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Title: **On the Channel Bandwidth of Hiperaccess Systems**

Agenda item: **HA PHY**

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Discussion	X
Information	X

Decision/action requested

A channel bandwidth for HA systems of 14 MHz, 28 MHz and 56 MHz is proposed.

Abstract

The channel bandwidth is one of the most important parameters for the design and the performance of Hiperaccess systems. There are good reasons for large bandwidths as well as for small bandwidths. For a reasonable compromise, various effects have to be considered. Two of these effects are discussed in more detail in this paper: Statistical multiplexing provides considerable benefits only if the bandwidth is large enough, whereas technology bounds on analog-to-digital converters imply restrictions on the maximum bandwidth.

1. Introduction

We consider a point-to-multipoint (PMP) architecture with TDM/TDMA using FDD. For the transmission in downlink from the base station to the terminals as well as for the uplink a single broadband carrier is supposed.

The bandwidth of this broadband carrier is called the **channel bandwidth**. Usually for FDD, the channel bandwidths for downlink and uplink are equal, but this is less important for this paper. However, all considerations here apply both for downlink and uplink. The specifications from ETSI TM4 allow channelizations of 3.5, 7, 14, 28, 56, 112 MHz, depending on the frequency range. In [6] data rates larger than 100 Mbit/s are mentioned for Hiperaccess. So the important question arises: what is the reasonable range for the channel bandwidth of Hiperaccess systems?

2. Lower and Upper Bounds on the Channel Bandwidth

The main effects implying **lower bounds on the minimum channel bandwidth** are summarized as follows:

- **Statistical multiplex gain and spectrum utilization**: should be as high as possible, see section 3 for further details and numerical results.
- **Peak data rate per user:** a peak data rate of 25 Mbit/s is not achievable with 28 MHz bandwidth under realistic conditions (robust coded QPSK, roll-off factor), see section 5.
- **Phase noise:** increasing frequency range and decreasing channel bandwidth (and thus decreasing baud rate) implies more challenges on oscillators and synchronisation.

The main effects implying **upper bounds on the maximum channel bandwidth** are summarized as follows:

- **ADC technology:** we should be aware that the technological progress of analog-to-digital (ADC) and digital-to-analog (DAC) converters is much slower than for digital signal processing circuits. Especially the ADC resolution implies a strict limit on the maximum baud rate in conjunction with the specific modulation and coding scheme (see sections 4 and 5 for further details and numerical results).
- **Sampling jitter**: this is related to the preceding item, since the ADC performance is mainly limited by aperture jitter.
- **High power amplifier (HPA):** a power limit is given, depending also on the tolerable costs of the HPA. The maximum power limit is further depending on the frequency range and on the required maximum radius of the sector.
- **Blocking and adjacent channel interference:** the larger the channel bandwidth, the higher the "chance" that unwanted interferers will occur.
- **Frequency-selective effects:** these effects produce intersymbol interferences and are caused by multipath propagation (and also by imperfect analog filters). Apparently, wider channels produce more distortion than smaller channels. Multipath propagation is mainly a problem for low frequency ranges (eg. 3.5 GHz) demanding for equalization or multicarrier transmission, but multipath propagation is hardly a problem for higher frequency ranges (eg. 26 GHz), where the main problem is rain fading.
- **Frequency planning**: to achieve a full cellular coverage, at least 4 (or 8) channels with (or without) polarization are required [5], thus there must be enough channels available to a single network operator.
- **Spurious lines**: are caused mainly by mixers and oscillators. To avoid these problems in case of large channel bandwidths, high intermediate frequencies and thus high sampling frequencies are required, which is infeasible (see section 4).
- **IF filtering**: high bandwidths cause higher requirements on IF filtering. Currently, SAW filters with 100 MHz passband or higher are not commercially available.
- **Digital signal processing**: the requirements are proportional to the sampling frequency. For example, an ADC with a sampling frequency of 400 MHz with 10 bit resolution delivers a data stream of 4 Gbit/s, which has to be processed in the first stage of a decimation filter.

The next section deals with the first item of the lower bounds list (statistical multiplex gain and spectrum utilization) and sections 4 and 5 cover the first item of the upper bounds list (ADC stuff).

3. Statistical Multiplex Gain and Spectrum Utilization

The spectrum of a sector of a PMP system is shared among many users (corresponding to terminals). Only a part of the ressource is allocated to a specific user, namely in form of time slots in case of TDM/TDMA, ie. a single terminal occupies the complete spectrum, but only for certain time slots (similar for downlink and uplink).

The channel bandwidth *B* determines the **total sector rate** $r_s = B/(1+\beta)$, where β denotes the roll-off factor. To ease the notation, we assume QPSK and coding with rate 1/2, so a symbol corresponds exactly to an information bit. Let r_a be the **average user data rate**, let *b* be the **burstiness** of the user data source, thus $r_a \cdot b$ is the peak data rate of the user. **The maximum number of users per sector** in case of *b*=1 is given by $N_{\max} = r_s / r_a$ and **the guaranteed maximum number of collision-free users** is given by $N_{coll-free} = r_s /(r_a \cdot b)$.

Due to the statistical multiplexing within the PMP system, typically the traffic peaks on all user data streams will not usually coincide ("usually" is determined exactly by the **cell loss rate** CLR). Therefore, if the number N_{eff} of users (which are multiplexed together) is large enough, then the required total sector rate is closer to the sum of the average user data rates than to the sum of the peak user data rates. Thus the effective maximum number N_{eff} of users is between $N_{coll-free}$ and $N_{\max}$.

The **statistical multiplex gain** *G* with respect to a specific CLR is defined as [7]

$$G = \frac{N_{eff}}{N_{coll-free}} = \frac{\max \#users\ with\ statistical\ multiplexing}{\max \#users\ with\ static\ collision-free\ multiplexing}$$
$$= \frac{required\ total\ \sec tor\ rate\ with\ static\ collision-free\ multiplexing}{required\ total\ \sec tor\ rate\ with\ statistical\ multiplexing}$$

Another important parameter is the **spectrum utilization** *U*, defined as

$$U = \frac{average\ total\ data\ rate\ in\ \sec tor}{total\ \sec tor\ rate} = \frac{G}{b}$$

The Figures 1 and 2 illustrate the statistical multiplex gain *G* and the spectrum utilization *U*, respectively, both over $r_a / r_s = 1/N_{\max}$ for various values of the burstiness *b*, assuming a CLR of 10^{-6}. Some general observations from Figures 1 and 2 are apparent:

- Increasing burstiness implies increasing statistical multiplex gain and decreasing spectrum utilization.
- For $r_a / r_s \to 0$ (or equivalently $N_{\max} \to \infty$), we have $G \to b$ and $U \to 1$.
- For $r_a / r_s \to 1$ (or equivalently $N_{\max} \to 1$), we have $G \to 1$ and $U \to 1/b$.
- Decreasing CLR (ie. less collisions or higher requirements) implies decreasing *G* and decreasing *U*.

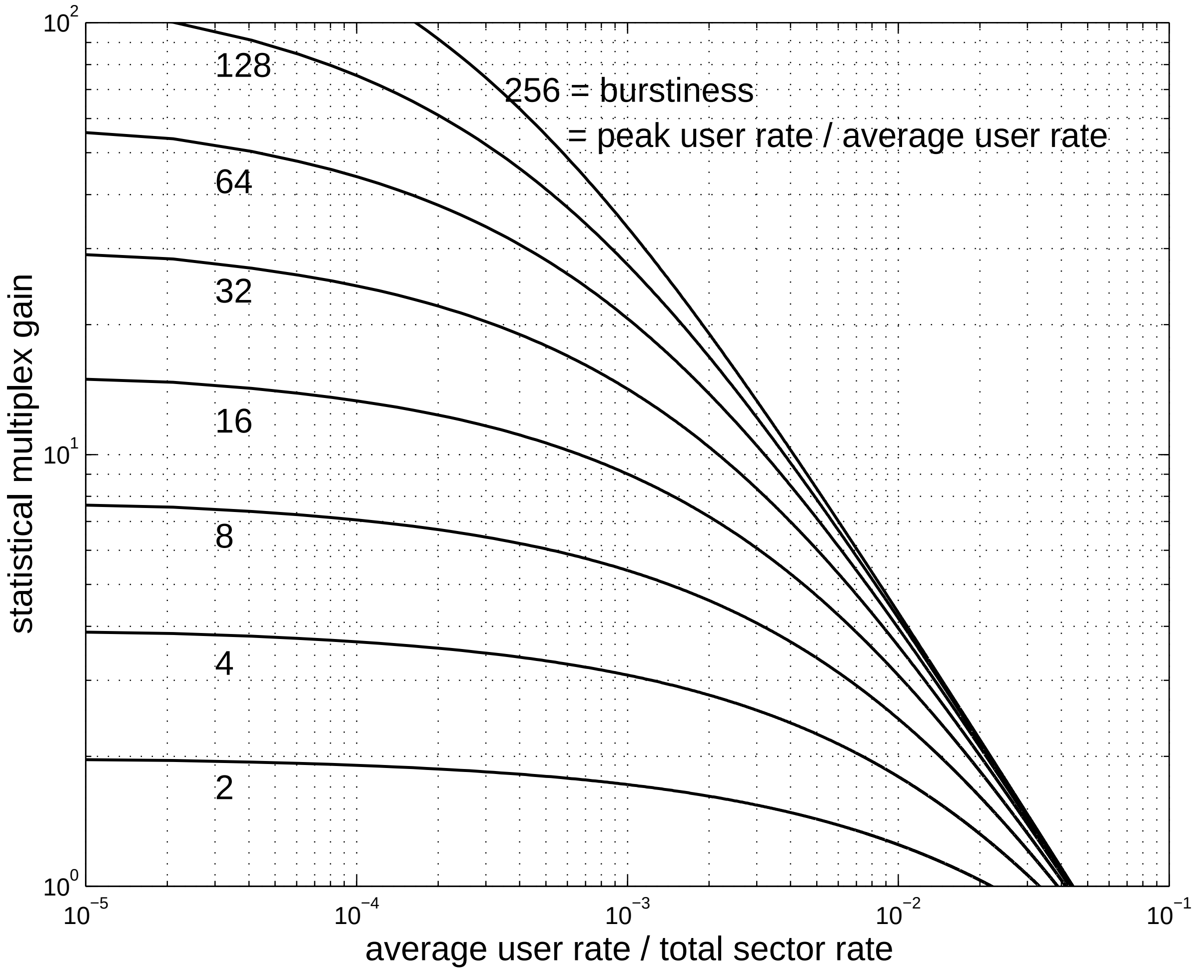

Figure 1: Statistical multiplex gain,
depending on burstiness and the ratio of average-user-rate to total-sector-rate

Remarks.
(1) The previous considerations are also valid for multicarrier transmission systems.
(2) Further investigations have to include the effects due to specific buffering and delaying strategies in the DLC layer.

The simple numerical example in Table 1 should illustrate clearly the interpretation and the relevance of the statistical multiplex gain and the spectrum utilization.

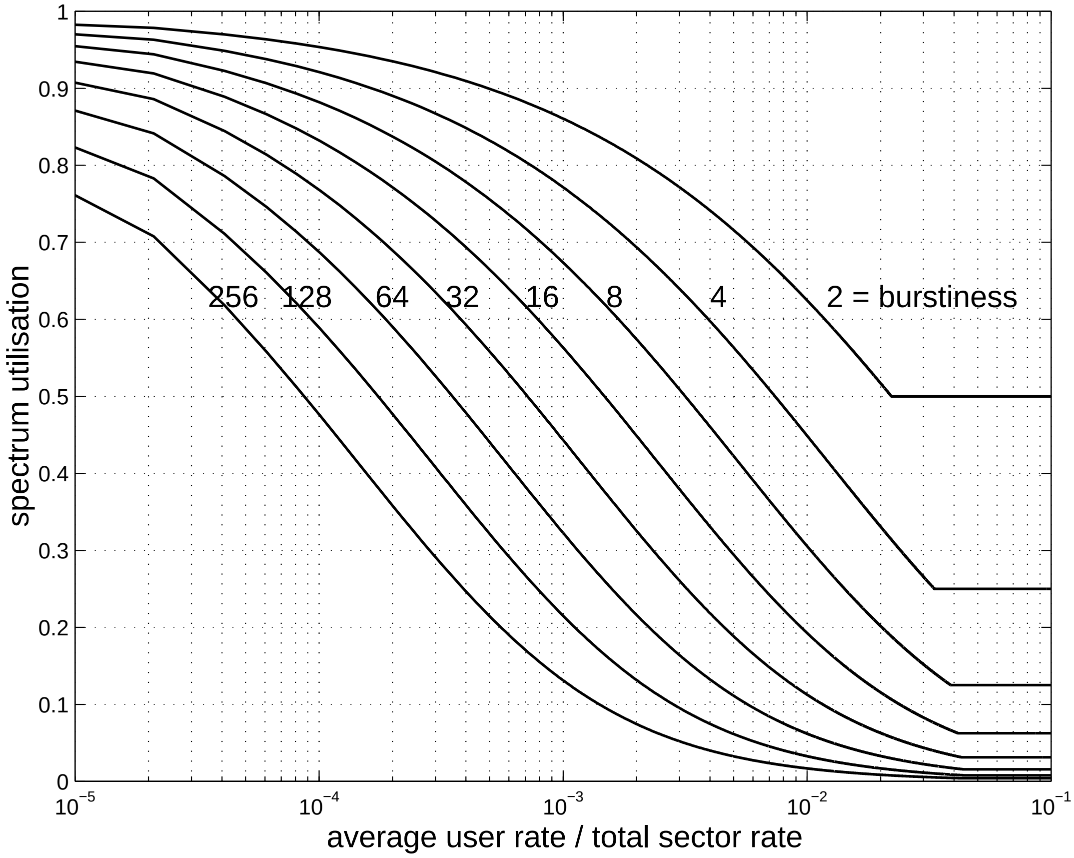

Figure 2: Spectrum utilization,
depending on burstiness and the ratio of average-user-rate to total-sector-rate

Source	average rate = r_a	28 kbit/s		
	burstiness = b	64		
	peak rate = $b \cdot r_a$	1.792 Mbit/s		
sector	total sector rate = r_s	14 MHz	28 MHz	56 MHz
	average-to-sector rate = r_a / r_s	0.002	0.001	0.0005
	statistical multiplex gain = G	13.92	20.64	28.17
Number of users	max #user (with b=1) $= r_s / r_a$	500	1000	2000
	collisionfree #users $= r_s /(b \cdot r_a)$	8	16	31
	effective #user with stat.mux. $= G \cdot r_s /(b \cdot r_a)$	109	322	880
	spectrum utilization	0.22	0.32	0.44

Table 1: A simple example
demonstrating the statistical multiplex gain and the spectrum utilization

4. State-of-the-Art ADC Technology

It is well known that the ADC performance shows only very slow progress over time, especially when compared to fast progress in digital signal processing technology. An up-to-date overview of high-performance ADC technology is shown in Figure 3 (adopted from [1]). A similar overview (which is often cited) for the year 1995 can be found in [3].

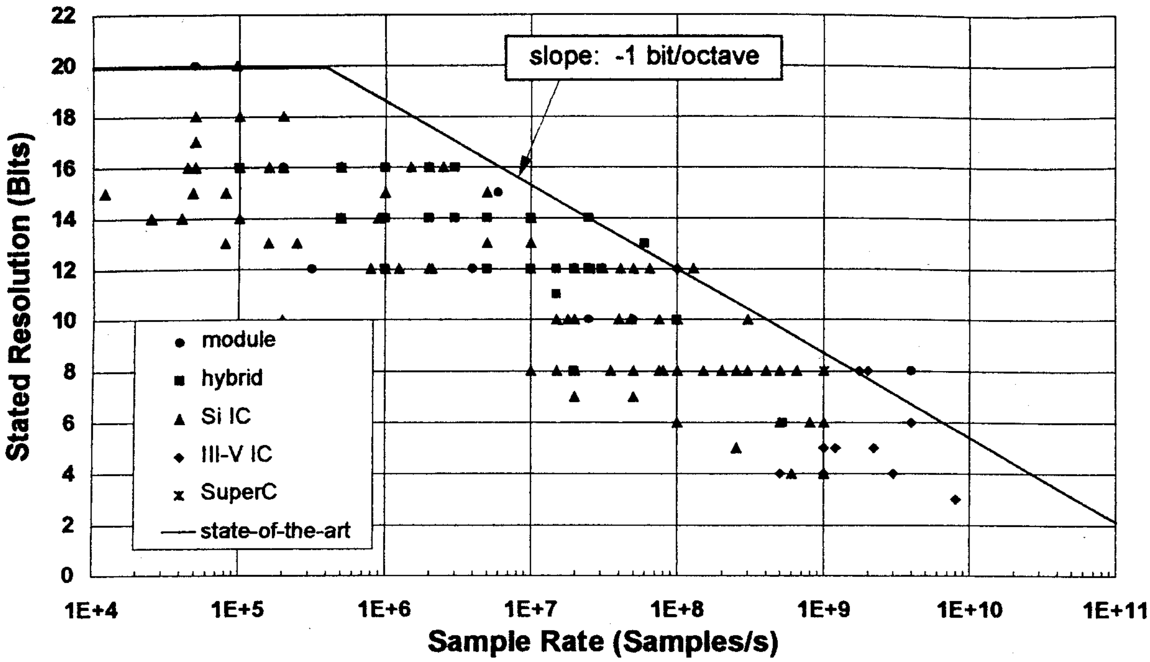

Figure 3: Stated resolution versus sampling rate for state-of-the-art analog-to-digital converters (adopted from [1]).

In Figure 3, the stated resolution in bits (also called wordlength *W*) is depicted over the sampling frequency. The "state-of-the-art" line has a slope of approximately -1 bit/octave, ie. doubling the sampling frequency implies a loss of 1 bit in resolution. This is valid for a broad range of sampling frequencies. The **figure of merit** (FOM) is defined as

$$FOM = \frac{2^W \cdot f_{sampling}}{P_{dissipation}}$$

and shows an improvement by a factor of 1.38 per year [4], where the improvement was fairly continuous over the last 25 years. However, a certain part of the improvement was achieved due to reductions in the power consumption, which seems to be less relevant for Hiperaccess systems. Hence the **resolution-speed product**

$$P = 2^W \cdot f_{sampling}$$

is more interesting. The continuous improvement is described by a factor of less than 1.2 per year [1], corresponding to less than 0.25 Bit per year or less than 1.5 dB in SNR per year (see below for SNR).

Hence, in 8 years time, we can expect an improvement of only less than 2 bit in resolution or less than 12 dB in SNR, given the same sampling frequency. This is equivalent to an increase of the sampling frequency by a factor of less than 4, given the same resolution.

The relation between **signal-to-quantization noise ratio** (SNR) and the resolution is given by

$$\begin{aligned} SNR[dB] &= 6.02 \cdot W + 4.77 - 20 \cdot \log(crest) \\ &= 6.02 \cdot W + 1.76 \quad for \quad crest = \sqrt{2} \end{aligned}$$

where the crest factor denotes the ratio of maximum signal amplitude to mean signal amplitude. Obviously, 1 bit resolution corresponds to 6 dB in SNR.

In the next section, the degradations due to the quantization noise are calculated for various digital modulation schemes. The results are very sensitive with respect to the exact type of the probability distribution of the quantization error. In theory, the quantization error has a uniform probability distribution. However, in practice the quantization error is approximately Gaussian distributed (white noise) due to aperture dither and additional error mechanisms [1]. A Gaussian shaped distribution is also enforced due to the digital filter operations between sampling and decoding.

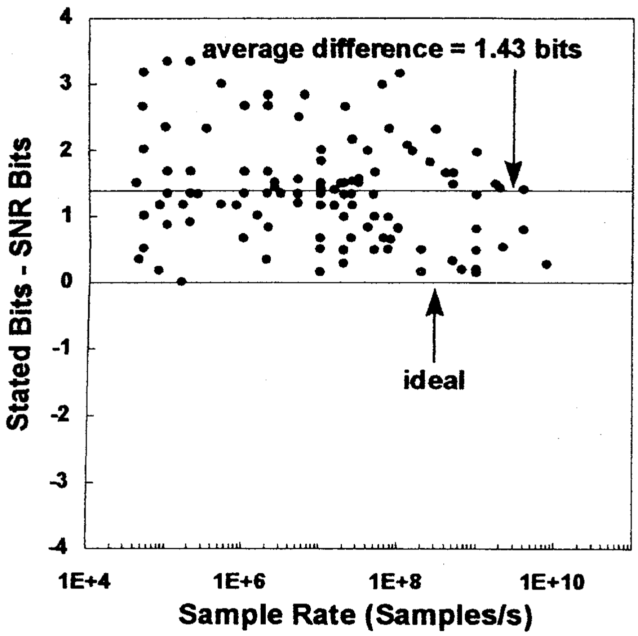

Figure 4: Difference between stated and effective resolution for state-of-the-art analog-to-digital converters (adopted from [1])

It is well known, that there is a certain difference between the stated ADC resolution as displayed in Figure 3 and the effective resolution measured in SNR. The difference between the effective performance and the stated performance, expressed in bits, is shown in Figure 4. The difference is quite large, in average about 1.5 Bit (corresponding to 9 dB in SNR). Additionally, the variance of the difference is also very large, ie. some ADCs are 3 bit worse than stated! This makes predictions for a specific ADC product pretty difficult. However, for the calculations in Section 5, a difference of only 1.5 bit is assumed.

5. Performance of Digital Modulation with ADC Quantization Noise

We assume a wideband receiver architecture with sampling at intermediate frequency f_{IF}, since demodulation in the digital domain is required in order to achieve cost-efficient mass-market receiver designs. Such a receiver approaches also the concept of software radio, offering advantages in flexibility and re-configurability.

As a reasonable approximation, the sampling frequency should be larger than three times of the channel bandwidth: $f_{sampling} > 3 \cdot B$ (the exact minimum depends on the roll-off factor). The crest-factor is assumed with 4, corresponding to 9 dB for IF sampling. Note that multicarrier transmission would require a higher crest factor.

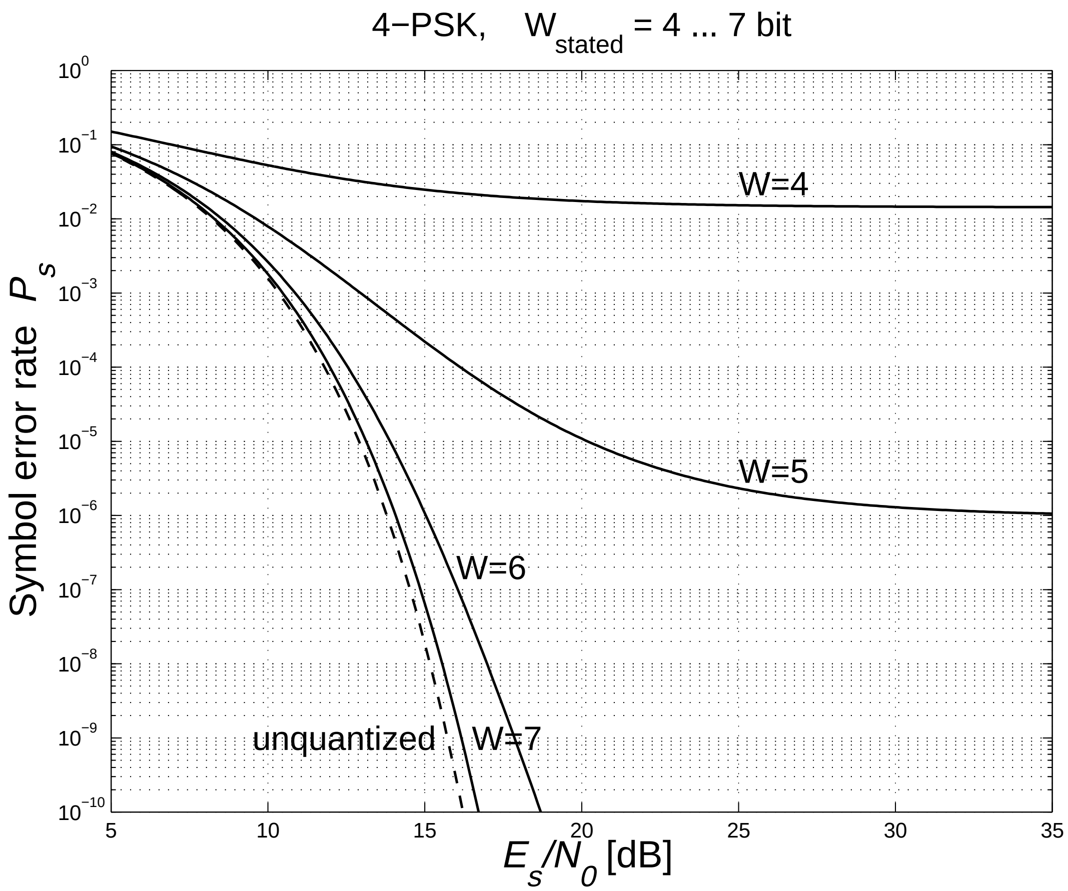

Figure 5: Performance of QPSK with quantization noise

The performance of QPSK and 16-PSK modulation with quantization noise is displayed in Figures 5 and 6 (the different effects of digital filtering on thermal and quantization noise have to be considered [4]). The solid lines refer to quantization and the single dashed line represents the theoretical limit of unquantized operation. With error control coding, the operation point for a reasonable design should be in the range from 10^{-4} to 10^{-2}. Similar investigations were performed for other modulation schemes. The results are summarized in Table 1.

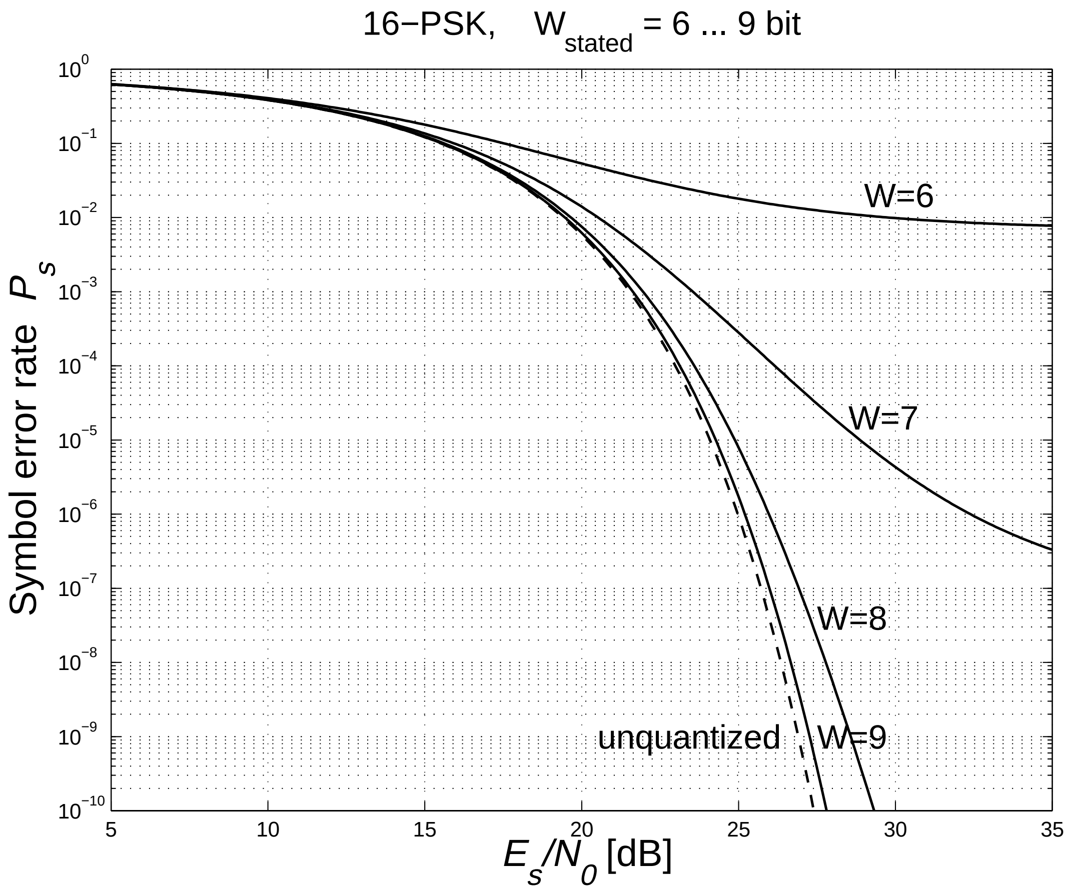

Figure 6: Performance of 16-PSK with quantization noise

Two scenarios have to be distinguished in Table 2:

- analog power control at IF prior to sampling.
- digital power control after sampling. The dynamics of fading due to rain are depending on frequency range, rain zone and required availability and are assumed here with 30 dB, corresponding to an increase of required ADC resolution of 5 bit.

Modulation	**Required resolution [bit]**	
	analog power control	**digital power control**
QPSK	**6**	**11**
16-PSK	**8**	**13**
16-QAM	**8**	**13**
64-QAM	**9**	**14**

Table 2: Required (stated) ADC resolution, depending on various coded modulation schemes

Similar as above, a cost-efficient mass-market receiver design can be achieved only with digital power control.

The most important modulation scheme is QPSK due to its robustness in cellular environments (applies both for mobile radio and wireless access). However, there are also applications for high-level modulation schemes, eg. in the inner area of a sector or in case of single cell deployments. Generally, the downlink is less sensitive to interferences from adjacent cells and thus more suited to high-level modulation schemes than the uplink, which is in line with the expected user data rates.

The relations between the bandwidth per channel, the total bandwidth per operator for full cellular coverage [5], the maximum achievable data rate (the peak data rate per terminal is bounded by the total sector rate), the required ADC sampling frequency and the achievable ADC resolution (given by the "state-of-the-art" line in Figure 3) are summarized in Table 3. A roll-off factor of $\beta = 0.3$, an overhead for signaling and synchronisation of 20% and coded QPSK with a code rate of 1/2 are assumed for the calculation of the data rate.

Bandwidth [MHz]	**28**	**56**	**112**
Total bandwidth for full coverage [MHz]	**112**	**224**	**448**
Maximum data rate with QPSK [Mbit/s]	**18**	**36**	**72**
Required ADC Sampling frequency [MHz]	**100**	**200**	**400**
Maximum ADC stated resolution [bit]	**12**	**11**	**10**

Table 3: Relations between bandwidth, data rate, sampling frequency and (stated) ADC resolution

The comparison between Tables 2 and 3 indicates a limit for the maximum channel bandwidth of approximately 56 MHz for QPSK.

6. Summary

We have considered several different issues and their impact on the channel bandwidth, especially the lower bound related to the statistical multiplex gain and the upper bound related to the ADC technology.

None of these bounds is absolutely tight, ie. there is no sharp border between possible and impossible bandwidths. The compromise is also influenced by the traffic models for the user data rates and the business case in general. In any case, the channel raster (channelization) should be compatible with ETSI TM4 specifications, ie. fit into the series of 3.5, 7, 14, 28, 56, 112 MHz.

In summary we propose:

BRAN Hiperaccess systems should be designed for bandwidths of 14 MHz, 28 MHz and 56 MHz. It seems more reasonable to use the progress in ADC technology for higher intermediate frequencies in order to simplify the analog transceiver front-end, to achieve less expensive designs and to approach the concept of software radios.

References

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