Parameter Controlled Software Defined Radio

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ABSTRACT

This paper starts with an introduction of the notions of Digital Radio (DR), Software Radio (SR), Software Defined Radio (SDR) and Cognitive Radio (CR). Different levels of reconfiguration within an SDR are introduced. Section 2 gives a classification of different radio communication standards to cordless, second and third generation cellular systems and wireless local area networks. Furthermore, the features of GSM, IS-136 and UTRA-FDD are compared. Section 3 gives an overview over the SDR transceiver's signal processing and deals with parametrization of standards. Section 4 shows how an SDR can be adapted to different standards by parametrization. As an example the signal processing structure of a general modulator, that can be used for GSM, IS-136 and UTRA-FDD is presented. Finally, the effects of GMSK linearization are discussed.

Keywords - Software Defined Radio, signal processing, reconfigurable terminals, parametrization

1. INTRODUCTION

To find a suitable starting point for a discussion about software radio, we briefly remember some important concepts. First it should be pointed out that we assume the use of transmission standards for all communication networks which are of commercial interest.

By *Software Radio* we understand a transceiver. Its functions are realized as programs running on a suitable processor. On its hardware different transmitter/receiver algorithms, which usually describe transmission standards, are implemented in software. An SR transceiver comprises all the layers of a communication system. The discussion in this contribution however concentrates on the air interface.

The baseband signal processing of a *Digital Radio* (DR) is invariably implemented on a digital signal processor. An ideal *Software Radio* (SR) directly samples the antenna output. A *Software Defined Radio* (SDR) is a presently realizable version of an SR: The received signals are sampled after a suitable band selection filter. A *Cognitive Radio* (CR) [1] combines an SR with a Personal Digital Assistant (PDA) and connects its owner to Intelligent Networks (INs). Our work and therefore this contribution is on SDRs.

According to its operational area an SDR can be:

- A *Multi Band System* which is supporting more than one dedicated frequency band used by a wireless standard (e.g. GSM 900, GSM 1800).

- A *Multi Standard System* that is supporting more than one air interface standard. Multi Standard Systems can work within one standard family (e.g. UTRA-FDD, UTRA-TDD for UMTS) or across different networks (e.g. DECT, GSM, UMTS, WLAN).

- A *Multi Service System* which provides different services (e.g. telephony, data, video streaming).

- A *Multi Channel System* that supports two or more independent transmission and receiving channels at the same time.

Our present discussion is on *Multi Mode Systems*, which are combinations of Multi Band and Multi Standard Systems.

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

- *Commissioning*: The configuration of the system is done once at the time of product shipping, when the customer has asked for a dedicated mode (standard and band). This is not a true **re**configuration.

- *Reconfiguration with downtime*: Reconfiguration is done only a few times during the product lifetime, e.g. when the network infrastructure changes. The reconfiguration will take some time, where the system is switched off. This may include the exchange of components.

- *Reconfiguration on a per call basis*: Reconfiguration is a highly dynamic process that works on a per call based decision. That means no downtime is acceptable. Only parts of the whole system (e.g. front end, digital baseband processing) can be rebooted.

- *Reconfiguration per timeslot*: Reconfiguration can even be done during a call.

Figure 1 shows an SDR transceiver that differs from a conventional transceiver only by the fact that it can be reconfigured via a control bus supplying the processing units with the parameters which describe the desired standard. Such a configuration guarantees that the transmission standard can be changed instantaneously if necessary (e.g. for inter standard handover). **Figure 2** describes the differences between a DR, an SDR and an ideal SR receiver for the example of an UMTS/WLAN Multi Mode System.

Fig. 1. SDR transceiver
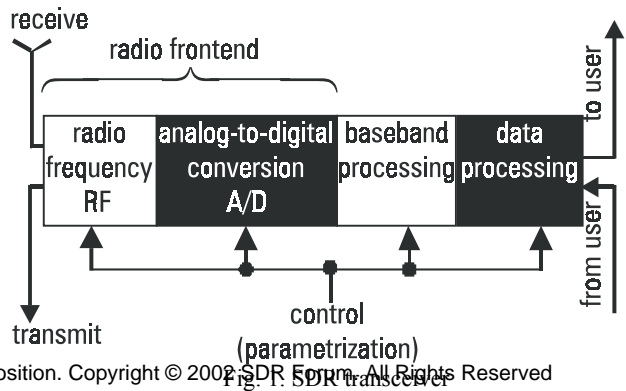
The rest of the paper is organized as follows: Section 2 gives a classification of different radio communications standards to cordless, second and third generation cellular systems and wireless local area networks. The features of GSM, IS-136 and UTRA-FDD are compared. Section 3 gives an overview over the SDR transceivers' signal processing and deals with parametrization of standards. Section 4 shows how an SDR can be adapted to different standards by parametrization. As an example the signal processing structure of a general modulator, that can be used for GSM, IS-136 and UTRA-FDD is presented. Finally, the effects of GMSK linearization are discussed.
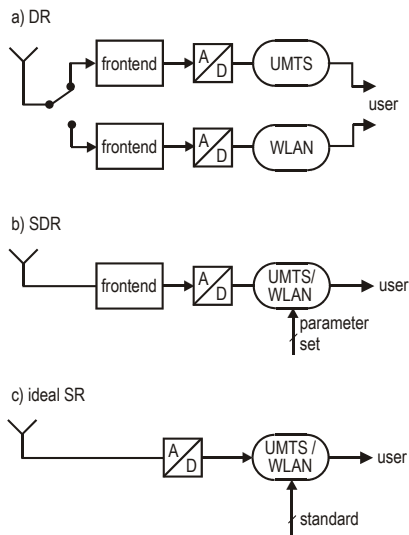

Fig. 2. UMTS/WLAN Multi Mode receivers

2. STANDARDS

Standards are defined to make systems that serve specific applications employable for mass markets. The most important mobile communication standards used in Europe are briefly described in the following paragraphs.

Cordless Phone

DECT (Digital Enhanced Cordless Telecommunications) provides a cordless connection of handsets to the fixed telephone system for in house applications. Its channel access mode is FDMA/TDMA and it uses TDD. The modulation mode of DECT is GMSK with a bandwidth time product $BT = 0.5$. The transmission is protected only with a CRC.

Cellular Systems

GSM (Global System for Mobile Communication) is presently the most successful mobile communications standard worldwide. Channel access is done via FDMA/TDMA and GSM uses FDD/TDD. The modulation mode of GSM is GMSK with a bandwidth time product $BT = 0.3$. Error correction coding is done by applying CRC as well as a convolutional code. GSM was originally planned to be mainly a voice communication system, but with its enhancements HSCSD, GPRS or EDGE it becomes more and more a data system too. In Europe GSM systems are operating in the 900 MHz (GSM 900) and in the 1800 MHz region a (GSM

1800). The North American equivalent of GSM is IS-136. Also IS-95, a second generation CDMA system, as well as GSM 1900 are widely used in the US. UMTS (Universal Mobile Communication System) is the European version of the third generation family of cellular standards within IMT-2000. One of the differences with respect to second generation systems is that third generation systems are mainly developed for data (multi media) transmission. UMTS applies two air interfaces: UTRA-FDD and UTRA-TDD according to the duplex modes used. The channel access mode is CDMA and CRC, convolutional codes and even turbo codes [2] are employed for error protection. The basic data modulation is QPSK. Furthermore, it should be mentioned that one mobile user within an UMTS-FDD cell can occupy up to seven channels (one control and six transport channels) simultaneously.

Wireless Local Area Networks (WLANs)

Today IEEE-802.11b is the most successful WLAN standard in Europe. It is expected that IEEE802.11a and HiperLAN/2 will be the future generation systems in this area. If one of these WLAN standards is to be implemented into an SDR it should be recognized that its modulation mode is OFDM. It should be pointed out that there are major efforts towards the development of joint UMTS/WLAN systems which use an SDR approach.

In the further discussion in this contribution we concentrate on the development of an SDR that employs the cellular standards GSM and UMTS. To show that SDR is a globally important development we additionally include the American IS-136 system. IS-136 is a cellular system that is in some sense equivalent to the European GSM. Its access mode is FDMA/TDMA and it uses FDD/TDD (like GSM). The modulation mode of IS-136 is $\pi/4$-DQPSK. For error protection CRC and convolutional codes are employed.

To have a sound basis for the description of an SDR that is switched between different standards the most important features of the GSM, IS-136 and UTRA-FDD air interfaces are summarized in **table I**.

3. MOBILE TERMINAL

The general structure of an SDR Terminal was already given in **figure 1**. Here we are going to discuss the SDR mobile transceiver structure a little bit more detailed. The main processing modules of an SDR terminal are the radio frequency (RF) unit, the analog-to-digital (A/D) unit, the baseband processing and the data processing.

3.1 Signal Processing

The first main step within the receiver branch is to convert the analog (reception) RF antenna signal into its complex baseband representation. This transformation is performed in the analog frontend that encloses the RF and the A/D units. Several solutions for the transformation of the antenna signal into its complex baseband representation are possible: Superhet, superhet combined with bandpass subsampling, low IF or zero IF receiver. It is very likely that the principle of choice for an SDR

receiver will be zero IF. **Figure 3** shows how it works:

Coming from the antenna the RF signal is first bandpass

TABLE I

FEATURES OF MOBILE CELLULAR AIR INTERFACES

	GSM	IS-136	UTRA-FDD
channel spacing	200 kHz	30 kHz	5 MHz
access mode Direct	FDMA/TDMA	FDMA/TDMA	Direct Sequence (DS) CDMA
duplex mode	FDD/TDD	FDD/TDD	FDD
users per carrier frequency	8	3	
net data rate	13 kbit/s	7.95 kbit/s	8 kbit/s to 2 Mbit/s
modulation mode	GMSK	$\pi/4$-DQPSK	QPSK
channel coding	CRC, convolutional	CRC, convolutional	convolutional, turbo, CRC coding with interleaving
symbol duration	3.692 μs	41.14 μs	depends on the spreading factor
bits per burst (slot)	156.25	324	depends on the spreading factor
burst (slot) duration	576.9 μs	6.67 μs	667 μs
frame duration	4.62 ms	40 ms	10 ms
channel bit rate	270.833 kbit/s	48.6 kbit/s	
maximum cell radius	35 km	20 km	few kilometers
user specific signatures			OVSF codes
spreading factor	1	1	2^k; k=2,3,…,8; 512 downlink only
chip rate			3.84 Mchip/s

filtered and then amplified. Following a two way signal splitter, the next processing step is an analog mixing with the locally generated RF frequency in the inphase (I) path and with the locally generated RF frequency phase shifted by $-\pi/2$ in the quadrature (Q) path. Afterwards the I and Q components of the signal are lowpass filtered and A/D converted. The sampling rate of the A/D converters should be fixed for all signals and has to be chosen in such a way that the conditions of Shannon's sampling theorem are fulfilled for the broadest signal to be processed. Within the baseband processing unit the signal is shaped according to its bandwidth first. The next step is the adaptation of the sampling rate to the signal's standard [3].
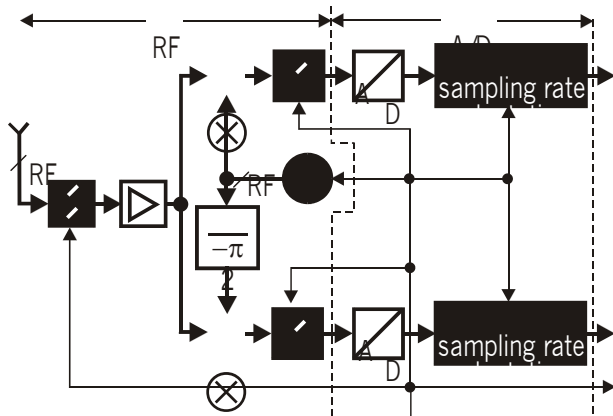

Fig. 3. SDR radio frontend, receiver branch

The reason for the sampling rate adaptation is that the signal processor should work at the minimum possible rate. For a given standard this minimum rate depends on $f_c=1/T_c$, the symbol or chip rate, respectively. Usually a sampling rate of $4 f_s$ is sufficient for the subsequent

signal processing where, after the precise synchronization, the sampling rate may be reduced by another factor of 4. If the fraction of the sampling rates at the resampler's output and input is rational, the sampling rate adaptation can be implemented by an increase of the sampling rate followed by an interpolation lowpass filter and a sampling rate decrease. The whole procedure is a cascade of interpolation and decimation. If the interpolation lowpass is realized by an FIR filter, the impulse response usually becomes quite long. The solution is to take the up and down sampling into account within the filter process: Since the upsampled signal is generated by the insertion of zeros, the processing of these zeros can be omitted within the filter. This leads to the polyphase structure of **figure 4**. Because different input/output ratios have to be realized, the number of filter coefficients to be stored may become large. If necessary a direct computation of the filter coefficients can be more efficient than their advance storage [3].

After sampling rate adaptation the signal is processed within the complex baseband unit (demodulation and decoding). This is discussed in some detail in section 4. The baseband unit hands over the decoded bits to the data processing unit. The SDR data processing within the higher protocol layers [4] is not considered in the present paper.

The transmission branch consists of the procedures inverse to that of the receiving branch. I.e. the signal to be transmitted is generated as a complex baseband signal, from which the real part is taken to be shifted to the (transmission) RF.
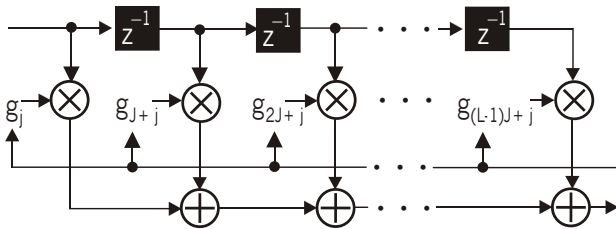
Fig. 4. Polyphase filter for sampling rate adaptation

3.2 Parametrization

For SDRs, adaptability means that the radio is able to process signals of different standards. One method to achieve adaptability is parametrization of standards.

As a communication standard we define a set of documents that describe the functions of a system in such a way that a manufacturer can develop terminals or infrastructure equipment on this basis. Standardization is one necessary condition to make a communication system successful on the market as exemplified by GSM. Standardization grasps all kinds of communication networks. Here we concentrate on *cellular mobile* systems.

Of course a standard has to contain all the functions of a system, especially for a mobile system at least the air interface as well as the protocol stack have to be specified. For our further discussion we focus on air interfaces and use the *notion of standard* more or less as a synonym to *air interface*.

Parametrization means that every standard is looked upon as one member of a family of standards [5]. The signal processing structure of the family is then developed in such a way that this structure may be switched by parameters to realize the different air interfaces.

4. ADAPTATION BY PARAMETRIZATION

In the following discussion we are going to describe how an SDR, that can be adapted to different communication standards by parametrization of its signal processing unit, may be developed [6]. In our example we are going to discuss the air interfaces GSM, IS-136 and UMTS-FDD. The main features of these standards were reviewed in **table 1**.

Of course there are substantial differences between the second generation TDMA standards GSM and IS-136 on the one hand and the third generation CDMA standard UMTS-FDD on the other. Within UMTS-FDD spreading at the transmitter and despreading at the receiver have to be realized additionally. Looking at the signal processing chains we remark that the error correcting codes of all the second generation standards are very similar: A combination of block codes for the most important bits and a convolutional code for the larger part of the voice bits is applied. Channel coding for data transmission is done by a powerful convolutional code. UTRA-FDD as a third generation air interface offers net data rates of up to 2 Mbit/s and guarantees BERs of up to 10^{-6} for specific applications. To reach these BERs turbo codes are employed. Of course within an SDR they have to be integrated into a general encoding/decoding structure. If UTRA-FDD supports voice transmission, error protection is provided by a convolutional code. Because the

development of a general encoding/decoding structure is essentially a matter of diligence, we are going to discuss the construction of a general modulator structure in greater detail.

4.1 A general modulator

The modulation modes of the air interfaces GSM, IS-136 and UTRA-FDD are GMSK, $\pi/4$-DQPSK and QPSK, respectively. Moreover, the UTRA-FDD signal is directly spread with a chip rate of 3.84 Mchip/s. QPSK and $\pi/4$-DQPSK are linear modulation modes while GMSK is non linear. One of our goals was to derive one modulator structure that can produce the signals of all the standards under investigation. Therefore we proposed the implementation of the linearized GMSK into an SDR.
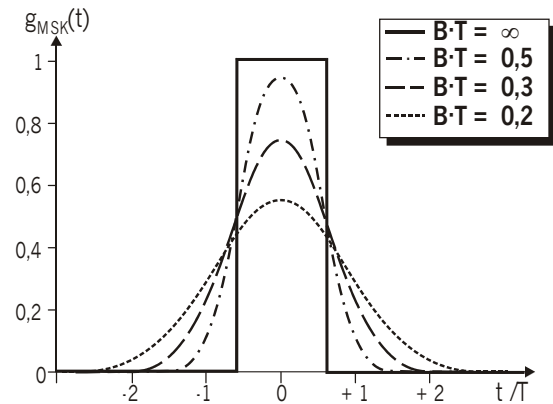

Fig. 5. Gaussian impulse formers (dependence on the $B \cdot T$ product)

MSK is a two frequency shift keying with modulation index $h = 0.5$. If the rectangular impulse former of the (linear) MSK is replaced by the Gaussian shaped impulse former $g_{GMSK}(t)$, the (non linear) GMSK results. The application of $g_{GMSK}(t)$ leads to a bandwidth reduction but at the same time causes inter symbol interference (ISI) (c.f. **figure 5**). ISI or equivalently the bandwidth reduction depends on the bandwidth-time product BT. Within GSM BT is defined to be $BT = 0.3$, that leads to a considerable bandwidth reduction but at the same time the implementation of an equalizer at the receiver becomes necessary because of ISI. **Figure 6** shows the Power Spectrum Densities (PSDs) of GMSK signals for different BTs.
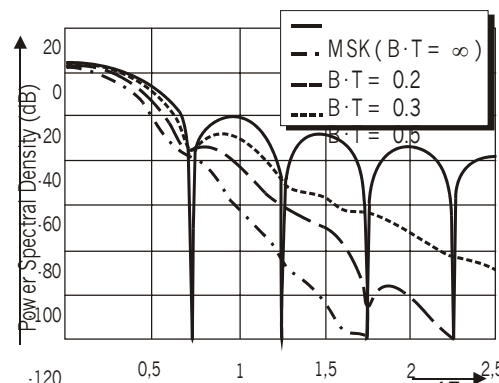

Fig. 6. PSDs of GMSK signals (dependence on the $B \cdot T$ product)

In the complex plane, the n-th symbol d_n to be transmitted leads to a phase rotation that has to be added to all the phase rotations of all previous symbols. For MSK the complex pointer rotates within one symbol duration exactly by $\pi/2$ or $-\pi/2$. For GMSK the complex envelop may be divided into a sum of two terms: The first one represents the linear, the second one represents the nonlinear part of the GMSK modulation [7]. The linear part carries about 99% of the signal's energy. Therefore a GMSK signal may quite well be approximated by its linear part. This means that in an SDR the transmitted symbols are formed by an impulse $C_0(t)$, that guarantees the linearity of the modulation method. Implementing this linearization, GMSK signals can be produced by a (linear) MPSK modulator. The structure of this general modulator, that is discussed together with its parametrization within the next paragraphs, is sketched in **figure 7**.

The general modulator is able to produce GSM, IS-136 and UMTS-FDD signals. Moreover, its architecture can be extended easily such that it may generate cdma2000 or UTRA-TDD signals too. For UTRA-FDD **figure 7** shows the uplink structure.

It should be noted here that GSM uses a differential precoding. For $b_k \in \{0,1\}$ this precoding is defined by

$$\beta_k = \beta_k + \beta_{k+1} \mod 2.$$

The initial value $b_{-1} = 1$ is given by the dummy bits that are transmitted before the first user bit, during the starting phase of a GSM burst.

The block **Precoder** within the modulator's block diagram is controlled by the parameters *BurstLength* and *Precoder_On_off*.

During the next step the signal is NRZ coded, which for GSM leads to

$$d_k = 1 - 2\beta_k.$$

TABLE II

PARAMETERS OF THE FUNCTIONAL BLOCK
MBIT2SYMBOL

modulation mode	ModulationNumber
GMSK	1
$\pi/4$-DQPSK	2
QPSK	3
dual QPSK	4

The block **NRZ** is parametrized by *NRZ_On_Off*. For *NRZ_On_Off* = 1 a bit $\beta = 0$ is transformed into a bit $\gamma = 1$ and $\beta = 1$ into $\gamma = -1$. *NRZ_On_Off* = -1 implies that $\beta = 0$ becomes $\gamma = -1$ and $\beta = 1$ becomes $\gamma = 1$. *NRZ_On_Off* = 0 indicates that no transformation is performed.

The functional block **MBIT2Symbol** maps the bits onto complex symbols z_k. The modulation mode is determined via the parameter *ModulationNumber* (c.f. **table II**). Since several modulation modes need a memory, a starting state must be defined for them. In an UTRA-FDD uplink the control data and the information of the first DPDCH are sent in the Q branch or DPDCH II.

This modulation process may be interpreted as dual QPSK for which the serial/parallel conversion is achieved by directing *I_Length* bits into the I branch and *Q_Length* bits into the Q branch. These two parameters are not needed for the generation of GSM or IS-136 signals. A further option is to switch several DPDCHs onto the I and Q branches. These channels are indicated in **figure 7** by broken lines because this option is defined for the spreading factor $N_s = 4$ only.

For UTRA-FDD the signal has to be spread. This operation is controlled by the parameter *Spreadingfactor*. The spreading sequences are stored in the transceiver's memory. For *Spreadingfactor* = 1 no spreading is performed. The subsequent weighting with the factors w_d and w_c as well as the complex scrambling are again necessary for UTRA-FDD signals only.

Finally the transmitted impulses are formed by an FIR filter that is specified by the parameter *Filter_Number* (c.f. **table III**). For GMSK the impulse $C_0(t)$ (linearization) is used here, for PSK modes root raised cosine roll-off filters are applied.

Table IV shows the parametrization of the general modulator for GSM, IS-136 and UTRA-FDD. For UTRA-FDD the burst length depends on the spreading factor. As an example *Spreadingfactor* = 8 was assumed in **table IV**. For the DPCCH *Spreadingfactor_Q* = 256 is used anyway.

4.2 Effects of GMSK Linearization

The linear approximation of GMSK causes a non constant amplitude of the transmitted signal. **Figure 8** shows the effect of GMSK linearization to the amplitude sketched in the complex signal plane for the bandwidth-time products $BT = 0.5$ and $BT = 0.3$ (GSM). It is evident that the effect of linearization is stronger for $BT = 0.3$. This can be explained by the fact that for $BT = 0.5$ the GMSK modulation itself is "almost" linear and the effect remains minimal in this case. On the other hand it is the constant envelope that makes GMSK very attractive for mobile radio, since power efficient C-class amplifiers can be employed in this case without causing severe intermodulation products.
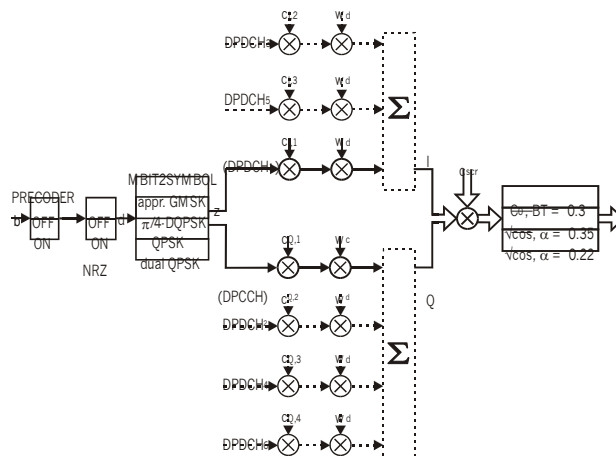

Fig. 7. General modulator structure

We are now interested in the effects of GMSK linearization, if the corresponding signal is power amplified. For our simulations we used a power amplifier model described in [8], that approximates well the measured properties of a real GaAs FET (Gallium Arsenide Field Effect Transistor). In **figure 9** the PSDs of exact and linearized modulated GMSK signals are compared. Without non linear amplification the PSD of the linearized GMSK signal meets the spectrum mask given by the GSM standard better than the PSD of the exact GSM

TABLE III

IMPULSE FORMING FILTERS

Filter	Filter_Number
main impulse C_0(t) of linearized GMSK with $BT = 0.3$	1
root raised cosine roll-off filter with roll-off factor $\alpha = 0.35$	2
root raised cosine roll-off filter with roll-off factor $\alpha = 0.22$	3

signal does. If power amplification is applied the PSD of the linearized GMSK signal closely approximates the GSM spectrum mask in the region around ±350 kHz from the carrier frequency. But the GSM standard is still met. Since within an SDR the final power amplifier has to meet the advanced demands of $\pi/4$-DQPSK and QPSK modulations, the linear GMSK approximation does not represent a loss in efficiency. For linear power amplifier characteristics we expect that the PSD of linearized GMSK signals meet the GSM standard's requirements closer than the amplifier used in our simulations does.
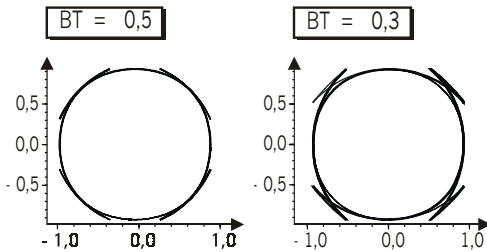

Fig. 8. Complex envelope of linearized GMSK signals

TABLE IV

PARAMETRIZATION OF THE GENERAL MODULATOR

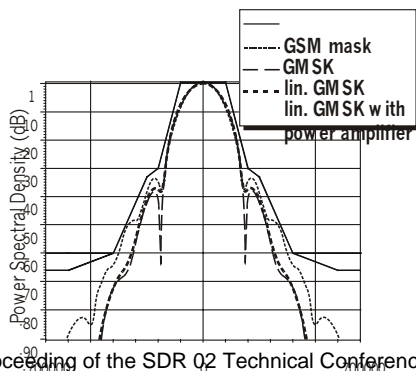| parameter	GSM	IS-136	UTRA-FDD
BurstLength	148	312	330
Precoder_On_OFF	1	0	0
NRZ_On_Off	1	1	-1
ModulationNumber	1	2	4
Spreadingfactor_I	1	1	8
Spreadingfactor_Q	1	1	256
Filter_Number	1	2	3
I_Length	-	-	320
Q_Length	-	-	10

Fig. 9. PSDs, linearized vs. "pure" GMSK

Now we are going to discuss the effect which GMSK linearization has on the BER. Of course the BER heavily depends on the receiver algorithms as well as on the mobile radio channel. For GSM this channel usually is frequency selective. The GSM channel models acquired by COST 207 suppose a maximum multipath delay of 20 µs, corresponding to an ISI of 6 symbols. Since the equalizer and the channel estimation algorithms usually applied in the receiver are based on the model of a linearly modulated signal, the application of the linearized GMSK seems to be advantageous with respect to the bit error rate. In this consideration the non linear part of the GSM signal is looked upon as an interference term. The results of this discussion can be deduced from the simulation results of **figure 10**. The simulations were performed with the COST 207 channel models. The differences between exact and linearized GMSK almost vanish and cannot be detected if channel coding is applied, since the energy of the non linear part of the GMSK signal is very small compared with the rest. But it is very important that the linearization of the GMSK signal does not cause performance degradations.
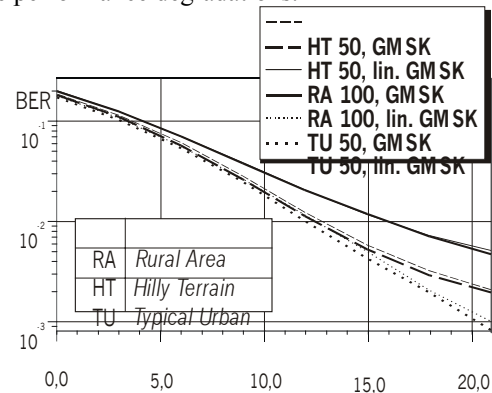

Fig. 10. BERs, linearized vs. "pure" GMSK

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