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A new digital front-end for flexible reception in software defined radio ☆

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ABSTRACT

Future mobile terminals are expected to support an ever increasing number of Radio Access Technologies (RAT) concurrently. This imposes a challenge to terminal designers already today. Software Defined Radio (SDR) solutions are a compelling alternative to address this issue in the digital baseband, given its high flexibility and low Non-Recurring Engineering (NRE) cost. However, the challenge still remains in the Digital Front-End (DFE), where many operations are too complex or energy hungry to be implemented as software instructions. Thus, new architectures are needed to feed the SDR digital baseband while keeping complexity and energy consumption at bay. In this article the architecture of a Digital Front-End Receiver (DFE-Rx) for the next-generation mobile terminals is presented. The flexibility needed for multi-standard support is demonstrated by detecting, synchronizing and reporting carrier-frequency offset, of multiple concurrent radio standards. Moreover, the proposed architecture has been fabricated in a 65 nm CMOS low power high-VT cell technology in a die size of 5 mm^2. The core module of the DFE-Rx, the synchronization engine, has been measured at 1.2 V and reports an average power consumption of 1.9 mW during Wireless Local Area Network (WLAN) reception and 1.6 mW during configuration, while running at 10 MHz.

1. Introduction

Wireless communications is one of the fastest growing market segments. According to estimations by the International Telecommunication Union (ITU) there is today the same number of mobile subscribers, as the number of people living on this planet [1]. Moreover, each mobile terminal is expected to concurrently support a variety of Radio Access Technologies (RATs), as mobile terminals require to connect to specific services via different interfaces.

Traditionally individual chip-sets customized per connecting RAT and interfaced in a system ecosystem to provide to the user a seamless connectivity experience. However, as the number of standards raises, this solution becomes, unpractical and cost-ineffective and imposes a high development risk. Furthermore, the multiple chip-set solution makes handover between radio technologies unfeasible.

It is well identified that simultaneous support of multi-standard data receptions using flexible hardware platforms is a great challenge. Although some early attempts have been presented in both academia and industry [2,3], experiments so far have been limited to the support of a single data stream. Switching between different standards is only possible through off-line configurations and is conducted by an external host controller. Despite not being reported, configuration time during context switching is envisioned to be on a scale of hundreds of clock cycles, since the host controller has to be interrupted to conduct the loading of appropriate programs/configurations before getting ready for new data receptions. Evidently, this off-line switching approach is highly unacceptable from user's experience point of view, as terminals are temporarily "disconnected" ever time when entering into a new radio environment.

Software Defined Radio (SDR) addresses this issue by abstracting hardware functionality into software oriented instructions [4]5. In this manner, a SDR mobile terminal will be able to move from standard to standard, by dynamically adapting its internal

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structure in accordance to the instantaneous mobility and data rate required. However, there is still a gap to be filled in the Digital Front-End (DFE) where the high throughput makes SDR solutions hard to develop. A brief overview of the Digital Front-End Receiver (DFE-Rx) described here has been already introduced in [6]. The current article takes the work presented in [6] and focuses on detailing the particulars of the crucial blocks of the entire architecture. Namely, the resampler, and the synchronization engine. Additional results are also included, such as performance plots and better visualization of the hardware complexity.

The outline of the current article can be described as follows. In Section 2 the multi-standard environment is described, together with the target application, i.e., synchronization during acquisition. In Section 3 an overview of all the blocks in the DFE-Rx are briefly described in order to understand their functionality and inter-connection between various modules of the architecture. In Section 4 the most relevant blocks are described in a more detailed manner, exposing the real value of the architecture. In Section 5 the hardware cost are presented and analyzed. Section 6 presents the results obtained from simulations and measurements. Finally conclusions are presented on Section 7.

2. Multi-standard environment in SDR

In the future wireless ubiquity, a mobile terminal will be subject to an uninterrupted multi-standard environment. In this scenario, the ability to adapt to the wide range of connectivity alternatives is essential.

2.1. Standard selection

In this study, however, it was decided to narrow down the number of standards to be supported. In order to motivate the final standard selection, take a look at Fig. 1, where some of the most popular standards are classified in relation to its data-rate and user-mobility. On the bottom-left corner are the standards that provide the lower data-rate under stationary conditions, which implies that they are considered as low energy consumers. Different standards cover different areas in the plot that also place different requirements on the terminals supporting them.

From the figure it can be seen that Orthogonal Frequency Division Multiplexing (OFDM)-based standards (i.e., Long Term Evolution (LTE), DAB, IEEE 802.11, IEEE 802.16, and DVB-H) are more dynamic, as they cover a larger portion of the plot, in addition to achieve the highest data-rate in the figure. Thus, supporting concurrent OFDM standards is a basic requirement in a reconfigurable DFE for SDR. Even though there is some research on reconfigurable hardware for multiple standards [8], to the best knowledge of the authors, no attempt has been done in focusing on OFDM-standards alone (taking advantage of their similarities), nor in considering concurrent support.

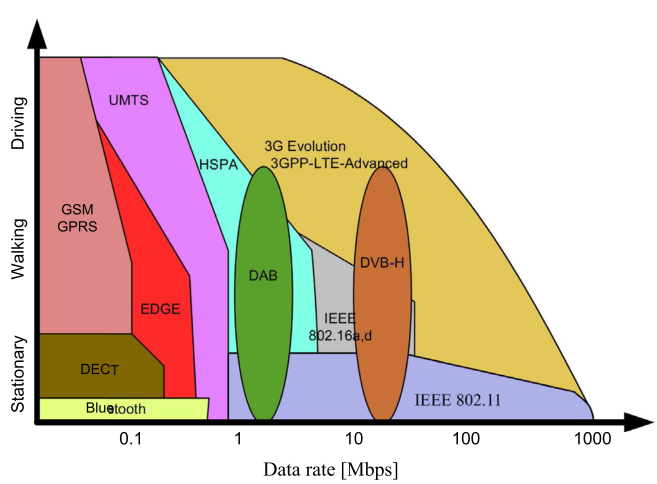

Fig. 1. Data rate transmission vs mobility for wireless standards extended from IMEC Scientific Report 2007 [7].

As a proof of concept, it was decided to focus on three OFDM standards that provide complimentary services, namely, Wireless Local Area Network (WLAN) contributing to high data-rate under stationary conditions, LTE for high mobility with moderate data-rate and Digital Video Broadcasting-Handheld (DVB-H) providing multimedia broadcasting services. Since the selected standards are OFDM, reuse in several hardware blocks is possible, while differences make reuse non-trivial.

2.2. Target application

The DFE is the first stage after the Analog to Digital Converter (ADC) and before the baseband processor, where the first operation in the baseband is the Fast Fourier Transform (FFT). In this part of the terminal one of the most important operations is the synchronization process.

The synchronization process is usually performed in time and frequency domain, commonly referred to as *acquisition* and *tracking* stage, respectively [9]. The acquisition stage aims to find the start of each OFDM symbol and to perform a rough estimation of Carrier Frequency Offset (CFO). The tracking stage aims to refine the parameters obtained from the acquisition stage. This study focuses on the acquisition stage and assumes that the channel impulse response is shorter than the length of CP.

Maximum Likelihood (ML) estimation [10] is commonly used to perform synchronization in OFDM systems. The algorithm is based on either pilots/preamble or CP in OFDM symbols. In the three standards under analysis, CP is present. Besides, IEEE 802.11n contains a preamble, which has specific Short Training Symbols (STSs) designed for data detection and time synchronization [11]. Given that all STSs are identical, the first STS can be considered as the CP of the remaining part in the short training field. Based on either CP or preamble, the ML estimate can be expressed as

$$\hat{\theta} = \begin{cases} \arg\max_n\{|\gamma[n]|\} & \text{if } |\gamma[n]| \geqslant T \\ 0 \text{ (estimate not found)} & \text{otherwise,} \end{cases} \quad (1)$$

with

$$\gamma[n] = \sum_{k=0}^{L-1} r[n-k]r^*[n-M-k], \quad (2)$$

where $r[k]$ is the received data vector, $\gamma[n]$ is the output of moving-sum, $\hat{\theta}$ indicates the estimated symbol start, and $(\cdot)^*$ denotes the complex conjugate operator. T represents a threshold value, used to find the symbol start by detecting the position of the maximum correlation value. T is adjusted in accordance to different standards and the expected Signal-to-Noise Ratio (SNR). L is the length of the moving-sum operation, and M is the autocorrelation distance, i.e., the number of samples from the start of CP to its corresponding copy within the OFDM symbol. The values of L and M vary among standards and also between different synchronization methods, i.e., CP-based for LTE and DVB-H and preamble-based for IEEE 802.11n. Table 1 summarizes the values of L, M and the number of subcarriers N_c for the three standards. In CP-based synchronization, the autocorrelation distance M equals to N_c, and the size of the moving-sum L equals to the length of the CP. LTE and DVB-H fall into this category. Since better synchronization accuracy is expected when using preambles, preamble-based approach is used for IEEE 802.11n. In this case, M corresponds to the size of a STS and