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Software-Defined Radio—Basics and Evolution to Cognitive Radio

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We provide a brief overview over the development of software-defined or reconfigurable radio systems. The need for software-defined radios is underlined and the most important notions used for such reconfigurable transceivers are thoroughly defined. The role of standards in radio development is emphasized and the usage of transmission mode parameters in the construction of software-defined radios is described. The software communications architecture is introduced as an example for a framework that allows an object-oriented development of software-defined radios. Cognitive radios are introduced as the next step in radio systems' evolution. The need for cognitive radios is exemplified by a comparison of present and advanced spectrum management strategies.

Keywords and phrases: software-defined radio, reconfigurable transceiver, mobile communication standards, cognitive radio, advanced spectrum management.

1. INTRODUCTION

Reconfigurability in radio development is not such a new technique as one might think. Already during the 1980s reconfigurable receivers were developed for radio intelligence in the short wave range. These receivers included interesting features like automatic recognition of the modulation mode of a received signal or bit stream analysis. Reconfigurability became familiar to many radio developers with the publication of the special issue on software radios of the IEEE Communication Magazine in April 1995.

We 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. An SR transceiver comprises all the layers of a communication system. The discussion in this paper, however, mainly concerns the physical layer (PHY).

The baseband signal processing of a *digital radio* (DR) is invariably implemented on a digital processor. An ideal SR directly samples the antenna output. A *software-defined radio* (SDR) is a practical version of an SR: the received signals are sampled after a suitable band selection filter. One remark concerning the relation between SRs and SDRs is necessary at this point: it is often argued that an SDR is a presently realizable version of an SR since state-of-the-art analog-to-digital (A/D) converters that can be employed in SRs are not available today. This argument, although it is correct, may lead to the completely wrong conclusion that an 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.[1] However, 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. 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 our point of view, a CR is a refined SDR while this again represents a refined DR.

[1] This is not an argument against the employment of multichannel or wideband receivers.

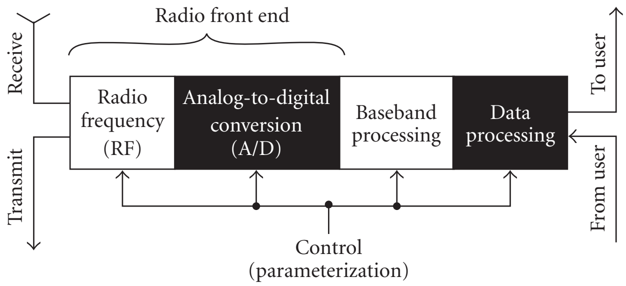

Figure 1: SDR transceiver.

According to its operational area an SDR can be

(i) a *multiband system* which is supporting more than one frequency band used by a wireless standard (e.g., GSM 900, GSM 1800, GSM 1900),
(ii) a *multistandard system* that is supporting more than one standard. Multistandard systems can work within one standard family (e.g., UTRA-FDD, UTRA-TDD for UMTS) or across different networks (e.g., DECT, GSM, UMTS, WLAN),
(iii) a *multiservice system* which provides different services (e.g., telephony, data, video streaming),
(iv) a *multichannel system* that supports two or more independent transmission and reception channels at the same time.

Our present discussion is on *multimode systems* which are combinations of multiband and multistandard systems.

The SDR approach allows different levels of reconfiguration within a transceiver.

(i) *Commissioning*: the configuration of the system is done once at the time of product shipping, when the costumer has asked for a dedicated mode (standard or band). This is not a true reconfiguration.
(ii) *Reconfiguration with downtime*: reconfiguration is only done a few times during product lifetime, for example, when the network infrastructure changes. The reconfiguration will take some time, where the transceiver is switched off. This may include the exchange of components.
(iii) *Reconfiguration on a per call basis*: reconfiguration is a highly dynamic process that works on a per call decision. That means no downtime is acceptable. Only parts of the whole system (e.g., front-end, digital baseband processing) can be rebooted.
(iv) *Reconfiguration per timeslot*: reconfiguration can even be done during a call.

Figure 1 shows an SDR transceiver that differs from a conventional transceiver only by the fact that it can be reconfigured via a control bus supplying the processing units with the parameters which describe the desired standard. Such a configuration, called a *parameter-controlled* (PaC) *SDR*, guarantees that the transmission can be changed instantaneously if necessary (e.g., for interstandard handover).

The rest of this paper is organized as follows. In Section 2 we take a look at the most important wireless transmission standards currently used in Europe and specify their main parameters. Section 3 provides an overview of design approaches for mobile SDR terminals, especially over PaC-SDRs. In Section 4 the software communications architecture (SCA), as it is used in the US Joint Tactical Radio System (JTRS), is introduced. The notion of cognitive radio (CR) is discussed in Section 5 and the need for a modified spectrum management in at least some major portions of the electromagnetic spectrum is underlined in Section 6. Finally, in Section 7 we propose the development of technology centric CRs as a first step towards terminals that may sense their environment and react upon their findings. Conclusions are drawn in Section 8.

2. MOBILE COMMUNICATION STANDARDS

Standards are used to publicly establish transmission methods that serve specific applications employable for mass markets. The presently most important mobile communication standards used in Europe are briefly described in the following paragraphs.

Personal area networks

Bluetooth is a short distance network connecting portable devices, for example, it enables links between computers, mobile phones or connectivity to the internet.

Cordless phone

DECT (digital enhanced cordless telecommunications) provides a cordless connection of handsets to the fixed telephone system for in-house applications. Its channel access mode is FDMA/TDMA and it uses TDD. The modulation mode of DECT is Gaussian minimum shift keying (GMSK) with a bandwidth (B) time (T) product of $BT = 0.5$. The transmission is protected only by a cyclic redundancy check (CRC).

Wireless local area networks

Today, IEEE 802.11b installations are the most widely used in Europe. Also, IEEE 802.11a systems are in operation. If IEEE.11a is to be implemented into an SDR, it should be recognized that its modulation mode is OFDM. It should be pointed out here that there are major efforts towards the development of joint UMTS/WLAN systems which use the SDR approach.

Cellular systems

GSM (global system for mobile communication) is presently the most successful mobile communication standard worldwide. Channel access is done via FDMA/TDMA and GSM uses FDD/TDD. The modulation mode of GSM is GMSK with a bandwidth time product of $BT = 0.3$. Error correction coding is done by applying CRC as well as a convolutional code. GSM was originally planned to be a voice communication system, but with its enhancements HSCSD, GPRS, or EDGE, it served more and more as a data system, too. In Europe, GSM systems are operating in the 900 MHz (GSM 900)

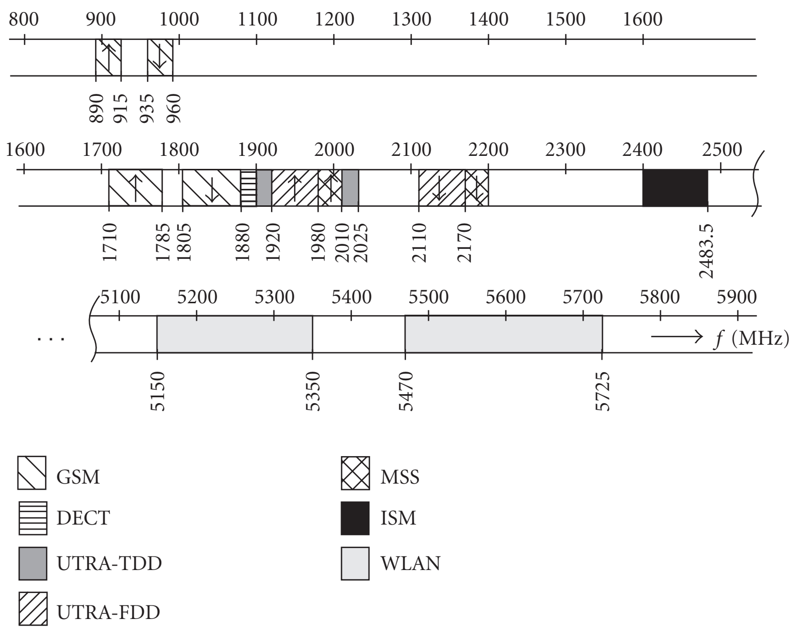

Figure 2: Mobile spectrum in Europe.

as well as in the 1800 MHz (GSM 1800) bands. The North American equivalent of GSM is IS-136. Also, GSM 1900 as well as IS-95, a second-generation CDMA system, are widely used in the US. UMTS (universal mobile telecommunication system) is the European version of the third-generation family of standards within IMT-2000. One of the differences with respect to second-generation systems is that third-generation systems are mainly developed for data (multimedia) transmission. UMTS applies two air interfaces: UTRA-FDD and UTRA-TDD according to the duplex modes used. The channel access mode is CDMA. CRC, convolutional codes, as well as turbo codes [1] are employed for error protection. The basic data modulation is QPSK. Furthermore, it should be mentioned that one mobile user within an UTRA-FDD cell can occupy up to seven channels (one control and six transport channels) simultaneously.

Figure 2 gives an overview over the present spectrum allocation for mobile communications in Europe. Besides the spectra of the standards mentioned above, also the spectra allocated to mobile satellite system (MSS) as well as to industrial, scientific, and medical (ISM) applications are specified. The arrows within some of the bands indicate whether uplink (mobile to base station) or downlink (base station to mobile) traffic is supported.

In connection with mobile communications, some additional groups of standards have to be discussed.

Professional mobile radio

PMR standards are developed for police, firefighters, and other administrative applications. The main difference to cellular systems is that they allow direct handheld to handheld communication. The main PMR systems in Europe are TETRA (recommended by ETSI) and TETRAPOL.

Location and navigation

One important feature of mobile terminals is their ability to determine their own location as well as to track location information. Today many location-dependent services rely on the global positioning system (GPS). Currently the European satellite location and navigation system Galileo is under development.

Digital broadcast

There is a possibility that digital broadcast systems may be used as downstreaming media within future mobile communication infrastructures. The main developments in Europe in this area are digital audio broadcast (DAB) and digital video broadcast (DVB).

To have a sound basis for the description of a PaC-SDR that can be switched between different standards, the most important parameters of selected air interfaces are summarized in Table 1.

3. MOBILE SDR TERMINALS

The general structure of a PaC-SDR terminal was already given in Figure 1. Now we are going to look into the PaC-SDR transceiver structure in a more detailed way. The main processing modules of an SDR terminal are the radio front-end, the baseband processing, and the data processing. Since a lot of information about baseband processing can be found in the literature [2, 3] and since data processing is out of the scope of this paper, we are going to focus on the front-end here.

The receiver branch transforms the analog RF antenna signal into its digital complex baseband representation.

Table 1: Parameters of selected air interfaces.

	Bluetooth	DECT	GSM	UTRA-FDD
Frequency range	2.4 GHz (ISM band)	1900 MHz	900, 1800, 1900 MHz	2 GHz
Channel bandwidth	1 MHz	1728 kHz	200 kHz	5 MHz
Access mode	TDMA	FDMA/TDMA	FDMA/TDMA	Direct sequence (DS) CDMA
Duplex mode	TDD	TDD	FDD	FDD
Users per carrier frequency	8 maximum	12	8	—
Modulation	FH sync. to master station, GFSK with modulation index between 0.28 and 0.35	GMSK	GMSK	QPSK
Error correction code	—	No (CRC)	CRC, convolutional	CRC, convolutional, turbo
Bit (chip) rate	1 Mbps	1152 kbps	270.833 kbps	3.840 Mchip/s
Number of bits (chips)/burst (slot)	625	480 (DECT P32)	156.25	2560
Frame duration	—	10 ms	4.615 ms	10 ms
Number of bursts (slots)/frame	—	24	8	15
Burst (slot) duration	0.625 ms	0.417 ms	0.577 ms	0.667 ms
Maximum cell radius	5–10 m (1 mW Tx power)	300 m	36 km (10 km)	Few km
Spreading sequences	—	—	—	User specific OVSF codes, call specific scrambling
Spreading factor	—	—	—	2^k $(k = 2, 3, \dots, 8)$, 512 for downlink only
Bit (chip) pulse shaping filter	Gauss (BT = 0.5)	Gauss (BT = 0.5)	Gauss (BT = 0.3)	Root-raised cosine, roll-off factor 0.22
Net data rate	1 Mbps	26 kbps	13 kbps	8 kbps to 2 Mbps
Evolutionary concepts	UWB	—	GPRS, HSCSD, EDGE	HSDPA
Comparable systems	—	PHS, PACS, WACS	IS-136, PDC	UMTS-TDD. Cdma2000

	TETRA	IEEE 802.11a	GPS	DVB-T
Frequency range	400 MHz	5.5 GHz	1200, 1500 MHz	VHF, UHF
Channel bandwidth	25 kHz	20 MHz	—	7 (VHF) or 8 MHz (UHF)
Access mode	TDMA	FDMA/TDMA	Direct sequence spread spectrum	FDMA
Duplex mode	FDD/TDD	Half duplex	—	—
Users/carrier frequency	4	—	—	—
Modulation	Π/4-DQPSK	OFDM with subcarrier modulation BPSK/QPSK/16QAM/64QAM	BPSK, QPSK	OFDM with subcarrier modulation QPSK/16QAM/64QAM
Error correction code	CRC, Reed-Muller, RCPC	Convolutional	—	Reed-Solomon, convolutional
Bit (chip) rate	36 kbps	6/9/12/18/24/36/48/54 Mbps	50 bps	9.143 Msamples/s for an 8 MHz channel
Number of bits (chips) per burst (slot)	510 (255 symbols)	52 modulated symbols per OFDM symbol	—	2k mode: 2048 + guard int. 8k mode: 8192 + guard int.
Frame duration	56.67 ms	Packets of several 100 μs	15 s (7500 bit)	68 OFDM symbols
Number of bursts (slots) per frame	4	Variable	5 subframes	68
Burst (slot) duration	14.167 ms	1 OFDM symbol of 3.3 μs + 0.8 μs guard time	30 s	2k mode: 224 μs + guard time 8k mode: 896 μs + guard time
Maximum cell radius	—	Some 10 m	—	—
Spreading sequences	—	—	Gold or PRN code	—
Spreading factor	—	—	1023 or 10 230	—
Bit (chip) pulse shaping filter	Root-raised cosine, roll-off factor 0.35	—	—	Rectangular, other filtering possible
Net data rate	Up to 28.8 kbps	Up to 25 Mbps	—	49.8–131.67 Mbps
Evolutionary concepts	—	IEEE 802.11n	Galileo	—
Comparable systems	TETRAPOL	HiperLAN/2	GLONASS	DAB

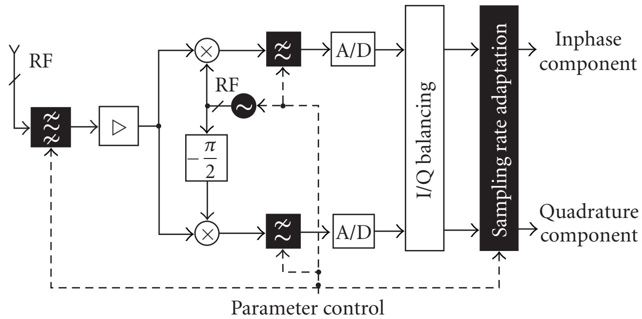

Figure 3: SDR/CR receiver front-end.

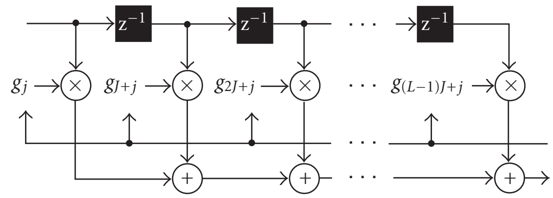

Figure 4: Polyphase filter for sampling rate adaptation.

Figure 3 shows how it works: coming from the antenna, the RF signal is first bandpass filtered and then amplified. Following a two-way signal splitter, the next step is an analog mixing with the locally generated RF frequency in the inphase (I) path and with the same frequency phase shifted by $-\pi/2$ in the quadrature (Q) path. Afterwards, the I and Q components of the signal are lowpass filtered and A/D converted. The sampling rate of the A/D converters should be fixed for all signals and has to be chosen in such a way that the conditions of Shannon's sampling theorem are fulfilled for the broadest signal to be processed. Before the sampling rate can be adapted to the signal's standard, the impairments of the two-branch signal processing that come from the analog mixers and filters as well as from the A/D converters themselves have to be corrected [4].

The reason for the Sampling rate adaptation is that the signal processor should work at the minimum possible rate. For a given standard, this minimum sampling rate depends on $f_c = 1/T_c$, the symbol or chip rate, respectively. Usually a sampling rate of $f_s = 4f_c$ is sufficient for the subsequent signal processing where, after the precise synchronization, the sampling rate may be reduced once more by a factor of 4. If the fraction of the sampling rates at the adaptor's output and input is rational (or may be sufficiently close approximated by a rational number), the sampling rate adaptation can be implemented by an increasing of the sampling rate followed by an interpolation lowpass filter and a decreasing of the sampling rate. If the interpolation lowpass is implemented by an FIR filter, the impulse response usually becomes quite long. The solution is to take the up and down sampling into account within the filter process. Since the upsampled signal is usually generated by the insertion of zeros, the processing of these zeros can be omitted within the filter. This leads to the polyphase structure of Figure 4. Because different input/output ratios have to be realized for different standards, the number of filter coefficients that must be stored may become large. If necessary, a direct computation of the filter coefficients can be more efficient than their advance storage [5]. After the sampling rate adaptation, the signal is processed within the complex baseband unit (demodulation and decoding). The SDR data processing within the higher protocol layers [6] is not considered in the present paper.

The SDR transmitter branch consists of the procedures inverse to that of the receiver branch. That is, the signal to be transmitted is generated as a complex baseband signal, from which, for example, the real part is taken to be shifted to the (transmission) RF.

For SDRs, reconfigurability means that the radio is able to process signals of different standards or even signals that are not standardized but exist in specific applications. One method to implement reconfigurability is parameterization of standards. We look at a *communication standard* as a set of documents that comprehensively describe all functions of a radio system in such a way that a manufacturer can develop terminals or infrastructure equipment on this basis. Standardization is one necessary condition to make a communication system successful on the market, as exemplified by GSM. Standardization pertains to all kinds of communication systems, that is, especially to personal, local, cellular, or global wireless networks. Of course, a standard has to contain precise descriptions of all the functions of the system. Especially for a mobile system, both the air interface and the protocol stack have to be specified. *Parameterization* means that every standard is looked upon as one member of a family of standards [7]. The signal processing structure of the family is then developed in such a way that this structure may be switched by parameters to realize the different standards.

When developing an SDR, one has to pay attention to the fact that there are substantial differences between the second-generation FDMA/TDMA standards (GSM or IS-136), the third-generation CDMA standards (UMTS or cdma2000), and the OFDM-modulated WLAN standards (IEEE 802.11a or HiperLAN/2) (cf. Table 1). Within UMTS, spreading at the transmitter and despreading at the receiver have to be realized. IFFT and FFT operations are necessary for WLAN transceivers. Aside from such fundamental differences, similarities among communication standards are predominant. For example, when looking at the signal processing chains, we remark that the error correction codes of all the second-generation standards are very similar: a combination of a block code for the most important bits and a convolutional code for the larger part of the voice bits is applied. Channel coding for data transmission is done by a powerful convolutional code. UTRA, as a third-generation air interface, offers net data rates of up to 2 Mbps and guarantees BERs, of up to 10^{-6} for specific applications. To reach these BERs turbo codes are employed for data transmission. Of course, within an SDR all these procedures have to be integrated into a general encoding/decoding structure. Also a common modulator/demodulator structure has to be specified. Solutions to these tasks are given, for example, in [2, 3, 7].

4. THE SOFTWARE COMMUNICATIONS ARCHITECTURE

The *Joint Tactical Radio System* (JTRS) represents the future (mobile) communications infrastructure of the US joint forces. Introducing JTRS stands for an essential step towards the unification of radio communication systems, the transparency of services, and the exchangeability of components. The development of the JTRS is accompanied and supervised by the US forces' *Joint Program Office* (JPO).

Development, production, and delivery continue to be the tasks of competing industrial communications software and hardware suppliers. An important new aspect added by the JTRS set-up is that the suppliers are guided to aim for a most perfect interchangeability of components due to the supervision function of the JPO. The tool used by the JPO is the *software communications architecture* (SCA) [8], an open framework that prescribes the developing engineers how the hardware or software blocks have to act together within the JTRS. The communication devices emerging from this philosophy are clearly SDRs.

A major group of suppliers and developers of communication software and hardware founded the SDR Forum [9] to promote their interests. The importance of the SDR Forum, however, reaches well beyond the application of SDRs in the JTRS. This is underlined by the SDR Forum membership of European and Asian industrial and research institutions that usually are mainly interested in the evolution of commercial mobile communication networks.

The SCA describes how *waveforms* are to be implemented onto appropriate hardware devices. A waveform is defined by the determination of the lower three layers (network, data link, physical) of the ISO/OSI model. Therefore, waveform is a synonym of standard or air interface. Based on the waveform definition, a transmission method is completely determined. The definition of a waveform, therefore, lays down the modulation, coding, access, and duplex modes as well as the protocol structure of the transmission method.

The SCA defines the software structure of an SDR that may be usable within the JTRS. The underlying hardware as well as the software is described in object-oriented terms. Moreover, the structures of application program interfaces (APIs) and of the security environment are described. Each component has to be documented in a generally accessible form.

The JTRS operating environment (OE) defined in the SCA consists of three main components:

(i) a real-time operating system,
(ii) a real-time request broker,
(iii) the SCA core framework.

When developing an SCA compliant radio device the supplier gets the operating system and the CORBA middleware from the commercial market. The core framework as well as the waveform is developed by him or he also gets it from the market or (in future) it may be contributed by the JPO.

The SCA is the description of an open architecture with distributed components. It strictly separates applications (waveforms) from the processing platform (hardware, operating system, object request broker, core framework). It segments the application functions and defines common interfaces for the management and the employment of software components. It defines common services and makes use of APIs to support the portability of hardware and software components and of applications.

The connections between the applications and the core framework within the SCA are given by the APIs. Standardized APIs are essential in assuring the portability of applications as well as for the exchangeability of devices. APIs guarantee that application and service programs may communicate with one another, independent of the operating system and the programming language used. APIs are waveform specific since uniform APIs for all waveforms would be inefficient for implementations with bounded resources. Therefore, the goal is to have a standard set of APIs for each waveform. The single APIs are essentially given by the layers of the ISO/OSI model.

(i) A *PHY API* supports initialization and configuration of the system in non-real-time. In real-time it takes care of the transformation of symbols (or bits) to RF in the transmitter branch. In the receiver branch it transforms RF signals to symbols (bits).

(ii) A *MAC API* supports all the MAC functions of the ISO/OSI layer model (e.g., timeslot control in TDMA or FEC control).

(iii) An *LLC API* makes available an interface for the waveform's link layer performance (according to the ISO/OSI layer model: data link services) on component level.

(iv) A *network API* makes available an interface for the waveform's network performance on component level.

(v) A *security API* serves for the integration of data security procedures (INFOSEC, TRANSEC).

(vi) An *input/output API* supports the input and output of audio, video, or other data.

The security relevant SCA aspects are written down in the *SCA security supplement* [8]. The SCA security functions and algorithms are of course defined with respect to the military security requirements of JTRS.

5. USER CENTRIC AND TECHNOLOGY CENTRIC COGNITIVE RADIO PROPERTIES

The description of CR given by Mitola and Maguire in their seminal paper [10] mainly focuses on the *radio knowledge representation language* (RKRL). CR is looked upon as a small part of the physical world using and providing information over very different time scales. Equipped with various sensors, a CR acquires knowledge from its environment. Employing software agents, it accesses data bases and contacts other sources of information. In this context, CR seems to become the indispensable electronic aid of its owner. Reading [10] leads to the impression that a CR must be a complex device that helps to overcome all problems of everyday life, all the same whether they are recognized by the CR's owner or not. Of course, these visions as well as the *recognition cycle for CRs* in [11] are strongly intended to stimulate new research and development. For a more pragmatic point of view, however, we approach CR in a different way.

The properties of CRs may be divided into two groups:

(i) user centric properties that comprise support functions like finding the address of an appropriate restaurant or a movie theater, recommendation of a travel route, or supervision of appointments,

(ii) technology centric properties like spectrum monitoring, localization, and tracking, awareness of processing capabilities for the partitioning or the scheduling of processes, information gathering, and knowledge processing.

From our point of view, many of the user centric properties can be implemented by using queries to data bases. This type of intelligence can be kept in the networks and activated by calls. In transceiver development, much more difficult design choices need to be made to realize the wanted technology centric properties of a CR. Therefore, we concentrate on the latter in the following sections.

6. THE NEED FOR ADVANCED SPECTRUM MANAGEMENT

Today, spectrum is *regulated* by governmental agencies. Spectrum is *assigned* to users or *licensed* to them on a long-term basis normally for huge regions like countries. Doing this, resources are wasted, because large-frequency regions are used very sporadically. The vision is to assign appropriate resources to end users only as long as they are needed for a geographically bounded region, that is, a personal, local, regional, or global cell. The spectrum access is then organized by the network, that is, by the users. First examples for self-regulation in mobile radio communications are to be found in the ISM (2400–2483.5 MHz) and in the WLAN (5150–5350 MHz and 5470–5725 MHz) bands.

Future advanced spectrum management will comprise [12] the following.

(i) *Spectrum reallocation*: the reallocation of bandwidth from government or other long-standing users to new services such as mobile communications, broadband internet access, and video distribution.

(ii) *Spectrum leases*: the relaxation of the technical and commercial limitations on existing licensees to use their spectrum for new or hybrid (e.g., satellite and terrestrial) services and granting most mobile radio licensees the right to lease their spectrum to third parties.

(iii) *Spectrum sharing*: the allocation of an unprecedented amount of spectrum that could be used for unlicensed or shared services.

If we look upon the users' behavior in an FDMA/TDMA system over the time/frequency plane (cf. Figure 5), we may find out that a considerable part of the area remains unused [12, 13]. This unused area marks the pool from which frequencies can be allocated to secondary users (SUs), for example, in a hotspot. In the following we denote the FDMA/TDMA users as primary users (PUs). In order to make the implementation of the SUs' system into the PUs' system feasible, two main assumptions should be fulfilled:

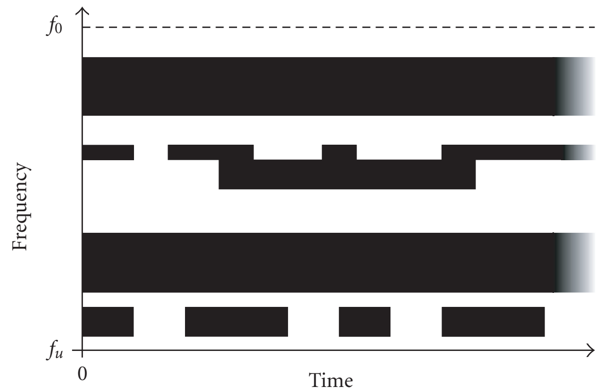

Figure 5: FDMA/TDMA signals over the time/frequency plane, spectrum pool.

(i) the PUs' system is not disturbed by the SUs' system,

(ii) the PUs' system remains unchanged (i.e., all signal processing that has to be done to avoid disturbances of the PUs communications must be implemented in the SUs' system).

Now we assume that the transmission method within the SUs' system is OFDM. Figure 6 gives a brief overview over an OFDM transmitter: the sequential data stream is converted to a parallel stream, the vectors of which are interpreted as signals in the frequency domain. By applying an inverse fast Fourier transform (IFFT), these data are transformed into the time domain and sent over the air on a set of orthogonal carriers with separation Δf on the frequency axis. If some carriers should not be used, it is necessary to transmit zeros on these carriers. This is the strategy to protect the PUs' system from disturbances originating from the SUs' system. In order to make the SUs' system work, the following problems have to be solved.

(i) The reliable detection of upcoming PUs' signals within an extremely short time interval. (This means that the detection has to be performed with a very high detection probability ensuring a moderate false alarm probability.)

(ii) The consideration of hidden stations.

(iii) The signaling of the present transmission situation in the PUs' system to all stations of the SUs' system such that these do not use the frequencies occupied by the PUs.

The solutions to these problems have recently been found [13]. The keywords for these solutions are distributed detection, boosting of the detection results and combining them in the hotspot's access point to an occupancy vector, and distributing the occupancy vector to all mobile stations in the hotspot.

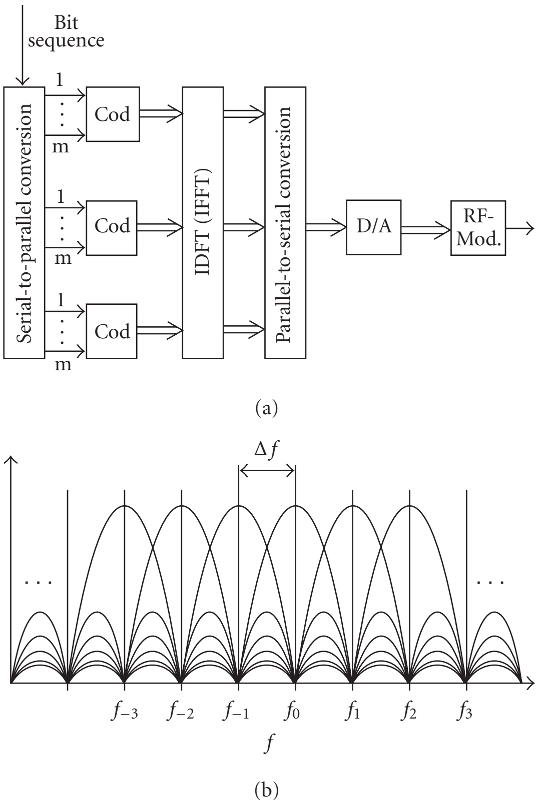

Figure 6: OFDM. (a) Transmitter. (b) Spectrum.

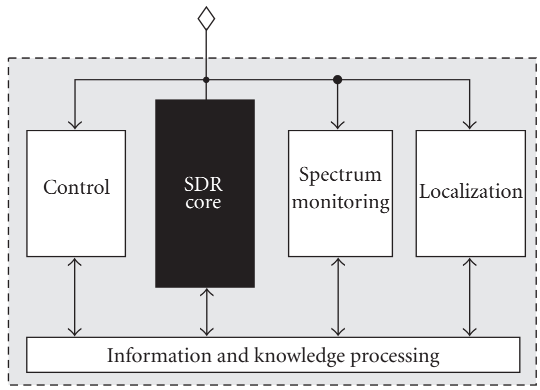

Figure 7: Technology centric cognitive radio.

The central point in our present discussion is that the SUs system's transceivers have in some sense to act like CRs. They have to sense their spectral neighborhood for PUs' signals and to react upon their findings.

7. TECHNOLOGY CENTRIC COGNITIVE RADIO

In a more advanced spectrum sharing system, CRs have to apply more advanced algorithms. If a portion of the spectrum may be accessed by any access mode, the following procedure becomes imaginable: starting from the transmission demand of its user, the CR decides about the data rate, the transmission mode, and therefore about the bandwidth of the transmission. Afterwards it has to find an appropriate resource for its transmission. This presumes that the CR knows where it is (self-location), what it is able to do (self-awareness), and where the reachable base stations are. To get more information about possible interferences it should, for example, be able to detect signals active in adjacent frequency bands and to recognize their transmission standards [14].

Summing up, a CR should have implemented the following technologies (possibly among others):

(i) *location sensors* (e.g., GPS or Galileo);

(ii) equipment to *monitor its spectral environment* in an intelligent[2] way;

(iii) in order to *track the location's or the spectral environment's developments*, learning and reasoning algorithms have to be implemented;

(iv) when complying with a communications etiquette, it has to *listen before talk* as well as to prevent the disturbance of *hidden stations*;

(v) in order to be fair it has to compromise its own demands with the demands of other users, most probably in making decisions in a competitive environment using the results of *game theory* [15];

(vi) it has to keep its owner informed via a highly sophisticated man-machine interface.

A first block diagram of a technology centric CR is given in Figure 7. One of the most important decisions that have to be made in an open access environment is whether a control channel is to be implemented or not. The most challenging development is that of the information and knowledge processing.

8. CONCLUSIONS

Standardization of a transmission mode is necessary to ensure its success on the market. From standards we can learn about the main parameters of a system and, by comparing different standards, we may conclude about similarities and dissimilarities within their signal processing chains. Keeping this knowledge in mind, we are able to construct PaC-SDRs. A far more general setup is given by the SCA which is a framework for the reconfigurablity of transceivers and for the portability of waveforms from one hardware platform to another. Starting from SDRs, the next step in the evolution of intelligent transmission devices leads to CRs that may be looked upon as a small part of the physical world using and providing information over very different time scales. Since this approach seems to be very futuristic, we take a look at the urgent problem of efficient spectrum usage. In order to introduce advanced spectrum management procedures (e.g., spectrum pooling), the employment of CRs that at least are able to monitor their electromagnetic environments and to track their own locations is necessary. Therefore, the development of technology centric CRs is proposed here as a first step towards general CRs.

[2]Intelligent means that searching for usable frequency bands is not done by just scanning the whole spectrum.

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Special Issue on
Quality of Service in Mobile Ad Hoc Networks

Call for Papers

Mobile ad hoc networking is a challenging task due to a lack of resources residing in the network as well as frequent changes in network topology. Although much research has been directed to supporting QoS in the Internet and traditional wireless networks, present results are not suitable for mobile ad hoc network (MANET). QoS support for mobile ad hoc networks remains an open problem, drawing interest from both academia and industry under military and commercial sponsorship. MANETs have certain unique characteristics that pose several difficulties in provisioning QoS, such as dynamically varying network topology, lack of precise state information, lack of central control, error-prone shared radio channels, limited resource availability, hidden terminal problems, and insecure media, and little consensus yet exists on which approaches may be optimal. Future MANETs are likely to be “multimode” or heterogeneous in nature. Thus, the routers comprising a MANET will employ multiple, physical-layer wireless technologies, with each new technology requiring a multiple-access (MAC) protocol for supporting QoS. Above the MAC layer, forwarding, routing, signaling, and admission control policies are required, and the best combination of these policies will change as the underlying hardware technology evolves.

The special issue solicits original papers dealing with state-of-the-art and up-to-date efforts in design, performance analysis, implementation and experimental results for various QoS issues in MANETs. Fundamental research results as well as practical implementations and demonstrators are encouraged.

Topics of interest include (but are not limited to):

- QoS models and performance evaluation of MANET
- QoS resource reservation signaling
- Various QoS routing protocols
- Flexible MAC protocols
- Robust modeling and analysis of MANET resource management
- Dynamic and hybrid resource allocation schemes
- Resource control and multimedia QoS support
- Channel characterization
- QoS management and traffic engineering
- Tools and techniques for MANET measurement and simulation
- Adaptive QoS provisioning issues
- Information assurance and reliability in MANET

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Special Issue on CMOS RF Circuits for Wireless Applications

Call for Papers

Advanced concepts for wireless communications present a vision of technology that is embedded in our surroundings and practically invisible, but present whenever required. From established radio techniques like GSM, 802.11, or Bluetooth to more emerging ones like ultra-wideband (UWB) or smart dust moats, a common denominator for future progress is underlying CMOS technology. Although the use of deep-submicron CMOS processes allows for an unprecedented degree of scaling in digital circuitry, it complicates implementation and integration of traditional RF circuits. The explosive growth of standard cellular radios and radically different new wireless applications makes it imperative to find architectural and circuit solutions to these design problems.

Two key issues for future silicon-based systems are scale of integration and ultra-low power dissipation. The concept of combining digital, memory, mixed-signal, and RF circuitry on one chip in the form of System-on-Chip (SoC) has been around for a while. However, the difficulty of integrating heterogeneous circuit design styles and processes onto one substrate still remains. Therefore, System-in-Package (SiP) concept seems to be gaining more acceptance.

While it is true that heterogeneous circuits and architectures originally developed for their native technologies cannot be effectively integrated "as is" into a deep-submicron CMOS process, one might ask the question whether those functions can be ported into more CMOS-friendly architectures to reap all the benefits of the digital design and flow. It is not predestined that RF wireless frequency synthesizers be always charge-pump-based PLLs with VCOs, RF transmit upconverters be I/Q modulators, receivers use only Gilbert cell or passive continuous-time mixers. Performance of modern CMOS transistors is nowadays good enough for multi-GHz RF applications.

Low power has always been important for wireless communications. With new developments in wireless sensor networks and wireless systems for medical applications, the power dissipation is becoming a number one issue. Wireless sensor network systems are being applied in critical applications in commerce, healthcare, and security. These systems have unique characteristics and face many implementation challenges. The requirement for long operating life for a wireless sensor node under limited energy supply imposes the most severe design constraints. This calls for innovative design methodologies at the circuit and system level to address this rigorous requirement.

Wireless systems for medical applications hold a number of advantages over wired alternatives, including the ease of use, reduced risk of infection, reduced risk of failure, reduced patient discomfort, enhanced mobility, and lower cost. Typically, applications demand expertise in multiple disciplines, varying from analog sensors to digital processing cores, suggesting opportunities for extensive hardware integration.

The special issue will address the state of the art in CMOS design in the context of wireless communication for 3G/4G cellular telephony, wireless sensor networks, and wireless medical applications.

Topics of interest include (but are not limited to):

- Hardware aspects of wireless networks
- Wireless CMOS circuits for healthcare and telemedicine
- Modulation schemes for low-power RF transmission
- RF transceiver architectures (low IF, direct conversion, super-regenerative)
- RF signal processing
- Phase-locked loops (PLLs)
- Digitally controlled oscillators
- LNAs, mixers, charge pumps, and VCOs in CMOS
- System-on-Chip (SoC) and System-in-Package (SiP) implementations
- RF design implementation challenges in deep-submicron CMOS processes

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EURASIP JOURNAL ON WIRELESS COMMUNICATIONS AND NETWORKING

Special Issue on

Ultra-Wideband (UWB) Communication Systems—Technology and Applications

Call for Papers

The opening of unlicensed frequency band between 3.1 GHz and 10.6 GHz (7.5 GHz) for indoor wireless communication systems by the Federal Communications Commission (FCC) spurred the development of ultra-wideband (UWB) communications. Several wireless personal area networking (WPAN) products have been demonstrated recently. These products implement one of the two leading proposals to the IEEE 802.15.3a High-Speed WPAN Standards Committee. On the other hand, the IEEE 802.15.4a Standards Committee is focusing on low power, low bit rate applications, emphasizing accurate localization. This flurry of activity has demonstrated the feasibility of high-bit-rate and low-bit-rate/low-power UWB communications. Further improvement in UWB transmission speed and reductions in power consumption and UWB transceiver cost require a comprehensive investigation of UWB communications that simultaneously addresses system issues, analog and digital implementation constraints, and RF circuitry limitations. In the application area, coexistence with other wireless standards plays an important role.

The aim of this special issue is to present recent research in UWB communication systems with emphasis on future applications in wireless communications. Prospective papers should be unpublished and present novel innovative contributions from either a methodological or an application perspective.

Suggested topics include (but are not limited) to:

- UWB channel modeling and measurement
- High-bit-rate UWB communications
- UWB modulation and multiple access
- Synchronization and channel estimation
- Pulse shaping and filtering
- UWB transceiver design and signal processing
- Interference and coexistence
- Ultra-low-power UWB transmission
- MIMO-UWB
- Multiband UWB
- Spectral management
- UWB wireless networks and related issues
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EURASIP JOURNAL ON WIRELESS COMMUNICATIONS AND NETWORKING

Special Issue on Wireless Network Security

Call for Papers

Recent advances in wireless network technologies have rapidly developed in recent years, as evidenced by wireless location area networks (WLANs), wireless personal area networks (WPANs), wireless metropolitan area networks (WMANs), and wireless wide area networks (WWANs), that is, cellular networks. A major impediment to their deployment, however, is wireless network security. For example, the lack of data confidentiality in wired equivalent privacy (WEP) protocol has been proven, and newly adopted standards such as IEEE 802.11i robust secruity network (RSN) and IEEE 802.15.3a ultra-wideband (UWB) are not fully tested and, as such, may expose unforeseen security vulnerabilities. The effort to improve wireless network security is linked with many technical challenges including compatibility with legacy wireless networks, complexity in implementation, and cost/performance trade-offs. The need to address wireless network security and to provide timely, solid technical contributions establishes the motivation behind this special issue.

This special issue will focus on novel and functional ways to improve wireless network security. Papers that do not focus on wireless network security will not be reviewed. Specific areas of interest in WLANs, WPANs, WMANs, and WWANs include, but are not limited to:

- Attacks, security mechanisms, and security services
- Authentication
- Access control
- Data confidentiality
- Data integrity
- Nonrepudiation
- Encryption and decryption
- Key management
- Fraudulent usage
- Wireless network security performance evaluation
- Wireless link layer security
- Tradeoff analysis between performance and security
- Authentication and authorization for mobile service network
- Wireless security standards (IEEE 802.11, IEEE 802.15, IEEE 802.16, 3GPP, and 3GPP2)

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EURASIP JOURNAL ON WIRELESS COMMUNICATIONS AND NETWORKING

Special Issue on Radio Resource Management in 3G+ Systems

Call for Papers

The 3G+ wireless systems can be characterized by aggregate bit rates in the range of Mbps, QoS support for interactive multimedia services, global mobility, service portability, enhanced ubiquity, and larger user capacity. All digital entirely packet-switched radio networks involving hybrid networking and access technologies are envisioned in 3G+ systems. In such systems, radio resource management (RRM) plays a major role in the provision of QoS and efficient utilization of scarce radio resources. With the required support for multimedia services to multiple users over diverse wireless networks and ever-increasing demand for high-quality wireless services, the need for effective and efficient RRM techniques becomes more important than ever. The addition of efficient packet data channels in both forward and reverse directions and QoS support in 3G standards leads to a more flexible network, but at the same time increases the complexity of determining the optimal allocation of resources especially on the radio interface. This special issue is devoted to addressing the urgent and important need for efficient and effective RRM techniques in the evolving next-generation wireless systems.

We are seeking original, high-quality, and unpublished papers representing the state-of-the-art research in radio resource management aspects of the next-generation wireless communication systems. Topics of interests include, but are not limited to:

- Resource optimization for multimedia services
- Rate allocation and adaptation
- Transmit power control and allocation
- Intelligent scheduling
- Subcarrier allocation in multicarrier systems
- Antenna selection techniques in MIMO systems
- Call admission control
- Load balancing, congestion, and flow control in radio networks
- Modeling and analysis of QoS in wireless networks
- Adaptive QoS control for wireless multimedia
- Delay and jitter management in wireless networks
- Handoff and mobility management
- RRM techniques in hybrid radio networks
- Distributed versus centralized RRM
- RRM in mesh networks
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- H-ARQ techniques and issues
- Performance of multihop and cooperative networks
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EURASIP JOURNAL ON WIRELESS COMMUNICATIONS AND NETWORKING

Special Issue on Multiuser Cooperative Diversity for Wireless Networks

Call for Papers

Multihop relaying technology is a promising solution for future cellular and ad-hoc wireless communications systems in order to achieve broader coverage and to mitigate wireless channels impairment without the need to use large power at the transmitter. Recently, a new concept that is being actively studied in multihop-augmented networks is multiuser cooperative diversity, where several terminals form a kind of coalition to assist each other with the transmission of their messages. In general, cooperative relaying systems have a source node multicasting a message to a number of cooperative relays, which in turn resend a processed version to the intended destination node. The destination node combines the signal received from the relays, possibly also taking into account the source's original signal. Cooperative diversity exploits two fundamental features of the wireless medium: its broadcast nature and its ability to achieve diversity through independent channels. There are three advantages from this:

(1) *Diversity.* This occurs because different paths are likely to fade independently. The impact of this is expected to be seen in the physical layer, in the design of a receiver that can exploit this diversity.
(2) *Beamforming gain*. The use of directed beams should improve the capacity on the individual wireless links. The gains may be particularly significant if space-time coding schemes are used.
(3) *Interference Mitigation*. A protocol that takes advantage of the wireless channel and the antennas and receivers available could achieve a substantial gain in system throughput by optimizing the processing done in the cooperative relays and in the scheduling of retransmissions by the relays so as to minimize mutual interference and facilitate information transmission by cooperation.

The special issue solicits original research papers dealing with up-to-date efforts in design, performance analysis, implementation and experimental results of cooperative diversity networks.

We seek original, high-quality, and unpublished papers representing the state-of-the-art research in the area of multiuser cooperative diversity as applied to the next generation multihop wireless communication systems. We encourage submission of high-quality papers that report original work in both theoretical and experimental research areas.

Topics of interests include, but are not limited to:

- Information theoretic aspects of cooperative diversity
    - Cooperative diversity from the standpoint of multiuser information theory: Shannon capacity
    - Cooperative diversity and its relation to network coding
    - Security aspects
- Physical layer and networking aspects of cooperative diversity
    - Cooperative protocols for wireless relay, ad hoc, and sensor multihop networks
    - Cross-layer protocol design
    - Power allocation in networks with cooperative diversity
    - Reducing transmission energy and extending terminal battery life in cooperative diversity networks
    - Relay networks architectures
- MIMO transmission and cooperative diversity networks
    - Cooperative systems with space-time coding
    - MIMO transmission in multihop networks
    - Cooperative MIMO

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Special Issue on

Signal Processing with High Complexity: Prototyping and Industrial Design

Call for Papers

Some modern applications require an extraordinary large amount of complexity in signal processing algorithms. For example, the 3rd generation of wireless cellular systems is expected to require 1000 times more complexity when compared to its 2nd generation predecessors, and future 3GPP standards will aim for even more number-crunching applications. Video and multimedia applications do not only drive the complexity to new peaks in wired and wireless systems but also in personal and home devices. Also in acoustics, modern hearing aids or algorithms for de-reverberation of rooms, blind source separation, and multichannel echo cancelation are complexity hungry. At the same time, the anticipated products also put on additional constraints like size and power consumption when mobile and thus battery powered. Furthermore, due to new developments in electroacoustic transducer design, it is possible to design very small and effective loudspeakers. Unfortunately, the linearity assumption does not hold any more for this kind of loudspeakers, leading to computationally demanding nonlinear cancelation and equalization algorithms.

Since standard design techniques would either consume too much time or do not result in solutions satisfying all constraints, more efficient development techniques are required to speed up this crucial phase. In general, such developments are rather expensive due to the required extraordinary high complexity. Thus, de-risking of a future product based on rapid prototyping is often an alternative approach. However, since prototyping would delay the development, it often makes only sense when it is well embedded in the product design process. Rapid prototyping has thus evolved by applying new design techniques more suitable to support a quick time to market requirement.

This special issue focuses on new development methods for applications with high complexity in signal processing and on showing the improved design obtained by such methods. Examples of such methods are virtual prototyping, HW/SW partitioning, automatic design flows, float to fix conversions, automatic testing and verification, and power aware designs.

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Special Issue on Field-Programmable Gate Arrays in Embedded Systems

Call for Papers

Field-Programmable Gate Arrays (FPGAs) are increasingly used in embedded systems to achieve high performance in a compact area. FPGAs are particularly well suited to processing data straight from sensors in embedded systems. More importantly, the reconfigurable aspects of FPGAs give the circuits the versatility to change their functionality based on processing requirements for different phases of an application, and for deploying new functionality.

Modern FPGAs integrate many different resources on a single chip. Embedded processors (both hard and soft cores), multipliers, RAM blocks, and DSP units are all available along with reconfigurable logic. Applications can use these heterogeneous resources to integrate several different functions on a single piece of silicon. This makes FPGAs particularly well suited to embedded applications.

This special issue focuses on applications that clearly show the benefit of using FPGAs in embedded applications, as well as on design tools that enable such applications. Specific topics of interest include the use of reconfiguration in embedded applications, hardware/software codesign targeting FPGAs, power-aware FPGA design, design environments for FPGAs, system signalling and protocols used by FPGAs in embedded environments, and system-level design targeting modern FPGA's heterogeneous resources.

Papers on other applicable topics will also be considered. All papers should address FPGA-based systems that are appropriate for embedded applications. Papers on subjects outside of this scope (i.e., not suitable for embedded applications) will not be considered.

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EURASIP JOURNAL ON EMBEDDED SYSTEMS

Special Issue on
Synchronous Paradigm in Embedded Systems

Call for Papers

Synchronous languages were introduced in the 1980s for programming reactive systems. Such systems are characterized by their continuous reaction to their environment, at a speed determined by the latter. Reactive systems include embedded control software and hardware. Synchronous languages have recently seen a tremendous interest from leading companies developing automatic control software and hardware for critical applications. Industrial success stories have been achieved by Schneider Electric, Airbus, Dassault Aviation, Snecma, MBDA, Arm, ST Microelectronics, Texas Instruments, Freescale, Intel .... The key advantage outlined by these companies resides in the rigorous mathematical semantics provided by the synchronous approach that allows system designers to develop critical software and hardware in a faster and safer way.

Indeed, an important feature of synchronous paradigm is that the tools and environments supporting development of synchronous programs are based upon a formal mathematical model defined by the semantics of the languages. The compilation involves the construction of these formal models, and their analysis for static properties, their optimization, the synthesis of executable sequential implementations, and the automated distribution of programs. It can also build a model of the dynamical behaviors, in the form of a transition system, upon which is based the analysis of dynamical properties, for example, through model-checking-based verification, or discrete controller synthesis. Hence, synchronous programming is at the crossroads of many approaches in compilation, formal analysis and verification techniques, and software or hardware implementations generation.

We invite original papers for a special issue of the journal to be published in the first quarter of 2007. Papers may be submitted on all aspects of the synchronous paradigm for embedded systems, including theory and applications. Some sample topics are:

- Synchronous languages design and compiling
- Novel application and implementation of synchronous languages
- Applications of synchronous design methods to embedded systems (hardware or software)
- Formal modeling, formal verification, controller synthesis, and abstract interpretation with synchronous-based tools
- Combining synchrony and asynchrony for embedded system design and, in particular, globally asynchronous and locally synchronous systems
- The role of synchronous models of computations in heterogeneous modeling
- The use of synchronous modeling techniques in model-driven design environment
- Design of distributed control systems using the synchronous paradigm

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