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A petri nets based design of cognitive radios using distributed signal processing

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Abstract

Reconfigurability for transceivers for wireless access networks like Bluetooth, WiMAX and W-LAN will become increasingly important. An appropriately flexible and reliable software architecture, allowing the concurrent processing of different controlling tasks for wireless terminals will hence be an important asset. Already during the 1980s reconfigurable receivers were developed for radio intelligence in the short wave range and the concept of software radio (SR) was born. A software defined radio (SDR) is a practical version of an SR: The received signals are sampled after a suitable band selection filter, usually in the base band or a low intermediate frequency band. The signal processing in both SR and SDR requires a considerable amount of concurrent processes. Since Petri nets (PNs) are both simple and strong tools for the description and the design of such concurrent processes, it is recommendable to deploy them for SDR. SDRs have paved the way towards cognitive radios (CRs), which are based on SDRs that additionally sense their environments, track changes, and react upon their findings. A CR is an autonomous unit in a communications environment that frequently exchanges information with the networks it is able to access as well as with other CRs. In this communication, the authors will introduce a realization concept for a CR which forms the basis of a hardware/firmware demonstrator developed by the authors. This demonstrator makes use of a digital signal processor (DSP) which forms the core of the design and flexibly programmable hardware accelerators based on field programmable gate arrays (FPGAs). The authors will describe the solution also in view of the recent developments of IEEE 802.22

Keywords: software defined radio (SDR); cognitive radio (CR); controller concept; petri net; reconfigurability

1. Introduction

Reconfigurability of transceivers for wireless access networks like Bluetooth, WiMAX (Worldwide Interoperability for Microwave Access) and W-LAN (wireless local area network) will become increasingly important in the forthcoming decade. An appropriately flexible and reliable software architecture, allowing the concurrent processing of different controlling tasks for wireless terminals will hence be an important asset. Since Petri nets (PNs) are both simple and strong tools for the description and the design of such concurrent processes, it is recommendable to deploy them for software defined radio (SDR) and cognitive radio (CR) concepts [1].

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Reconfigurability in radio development is not a very novel technique [2]. Already during the 1980s reconfigurable receivers were developed for radio intelligence in the short wave range. However, reconfigurability became familiar to many radio developers with the publication of the special issues on software radios of the IEEE Communication Magazine[3],[4].

The authors in [2] refer to a transceiver as a software radio (SR) if its communication functions are realized as programs running on a suitable processor. Based on the same hardware, different transmitter/receiver algorithms, which usually describe transmission standards, are implemented in software. A SR transceiver comprises all the layers of a communication system, in particular the physical layer, usually abbreviated by PHY layer, and the medium access control layer, denoted by MAC layer.

The baseband signal processing of a digital radio (DR) is invariably implemented on a digital processor. An ideal SR samples the antenna output directly. A software defined radio (SDR) is a practical version of a SR: The received signals are sampled after a suitable band selection filter, usually in the base band or a low intermediate frequency band. One remark concerning the relation between SRs and SDRs is necessary at this point: It is often argued that a SDR is a presently realizable version of a SR because state-of-the-art analog-to-digital converters (ADCs) that can be employed in SRs are not available today. This argument, although it is correct, may lead to the completely wrong conclusion that a SR which directly digitizes the antenna output should be a major goal of future developments. Fact is that the digitization of an unnecessary huge bandwidth filled with many different signals of which only a small part is determined for reception is neither technologically nor commercially desirable.

Hence, there is no reason for a receiver to extremely oversample the desired signals while respecting extraordinary dynamic range requirements for the undesired in-band signals at the same time. Furthermore, the largest portion of the generated digital information, which stems from all undesired in-band signals, is filtered out in the first digital signal processing step.

A cognitive radio (CR) is an SDR that additionally senses its environment, tracks changes, and reacts upon its findings [3]. A CR is an autonomous unit in a communications environment that frequently exchanges information with the networks it is able to access as well as with other CRs. From the authors' point of view, a CR is a refined SDR while this again represents a refined DR. Although CR could be realized without SDR, SDR is an important enabling technology and will be regarded as prerequisite for CR in this paper.

In this sense, SDR and CR transceivers differ from conventional transceivers by the fact that they can be reconfigured via control units. Such control units need information about the type and standard of the radio communications link and software modules for the signal processing path in order to reconfigure the receiver properly.

This usually includes a download procedure to obtain some information from the network, the radio communicates with. This download procedure is very vulnerable, because very sensitive data are transferred. An error in the reconfiguration parameters or signal processing software may cause a total malfunction of the SDR. This may include cases where no further reconfiguration is possible due to the fact that no communication to the network is possible anymore because of a disconfigured radio. The reconfiguration has to be a very reliable process for this reason. A side effect of this feature is the possibility to offer a remote diagnosis support for the terminal including remote bug-fixing which could be offered by network operators as well as terminal providers.

In many available publications such as e.g. [4] more or less inflexible implementation platforms or hardware oriented processing architectures for the control unit have been discussed rather than the software architecture and real-time operation of reliable reconfiguration. In [5] the basic idea of reconfiguration in a wireless environment was addressed. The authors discussed procedures which are relevant to the network and the negotiation process for the updating. However, the software architecture and processing schemes inside terminals were not considered in detail.

2. Petri net based master controller

The way of reconfiguring the terminal, in particular the realization of a processor with master controller and a Petri net based approach, which allows concurrent mode of operation, high reliability and secure applications, has not yet been treated. In this communication, the authors propose a viable and new approach for such a reconfiguration. The new approach consists of a master controller which is responsible for a reliable reconfiguration. In addition, there has to be a unit, which can communicate with the network, a PHY and MAC engine. This PHY and MAC engine needs software modules with signal processing algorithms for the data processing path. The third part is a memory, which contains these software modules. The master controller starts a cognitive operation in order to obtain the best reconfiguration and software modules needed for the SDR.

The reconfiguration then consists of linking software modules existing in the memory, and installing them into the SDR to use the software modules in the regular signal processing chain. The master controller works with Petri net based software architecture. It needs a scalable control program by using e.g. Petri net compilers. The implementation and validation of the master controller based concept on a PCB level integration will be done by setting out from currently used demonstrator platforms. It will be implemented in a single chip processor after validation of the PCB level integration.

The key component is the concept of the master controller including the appropriate Petri net based controlling schemes. Some anticipated concurrent tasks are shown in Fig. 1, namely the linking operation, the cognitive operation and the regular operation.

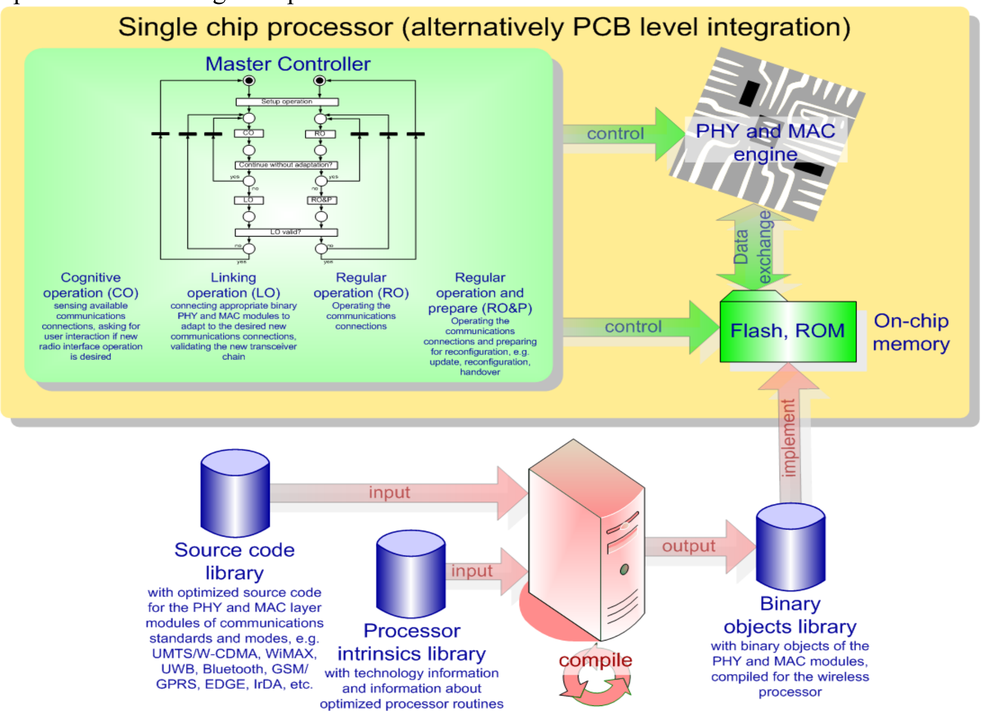

Fig. 1. Concept of the master controller for reliable reconfiguration of CRs

After power on reset, the master controller starts a setup operation. The parameters and software modules for the last used wireless communication standard are then loaded from the single chip processor's on-chip memory into its PHY and MAC engine, which is then the ready to communicate using the wireless communication standards. Then, the regular operation (RO) is started, which operates the communication connections of the device. During the setup operation, the Cognitive operation (CO) is prepared. It operates at the same time as the RO, but it senses for available communication connections. If it has been successful in perceiving a new connection, it asks for user interaction, if the new radio interface operation is desired. The user interaction may be skipped, if the user has allowed this.

In case of a reconfiguration to take place, the linking operation (LO) is started. It connects appropriate binary PHY and MAC modules in order to adapt to the desired new communications connections and it validates the new transceiver chain. At the same time, the regular operation & prepare (RO&P) prepares the system for reconfiguration, e.g. update, reconfiguration and handover, while operating the communication connections at the same time.

The validation of the linked modules is necessary to avoid conflicts which may arise when the linked signal processing path is not able to work properly with the new wireless communications standard and to increase reliability. A complete malfunction of the device may be possible, if no such validation is made. In case of a negative validation, the RO and CO start again as before. No change will be done in the signal processing path. In case of a positive validation a new setup process starts, which reconfigures the SDR starting the RO and CO including the new signal processing path for the newly adapted wireless communications link.

The master controller is Petri net based to simplify the software design, which leads to a better service quality of the controller. Main part of the whole system is the PHY and MAC engine, which runs the software modules for the different wireless modes and standards. It contains a processor for the digital signal processing.

The software modules must be validated with such a PHY and MAC engine before they are released for use in devices by storing them into the memory.

3. Iterative frequency sensing method

As discussed before, cognitive operation in a mobile terminal requires a frequency or a network sensing capability, by means of sensing for available wireless services and systems which can potentially provide service to user equipment. Because of these reasons, frequency sensing is one of the most important issues in cognitive radio. Frequency sensing must be accomplished seamlessly and repeatedly at the user equipment. The implementation has to be done very efficiently to require lowest implementation complexity and to run with the lowest possible power consumption. Hence, an iterative method is recommendable.

User equipment for cognitive radio applications is inherently multistandard/multimode capable. In such user equipment, all frequency bands potentially being allocated to systems and modes which the user equipment can connect to, must be scanned and the available standards and modes must be identified. This scanning of the frequency bands can be done continuously, i.e. persistently which implies dedicated RF-hardware which delivers information about changes in network services immediately. The scanning process could also be implemented discontinuously, i.e. non-persistently, which does not necessarily require dedicated hardware but has the disadvantage of an increased reaction time in the system until changes are recognized.

In the case of a successful recognition the offered services must be identified and the result must be ranked with respect to the provided service classes and the available and offered QOS (quality of service) e.g. based on rate, delay, BLER (block error ratio) and received signal strength. According to this ranking, possible candidate networks providing services to the terminal are identified and user interaction has to be considered, too.

Conventional terminal implementations basically strive for the evaluation of a single standard and single mode at a time. The mode of operation is based on the detection of the radio beacon e.g. BCCH (Broadcast Control Channel) in GSM (Global System for Mobile Communications) terminology associated with a particular standard, including coarse and fine frequency acquisition and cell selection by frame and slot synchronization. To the best knowledge of the authors, decisions made on the available modes or even multiple standards have not been considered yet. An extension of existing algorithms is therefore required to formulate a novel strategy.

The proposed method is user equipment oriented or mobile originated in GSM terminology. This operational step will be included in the cognitive operation of the master controller, which is described in chapter 2. The implementation of frequency sensing can be done centrically in analog domain, digital domain or mixed mode. The algorithm could be implemented in an all parallel version or an all sequential version. The first case is illustrated in Fig. 2.

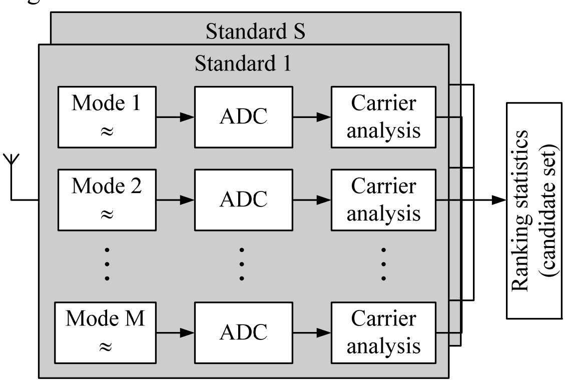

Fig. 2. Frequency sensing method in parallel configuration

The proposed carrier analysis evaluates the energy/power within each carrier and ranks the carriers according to their power. For each mode, the carrier has to be synchronized according to its rank and available service parameters have to be evaluated. A simplification or reduction of complexity could be accomplished by just evaluating the strongest carrier per mode or the ranking of the Z strongest carriers over all modes and standards only.

4 Cognitive Radio Demonstrator Design

A major outcome of the work presented in this thesis is a hardware demonstrator, which demonstrates CR at the example of IEEE 802.22. IEEE 802.22 is a Wireless Regional Area Network communication standard, which is designed to operate in the VHF/UHF bands in parallel to existing TV broadcasting services. Similar concepts were addressed in [6]-[8]. Cognitive operations are necessary for the interference free operation of the broadcasting services, referred to as primary system, and the data communication system, referred to as secondary system, respectively. Without loss of generality, the primary system is chosen to be a digital television standard according to Advanced Television Systems Committee (ATSC), while the secondary communication standard is implemented according to IEEE 802.16e, "Mobile WiMAX".

A principle block diagram of the demonstrator is shown in Figure 3. The demonstrator is based on a Texas Instruments fixed point Digital Signal Processor (DSP) TMS320C6455 running at 1.2 GHz. For hardware acceleration, a commercially available Xilinx Virtex5LX110 platform is attached to the DSP using a Peripheral Component Interconnect (PCI) interface delivering a theoretical peak throughput of approximately 1 GBit/s. The FPGA is connected to a PC which is used for data evaluation and visualization purposes using GBit-Ethernet and USB 2.0. For signal sampling and reconstruction, a self designed mixed-signal board is attached to the DSP using the DSP´s external memory interface. Two Spartan3 FPGAs are located on that board for the implementation of glue logic, FIFO buffering and signal processing tasks, like e.g. filtering. At the receiver side, the incoming signal is downconverted to an intermediate frequency (IF) using a commercially available ATSC tuner. The Tuner module allows carrier frequencies in the VHF/UHF bands. The real valued IF signal is sampled using an Analog Devices analog to digital converter AD6655. This chip is also used to downconvert the signal to complex baseband using a digital quadrature oscillator and mixer. During this step, carrier frequency offsets can be eliminated very efficiently. After some filtering and decimation operations, the signal is fed into the RX-FPGA, which interfaces to the DSP. For signal reconstruction an Analog Devices analog to digital converter AD9957 is implemented on the demonstrator. The converter provides a I/Q interface. After upsampling to a suitable intermediate frequency, the signal is combined resulting in a real valued signal which is digital to analog converted. After applying an analog reconstruction low pass filter the signal is upconverted to the desired carrier frequency. The DSP implements the major part of the physical layer processing. In addition the algorithms for the cognitive operation, i.e. ATSC signal detection is implemented here. The demonstration scenario consists of a WiMAX based signal transmission in a VHF band. As soon as the presence of a primary signal is detected, the demonstrator either changes to an unused band or stops the transmission. The demonstrator is used to evaluate the performance of the cognitive algorithms in dependence of power at receiver antenna. Especially, the probability of detection in case of a non present primary signal and the unsuccessful detection of a present primary signal are evaluated.

5. Conclusions

The present paper introduces basic aspects on the Software Radio and Software Defined Radio technology. Cognitive Radio is defined as an extension to Software Defined radio to enable the exploitation a high reconfigurability as a result of the findings of a coginitve engine. A design methodology for Cognitive Radios is described which is entirely based on Petri Nets and which is a very efficient way to describe concurrent processes. Furthermore, the paper describes iterative frequency sensing method which is a basic prerequisite for cognitive operation. A demonstrator is introduced, which is built up using a combination of DSP and FPGA hardware and which demonstrates the IEEE 802.22 at the example of a primary ATSC signal with a secondary WiMAX data communication.

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