed in the host block and provides the following services:

- Registration of the radio - stores the radio on CM
- Load a radio - loads the radio from CM
- Operation state change - manage the radio's state, as described in section C

Configuration manager The CM permits installing, uninstalling and loading different radio systems into the radio computer as well as managing the radio system parameters. It works as a shelf where the radios and respective configurations are stored.

BB-RM As depicted in Figure 8, the Base Band Resource Manager (BB-RM) is driven by the Global RM, supporting the creation, suspension, resume and elimination of radios in the corresponding platform. The other way around, the BB-RM uses the SoD Network Manager (NM) Application Programmer's Interface (API) to allocate the radio. Due to its importance to this work, the BB-RM component will be described with more detailed further ahead in this document.

SoD Nowadays the hardware of multiple and heterogeneous systems changes rapidly, and with it the software needed to go along with this evolution.
The SoD streaming infrastructure provides an environment that enables the reuse of the software in different hardware topologies. Such hardware abstraction is related to many architecture parameters, such as how and which type of DSP's are available, how the DSP's are interconnect, whether or not there is a CPU dedicated to execute control, if such a CPU is available, whether or not it will execute some signal processing as well, etc (15).

Typical heterogeneous systems comprise both DSP's and CPU's. The DSP's are developed to execute specialized compute-intensive code efficiently, while CPU's are developed to execute more general control code. SoD takes into account this property to create a cost-effective system.

The SoD is structured in two main components, the NM and the SK.

The NM provides the API with the ability to manage the signal processing tasks running on a signal processor (CPU). This API implements the following services:

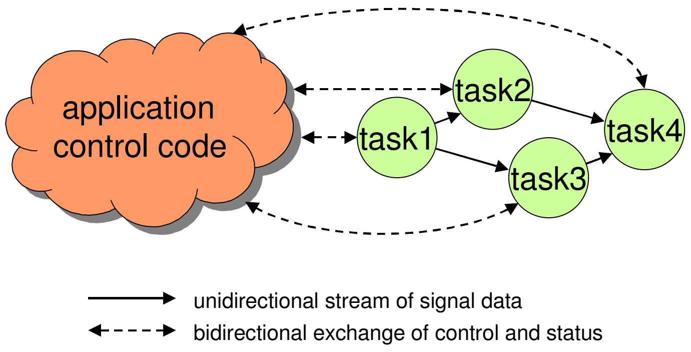
- Create/delete processing tasks
- Set up the task graphs by connecting/disconnecting tasks via communication channels

- Suspend/resume tasks
- Provide exchange of commands and status information with tasks

The SK executes the task scheduler and supports the data communication required by the processing tasks by doing the following:

- Dispatching the signal processing tasks on the DSP or control processor
- Controlling the flow of signal data by managing the data dependencies between the processing tasks
- Handling data exchange between tasks through communication buffers

As depicted in Figure 9 the SoD has a conceptual view of the system as a streaming graph bound by processing tasks. The application control code is exchanging commands and status information with the signal processing tasks that cooperate in a streaming graph.


application control code
task1
task2
task3
task4
unidirectional stream of signal data
bidirectional exchange of control and status
Figure 9 : SoD conceptual view from [5]

The execution architecture is depicted in Figure 10, where it can be seen that the tasks are not connected with each other. The streaming kernel provides the connections among the processing tasks.

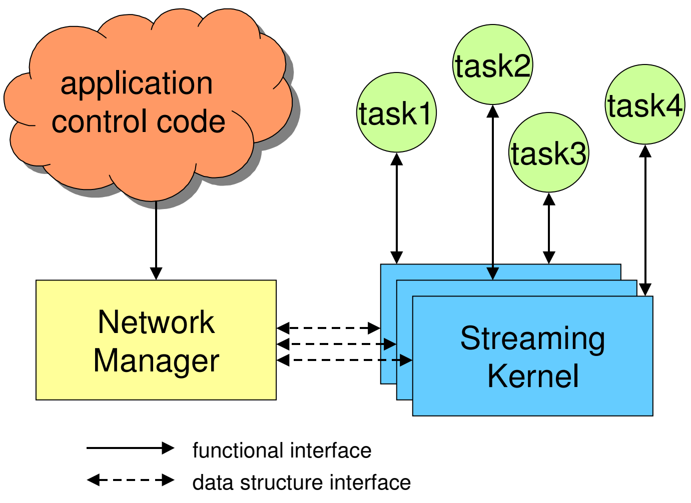


Figure 10 : SoD execution architecture from [5]

The SoD system architecture was designed to support data-flow applications. In this data-flow the SoD supports three types of processing tasks:

- ***Streaming tasks* -** These signal processing tasks are dispatched by the Streaming Kernel
- ***ISR tasks* -** An ISR task detects whether a certain interrupt has occurred and service it
- ***Control tasks* -** A control task detects whether a certain control event has occurred and defines how to service it

The communication between producer tasks and consumer tasks occurs by data streaming and requires synchronization between them to make sure that the data is sent correctly. The SoD supports these synchronization types:

- ***Implicit synchronization* -** The processing function simply assumes that when the task is dispatched, the required input data and the required room to write the output data are available
- ***Explicit synchronization* -** Checks if the required data is available before reading and checks if data can be written prior issuing the write

Data communication dispatcher This module is responsible for several functions, the most important two being:

- **PC communication** - This function allows the communication among the radio components and the PC depicted in Figure 8 as FIFO Comm(1);
- **Antenna communication** - Provides the communication among the radio components, more exactly the processing components, and the board's antenna through the same FIFO Comm(1).

Real-Time Operating System During runtime, the data communication dispatcher and SoD dispute access to the platform resources. The function of the Real-Time Operating System (RTOS) is scheduling properly these components to allow met their real-time requirements.

The RTOS used in the platform is the Micro-Controller Operating System - II (uC/OS - II) by Micrium Inc (16).

The most important features of uC/OS – II are:

- Small memory footprint is about 20KB for a fully functional kernel
- Thread aware debugging - in debug time, the uC/OS – II allows the observation of the current state of all threads within the application; even the back traces and registers values
- Preemptible priority-driven real-time scheduling:
    - 64 priority levels (max 64 tasks), 8 of them reserved for *u*C/OS-II
    - Each task is an infinite loop
- Nested interrupts can go up to 256 levels
- Supports of various 8-bit to 64-bit platforms: x86, 68x, MIPS, 8051, etc
- Easy for development

Radio functions As will be referred in section C, a radio is represented as a SRDF. Figure 11 depicts an example of one WLAN radio. There it can see the radios functions, ahead called processing components, and connecting components. To form a radio processor components are connected with each other, communicating via the communication components, which are depicted in Figure 8 as FIFO Comm(2).

The SRDF graph includes, inside each individual processing component, the name of the function and the number of CPU cycles necessary for executing such function. The communication components label describes the input/output tokens relation.

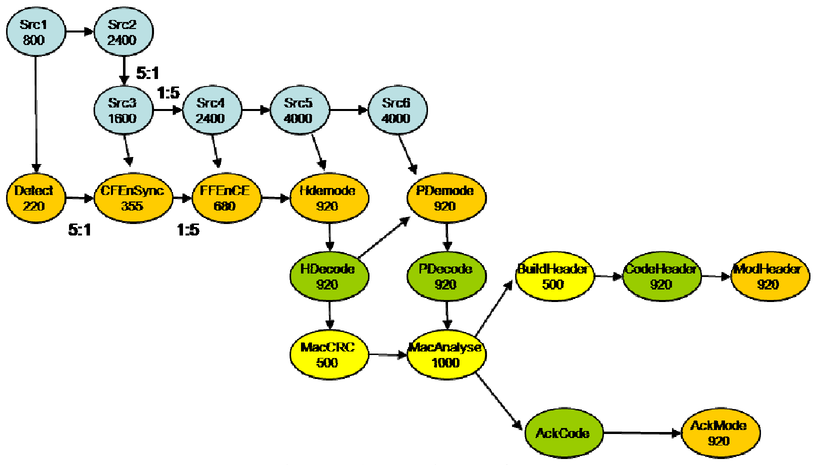


Figure 11 : WLAN datflow

C. *Radio model*

A radio is composed by a set of functions that have to be dispatched in a sequential order, defined by the data availability dependencies. Each radio function is a node in SRDF and each node is a processing component for BB-RM. The result of one function is the input data for the next function. The data transport, represented in SRDF by the edges, corresponds to a communication component in the BB-RM (7).

Processing component

A processing component is fired (dispatched) when all of it inputs have tokens (radio data) to process. When execution is finished, the processing component places output tokens in all of its outputs.
Each component has a component ID which identifies the functions of the processing component in the radio. Each radio can have more than one processing component of same ID. That means the radio can use the same functions several times in different places on the radio dataflow.
Since the radio is supported by heterogeneous multi-processor systems, it is necessary to decide on the mapping between the processing components and the target execution cores. For instance, some radio functions run quicker in a vector processor (EVP) than in a RISC processor (ARM). Therefore the processing component must be specified to the particular core in which it should be executed. This information is specified on the component

structure. For this reason the radio structure (section D), comprises a field that permits specifying the permitted execution hardware of the processing components. Each processing component can either be allocated to a specific core or to a core type of the available core types in the platform.

The instantiation of a processing component requires different types of resources: code memory, where the instructions of the processing component are already stored; data state memory to store the temporary variables and component state; and a CPU to execute the code.

Communication component

This platform is based on a distributed architecture, thus communication channels are required to allow the proper cooperation between the diverse system components. This service is provided by the communication components. Making the analogy between the radio description and a SRDF graph, the communication component in radio description corresponds to an arrow in a SRDF.
The communication components implement a FIFO discipline and are responsible for handling the tokens from each producer processing component to the corresponding consumer processing component. Communication components have the information about who are the producer and consumer processing components, as well as their port IDs.
Depending on the placement of the involved nodes the communication process may be local or involve two different tiles. When the communication is on the same tile, the reserved FIFO memory is also on the same tile and is directly addressable by both processes. On the other hand, if the communication is among two components placed in different tiles the FIFO memory must reside physically on only one of those two tiles. In this case the communication component can have already defined in which tile the FIFO memory shall be created or, if this information is not provided in advance, the BB-RM at allocation time chooses in which tile it will reserve the FIFO memory. In both cases each communication component has to reserve enough memory resources to guarantee lossless token delivery.

The radio activity has disparate behaviors, depending on which function is being executed in each instant. The radios might be receiving data, sending data or just waiting for some synchronous signal. Such behaviors produce different radio functions, i.e., the radio data flow is different for each behavior. These different behaviors experienced by the radios are called radio states. Besides the operating states, associated with the specific tasks that have to be carried out by the processing nodes, additional radio states are created explicitly in order to optimize the platform resources. For example, when the radio is not processing data its state can change to some specific idle state that allows saving battery.

D. Radio structure and design

The radio structure design has as its main driving directions modularity, simplicity and low runtime overheads. These requirements have impact in diverse architectural and implementation aspects.

Fixed size structures, independent of the number of components and even of the topology (component connections), have been used to simplify and reduce the overhead associated with the memory management. The radio access was made independent of the particular radio characteristics to facilitate the radio management by the G-RM and BB-RM. Another desirable feature that the radio should exhibit is a clear separation among resources and topology. This separation allows the manager to handle radios without having to be aware of the topology as well as traverse the radios without needing to be aware of the component resources.

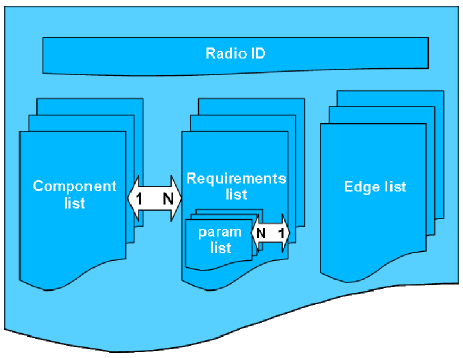


Figure 12 : Radio structure

Figure 12 depicts the organization of the radio structure. It is composed by a radio ID which identifies the radio type and state, and the following three main structures:

- Component list - this entry holds information about the processing and communication components. The first field contains the component ID. The component ID also codes its type. If the component ID ends with a "0", that means it's a communication component, otherwise it is a processing component. For the processing component case, the ID identifies the function executed by the processing component.
  Besides the ID/type field, this entry also defines the target core. For processing components it permits identifying a specific core or a core type. For communication components, the core field defines the tile in which the FIFO memory is reserved
- Requirements list - this entry holds the list of requirements of each component. Some requirements need more than one parameter. For example, the CPU requires the number of execution cycles and the number of cycles to deadline. So, for each requirement there exists a list of parameters, as illustrated in Figure 12
- Edge list - in order to separate the topology from the requirements, it was created an independent edge structure. The edge structures stores the producer component ID, the consumer component ID and correspondent producer and consumer ports

E. *Radio example*

The example on Figure 13 is a Wireless Local Area Network (WLAN) radio represented as a SRDF, where the processing components are groups of "C" language instructions executing a radio function. The edges are communication components and implement FIFO semantics.

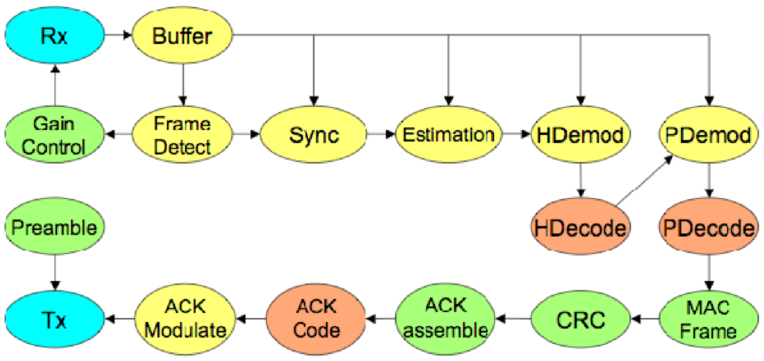


Figure 13 : WLAN 802.11a example from [12]

4. Design space, problems and solutions

This chapter presents the implementation of the BB-RM. It will start by describing the functionality provided by the BB-RM, followed by a description of the interfaces between the BB-RM and the other software components of the radio system. Having described both the intended functionality and interfaces of the BB-RM, the attention is turned to the practical problem of implementing this functionality within the existing framework, while taking into account all sorts of constraints, such as the ones imposed by the hardware and limitations of the software that it must re-use. Four different implementation solutions are proposed and assessed, one of them being selected for implementation.

A. Goals of BB-RM

As was explained in chapter 3 section B, the BB-RM functionality establishes an interface between the G-RM and the SoD modules.

BB-RM must support a wide variety of radios and radio combinations, with different software components, topologies and temporal requirements. Furthermore, it must also provide RT guarantees for each running radio, even without having at compile-time the complete knowledge of all the possible radio combinations that may be active in the device. Each radio needs to meet its timing requirements, and it must do it independently of other radios that are running simultaneously. To turn this possible, the BB-RM has to guarantee to each different radio that a certain amount of system resources (processor cycles, memory, communication), that match its resource requirements as computed at compile-time, are available at runtime.

There are two main features that the BB-RM needs to support in order to provide this functionality:

- Strict admission control - radio instances can only start if there are enough resources available in the platform to guarantee the RT behavior
- Strict resource reservation - each radio is only allowed to use the resources that have been allocated to it by BB-RM

The BB-RM functionality is distinct from the G-RM functionality because the G-RM is platform independent and, therefore, not aware of the specific hardware resources of the BB platform.

The SoD Network Manager API, on the other hand, only allows for tasks to be started, stopped and connected via FIFO queues. Although it does allocate memory resources for the tasks and queues, it does not consider groups of interconnected tasks as a whole that must be admitted or rejected atomically, depending on resource availability. It merely checks for the availability of resources for a single task. Also, the SoD does not allocate processor cycles to a task. It simply adds it to a processor's streaming kernel of running tasks, without checking if the CPU demand of the tasks is small enough to allow each task to get enough cycles per schedule period to meet its deadlines, i.e., without carrying out any kind of scheduling test. The SoD also lacks any sort of intelligence to decide on the mapping of tasks to processors. It merely provides the primitives that allow starting tasks on processors, and it is the user code that must decide on the actual processor mapping. Therefore, the BB-RM must take care of all of these tasks, in order to allow allocation of multiple jobs, with job combinations unknown at compile-time to a multiprocessor while allowing real-time guarantees to be given for running jobs.

Since as many radio combinations as possible should be supported, the BB-RM must be equipped with algorithms and methods that allow it to make good decisions about where allocate radio components, where a "good" decisions means that a feasible allocation should be found if there is one, and that if several feasible allocations are possible, then the one that increases the likelihood that a feasible allocation exists for subsequent radio start requests should be chosen. This objective, however, must be achieved while taking into account that the BB-RM is a run-time component, and thus that the search for a feasible allocation should be fast.

B. Design space

As depicted in Figure 14, BB-RM receives commands to add, resume, suspend and remove radios from the G-RM block. Its request must be processed in an atomic way, i.e., all the components of the radio must fit in the available platform resources, or the radio is rejected. On the other hand, the interface with SoD is made at the task and connection level.

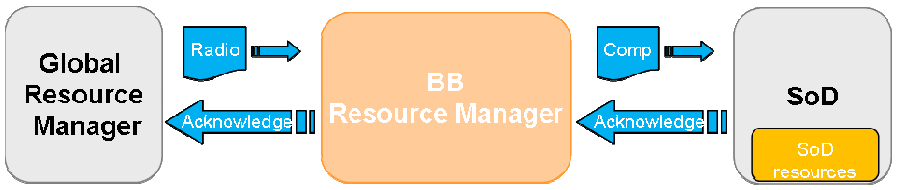


Figure 14 : BB-RM design space

Before thinking about possible implementations of the required functionality it is useful to present an overview of the main issues and constraints involved. The following list enumerates the most relevant issues that have been initially identified:

- BB-RM's API must allocate full radios atomically and SoD's API works only at component level (processing components and communication components).
- A radio can only be admitted if all of its components (processing and communication components) and they requirements fit in the platform without disturbing any radios that are already running.
- The SoD's API does not allow access to the status of the platform resources that are allocated by the SoD itself. This includes task state and FIFO state allocation. For these resource types the BB-RM cannot know what amount of resources is free on the platform, and must delegate resource management to the SoD.
- The SoD does not offer code memory allocation for the processing components, since it assumes that the code for all tasks is already pre-loaded in each processor. Since it wants to add the possibility of dynamically loading and linking tasks, this service must also be provided by the BB-RM module.
- As was explained in section B of the last chapter, the RTOS just provides RT behavior among SoD NM and the data communications dispatcher. Thus, at the component level no entity provides RT behavior support services, which thus must be into BB-RM account.
- In section A of the last chapter it was referred the issues around the time access to the FIFO allocation when the components are in different tiles. The FIFO should be physically placed in the same tile as the reader process, which is an important optimization factor that the BB-RM should also take care.
- Another aspect that has to be taken into account is the inter-tile resource fragmentation. For example assume that a bunch of radios are already running on a platform and that each tile has 20% of its memory available. If the BB-RM module needs allocate one new processing component requiring more than 20% of the tile's memory it will not fit in any single tile despite the fact that total amount of memory (i.e. the sum of the free memory blocks in the diverse tiles) is considerably higher than the amount requested.
- Using the above example, after some allocations and releases the platform memory in each tile eventually becomes fragmented. The data reservations associated with the components need to be physically continuous, thus chances are that at a given point in time the allocation of a block of memory with a size smaller than the total amount of free memory in the tile fails. This source of fragmentation is designated by intra-tile fragmentation.

C. Solutions

Having in mind the problems above listed, the global system architecture and the interfaces between the diverse software modules, the following candidate approaches have been identified.

Solution-1

As the BB-RM does not know the status of the resources in the platform, the easiest and simplest solution to solve the problem is depicted in Figure 15. When the BB-RM receives a radio request it tries allocating each radio component, one by one. If all radio components fit in the platform, the BB-RM consider that the radio can run in the platform.

At a first look, this solution seams easy to implement and does not require changes on the other software modules. Thus this BB-RM is SoD independent and, consequently, platform independent. But, on the other hand, the SoD module does not permit testing the radio component allocation and so testing (from the BB-RM side) already allocates resources (on the SoD side). The problem is that the SoD NM allocation takes a considerable amount of time, because SoD NM needs to communicate with SoD SK and afterwards, allocate the component in platform. Releasing the resources also requires a non-negligible amount of time. Thus, despite conceptually simple, this approach is extremely inefficient in case of failures, incurring in a high latency and overhead.

Furthermore, in this approach there is no precise information about what went wrong or about the status of the platform. Hence the BB-RM has no means to decide where to allocate the radio components.

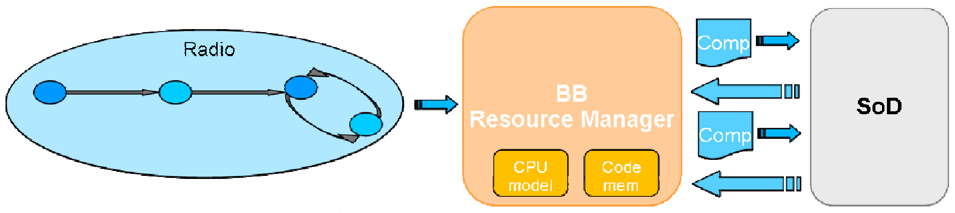


Figure 15 : BB-RM solution-1

Solution-2

A second possible solution considered in the scope of this work consists in integrating the BB-RM into the SoD, as depicted in Figure 16. With respect to the previously considered approach, this solution has one big advantage since in this case BB-RM has complete knowledge about the platform status and, therefore, can make informed choices according to the effective platform resource usage. However, this view is more complex to implement because it requires changing the SoD API and many internal structures. This solution is also less modular since the BB-RM would be tied to the particular SoD and each SoD only works in a specific platform. Thus the BB-RM would have to be rebuilt for each platform, which is inconvenient and requires a significant amount of development and debug effort.

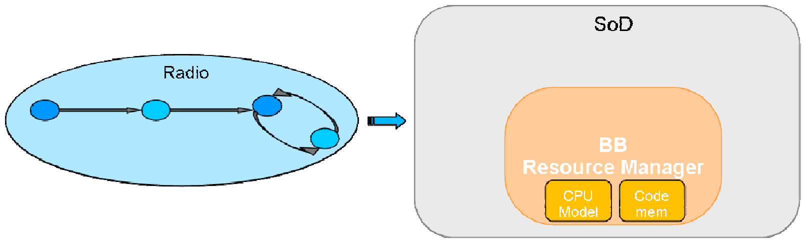


Figure 16 : BB-RM solution-2

Solution-3

Another possible solution consists in adding a second virtual SoD module to the platform. This virtual SoD module is incomplete, having a NM but no SK (Figure 17). As explained in chapter 3 section B the SoD NM knows the status of the platform and the SoD SK allocates the components in the tile. Thus, the virtual SoD cannot allocate components, because the absence of SK, thus enabling the BB-RM to test the radio components in the incomplete SoD and allocate the resources, via the complete SoD only when all radio components fit. The code is still modular, so the BB-RM can work in any SoD and it's easy to implement.
As was explained in chapter 3 section B the SoD is allocated in the F-ARM. Implementing the second SoD doubles the memory requirements in the FPGA tile. In addition to the increased memory consumption, the BB-RM still has no knowledge about the free resources on the platform. So there is no room for planning, and each request has to be handled in a trial basis, which is expensive in terms of memory and CPU utilization.

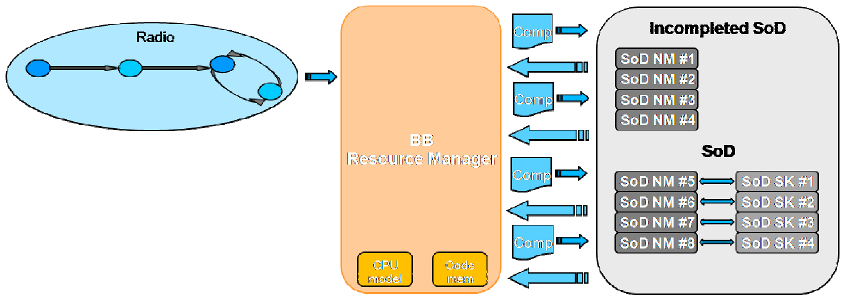


Figure 17 : BB-RM solution-3

Solution-4

One problem common to all of the approaches above mentioned is the lack of information about the available resources. A possible way to solve this problem is equipping the BB-RM with resource models (Figure 18). Those resource models, called BB-RM resources, are one image of the real resources present in the platform. In this case the BB-RM tests the availability of radio components in the BB-RM resource models and, only when they fit, allocates them both in SoD and in the BB-RM resources, to keep the model consistent. There is an issue regarding the memory, because the BB-RM does not take into it account the memory fragmentation problem. This problem will be addressed latter on.

This solution has two main advantages. The first one is that the code still is modular, so this BB-RM is SoD independent. The second is that now the BB-RM has a complete knowledge about the platform resources status and thus can make decisions to optimize the allocation through algorithms that will be detailed ahead.

As referred before, the memory model has some issues with the memory fragmentation and thus the image of the SoD resources is not exact. Consequently, problems may still arise during the radio allocation. One example is the memory intra-tile fragmentation problem that may lead to false-positive situations, in which a radio component passes the test in BB-RM resources but fails to fit in the real platform. A possible solution to fix this issue is proposed in chapter 7 section A.

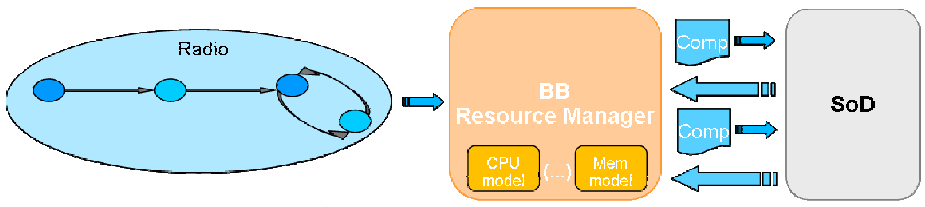


Figure 18 : BB-RM solution-4

D. Solution assessment

Among the four solutions presented in this chapter, none of them is an ideal solution. Each one has advantages and drawbacks. Which means that the best solution must be chosen based on priorities.

The first most important feature is the modularity of the code. This feature has two great advantages. One of them is that BB-RM works without taking in account how the other models are built, which means any upper or lower software can be created independently and vice-versa, and still interact with each other. The second one is related with the usability of the code in other systems. As referred before, in one modular system, the code can run in different platforms, with different core configurations. Hence the second solution is undesirable.

An additional important feature for BB-RM is the capability to choose the radio components allocation. In a heterogeneous multi-processor system the amount of allocation possibilities is high, although if the BB-RM doesn’t know the status of each resource in the platform, it cannot adjudicate one component to one tile, based on the resources required by the component. Then in this case the first solution is also undesirable.

SoD is software that’s still in construction and with new features built each week. Most of the work still remains to be done on the SoD, and it is not a priority to build a virtual SoD when the real SoD is still under construction. Furthermore the virtual SoD is a hard task that will take up too much time.

Thus, due to its higher modularity, the treated solution appears advantages compared with the third one and, consequently is the chosen solution.

5. Implementation of the BB-RM

In the last chapter it was described four feasible solutions to implement a BB-RM. Here it will dig a little deeper into the details. In its essence, the BB-RM is an allocator of instances of radio applications. These instances are called *jobs*. In the following text, it will further refine the concept of job in section A.
Section B briefly examines the main functions of the BB-RM.

One of the actions the BB-RM needs to perform is mapping the radio to the hardware platform. Since the problem is NP-complete, BB-RM uses an approach based on adapting heuristics used to solve the VBP Problem (section G) to allocate the radio components to the hardware resources. Most heuristics for VBP define a couple of strategies to solve sub-problems. One of the sub-problems is how to define the order in which the components are mapped. The other sub-problem is choosing on which tile a radio component should be allocated to. The strategies used in this work are described in sections H and J of this chapter.

Finally, section K, describes the evolution of features across different versions of BB-RM and the directory tree of the project.

A. Job – radio instance

As mentioned before, the main purpose of this project is to run multiple radios, sharing resources with each other, and allow for many combinations of radios as possible. Note that multiple instances of the same radio can be active simultaneously.

In chapter 3 at section C, a radio is described as a unique entity. To distinguish between the unique unallocated radio and the allocated radio instances, it is defined the concept of job.

Each time a radio is allocated to the platform, a different radio instance – a Job -is created. The same logic is used when a radio software component is allocated to the platform; it gets a radio processor component instance, which it refers to as a task. The instance of a communication component is referred to as a FIFO. In summary, a radio is composed of processing components and communication components. A job is composed of tasks and FIFOs.

B. BB-RM functions

Until now, the BB-RM has been described as a black box with an input and an output. This section will provide some brief information about each BB-RM function. Further ahead the BBRM functions are described in more detail.

- BBRM_initialize - fills the job list with null values.
- BBRM_Job_test - tests if the given radio requirements can run in the HW platform but will not allocate it.
- BBRM_Job_create - tests the radio requirements and allocates the radio in the hardware platform; the created job is left on suspended mode.
- BBRM_Job_resume - runs the allocated job.
- BBRM_Job_suspend - suspends the running job.
- BBRM_Job_remove - removes the suspended job from the hardware platform.

C. Data structure of BB-RM

This section will show how the BB-RM stores and manages the information concerning to jobs.

In the field, G-RM will provide the radio information when the *BBRM_Job_create* function is called. Due to that, the BB-RM should store all information that it will need to resume, suspend and remove a job.

After calling *BBRM_Job_create*, BB-RM returns a new job ID. This handler is used to call the additional functions (job resume, job suspend, job remove).

Job list

Figure 19 shows the major internal structures of BB-RM. The job list, where BB-RM stores all the information about jobs is depicted on the left side of this figure. In the job list, one job entry is composed by a job settings and a task list. The job settings structure has a pointer to the radio source and the radio ID; through it BB-RM can get information about the radio components, its requirements, and the radio topology. Another field of job settings structure is the job state, which save the status of the job (suspended, running, resumed and invalid). These states will be detailed in the next section.

As explained before, BB-RM receives a complete radio from G-RM to allocate, but SoD allocates components one by one. In this level each allocated component is called a task and saved on a task list. BB-RM can choose where to allocate each component among the different tiles. The algorithms to choose one tile for each component will be detailed in section I. From this point on BB-RM should take care of the requirements of this component to fit in the tile. This information is on the task settings structure. The source component ID is saved in task settings.

On the SoD side, each task has a unique ID. This task ID identifies one specific function belonging to a specific job. As a reminder, one radio can have some components doing the same functions and even using the same component ID. But when the task is allocated, the attributed ID is unique and identifies the specific task belonging to a specific job. The task ID is saved in task setting as well.

One task has several requirements, like CPU cycles, data memory, and so forth. Each requirement is tested and allocated one by one in BB-RM resources. Thus, after each allocation, the requirement parameter in the requirement list is filled.

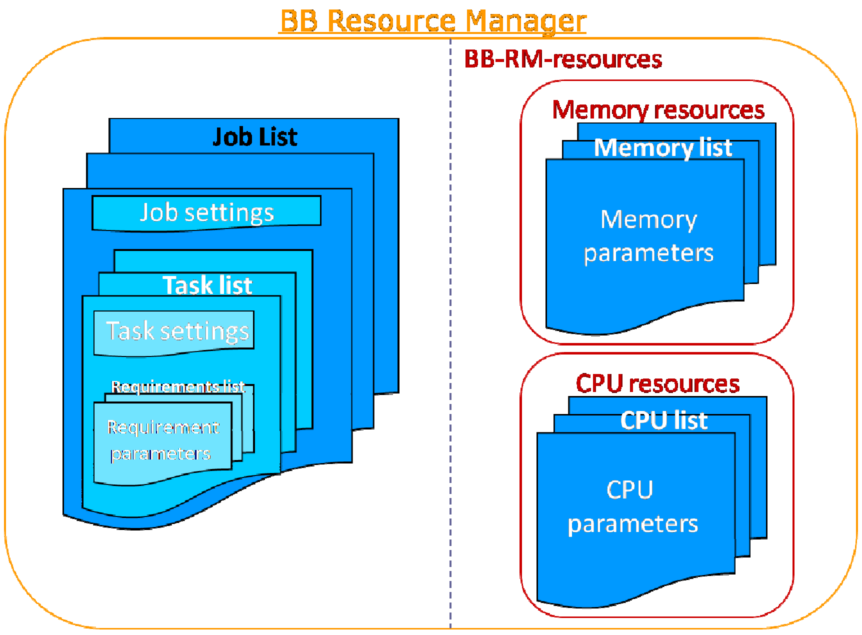


Figure 19 : BB-RM data structure

BB-RM Memory resource

This paragraph describes how the BB-RM memory resources are represented.
The memory model structure is composed of a memory configuration for each tile, composing a memory list. The memory model has two modes, described as follows:

- Running mode - blocking the access to the memory resource. This means that it is not permitted to add or remove memory resources.
- Simulation mode - in this state the current status of the memory is saved as an image. Then it's allowed to add and remove requirements.

Each memory has a stored memory state. To add a radio it is necessary to test the components one by one and for each component to test all the resources. The objective of these two states is to facilitate the memory test. For instance, to create a radio with 3 processing components and 2 communication components, where all the components have only memory requirements, the memory is set in simulation mode. After this, a test of all the component requirements is done. If all components fit in the memory it can be set to running mode.

The other parameters stored in the memory structure are the free data and FIFO memory counter. The data memory counter has the number of free blocks in data memory. The FIFO memory counter has the number of free blocks in FIFO memory.

This is the simplest way to implement a memory resource. As adverted in Solution-4 in section C of the chapter 4, this solution does not take into account the intra-tile memory fragmentation problem.

A new memory resource model was being built that includes a memory map and algorithms that account for and try to avoid fragmentation, but it is still unfinished.

A set of functions (API) was created to implement the functionality of BB-RM:

- Mem_initialize - initialize the memory structure.
- Mem_set_simulation - backup an image of the actual memory status and set the memory resource in simulation mode.
- Mem_add_comp - add a component memory resource decreasing the number of free blocks.
- Mem_rem_comp - remove a component memory resource increasing the number of free blocks.
- Mem_set_restore - restore the previous image of the memory model and set the memory in running mode.
- Mem_set_run - remove the backup memory image and set the memory model in running mode.

The memory requests are done in a number of blocks. A component specifies certain requirement parameters, for example, 15 blocks of data memory or 10 blocks of FIFO memory.

BB-RM CPU resource

The scheduler, represented by the CPU model, is a Round Robin scheduling.

Round Robin scheduling The Round Robin (RR) scheduler is one of the simplest schedulers. Without any priority, the tasks are sorted by request order. The RR scheduler time slice for each task, its adjustable depending only of the task requirements (17) (18).

When a new task ($_{NT}$) requires an amount of CPU execution cycles (E_{NT}) and a deadline (D_{NT}), the RR scheduler model verifies the conditions mathematically expressed in Equation 1.

The minimum deadline between the smallest deadline of a running task deadline (D_{LR}) and the deadline of the new task (D_{NT}) has to be less or equal than the sum of the execution cycles (E) of the J running tasks, added to the execution cycles of the new task (E_{NT}).

$$\min(D_{LR}, D_{NT}) \geq \sum_{1}^{J} E_J + E_{NT}$$

Equation 1 : Round Robin rule

If this condition is accomplished, the RR scheduler guarantees that the new task fits in the CPU, meeting its deadline and the remaining running tasks still meet their deadlines.

This implementation has one CPU scheduler per tile creating a CPU list. Like in the Memory Resource Model described above, if the CPU resource model is in running mode, one cannot add or remove components to the CPU. In simulation mode, an image is stored of the actual status of the CPU, and then it is allowed to add or remove components to\from CPU to test a radio. This status is the first field of the CPU structure.

As stated in section C, the two parameters that are needed to apply the add rule are the sum of the execution cycles and the smallest deadline. These parameters are exactly what the CPU structure saves for each scheduler.

The interface created to manage the CPU resource is elaborated below.

- CPU_initialize - initialize the CPU model.
- CPU_test_comp - test the component CPU requests.
- CPU_set_simulation - backup an image of the actual status of the CPU schedulers and set the CPU schedulers into simulation mode.
- CPU_add_comp - add a CPU requirement to the RR scheduler.
- CPU_rem_comp - remove a CPU requirement from the RR scheduler
- CPU_set_restore - restore a saved image to the CPU schedulers and set it to running mode.
- CPU_set_run - erase the saved CPU image and set the CPU schedulers in running mode.

D. *Job states*

Let's look at how the functions interoperate. A sequence of function calls and the related job states are depicted in the Figure 20. As described in section B, BBRM_initialize initializes the job list. As the example depicted in Figure 20 is for a unique job the BBRM_initialize function was not represented. The functions procedures will be detailed in section E.

Supposing that the BBRM_initialize function was called before and is calling the BBRM_Job_test function the radio was given as argument. Meanwhile the BB-RM tests all radio components and for each component tests all requirements. In this point the job state remains in **simulation state.** After finishing the test, the BBRM_Job_test function returns the result (accept or reject), and changes the job state back to **invalid state**. During this process, transactions are internal to the BB-RM because the test is done in BB-RM resources and not in the platform.

When the BBRM_Job_create function is called, the state of the job changes to **simulation state** and the BB-RM tests the radio requirements in it resources. After test the resource in BB-RM resources with success the job state is changed to **tested state**. The next step allocates the radio on the hardware platform. Whenever everything goes well, the job is changed to **suspended state**. Now the job is loaded on platform and ready to run. While in this state, two operations can be performed, resume or remove. Resume triggers the job on platform and it starts running. The job state becomes **run state** as well. Another option is to remove the job from the platform; this causes the job state to be change to **invalid state**.

The last available function is the BBRM_Job_suspend. This function stops the job but keeps it installed on the platform, changing the job state from **run state** to **suspended state** as well.

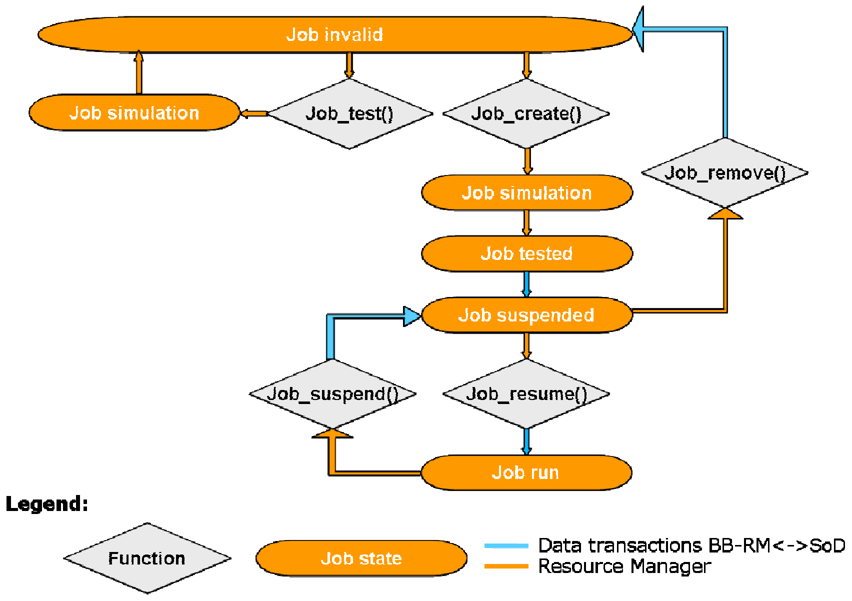


Figure 20 : Job states

E. *Interface G-RM <-> BB-RM*

In this section the BB-RM will be further detailed, while keeping focus on the functional description and not in "C" language implementation details such as arguments or type of outputs. Those details can be explored in the doxygen C documentation provided in appendix [A]. Each function is described by essential functional blocks connected to each other by result dependencies. These high level functions are used by G-RM.

BBRM_initialize( )

BB-RM reserves a fixed data memory to allocate its internal structures and variables. The main reason for this procedure is because the dynamic memory allocation needs turns the memory access slower and complex. When the system starts the contents of the memory is unpredictable.

The procedure flow of BBRM_initialize is shown in Figure 21. There the BBRM_initialize function has the responsibility to initialize the SoD framework by initializing the SoD NM and SoD SK. In BB-RM side this function resets the job list and the BB-RM resources parameters. In the end if all processes had success the function returns a state message, or an error message in other way around. The error message has two types; a normal error if the program can live with this problem, or a fatal error if is a critical problem has occurred and it cannot continue by normal procedure.

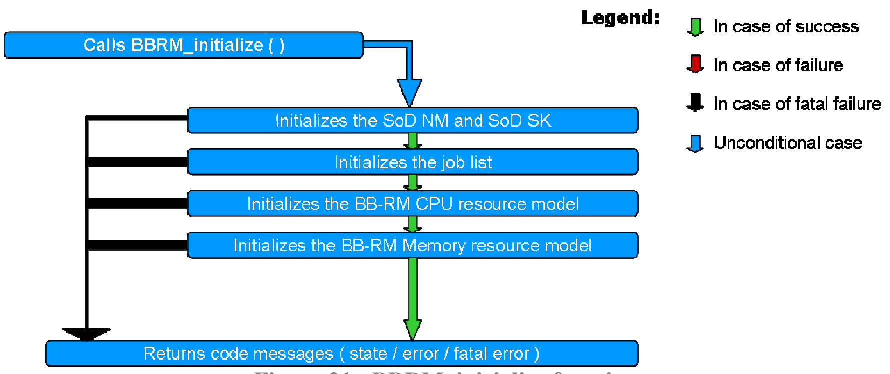

Legend:
In case of success
In case of failure
In case of fatal failure
Unconditional case
Calls BBRM_initialize ( )
Initializes the SoD NM and SoD SK
Initializes the job list
Initializes the BB-RM CPU resource model
Initializes the BB-RM Memory resource model
Returns code messages (state / error / fatal error)

Figure 21 : BBRM_inicialize function

BBRM_Job_test( )

G-RM should take some decisions about radio allocations and radio states (chapter 3 section C). For instance, if G-RM has two radios to allocate; one GSM radio and one WLAN radio the platform may not has enough resources for run both radios. Then with BBRM_Job_test function G-RM can test both radios to see if both fit separately in platform and decide which radio will go to platform based on the radio priority.

Depicted in Figure 22 is the procedure flow of BBRM_Job_test function. The BB-RM has a fixed number of jobs entries, consequently the first step before test the job is seek for a free entry in job list, which means seek for a job at invalid state. Going forward, the next step is set all BB-RM resources to simulation mode to get the authorization to test the radio requirements. If all radio requirements fit in BB-RM resources the radio has a strong probability to fit in platform. It’s not sure because BB-RM resources does not take into account the intra-fragmentation problems as referred in previous chapter at section B. To finalize BB-RM restores the previous status of the BB-RM resources, sets the job as invalid and returns the test result.

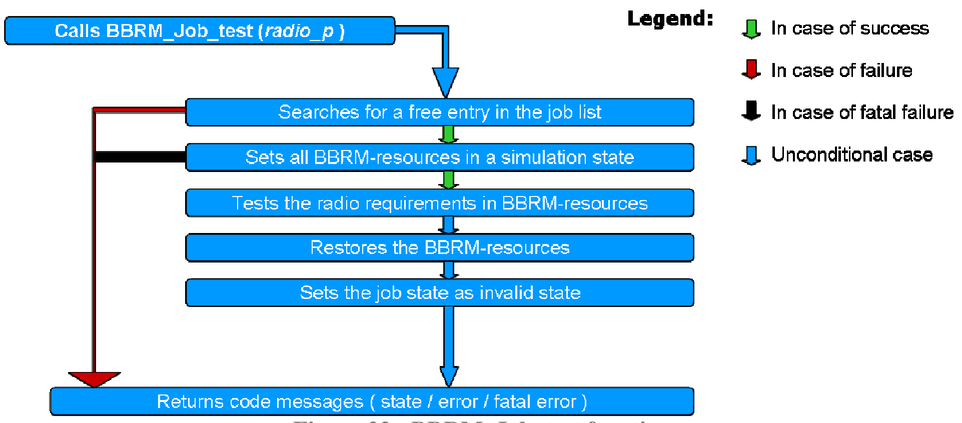

Legend:
In case of success
In case of failure
In case of fatal failure
Unconditional case
Calls BBRM_Job_test (radio_p)
Searches for a free entry in the job list
Sets all BBRM-resources in a simulation state
Tests the radio requirements in BBRM-resources
Restores the BBRM-resources
Sets the job state as invalid state
Returns code messages (state / error / fatal error)

Figure 22 : BBRM_Job_test function

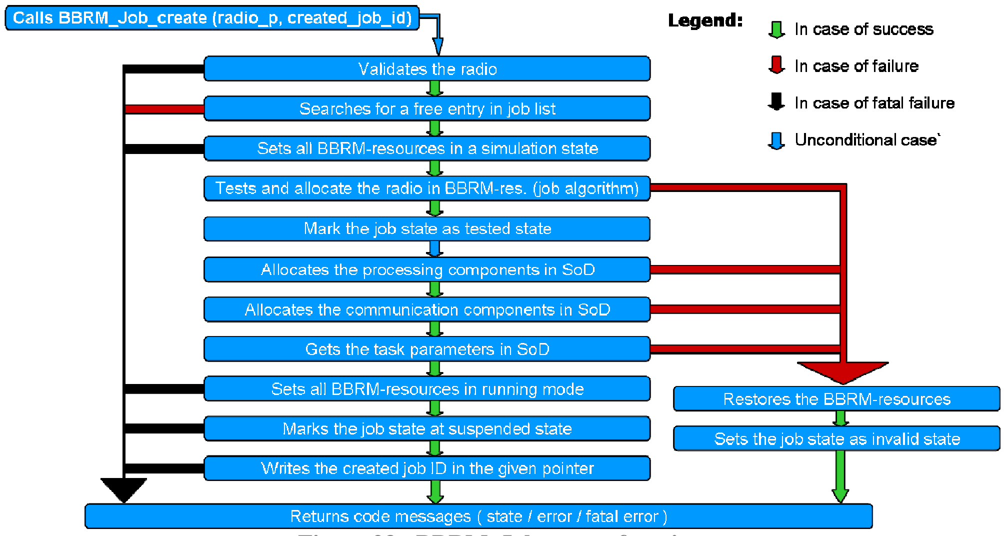
BBRM_Job_create( )

BBRM_Job_create is the most complex function in BB-RM. Having a large number of aggregated sub functions as is depicted in Figure 23. The way how the BBRM_Job_create function allocates the job in the platform should certify if the radio is consistent. For example, if there are some unconnected processing components, if all communication components have source/sink and so on. This is done in the first functional block. Subsequently BB-RM will search for an invalid job in job list and sets the job state to simulation state. Now the job is ready to be tested in BB-RM resources. This functional block is more complex than it seems, and important as well. Its relevance will be explained in the next three sections.

After testing the radio in BB-RM resources, BB-RM sets the job to tested state. As explained in chapter 4, section B, the SoD allocation is done in the components level. The processing components are allocated before the communication components, represented also in functional blocks.

In that section it is also stated that the SoD manages the code memory addresses of the tasks. These addresses are obtained through one SoD API, better reported in section F.

As the job is already in the platform, BB-RM can set the BB-RM resources to running mode and change the job state to suspended state. At the end the BB-RM returns the job ID of this new allocated job and one of these three types of output message; state message to report the result veracity, an error message if the program can still run without violating the resources veracity, or a fatal error when the problem is critical and can affect the stability of the system.


Calls BBRM_Job_create (radio_p, created_job_id)
Legend:
In case of success
In case of failure
In case of fatal failure
Unconditional case`
Validates the radio
Searches for a free entry in job list
Sets all BBRM-resources in a simulation state
Tests and allocate the radio in BBRM-res. (job algorithm)
Mark the job state as tested state
Allocates the processing components in SoD
Allocates the communication components in SoD
Gets the task parameters in SoD
Sets all BBRM-resources in running mode
Marks the job state at suspended state
Writes the created job ID in the given pointer
Restores the BBRM-resources
Sets the job state as invalid state
Returns code messages (state / error / fatal error)
Figure 23 : BBRM_Job_create function

BBRM_Job_resume( )

As explained before, when the job is created it is allocated on the platform but remains in suspended mode. G-BM decides when it should put the job in running mode by calling BBRM_Job_resume function.

As depicted in Figure 24, BBRM_Job_resume is a simple function which starts by checking if the job state is in suspended mode. If the job state is in suspended mode BB-RM puts the tasks running on the platform resuming each task in SoD.

After that it sets the job state to run state and returns one of the three possible error codes explained before.

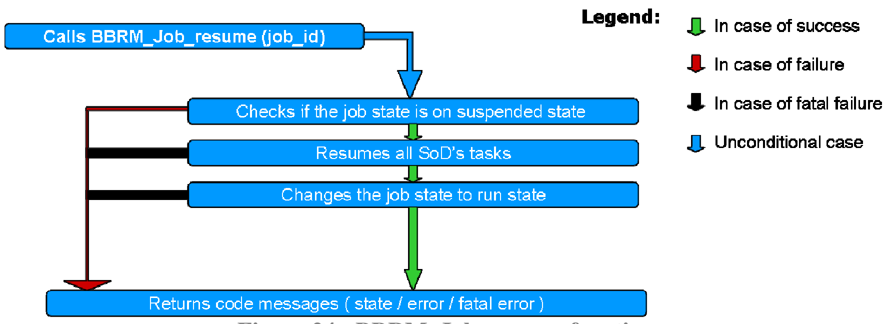

Legend:
In case of success
In case of failure
In case of fatal failure
Unconditional case
Calls BBRM_Job_resume (job_id)
Checks if the job state is on suspended state
Resumes all SoD's tasks
Changes the job state to run state
Returns code messages (state / error / fatal error)

Figure 24 : BBRM_Job_resume function

BBRM_Job_suspend( )

In some instances, the job manager can suspend a job that is not being used at that moment. This decision can be taken according to several factors like energy saving, radio priority and so forth. In addition, to remove a job from the platform G-RM needs stop it first. As described in Figure 25, the first operation of BBRM_Job_suspend is to confirm whether the job is in run state. Later it suspends each task on SoD and finishes by returning the already explained three types of messages (state, error or fatal error).

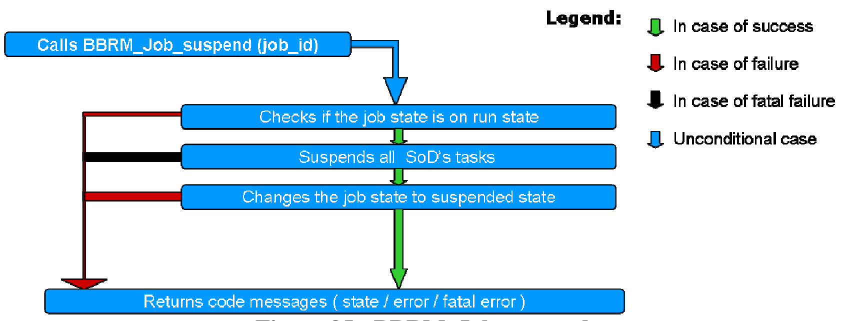

Legend:
In case of success
In case of failure
In case of fatal failure
Unconditional case
Calls BBRM_Job_suspend (job_id)
Checks if the job state is on run state
Suspends all SoD's tasks
Changes the job state to suspended state
Returns code messages (state / error / fatal error)

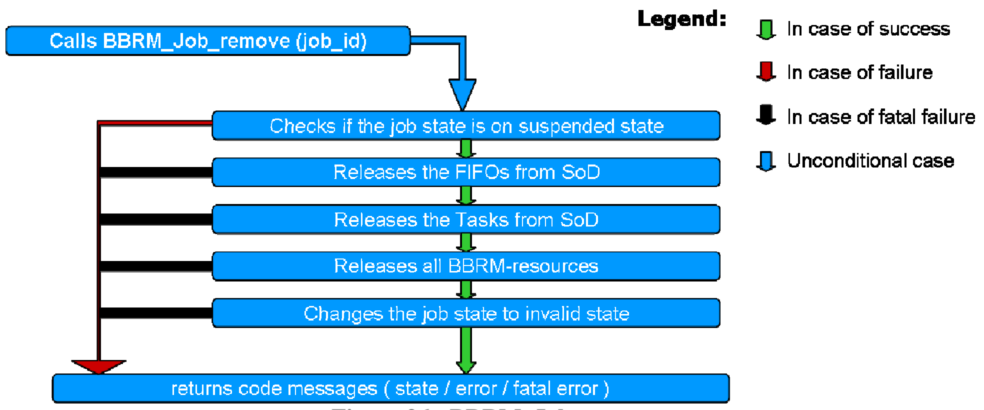
Figure 25 : BBRM_Job_suspend

BBRM_Job_remove( )

Radios may change its state depending on what sort of operation the radio should do. For BB-RM one radio state change is actually a change of radios. In other words, for BB-RM one radio with two states is actually two different radios. In order to change the radio in the platform G-RM needs to first remove the running job (radio instance) and afterwards add the new radio state.

Moreover one job can be simply removed from the platform when it's no longer needed.

Removing a Job from the platform is made by BBRM_Job_remove function. In Figure 26 the functional blocks of the BBRM_Job_remove function are described. The first step of this function is to certify if the job can be removed from the platform, that's if the job state is suspended. If it is, the next step is to release the connections between the tasks, FIFOs, and then release the tasks. Whether both release procedures ran well or not, BB-RM can remove the job requirements in its BB-RM resources. After that, the job is no longer in the platform and the BB-RM allocated resources are freed. Now the job can be released and changed to invalid. At the end, BBRM_Job_remove returns the code message to G-RM.


Calls BBRM_Job_remove (job_id)
Legend:
In case of success
In case of failure
In case of fatal failure
Unconditional case
Checks if the job state is on suspended state
Releases the FIFOs from SoD
Releases the Tasks from SoD
Releases all BBRM-resources
Changes the job state to invalid state
returns code messages (state / error / fatal error)
Figure 26 : BBRM_Job_remove

F. *Interface BB-RM <-> SoD*

The following functions are used in some functional blocks explained above.

- phSodNmTask_Create( ) - Allocate a task on the specified tile in the platform. The code of the task is already allocated in memory.
- phSodNmPort_Connect( ) - This function connects an output of a producer task to an input of a consumer task. In case the connection is a loop, the task producer and consumer are the same. The connection is made through a buffer (FIFO).
- phSodNmTask_resume( ) - Dispatching the task to the Streaming Kernel.
- phSodNmTask_suspend( ) - Deny the dispatching of the task to the SK.
- phSodNmTask_GetParameterLocation() - Obtain the pointer to the input and output parameters of a task.
- phSodNmTask_Delete( ) - Delete a suspended task from the platform.
- phSodNmPort_Disconnect( ) - Disconnect the output port of the producer task and the input port of the consumer task.

G. Resource allocation problem

As stated in section D of chapter 3, radio components are referred to an aimed core which can be a specific core or a group of cores.

If G-RM orders BB-RM to allocate a radio where all radio components are aimed for a specific core, it has only a dispatcher function, because it cannot make any choices. Just receives a radio, sees if the radio fits and allocates it or not. Thus, in this case BB-RM is completely limited by the radio parameters.

On the other hand, when the target is only restricts the core type the BB-RM has some freedom to decide where to allocate the component. For instance, if one radio component has defined in its core structure that it can run in either EVP core in the platform, then BB-RM can choose which EVP is better for this component.

To sum up, the BB-RM has to compute which is the best tile to allocate the radio component. Such problem just depends on the radio component requirements, and the decision is based on these requirements.

Whenever a radio creation request arrives, BB-RM has to find a suitable assignment for all radio components onto the tiles. Different combinations of suitable assignments can be created, resulting in different mappings.

The algorithms that choose the best mapping should not be too complex because the mapping creation and the mapping choice are made at run time. The algorithms which have to try find a mapping such that radios arriving in the future have a higher chance of being mapped as well.

As discussed in the beginning of this chapter, the Resource Allocation Problem (RAP) is quite similar to a Vector Bin-Packing (VBP) (19) problem.

Vector Bin-Packing

The resource allocation problem (RAP) can be transformed into a VBP problem, where the bins are the BB-RM resources in each tile that can bear the component requirements, which are called items in the original VBP problem. From here, the VBP has the same dimension as the resources. In Figure 27 there is a two dimension example for one platform with two tiles. Each bin (resource) has already some allocated requirements and now needs to allocate one more component with two requirements (items).

There are many heuristics algorithms like First Fit (FF), Best Fit (BF) and so forth to accomplish these results.

This model does not account for the bandwidth used by the radio components which communicate with each other among the distinct tiles.

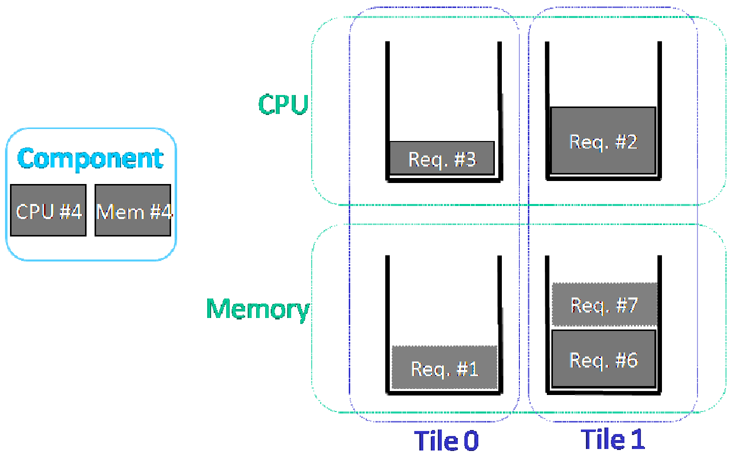


Figure 27 : VBP example

In order to choose in which tile to allocate each radio component based on VBP, the connection between components in the distinct tiles will be neglected. In section I, a description is given on how to minimize the connection bandwidth. After some jobs have been created and released, the memory resource in the platform starts to be fragmented, internally to each tile. The VBP approach does not take this problem into account.

This situation can cause problems to the components mapping. VBP does not validate the state of the fragmented memory on a BB-RM Resources, although if run on a real platform, component allocation could not occur. Since the real number of mapping possibilities could be less than what the BB-RM calculates, its final choice might not always be the best choice.

Next is shown the heuristics implemented in BB-RM, namely First Fit (FF) and BF.

First Fit

The FF algorithm takes the requirements of a component and tries to allocate it in the first available tile. In the case that it does not fit, FF tries the next tile until it finds a suitable tile where all component requirements can be accommodated.

Because FF does not test all the tiles available for a possible fit, it is faster than the BF solution. But the solution thus obtained can waste more resources than other solutions would.

Best Fit

The best fit strategy tries to minimize the space wasted by the allocation of a software component using the smallest space available which is big enough to allocate the requirement.

To know which is the best tile to allocate the requirement in the whole platform, the algorithm needs to try all of the tiles. Because of this, it takes more time than a First Fit strategy. This can be a big drawback. On the other hand, it guarantees the best allocation of a given software component on the platform. Note however that this may not be the best allocation when one considers the complete radio job.

The dimension of the problem is another issue to take into account. In two dimensions (CPU and memory) the problem becomes more complex. For each resource and for each tile the BF algorithm determines the remaining free space through a resource matrix. In the end it merges all the information in order to choose which tile will offer the best solution.

H. Sort strategy

In the last section, it was explained that the algorithms to determine which the best tile to allocate a specific component is based on its requirements. These algorithms are used in one component, but the radio has more than one component. Thus it's necessary to know in which order the BB-RM should allocate the components.

Firstly, it is relevant to analyze what kind of order can optimize the platform resources. The radio components have different requirements in several dimensions. That is, in a two dimensional problem, (CPU and memory) a component has different requirements in each dimension. Keeping the bin package analogy, it has several bins representing hardware resources and a list of radio components to put in such bins. In (19) it was proven that, in general, better results will be obtained (i.e. less bins will be necessary) if items with bigger requirements are allocated first. The intuitive idea behind this theory is simple: when the bigger items are first allocated, the smallest components can fill the free holes in the bins. This technique reduces the inter-tile fragmentation described on section B of the previous chapter.

To summarize it's needed to implement methods to sort the components based on their requirements and from the biggest to smallest, for items that are multidimensional.

To sort out the order of the components two different methods were implemented, the first is Module Weights (MW) and the other is Relative Weights (RW).

Module Weights

One way to implement a method to sort the radio components is taking the vector module as the weight of the component requirements resource vector. In Figure 28 it's shown a small radio example. The radio has three components, and, for each component, the requirements are listed. To calculate the MW for a component, is used the N component requirements of the component. The vector sum is calculated by the following formula:

$$MW = \sqrt{(resource\_1)^2 + \ldots + (resource\_N)^2}$$

Equation 2 : Module Weight

After obtaining the MW for all components, the components can be sorted. The order is made from the heaviest component to lightest one in terms of the MW. In the depicted example, the first component that will be allocated is component 3, followed by component 1 and finally component 2.

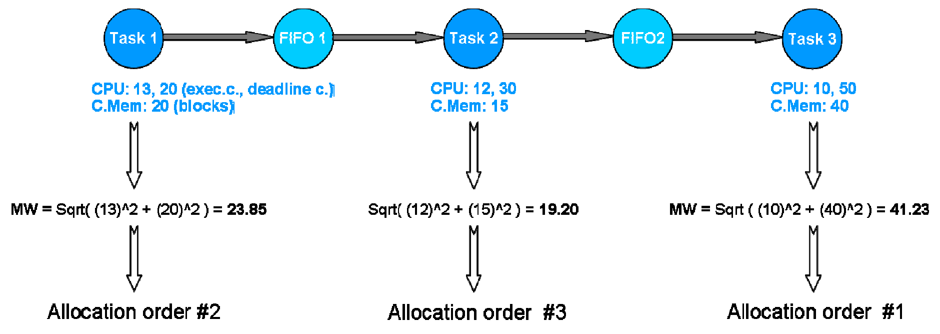


Figure 28 : MW example

Relative Weights

An additional method to sort the radio components is the relation between the component requirements and the platform resources. The balance between the radio requirements and the platform resources is not perfect, that is, some radios need more than one resource (dimension) than the other and the platform has more than one type of resources. To normalize the resources among both components this method was implemented. Depicted in Figure 29 it has the same example than the previous method (MW). In this platform, the memory is the scarcest resource and so the RM method must give more weight to memory resources than to CPU resources. To manage this, 30% of the weight was configured for the CPU resource and 70% for memory resource.

RW will calculate the relative weight based on the relation between the needed resource and the platform resource availability and give the weight for this relation. The used formula for N resources is.

$$RW = \sum (require_N / resource_N) * resource\_weight_N$$

Equation 3 : Relative Weight

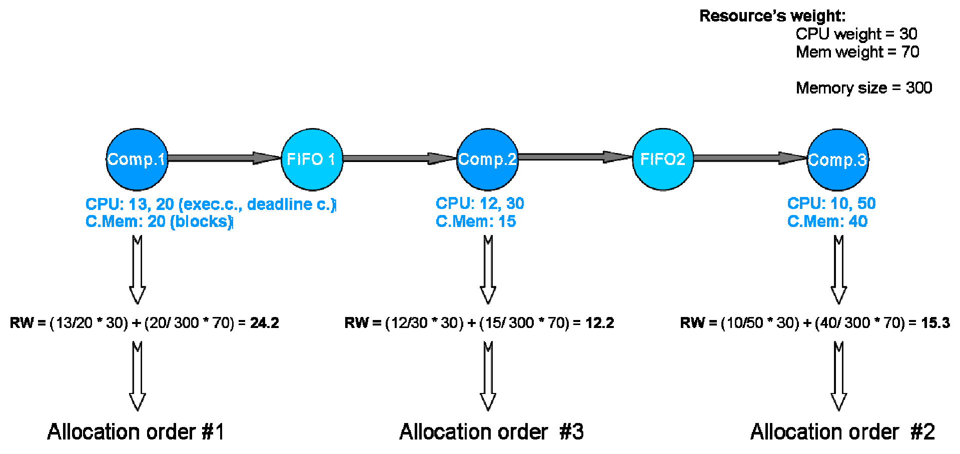


Figure 29 : RW example

As seen in this example, it returns a different result than the MW method. In this case the allocation order is component 1 then, component 3 and component 2.

The static resource dimensions can be converted to dynamic resource weights. At run time the most required resource is only dependent on the radio allocations and their requirements. This means that the most used resource can be difficult to predict. Using dynamic weights, the weight values for each resource type change at run-time. This change is according to the current resource availability across the platform.

I. *Complete RAP heuristics, including communication*

Section G described the strategies implemented for selecting the tile for allocating one specific component based on its requirements, and section H describes the strategies implemented to choose in which order to allocate components to the platform – the “sort strategy”.

In the radio structure presented in the section C of chapter 3, the radio is defined as a set of processing components and communication components. Until now, the focus has been on the processing components, but now the communication components will come into play.

A communication component is the mechanism that delivers tokens (data containers of fixed sized) from the source to the sink software components. As explained in (19), communication component require resources at both endpoints, i.e., buffers on both sides, were tokens can be stored. However, if those endpoints are in the same tile, the communication is completely internal. That means that the communication component does not require bus resources, or separate send and receive buffers.

The complete RAP is a solution to allocate the radio, taking into account the processing components and the communication components. Using expert knowledge and heuristics, the complete RAP can do two main optimizations when mapping a radio. One is to minimize bus bandwidth usage, since lower bandwidth requirements means lower chances of network congestion. The other is to minimize fragmentation or tile resources.

Two RAP heuristics have been implemented in the BB-RM.

Best Fit with Decreasing Module Weights (BFDMW)

This heuristic is to optimize the inter-tile resources fragmentation. Even when the sums of available resources are bigger than the radio requirements, the fragmentation problem may private the radio activation. So, the fragmentation reduces the number of running radios at the same time. Using the module weight methods, it orders the radio processing components from the bigger to the smaller (section H). Tracing the components by that order, it allocates each processing component by Best Fit algorithm.

First Fit with Clustering (FFC)

As mentioned above, when two radio components are in the same tile they do not need a network channel or separate buffers. To reduce the bandwidth among the tiles the First Fit with Clustering (FFC) algorithm was implemented. A detailed explanation of this algorithm is available in (19). It is a First Fit Decreasing algorithm that, after assigning an actor to a tile, looks at the neighbors of that actor in the radio job graph, to see if any of them can be placed in the same tile.

J. Debug

The BB-RM was developed in an incremental manner; with each change, a new feature was added. To make the work more independent of other modules that are still in development, the BB-RM was built in a simulation framework. In the real platform, the SoD NM process runs on top of uC/OS – II and a SoD SK runs on each core. On the simulation framework all processes run on the PC's Operating System. In fact, the OS simulates the behavior of the real hardware platform.

To help the developing process a three level debug system was put in place. At compilation, a debug level is chosen depending on the level of information that is required from the following execution. These debug levels are listed next.

- Debug level 1 - shows the info, error or fatal error messages from BB-RM API explained in section E.
- Debug level 2 - shows the info, error or fatal error messages from the internal functions of BB-RM. That means the first functions instance internal of BB-RM.
- Debug level 3 - shows the messages from the BB-RM library which has the most used function of BB-RM, modules weight to order the components, the requirements algorithms to choose the tile and BB-RM resources, that is, all external modules of BB-RM.

The debug messages were chosen in such a way as to easily identify their error source. First they show the origin file, i.e. Resource Manage, Resource Manage Library, Emulate, CPU Library and so forth. The second information is about the type of message; information, error or fatal error. The information messages show the trace of the running code.

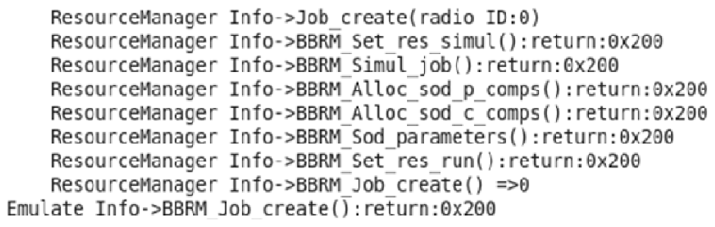
The error messages, when shown mean that something not expected happened but the program can still run without inconsistency. The fatal error appears when the code becomes corrupt. One example is when the content of BB-RM resource is different than real resources in platform.

The next item shown in debug messages is the function that prints the debug message and the message content. Normally the information messages contents tells us about the input arguments or a returned value. The error messages and fatal error messages content is a problem description.

Figure 30 has one example where it can see some info messages from the Resource Manager. The first function to be called was BBRM_Job_create (), to create the job from the radio ID #3. The next information messages are from functions that were described in section E. At the end, BB-RM returns the number of the created job ID, which is zero in this example.

Among the debug messages, an info message from Emulate is shown.

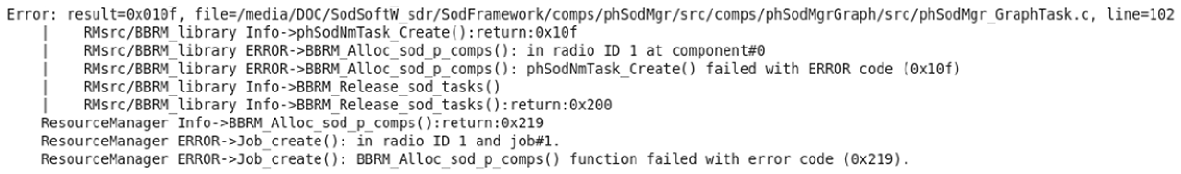
Emulate is a file which contains a small example to test the BB-RM API. There are two radio examples created to call the BB-RM APIs and analyze the return messages. The BBRM_Job_create function is successful because it returns the information code 0x200, shown in appendix [A].



```
    ResourceManager Info->Job_create(radio ID:0)
    ResourceManager Info->BBRM_Set_res_simul():return:0x200
    ResourceManager Info->BBRM_Simul_job():return:0x200
    ResourceManager Info->BBRM_Alloc_sod_p_comps():return:0x200
    ResourceManager Info->BBRM_Alloc_sod_c_comps():return:0x200
    ResourceManager Info->BBRM_Sod_parameters():return:0x200
    ResourceManager Info->BBRM_Set_res_run():return:0x200
    ResourceManager Info->BBRM_Job_create() =>0
Emulate Info->BBRM_Job_create():return:0x200
```

Figure 30 : Debug messages

In the next example, the output file of the third debug level is shown, Figure 31, as well as the indent BB-RM library The first message is one error message from SoD, the second message is from BB-RM library reporting the returned error then the functions which called the SoD function returns a error message reporting the error description, third and forth messages. The procedure to report error messages from SoD is always like this one. It first reports the returned code from SoD (Figure 31 line 2) then reports a detailed description of the error dependently of it decision according to the SoD error (Figure 31 line 3 and 4).



```
Error: result=0x010f, file=/media/DOC/SodSoftW_sdr/SodFramework/comps/phSodMgr/src/comps/phSodMgrGraph/src/phSodMgr_GraphTask.c, line=102
  |    RMsrc/BBRM_library Info->phSodNmTask_Create():return:0x10f
  |    RMsrc/BBRM_library ERROR->BBRM_Alloc_sod_p_comps(): in radio ID 1 at component#0
  |    RMsrc/BBRM_library ERROR->BBRM_Alloc_sod_p_comps(): phSodNmTask_Create() failed with ERROR code (0x10f)
  |    RMsrc/BBRM_library Info->BBRM_Release_sod_tasks()
  |    RMsrc/BBRM_library Info->BBRM_Release_sod_tasks():return:0x200
    ResourceManager Info->BBRM_Alloc_sod_p_comps():return:0x219
    ResourceManager ERROR->Job_create(): in radio ID 1 and job#1.
    ResourceManager ERROR->Job_create(): BBRM_Alloc_sod_p_comps() function failed with error code (0x219).
```

Figure 31 : Error messages

K. BB-RM versions

The BB-RM building process was incremental. Each step was tested in the simulation framework first, and then in real platform. Every improvement was tagged with a version number after testing. Starting with version 1.0 and finish in version 1.7, each one has a new feature. There are several things worth mentioning.

The major idea of the version 1.0 was to just define what arguments are passed and which message is returned in the interface with the G-RM. For the input arguments was created a file with all BB-RM structures. To handle the return messages, a Debug module was created, as explained in section J. BB-RM does not have any interaction with SoD.

In order to explore the SoD API, version 1.1 was developed. There, the BB-RM just picks up the radio components given from G-RM and allocates them in SoD.

To implement a real functional block, i.e. some code that receives something and acts with something it builds the version 1.2. There, the given radio is allocated in SoD without any method or algorithm. Was implemented as well the CPU model and the memory model to BB-RM has the knowledge of the platform resources.

With the referred modules the BB-RM code became too big, occupying around 80% of the dedicated memory for it. By that reason was necessary making some optimization in code. Those optimizations will be better described in next section. For this section is just interesting know that the version 1.3 is one optimization code of version 1.2.

As explained before, the first step when the BB-RM receives a radio, more specific when BBRM_Job_create function receives a radio, is order the components. The relative weight and the module weight order methods were created in version 1.4.

In version 1.5, the algorithms to allocate the component requirements were implemented as well as the complete RAP algorithms. There is combined the methods to order the radio components and the algorithms to allocate them requirements.

Line by line the code became bigger. As a result the debug task turns hard as well. To minimize this issue the debug module was improved with three types of messages, state, error and fatal error. This change was saved as version 1.6.

Finally, using two radios with a structure similar to a real one, a stress test was done. Due to the results of this stress test, some settings were tuned in version 1.7 to adjust the behavior of the BB-RM to the real environment.

L. Source code

The file structure was constructed according to the modules structure. All shared files were placed in the root. Example of this is the Platform.h which contains the platform configuration, or de radio structure definition on Radio.h file, the Resource Manager API on BBResourcemanger.h file, and the API return codes in BBRM_code_return.h file.

Describing the folders from the top to the bottom in Figure 32, is formed the BBRMResources folder, which contains the CPU and memory resources. Each resource has three files; the first one is a source file contains all functions of this resource, a code return file which contains the code definitions, and the last one the header file containing the functions prototypes.

The adjacent folder is the BBRMsrc folder that leads to the source files of BB-RM. Such folder has the BBRM library which contains the internal functions of BB-RM. Has also the BB-RM configuration file where it can be chosen the allocation algorithms and methods, and finally the debug file which takes into account the debug functions.

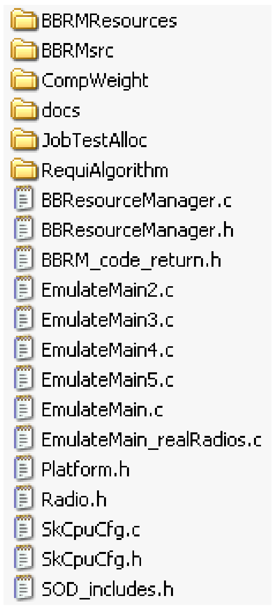
The CompWeight folder has the files to order the components by weight. It contains the two implemented methods, relative weight and module weight explained before.

Created by the doxygen tool the docs' folder has the code documentation. Each function is documented with the following items:

- A brief description about the function
- Simplified list of the internal procedures
- A list of the input parameters description
- A list of the possible return messages.

The two Complete RAP heuristics specified in section I are in JobTestAlloc folder. Each one has the source file which contains the functional code and the library file with the function prototypes.

Last but not the least there is the RequireAlgorithm folder. There it has the two implemented algorithms; First Fit and Best Fit. Those algorithms are to choose the tile for each processor component based on the processor component requirement.



BBRMResources
BBRMsrc
CompWeight
docs
JobTestAlloc
RequiAlgorithm
BBResourceManager.c
BBResourceManager.h
BBRM_code_return.h
EmulateMain2.c
EmulateMain3.c
EmulateMain4.c
EmulateMain5.c
EmulateMain.c
EmulateMain_realRadios.c
Platform.h
Radio.h
SkCpuCfg.c
SkCpuCfg.h
SOD_includes.h

Figure 32 : Files structure

(This page was left blank delivered)

6. Experimental results

The work developed in the scope of this dissertation has been extensively assessed and verified. This section presents some experimental results addressing several aspects of the work, namely optimizations that have to been carried out to reduce the code size, resource allocation strategies assessment and verification of the occurrence of fragmentation.

A. Optimizations

In the beginning the BB-RM operation was relatively simple, consisting only in allocating radio components without any global strategy. As the work progressed; several features have been added and the BB-RM became more efficient but, at the same time, more complex and bigger.
Eventually, in BB-RM version 1.2, the code became too big, using about 80% of the reserved F-ARM memory for itself. To reduce the code size several optimizations were done, some of them ending up in execution time improvements as well. This section presents the main optimizations that have been implemented.

The first optimization addressed the data structures used by the BB-RM. An exhaustive study about each variable's usage permitted to establish its bounds in the value domain. The conclusion was that some variables were oversized. Resizing the variables permitted a considerable gain in memory utilization, which went from the original 1.776 KB per radio to 1.103KB per radio, that is, a reduction of approximately 37.9%.
The same process was applied to all the other structures in the BB-RM resources.

Another kind of optimization consisted in the reduction of the components state data (Table 1). Originally, when a radio component needed CPU resources to be allocated, all relevant information about the component was saved on the CPU resource database. Similarly, when the component required memory, the relevant information was saved on the memory resource database. This approach drives to the existence of duplicated information in memory. To avoid this situation it was developed a new approach, in which only relevant information about the allocations is saved in the job structure. The new approach consists of just signalizing in the job list structure where the component is allocated, so it is not necessary anymore to save the component's information in each resource database. This approach permitted a significant improvement on the resource memory, as expected, but at expenses of an increase of the size of the job structure, as shown in Table 1 and Table 2, respectively.

Resource per tile	Before optimization	After optimization	Gain
Memory	616 Bytes	9 Bytes	**98.5%**
CPU	816 Bytes	9 Bytes	**98.9%**

Table 1 : Resource optimization

Structure	Before optimization	After optimization	Loss
Job list	1260 Bytes	1745 Bytes	72.2%

Table 2 : Job optimization

The amount of bytes saved in the resources is done per tile and the platform has four tiles in total. On the other hand, the job list structure is common. Thus, the global balance is positive. Table 3 shows that the total amount of bytes saved is 5171, corresponding to a reduction of 73.9% comparatively with the total amount of memory originally used.

	Total size of the structure before optimization	Total size of the structure after optimization	Difference in Bytes	Difference in %
Memory resource	2464 Bytes	36 Bytes	- 2428 Bytes	**- 98.5 %**
CPU resource	3264 Bytes	36 Bytes	- 3228 Bytes	**- 98.9 %**
Job list	1260 Bytes	1745 Bytes	+ 485 Bytes	**+ 72.2 %**
Total	6988 Bytes	1817 Bytes	- 5171 Bytes	**- 73.9 %**

Table 3 : Optimization results

The BB-RM module was developed as modular as possible. This means that each functional block is logically separated, has a specific function and a well defined interface. This approach has several well documented advantages, but incurs in memory and CPU overheads. A thorough code analysis has permitted identifying the existence of memory reserved for variables in several functions that in fact had the same contents. Thus, physically, the memory had duplicated variables with the same contents.
To minimize this problem, common (global) variables were used in several places. The size of these variables was also optimized to accommodate, as tightly as possible, the value domain bounds.

In the first BB-RM version, just the allocation information was saved in the job list, i.e., the tile where the component was allocated and it's ID.
In order to make the connections in the SoD, the BB-RM needed to search the radio topology. This imposed that the BB-RM had to save the complete radio when it was given to BBRM_Job_create function. So, when the BBRM_Job_create function is called BB-RM must keep the radio and create an instance of it (job) when it's allocated.

Despite simple, this approach is expensive in terms of memory because a radio structure and a job structure have to be saved. So a more memory-efficient approach was sought. The optimization that was implemented consists in having the BB-RM saving only the relevant fields of the radio in the job list structure instead of saving the whole radio, when calling Job-create function. Consequently the radio list from BB-RM is removed and some memory is saved.

In one brief look at the arguments of the BB-RM functions it is possible to note that the types of arguments are homogeneous among the internal functions of the BB-RM. The three mostly used arguments in functions are a radio component, a radio component requirement or a whole job. Instead of having a big radio structure with all its contents inside, the structure is split into several sub-structures. Now the job structure can use individually these radio sub-structures, even as arguments for the internal functions.

The optimization with higher impact consisted in changing the arguments of the functions to pointers. Now, every function has as arguments pointers and, when necessary, returns values in pointers.
Besides saving memory, this modification also has a significant impact in terms of CPU utilization, as shown in Table 4.

To assess the actual improvement in the runtime performance of these optimizations, it was carried out a stress test. This test consists in allocating four radios and removing them again. This procedure was repeated 500 000 times, resulting in 2 000 000 radio allocations and releases. Detailed results for the versions 1.2 and 1.3 are presented in appendixes B and C. Table 4 summarizes these results.

Functions	BB-RM Version	Cumulative seconds	Self seconds	Time per radio (µs)
BBRM_Job_create	1.2	23.82	0.32	**11.91**
	1.3	22.66	0.25	**11.33**
	1.4	25.93	0.20	**12.97**
BBRM_Job_remove	1.2	27.02	0.20	**13.51**
	1.3	24.28	0.15	**12.14**
	1.4	28.31	0.14	**14.16**

Table 4 : Functions performances

In the above table, the cumulative seconds are running sums of the number of seconds accounted for by the function itself and those called by it. The self seconds are the number of seconds accounted for the function alone.

Using the 1.2 version as a reference, because the optimization process started at this version, there are some aspects that worth noticing here. The first, and the most important one in the performance context, is the fact that the version 1.3 is in both functions quicker than the following 1.4 version. Looking at the figures, the BBRM_Job_create function is quicker by about 0.58 us per radio, while the BBRM_Job_remove won 1.37 us per radio, representing an improvement of 4.8% and 10.1%, respectively. Another aspect that deserves a specific comment is related with the performance degradation seen in version 1.4. The self time of both functions is lower. The cumulative time increased in consequence of a higher complexity of the sub-functions, which in this version started to implement the sort strategy referred in chapter 5, section H. Thus, in version 1.4 the cumulative time becomes bigger in result of the addition of new algorithms that result in higher computational complexity.

B. MW Vs RW results

The first step that BB-RM does when mapping a plan to allocate a radio is sorting the radio components. The sort operation defines the order in which the components will be allocated in the platform.

A specific test was developed to assess the effectiveness of the sorting methods. This test was done over the simulation framework. There, a simulated platform with three cores of the same type was used. As the target of this test is to analyze the results of using different processing components allocation orders, the radio topology is not important. For allocating the radios the BB-RM must sort the components and use the allocation algorithms explained in chapter 5, section G. The test is done using each one of these algorithms.
The basic idea is to allocate an amount of radios in such a way that the platform reaches the limit in the resource domain. To get this effect a radio depicted in Figure 33 is created.

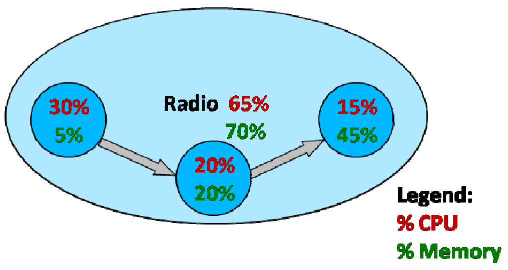


Figure 33 : Radio to test the MW and RW methods

This radio uses a total of 65% of a CPU resource (red) and 70% of a memory resource (green). It has three processing components, each one describing the amount of resources needed. As the sorting methods order the components by their requirements, the processing components in the created radios have different resource amounts. In order to give to BB-RM the full freedom to choose the allocation mapping of the radio components the cores are not aimed to a specific tile. The test consists in allocating the same radio (Figure 33) as many times as possible.

The platform has 300% of free resources to allocate the radios. This means that potentially can be allocated up to 4 radios (Equation 4). The memory resource is the tightest for this radio configuration.

$$\frac{\sum R_P}{\sum R_{CPU}} = \frac{300}{65} = 4.61$$

$$\frac{\sum R_P}{\sum R_{Mem}} = \frac{300}{70} = 4.28$$

Equation 4 : MW and RW theorical notes

As referred in chapter 5 section H, the RW method is adjustable to the platform needs. In order to save memory it is given a higher importance to this resource, by balancing 30% to the CPU and 70% to the memory.

Component order	Requirements allocation algorithm	Number of allocated radios
MW	FF	3
	BF	3
RW	FF	**4**
(**30%** - **70%**)	BF	**4**

Table 5 : MW and RW results

Table 5 presents the obtained results. It's clear that the RW method had better results independently of the requirements allocation algorithm. It can allocate four radios against three allocated by MW.

The difference between these two methods is that RW sorts the components in a way that minimizes the inter-tile fragmentation in memory. As the memory is the most required resource by the radio, the RW takes better decisions.

The MW method does not care about unbalanced resource needs, looking for each resource equally. This method of operation results in an increased inter-tile fragmentation, which penalizes its efficiency. This fragmentation type is detailed in chapter 4 section B.

These tests show that the RW algorithm is more efficient in ordering the radio components. It needs approximately the same computational resources, but achieves better results. With this algorithm it is possible to balance the weight of each resource. This feature allows the BB-RM to adjust these weights to favor the resources that are scarcer.

C. BF Vs FF results

According to the quote about BBRM_Job_create function in chapter 5 section E, after sorting the radio components the second step of BB-RM is to allocate each component. To allocate a component it is necessary to reserve resources for it. It is at this point that the requirements algorithms come in.

To appraise if these two algorithms are useful and which algorithm is better, a custom test was created. Using the same simulation framework used before, it was created the radio depicted in Figure 34.

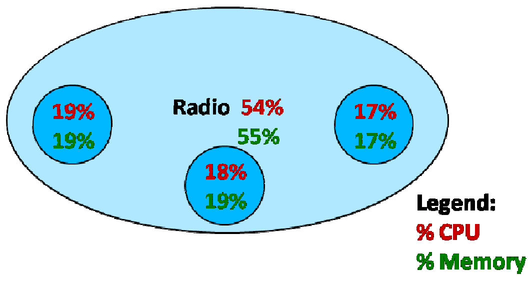


Figure 34 : Radio to test the BF and FF algorithms

The radio uses a total 54% of the CPU and 55% of the memory. It still has three components and no radio topology, which means there are no communication components. The idea is not to test the methods used to sort the radio components, but to test the algorithms to allocate the processing components in the radio (Figure 34). The same amount of resource requests will be used among them in each component. As indicated in Equation 5, the platform can support up to 5 radios.

$$\frac{\sum R_P}{\sum R_{CPU}} = \frac{300}{54} = 5.5(5)$$

$$\frac{\sum R_P}{\sum R_{Mem}} = \frac{300}{55} = 5.45$$

Equation 5 : BF and FF theorical notes

Method to order the components	Requirements algorithm	Number of allocated radios
MW	FF	4
	BF	5
RW	FF	4
	BF	5

Table 6 : BF and FF results

Looking to the results presented in Table 6 it is possible to conclude that the BF algorithm is the best mapping allocation strategy, allocating one more radio than the FF algorithm. Once again it is possible to note that the inter-tile fragmentation is a real problem (see chapter 4 section B). The platform has resources than can support up to five radios and in some cases only four have been allocated in practice. Further ahead, this scenario will be tested more intensely.
The BF algorithm is, in almost all the cases, the best algorithm, although it spends more computational resources than FF. This drawback may turn the use of the BF algorithm undesirable, despite its better resource allocation efficiency, for instance when the platform has strict time constraints in the radio creation time.

D. Complete Resource Allocation Problem results

There are two types of RAP heuristics worth noticing. The first type is when it uses one of the two implemented methods to sort the radio components and one of the two algorithms to allocate the component requirements. Thus, this type of heuristic is a strict combination among various methods and algorithms. One example of this heuristic is the BFDMW explained in chapter 5 section I. The other type of heuristic uses an implemented method and an algorithm as well, but adds specific optimizations. As an example of this latter class is the FFC complete RAP, presented in chapter 5 section I.

The performance assessment of the BFDMW does not need specific testing because the results are a combination of the base sorting method and algorithm results. On the other hand, the FFC was developed to save the bandwidth communication among the tiles. Consequently the connection times are reduced and the radio becomes faster. Thus, it would be relevant to measure the resulting performance improvement of this strategy. However, the simulation framework has a tool to measure the time of the management code but is unable to measure the radio performance, preventing the possibility of testing the complete RAP.

E. Fragmentation results

The tests done in the last two sections proved the actual appearance of inter-tile fragmentation, which caused allocation problems. A paradigmatic example was the FF results (section C), where the platform had enough resources to allocate five radios and in practice was only able to allocate four. This section presents a test that addresses the experimental verification of the inter-tile fragmentation problem.

One problem of the BB-RM is that it does not account for the intra-tile fragmentation problem in its resource model. Due to this fact, the BB-RM can give an approval to a radio that, in the real platform, will not fit. This situation can happen in two memory parts of the tile: data & status memory and FIFO memory (see chapter 3 section A). The problem is similar in both cases, thus our tests have been directed to the FIFO memory fragmentation, only. In this case the test uses both on the simulation and the real platform, since the simulation framework does not model the fragmentation problems.

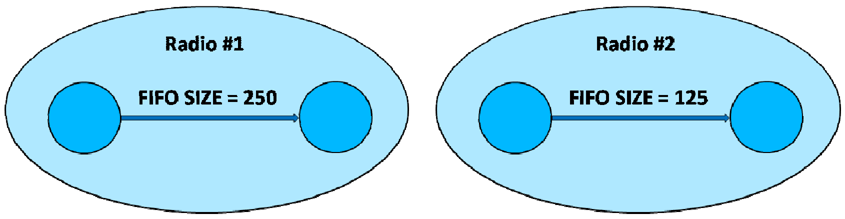


Figure 35 : Radios to test the FIFO fragmentation

Two different radios were created, Radio #1 that needs a FIFO size of 250 bytes to transport the information from the first processing component to the second processing component, and Radio #2 that needs a FIFO size with 125 bytes for the same purpose. As the objective is to test the FIFO memory fragmentation, the requirements of the processing components are not considered.

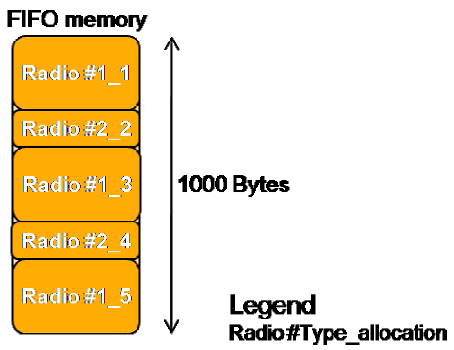


Figure 36 : FIFO memory

The simulation framework was configured to have 1000 bytes in the FIFO memory in each tile. Depicted in Figure 36 it is a tile memory with five radios already allocated. Radio #1 occupies 1/4 of the total FIFO memory and radio #2 occupies 1/8.

The test starts by allocating five radios according to the top to bottom order shown in Figure 36. In this moment the FIFO memory is completely full. The next step is to release Radio #2_2 and Radio #2_4. Afterwards it tries to allocate a new instance of Radio #1 that needs the double of the FIFO memory as Radio #2. This allocation was a success in BB-RM resources (without fragmentation) but failed in the real platform (inter-tile fragmentation problem). Thus, this experiment shown that the inter-tile fragmentation may affect the performance of the BB-RM by reducing the number of possible radio allocations.

7. Conclusions and future work

The main objective of this dissertation was the development of a Baseband Resource Manager module for heterogeneous multi-processor radio platforms. The developed BB-RM provides:

- Admission control - The BB-RM only allows the creation of additional radios only if enough resources are available. Thus, new radios do not disturb the already running radios. As the radios have RT requirements, the BB-RM guarantees that the deadlines associated with the computations of all the radios (the already running radios as well as newly added ones) are met.
- Resource reservation - Each radio can only use the resources that have been reserved for it.

The BB-RM allows and guarantees different rates of operation among functions within the radio and even among radios. The unpredictable start/stop times of a radio will not disturb the requirement of the running radios.

In order to be applied in several infotainment mediums, the BB-RM supports a wide variety of radios and even radio combinations, which makes it completely adjustable to the platform. The tile configuration or even the processor type is configurable as well. For instance, in the future it will be possible to run this BB-RM in a platform with the double or triple of the number of processors. This was accomplished without changing the SoD, turning the BB-RM autonomous from the SoD platform.

It is estimated that for the current platform, called AeroProto2, it is possible to run at least five radios simultaneously. In this context BB-RM allows dynamically changing the radios executed in each instant.

The BB-RM has proven to have a good performance despite using limited computational resources. In the simulation framework the whole system needs around 14µs to allocate a radio. This time is acceptable in land radio platforms.

The implemented heuristics to allocate the radio components are working perfectly. In this land radio platform, the RW proved to be the best method to order the radio components, being able to allocate one more radio than MW (Table 5). The BF allocation algorithm has proved to be better than FF. In the tests, the BF algorithm allocated one more radio than FF (Table 6). In conclusion, if the platform has enough computation resources, the best combination to a complete RAP is RW with BF. On the other hand, if the computation resources are scarce, the best combination to solve the complete RAP is RW with FF. In theory the FFC complete RAP should to be a good solution to reduce the communications bandwidth but it was not possible to prove it on the real platform or even in simulation framework.

A. Future work

Despite all the effort put in this project, some aspects remain to be solved.

Within each tile the memory can become fragmented (intra-tile fragmentation). The amount of fragmentation increases with memory usage. In its current state the BB-RM cannot model fragmentation, potentially leading to allocation inconsistencies. This inconsistency is created when the radio passes the BB-RM tests and it does not fit in the real platform. This inconsistency is caused by the VBP algorithm used by BB-RM which does not account with the fragmentation problem, as detailed in chapter 5, section I. To solve this issue, the BB-RM should implement in the same memory allocation algorithm as the one used in the real platform. This way the BB-RM would have an exact copy of the memory mapping of the real platform, solving the inconsistency problem.

Another improvement that can be done in BB-RM is on the RW sort strategy. This method is used to order the components in an efficient way, this if the resource weights are properly defined. It is possible to set the right resource weight in the beginning and, after some allocations, the resource weights may need to be adjusted. This happens because different radios use different amounts of each resource. To solve this issue the resource weight should be dynamically adjusted in run-time. Having the knowledge of the resource status, the resource weights could to be manipulated to save the more scarce resources in each instant.

8. Bibliography

1. **Mehrotra, Asha.** *Cellular radio performance engineering.* s.l. : Artech House, 1994.
2. *Radio computer: vision, value, stakeholder views, Radio Programming Interface scenarios.* **Tolonen, Pertti and Berkel, Kess van.**
3. gsmworld. [Online] [Cited: October 12, 2008.] http://www.gsmworld.com/about/history.shtml.
4. **Hennessy, John L. and Patterson, David A.** *Computer Architecture.* s.l. : third edition.
5. **Sepillo, A. L.** *A Comparative Study on Symmetric and Asymmetric Multiprocessors.* Diliman : University of the Philippines.
6. **Ahtiainen, Ari, et al.** *SDR Functional Architecture Overview.* 2008.
7. *Self-Timed Scheduling Analysis for a Real-Time Applications.* **Moreira, Orlando and Bekooij, Marco.**
8. **Pedreiras, Paulo e Almeida, Luis.** *Sistemas de Tempo-Real.* Aveiro : s.n., 2008.
9. **Herlihy, Maurice and Shavit, Nir.** *The Art of Multiprocessor Programming.*
10. **Tanenbaum, Andrew S.** *Operating Systems Design and Implementation.* s.l. : third edition.
11. **Timothy, O'Neil W., Edwin, H. and Sha, M.** *Retiming Synchronous Data-Flow Graphs to Reduce Execution Time.*
12. **NXP.** *User's manuel for AeroSOFT development board.* Netherlands : NXP, 2008.
13. **Kourzanov, Pjotr.** [Online] [Cited: 11 5, 2008.] ://www.bitbucket.org/pjotr/lime/src/.
14. *LIME: a future-proof programming model for multi-core.* **Kouranov, Pjotr, Moreira, Orlando and Sips, Henk.**
15. **Pol, E. J., Rutten, M. and Splunter, M. van.** *Sea of DSP Programmer's user manual.*
16. **Labrosse, Jean J.** *MicroC/OS-II - The Real Time Kernel.* CMP.
17. *Scheduling Multiple Independet Hard-Real-Time Jobs on a Heterogeneous Multiprocessor.* **Moreira, Olando, Valente, Frederico and Bekooij, Marco.**
18. *Online Resource Management in a Multiprocessor with a Network-on-Chip.* **Moreira, Orlando, Mol, Jacob Jan-David and Bekooij, Marco.**
19. **Moreira, Orlando, et al.** *Multiprocessor resource allocator for Hard-real-time Streaming with a Dynamic job-mix.*
20. **Douglass, Bruce Powel.** *Real-Time design Pattens: Robust Scalable Architecture for Real-Time Systems.*

(This page was left blank delivered)

9. Appendices

A. Doxygen API code documentation

bbrm_code_return_t BBRM_initialize (void)

This function must be called in the system starter.

This function initializes:

- the Streaming Kernel in SoD by calling phSodEmulateInit() function;
- the **job** list, by calling **BBRM_initialize()** function;
- the CPU BB-RM resource model, by calling **CPU_initialize()** function;
- the memory BB-RM resource model, by calling **Mem_initialize()** function.

Returns:

- BBRM_FATAL_ERROR_SOD_FAILED - Fatal SOD function failed.
- BBRM_FATAL_ERROR_CPU_FAILED - Round Robin function failed.
- BBRM_FATAL_ERROR_MEM_FAILED - Memory function failed.
- BBRM_OK - Operation successful.

bbrm_code_return_t BBRM_Job_test (const radio_t * radio_p)

The BBRM_Job_test function tests whether instantiation of a **job** is possible

The internal procedures are:

- finds the free entry in **job** list;
- fills the **job** entry with:
  - source **radio** pointer;
  - source **radio** ID;
  - changes the **job** state to SIMULATION MODE;
- sets all BB-RM resources in a simulation mode by calling the **BBRM_Set_res_simul()** function;
  - if failed clean the **job** in **job** list by calling **BBRM_initialize()** function;
- allocates the **radio** requirements by calling the **BBRM_Simul_job()** function;
- restores the resources by calling **BBRM_Set_res_restore()** function;

- cleans the **job** in **job** list by calling **BBRM_initialize()** function;

Parameters:

radio_p (IN) Pointer to the **radio**.

Returns:

- BBRM_FATAL_ERROR_RES_STATE - Error while change the BB-RM resources states.
- BBRM_ERROR_SIMUL - This **radio** fail in requirements simulation.
- BBRM_OK - Operation successful.

*bbrm_code_return_t BBRM_Job_create (const radio_t ** **radio_p**, *uint8_t *const* **created_job_id***)*

The BBRM_Job_create function creates a **job**, (**radio** instance) and sets it on suspend mode, to put the **job** running it needs call the **BBRM_Job_resume()** function.

The internal procedures are:

- validates the **radio** by calling the **BBRM_Test_radio()** function;
- finds the free entry in **job** list;
- fills the **job** entry with:
  - source **radio** pointer;
  - source **radio** ID;
  - changes the **job** state to SIMULATION MODE;
- sets all resources in a simulation mode by calling the **BBRM_Set_res_simul()** function;
  - if failed cleans the **job** in **job** list by calling **BBRM_initialize()** function;
- allocates the **radio** requirements by calling the **BBRM_Simul_job()** function;
  - if the test failed:
    - restores the resources by calling **BBRM_Set_res_restore()** function;
    - cleans the **job** in **job** list by calling **BBRM_initialize()** function;
  - in case of success sets the **job** state as TESTED MODE;
- allocates the **radio** tasks in SoD by calling the **BBRM_Alloc_sod_c_comps()** function;
  - if the test failed:
    - restores the BB-RM resources by calling **BBRM_Set_res_restore()** function;
    - cleans the **job** in **job** list by calling **BBRM_initialize()** function;
  -
- allocates the **radio** FIFOs in SoD by calling the **BBRM_Alloc_sod_c_comps()** function;
  - if the test failed:
    - restores the BB-RM resources by calling **BBRM_Set_res_restore()** function;
    - cleans the **job** in **job** list by calling BBRM_**initialize()** function;
  -
- sets the task parameters in SoD by calling the **BBRM_Sod_parameters()** function;
  - if the test failed:
    - restores the BB-RM resources by calling **BBRM_Set_res_restore()** function;

- cleans the **job** in **job** list by calling **BBRM_initialize()** function;
-
- sets all resources in RUNNING MODE;
- sets the **job** state at SUSPEND MODE;
- returns the created **job** ID.

Parameters:

radio_p (IN) Radio pointer with all Radio parameters.
created_job_id (OUT) Returns the created **job** ID.

Returns:

- BBRM_FATAL_ERROR_RADIO - This **radio** can't to be run.
- BBRM_FATAL_ERROR_RES_STATE - Error while change the BB-RM resources states.
- BBRM_ERROR_SIMUL - This **radio** fail in requirements simulation.
- BBRM_FATAL_ERROR_UNAL_T - Tasks release fail.
- BBRM_ERROR_SOD_FAILED - SOD function failed.
- BBRM_FATAL_ERROR_ALLOC_F - Error while allocating the FIFOs in Sod platform.
- BBRM_ERROR_PARAM - Error while set the task parameters in SoD.
- BBRM_OK - Operation successful.

bbrm_code_return_t BBRM_Job_resume (const uint8_t job_id*)*

This function sets the given **job** running in the platform.

The internal procedures are:

- Validates if the **job** state, must be in suspend mode;
- For each task in **job**:
  - resumes the task in SoD by calling phSodNmTask_Resume() function;
  - validates the result;
- Changes the **job** state.

Parameters:

job_id (IN) ID of the **job** that will be resumed.

Returns:

- BBRM_ERROR_JOB_RES - Job is not ready to be resumed.
- BBRM_FATAL_ERROR_SOD_FAILED - SOD function failed.
- BBRM_OK - Operation successful.

bbrm_code_return_t BBRM_Job_suspend (const uint8_t job_id*)*

This function changes the running **job** to a suspended **job**, but the **job** still in the platform, that means, all requirements of this **job** still reserved for it.

The internal procedures are:

- verifies if the given **job** ID is on running mode;
- determines the number of components in **radio** by calling the **BBRM_Nr_of_p_comps()** function;
- traces all components inside the given **job** and suspend each one by calling the phSodNmTask_Suspend() function.
- sets the **job** state as suspend mode.

Parameters:

job_id (IN) ID of the **job** that will be suspended.

Returns:

- BBRM_ERROR_JOB_SUS - Job is not ready to be suspended (must be in run state).
- BBRM_FATAL_ERROR_SOD_FAILED - SOD function failed.
- BBRM_OK - Operation successful.

bbrm_code_return_t BBRM_Job_remove (const uint8_t job_id*)*

The BBRM_Job_remove function removes the suspended **job** and remove it from the SoD. That means all resources used by this **job** are released in BB-RM.

The internal procedures are:

- verifies if the **job** state is in suspended mode;
- release from SoD:
  - calls **BBRM_Release_sod_fifos()** function to remove all FIFOs of this **job**;
  - calls **BBRM_Release_sod_tasks()** function to remove all Tasks of this **job**;
- releases the BB-RM resources: by calling **BBRM_Release_comp_reqs()** function;
- cleans the **job** in **job** list by calling **BBRM_initialize()** function;

Parameters:

job_id (IN) ID of the **job** that will be removed.

Returns:

- BBRM_ERROR_JOB_NREADY - Job is not ready to be removed (must be in SUSPEND state).
- BBRM_FATAL_ERROR_CPU_FAILED - Round Robin function failed.
- BBRM_FATAL_ERROR_MEM_FAILED - Memory function failed.
- BBRM_FATAL_ERROR_UNALLOC - (At least one) requirement did not be release.

- BBRM_FATAL_ERROR_UNAL_F - FIFOs unallocated failed.
- BBRM_FATAL_ERROR_UNAL_T - Tasks unallocated failed.
- BBRM_OK - Operation successful.

B. Functions performances in version 1.2

To measure the performance of the BB-RM functions the GNU Profiling (gprof) program was used. A stress test was created to calls 2000000 times each BB-RM function. The results of the version 1.2 are next.

```
Flat profile:

Each sample counts as 0.01 seconds.

  %   cumulative   self              self     total
 time   seconds   seconds    calls   us/call  us/call  name
  1.04    23.82     0.32   2000000     0.16     4.28   BBRM_Job_create
  1.04    24.14     0.32                               phSodNmPort_Connect
  1.04    24.46     0.32                               phSodNmTask_Delete
  0.98    24.77     0.30                               phSodMgr_TileInitialized
  0.95    25.05     0.29                               phSodNmPort_Disconnect
  0.65    27.02     0.20   2000000     0.10     1.00   BBRM_Job_remove
  0.64    27.21     0.20                               phSodMgr_MemStateBlockAlloc
  0.00    30.63     0.00         1     0.00     0.00   BBRM_initialize
```

% time - the percentage of the total running time of the program used by this function.

cumulative seconds - a running sum of the number of seconds accounted for by this function and those listed above it.

self seconds - the number of seconds accounted for by this function alone. This is the major sort for this listing.

calls - the number of times this function was invoked, if this function is profiled, else blank.

self ms/call - the average number of milliseconds spent in this function per call, if this function is profiled, else blank.

total ms/call - the average number of milliseconds spent in this function and its descendents per call, if this function is profiled, else blank.

name - the name of the function. This is the minor sort for this listing. The index shows the location of the function in the gprof listing. If the index is in parenthesis it shows where it would appear in the gprof listing if it were to be printed.

```
                    Call graph (explanation follows)


granularity: each sample hit covers 4 byte(s) for 0.03% of 30.63 seconds

index % time    self  children    called     name
                                             <spontaneous>
[1]     35.0    0.17   10.54                 main [1]
                0.32    8.23 2000000/2000000     BBRM_Job_create [2]
                0.20    1.79 2000000/2000000     BBRM_Job_remove [6]
                0.00    0.00       1/1           BBRM_initialize [76]
-----------------------------------------------
                0.32    8.23 2000000/2000000     main [1]
[2]     27.9    0.32    8.23 2000000         BBRM_Job_create [2]
                0.19    4.46 2000000/2000000     BBRM_Simul_radio_reqs [4]
                1.65    0.00 2000000/2000000     BBRM_Test_radio [8]
                0.74    0.00 2000000/2000000     BBRM_Alloc_sod_fifos [15]
                0.05    0.50 2000000/2000000     BBRM_Set_res_simul [20]
                0.01    0.35 2000000/2000000     BBRM_Set_res_run [25]
                0.19    0.00 2000000/2000000     BBRM_Alloc_sod_tasks [42]
                0.09    0.00 2000000/2000000     BBRM_Sod_parameters [57]
-----------------------------------------------
                0.20    1.79 2000000/2000000     main [1]
[6]      6.5    0.20    1.79 2000000         BBRM_Job_remove [6]
                0.56    0.81 10000000/10000000     BBRM_Unalloc_node_reqs [9]
                0.33    0.00 2000000/2000000     BBRM_Unalloc_sod_fifos [28]
                0.09    0.00 2000000/2000000     BBRM_Unalloc_sod_tasks [58]
-----------------------------------------------
 [76]     0.0    0.00    0.00       1         BBRM_initialize [76]
-----------------------------------------------
```

This table describes the call tree of the program, and was sorted by the total amount of time spent in each function and its children.

Each entry in this table consists of several lines. The line with the index number at the left hand margin lists the current function. The lines above it list the functions that called this function, and the lines below it list the functions this one called.

This line lists:
    Index - A unique number given to each element of the table. Index numbers are sorted numerically. The index number is printed next to every function name so it is easier to look up where the function in the table.

% time - This is the percentage of the `total' time that was spent in this function and its children. Note that due to different viewpoints, functions excluded by options, etc, these numbers will NOT add up to 100%.

self - This is the total amount of time spent in this function.

children - This is the total amount of time propagated into this function by its children.

called - This is the number of times the function was called. If the function called itself recursively, the number only includes non-recursive calls, and is followed by a `+' and the number of recursive calls.

name - The name of the current function. The index number is printed after it. If the function is a member of a cycle, the cycle number is printed between the function's name and the index number.

For the function's parents, the fields have the following meanings:

self - This is the amount of time that was propagated directly from the function into this parent.

children - This is the amount of time that was propagated from the function's children into this parent.

called - This is the number of times this parent called the function `/' the total number of times the function was called. Recursive calls to the function are not included in the number after the `/'.

name - This is the name of the parent. The parent's index number is printed after it. If the parent is a member of a cycle, the cycle number is printed between the name and the index number.

If the parents of the function cannot be determined, the word `<spontaneous>' is printed in the `name' field, and all the other fields are blank.

For the function's children, the fields have the following meanings:

self - This is the amount of time that was propagated directly from the child into the function.

children - This is the amount of time that was propagated from the child's children to the function.

called - This is the number of times the function called this child `/' the total number of times the child was called. Recursive calls by the child are not listed in the number after the `/'.

name - This is the name of the child. The child's index number is printed after it. If the child is a member of a cycle, the cycle number is printed between the name and the index number.

If there are any cycles (circles) in the call graph, there is an entry for the cycle-as-a-whole. This entry shows who called the cycle (as parents) and the members of the cycle (as children.)
The `+' recursive calls entry shows the number of function calls that were internal to the cycle, and the calls entry for each member shows, for that member, how many times it was called from other members of the cycle.

Index by function name

```
   [1] main
   [2] BBRM_Job_create
   [6] BBRM_Job_remove
  [76] BBRM_initialize
```

C. Functions performances in version 1.3

The same example was used to test the version 1.3 and the results are listed next.

Flat profile:

```
Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls  ms/call  ms/call  name
  0.93     22.66     0.25  2000000     0.00     0.00  BBRM_Job_create
  0.90     22.89     0.24                             phSodMgr_TileInitialized
  0.78     23.11     0.21                             phSodNmPort_Connect
  0.56     24.28     0.15  2000000     0.00     0.00  BBRM_Job_remove
  0.56     24.43     0.15                             phSodMgr_MemFifoBlockAlloc
  0.56     24.58     0.15                             phSodMgr_MemTaskAlloc
  0.00     26.76     0.00        1     0.00     0.00  BBRM_initialize
```

% time - the percentage of the total running time of the program used by this function.

cumulative seconds - a running sum of the number of seconds accounted for by this function and those listed above it.

self seconds - the number of seconds accounted for by this function alone. This is the major sort for this listing.

calls - the number of times this function was invoked, if this function is profiled, else blank.

self ms/call - the average number of milliseconds spent in this function per call, if this function is profiled, else blank.

total ms/call - the average number of milliseconds spent in this function and its descendents per call, if this function is profiled, else blank.

name - the name of the function. This is the minor sort for this listing. The index shows the location of the function in the gprof listing. If the index is in parenthesis it shows where it would appear in the gprof listing if it were to be printed.

```
                    Call graph (explanation follows)


granularity: each sample hit covers 4 byte(s) for 0.04% of 26.76 seconds

index % time    self  children    called     name
                                             <spontaneous>
[2]     25.9    0.02    6.91                 main [2]
                0.25    5.12 2000000/2000000     BBRM_Job_create [3]
                0.15    1.39 2000000/2000000     BBRM_Job_remove [6]
                0.00    0.00       1/1           BBRM_initialize [79]
-----------------------------------------------
                0.25    5.12 2000000/2000000     main [2]
[3]     20.1    0.25    5.12 2000000         BBRM_Job_create [3]
                0.14    3.00 2000000/2000000     BBRM_Simul_radio_reqs [4]
                1.01    0.00 2000000/2000000     BBRM_Test_radio [10]
                0.40    0.00 2000000/2000000     BBRM_Alloc_sod_fifos [19]
                0.03    0.21 2000000/2000000     BBRM_Set_res_simul [32]
                0.00    0.18 2000000/2000000     BBRM_Set_res_run [35]
                0.10    0.00 2000000/2000000     BBRM_Alloc_sod_tasks [50]
                0.05    0.00 2000000/2000000     BBRM_Sod_parameters [60]
-----------------------------------------------
                0.15    1.39 2000000/2000000     main [2]
[6]      5.7    0.15    1.39 2000000         BBRM_Job_remove [6]
                0.28    0.84 10000000/10000000     BBRM_Release_node_reqs [9]
                0.18    0.00 2000000/2000000     BBRM_Release_sod_fifos [37]
                0.09    0.00 2000000/2000000     BBRM_Release_sod_tasks [55]
-----------------------------------------------
 [77]     0.0    0.00    0.00       1         BBRM_initialize [77]
-----------------------------------------------
```

This table describes the call tree of the program, and was sorted by the total amount of time spent in each function and its children.

Each entry in this table consists of several lines. The line with the index number at the left hand margin lists the current function. The lines above it list the functions that called this function, and the lines below it list the functions this one called.

This line lists:
Index - A unique number given to each element of the table. Index numbers are sorted numerically. The index number is printed next to every function name so it is easier to look up where the function in the table.

% time - This is the percentage of the `total' time that was spent in this function and its children. Note that due to different viewpoints, functions excluded by options, etc, these numbers will NOT add up to 100%.

self - This is the total amount of time spent in this function.

children - This is the total amount of time propagated into this function by its children.

called - This is the number of times the function was called. If the function called itself recursively, the number only includes non-recursive calls, and is followed by a `+' and the number of recursive calls.

name - The name of the current function. The index number is printed after it. If the function is a member of a cycle, the cycle number is printed between the function's name and the index number.

For the function's parents, the fields have the following meanings:

self - This is the amount of time that was propagated directly from the function into this parent.

children - This is the amount of time that was propagated from the function's children into this parent.

called - This is the number of times this parent called the function `/' the total number of times the function was called. Recursive calls to the function are not included in the number after the `/'.

name - This is the name of the parent. The parent's index number is printed after it. If the parent is a member of a cycle, the cycle number is printed between the name and the index number.

If the parents of the function cannot be determined, the word `<spontaneous>' is printed in the `name' field, and all the other fields are blank.

For the function's children, the fields have the following meanings:

self - This is the amount of time that was propagated directly from the child into the function.

children - This is the amount of time that was propagated from the child's children to the function.

called - This is the number of times the function called this child `/' the total number of times the child was called. Recursive calls by the child are not listed in the number after the `/'.

name - This is the name of the child. The child's index number is printed after it. If the child is a member of a cycle, the cycle number is printed between the name and the index number.

If there are any cycles (circles) in the call graph, there is an entry for the cycle-as-a-whole. This entry shows who called the cycle (as parents) and the members of the cycle (as children.)
The `+' recursive calls entry shows the number of function calls that were internal to the cycle, and the calls entry for each member shows, for that member, how many times it was called from other members of the cycle.

Index by function name

[2] main
[3] BBRM_Job_create
[6] BBRM_Job_remove
[77] BBRM_initialize