Chapter 2
Fundamentals

Reconfigurability, a concept of utmost importance in communication systems has been foreseen over two decades ago [1, 2]. Reconfiguration of a radio to achieve higher hardware performance is turning to be not only a requirement, but also a necessity in current radio architectures for services and portable devices in the frequency spectrum below 6 GHz. Advances in software and hardware development have been targeting this idea, and thus, leading to an evolution for modern radio architectures relaying in key concepts, such as Software Defined Radio and Cognitive Radio.

Ideally, a Software Defined Radio has the ability to accommodate an RF-band across a spectrum determined by the user or the platform itself, i.e. to perform a transition and/or coexistence of frequencies considering different air interfaces [3, 4]. Moreover, by accompanying the radio with the use of Cognitive Radio techniques,[1] a certain level of recognition is provided based on the observation or sensing of the environment [5]. That means, a reconfiguration of the communication platform to exploit the available resources is performed.

The amount of circuitry present in a device is continuously optimized and reduced. For instance, according to the road map in semiconductor technology, Moore's Law for integrated circuits in nanometer ranges [6] and carbon nanotubes [7, 8] are considered as an alternative to silicon technology in future microelectronics. Thus, an ambitious revolution is proposed for communication standards and protocols. Nevertheless, these standards and protocols are barely in process to be fulfilled by current devices in mobile systems. For example, IMT-Advanced for 4G [9], and the not yet standardized 5G [10]. As a consequence, these upcoming communications require hardware architectures that are still limited by the complexity and high energy consumption that a multiband and multistandard device represents.

[1]For example, programming of baseband algorithms that reconfigure the overall communication architecture according to the capabilities of the employed hardware in the RF-Frontend.

E. Gonzalez Rodriguez, *Reconfigurable Transceiver Architecture for Multiband RF-Frontends*, Smart Sensors, Measurement and Instrumentation 17,
DOI 10.1007/978-3-319-24581-2_2

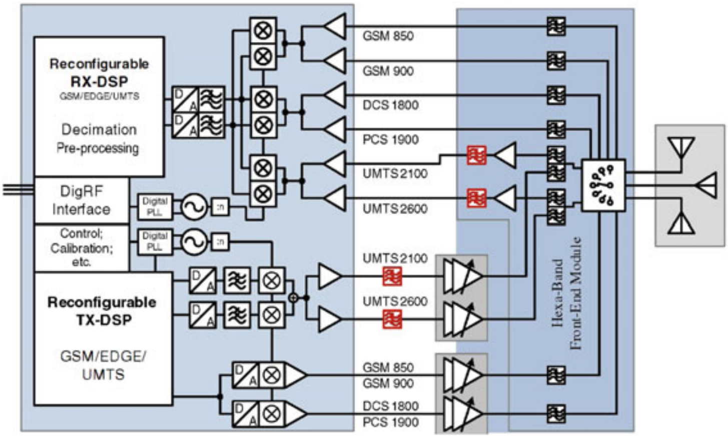

Fig. 2.1 Transmitter and receiver chains of a state-of-the-art multiband and multistandard RF-Frontend with parallelized RF components [11]. The radio is conformed by multiple: filters, amplifiers (PA and LNA), switch/duplexers, and antennas

To exemplify this issue, transmitter and receiver chains of a state-of-the-art multiband and multistandard RF-Frontend supporting 2G and 3G technology standards are shown in Fig. 2.1. Due to the increase in the demand of services, RF components like filters and duplexers are present in large amount of elements in the frontend of the device. Realization is carried out by including, for almost every service, a chain of RF components, resulting in an increment of circuitry, hardware complexity and power consumption.

Thereby, a reduction of parallel chains is fundamental since new standards and more services for communication constantly appear, and therefore, are required to coexist within the same architecture. Hence, if a decrease in the employed circuitry is realized, an improvement of the energy consumption can be obtained while the device is enabled to offer the required multifunctionality covering diverse services.

Considering future trends in communications, reconfigurable frontends, mainly, have to meet specifications such as:

- overall wide tuning range of the transceiver for global functionality,
- control of harmonic rejection due to extended bandwidth,
- required SNR level while allocating a defined channel,
- full-duplex operation for simultaneous transmission and reception,
- compactness of multiband antennas,
- overall low power consumption.

As a consequence of this, reconfigurability plays a key role to enhance the usage and compatibility of a device or user equipment. Hence, this can result in a wide tuning range of the transceiver by means of the components' tunability.

2.1 RF-Spectrum and Requirements for Mobile Communications

During the last decade, the way to communicate with a mobile device has dramatically evolved. The trend is that a mobile phone will perform many more tasks than just a telephone call, e.g. wireless network access considering diverse scenarios (PAN, LAN, MAN, WAN), access to global navigation systems (GNSS), mobile-TV (DVB-NGH), contactless payment and identification using Radio Frequency Identification (RFID). For this reason, the notable augment in hardware to provide signal diversity and global roaming functionality, e.g. MIMO (Multiple Input Multiple Output) applications with multiple antenna links, demands for multiband and multistandard operation [12]. Technologies using present and future communication standards such as LTE, UMTS, GSM, WLAN, WiMAX, NFC, among others, are desired to be all packed into the same architecture rather than using a different device or RF module for each standard [13, 14]. The frequency spectrum allocation of different categorized services typically used in current mobile and portable devices is shown in Fig. 2.2. The used spectrum is covered mainly up to 4 GHz, and from 5 to 6 GHz, while white spaces and unlicensed frequencies are located in the low frequency range below 1 GHz, around 3.2 GHz, and between 4 and 5 GHz.

Thus, if a device aims for global access, the communication platform requires to increase its reconfigurability and flexibility [15]. In other words, modern devices like smartphones or tablets still need to be improved in terms of adaptability and efficiency. That means, a high quality of service to cope with identified constraints such as battery lifetime, alltime online connectivity, dropped calls, and packet loss [16] is required.

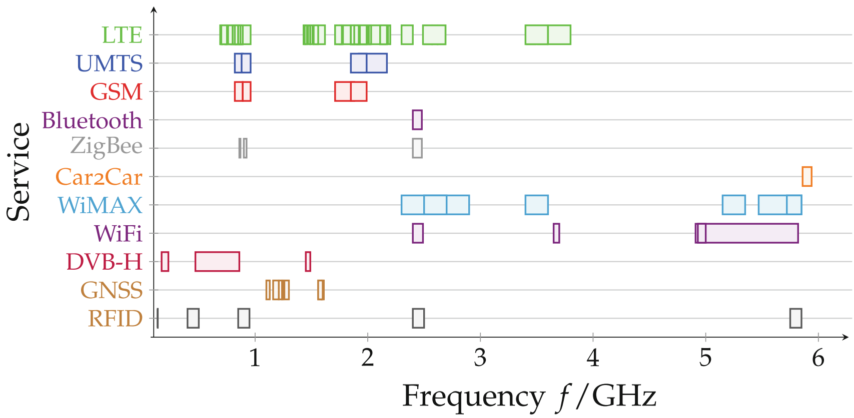

Fig. 2.2 Frequency spectrum allocation of current and future services for global mobile systems and portable devices [17–25]

2.2 Future Mobile and Cognitive Radio Applications

Dynamic and adaptable communication approaches are strongly required with the steady growth of services and applications for portable devices. In that way, an agile reconfiguration should take into account every layer of a typical communication system, i.e. from the application layer to the physical layer [26]. Nevertheless, while a clear road map for protocols and standards has been developed, at the physical layer, the RF-Frontend of a device reaches a bottleneck. This limitation, for example, avoids that forthcoming demands are satisfied according to the technological needs in today's urban areas [27].

Increasing interest towards design and implementation of smart cities and Internet of Things (IoT) has emerged in recent years. The idea of having such a city consists in the employment of technology and advanced systems so that daily life happens in a more efficient and functional way. That means, the integration of physical infrastructures with the digital technologies is what significantly contributes to improve the smartness of a city [28]. An advantage of this, is that a proper utilization of the available technology can greatly improve the interaction of users with their surrounding environment [29, 30]. In this way, a critical demand to face involves the development of high quality devices and the compatibility between them to achieve a smart air interface, i.e. an interface that constantly adapts the necessities or requirements of the user with its environment. Thus, integration of distributed sensors, networks and portable devices like mobile phones, PDAs, and tablets, is required to develop the convergence of the information and communication technologies into global service devices [31].

Based on the general concept to transform conventional communication into an adaptive and energy efficient interoperation of resources, the exchange of data by means of Cooperative Sensor Networks represents a promising attempt to turn a common city into a smart city. CSN are based on a group of interconnected sensors that assist in communication sharing data within a certain area, e.g. to obtain high energy savings of a wireless node [32]. Implementation of embedded system applications connected by cooperative computing provides a flexible solution for sensor networks [33]. For example, to enable mobile cloud computing, an emerging technology that improves the quality of mobile services shares the radio and computing resources [34, 35]. Furthermore, such networks have the characteristic to work dynamically in order to carry out an updated flow of information, either to the end-user or just to another node assigned to perform a predefined task. Thereby, this wireless coordination of sensing devices can perform tasks like monitoring, tracking, warning and surveillance [36].

Strategically located distributed nodes, which continuously sense the environment, are required to be linked and to supply assorted categorized information to the user. Moreover, a user device needs to fulfill demands such as high reliability, mobility and functionality to offer a cost-effective performance of services [37]. That is, the development of smart cities require multiband and multistandard, or even band-less and/or standard-less devices to achieve an efficient communication of the network

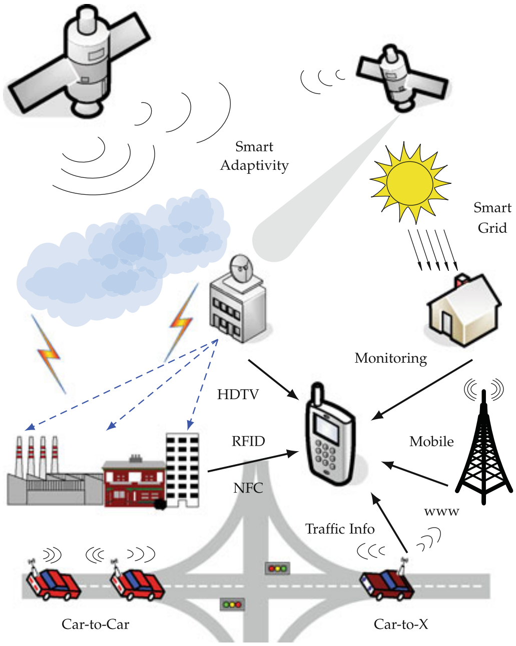

Fig. 2.3 Smart city with interoperation of services and convergence of diverse applications in a multiband and multistandard environment

elements, e.g. between the different nodes, services, and sources of information. Nevertheless, as a result of utilizing different RF modules to handle different services, a lack of a global, energy efficient, and adaptive transmission/reception of information in a device of current architectures is present at the user side [38, 39]. This means, that the current solution is to employ a single hardware module per service if a service is intended to be used [40]. Hence, effective interconnection of living areas between buildings, supermarkets, houses, offices, shopping centers, streets, cars, and parking places, among others is becoming a significant challenge to be solved [41]. Furthermore, other factors like interference and bandwidth constraints will emerge due to the new allocation of services or to the reuse of the frequency spectrum [42].

A smart allocation of frequencies for upcoming applications and services, while supporting current technologies is becoming a particular major issue in today's hardware development [43]. To exemplify this scenario, in Fig. 2.3 possible services and applications within a sensed urban area of a smart city are shown. Alltime online mobile phones, Machine-to-Machine communication (M2M), Car-to-Car communication (C2C & C2X), and smart management of energy in urban areas are just a few examples of on-going developing features. These features demand for the evolution of existing cities, with new kind of architectures, to handle different sources of information within the same device.

Machine-to-Machine Communications

A concept that has been maturing during the last decade is Machine-to-Machine communication (M2M) [44, 45]. This essential part of a smart city has the task to communicate wired or wireless devices which belong to a determined system, or commonly also known as cloud. At another size level compared to a smart city but in a similar fashion, M2M aims to share, improve and monitor, among other characteristics, defined tasks either by the user or by a whole community. For instance, to enable this type of technology using cellular infrastructures, the Third Generation Partnership Project (3GPP) provides machine-type communication when it is used over LTE technology. One characteristic is that a cognitive M2M communication is expected to provide a good approach for dealing with excessive traffic in the network [46].

Here, the management of diverse devices utilizing a variety of mobile technologies, i.e. protocols and standards, represents the use of different kind of devices to realize a defined task. Consequently, the most promising solution is the employment of reconfigurable architectures that are able to handle multifunctionality. For example, by using the minimum amount of hardware to provide a maximum number of services.

Car-to-Car Communications

In a more specific area called Intelligent Transport Systems (ITS), a wireless concept known as Car-to-Car (C2C) communication is arising [47, 48]. It aims at easing road travelling as well as increasing road safety and traffic efficiency. Novelty in the network layer for the exchange of information is established together with the operation at 5.9 GHz defined in the physical layer. Therefore, to provide proper functionality at this frequency band in terms of RF hardware, an increment in the number of architecture elements is expected according to current approaches. Specifically, in the case of components such as antenna, filter, amplifier, and matching network, to enable this mobile technology. This means, that when this technology is adapted into a vehicle, compatibility with other technologies have to be improved in a cost-effective way [49], e.g. to avoid possible sources of interference, and to keep compactness in the RF-Frontend of the portable device.

On top of the described novelty in the concepts of previous examples, M2M and C2C, there is one common denominator which can be translated as an unavoidable increase of hardware. That is, on the one hand, the present solution is to develop a single device for each service to make use of each of these latest features, or to include multiple hardware modules into the current architecture. On the other hand, however, a reconfigurable architecture can overcome the increase of RF modules and hardware complexity.

Wireless Multiband Transceivers

Different approaches to face the challenge of an efficient spectrum management from the hardware point of view are emerging, e.g. at the antenna side of a reconfigurable RF-Frontend [50, 51], or in recent years by implementing fully integrated CMOS based transceivers for SDR applications [52].

A summary of current multiband RF chip transceivers is shown in Table 2.1. These RF-signal processors are used in deployments compliant with standards and technologies employed in nowadays mobile communication systems. Furthermore, this

Table 2.1 Performance of different commercial ICs RF transceivers

	LMS6002D	LMS7002D	AD9361
Communication mode	SISO	MIMO (2 × 2)	MIMO (2 × 2)
RF frequency range	0.3 ∼ 3.8 GHz	0.05 ∼ 3.8 GHz	0.07 ∼ 6 GHz
Baseband BW	0.7 ... 14 MHz	0.1 ... 54 MHz	0.2 ... 56 MHz
Supply voltage	1.8 V	1.8 V	1.3 V
Transmitter			
Maximum output power	<+6 dBm	<+19 dBm	<+9.5 dBm
Gain control	56 dB	70 dB	90 dB
Gain control step	1 dB	1 dB	0.25 dB
D/A converter	12 bits	12 bits	10 bits
LO leakage	<−50 dBc	<−50 dBc	<−50 dBc
DC current	280 mA	<200 mA (2 Tx)	<820 mA (2 Tx)
	@+6 dBm	@−7 dBm	@+7 dBm
Receiver			
Gain control	<61 dB	<70 dB	<75 dB
Gain control step	3 dB	1 dB	1 dB
Noise figure	<10 dB	<3.6 dB	<3.8 dB
IIP3	−1 dBm	3 dBm	>−18 dBm
A/D converter	12 bits	12 bits	12 bits
DC current	220 mA	280 mA (2 Rx)	<445 mA (2 Rx)

This comparison takes different general parameters into account for the signal processors, considering their transmitter and receiver characteristics [53, 54]

kind of transceivers can make use of its flexibility so that additional implementations of reconfigurable transceivers based on CR and SDR techniques can be enabled. Three different signal processors are compared: LMS6002D and LMS7002D from Lime Microsystems [53], and AD9361 [54] from Analog Devices. While the first chip transceiver supports only SISO (Single Input Single Output) communication, the last two ICs are MIMO enabled.

At the time of realization of this work, only the RF-signal processor LMS6002D was commercially available, and therefore, it was taken into account for the development of hardware demonstrations. However, these demonstrations are fully compatible with the current version of the IC LMS7002D.

To summarize this section it should be mentioned that different approaches, such as the combination of SDR and CR techniques, and technologies can enable agile radios depending on the necessities and constraints of the design itself. For example, frequency of operation, required tunability and power handling. Furthermore, special attention to integrate the RF-Frontend in the transceiver should be given based on the hardware control of all RF components to optimize the narrowband signal at the desired frequency. In this way, the best performance in the overall architecture can be guaranteed. That is, the combination of wide tuning reconfigurable transceivers, as well as state-of-the-art material technologies that enable microwave components and integrated circuits, represent an attractive solution to cover the complete spectrum where allocated mobile services, current and future portable applications form part of the ever-increasing smart interfaces.

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http://www.springer.com/978-3-319-24579-9

Reconfigurable Transceiver Architecture for Multiband RF-Frontends
Gonzalez Rodriguez, E.
2016, XIV, 114 p. 77 illus., 56 illus. in color., Hardcover
ISBN: 978-3-319-24579-9