Implementation of Signal Processing Algorithms for 3G and Beyond

Josef Hausner, *Member, IEEE*, and Robert Denk

***Abstract*—For communication systems of third generation and beyond, the algorithmic complexity will increase significantly compared with 2G and 2.5G systems, as we can see from the example of channel estimation. The answer to these demands will consist of transceivers with re-configurable hardware accelerators in advanced CMOS technology.**

***Index Terms*—Multi-access communication, multipath channels, signal processing.**

I. Introduction

CONTRARY to the development of 2G systems which was mainly technology driven, present and future communication systems are developed from applications and user-satisfaction needs point of view. This includes services like online video conferencing, interactive games and online banking, requiring large data rates, additional computational power and security features. This results in high and asymmetric data rates. First UMTS systems will have peak data rates of 384 kbps, later phases of 3G systems will allow data rates up to 2 Mbps, and in research projects beyond 3G data rates up to 150 Mbps are discussed. In contrast to classical voice centric devices, future cellular systems will be data centric devices. The Pocket PC, PDA and cellular worlds merge into combined devices, implying a shift of the mobile world toward a PC-like model (see also the discussion in [1]).

Baseband chips for future terminals will also integrate additional standards for short range connectivity like Bluetooth. The demands on the data rate heavily depends on the mobility and the range of the communication system, see Fig. 1. The different access systems are organized in a layered structure. Main layers are

- distribution layer (DAB, DVB, Satellite, HAP);
- cellular layer (GSM/TDMA, UMTS/IMT-2000);
- hot spot layer (IEEE 802.11 a, HIPERLAN2);
- personal network layer (DECT, Bluetooth);
- fixed wired layer (fiber, xDSL, cable modem).

For a comparison of different key technologies on wireless and wirebound access, see [2]. Mobile terminals must be capable of dealing not only with horizontal handovers within one layer but also with vertical handovers between different layers.

Compared to the first GSM systems, present and future multimode mobile terminals face much harder algorithmic requirements. The higher complexity of W-CDMA signal structure defined by the corresponding 3G standards results in drastically increasing number of instructions per second. The higher complexity of 3G communication is based on several additional requirements. Apart from the more complex UMTS protocol layer, one also has to think of additional multimode tasks like the handling of asynchronous GSM and UMTS clock domains. Essential features of UMTS are fast closed power-control loop, soft handover and first instances of space-time transmit diversity. All these features result in higher complexity of the signal processing algorithms and their realizations.

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The authors are with Infineon Technologies AG, D-81609 Munich, Germany (e-mail: josef.hausner@infineon.com; robert.denk@infineon.com).

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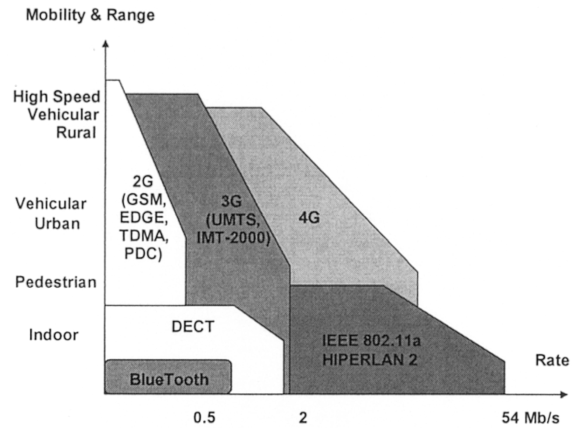

Fig. 1. Mobility and range of communication systems.

The complexity of signal detection will be increased even more in future systems where smart antenna systems are assumed to play an essential role ([3], [4]). Methods of beamforming and space-time processing will allow data rates beyond presently developed 3G cellular systems. For the mobile stations, smart antenna technology becomes feasible if the terminal size is larger than half of the wave-length (we have $\lambda/2 = 7.5\ \mathrm{cm}$ in UMTS and $\lambda/2 = 3\ \mathrm{cm}$ in HIPERLAN).

II. Channel Estimation: An Example

As an example of the increasing algorithmic demands of cellular systems, let us take a closer look into channel estimation (on the basis of pilot symbols) which is a central part of every mobile station receiver.

In GSM systems, the signal is sent in time bursts during which the channel (i.e., the propagation conditions for a specific propagation path) may be assumed to be constant. The insertion of pilot bits into the transmitted data bits makes burstwise channel estimation and, consequently, improved data recognition possible. To estimate the propagation channel in GSM, one obtains an estimate of the channel impulse response by correlation with

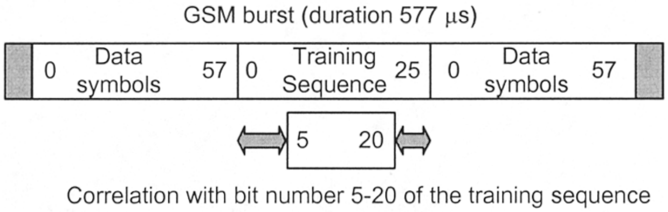

Fig. 2. GSM channel estimation by correlation.

the 26 bit training sequence (see Fig. 1). Due to special autocorrelation properties of the training sequence, we obtain an estimate for the channel impulse response with an assumed length of six symbols. Altogether, we arrive at an algorithmic effort of approximately 0.7 million instructions per second (MIPS).

In UMTS signal processing, the method of channel estimation is quite different (Fig. 2). Here, we have a continuous pilot signal (Common Pilot Channel, CPICH). Thus, we have to take the time-varying property of the channel into account.

First, channel estimation has to be done for every Rake finger separately, and then the data symbols are corrected due to the estimated channel weights and fed into the maximum ratio combining block where different propagation paths and signals from several base stations for the same logical channels are combined together.

We have to find an estimate of the channel impulse response $\mathrm{c}(\mathrm{t},\tau)$ depending on the time t and the propagation delay τ. Following the standard Jakes-Rayleigh channel model, we have a WSSUS channel of the form

$$c(t,\tau)=\sum_{l=1}^{L}\alpha_l(t)\cdot\exp(j\varphi_l(t))\cdot\delta(\tau-\tau_l). \tag{1}$$

Here, the channel impulse response is a sum of L propagation rays whose amplitude $\alpha_l(\mathrm{t})$ is Rayleigh distributed and with uniformly distributed phase $\varphi_l(\mathrm{t})$. The power delay profile consists of several exponentially decaying rays, and the Doppler spectrum is U-shaped. From this stochastic description, statistical signal theory can tell us optimal estimators in the sense of maximum likelihood (ML), maximum *a posteriori* (MAP), or minimum mean square error (MMSE).

For a fixed ray with number l, assume that we have given the (discrete-time sampled) observations $\mathrm{r_k}$, $\mathrm{k}=1,2,\ldots$. We want to obtain an estimate for the channel coefficient

$$c_{\mathrm{k}}=c(k\cdot T_s,\tau_l)=\alpha_l(t)\cdot\exp(j\varphi_l(t)). \tag{2}$$

It turns out that based on N observations $\mathrm{r_k},\mathrm{r_{k-1}},\ldots,\mathrm{r_{k-N+1}}$, the ML estimate for the channel coefficient is given by

$$\hat{r}_{ML,\mathrm{k}}=\frac{r_{\mathrm{k}}}{a_{\mathrm{k}}} \tag{3}$$

where $\mathrm{a_k}$ stands for the transmitted pilot symbol. As we have *a priori* information on the stochastic properties of the channel, it is better to use the MAP approach. It can be shown (see [5]) that the MAP estimate equals the linear MMSE estimate and has the form

$$\hat{c}_{MAP}=v^T\cdot(\Phi+N_0I)^{-1}\cdot\hat{c}_{ML}. \tag{4}$$

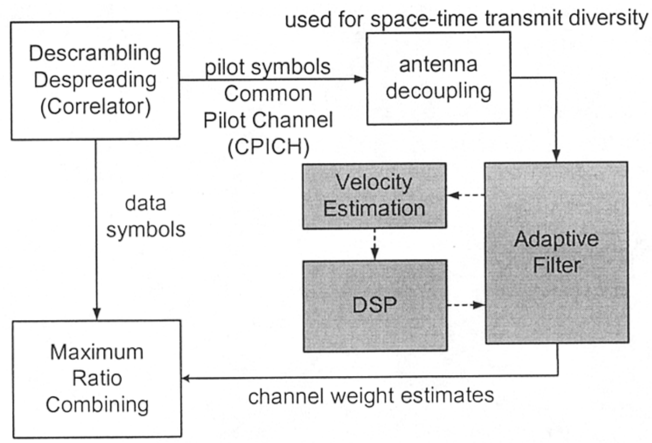

Fig. 3. Block structure of UMTS channel estimation.

Here, $\hat{c}_{ML}$ stands for the vector of ML estimates with index $\mathrm{k}-\mathrm{N}+1,\ldots,\mathrm{k}-1,\mathrm{k}$. The coefficients of the autocorrelation matrix Φ and the vector v can be computed explicitly in terms of the Bessel function. As the autocorrelation matrix and the vector v depend on the signal and interference to noise ratio (SINR) of the CPICH path and on the relative velocity of the mobile station, we have an example of adaptive filtering (so-called Wiener filtering, see, e.g., [6]).

The formulas above show that optimal estimation of the channel coefficient implies a huge computational effort. We first have to estimate the autocorrelation matrix and compute its inverse. Moreover, the Wiener filter depends on the pathwise SINR and therefore is path-specific. From a hardware point of view, this approach is not applicable. One has to simplify this approach, nevertheless relating to the optimality criteria given by statistical signal theory. First, one could ignore the dependence of the filter coefficients on the pathwise SINR and choose typical SINR values. Then, the online computation and inversion of the autocorrelation matrix could be avoided by fixing a set of filter coefficients which correspond to a finite set of velocity and SINR values. Altogether, we arrive at a simplified but still adaptive filter structure which is an approximation of the MMSE approach as it is given by Wiener filtering. Fig. 3 shows a typical block structure of UMTS channel estimation.

Finally, let us take us take a look onto Multiple Input Multiple Output (MIMO) systems. Here the time varying channel impulse response $\mathrm{c}(\mathrm{t},\tau)$ consists of a matrix whose dimensions are given by the number of transmit and receive antennas. This directly implies a corresponding increase of processing power. For a 4×2 MIMO system we easily require more than 100 MIPS just for channel estimation.

III. Advances in Semiconductor Technology

The demand of increasing data rates and complexity due to additional features is answered by a continuous evolution of microelectronics. Advanced CMOS technology in 0.13 $\mu\mathrm{m}$ and beyond gives us the possibility to deal with the challenge of 3G systems and their successors. As an example, let us mention Infineon's baseband chip family [7] which started with 540 k transistors at the GSM chip GOLD V1 and now reached at 25 mil-

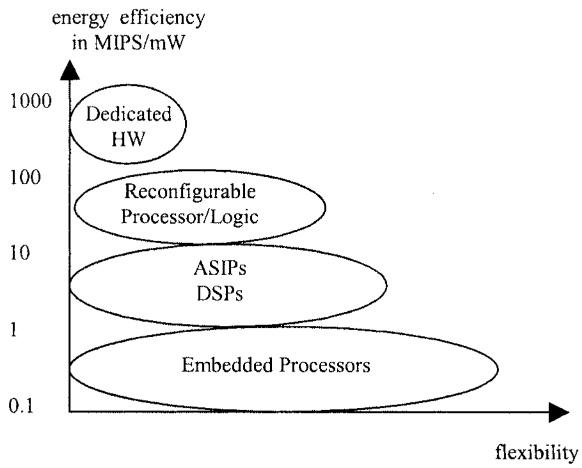

Fig. 4. Energy efficiency versus flexibility.

lion transistors for the GPRS/EDGE solution SGOLD and will consist of more than 40 million transistors for the UMTS chip.

Advanced CMOS circuit designs and analog process capability allow to integrate the analog interface into the baseband. The resulting single chip baseband processor implies smaller area, less pins and less power consumption. For the architecture, the analog and mixed signal integration gives us additional degrees of freedom in circuit design. In today's 2.5G systems there is a tendency to single-chip RF dual band handheld processors. For the RF front-end one can observe a decrease of the number of components from about 500 in the mid 1990s down to 100 at present which will continue. For UMTS transceivers the same tendency of integration can be observed. Finally, this development path of integration will result in a highly integrated single chip RF and baseband solution.

One of the critical points in further development is the question of power consumption. While the battery capacity remains (almost) constant, the number of MIPS increases significantly, and energy efficiency becomes a central question. From this point of view, dedicated hardware has to be preferred; see Fig. 4. On the other hand, future terminal devices will use an open platform approach to ensure easy software integration. Moreover, suitable processors are needed to support operating systems like Java and particular demands from applications. Future handheld solutions should also be able to react on changes and extensions of the system given by changes in the standard requirements of by applications.

Therefore, future mobile stations will include generic programmable interfaces with sufficient flexibility and re-configurable hardware accelerators which take MIPS load away from DSP and CPU. The CPU will include standard operating systems, and hardware accelerators for the data path will allow large number of MIPS with sufficiently low power consumption. The concept of "re-configurable silicon" includes also switching on and off specific data paths and will give the desired flexibility combined with enough processing power to realize advanced signal processing algorithms. We believe that CMOS technology can provide this capability.

IV. Conclusion

In this letter, we discussed what technologies will be needed to implement future generation wireless systems. We considered the increasing complexity of signal processing caused by multi-standard handling, more complicated protocol structure and additional algorithmic effort. As an example for increasing algorithmic demand, channel estimation was investigated. Finally, we discussed the impact on the architecture of future mobile stations (which will be based on re-configurable hardware accelerators) and on the required CMOS technology.

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