A Reconfigurable Multi-standard Radio Platform

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Abstract. This paper presents a dynamically reconfigurable multiradio RF architecture concept, which can be used for RF platform and control optimization. The platform realization is based on the RF hardware and its configuration mechanisms. The related control software is realized through functional separation of configuration management and timing control. Both key HW and SW elements are discussed and optimization opportunities evaluated using high level analysis on key building blocks.

Keywords: RF architecture, SDR, Multiradio, dynamic scheduling.

1 Introduction

The complexity of the mobile radio communication platforms is rising rapidly. At the same time the mobile industry is under consolidation and pressure to reduce investments. These two issues together pose new kind of challenges for the ecosystem.

Modern multi-media phones and mobile internets devices (MIDS) are already having multiple radio protocols to support different tasks and services they provide for consumers.

In current approach, the communication systems are mostly implemented by using dedicated HW for each communication protocol. It is not easy to provide flexibility to optimize the resources and to minimize energy consumption when multiple radio protocols are operated using the same HW. This is aggravated when the dynamic behavior of different protocols in is taken into account. In order to be capable of managing and optimizing the platform during the design phase and especially during the run-time, one must develop a rigorous framework and abstraction scheme for the control of the multiradio RF. The purpose of the abstraction is to avoid too sturdy and cumbersome control schemes. Furthermore, abstraction allows the platform independent SW development without detailed information of underlying HW. In a radio, RF processing is a specific entity because it can not utilize any memory during

J. Rodriguez, R. Tafazolli, C. Verikoukis (Eds.): MOBIMEDIA 2010, LNICST 77, pp. 661–671, 2012.

transmission and reception. Hence, scheduling must be based on the radio protocols occupying complete but programmable and flexible RF signal chains. In software defined radio (SDR) RF platform, a part of the HW components could be made tunable to serve multiple protocols.

The problem of co-existence of radios has been addressed for example in [1] and a solution for MAC based on functionality splitting has been proposed by [2]. We address the same problem domain, but using protocol assisted isolation mechanisms that leave space for various solution of radio cognition [3].

The selected approach creates a usage-centric platform control framework such that the RF and its control are abstracted from the protocol layers i.e. the platform is transport independent. In this context, transport independence means none of the protocols will have dedicated resources received for their requests.

The resources needed to perform the tasks requested by the applications (i.e. radio protocols) are solely allocated and controlled locally by the control framework.

This paper is organized as follows. Section 2 presents the system architecture. The proposed RF platform and RF resource management are presented in sections 3 and 4. Section 5 presents platform configuration HW analysis.

2 System Architecture

The key challenge for the system architecture [4] is to have flexibility to assign different radio systems independently onto a SDR. In Baseband processing this can rely on vector processing or other computing elements. The concept of configurable RF is presented in Fig. 1. HW has multiple, configurable signal chains both for transmission and reception. The emphasis in this paper is on the receiver side. However, the same approach applies to transmitter side as well. The desired configurations can be made by multiplexing the switch matrix. This is a good approximation of the configuration opportunities that state-of-the art RF transceivers can provide. RF blocks are assumed to be flexible enough to support multiple protocols with known band limitations. For example, block BB1 is used by protocols 1 and 3 in this figure.

In foreseeable demanding use-cases, two or more protocols out of 5-10 protocols could be active at a time. Most of the activated protocols are merely maintaining links to guarantee mobility. Hence, it is reasonable to assume that the resource hungry high-speed traffic is carried out by one or maximally by two of the protocols at a time. To allow the link-maintaining and low-speed traffic radios to share a signal chain, the RF subsystem must support dynamic scheduling and configuration of hardware.

RF band and performance requirements will have major impact on the configuration. Not all of the RF elements can be stretched to support all frequency bands and operating conditions. Thus, the performance cannot be controlled without HW specific information. However, performance information does not need to be protocol specific by nature.

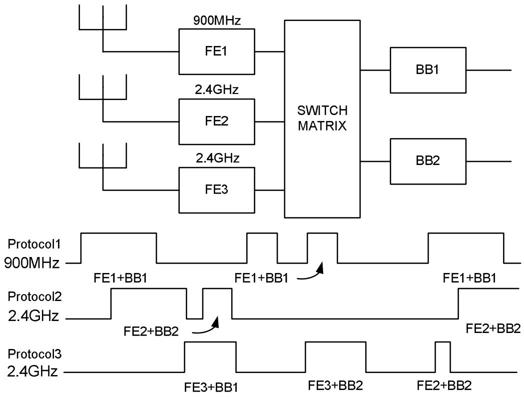

Fig. 1. Concept of configurable RF

Radio standards specify requirements for performance, but do not define the implementation. For RF platform, the key differences between protocols that need to be taken into account are radio frequency bands, channel bandwidths, sensitivity (i.e. noise performance) and selectivity (i.e. ability to tolerate interference). Due to dynamic nature and a complex set of different requirements over different protocols, the performance tuning should have an abstracted overlay with other configuration parameters to be manageable on a multiradio platform. An approach towards abstracted RF control is described in Fig. 2.

Only some of the protocol specifications guarantee interoperability with the others. For example, internal interoperability between GSM, EDGE, WCDMA, HSPA, and LTE guarantees that those can use the same resources to some extent and perform necessary monitoring actions without multiplying the HW. Thus, because of variance and number of the protocols involved in contemporary smart phones, the analysis of the requirements is exhaustive. To cope with future complexity, mechanisms at a suitable abstraction level are needed to ensure realization of interoperability on a multiradio platform.

Our system architecture consists of a reconfigurable RF platform, platform control, digital baseband processing (PHY & MAC) and network stacks, as illustrated in Fig. 3. The platform control consists of multi-radio controller, resource manager and I/O sequencer. The multi-radio controller can synchronize transmissions of mutually interfering radio protocols, such as 802.11g and Bluetooth. The resource manager maintains schedules for the configuration of the RF platform. The schedules are executed by the I/O sequencer to achieve precise timing in RF configuration and transmission latching.

HW resource scheduling is driven by the protocols and the multiradio controller. This enables scheduling of specific HW resources, as resource demand can be estimated in advance.

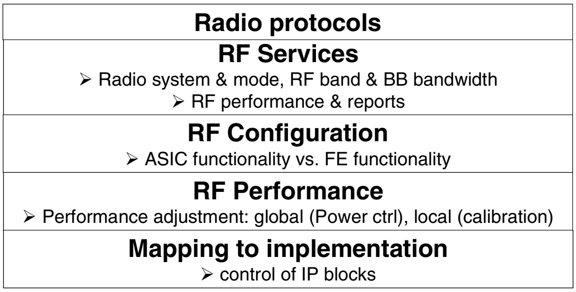

Fig. 2. Abstracted RF control

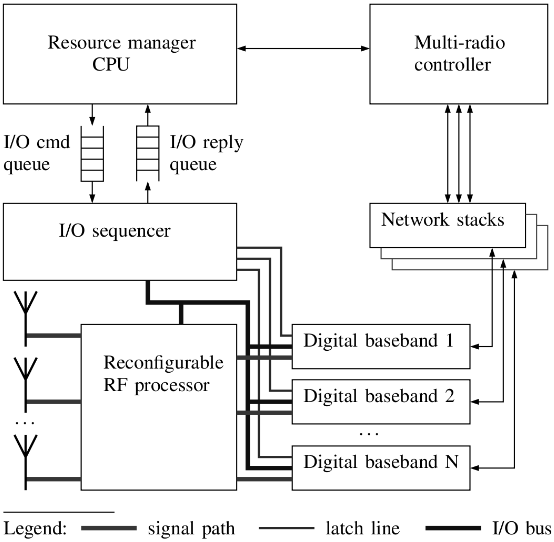

Fig. 3. The overall system architecture

Flexibility and predictability are important scheduling characteristics and they vary between protocols.

To support sub-microsecond precision for platform reconfiguration, we use hardware-assistance in configuring and scheduling the use of HW resources.

3 RF Platform

In conventional implementations, it is not possible to do any run-time reconfigurations or run-time resource sharing between protocols. To illustrate the situation we show an example of a possible implementation of a GSM/WCDMA/LTE/WLAN receiver, Fig. 4. Solution reflects current state-of-the art WEDGE receiver [5] with added LTE functionality at 2.5GHz band. LTE can be adopted at various cellular bands but here we have limited the cellular MIMO functionality, required in LTE, only to one band. This does not restrict the approach being used in more complex scenarios.

The key technology limitations are related to RF filters. Current technology does not enable implementations of tunable RF filters with adequate performance. Especially in near future when the number of systems and frequency bands is increasing this poses a major obstacle.

Within the industry, substantial amount of work have been done to achieve more flexibility in HW [5-8] in cellular and WLAN domain separately. Despite of more flexible HW architectures, increased number of specified frequency bands combined with limited tuneability of RF filters is shifting the complexity to even more parallel radio frequency processing. Emerging MIMO technology will further complicate this issue in adding more parallel signal paths to the HW platform. Cellular communications is an excellent example of resource sharing opportunity embedded into protocols where second and third generation systems (GSM/EDGE & WCDMA/HSPA) could share most of the low-frequency processing elements and the same is foreseeable in the fourth generation (LTE). In addition solutions where systems share resources with customized interoperability mechanisms have been presented. For example, GPS has been adapted to diversity path of an RF solution [9]. Dynamic resource sharing and run-time reconfigurability can be enhanced to allow concurrent operation of multiple protocols using at least some shared resources in the platform. However, this requires improved scheduling awareness and careful characterization of realistic use scenarios as described later in this paper.

The RF platform model in the analysis consists of parallel processing elements that can be interconnected flexibly to form desired transmitter (TX) and receiver (RX) chains. Processing blocks are divided in different logical categories based on physical constraints, interconnection possibilities and functionality of the blocks. Following

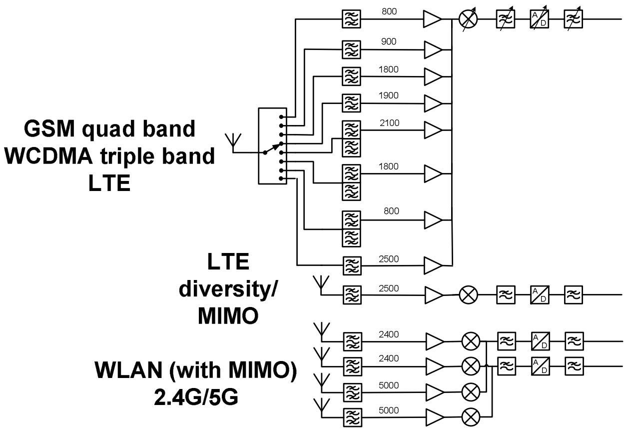

Fig. 4. Receiver architecture with dedicated resources

logical entities, illustrated in Fig. 5, can be identified: RF front-end (RF FE), RF ASIC, baseband (BB), and synthesizer (SX). This division is natural, and reflects the functionalities of the blocks.

In this scheme, RF FE consists of antennas, switches, and RF filters both in RX and TX. RF FE-ASIC interface is the first natural boundary from antenna in design space. Hence any external TX power amplifiers (PA's) and RX low noise amplifiers (LNA's) should be included into RF FE. These RF FE blocks can be interconnected to set of RF ASIC elements that carry out other RF processing functionalities (amplification, frequency conversion, etc) and again RF ASIC blocs can be connected to BB processing entity. Synthesizer (SX) is solely responsible for the generation of LO frequencies for RX and TX chains.

The performance of the logical blocks has to be described sufficiently for the analysis. However, the level of modeling should be kept as simple as possible to avoid excessive complexity. RF frequency analysis is on the top of the analysis. For that reason, RF frequency range and BB bandwidth are the key parameters. In synthesizer, frequency range and frequency step are the most important parameters. Anyhow, the level of modeling is not restricted to these and conventional performance analysis is one of the underlying elements as shown in Fig. 2.

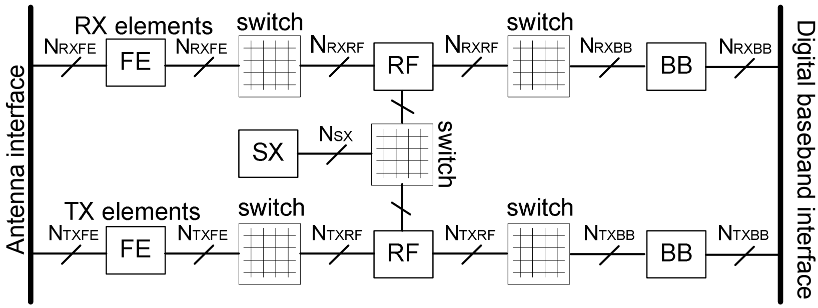

Fig. 5. Logical separation of RF elements

Configuration of RX and TX chains for specific protocol is based mainly on frequency range characteristics of processing elements. Other underlying key parameters like noise and linearity can also be used, if the configuration scheme is built such that it is capable to take into account the clear dependence with these parameters and the RF frequency and bandwidth.

4 RF Resource Management

Our management of HW resources is based on separation of tasks between the resource manager, multi-radio controller and I/O sequencer. The concept is general and designed especially for the management of shared hardware blocks like RF signal processing chains and hardware accelerators.

The resource manager ties radio protocol drivers to the reconfigurable multi-radio platform by mapping RF requirements to platform configurations. Thus, protocol drivers are isolated from the hardware by hiding the actual configuration used in the task execution.

The multi-radio controller does the resource allocation, the configuration management, the scheduling and the policy management needed in managing the RF HW. It also detects and solves spectral conflicts between radios.

An active radio is in one of several radio-specific operational states characterized by its communication behavior and resource usage. Operational states capture the varying resource demands when the radio is performing different kinds of activity (e.g. communicating, scanning, maintaining link, etc). Resource allocation is based on characteristics of radio usage, such as frequency band and RF resource utilization properties. These are used to dynamically determine whether the platform can serve the request. In case of insufficient resources, the request cannot be granted. Extra resources can be used to, e.g., enable MIMO for some radio.

The configuration management finds alternative configurations of real hardware for realizing radio resource requests. It assigns a cost parameter to each alternative configuration based on performance and energy consumption estimates and interference. This enables optimizations in resource scheduling, such as choosing cheaper-to-use resources in good transmission conditions.

The reconfiguration scheduler processes RF utilization requests from protocol drivers and, in conjunction with configuration manager, produces scheduling of hardware resources. The allocation schedules for individual HW resources are maintained pro-actively for the future in the extent that the protocol drivers can predict their workload.

Schedules are maintained by software and their execution is done by sequencing hardware. Considering the software, better than 1 ms reconfiguration response times should be obtainable for new utilization requests. For protocols with sufficient predictability, each RF resource requirement can be processed individually. These include current 3GPP protocols, even in the case of LTE HARQ processing. However, some protocols require considerably tighter response times, e.g., IEEE 802.11. In these cases, instead of allocating RX/TX jobs, potential of RX/TX job execution is allocated.

An example simulation run is presented in Fig. 6, which handles a combination of GSM 1900 and WLAN 802.11g load by using switch topology of Fig. 5. In RX, front-end (rx-feX) and RF (rx-rfX) elements 1-4 are dedicated for the four GSM band, and elements (rx-fe5, rx-rf5) are for WLAN. Baseband elements (rx-bbX) are symmetric. In TX, tx-fe1 and tx-rf1 are used for GSM 850/900 bands, tx-fe2 and tx-rf2 are used for GSM 1800/1900 bands, and tx-fe3 and tx-rf3 are used for WLAN. Baseband elements (tx-bbX) are symmetric also in TX. Signal generators are shared between RX and TX tasks.

As shared resources are utilized, resource conflicts are sometimes unavoidable. This could be due to mutually interfering radio tasks or plainly because of momentarily insufficient available resources. Fortunately, RF protocols are designed

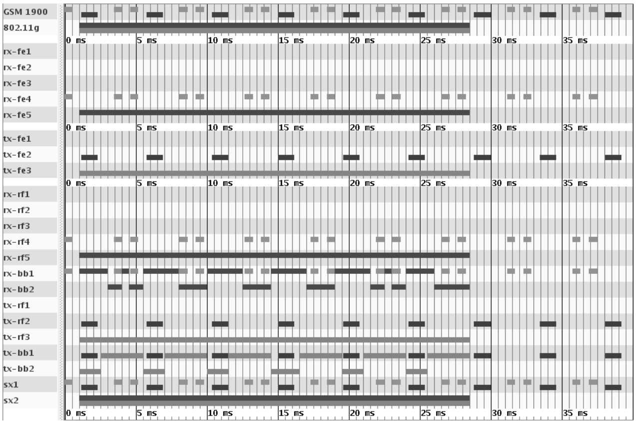

Fig. 6. Example of allocation scheduling. In each row, the upper part denotes allocation for RX tasks and lower part is for TX tasks, respectively.

to tolerate some level of skipped or lost TX and RX transmissions, and therefore, conflicts are acceptable as long as the skip probability is low enough (e.g. $< 1\%$). When conflicts do happen, the priority assigned by the policy manager is used to determine which jobs are skipped.

Finally, as the utilization load is predictable to at least few milliseconds in future, it is possible to almost always find predictable idle slots in resources schedules. This can be used to execute background RF tasks—such as spectrum sensing—and background radio protocols. We expect this functionality to be useful in the next generation cognitive radio protocols.

5 Platform Configuration HW Analysis

Having flexible RF platform allowing run-time reconfigurations and resource sharing it is possible to reduce the number of HW components. Energy consumption does not automatically scale down with the number of required components, but reductions are also possible as described later in this chapter. In general, the possibility to utilize same resources depends on the time domain behavior of the protocols, ability to schedule them, and their frequency bands. For example LTE band 7 and WLAN could in principle share HW resources because they both utilize packet-form transmission and reception and the operating frequencies are close enough (WLAN 2.4GHz and LTE 2.5GHz). However, this may lead to significant data rate reductions if use scenarios are not carefully considered. Here we assume that only one protocol (cellular or WLAN) will transfer information at peak data rate and the other link can be fully functional but will not provide full data rate connection simultaneously.

One of the essential issues in HW platform design is to minimize the area and energy consumption in order to save costs. Once Moore's law ensures the reduction of digital processing RF HW does not scale accordingly. This calls for other means to reduce cost. Cost is mostly linked to the area and thus to the actual numbers of HW block used in the implementation. In addition to this, the energy consumption of the implementation can be regarded as cost. To show the benefits of a flexible reconfigurable RF platform, we analyze different receiver implementation approaches with respect to configurability.

The system portfolio is the following in our analysis: quad-band GSM, triple-band WCDMA, LTE with 2x MIMO capabilities + WLAN 2.5/5GHz with 2x MIMO capabilities. This kind of feature set realistically depicts the required functionality of future receivers.

One can see three HW approaches to construct RF receiver:

1) Fully system-dedicated receiver chain where protocols use only resources dedicated for them
2) More tunable but still frequency selective receiver chain
3) Fully broadband receiver chain

In approach 1, resources are dedicated for the used protocols and thus there is no flexibility. In approach 2, the blocks can be tuned as follows. RF can be tuned between frequency ranges of 0.4-1.0Ghz, 0.8-2GHz, 1.7-2.6GHz, and 2.4-5.5GHz. BB can be tuned to handle all required bandwidths. In approach 3, it is assumed that RF and BB can be tuned to cover the whole frequency range. In all of these approaches, SX frequency range is assumed to be 0.5-5.5GHz. However, it may consist of more than one VCO cores due to restricted frequency tuning range. Cellular requires one SX for RX (+another for TX in FDD modes like WCDMA and LTE). WLAN requires one SX, and both RX and TX can use it.

The receiver presented in Fig. 4 depicts approach 1.The corresponding most flexible implementation utilizing commercially presented technology is presented in Fig. 7.In Fig. 7, the Multi-band RF-FE is similar as in Fig. 4.

We discuss four different classes of worst use cases:

A) Cellular 2G/3G/4G (LTE only at 2.5GHz with MIMO) + WLAN 802.11n (MIMO)
B) Cellular 2G/3G/4G (LTE only at 2.5GHz with MIMO) + WLAN 802.11a/g (SISO)
C) Cellular SISO (2G/3G) + WLAN 802.11n (MIMO)
D) Cellular 2G/3G/4G (LTE only at 2.5GHz with MIMO) prioritized, WLAN (802.11a/g/n) can send/receive packets only if cellular is not allocating traffic (run time reconfiguration is possible if platform construction allows it)

Based on simulations and analysis, the number of HW entities needed to fulfill the required functionality in these approaches is collected in Table 1. The conventional approach 1 results as the biggest HW entity number. Due to the dedicated resources, especially the number of RF entities is significantly larger than in other approaches. Approaches 2 and 3 differ only in the numbers of RF entities. Anyhow, approach 3 can not by default be claimed to be better among these two due to the different kind of characteristics of the approaches. In general, energy consumption is naturally related to the implementation techniques and especially to the bandwidth, the more wideband implementation the more energy it consumes. Fully broadband receiver in approach 3 consumes more power than receiver in approach 2 and is more vulnerable to interferences due to the wideband nature. Thus, the design phase platform optimization is vital when considering tradeoffs like power consumption versus entity count or interference toleration versus number of RF entities. The lowest numbers of HW RF and HW BB entities are reached in use cases where run-time resource sharing is utilized. These cases are shaded and bolded in Table 1. In platform design phase, the block-level energy consumption and interference issues should also be considered in addition to HW entity numbers. In platform usage, the block-level energy consumption and interference are the basis for cost functions on which the most optimal resource allocations are based as described in chapter 4.

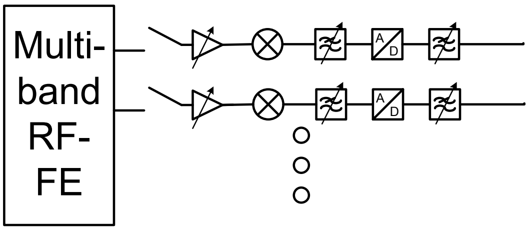

Fig. 7. Flexible receiver

Table 1. Number of HW entities with different approaches and use cases

Approach/Use case	RF	BB	SX
1/A	13	4	2
1/B	10	3	2
1/C	12	3	2
1/D	**13**	**4**	**2**
2/A	5	4	2
2/B	4	3	2
2/C	4	3	2
2/D	**3**	**2**	**2**
3/A	4	4	2
3/B	3	3	2
3/C	3	3	2
3/D	**2**	**2**	**2**

6 Conclusions

In this paper a run-time reconfigurable platform was presented. The approach introduces abstraction concept of the platform that is required to utilize the presented scheduling and run-time reconfiguration schemes.

The run-time RF resource management concept combined with run-time reconfigurable RF platform offers chances to decrease the number of HW entities and also in certain conditions to lower the energy consumption. It offers possibilities to do design-time platform exploration where tradeoffs like number of HW entities versus power consumption can be considered. Most importantly, if enables run-time platform optimization where the most energy efficient platform resource combinations can be allocated for each use scenario.

The presented approach offers new opportunities to bring SDR features more effectively into multiradio solutions. Physical bottlenecks related to certain RF components, like filters, can not be overcome easily. However, efficient scheduling and possibility to protocol independent platform control can allow enhanced complexity and adopt rapidly new improved technologies to minimize cost and power consumption.

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