PAR4CR: THE DEVELOPMENT OF A NEW SDR-BASED PLATFORM TOWARDS COGNITIVE RADIO

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ABSTRACT

Today, Software Defined and Cognitive Radios have become very attractive topics in the wireless communications arena. Such a system supports the coexistence of many communication standards inside a single device while still providing a highly flexible solution that is seamlessly reconfigurable and adjustable in order to adapt to a changeable environment. Par4CR is a European project that targets the development of cognitive radio. It is a cooperation program based on the knowledge exchange between seven partners from Industry and Academia. The purpose of this research activity is to analyze in details the current situation on the Software Defined Radio (SDR) from the physical layer point of view and to investigate the impact of recent and future technologies in the materials, elements and system areas in order to enable a smooth transfer from SDR to Cognitive Radio (CR). The main focus of the investigation is aimed at the evaluation of the system performance by means of behavioral model description. The methodology and main functions of this approach are described in this paper.

1. INTRODUCTION

The number of different wireless standards and wireless communication systems is rising at a high pace in order to support users' increasing demands for voice and data communication. The need for interoperability in multi-standard environments leads to a demand for highly flexible front-ends, given each wireless standard has different physical layer specifications compared to others wireless standards.

As a result, the frequency spectrum is becoming increasingly crowded. However, since instantaneous spectrum use is subject to change, the use of temporarily available white space in the spectrum becomes more interesting. In order to address these demands, a flexible radio solution called cognitive radio (CR) is being investigated worldwide. Based on its enabling technology, software defined radio (SDR), CR has to be able to detect and utilize unoccupied frequency bands, in order to increase the spectrum (re-)use. Ultimately, CR allows for multi-mode operation in a multi-standard environment, based on a single, reconfigurable architecture. This highly flexible system has to compete with a single standard radio, while at the same time, offering a very high flexibility.

Par4CR, the Partnership for the Development of Cognitive Radio, is a four-year European project (FP7-IAPP framework) that has started in October 2009 and brings together seven major partners from industry and academia, to investigate possible solutions for an SDR-based platform towards CR. From industry: NXP Semiconductors, France; IMST GmbH, Germany; Catena Holding, the Netherlands and Sweden, and from academia: Eindhoven University of Technology, the Netherlands; ESIEE, France; ITE, Poland and TNO, the Netherlands. Based on knowledge exchanges between industry and academia, and vice versa, ongoing work at the partners is combined and applied to the development of a structure for cognitive transceiver architecture.

The project structure contains seven work packages. In WP1 the general project strategy and the roadmap for the project have been identified. Par4CR will target cognitive radio for a wide frequency range from 50 MHz to 5.8 GHz. This frequency range includes communication standards like audio/video broadcasting (DAB, DVB), voice-oriented technologies (GSM 900/1800, UMTS, LTE), and data-oriented technologies (Wi-Fi, Bluetooth, and WiMAX). Each of these standards has specific bandwidth and transmitted power requirements that have to be taken into account.

Based on the identified project strategy, three work packages (WP2, 4, and 6) have started. Each of them is dedicated to one of the main system stages: Transmitter, Receiver, and Antenna. Since the antenna of the cognitive radio has to cover a wide range of frequencies, and since it influences both the transmitter and receiver part, this is a separate work package. Based on in-depth studies of the general system specifications and the identification of road blocks in each of these work packages, implementation and validation of the designed elements will take place through WP3, 5, and 7.

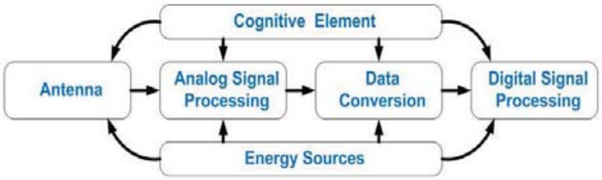

Figure 1. Main project focus points.

Based on the project strategy, derived in WP1, common stages for the transmitter and receiver have been identified. This has resulted in several focus points for the CR-platform, as depicted in Figure 1. The central line of the system consists of four stages: antenna, analog signal processing, data conversion, and digital signal processing. Cognitive features (indicated by the cognitive element in Figure 1) need to be incorporated in every stage of this central line in order to provide flexibility. In addition, Par4CR also covers the green aspect of technology, thereby targeting the minimization of the energy consumption of the complete system through optimal distribution of the energy sources.

The goal of the project is the development of a new SDR platform towards CR, based on a cognitive transceiver (CT). The CT is a flexible system with an SDR-based physical layer and with cognitive elements on the MAC/Network layer. The flexibility, provided through these cognitive elements, will allow the system to operate with maximum efficiency in a highly variable wireless environment.

The described work packages cover the various blocks depicted in Figure 1, both in a bottom-up and top-down approach. Studies take place at general (top-down) architectural level (see also Sections 3 and 4), but also at more detailed (bottom-up) level, such as filtering, matching networks and beamforming (see Section 5). The combined studies, at various levels in the system, will enhance system performance of the overall system solution. In the context of Par4CR, the CT is defined as follows:

A Cognitive Transceiver is a flexible radio system that transmits and/or receives (and fully processes) a number of ***N*** *wireless links in a wideband frequency range, and performs the cognition of the frequency spectrum environment in order to adjust itself accordingly*.

Ideally, the CT is a standard-independent system that can easily adjust itself to any wireless environment and reconfigure its hardware/software for the best performance. It is energy efficient while, at the same time, it provides sufficient quality of service (QoS).

Several technologies are available for the components in the CT. Currently available technologies may pose physical limitations for the implementation. Emerging technologies may provide the missing link for some components in the architecture. Possible technologies have to be properly identified and assessed in order to evaluate their impact on the system performance and to arrive at a feasible solution for the CT.

The rest of the paper is organized as follows. First, we will discuss the system requirements specified for the future flexible system in Section 2. After, we will present the CT design model in Section 3. The system architecture for the CT considered in this project will be described in Section 4. In Section 5 a more detailed description of parts of the architecture will be given and critical blocks will be identified. Finally, in Section 6 a discussion of the approach will be provided, together with an outlook to future work.

2. SYSTEM REQUIREMENTS FOR THE COGNITIVE TRANSCEIVER

In this section, the main requirements for the CT from a multi-band system point of view will be described. According to definition of the CT given in Section 1, system requirements can be split into two general groups: flexibility related and cognitivity related.

The first group is dedicated to the multi-band nature of the system. These requirements characterize the specification for the standards that can be processed by the system, for example, modulation type, bandwidth, system sensitivity, Noise Figure, Gain, and VSWR. In principle these requirements can show the performance of the system. This group is very important for the system design and for the choice of the basic system architecture. These requirements are derived from standards specifications for the signal transmission/reception via calculations. Following the top-down approach it is possible to define values for the system in general and to distribute these among contributing elements. The specifications for the standards (from the User Equipment (UE) point of view) which are under consideration can be found in Table 1.

The second group relates to the requirements that must satisfy the cognition part of the systems, such as spectrum sensing, white space identification, resource management, and reconfiguration decisions (e.g. sensing time, identification algorithms).

To satisfy the requirements listed in Table 1 we need to design and evaluate every part of the system in details, which is very time-consuming. Instead we intend to model the system elements by introducing describing functions that characterizes their behavior very accurately [1].

Table 1. General Specification of considered Wireless Radio Technologies.

WRT/Specs	Access/ Duplex	Modulation scheme	Bands, F_L–F_U, MHz	Allocated BW, MHz	P_{TX} dBm	Sensitivity dBm	SNR, dB
DVB	C/OFDM	QPSK, 16QAM,64QAM	174-750	280	N/A	-90	13/18
DAB	OFDM	DQPSK	174-240	66	N/A	-81	16
DECT	TDMA/TDD	pi/4 shift DQPSK	1881-1897	15	26	-86	12
GSM900/1800	TDMA or FDMA /FDD	GMSK	UL:880-915/1710-1785 DL: 925-960/1805-1880		33	-104	8/12
UMTS/LTE	WCDMA or TDMA/ FDD or TDD	QPSK	UL:1920-1980 DL:2110-2170	60	24/33	-117	7.7
IEEE 802.11	CSMA/CA or OFDM	BPSK,QPSK, 16QAM,64QAM	2400-2483.5 5120-5350 5470-5725	83.5 230 255	29	-82	5/22 3/8
IEEE 802.15.3	FHSS/TDD	GFSK	2400 -2483.5	83.5	20	-70	16
IEEE 802.16	OFDM or S-OFDMA/ FDD or TDD	BPSK,QPSK, 16QAM,64QAM	2300-2690 3400-3800 5120-5250 5725-5850	390 400 130 125	23	-92.9 (3.5MHz QPSK ½)	5/20

3. COGNITIVE TRANSCEIVER MODEL

As indicated in Section 1, the development of the SDR platform is mainly based on synergetic effects from knowledge exchanges between project partners from industry and academia. However, the developments and approaches obtained in this way may be technology dependent, or based on technology available at a specific partner only. In order to develop the models in platform in a technology-independent way, or to remove uncertainties related to specific technologies, their effects have to be accounted for. For this purpose, it is useful to create *behavioral* models that are able to describe possible solutions for system components while decoupling them from a specific technology.

In this project we are targeting on two main models: Performance and Power. The performance model evaluates the system behavior from the signal point of view. The power model addresses the estimation of the power consumption/dissipation. This is important for UE where battery life plays a significant role.

The performance model includes five main elements (as depicted in Figure 2): the cognitive element, the antenna, the analog signal processing, data conversion, and the digital signal processing. Each of these stages has its specifications and parameters. We describe every element below in this section.

In most of the cases in literature, the analog stage (particularly RF Front-end) is considered as the main ingredient of the behavior system model and the remaining elements get little attention [1]. In our modeling approach we target the complete system by investigating solutions for all the elements depicted in Figure 2. Details for each of these will be given in Sections 3.1 – 3.6.

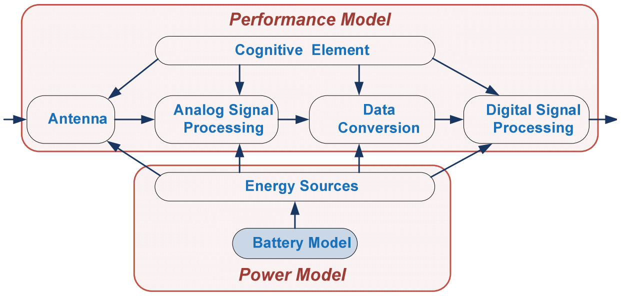

Figure 2. Overall system design model of the CT.

In order to start modeling several assumptions have to be made. As described in Section 2, general requirements for the system can be derived from the standards specifications that in turns constraints the system model. As shown in Table 1, eight different standards are under consideration in this work. The frequency range to be covered is from f_L = 174 MHz (lowest frequency of DVB/DAB band) till f_H = 5850 MHz (Highest frequency of WiMAX Band). This gives us a total system bandwidth which is much wider than any BW of the processed signals.

General properties that are relevant for the system model are presented in Table 2.

Table 2. General system parameters.

Constraint	Symbol	Unit
Lowest frequency	f_L	Hz
Highest frequency	f_H	Hz
System bandwidth	BW	Hz
System Latency	τ	Second
System Noise Figure	NF	dB
Sampling rate (accuracy)	n	Samples/second
Spectrum Efficiency	η	Bit/Hz
Selectivity	S	dB
Computational time	T	Seconds
Data rate	R	Bit/second
Battery power	E_{bat}	Joule

3.1. Antenna

The antenna plays a significant role in the system design. It forms the interface from the CR to the communication network. Ideally, the antenna acts as a multi-mode antenna, which is able to operate within the whole frequency range of interest with sufficient bandwidth. This requires the investigation of new, and possibly reconfigurable, antenna concepts. In order to assess the antenna efficiency with respect to the CT, main design parameters of importance are, for instance, the bandwidth, and the return loss (or, equivalently, VSWR) versus operation frequency. An optimal solution has to be found with respect to these parameters. In addition, specific antenna parameters such as polarization and radiation pattern are related to the geometry and the antenna type and depend on the frequency. These have to be considered as well.

Furthermore, the antenna configuration has to allow for future functionalities of a CR system such as the possibility for MIMO or beamsteering. For the moment, these techniques are under investigation for base station or access point applications (see also Section 5.3), but for future UE applications, they may also become relevant.

3.2. Analog Signal Processing – Front End

This element is a core of the entire system, particularly because of the very demanding flexibility requirements in CT. This element might include blocks as amplifiers, matching networks, RF filtering, frequency synthesizer and mixers.

General metrics that allow for evaluation of system performance are noise and linearity [3]. The effect of noise can be evaluated via calculations of the Noise Figure for every element involved in the signal processing chain.

A measure of linearity can be obtained by taking non-linear effects of each block into account. Non-linearities are detrimental to the system performance. Every electronic device has inherent non-linear behavior. In some cases this behavior is desired (e.g. mixer), but in most cases non-linear effects are not and their influence on the performances must be considered.

The behavior model of this element includes non-linearity in order to consider these effects and observe the system performance in the presence of multi-tone signals (blockers from crowded frequency spectrum). The non-linear effects can be quantified by metrics such as 1dB compression point, inter-modulation products (in particular third-order products and cross modulation products) and gain.

Memory effects also affect this Analog Signal Processing element and should be included in the advanced model [4]. Constraints on the Analog Signal Processing element are directly related to the Data Conversion and can relax or increase the requirements of this last element.

This element will be further discussed in Section 4.

3.3. Data Conversion

The choice of the data converters is determined via dynamic range, sampling rate, resolution and power consumption. However, there is a tradeoff between these parameters. It is important to find the best combination in order to reach an optimal system performance for the given configuration. To model the behavior of this stage we refer to [1][5], where it was shown that fundamental physical limits can constraint a general model in sense of dynamic rage and number of bits.

3.4. Digital Signal Processing

The choice of the system architecture to model this element is quite complicated since it has to define the proper combination of available processing engines such as General Purpose Processor, Field-programmable Gate Array, Application-Specific Integrated Circuit and Digital Signal Processor. There are many solutions available for the processor architecture and there is no common one which will perform with acceptable quality for every given communication protocol [5]. Therefore, the model has to describe the general DSP behavior and has to track different combinations between processors. In this way, we can define main design parameters derived from the system performance and map them accordingly to the available technology solutions in order to see which one performs best within given environmental settings.

Moreover, a well-chosen balance between performance and power consumption needs to be achieved.

3.5. Cognitive Element

To a certain extent cognitivity has to be present in every element described before. It also influences the performance model and power model, since it requires extra energy resource to perform, for example, spectrum scanning, or reconfiguration of the baseband processors' architecture according to the available air-interface parameters. The behavior of the CE in total can be described via set of functions. These functions are: spectrum sensing, multiuser detection, pre-coding and beamforming [7]. Within the scope of the Par4CR, we consider all functions of the CE and will define the most efficient way to evaluate their impact on the system performance.

3.6. Energy Sources

For the analysis of the energy source performance analysis we define the power model for the overall system. In addition, for the UE we have to consider the battery model. A comprehensive analysis for the power models of every element for the Analog Signal Processing and Data Conversion was given in [8]. We adapt these models and apply them according the proposed CT architecture. Furthermore, energy models for the DSP and the antenna and the impact of the cognitive element have to be added.

4. SYSTEM ARCHITECTURE ANALYSIS

In this section we present a possible CT architecture and the reasons that have led to this choice. Furthermore, we will discuss critical blocks in this architecture that have an influence on the overall system performance.

One of the main functions of an SDR-based transceiver is to be able to provide reconfigurability among various wireless links by means of selection of a specific frequency band. This function has to be supported by well-designed filtering networks and/or by a highly selective amplifying system. Also a support for the smooth transfer to CT will require a wideband functionality of the transceiver, while, at the same time, maintaining a high overall system efficiency.

The candidate SDR-based transceiver architecture must also provide reconfigurability freedom in order to receive/transmit from/to a specific frequency band with *any* channel bandwidth carrying any modulation scheme. Moreover, while maintaining power efficiency, the SDR-based transceiver must provide good quality of service like fast radio link establishment and as long as possible talk time.

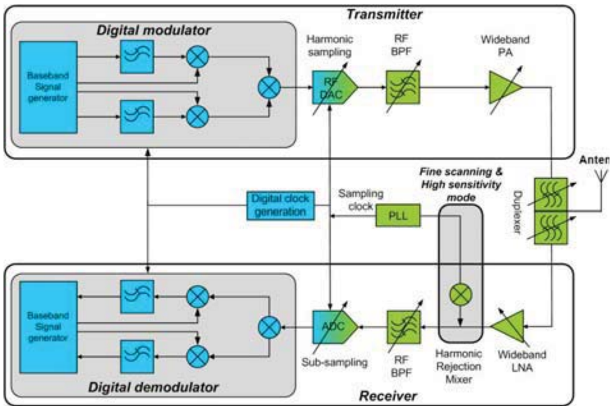

Figure 3. General system architecture.

There are several main requirements that the CT must satisfy, in order to coexist with available systems without disturbing them:

- flexibility: the CT has to be able to handle a wide variety of modulation standards, each with specific characteristics, such as the Peak-to-average power ratio (PAPR);
- agility: the CT needs to be able to quickly select unoccupied frequency bands, or switch between frequency bands for secondary spectrum use.
- ruggedness: the CT has to be robust with respect to power handling, since it has to operate within various standards requiring various power levels;
- linearity: the CT has to be highly linear in order not to create spurious spectrum content;
- frequency selectivity: once the CT has chosen a frequency band, it needs to be very selective and satisfy the spectral masks for both the transmitter and the receiver;
- power efficiency: the CT has to be power efficient, in order to facilitate battery operation. In addition, the CT has to support various output power levels, which differ per standard;
- sensitivity: CT must be sensitive enough to be able to distinguish signals, sometimes even around the noise level, as it can be seen in WCDMA where the signal is spread till the level of noise.

Different RF transceiver architectures are possible for a cognitive radio system [5] . From reconfigurability point of view, blocks with the most challenging requirements are located at the interfaces from/to the antenna (i.e. filtering, matching networks and amplifiers) and at the digital/analog domain (i.e. ADC/DAC converters). Performance requirements for front-end and converters are linked together. For example, relaxing filtering requirements (e.g. quality factor) leads to tougher converter requirements for converters (dynamic range for blockers in RX, TX noise in RX band).

From a CMOS integration point of view, analog filtering located at IF frequency domain is bulky, and will be more and more expensive with the most advanced CMOS process nodes. Moreover, when adding programmability, this drawback is even worse. Therefore, removing the IF filtering from analog domain would be beneficial. This means that the channel selection will be done in the digital domain of the receiver. Drawbacks of this approach are that a higher dynamic range is required from the data converter, and that the required quality factor of the filter networks will be higher than in a regular architecture.

A possible architecture for user equipment that may satisfy these requirements is depicted in
Figure 3. The receiver part is based on RF sampling [9] and includes a switchable mixer. This mixer is switched ON only when the connection with a Base Station (BS)/Access Point (AP) is established and data transmission has started. Of course, the activation of the mixer depends on the dynamic range requirements and the carrier frequency of the standard supported by the free channel. If connection QoS cannot be guaranteed, then mixer is required. Thus, the main purpose of this mixer is to optimize the ADC power consumption while the receiver continues to receive properly the desired signal located at a high carrier frequency. The harmonics rejection nature of the mixer (HRM) is to relax the RF filtering requirements concerning the blockers/noise located at multiple harmonics of the LO signal [10].

A main advantage of the proposed architecture is that only a single mixer is needed in the analog domain in the receiver. In this way, I/Q signal matching requirements for the demodulator are easily met in the digital domain.

In the same way, the transmitter has an up-mixer connected to RF DAC output without IF reconstruction filter to remove bulky elements [11][12]. A proper sampling frequency together with well-tuned RF bandpass filtering can remove the images. The usage of the mixer can be explained as follows. When the RF DAC (used in sub-sampling without mixer), is running at a rate far from the carrier frequency of interest (which means that an image of high order has to be kept), the SNR is possibly very low. This is not especially an issue for the signal to be send, but potentially a problem of TX noise within the RX band (because the desired signal has to be amplified a lot to meet the output power requirement specified by the standard) and possibly the TX spectral mask is not met. Addition of the mixer will help to improve the SNR by selecting an image of lower order. Then the TX mask can be respected and the duplexer filter attenuation from TX to RX requirement can be relaxed, as signal has to be less amplified in order to reach targeted output power.

In order to establish a connection with a BS/AP, the CT will follow a two-step procedure, thereby utilizing two different transmit/receive modes.

1) Spectrum Sensing: in this step, only the receiver is activated (bottom part in
2) Figure 3), without the harmonic rejection mixer. Based on a spectrum sweep with a broadband tunable filter, the system will perform a coarse scan of the spectrum. By means of the power detection and signal processing, it will determine the locations of white spaces in the spectrum that are relevant/possible for the cognitive radio.
   From the RX side, the mixer is deactivated during sensing because we need more of the power detection/spectrum to analyze. Therefore, the dynamic range of the ADC can be lowered, allowing the sampling rate to be higher to capture a large part of the spectrum at once. Consequently, the RF filter must be tuned to accept a wider frequency bandwidth. In this case, sub-sampling becomes interesting in order to avoid using a too high sampling frequency.
3) Data Connection: In the second step, both the transmitter and receiver in

4) Figure **3** are activated. First, based on the identified spectrum white space(s) in step 1, the system will check the spectrum again, using a finely tuned filter, to determine the exact frequency band and channel of the white space. Next, it will try to confirm the spectrum availability with the BS/AP that controls the cell. Once this has been achieved, both the transmitter and the receiver will be configured for the selected frequency band and channel. In the receive part, a harmonic rejection mixer will then be included into the receive chain in order to reduce the power requirements on the tunable ADC.

There is a trade-off between a power consumption and dynamic range of ADC/DAC. Indeed, for instance concerning the RX part, ADC survey [13] illustrates that the high SNDR with high bandwidth requirement leads to high power dissipation which is not compatible with handheld devices from Mitola's SDR point of view [14]. So, it means that the power consumption is too high in case of high carrier frequency (5.8 GHz for instance) while targeting high dynamic range due to remaining blockers which are not removed by an RF filter with limited Q. It must be kept in mind that the CT might work within a very aggressive environment. Naturally, in order to get long talk/data exchange time, it is required to reduce the ADC sampling rate as much as possible.

Regarding the cognitive behavior of the CT, a fast scan is needed to check available frequency bands. As the device is doing this only periodically (not continuously), a fast and high consuming ADC capturing large frequency band in sub-sampling can be used. In this way, the average power dissipation is not too high. Fast scanning is desired to get fast information on the available networks or white spaces.

The building blocks of the architecture in Figure 3 have to be flexible enough to provide high linearity and low loss. This also affects the passive stage elements which are presented by matching networks and filtering systems. Important functions of these building blocks are the following:

- to guarantee sensitivity of the system by limiting the noise bandwidth;
- to guarantee the selectivity of the system (coexistence) by a tight passband in order to achieve rejection of undesired signals and to reduce requirements on subsequent blocks in the architecture (e.g. dynamic range and sample rate requirements in the ADC);
- to prevent aliasing during the ADC process;
- to relax the requirements on the power consumption of ADC due to high dynamic range.

Furthermore, depending on the mode the CT is in, different requirements in terms of tuning range and flexibility are imposed on the architecture.

The elaboration of active parts in a CT is frequently addressed. Our work emphasizes the relevance of RF filter tuning and the duplexer challenges. The matching networks and filtering systems have to be very flexible/adjustable. In the next section, the flexible matching networks and filtering systems will be considered.

5. SYSTEM COMPONENTS

In this section we highlight several system components that are currently under investigation. The need for flexible matching networks and filtering systems has been indicated in the previous section. Additionally, the possibility for techniques based on multiple antennas is considered.

5.1. Flexible Matching Networks

In this subsection we investigate the state-of-the-art on matching networks and sum up critical variables that influence the CT model. We summarize available technological solutions for the Flexible Matching Networks (FMN) with main focus on SDR-based applications and CR. First, we consider requirements for FMN that have been derived from the previous section on the transceiver architecture. Next, we give an overview of existing solutions for a high reconfigurability which leads to the flexibility of the system.

The mechanisms for FMN can be divided into continuously tunable systems and switchable systems, depending on the application. The SDR applications require, in principle, fast switchable matching networks (critical for high data rate applications), that are able to work in a specified frequency band. In contrary to SDR applications, CR-based systems must be continuously tunable and able to operate in a wide frequency range in order to provide continuous spectrum scanning and seamless links handover. The main goals for the development of FMN are:

- to provide impedance matching for a multi-standard environment, which is needed, for instance, for limiting losses, for transmitter power efficiency, and for receive sensitivity. There are many research works that have achieved very good results for tunable matching networks within one particular standard [15]. In our work, we consider a multi-standard wireless environment. Therefore, the goal of FMN is to be reconfigurable, both intra-band and inter-band, for a wide range of wireless applications;
- to reduce power dissipation in order to achieve low losses (below 1 dB). The losses significantly affect the total power efficiency of the CT;
- to provide high isolation between the transmit and receive chain, which would deteriorate the receiver sensitivity;
- to minimize the filter footprint (chip area).

This leads to the need for highly linear and lossless matching networks. Moreover, FMN have to satisfy power requirements, derived from the description of standards. One of the important challenges for the transmitter is the output power, which equals 35 dBm for GSM handset applications, for instance. From the receiver perspective, the required sensitivity level is also quite challenging, for instance −117 dBm for UMTS. This obliges FMN to have very reliable and highly efficient tuning elements. In the past few years, many solutions have become available for FMN, which are based on different approaches for the tuning element. The following solutions from literature seem to be suitable:

- *Varactors* are more preferable for Power Amplifier output matching networks. These varactors can be fabricated based on RF MEMS technologies, having low insertion loss (IL) and a wide tuning range; Ferroelectric/BST with a high switching speed and input power level up to 30 dBm [16] and loss about 0.36 dB [17]; GaAs technology that allows to achieve a tuning range of 9 : 1 with a Q of about 50 at 2 GHz frequency [18];
- *Switches* can be implemented on the receiver side for the LNA input-impedance matching networks with GaAs HEMT or SOI/SOS CMOS technologies. These promise to support a frequency range from dc to 3 GHz and provide a figure-of-merit (FOM) by the R_{on}-C_{off} product down to 448 fs [19] resulting in a loss of 0.34

dB. Capacitive MEMS can provide IL of 0.32 dB and isolation of 33 dB at 2 GHz but they may have actuation voltages up to 80 V [20] and are preferred for use above 2 GHz;

- *Capacitors* are implemented as Digital Tuning and manufactured in a CMOS-on-Sapphire technology can achieve R_{on}-C_{off} of 500 fs [21]. Covered frequency bands are from 698 MHz to 960 MHz and from 1710 MHz to 2170MHz. A mismatch loss of 0.5 dB is expected, with VSWR of 2:1, and IL for low range lies between 0.6 and 0.4 dB, for upper range between 1.5 and 0.4 dB.
- *Transmission lines* with main accent on distributed RF MEMS (DMTL) [22]. The design is based on a cascade combination of DMTL sections into one device. The basic element that provides tunability is a tri-state RF MEMS switch. An actuation voltage of 32 V is needed for switching. Such a network is able to cover a frequency range from 5 GHz to 22 GHz with a finite number of perfectly matched impedance values and with a transducer gain better than 1 dB.

As can be seen, there are many technologies for the tuning element, each possibly leading to a solution that satisfies the requirements. However, there is a trade-off between, on the one hand, a narrowband FMN, which requires very precisely tunable elements (high *Q*), and, on the other hand, a wideband FMN requiring good performance over a very large frequency range. This leads to a combined architecture of the FMN with a number of constructive elements that in turn can be tuned accordingly.

The choice of the particular technology for the FMN must be done after an extensive study. Since the goal of the *future* CT is that it has to be able to operate in a highly dynamic environment, we have to take into account the effect that novel technologies will develop to a mature level within the next decades. This will give us a possibility to evaluate the future system performances with respect to the technology's growth. Therefore, we consider RF MEMS technology as a good candidate, although their drawbacks (reliability, power handling) are to be investigated.

Moreover, the trend towards nanoelectronic systems, which have a good perspective for CMOS integration, is one of the possible future directions.

In terms of the system design model we need to identify main variables that impact on the overall performance. In principle, this stage of the system should behave as a linear function while still providing wide tuning range, but it can lead to high-order non-linear impedance characteristics. Moreover, for the transmitter side, the use of varactors seems to be the most perspective solution due their resistance to high incoming power and superior linearity, reliability, capacitance tuning speed and *Q*, however their non-linear behavior still has to be considered in the system model via Volterra series.

For the design process of the FMN we consider following parameters: effective capacitance tuning range; control voltage; insertion loss and isolation (evaluated via R_{on}-C_{off} product); linearity that is especially critical for wideband applications.

The next step in the design process is to choose the flexible network topology. In our system behavior model we intend to track the impact of the different topologies on the system performance through the parameters mentioned above. This approach allows us to find the most appropriate solution for FMN that meets the SDR requirements.

5.2. Filtering System

In the context of CR applications, RF filtering presents more constraints than any other filtering stage in transceiver architectures.

This section will focus on RF filtering requirements and will present some available technological solutions. First consider the different characteristics of RF band-pass filters required in the CT architecture in

Figure 3. It is important to emphasize that the precise role and specifications of the RF band-pass filters may vary, depending on the regulation, on the standard requirements, on the architecture of the transceiver, and also on the duplex scheme. Among the important parameters that influence the RF band-pass filter's specifications and the choice of the filtering technology are: frequency bands (filter's central operation frequency), allocated bandwidth (filter's bandwidth), transmit power (filter's power handling for the transmitter case where the RF filter follows the PA), output RF spectral mask (linearity), limit on spurious emissions, and adjacent channel interference (filter's out-of-band rejection). Furthermore, low insertion loss, good temperature stability and high integrability are also required from the RF filters. Because of technological limitations, a single reconfigurable RF filter in the transceiver cannot fulfill all RF filtering requirements. A filter bank including continuously tunable filters, covering different frequency bands seems a possible solution. Tunable RF filters are necessary for reconfigurable front-ends that can support several standards and applications.

A challenge is to achieve tunable filters that can be integrated on-die. For this reason, some available RF filtering technologies like ceramic filters, surface acoustic wave (SAW) filters, bulk acoustic wave (BAW) filters and low temperature co-fired ceramic (LTCC) filters are not considered in the scope of this project. LC filters can support high frequencies and can be integrated as a System-on-Chip. However, their main drawbacks are that they require too much area and offer only a limited Q. A high Q is important for RF filtering. CMOS SOI (CMOS Silicon on Insulator) technology evolution allows today to consider the implementation of LC filters. The achievements in terms of Q are significantly improved compared to Si-technologies [23]. Active circuits can also be considered to enhance the Q of LC resonators. These resonators can also be cascaded to form wide bandwidth filters and to allow for tuning in both center frequency and bandwidth [24].

On the other hand, tunable filters can be also obtained from different types of RF MEMS, two examples are presented by [25]: an inductively-loaded microstrip 1.06–1.23 GHz tunable filter and a surface-integrated-waveguide (SIW) 1.8–2.3 GHz tunable filter. The first has a measured IL between 1.6–2.3 dB over the tuning range and Q varying from 127 to 75 as the filter is tuned. The second has eight RF MEMS switches providing six states with IL between 2.5–3.3 dB and return loss better than 15 dB for all tuning states.

RF Filtering perspectives for an *integrated* CT are then basically on LC networks with varactors and switches, which can be implemented in CMOS. Active inductances allow for obtaining higher Q but could present oscillation issues. The final choice of the particular technology must be done after careful considerations. If MEMS technology is required for other building blocks in the transceiver, such as FMN and the antenna, RF MEMS filters could then be also considered and the literature presents promising performances.

5.3. Beamsteering for CR

As mentioned in Section 3.1, multi-antenna techniques may be relevant for cognitive radio systems. One possible application of these is beamsteering, based on phased arrays [26][27], which may provide interesting features for cognitive radio. Since these techniques are based on multiple antennas in an array configuration (which increases the form factor) the application of beamsteering will be mainly limited to fixed stations and access points. In the future, this may become relevant for UE applications.

In this study, the impact of beamsteering on the transmit architecture of the cognitive transceiver is being investigated. The need for beamsteering has already been foreseen in the context of multi-antenna techniques in the specifications for LTE [28]. The goal of the study is to obtain insights in the trade-offs related to beamsteering that are present in the transmit architecture. For this purpose, we investigate the impact of beamsteering on the architecture in terms of cost, efficiency, power consumption, scalability with frequency, and type of beamsteering (RF, digital, or a hybrid form).

Beamsteering allows for shaping of the radiation pattern emitted/received by the antenna array. It can ensure that the antenna pattern is always optimal for the environment. It can result in improved (re-)configurability of the front-end and allows for spatial separation between users. For cognitive radio, beamsteering can yield the following benefits.

- Interference reduction: the antenna radiation pattern can be steered in such a way that interference from or on other users can be reduced. Zeroes of an array pattern can be placed at desired locations (interferers) adaptively. As a result, less power will be needed and less dynamic range will be required in the receive part.
- Increased spectrum re-use: due to the directivity gain of the antenna, a higher spatial density of users is possible.
- Lower radiated power: due to the freedom in redistribution of antenna radiation, beamsteering can lower the RF radiation users are subjected to (healthcare benefit). The more directive beam causes less power to be radiated in undesired directions. Also it can allow for smaller cells, which radiate less power.
- Reduced power requirements: due to a different transmit architecture, which is required to accommodate for a phased array, power requirements and consumption may change significantly. Such an architecture may consist of multiple unit transmit chains, with a varying level of complexity, depending on the type of beamsteering that is chosen (RF/digital). For multi-mode operation (e.g. for switching between different standards requiring a different output power), it is possible to customize the output power by means of switching transmit units on or off. This can also be used for the varying power requirements in a day/night cycle.

An effect that also is taken into account is that, by using multiple transmit chains a distributed approach for the PA in the architecture may be possible. This lowers the requirements for the individual PAs, and may allow them to be fabricated using different (cheaper) technology processes.

The abovementioned cognitive features comply with the green aspect of technology, according to which the energy has to be distributed optimally over the system.

6. DISCUSSIONS

We have described recent work in the framework of the Par4CR project. The project targets a wide range of topics that enable the development of a SDR platform towards cognitive radio.

The outline for a generic simulation model, based on behavioral models of system functionalities has been presented. The system requirements and basic system properties have been specified. Detailed studies on parts and building blocks of the cognitive transceiver and the software defined radio platform are currently ongoing, based on dedicated simulation approaches. However, fully detailed simulations of cognitive radio system as a whole are out of the scope of the Par4CR project. This paper has also described a multi-standard front-end, being one of the most challenging parts in the CT and has identified current and future technologies that can contribute to the seamless evolutionary path towards CR

Future work includes detailed study of the performance of this architecture in terms of the derived system parameters. The validation of the concept of the different architectures in order to identify the most convenient solution for the SDR-platform will also be performed. The CT model for SDR will incorporate behavioral parameters from existing technological solutions in order to evaluate their impact on the architectures.

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