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MUMOR

D4.4

Extending MuMoR SDR Architecture Towards 4th Generation Radio Systems

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Abstract:

The purpose of this deliverable is to present possibilities to extend the developed 3G system architectures towards 4G systems. Both digital baseband and analog front-end architectures will be investigated. Because there is no such standard available right now, in the beginning of this report a vision about the 4G system will be created or to be more precise different possibilities of how a 4G system could look like will be discussed. From this vision the system parameters and the value ranges, which are relevant for the physical layer implementation will be derived. Then it is shown how the developed architectures can be augmented to also implement the different views of how a 4G system could look like.

Keyword list: UMTS, HSDPA, FDD, TDD, WLAN, MC-CDMA, 4G, Front-End, Baseband

Abbreviations / Terminology

Note: Some of the abbreviations, terminology and vocabulary, which are frequently used in the 3GPP specification are considered as "well known" and are used in the present document without being explained. Please refer to the 3GPP "Vocabulary" document (3G TR 25.990) in this case.

AP	Access Point
B3G	Beyond 3G
BSS	Blind Source Separation
BT	Bluetooth
CCK	Complementary Code Keying
CORDIC	Coordinate Rotation Digital Computer
CPICH	Common Pilot Channel (UMTS)
DAB	Digital Audio Broadcasting
DL	Downlink
DVB-H	Digital Video Broadcasting (Handheld)
DVB-T	Digital Video Broadcasting (Terrestrial)
EUDCH	Enhanced Uplink Dedicated Channel
FD	Frequency Domain
FD	Frequency Domain
FDD	Frequency Division Duplex
FFT	Fast Fourier Transformation
FM-UWB	Frequency Modulation Ultra Wide Band
HSDPA	High-speed downlink packet access
IFFT	Inverse Fast Fourier Transformation
IR-UWB	Impulse Radio Ultra Wide Band
LTS	Long Training Symbols
MAC	Multiply Accumulate
MANET	Mobile Ad-hoc Network
MBMS	Multimedia Broadcast Multicast Service
MC-CDMA	Multi-Carrier Code Division Multiple Access
NFC	Near Field Communication
OFDM	Orthogonal Frequency Division Multiplex
PAN	Personal Area Network
PE	Processing Element
PN	Personal Network

POTS	Plain old telephone service
RAN	Radio Access Network
RF-ID	Radio Frequency Identification
SI	Study Item (in 3GPP)
STS	Short Training Symbols (WLAN)
TD	Time Domain
TDD	Frequency Division Duplex
UL	Uplink
UWB	Ultra Wide Band
WI	Work Item (in 3GPP)

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1 Introduction

The purpose of the MuMoR project is to design and demonstrate a multi-mode capable radio physical layer front-end and baseband for mobile terminals. The main application for the investigation of appropriate design approaches mainly were the various operational modes of the 3rd generation standard for mobile communication. The different duplex modes FDD and TDD of the 3GPP system have been considered as well as the standardised extension HSDPA in FDD mode. For the front-end also the combination with legacy systems like GSM have been investigated already during the project.

In the front-end domain flexible components have been designed to cope with the requirements of the different standards in terms of

- bandwidth,
- gain,
- speed,
- accuracy,
- linearity,
- noise,
- power consumption

and further criteria to be able to implement an optimised multi-mode analog front-end, which is feasible for small battery-operated devices.

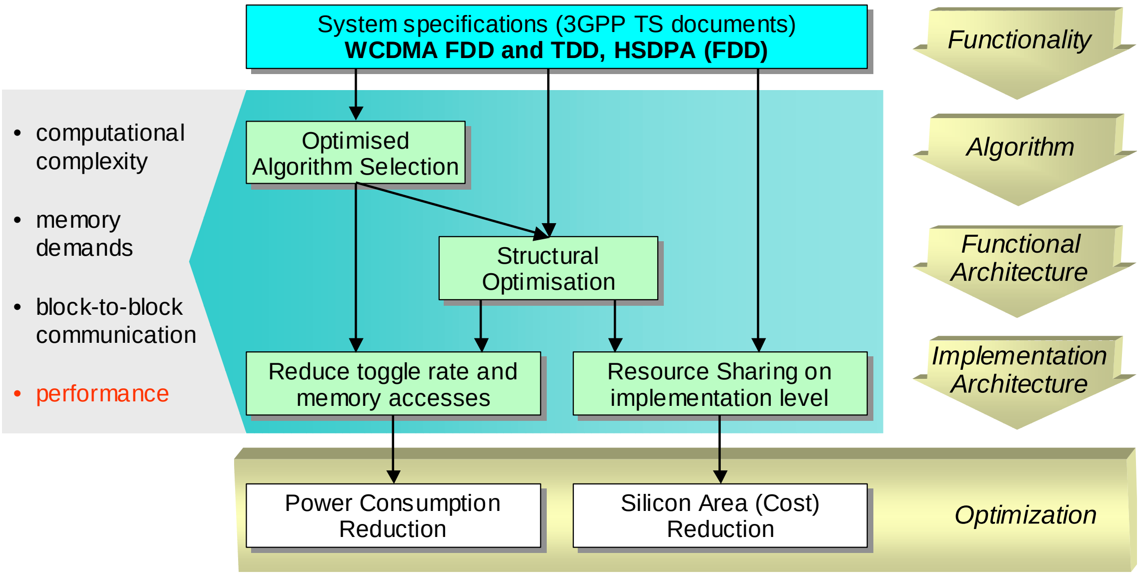


Figure 1.1: Optimisation is baseband domain

In the digital baseband design different activities have been done to optimise the implementation in terms of silicon area demands and power consumption. Figure 1.1 shows the different levels of optimisations that have been done. Based on the underlying standardisation, which basically defines the system from functional perspective, the appropriate algorithms have been well selected to either directly allow simplifications in the implementation architecture or indirectly lead to a decreased power consumption or silicon area (mainly to achieve better yield for cost reduction).

The different kinds of optimisations for flexible, yet efficient, design implementations are not limited to the investigated radio systems. Consequently an additional concern of the project is the extension of the approaches for multi-mode design also towards forthcoming generations of mobile terminal devices and the radio communication standards to be supported. This outlook towards the 4th generation radio systems will be done in this report.

Obviously at this point in time there is no such thing like a standard document for a 4G system. There has not even yet a group or association formed for creating and evaluating proposals. However, there are already a number of visions and ideas how this system might look like. The potential 4G system from MuMoR perspective will be introduced in chapter 2. Based on this view of how a 4G system might look like the implications for the respective analog front-end of such a terminal receiver will be presented in chapter 3. The same information about the digital baseband will be given in chapter 4.

2 Vision of the 4th Generation Radio Radio System

2.1 Motivation for 4G System

The transition from the 2nd generation of mobile cellular networks to the 3rd one was motivated by the introduction of mobile multimedia services. It can be already anticipated that the demand for much higher bit rate services with high mobility will increase rapidly. This kind of demand requires a new air interface technology since current systems offer high bit rate for low mobility or low bit rate for high mobility. Figure 2.1 shows the deployment area and the bit rates of existing systems and the area and bit rate that are foreseen for the new air interface.

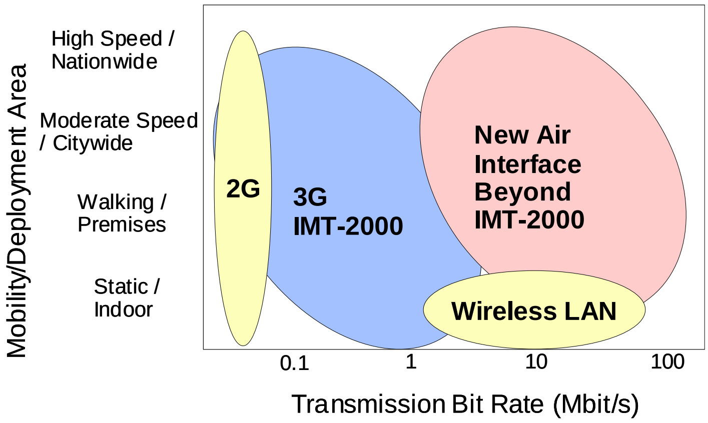


Figure 2.1: Comparison of Deployment area and Bit Rates of existing and new systems

3 Implications for the Analog Front-End

This chapter investigates the capability of extending the different front-end subsystems towards the requirements of 4th generation systems. As mentioned above there is still no proposal for 4G systems, so the discussions in this chapter cover topics that are seen to be relevant by the view of MuMoR consortium. These topics are

- Extending the multi-radio approach towards a high variety of different standards
- Combination of totally different air interfaces
- Increase of signal bandwidth and linearity requirements
- Multi-antenna design

The 4th generation of wireless systems will very probably introduce the challenge to bring very different standards together. Looking to current multi-mode and multi-standard systems (GSM/GPRS/EDGE variants in 2G, WCDMA/HSDPA variants in 3G), they usually support standards that that allow re-configurability of block parameters by keeping the block architecture similar for all supported standards. A lot of research is currently ongoing to combine 2G and 3G requirements into configurable hardware, as systems that are available on the marked mainly operate with parallel signal paths. Results of MuMoR project indicated that a simple parameterization of blocks is no longer sufficient for quite different standards, especially if parameters like power consumption and cost (area) shall be optimised, too. That dilemma will increase in 4th generation systems, as the variety of standards that pose totally different requirements to the front-end will increase. The effect to the front-end can be shown by the example of OFDM support. Here, the peak-to-average ratio is much higher than in current CDMA systems. A transmitter that has to support both CDMA and OFDM signals is hard to optimise for both systems, as the result has to be a trade-off between linearity and power consumption requirements. That indicates that a multi-architecture approach as it has been developed in MuMoR for frequency synthesizers gives a high potential to other front-end sub-systems.

First results about combining spread-spectrum and OFDM systems have been obtained by the German funded project RMS (Re-configurable Mobile Systems) that was active from 2001 until 2004. System partitioning was deeply investigated with the constraints of technology availability and cost, resulting in a block-by-block consideration about parallelization or re-configuration. The RMS project showed that re-configurability of low-frequency blocks (analog baseband) is possible even in a wide parameter range, whereas it is difficult to find optimised cost functions for performance, area, and power consumption for radio-frequency parts of the circuit.

The role of power consumption will surely increase with upcoming 4G systems. Higher data rates require wider bandwidth, higher sampling, and higher accuracy. All that parameters have direct impact on power consumption. Considering multi-antenna systems (MIMO) that will probably find their way into 4G, energy consumption might even limit the feasibility of a wireless system. MIMO requires fully parallel transceiver front-ends for each antenna, resulting in a dramatic increasement of power. Even if technology progress allows the reduction of required area, the supply currents will not scale down in the same way, causing punctual heat concentrations in the circuit that prevent proper operation.

Considering the user requirements for 4G systems, main decisions about buying a device or not will still be parameters like talk and standby times, as well as design parameters like volume and weight of a device. These are mainly given by the battery and, with that, by power consumption. A non-acceptance of that parameters by the customer could endanger the whole development of 4G to a technologically sophisticated standard. A current example can be found in the WLAN integration to mobile phones that is retarded by the high power consumption of the relevant modules.

The following chapters discuss the effect of 4th generation radio system requirements to the front-end subsystems in detail.

3.1 Implications for frequency synthesizers

If the 3G systems already require a mobile transceiver to handle several air interfaces, the 4G systems :

1) will reinforce this trend with more different air interfaces to deal with;

2) may see the coming of new air interfaces allowing higher data rates than today.

The first point will lead to a redefinition of the reconfigurability whereas the second will put tighter constraints on the frequency synthesis (PLL).

On the technology side the future sub-micron processes as well as above-IC processes will open the way to new architectures.

3.1.1 Redefining reconfigurability

Current multi-mode transceivers usually deal with a small number of standards having similar frequency ranges and phase noise specifications, namely the GSM, DCS and W-CDMA. Roughly speaking it is then possible to use the same PLL architecture (for example the frac-N one) for all these standards with rather small adaptations (the frequency range, the loop bandwidth, the VCO phase noise, …). The PLL can have some parts being reconfigured or connected on demand while the others are always in use.

On the other hand the future transceivers should be connected to high data-rate Wireless Local Area Networks (WLAN) as well as short-distance low data-rate Person Area Networks (PAN).

The former require a low phase noise PLL, the latter low-consumption PLL. Having the same PLL reconfigured for such standards may be unfeasible and whatever may not be efficient.

The LC-VCO developed within MuMoR has already made obvious this last point. While fulfilling phase noise specifications of both RX and TX W-CDMA modes, it was overspecified in term of phase noise for the RX mode although its power has been set to its minimum. But the LC architecture chosen require a minimum power to keep the oscillation on. In fact this VCO was too luxurious for the RX and only another architecture could provide the specified phase noise with an ever lower power consumption.

For the high-end standards the expected higher performance required from the PLLs will generalize the use of digital techniques to go beyond the intrinsic limitations of the technology as long as analog performance is concerned. For example an auto-calibration sequence will periodically compare the PLL frequency to a stable reference (the down link signal for example) to deal with static (i.e. process) and dynamic (i.e. temperature and supply voltage) variations. With the availability of sub-micron processes it will also be possible to make the base band signal processor correct the frequency shift of the PLL. This digital stuff will at the same time alleviate the analog design task and improve the overall performance of the transceiver.

We see that the reconfigurability will, at the same time, be less ambitious at the analog level (the all-in-one block is senseless) and widen its scope to include the digital part of the transceiver.

3.1.2 Taking advantage of new technologies

For the low-end standards (PAN networks) the sub-micron processes will allow to investigate new concepts of PLL while still keeping the power consumption at a low level.

Digital PLLs seem promising as far as moderate phase noise is needed.

The concept of synchronous oscillators investigated within MuMoR is applicable to all kinds of oscillators. Such structures like relaxation or delay cell oscillators which rely on full CMOS devices could pave the way to new types of PLLs combining moderate performance, low area and low cost.

Above-IC processes such as bulk acoustic waves will make high-Q resonators a reality. With such devices PLL designers can re-think the PLL architecture from scratch with possible innovative designs at the end, which, in turn, will impact the overall transceiver.

3.2 TX

The impact of the requirements of the different standards is much more demanding for the TX than for the RX. The generation of high power signal is much more sensitive to signal details like crest factor. The relative spurious and noise emissions depend from the signal power transmitted and from other details like the utilization of time or frequency division duplex.

Even the integration of the 2G and 3G standards GSM and FDD/TDD require partly separate signals paths due to their too different system requirements. In Figure 2, the solution proposed in the MuMoR project is shown. In this architecture, both signals are generated at the transmit frequency using an IQ-modulator. For the FDD/TDD path, the signal passes an variable gain amplifier VGA and after filtering it is applied to the PA. The GSM path require additional on-chip filtering, which is accomplished using an variant of the commonly used offset-PLL.

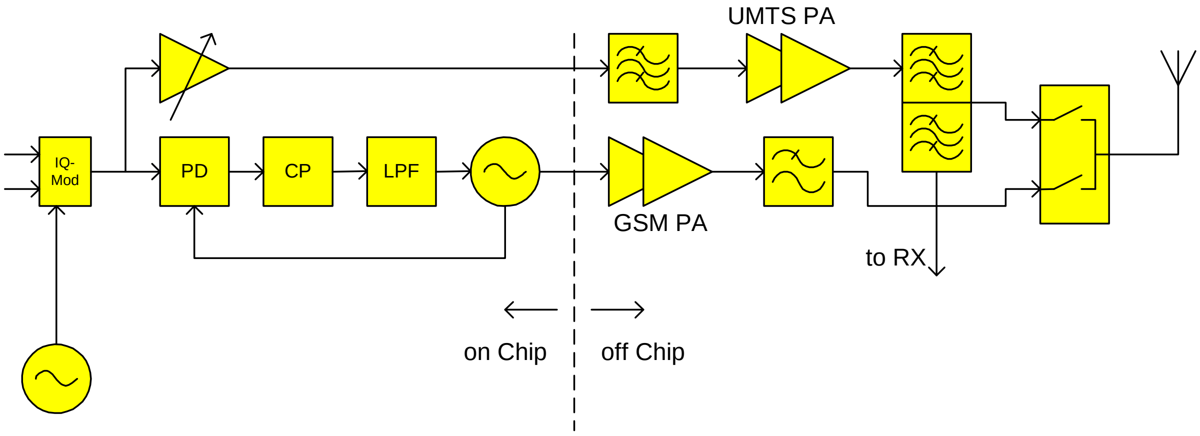


Figure 2: Multi-mode GSM/FDD/TDD transmitter using direct PLL for filtering of GSM signal.

The availability of on-chip filters greatly changes the trade-offs in the architectural design of the transmitter. Usually, filters are external and costly. They require additional pins, the IC is always short of. The system designer of a transceiver IC tries to avoid filters as much as possible. When having filters internally on the die, the preferred architecture is completely different.

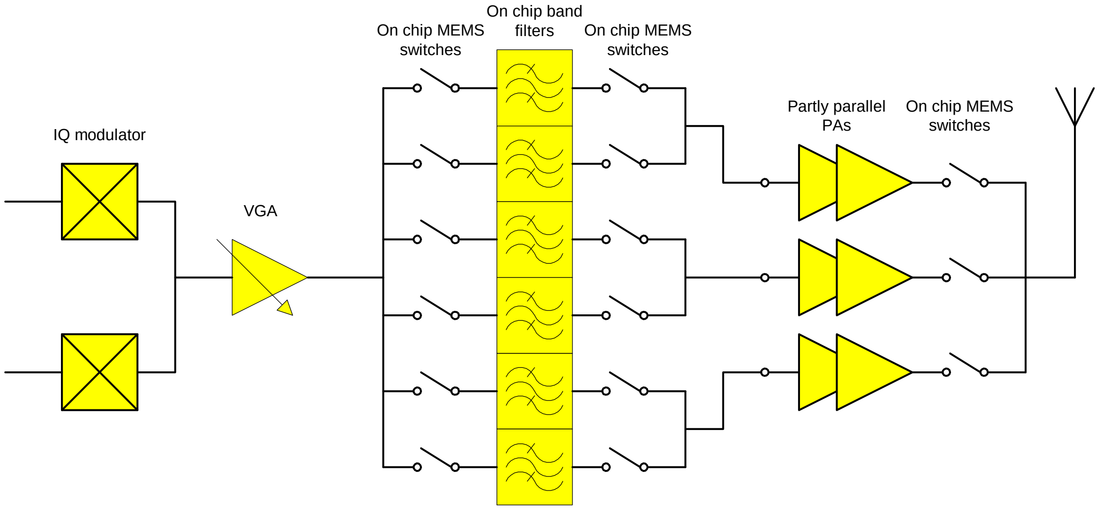


Figure 3: Multi-band multi-mode transmitter.

Figure 3 shows an example if a multi-band multi-mode transmitter using on chip filters. The signal is generated using a direct modulator and level adjusted in the VGA. To ensure the spurious and noise emission requirement for each standard, a bank of switchable filters is integrated in the chip.

Having these filters available, the noise requirements for the remaining components can be reduced. This has some implications on the block level specification.

- The current consumption for the building blocks can be reduced. The resulting additional noise will be eliminated using the on-chip filters.
- A cheaper technology can be used having inherently worse noise performance.

3.2.1 Implications on Mixer and VGA design

Having on-chip filters available, the trend in the design of IC building blocks will be with the scope of extremely low current consumption while still having a moderate noise level with filtering suitable to the requirements of the standards. Without filtering, bias current of the different stages has to be chosen to ensure sufficiently good wideband SN; usually the active devices chosen did not have minimum feature size.

If the required SNR of the mixer can be reduced by 20 to 30 dB due to additional filtering, minimum feature size active devices can be used, the bias of these components would be as low as possible to reduce current consumption.

3.3 RX

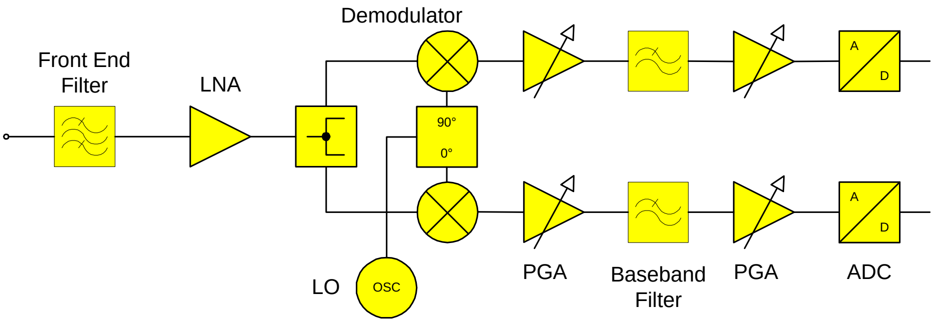


Figure 4: Direct conversion receiver.

The architecture of choice for the later 2G and 3G systems is the DCR. It has the advantages:

- Suitable for integration
- Straightforward change of receive signal bandwidth

The elimination of external channel select filters is effective in cutting cost, so that currently all cellular receivers are DCR. However, a DCR also suffers from some inherent problems:

- DC offset
- AM-detection

These problems have been overcome within the past years, so that currently the DCR is a mature architecture for cellular systems. However, additional circuitry is necessary compared to a superhet.

The trade-offs might change with the upcoming of integrated MEMS filters, allowing the integration of channel select filters and also band filters on the chip. Having these filters available, there is no need to choose a DCR and the associated circuitry like DC-offset correction can be avoided.

3.3.1 LNA

In today’s multi band cellular ICs, one LNA is used for each band. The reason for this is twofold:

- Each LNA need a specific band filter (SAW filter) to ensure the out band blocking requirements of the complete phone. Connecting these filters to one broadband LNA would require an additional switch and therefore additional loss, which has to be avoided.
- Each LNA needs a specific matching to minimize the noise figure in this particular frequency band.

Today’s quad band GSM phones already have four differential LNAs, resulting in eight pins for the signal and additional pins for Vcc and Gnd at the receiver IC. Extending these phones — and the respective transceiver ICs — to multi-mode multi-band, would require even more LNAs and pins at the transceiver IC. The scenario for a world phone could be:

- GSM 850
- GSM 900
- GSM 1800
- GSM 1900
- FDD (ITU region I)
- FDD (ITU region II)
- FDD (ITU region III)
- TDD (ITU region I)
- TDD (ITU region II)
- TDD (ITU region III)
- WLAN (IEEE 802.11b)
- WLAN (IEEE 802.11g)

It is clear, that all these different frequency bands should not be handled by separate LNAs. This would require a large chip area and also a too high number of pins at the transceiver IC.

Usually, LNAs in transceiver ICs for cellular standards are quite broadband. The frequency selection is carried out using the band filters. So at least all the standards operating at approximately 2 GHz can be handled using one single LNA (having only 2 external pins).

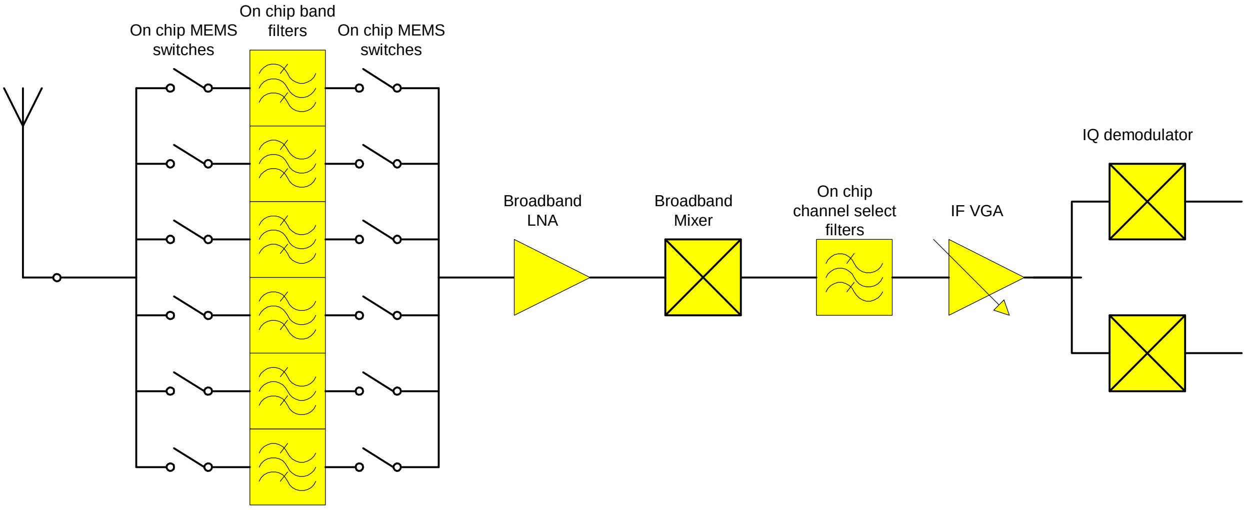


Figure 5: Completely integrated receiver.

Figure 5 shows a block diagram of a receiver having all filters and switches integrated in the IC. MEMS filters are used for switching due to their low insertion loss. For band and channel select filtering integrated MEMS filters like FBAR can be used. It is clear, that, compared to the currently used DCR with external filters, such a receiver have several advantages:

- No external filters.
- Small size
  - Only one LNA
  - Only one mixer
  - Only one external input signal pin.
- Passive IF filter
  - No current consumption of IF filter
- No DCR related problems like DC-offset and AM-detection.

The superhet requires two LO signals, one for the first mixer and one for the IQ-demodulator. To avoid two complete synthesizers, the second LO signal can be generated from the first LO simply using a divider, which will require fractional-N synthesizers.

Implications for LNA design:

In the proposed architecture, one single LNA has to be capable of handling all the different standards at different frequency bands. The LNA matching is sometimes placed off-chip to reduce the die size and also due to the lower loss of an external matching network. However, no single matching at the LNA input will give a low noise figure in all bands. This will give some implications on the LNA design:

- The LNA should have an input impedance very close to the impedance if the on-chip filters. Since the filters are matched to 50 Ohm at the antenna side, the impedance at the LNA side will also be close to 50 Ohm.
- Having all matchings completely between the on-chip-filters and the switches will result in a large space consumption on the die. Instead, the main part of the matching — using a fairly large inductor — is placed directly at the LNA input; the fine tuning of the matching in the different frequency ranges is performed directly at the filters. This is shown in Figure 6.

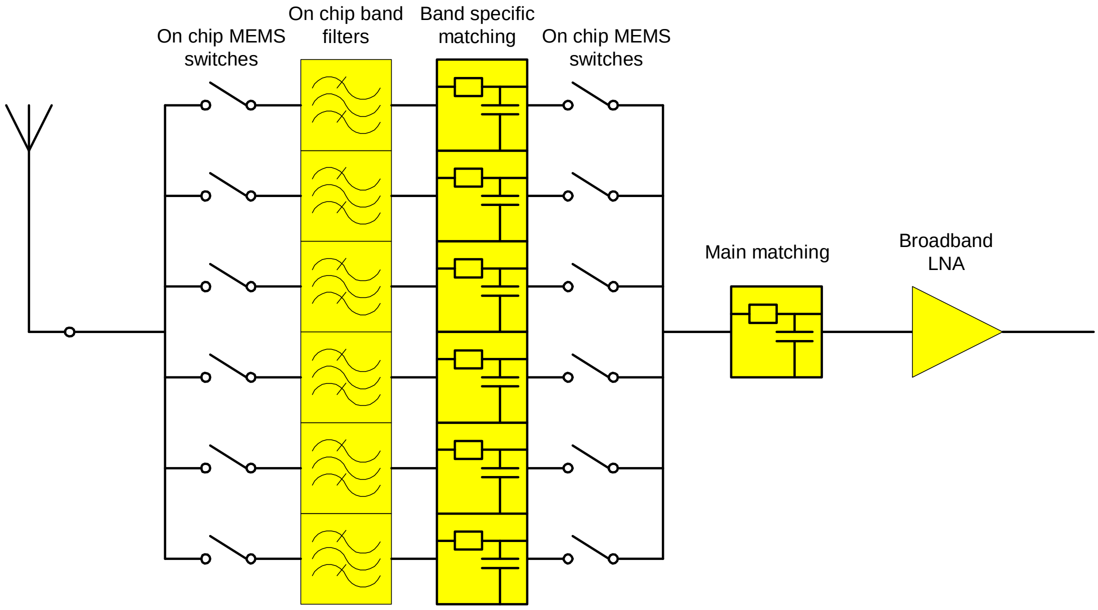


Figure 6: Separation of-on-chip matching to save chip space.

3.3.2 Parallel signal reception

One disadvantage of multi-mode receivers is, that they usually do not allow reception of signals in parallel.

4 Implications for the Digital Baseband

In this chapter the architecture of the digital baseband part is investigated in terms of its capability to be extended to 4G systems. Before this is done the aspects of the 4G visions, which influence the PHY layer, are extracted and presented. This analysis is done separately for the two main directions of assumptions:

(1) 4G is the seamless integration of different air interfaces (chapter 4.1)

(2) 4G will be based on a dedicated new air interface (chapter 4.2).

Additionally in chapter 0 general concerns of applying multiple antennas at the receiver to enable the utilization of MIMO are presented.

4.1 Integration of Different Standards

One vision for 4G mobile communication that is relevant for the digital baseband implementation is seeing the system as a seamless integration of existing or soon arising wireless networking air interfaces rather than the a new developed radio access network (RAN) like 3G was. In this case there are typically three kinds of networks mentioned in addition to the wide-area mobile communications RAN:

- High data-rate local mobility: Wireless Local Area Network (WLAN)
- Proximity Ad-hoc Networks or Person area networking (PAN)
- Broadcasting technologies

The mixture of different networking technologies has been investigated from entertainment perspective within the IST-Project mGain [MG_D823]. In its deliverable “Mobile Entertainment” among other topics the technologies enabling mobile entertainment have been investigated. For this report the network technologies are of major focus. Figure 4.1 shows a multi-interface terminal within a scenario environment.

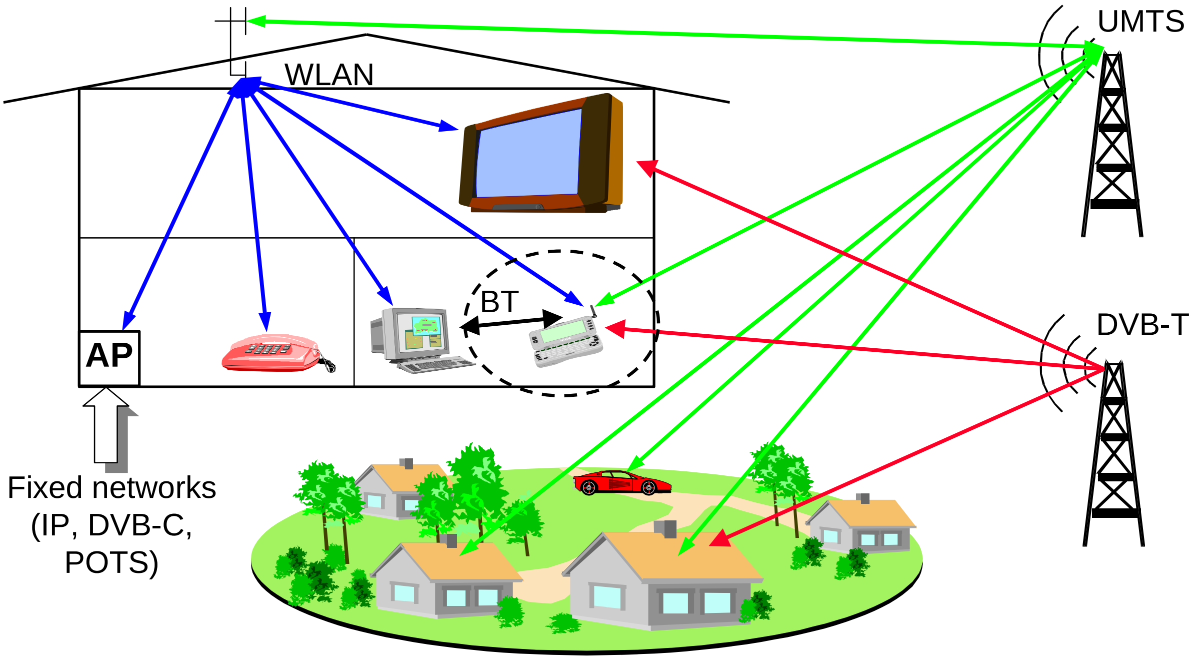


Figure 4.1: Multi-interface terminal (in dashed circle) in a scenario environment

4.1.1 Wireless Local Area Network

In [MG_D823] it is stated that the capacity of high data rate fixed networking can be extended locally with wireless local area networking technologies. These technologies are many times seen as “cable-replacement” technologies in home and office environment. However, wireless local area networks are nowadays also used for providing wireless high data rate local Internet access in many public environments, such as airports and hotels. There is a growing tendency towards high-speed wireless local area networking (also referred as hot spot services). These networks are interesting as an alternative or complementing networking technology for wide-area networks such GPRS and UMTS.

From physical layer point of view it is important to consider that the state-of-the-art WLAN standards are based on OFDM. For example IEEE 802.11a and Hiperlan/II are both using OFDM to achieve 54 Mbps. The main difference is apparent in the MAC layer, which not relevant for this report.

However, there are other solutions than OFDM that have been previously used and are candidates for future implementation. For example the IEEE 802.11b physical layer is using CCK modulation to achieve 5.5 or 11 Mbps. But also the task group IEEE 802.11g that was formed to draft a standard that achieves higher data rates in the 2.4 GHz band currently has two leading PHY layer candidates: single-carrier-coded 8-PSK modulation and OFDM identical to the 802.11a modulation.

4.1.2 Proximity Ad-hoc Networks

In contrast to the WLAN that mostly operates with access point connected to a wired backbone the ad-hoc networks do not have such a specific device within the network, thus implementing true peer-to-peer connectivity. This statement is true at least from the physical point of view. The logical level structure of an ad-hoc network often requires the existence of a central control instance to handle the medium access control efficiently. This device has to transmit beacon signals to keep the frame timing alive and synchronous. The difference to AP based networks is that in the ad-hoc peer-to-peer network, each device can take over that role.

Ad hoc and peer-to-peer networking are one of the most interesting emerging and future networking concepts. They both refer to the ability of peer networking nodes (such as mobile or portable devices) to establishing wireless communication link with neighbouring nodes in a spontaneous manner. Standardisation and development work is undertaken by IETF under the MANET (mobile ad hoc networks) [MANET] to develop ad-hoc routing protocols. Ad hoc networking is reality today with peer-to-peer connections in for example communication devices such as Bluetooth that are aimed to form ad hoc connections with neighbouring Bluetooth devices.

In IST-Project MAGNET currently there are several types of air interfaces concepts under development and discussion based on different physical layers. Here scenarios with and without access point are investigated. The scenario with access point is meant for the augmentation of the PAN to a personal network (PN). In a PN not only access to the data and devices carried along with the person can be granted but also to remote data and devices, e.g. at home or in the office, via additional networks. Under investigation are [MAG_D321]:

- MC-CDMA: The target of the MC-CDMA activities in MAGNET is to investigate the application of MC-techniques along with CDMA in a PAN scenario and to develop a PAN air interface based on these techniques. Combination of MC with CDMA does not only encompass pure MC-CDMA where symbols are spread in frequency domain but also spreading in time domain and combinations thereof. CDMA will be part of the multiple access scheme; still, the MC-CDMA approach does not restrict the system from using other division methods for duplexing and multiple access.
- OFDM-TDMA: The target of the OFDM-TDMA activities is to investigate the suitability of OFDM as an air-interface for PANs. The OFDM-TDMA system will fulfil the requirements of the PAN AP scenario where an access point controls all communications and only link

between mobile devices and the AP are considered. Direct communications between devices could be considered in the future.

- MC-UWB: This activity is focused on the design and the evaluation of Very High Data Rate WPANs where the transmission is performed with bit rates ranged from 150 to 600 Mbps along the UWB system definition. UWB systems are defined in connection with the FCC rules, as wireless systems with a transmission bandwidth superior to 500 MHz or systems with a fractional bandwidth superior to 20% devoted to high bit rate transmissions and low power consumption.
- IR-UWB and
- FM-UWB.

4.1.3 Digital Broadcasting

According to [MG_D823] one of the most interesting new application scenarios for mobile entertainment is the integration of digital TV broadcast content into mobile handset technologies. This content could be transmitted with 3G data rates with legacy IP applications and streaming technologies. Problems with this options are, however, delay variance of the packets. Another alternative with better quality of service expectations is Digital Video Broadcasting (DVB), which enables point-to-multipoint type of networking and sending video broadcast also to mobile devices equipped with appropriate receivers.

For the digital broadcasting there are several standards, which have been established already or just about to be established. The important ones to mention are DVB-T, DVB-H and DAB. All of those are based on OFDM technology.

4.1.4 Additional Features

Additional features for wireless communication networks integrated into the multi-standard terminal are positioning and sensor technologies (for example, to measure temperature). This will enable more integrated features of the mobile entertainment end-user devices [MG_D823]. Since both positioning and sensor networking are currently not considered as to become a part of the 4G system they are not considered any further.

Also the very short range RF-ID or near field communication (NFC) will become part of the terminal, but is not considered as belonging to 4G. The NFC technology evolved from a combination of contactless identification (RFID) and interconnection technologies. NFC operates in the 13.56 MHz frequency range, over a distance of typically a few centimetres. NFC technology is standardized in ISO 18092, ECMA 340, and ETSI TS 102 190. [NFC04].

4.2 New Air Interfaces

Beside the integration of different existing radio standards with specified air interfaces, the 4th generation radio system may also use a new air interface definition for the wide-area mobile communications. The detailed parameters of these candidates for this new air interface are not clear up to now, but there is a tendency towards multi-carrier systems. Two kinds of this system are under further investigation: Multi-Carrier CDMA and OFDM-TDMA. Both are introduced in this chapter and the impact on the multi-mode radio system baseband architecture is discussed. The system definition and parameters for the potential MC-CDMA system have been taken from the IST project MATRICE. For OFDM-TDMA only a general analysis can be made here because of the lack of specific system definition.

4.2.1 Multi-Carrier CDMA

The IST-Project MATRICE targets at the definition of a such a 4G radio based on a combination of OFDM and CDMA (MC-CDMA) technique, which in terms of its functional definition allows the reuse of components of a 3G system in the implementation [MAT_D1.4].

The idea followed in MATICE is that for introducing this 4G system that evolves and improves the technologies underlying the 3G systems it is very helpful to directly consider certain compatibilities to the existing and upcoming 3G standards. This will especially be important when mobile terminals are supposed to support multiple standards to keep the complexity of the terminals in affordable borders. In order to facilitate the development of such multi mode terminals certain parameters need to be chosen as consistent as possible to the 3G systems. Motivation to have these aligned parameters is the increased potential to derive power efficient designs for the multi mode terminals. Further it will allow decreasing the form factor of the terminal, since certain parts do not need to be included twice in the implementation. In addition the development time can be kept shorter. Potential candidates for alignment are the sampling rate, the frame size and structure as well as the interface to higher layers such as the data and control channels. This approach of course aims at simplifying the extension of the existing MUMOR baseband architecture towards the new air interface. In the subsequent chapter the system proposal is introduced in more detail and then selected issues for architecture extension are discussed.

4.2.1.1 Motivation for using OFDM/CDMA

In order to reach the goal of high mobility and high bit rates OFDM and its combination with CDMA (OFDM-CDMA or Multi Carrier CDMA) are the potential access technologies for 4G. MC-CDMA increases the degrees of freedom in the system design. Using these degrees of freedom in sophisticated ways allows to mitigate multiple access interference and to cope with unpleasant channel conditions. In the end this will allow high mobility with high data rates through adaptation to environment.

Frequency diversity is one example of a benefit that can be gained from MC-CDMA, if the data is spread over large parts of the available frequency band. From pure Direct Sequence CDMA MC-CDMA inherits the granularity in terms of data rate and cell capacity. The equalisation in OFDM is generally easier achieved than in CDMA. This can be exploited for MC-CDMA, which has OFDM as an underlying technology. Since sophisticated MC-CDMA receivers have to cope with the multiple access interference from other codes the equalisers may be more complex than those of OFDM, but potentially still simpler than those for CDMA as e.g. in HSDPA.

4.2.1.2 System Proposal

When investigating and designing the baseband part of an air interface it is critical to investigate the whole transmission scheme from channel encoding to the decoding. Only by doing this we can derive valid results concerning the bit and, more important, the packet error rate. Therefore we model the whole system including channel coding. The overall baseband system is depicted for the downlink in Figure 4.2. This includes the channel en- and de-coder, an appropriate puncturing scheme to match the rates of the coded bit stream with the rate of the frame. We also consider channel interleaving to gain from time diversity. The next module that the system consists of is the mapping module that modulates the bits into the I/Q constellation. This is typically achieved by a QPSK, 16 QAM or higher order modulations like 64 QAM. Further a module carries out the spreading of the data. In this study we consider Walsh-Hadamard codes for spreading. Next the spread chips are time/frequency mapped into the OFDM data frame. Afterwards the data signal is multiplexed with pilots by the framing module. Finally the frequency domain is OFDM modulated, which means that it is transferred into the time domain by an IFFT and that a guar interval is inserted to cope with inter symbol interference resulting from the multi path channel.

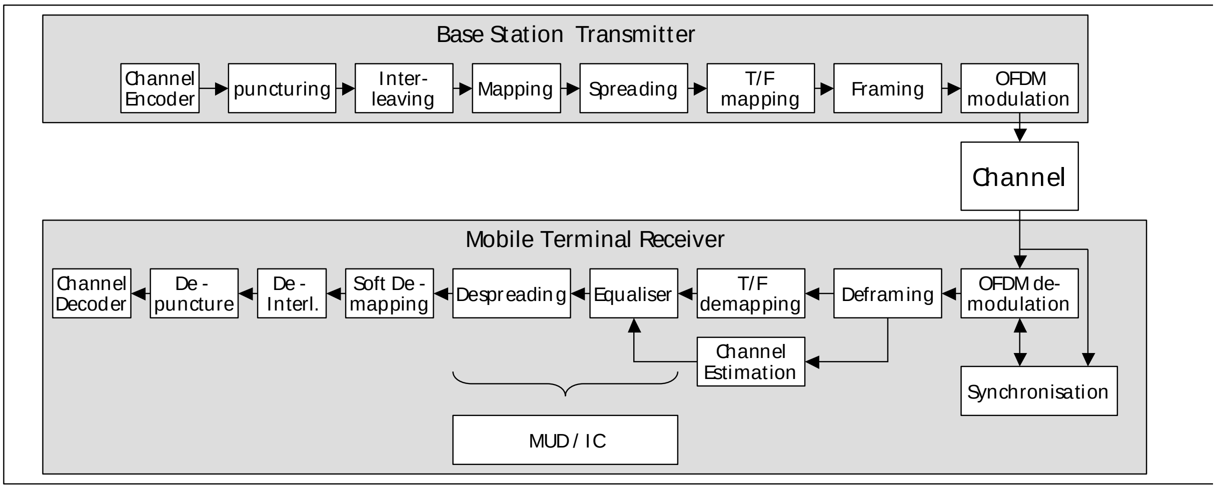


Figure 4.2: Block diagram of the baseband of the MC-CDMA air interface showing the DL

4.2.2 OFDM-TDMA

The OFDM-TDMA technology is not only under investigation for ad-hoc proximity networks (see chapter 4.1.2), but also as one air interface candidate for the 4G system. In fact already for the extension of the 3G system OFDM is a topic in the 3GPP RAN meetings. As this development is currently the most specific research targeting on using OFDM for a wide-area mobile communication.

Parameter	Set 1	Set 2	Remarks
TTI duration (msec)	2	2	identical to HSDPA
FFT size (points)	512	1024	
OFDM sampling rate (Msamples/sec)	7.68	6.528	
Ratio of OFDM sampling rate to UMTS chip rate	2	17/10	
Guard time interval (cyclic prefix) (samples/µsec)	56 / 7.29 57 / 7.42 (*)	64/9.803	(*) Requires one extra prefix sample for 8 out of 9 OFDM symbols
Subcarrier separation (kHz)	15	6.375	
# of OFDM symbols per TTI	27	12	
OFDM symbol duration (µsec) including guard intercal	73.96 / 74.09 (*)	166.67	(*) Depending on guard interval duration
# of useful subcarriers per OFDM symbol	299	705	Including pilots
OFDM bandwidth (MHz)	4.485	4.495	

Table 4.1: OFDM Parameter Sets [3G_25892]

One major aspect of using OFDM is the good spectral efficiency that can be achieved with an adaptive modulation of the subcarriers according to the requirements and demands of the respective users considering the channel state conditions of the available subcarriers. With this adaptability – which of course requires a certain flexibility in the baseband implementation – a bigger average data throuput can be achieved due to the fine granularity of the channel resources. However it is expected that the complexity of the receiver can be simpler for the same performance in terms of successful data transmission. This is relevant for both each single link and for a “per cell” view.

In the 3GPP standardisation the OFDM has been dealt with as a study item (SI) until May 2004 (RAN WG 1 Meeting#37) for being used in potential extension bands of the 3G system. During this time the studies have been reduced to simple schoolbook-like features offered by OFDM, i.e. any advanced properties offered by the system had been neglected. After the more urgent topics Multimedia Broadcast Multicast Service (MBMS) and Enhanced Uplink Dedicated Channel (EUDCH) have been completed by beginning of the year 2005 the OFDM topic may be continued with a broader scope and probably with the status of a Work Item (WI).

Table 4.1 shows the currently discussed reference OFDM parameter sets.

The parameter set 1 consists of nine OFDM symbols that fit into a 0.667 us timeslot. The useful symbol duration is equal to 512 samples. The guard interval is equal to 56 samples for the 0th symbol, and 57 samples for symbols 1..8 of every timeslot, as illustrated in figure 14. The actual position of the 56-sample GI symbol is believed to be inconsequential as long as it is known by both the transmitter and receiver. Therefore, it may be revisited in future, should a different location be deemed more favourable [3G_25892].

4.3 Multi-antenna Design

When augmenting an existing SISO radio communication system by multi antenna coding and transmission schemes it will unavoidably get more complex in terms of its design and implementation. For a mobile communication system this leads to more expensive equipment on both the network operator side and the end user side. The Base Transceiver Station (BTS), like the Node B in a 3G system, as well as the User Equipment (UE) require additional HW. Antenna and RF front-end plus additional processing capabilities in the digital baseband have to be provided.

Figure 4.3 shows the architecture of a dual-antenna receiver for a CDMA-based system like WCDMA and HSDPA. This receiver is meant to receive and decode data transmitted in spatial multiplexing, i.e. the multiple antennas at the transmitter are used to simultaneously transmit multiple independent data streams. A receiver, which solely uses the multiple antennas for receiver diversity would be much less complex in the baseband processing. However the antenna and RF front-end complexity are similar for both kinds of multi-antenna receiver.

As shown in the figure several components have to be doubled due to existence of a second antenna at the receiver:

- There have to be two antennas and also parts of the RF front-end have to be doubled (LNA, mixer, filter). Some parts may be shared, e.g. local oscillator.
- The separation of the received CDMA spreading and scrambling codes has to be done twice, i.e. once per code and antenna. The received signals cannot be combined before the dispreading/descrambling, because the antennas have not yet been separated. Thus the information, which is required to separate the channels would be lost if signals were combined before. Each box in the figure indicating the despreading functionality actually means despreading for each channel tap, thus representing e.g. 4 correlators in case of a 4-tap channel.
- In the next step the signals received from the two antennas, which use the same code for separation, have to be distinguished based on the different channel characteristics, i.e. based on the information provided by the channel estimation. This processing is not required in a single-antenna (SISO) design. In CDMA system this signal processing requires particular effort as the signals coming from the code separation are typically already soiled by interference due to the lost code orthogonality in a multi-path channel environment. In the figure a Minimum Mean Square Error (MMSE) linear equalizer has been selected for the

antenna separation task. After this processing the independent data streams should be recovered as sent out by the transmit antennas, but still including echo paths from the channel.

- After serializing the recovered transmit data streams the received energy spread over several echo taps has to be combined, e.g. by a maximum ratio combiner (MRC). The component can also be found in a SISO receiver but in this case two of those are required.
- The receiver in the figure below is capable of supporting a special feature in addition to the spatial multiplexing that is that the data rate transmitted over each antenna can be independently selected as well as the channel coding parameters. Therefore the decoding will be done before the final parallel to serial multiplexer resulting in the existence of two decoders in the receiver.
- Not shown in the figure: The complex amplitudes of the multi-path taps of the transmission channel differ between the signals received by the two antennas. Thus the estimation of the power delay profile (channel estimation) has to be done for both receive antennas. However it is assumed that the delays of the received channel taps are equal for both antennas and only amplitude and phase differ between the two antennas.

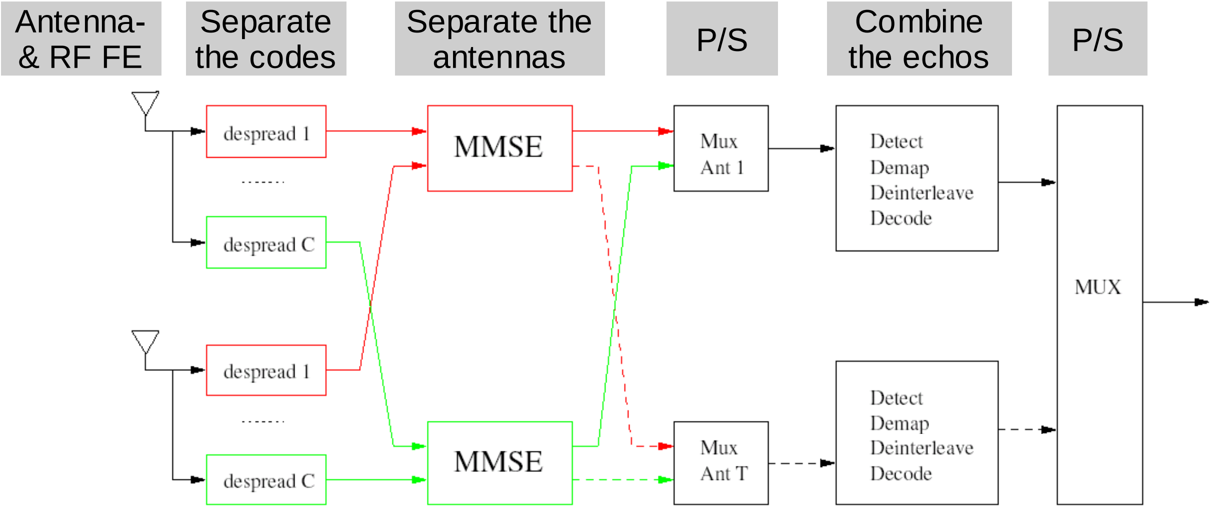


Figure 4.3: Architecture of Receiver for dual-antenna CDMA-based system

In addition to the mere existence of additional kinds and instances of receiver components also the complexity of the components has to be considered. A major aspect to be mentioned in this regard is the significant impact of the system is the receiver algorithm on the performance. Simple algorithms detect each transmitted code separately and consider the other codes as noise. The performance can be increased considerably if all codes used in the system are taken into account during detection. These sophisticated detectors are called multi-user detectors (MUD) and are researched at the moment. The problem using MUDs in real systems is the large computation complexity of these algorithms. The performance in conjunction with multiple-input multiple-output (MIMO) systems is of particular interest because algorithms favoured in single antenna systems do not always show the same performance in MIMO systems, but more complex solutions have to be applied due to the increased level of interference, especially in the anyhow interference limited CDMA system.

As a conclusion especially for multi-antenna systems it is very important to minimize the additional effort in terms of system complexity to keep the cost for the implementation in reasonable borders. As it is anticipated that future systems will operate with both

- multiple antennas and will
- most probably apply a multi-carrier (OFDM) based air interface

an optimisation for the MIMO-receiver in conjunction with OFDM is beneficial.

Typical components in an OFDM system as presented in the previous chapters are the FFT/IFFT required for the OFDM modulation and demodulation. This component is quite complex for such systems due to its length, i.e. number of required constellation point and sub-carriers respectively (In MATRICE the FFT size is $N_{FFT} = 1024$). For this reason an exploitation for different purposes within the physical layer is appreciated for design optimisation. The physical layer of the 3G system does not inherently define a function that requires an FFT/IFFT. However, at the receiver several functions have to be performed, which allow different possibilities for realisation.

Andreas Burg et al. show in [Burg03] that the calculation of the coefficients for the linear MIMO equalisation can efficiently be done it the frequency domain, based on an estimate of the channel impulse responses. It has been shown that by using the cyclic FD-equalisation as special case of the windowed FD-equalisation a sufficient accuracy can be achieved, even with comparably low complexity. Of course this procedure requires a transformation from time- to frequency domain for which again an FFT is required. This offers potential for sharing components.

4.4 Baseband Architecture Extensions

4.4.1 General Assumptions

When dealing with terminals operating in multiple-modes a very important distinction has to be made:

Which modes or combination of modes have to operate simultaneously
and which operate mutually exclusive in time.

When exploring the space for re-configuration and reuse of terminal hardware in the digital baseband it has a major impact, if certain modes are assumed to operate simultaneously. This question becomes especially important in the 4G approach integrating several different air interfaces. The definition of the air interfaces to run simultaneously is on the one hand coupled with the user experience that should be fulfilled with the system and on the other hand limited by technical constraints in the system implementation. The ideal case of seamless interworking of all networks would require a smooth vertical handover, i.e. a handover from one access technology to another. The error-free operation of horizontal handover is anyway assumed.

To be able to perform a vertical handover, especially when it should be possible that the terminal can initiate it, required that at least capability of the terminal to monitor some or all of the available radio systems. But in certain cases several access technologies have to be active at the same time. Latter case puts hard constraints on the minimum radio access capabilities of the terminal. But even in mobile terminals nowadays, different air interfaces are independently active at the same time in particular use cases – even without the 4G seamless interworking.

Building the bridge between the high level use case scenarios and the actual impact that these have for the physical layer implementation of the future 4G terminal is not easy to do. Therefore before doing this transfer here it is important to check for existing definitions. Though some of these definitions are also subject to change and rather functioning as temporary working assumptions to continue further research before having a stable scenario defined that has proven to fit to the use cases.

In the feasibility study for (OFDM) for UTRAN enhancement [3G_25892] an initial reference system configuration is proposed to evaluate an OFDM downlink. In the proposed configuration, new data services are provided through the use of a separate 5 MHz downlink carrier, supporting the OFDM HS-DSCH transmission. The reference architecture is shown in Figure 4.4.

In the described scenario the separate OFDM DL carrier is operated using HSDPA features, such as link adaptation and HARQ. At this stage, it is assumed that network access is performed through the WCDMA architecture, and handover to the OFDM carrier occurs, when needed, for interactive background and streaming data services. In this case, a UE with OFDM HS-DSCH receiving capabilities would also have WCDMA receiving capabilities. In the first stage, the WCDMA link would be used to achieve the initial network access. However, when there is a requirement for high bit rate traffic, the HS-DSCH mode may be initiated, using either the WCDMA DL carrier or the separate OFDM DL carrier [3G_25892].

Based on this initial reference scenario, a UE with OFDM HS-DSCH receiving capabilities is not required to receive the WCDMA and OFDM carriers simultaneously. This implies that, if there is a need for real time services, such as voice communications supported only on the WCDMA carrier, the UE would use the WCDMA mode. Note however that if OFDM proves to be useful in the HS-DSCH scenario, other services could also be mapped to the OFDM downlink in future work. In the proposed configuration, the current UMTS uplink carrier is reused and is considered to have sufficient capacity to support either a Rel 5 WCDMA DL carrier, or the separate OFDM DL carrier. There is no special assumption about the separate carrier frequency [3G_25892].

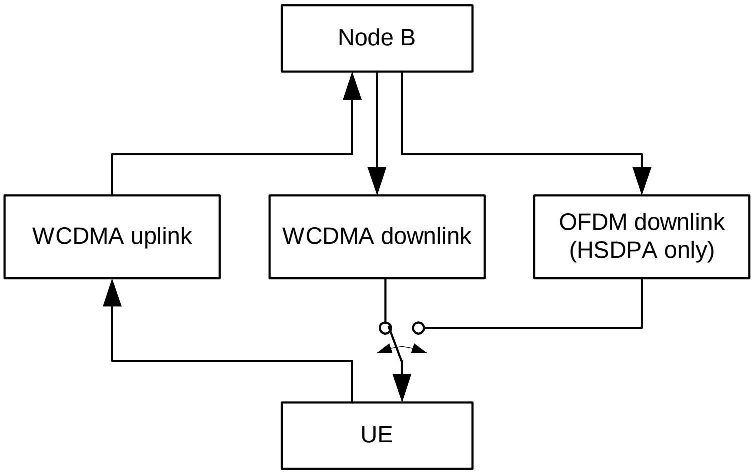


Figure 4.4: Network deployment for the OFDM HS-DSCH transmission [3G_25892]

In the IST-Project MATRICE also some assumptions had to be made, because in this project the simple transition from 3G terminal to a new 4G air interface based on MC-CDMA is a central driver. So it is inevitable to define in which cases simultaneous use of air interfaces is demanded. In MATRCE two correlating issues have been defined separately, that is the general number of supported air interfaces and the number of simultaneously used ones [MAT_D1.4]:

- Number of Implemented air-interfaces: Future terminals need to support a multitude of different air-interfaces. Simple and thus cost efficient solutions will start with two air-interfaces (UMTS/2xMC-CDMA). More complex and more expensive terminals will have more than two interfaces (UMTS/8xMC-CDMA/GPRS/WLAN …).
- Simultaneous use of air-interfaces: An important factor for the cost of a terminal will be the capability of having more than one simultaneously active air connection using different air-interfaces. Simple and cheap terminals will not support this feature, whereas the high end terminals will need to implement at least two simultaneously active connections (e.g.: MC-CDMA – WLAN)

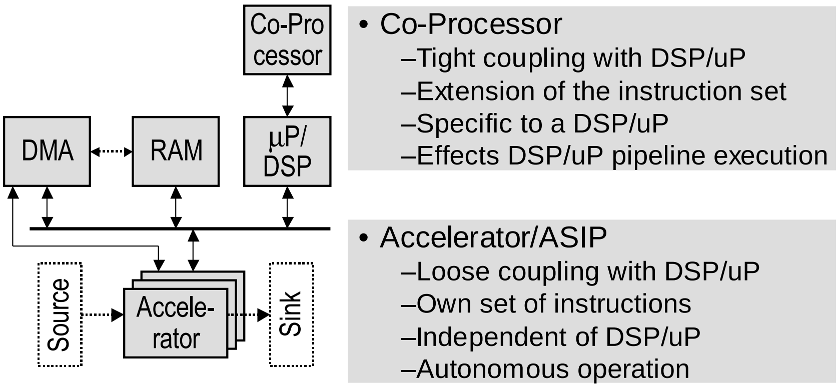
Here by introducing terminals of different capabilities (and thus complexity) a very important distinction has been made. It can hardly be defined for all terminals which air interfaces are implemented at all and, in case several are implemented, which of them have to operate simultaneously and between which air interfaces, vertical handover has to be considered with all the required monitoring capabilities that the physical layer has to provide for it.

4.4.2 Architecture Extension Approaches

The 4G visions are very speculative for the moment. When analysing the list of potential candidates it can be easily foreseen that in all kinds of extension the OFDM system plays an important role. It is under discussion for 3G extensions in the standardisation forum 3GPP, i.e. B3G, it is already used in different kinds of air interfaces like WLAN, DVB, DAB. It is investigated in projects looking for a suitable air interface for personal area networks. Additionally MC-CDMA based air interfaces, which are under discussion for 4G and PAN systems apply the basic principle of OFDM to generate the multiple sub-carriers within the given frequency band.

Because of this penetration of OFDM throughout such different communication standards it is especially investigated here how far the MUMOR baseband architecture can be extended towards OFDM support. Technical details will be investigated in this chapter. The existing WLAN standard IEEE 802.11a based on OFDM has been selected as example system for showing approaches to extend the CDMA based MUMOR baseband architecture. Even if both are based on different access schemes (CDMA vs. OFDM), algorithm adaptation and resource sharing are offering potential optimisation possibilities. The idea is to reuse part of the hardware resources for both systems. There are different possibilities for supporting this kind of resource sharing. This means that the flexible re-configurable architecture currently supporting the different modes of the 3GPP system UMTS/FDD, UMTS/TDD and HSDPA/FDD will be extended in a way that it also can support the IEEE 802.11a standard efficiently. To extend the functionality of the MUMOR digital baseband the same approaches shall be applied. The most critical parts of the digital baseband will be investigated, where “critical” means the most complex components, which are assumed to operated rather in hardware than in software. This is important to be mentioned because the components operating purely in software typically offer more flexibility inherently. Though even here multi-mode optimisation can be applied, e.g. by code sharing (same procedures or objects used in the different modes) or by sharing of the memory.

As discussed above re-configurable systems will be the enabling technology sharing hardware resources for different purposes. Reconfiguration, here, means using the same hardware platform for both standards, with as little standard specific hardware as possible. Dedicated hardware is developed for common structures of two different standards UMTS and WLAN whereas differences are accommodated by reconfiguration. Dedicated hardware accelerators are used to free the microprocessor and/or DSP from doing complex and performance intensive calculations. The accelerator will do the operations, running autonomously without interaction from the microprocessor/DSP. The possibilities to share resources for UMTS and WLAN have been investigated in the MUMOR project. In the deliverable [M_D3.5] the approach for one accelerator for the 3GPP system has been introduced, together with the general approach for accelerators. However this deliverable has the dissemination level “restricted” so here a short introduction to the basic idea.



- Co-Processor
  - –Tight coupling with DSP/uP
  - –Extension of the instruction set
  - –Specific to a DSP/uP
  - –Effects DSP/uP pipeline execution
- Accelerator/ASIP
  - –Loose coupling with DSP/uP
  - –Own set of instructions
  - –Independent of DSP/uP
  - –Autonomous operation

Figure 4.5: Architecture with accelerator

The extensions to the processor are here referred to as hardware accelerators. These accelerators have to be both flexible and autonomous. The flexibility is required to support the different operating modes of the multi-mode system. Thus the same hardware can fulfil operations for more than just one mode, however not being as flexible as a microprocessor. Furthermore the accelerator cells have to work as autonomous as possible to reduce the number of disturbances, i.e. interrupts, of the controlling processor. Only a reduction of these disturbances to a minimum can prevent the hosting microprocessor from getting inefficient, because each interrupt causes a control overhead. This property is the major difference between an accelerator or ASIP (Application Specific Instruction-Set Processor) and a co-processor (Figure 4.6).

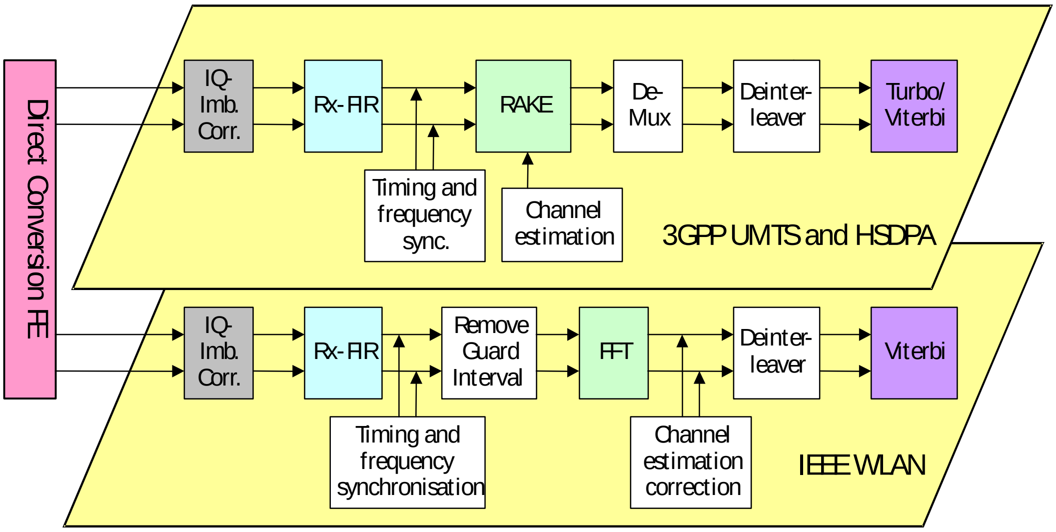


Figure 4.6: UMTS and WLAN downlink terminal receiver digital baseband

In the following sections a selection of complex components will be investigated in terms of their multi-mode capabilities. The approach is to use the same (types of) algorithms for the functions in CDMA and OFDM based system, where one “type of” algorithm means that it can be executed on the same hardware with a certain degree of re-configuration possibilities. Throughout the multi-mode optimisations carried out in MUMOR the starting point always has been a high abstraction namely algorithm selection (see Figure 1.1). This approach has been chosen because a well-selected set of algorithms to be executed in the terminal offers the best possibilities to optimise the hardware for multi-mode operation. For this reason the subsequent chapters take a look on the extension of the current MUMOR baseband –the 3GPP modes– from algorithm selection point of view. When the algorithms are well selected, the lower level (Functional and implementation Architecture) optimisations can be done for MUMOR extensions in a similar way as with in the previous MUMOR research.

4.4.2.1 Frequency Synchronisation

Frequency Synchronization is necessary in digital communication receivers in order to compensate the imperfections of the analog oscillators from the front-end and the Doppler frequency originated by movements of the mobile user. These effects would result in carrier frequency offset, which is characterized by the rotation of the constellation points, prohibiting therefore the use of larger constellation alphabets. In the case of OFDM systems, the frequency offset disturbs the orthogonality between the sub-carriers causing intercarrier interference.

The frequency synchronization scheme comprehends two parts: estimation of the frequency offset and its compensation. In the scope of this project the frequency estimators should be able to detect offsets as high as 20 kHz for UMTS and 50 kHz for WLAN. For this purpose, some efficient algorithms are available and they can be classified into three basic groups:

- FFT-Based Algorithms
- Phase Increment Based Algorithms
- Autocorrelation Based Algorithms

In all the algorithms above, the resources used for estimation of the frequency deviation are the short training symbols (STS) of the WLAN preamble and the common pilot channel (CPICH) for the UMTS/FDD case.

For the FFT-based algorithm case the block diagram of the frequency error estimator is shown in Figure 4.7. In this figure, the block Sorter is used to form the vectors (zero-padding to 64) with the samples that have the same positions within each short symbol, the block "SUM" is used only in WLAN mode and the signal Mode selects whether the estimator is being used in the UMTS/FDD or WLAN mode.

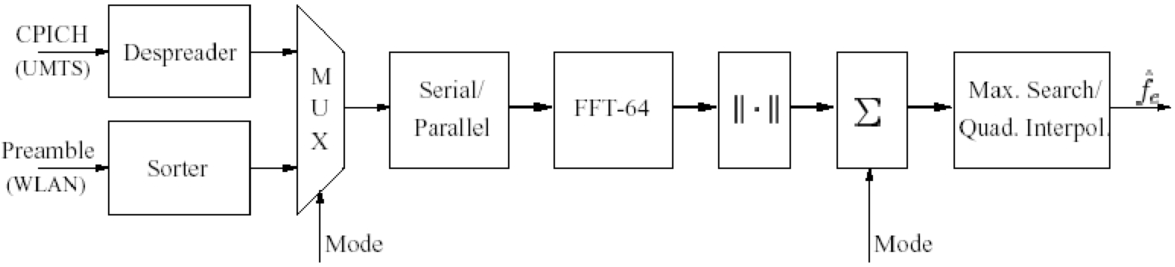


Figure 4.7: Block diagram of the UMTS-WLAN FFT based frequency estimator

The drawback of this FFT estimator is the quite high computation requirements: a 64- point FFT has to be performed for every frequency estimation in UMTS/FDD and for WLAN the same has to be performed up to 16 times. Not forgetting that this should be added to the Maximum Search and Quadratic Interpolation procedures. Consequently, the use of the FFT Estimator could only be justified by the exploitation of the already implemented FFT for the OFDM modulation and, when this is the case, by its superior performance in comparison to other estimation methods. Recalling the former reason, it is well known that not only the used area, but also the number of operations (translated into power consumption and required processing speed) plays an important role in the VLSI design. Thus, simpler phase increment based estimators are going to be studied in this section. Basically, these algorithms solve the problem of estimation of the frequency offset through a linear regression, like the Phase Increment Based Estimator (Figure 4.8).

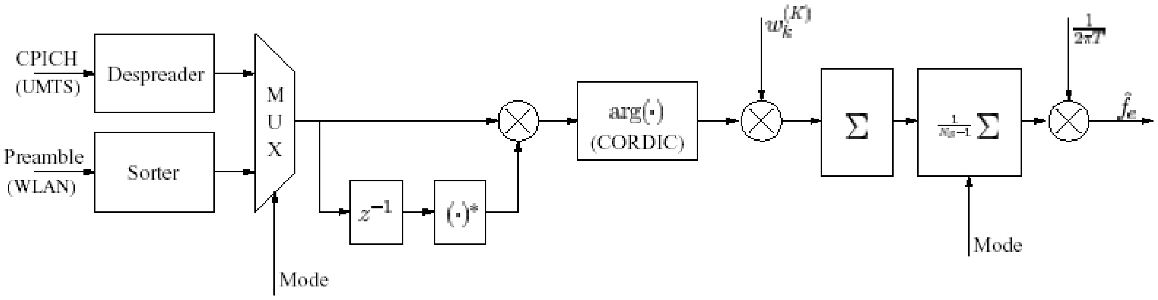


Figure 4.8: Block diagram of the UMTS-WLAN phase increment frequency estimator

The block arg(.) can be implemented using the CORDIC algorithm and the block is used only in the WLAN mode and its function is averaging over the sample positions within an STS.

The Autocorrelation Based Estimators consists in an improvement of the phase increment based algorithms. The problem here is condensed in determining the mean of the colored Gaussian noise process.

Once that the frequency error was determined using any of these kinds of algorithms, this error must be compensated digitally. This compensation can be carried out in a feed-forward or feedback way. Here, frequency compensation schemes for UMTS/FDD (Figure 4.9) and WLAN (Figure 4.10) are presented.

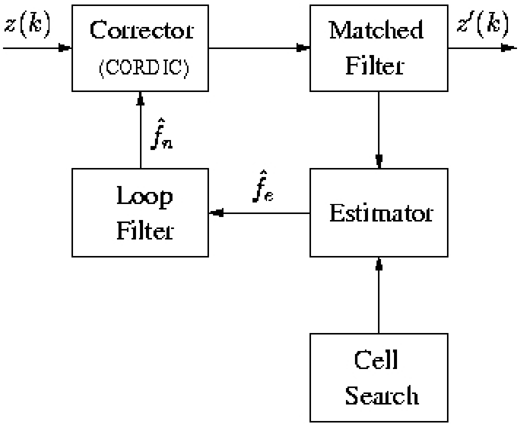


Figure 4.9: UMTS/FDD Frequency Synchronization Scheme

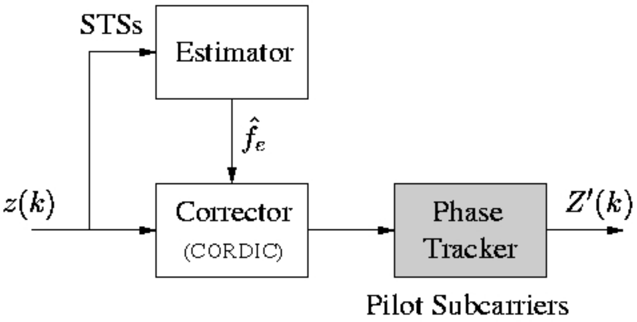


Figure 4.10: WLAN Frequency Synchronization Scheme

4.4.2.2 Channel Estimation

The signal incoming at the receiver through the wireless channel consists in attenuated, phase-shifted and time-delayed replicas of the transmitted signal. In order to process the received signal correctly, the receiver has to compensate for this distortions caused by the channel. This compensation is only possible if necessary characteristics of the channel are available in the receiver. Therefore results the necessity of channel acquisition units in the receiving part.

From the algorithmic point of view, one can observe that in the channel estimation the differences between the receivers of UMTS/FDD and WLAN become most visible. While for WLAN applications a quasi-static estimation scheme is sufficient, the UMTS/FDD Rake based receiver has to be designed to cope with very dynamic scenarios and thus refined channel tracking algorithms are required. In this section, the channel estimation algorithms for both systems are going to be analysed together with multi-standard implementation aspects.

The WLAN channel estimation must be performed by the beginning of each packet with the help of the long training symbols (LTS) from the preamble and the results of the estimation are used to correct the received data for the rest of the packet. There are two ways to perform this estimation: before the FFT (time domain, TD) and after the FFT (frequency domain, FD).

The theoretical analysis of these two kinds of estimators has shown that performance of the TD estimator is better than the FD estimator. Figure 4.11 shows a comparison between the estimates in terms of bit-error-rate (BER) to reinforce theoretical results. The channel used in this simulation is a Rayleigh channel with exponential power delay profile and the assumption is done that the channel is practically constant during a packet. The constellation used for this analysis is 16-QAM. As it can be observed, the TD estimation provides a gain of about 1 dB against the FD estimation. In UMTS/FDD the receiver scheme used to combat the distortion effects of the mobile channel is the Rake receiver that has been used in the MUMOR baseband architecture.

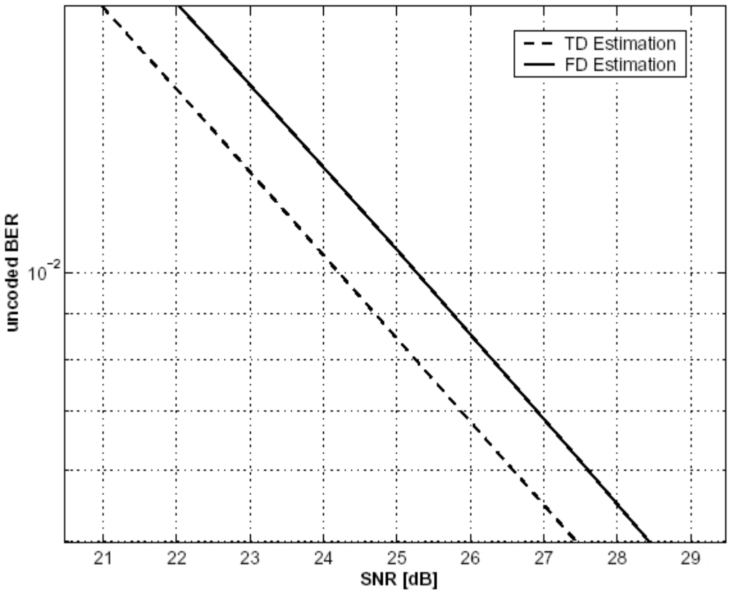


Figure 4.11: Channel Estimation Performance for WLAN: Time Domain vs. Frequency Domain

One might now be asking how to achieve a multi-standard implementation for the channel estimation/ equalization algorithms in such disparate circumstances, where, from the algorithmic point of view, the channel estimation for WLAN is performed using blocks of samples (LTSs), and for UMTS, snapshots of the channel have to be taken and noise/interference reduced estimates have to be provided for every new incoming symbol. Unfortunately, the parameterisation approach that was used for the multi-standard frequency synchronization cannot be employed here, since no common algorithms in the separate channel estimation architectures have been found that provide enough accuracy for feasible complexity.

The solution to this problem can be found by "zooming into the different algorithms" and taking a look at the mathematical operations and hardware structures required by the architectures in question. The channel estimation for WLAN consists in a simple matrix-vector multiplication. In the Rake receiver, the interference canceller, the Wiener filter and the delay acquisition are architectures that use vector-vector, vector-matrix and matrix-matrix multiplications in their implementation. All these operations have a common core operation, viz multiply and accumulate (MAC). These MAC operations can be implemented using processing elements and thus the core operations of the separate algorithms can be implemented together taking advantage of the reconfigurability provided by the hardware accelerator structure. Therefore, a convenient resource sharing multi- standard architecture can be targeted.

Naturally this fine coarse granular reconfiguration requires a bigger control overhead than solutions applying the same algorithm with different parameters. Nevertheless reducing the number of implementations of the mighty MAC operation is typically worth the effort in terms of implementation optimisation.

4.4.2.3 Fast Fourier Transform (FFT)

Beside the specific algorithm comparison targeting at finding solutions that suit both UMTS and WLAN system there are a general HW optimisation possible. In the specific case discussed here the application of a CORDIC component can be used to support the UMTS and the WLAN system for different purposes.

For increasing the flexibility of the FFT operations, e.g. to support a wide number of different FFT lengths with the same hardware, a pure CORDIC based architecture for the calculation of the FFT can be applied. The performance of this approach can compete with the ordinary MAC based implementation, although the main advantage is the possibility to implement the FFT on a reconfigurable CORDIC processor array.

As an additional benefit this array can also be used for other tasks such as a substitute for the Rake receiver in UMTS terminals. It has also been shown that the result of the CORDIC based architecture is much more accurate than that of the MAC approach. Thus a solution to replace the MAC based FFT computation of the DFT by a solely CORDIC based FFT is feasible and useful. Previous DFT implementations also used CORDICs for parts of the calculations, but not for the entire computation. It was already shown that the Rake receiver can be replaced by a CORDIC based algorithm, which even results in a better performance. A way to implement the 64-FFT used in the WLAN baseband is presented on the same architecture as used for the Rake alternative without a significant performance loss.

An eight point FFT leads to the network shown in Figure 4.12. A complete 8-FFT based on CORDIC operations is shown in Figure 4.13.

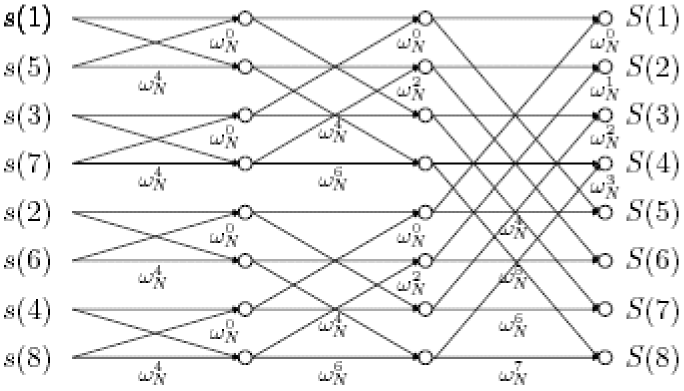


Figure 4.12: Regular FFT implementation

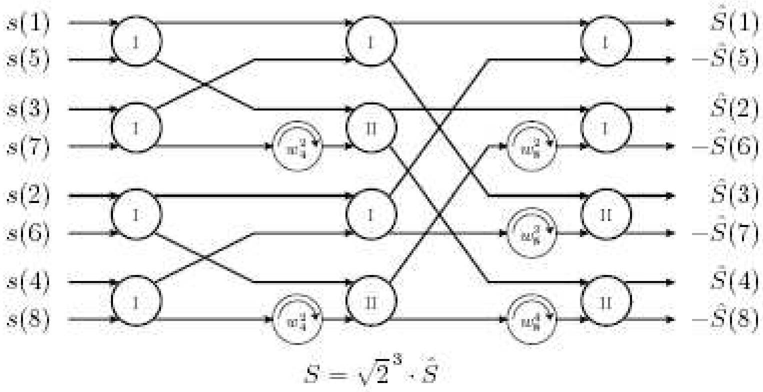


Figure 4.13: CORDIC based FFT

Comparison of the complexity: If N is the size of the FFT, the number of CORDIC operations is:

$$OP_{CORDIC} = 3N 2 (log2(N) 1) + 2$$

The same architecture used to implement the CORDIC array also provides a MAC processing element. This PE needs

$$OP_{MAC} = (N + 2) log2(N)$$

activations for an FFT of size N. These two functions are compared in Figure 4.14. It can be seen that for small FFT sizes the operation count OP_{CORDIC} is even lower than for OP_{MAC}. For the 64-FFT used in a WLAN receiver OP_{CORDIC} is 482 and OP_{MAC} is 396. When implementing two parallel PEs these numbers can be halved to get the number of accelerator activations (198 for the MAC, 241 for the CORDIC). So the CORDIC based FFT is slightly slower than the MAC based implementation, but on the other hand one CORDIC based reconfigurable hardware architecture can now be used to implement the FFT for WLAN and the Rake substitute for UMTS.

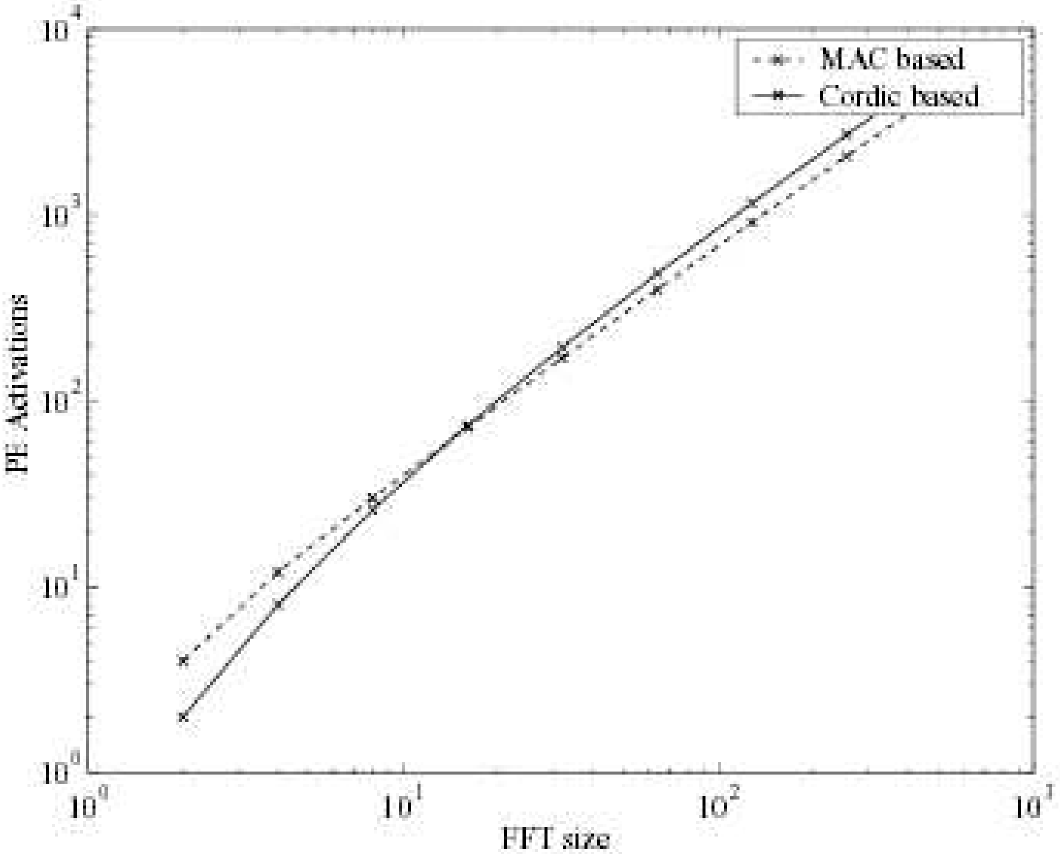


Figure 4.14: Number of PE activations for MAC and Cordic based FFTs

5 Summary and Conclusion

For the digital baseband processing the focus of the system extensions has been set on OFDM technologies in general and the WLAN system in particular. Investigations have shown that the OFDM system is already well present in existing air interfaces for different purposes (local area data and broadcasting networks). Additionally OFDM and MC-CDMA with OFDM as underlying technology is under investigation for personal area networks and –more important– for 3G extensions.

Thus no matter if the 4G vision is heading towards a new system with a dedicated air interface or if the vision rather aims at the integration of several existing air interfaces OFDM can be understood as a “constant factor”, meaning that when considering the extension of the MUMOR baseband architecture the first parameter to think about is an extension towards OFDM.

Therefore general aspects for supporting OFDM with the MUMOR architecture have been investigated. During this investigation the strategy for multi-mode optimisations, which has been applied during the entire project, has been also applied here. This strategy includes the high level considerations throughout the optimisation. In particular this implies starting the optimisation on higher level that is already at the algorithm selection phase. Figure 1.1 points out this strategy showing that on this level major impact on the final implementation will be made – either explicit or implicit. The selection of similar algorithms is an enabler for multi-mode optimisation on the final implementation. Consequently this report targets at showing the possibilities of using similar algorithms for the system investigated during MUMOR and the potential extensions. Optimisations of the implementation details have not been investigated here. Though the same accelerator based approach that has been applied for the 3GPP multi-mode baseband can also be extended for any system as long as similar algorithms can be applied. Latter has been shown in this report.

References

[3G_25892]	3GPP Specification, TR25.892, “Feasibility Study for Orthogonal Frequency Division Multiplexing (OFDM) for UTRAN enhancement (Release 6)”, Version 6.0.0 (2004-06)
[Burg03]	A. Burg, M. Rupp, N. Felber, W. Fichtner “Practical Low Complexity Linear Equalization for MIMO-CDMA Systems”, IEEE 35th Asilomar Conference on Signals,Systems and Computers, Pacific Grove, CA, USA, 2003.
[M_D3.5]	MUMOR D3.5 “Design Report of Digital Baseband”, Doc Number: IST-2001-34561/ NOKIA/WP3/R/RE/007 (Dissemination Level: Restricted)
[MAG_D321]	IST-MAGNET Project, Deliverable D3.2.1: “Requirement Specification for PHY-Layer”, www.ist-magnet.org
[MANET]	http://www.ietf.org/html.charters/manet-charter.html
[MAT_D1.4]	IST-MATRICE Project, Deliverable D1.4: “Reference scenario specification: final description”, www.ist-matrice.org
[MG_D823]	IST-MGAIN, Deliverable D8.2.3: “Mobile Entertainment”, www.mgain.org
[NFC04]	http://press.nokia.com/PR/200403/938518_5.html
[Ryka_04]	P. Rykaczewski, J. Brakensiek, F. Jondral: *Decision Directed Methods of I/Q Imbalance Compensation in OFDM Systems*, 60th IEEE Vehicular Technology Conference (VTC F'04), Los Angeles, Sep. 2004 (accepted)