Cognitive Radio for Emergency Networks

Qiwei Zhang, Andre B.J. Kokkeler and Gerard J.M. Smit
University of Twente, Enschede, The Netherlands
Email: Q.Zhang@utwente.nl

***Abstract*— In the scope of the Adaptive Ad-hoc Freeband (AAF) project, an emergency network built on top of Cognitive Radio is proposed to alleviate the spectrum shortage problem which is the major limitation for emergency networks. Cognitive Radio has been proposed as a promising technology to solve today's spectrum scarcity problem by allowing a secondary user in the non-used parts of the spectrum that actually are assigned to primary services. Cognitive Radio has to work in different frequency bands and various wireless channels and supports multimedia services. A heterogenous reconfigurable System-on-Chip (SoC) architecture is proposed to enable the evolution from the traditional software defined radio to Cognitive Radio.**

***Index Terms*— Cognitive Radio, Emergency Network, Spectrum Sensing, OFDM, Heterogenous Reconfigurable System-on-Chip, Montium**

I. Introduction

Recent studies show that most of the assigned spectrum is underutilized. On the other hand, the increasing number of wireless multimedia applications leads to a spectrum scarcity. Cognitive Radio ([1], [2]) is proposed as a promising technology to solve the imbalance between spectrum scarcity and spectrum under-utilization. In Cognitive Radio, spectrum sensing is done in order to locate the unused spectrum segments in a targeted spectrum pool and use these segments optimally without harmful interference to the licensed user. In the Adaptive Ad-hoc Freeband (AAF) [3] project, we design a Cognitive Radio based wireless ad-hoc network for emergency situations. Although the AAF project addresses Cognitive Radio in a complete fashion from physical layer to networking issues, this paper mainly focuses on the physical layer related issues including: spectrum sensing, baseband transmission and physical layer reconfigurability.

A. Related Work on Cognitive Radio

The idea of Cognitive Radio was first presented by Joseph Mitola III in his paper [4], where he proposed that Cognitive Radio can enhance the personal wireless service by a radio knowledge representation language (RKRL). A comprehensive conceptual architecture of Cognitive Radio was later presented in [1], where Cognitive Radio was thought as a final point of the software-defined radio platform evolution: a fully reconfigurable radio that changes its communication functions depending on network and/or user demands.

In November 2002, the Federal Communications Commission (FCC) in the United States released a report [5] aimed at improving the management of spectrum resources in the US. The report concluded that the current spectrum scarcity problem is largely due to the strict regulation on spectrum access. The spectrum measurements conducted by the FCC indicated that only small portions of the spectrum are heavily used while other frequency bands are either partially used or unoccupied most of the time. So, spectrum utilization can be improved by making it possible for a secondary user (who doesn't have the license for spectrum) to access the spectrum which is not occupied by the licensed user (primary user). This secondary user has the awareness of the spectrum and adapts its transmission accordingly on a non-interference basis. This spectrum access and awareness scheme is referred to as Cognitive Radio by the FCC, which is a narrower definition compared with the original concept brought up by Mitola.

Since the concept of Cognitive Radio first appeared, research activities have started around the world. Recently, Cognitive Radio became a very hot topic due to its impact on future spectrum policy which could fundamentally change the current status of radio communication. We mention a few research projects related to Cognitive Radio. In Berkeley Wireless Research Center (BWRC), a dedicated Cognitive Radio Research (CRR) project is in progress. Their motivation is to improve the spectrum utilization by opportunistic use of the spectrum, which is the same as the FCC's initiative. They treat the subject in a complete fashion: from physical layer issues to MAC layer issues and from analog frontend to computing platform supporting baseband processing. Spectrum pooling [6] is investigated by Jondral from the University of Karlsruhe. The basic idea is that a secondary user can dynamically access the licensed band by switching on and off OFDM subcarriers to avoid interference to the licensed user (primary user). The Cognitive Radio project [7] at Virginia Tech. does not specifically aim to improve spectrum utilization. This project is based on the observation that Cognitive Radio distinguishes itself by awareness and learning. In [8], a genetic algorithm based cognitive engine is proposed to learn its environment and respond with an optimal adaption.

B. Requirements for Emergency Networks

Current day emergency services rely for data communications on public radio networks like GPRS. Sometimes in disaster situations, even GSM is used for voice communication between relief workers. However, in case of emergency the public networks may get overloaded. Moreover, the relief network must be able to handle multimedia signals and has to deal with large, possibly unpredictable amounts of data. The use of generally available public networks is not considered to be reliable enough for emergency situations because public networks lack capabilities (e.g. in offered data rates or multimedia traffic support) and are susceptible to the destruction of their infrastructures. If dedicated emergency networks are used, the major drawback is their spectrum scarcity [9] because current emergency networks are assigned with a limited spectrum and fixed bandwidth. However, the large amounts of multimedia data in the emergency networks require a large amount of radio resources. One band can easily get congested due to heavy traffic, which makes it inadequate for emergency use. If several fragmented bands are assigned to emergency use, the interoperability and the lack of standards will become another problem [10]. Therefore to alleviate this spectrum shortage problem, a radio which dynamically accesses free spectrum resources turns out to be an interesting solution.

The first step in the AAF project is to focus on identification of free resources in the frequency domain by spectrum sensing. Subsequentially we identify an OFDM-based system which is theoretically optimal in approaching the Shannon capacity in the segmented spectrum by sending at different rates and powers over each subcarrier. We believe that the capacity to nullify individual carriers poses interesting opportunities for cognition, as was also observed in [6]. Cognitive Radio has to operate in different frequency bands, combat various negative effects of wireless channels and support various multimedia services. Therefore Cognitive Radio needs physical layer reconfigurability. So, we propose a heterogeneous reconfigurable platform to enable the evolution from the traditional software defined radio to Cognitive Radio.

The paper is organized as follows. In section II the system level physical layer architecture for Cognitive Radio is proposed. We will focus on the new features in the physical layer of Cognitive Radio in section III and section IV. A heterogeneous reconfigurable architecture is proposed to support the physical layer reconfigurability of Cognitive Radio in section V. The last section concludes the paper.

II. The Physical Layer Architecture for Cognitive Radio

In this section, we introduce the physical layer architecture (see Figure 1) of a Cognitive Radio node in the AAF network. Within a Cognitive Radio node, three types of functional channels are supported:

- **Sensing Channel** is dedicated for spectrum sensing. It constantly listens to the radio environment and searches for the unoccupied spectrum.
- **Data Channel** is used to exchange the user data. We propose to apply OFDM for data transmission because OFDM could optimally use the segmented spectrum. The detailed discussion on adaptive OFDM for Cognitive Radio is in section IV.
- **Control Channel** is needed for the information exchange between Cognitive Radio nodes. These information includes frequency occupancy information and data control information. We think control channel should be independent of data channel because the dissemination of frequency occupancy information is done on a constant basis. Therefore the transmission scheme of control channel could be different with the normal data transmission. In [11], three options for establishing control channels are mentioned: dedicated spectrum, an unlicensed band such as the ISM/UNII band or unlicenced UltraWide Band (UWB). Several reasons are mentioned why the UWB option is most attractive; no license is needed and an UWB system has low impact on other types of communications.

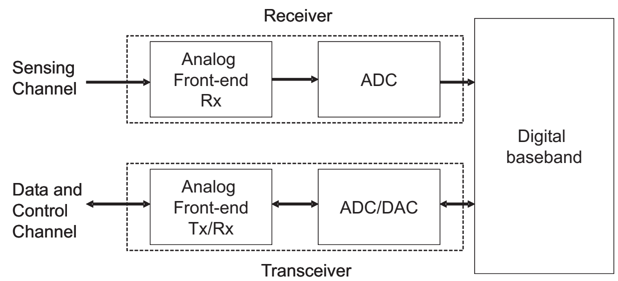

Fig. 1. The physical layer architecture of a Cognitive Radio node

From a hardware point of view, a Cognitive Radio node consists of a dedicated receiver for spectrum sensing which is independent of data transmission and a transceiver for the exchange of data and control information. All digital baseband processing can share the same hardware resource, which is a heterogeneous reconfigurable platform (details are in section V.). The transceiver is connected to the antenna(s) via an Analog Front-end. Received analog signals are converted to digital signals by an Analog to Digital converter (ADC). Signals to be transmitted are converted from digital to analog by a Digital to Analog converter (DAC). The ADC and DAC are conceptually combined into a same block which is connected to the digital baseband. In this paper, our discussions will only focus on digital baseband.

III. Spectrum Sensing

In order to identify the licensed user and locate unused spectrum, the system has to sense the spectrum. So, spectrum sensing is an essential component for Cognitive Radio. Spectrum sensing is not a new topic since a lot of research has been done in the area of signal detection and estimation. Three signal processing techniques are commonly used for signal detection: matched filtering, energy detection and cyclostationary feature detection. Matched filtering is an optimal way for signal detection in communication systems. It correlates the received signal with a *known signal pattern* which maximizes the received signal to noise ratio. However, Cognitive Radio may not have any prior knowledge on the licensed user signal and the strict timing and frequency synchronizations are also required for the coherent detection. Therefore, matched filtering is not an option for spectrum sensing. In situations where not much knowledge concerning the signal is available energy detection [12] is often used to determine the presence of the signal. It measures the signal power at a certain time interval and for a certain frequency band. The detection decision is based on a noise threshold. However, there are limitations for the energy detection are: 1) the decision threshold is subject to changing signal to noise ratios. 2) it can not distinguish interference from signals. 3) it is not effective for spectrum spreading signal whose power has been spread over the wideband.

Therefore, energy detection is not inadequate. Cyclostationary feature detection [13] is used to extract signal features in the background of noise. Since the modulated signal can be model as a cyclostationary process in which signal varies in time with certain periodicities, it contains spectral redundancy information which can be exploited by the analysis of cyclic spectrum. On the other hand, random noise doesn't have periodicity and therefore can be easily recognized in cyclic spectrum regardless of its power level. The advantages of cyclostationary feature detection over energy detection has been recognized in [14]. We think cyclostationary feature detection is a promising option for the spectrum sensing, especially in the situation where energy detection is not so effective. Therefore, we focus on energy detection and cyclostationary feature detection for our Cognitive Radio system. Energy detection and cyclostationary feature detection can be both implemented as DSP algorithms. Here we propose a system level architecture for spectrum sensing (see Figure 2. The detailed theory on these DSP algorithms are skipped, but good reference can be found in [12], [13]. On the system level, energy detection can be implemented as an FFT algorithm, which has a computational complexity of $O(\frac{N}{2}\log_2 N)$ where N is the size of FFT. Cyclostationary feature detection is a combination of an FFT and spectral correlation, which has a computational complexity of $O(N^2 + \frac{N}{2}\log_2 N)$. When large N is used, the processing of cyclostationary feature detection can be prohibitive in terms of performance and computational power. It means that building a dedicated cyclostationary feature detector is simply too expensive. Therefore, our recommendation is that cyclostationary feature detection is a complimentary option when energy detection fails. So in our proposed architecture energy detection can be switched to cyclostationary feature detection by turning on the spectrum correlation functional module (see the dashed box in Figure 2). This option can be supported by a reconfigurable platform where the processing elements for spectral correlation can be switched on/off. A spectrum sensing system with different frequency resolutions, which is achieved by using size-reconfigurable FFT, can also be beneficial in terms of performance and computational power.

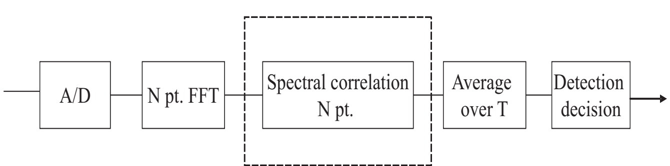

Fig. 2. System level architecture of spectrum sensing with the cyclostationary feature detection option

IV. OFDM Based Cognitive Radio Baseband System

A. Adaptive bit loading and adaptive power loading

Theoretically, an OFDM based Cognitive Radio system is optimal in the sense that it approaches the Shannon capacity in the segmented spectrum by adaptive resource allocation including adaptive bit loading and adaptive power loading.

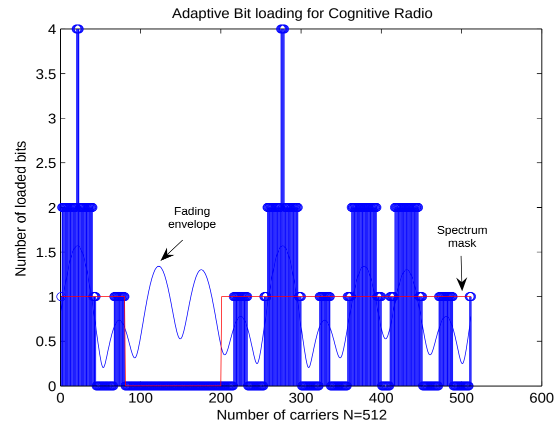

Fig. 3. Adaptive bit loading for Cognitive Radio

Information bits are loaded as different modulation types onto each subcarrier depending on the subcarrier's signal to noise ratio and its availability to Cognitive Radio. Two common optimization methods for the adaptive resource allocation are used. 1) We could maximize the data rate of the system under a certain power constraint. It is formulated as follows:

$$\begin{aligned} &\textit{Max } R = \sum_{k=1}^{K} \frac{F_k}{K}\log_2(1+\frac{h_k^2 p_k}{N_0\frac{B}{K}}) \\ &\textit{Subject to: } \sum_{k=1}^{K} p_k \le P_{total} \\ &F_k = \{0,1\} \text{ for all } k \\ &p_k = 0 \text{ for all } k \text{ which satisfies } F_k = 0 \end{aligned} \tag{1}$$

where R is the data rate; K is the number of the subcarriers. N_0 is the noise power density, B is the band of the interest for Cognitive Radio, h_k is the subcarrier gain and p_k is the power allocated to the corresponding subcarrier. F_k is the factor indicating the availability of subcarrier k to Cognitive Radio, where $F_k = 1$ means the kth carrier can be used by Cognitive Radio. 2) The system power minimization can also be applied under the constraint of a constant data rate. We formulate it as follows:

$$\begin{aligned} &\textit{Min } \sum_{k=1}^{K} p_k = P_{total} \\ &\textit{Subject to: } R = \sum_{k=1}^{K} \frac{F_k}{K}\log_2(1+\frac{h_k^2 p_k}{N_0\frac{B}{K}}) \\ &F_k = \{0,1\} \text{ for all } k \\ &p_k = 0 \text{ for all } k \text{ which satisfies } F_k = 0 \end{aligned} \tag{2}$$

The simulation result of adaptive bit loading is shown in Figure 3. In the simulation, we assume a constant data rate of 400 bits for 512 subcarriers in a frequency selective channel. A binary spectrum mask is given by the higher layer to indicate the spectrum availability, a 1 means the subcarrier is available to Cognitive Radio. The optimization method in eq. 2 is applied to achieve constant data rate and with the power optimization.

B. OFDM baseband processing

OFDM is widely used in current standards such as HiperLAN/2 [15], DAB [16] and DRM [17]. Due to various system requirements and different radio propagations on different frequency bands, OFDM standards vary a lot in the number of carriers and the transmission bandwidth. Table I summarizes

	Hiper LAN/2	DAB II	DRM A	DRM B
Operating frequency[Hz]	5-6G	1.4G	<30M	<30M
Bandwidth[MHz]	20	1.54	0.012	0.012
Used carrier number	52	384	226	206
Symbol time [μs]	4	312	26667	26667
Frame time [ms]	2	24	400	400
FFT size	64	512	288	256

TABLE I
PROPERTIES OF THE DIFFERENT OFDM STANDARDS

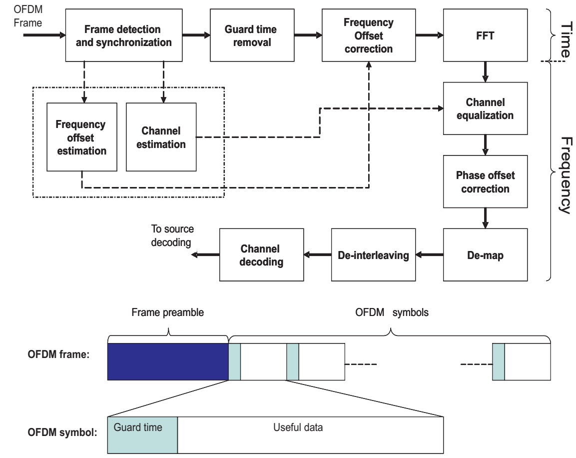

Fig. 4. Basic OFDM processing tasks

the OFDM properties for different standards. Within one standard, multiple modes can be used to cope with various transmission channels by adopting different parameter sets. For example in DRM, Mode A is applied for transmissions over Gaussian channels or channels with minor fading which are typical for ground-wave transmissions (medium wave, long wave). The other modes can cope with more time and frequency selective channels which are typical for sky-wave transmissions (short wave and medium wave at night). As we mentioned, Cognitive Radio can operate in different frequency bands, provide multimedia services with various QoS and cope with different channel conditions, therefore Cognitive Radio is able to adapt to different OFDM systems.

Although there are a lot of differences in various OFDM systems, the basic baseband processing is rather similar. This makes OFDM based Cognitive Radio feasible. An OFDM baseband receiver generally consists of the following basic tasks (Figure 4):

- **Packet/frame detection and synchronization** is used to determine the starting point of an OFDM frame. This is usually achieved by correlating the received signal with known preambles. We also refer to this frame synchronization as coarse synchronization in contrast with the fine synchronization of the OFDM symbols.
- **Frequency offset estimation and correction** are done to remove the frequency offset which destroys the frequency orthogonality of subcarriers. Frequency offset estimation is done on the frame basis in the preamble section (see Figure 4) before data symbols. A frequency correction coefficient determined by the frequency offset estimation is multiplied by each OFDM data symbol.
- **Channel estimation and equalization** are used to correct the frequency selective fading. Due to the robustness of OFDM to frequency selective fading, less complex frequency domain equalization techniques can be used.
- **Guard time removal** is done after the fine synchronization of OFDM symbols.
- **FFT** is the basic component of all OFDM systems which transforms the signal into the frequency domain.
- **Phase offset tracking and correction** correct the frequency offset residual error by using the pilots in each OFDM symbol.
- **De-map** transforms the complex numbers to a bitstream according to their modulation types. Different modulation types can be loaded on each subcarrier by applying adaptive bit-loading as we have mentioned.
- **De-interleaving** is the opposite task of data interleaving. The idea of data interleaving is that the original data is re-arranged at a transmitter in order to reduce burst errors on a receiver. De-interleaving is the inverse operation of interleaving.
- **Channel decoding** exists in all communication systems not only in OFDM systems. However, OFDM is almost always used in conjunction with channel coding to create coded OFDM (COFDM). A Viterbi code is commonly used, but other channel codes such as turbo code or a LDPC code can also be applied. The code rate can be adaptive to provide different degrees of error protection.

For simplicity we only mentioned the tasks performed by the receiver. The transmitter basically does the inverse operations which are less complex. The aforementioned functional blocks can be found in all OFDM systems, but different standards may use different algorithms for each functional block. This means the communication system can select an algorithm to perform each function depending on the requirements of the system. For example, different channel encoders/decoders (codecs) can be applied to achieve different QoS requirements. For a specific algorithm, there are also opportunities for adaptivity by changing parameters of the algorithm. For example the size of FFT and the code rate of Viterbi codec can be tuned by different standards or modes. Therefore a fully reconfigurable hardware platform is required to support the adaptivity of Cognitive Radio.

V. A HETEROGENEOUS RECONFIGURABLE PLATFORM FOR COGNITIVE RADIO

As already foreseen by Mitola [1], a Cognitive Radio is the final point of software-defined radio platform evolution: a fully reconfigurable radio that changes its communication functions depending on network and/or user demands. His definition on reconfigurability is very broad and we focus on a reconfigurable hardware platform which supports Cognitive Radio. In this section, we present a heterogeneous reconfigurable hardware platform for Cognitive Radio digital baseband processing.

A. A Heterogeneous Reconfigurable System-on-Chip Architecture

With the evolution of semiconductor technology, more and more transistors can be integrated on a single chip which makes it possible to build large systems, on a chip level rather than on a board level. This approach is called System-on-Chip (SoC). The reconfigurable platform we propose for Cognitive Radio is a heterogeneous reconfigurable SoC architecture shown in Figure 5. This SoC is a heterogeneous tiled

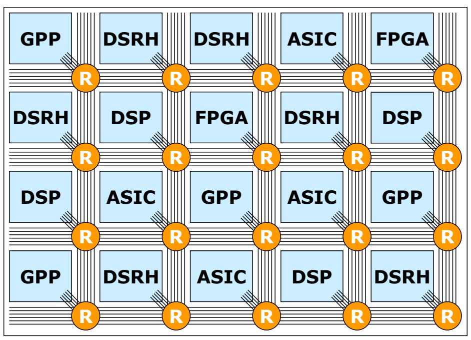

Fig. 5. An example of a heterogeneous System on Chip (SoC). DSRH = Domain Specific Reconfigurable Hardware

architecture, where tiles can be various processing elements including General Purpose Processors (GPPs), Field Programmable Gate Arrays (FPGAs), Application Specific Integrated Circuits (ASICs) and Domain Specific Reconfigurable Hardware (DSRH) modules. The tiles in the SoC are interconnected by a Network-on- Chip (NoC). Both the SoC and NoC can be dynamically reconfigurable, which means that the programs (running on the reconfigurable processing elements) as well as the communication links between the processing elements are configured at run-time. Different processing elements are used for different purposes. The general purpose processors are fully programmable to perform different computational tasks, but they are not energy-efficient. The dedicated ASICs are optimized for power and cost. However, they can not be reconfigured to adapt to new applications. FPGAs which are reconfigurable by nature, are good at performing bit-level operations but not that efficient for word level DSP operations. The Domain Specific Reconfigurable Hardware (DSRH) is a relatively new type of processing element, where the configurable hardware is tailored towards a specific application domain. The Montium [18] tile processor (see Figure 6) developed at the University of Twente, and recently commercialized by Recore Systems, is an example of DSRH. It targets the digital signal processing (DSP) algorithm domain, which is the heart of the wireless baseband processing. In our previous work [19] [20] [21], several DSP algorithms used

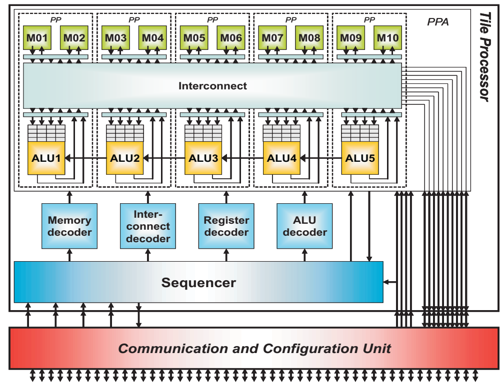

Fig. 6. An example of DSRH: a Montium processor

in wireless communication have been mapped onto the Montium architecture. The implementation results show that the Montium architecture is flexible enough to adapt to different algorithms with good energy-efficiency. For Cognitive Radio devices working in the emergency network, energy-efficiency is really a crucial issue because the battery life of radio devices can be a limitation for successful operations. Therefore the reconfigurable platform we propose not only targets flexibility but also energy-efficiency. In the next section, we will introduce the key element of this platform, the Montium tile processor.

B. The Montium Tile Processor

The Montium is an example of DSRH which targets the 16-bit digital signal processing (DSP) algorithm domain. At first glance the Montium architecture bears a resemblance to a Very Long Instruction Word (VLIW) processor. However, the control structure of the Montium is very different. For (energy-) efficiency it is imperative to minimize the control overhead. This can be accomplished by statically scheduling instructions and using instruction decoders. The lower part of Figure 6 shows the Communication and Configuration Unit (CCU) and the upper part shows the reconfigurable Tile Processor (TP). The CCU implements the interface for off-tile communication. The definition of the off-tile interface depends on the NoC technology that is used in the SoC. The CCU enables the Montium to run in 'streaming' as well as in 'block' mode. In 'streaming' mode the CCU and the Montium run in parallel (communication and computation overlap in time). In 'block' mode the CCU first reads a block of data, then starts the Montium, and finally after completion of the Montium, the CCU sends the results to the next tile. The TP is the computing part that can be configured to implement a particular algorithm.

The Montium architecture has been refined to perform common DSP algorithms used in wireless communication. Besides its flexibility, the Montium is very energy-efficient. By statically scheduling instructions at compile time, the overhead of both communication and control is reduced. A good example, presented in [18], is that a FIR filtering algorithm implemented on the Montium does not change the instructions in 99% of the time. Therefore, the instruction decoding does

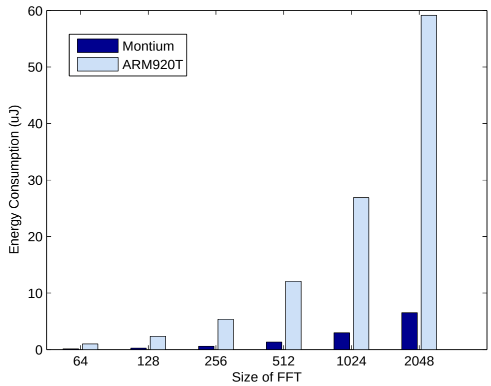

Fig. 7. Energy consumption (in μJ) comparison between the Montium and ARM

not result in excessive switching of control signals. To give a better idea how energy-efficient the Montium is, we show the implementation results of the FFT. This algorithm is one of the most computationally intensive parts, therefore the most energy consuming in OFDM baseband processing and spectrum sensing. It is common practice to implement these algorithms on dedicated ASICs, however this dedicated hardware can not be reconfigured because, for example, the size of the implemented FFT is fixed. The Cognitive Radio we conceive has to be flexible. Therefore a dedicated ASIC is not a solution. The size of the FFT has to be adaptive for the OFDM baseband system. Moreover, spectrum sensing may apply coarse sensing or fine sensing with variable sized FFTs. Let us consider the most common radix-2 FFT. As the size of FFT increases, the computational complexity of the FFT increases on a logarithmic scale because the order of the complexity is $\frac{N}{2}\log_2 N$. So, FFT processing especially for large size FFTs have tough demands for the processor in terms of timing and energy consumption. A general purpose embedded solution like the ARM (a reduced instruction set computer (RISC) processor architecture) is inefficient for these type of applications. According to [18], the execution part of an FFT butterfly takes 21 clock cycles on an ARM920T running at 250MHz while it takes only 1 clock cycle on the Montium running only at 100MHz. Put in a simple way, a Montium is about ten times faster than an ARM. The energy consumption of the Montium is significantly lower than of the ARM, as illustrated in Figure 7. For fair comparison, the ARM implementation is optimized and both implementations are implemented in 0.13 μm technology. If a 1024 points FFT is being executed for spectrum sensing while another 1024 points FFT is required for OFDM baseband processing at the same time, the energy saving of the Montium implementation will be significant compared with the ARM implementation as shown in Figure 7.

VI. Conclusion

In paper, we introduce Cognitive Radio in the context of emergency networks. The physical layer architecture for a Cognitive Radio node is proposed. Our focus on Cognitive Radio is to search for under-utilised spectrum and to (rapidly) adapt transmission settings accordingly to meet various system requirements of emergency networks. Therefore, the research on Cognitive Radio concentrates on frequency sensing and adaptive baseband processing. Cognitive Radio is foreseen as a highly adaptive system since it has to operate in different frequency bands, it has to deal with various effects of wireless channels like fading and shadowing and it has to support various multimedia services. In order to support a flexible Cognitive Radio, a heterogenous reconfigurable SoC platform is proposed, similar to a Software Defined Radio. The key element in the platform, the domain specific reconfigurable hardware(the Montium), enables the reconfigurability in combination with the energy-efficiency.

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