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Title: **The MEDIAN Physical Layer**

Agenda item:

Document for:

Decision	
Discussion	**x**
Information	**x**

1 Decision/action requested

This paper is intended to give a system and performance reference for a high data rate OFDM scheme to WG3 for use in Hiperlan **II** and other future BRAN standards

2 Introduction

MEDIAN is project AC006 in the European ACTS programme and makes use of the OFDM modulation technique. The main target of MEDIAN is design of a Wireless ATM LAN for 150Mbps net data rate using the 60GHz radio band and proof of concept by setup of a hardware demonstrator.

OFDM has been adopted as the baseband modulation method for a number of wireless LAN and mobile communications research programs. Several documents on OFDM or similar techniques have already been submitted to ETSI groups by different consortia or companies including MEDIAN [1,**Error! Reference source not found.**]. This paper gives a general overview on the MEDIAN physical layer design and its predicted performance to illustrate the potential of a high speed OFDM system and allow comparison with other proposals. Parallel papers discuss other aspects like turbo coding and ARQ strategies.

3 Physical Layer Description

3.1 Overview

Figure 1 provides an overview of the basic functions performed within the MEDIAN physical layer (PHY). These are coding/decoding (CODEC), subcarrier modulation/demodulation with differential encoding (DQPSK), OFDM modulation/demodulation (FFT), frame time and frequency synchronisation (SYNC).

Figure 1: Digital Baseband Physical Layer Block Diagram

All signal processing is performed with complex operations in the equivalent lowpass domain. Some implementation details with partially significant performance impact like digital magnitude precorrection, floating point to integer scaling and Tx cosine roll off windowing are not indicated in this principle diagram but are considered for implementation and/or performance prediction, respectively. The interface to the IF/RF subsystem is defined after the D/A (Tx) or before the A/D converter (Rx).

The IF/RF radio part consists of 2 IF stages and the RF stage, as well as the antenna. The signal center frequencies are as follows: 900MHz (IF2), 5.2GHz (IF1) and 61.2GHz (RF). Antialiasing filtering after digital to analog conversion (DAC) is jointly done by filters in I/Q-baseband branches and a steep filter in the 1st IF.

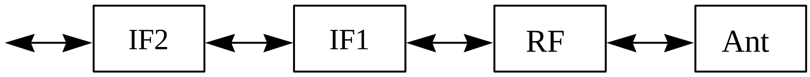

Figure 2: IF/RF Physical Layer Block Diagram

Different types of antennas are used for base station and portable stations. Since a direct line of sight (LOS) radio link is a prerequisite for the function of the MEDIAN demonstrator for today's 60GHz technology (power budget) reasons, both antennas are of directional type here! In a future MEDIAN system there will be omni-directional antennas in the portable stations what corresponds to a non line of sight (NLOS) radio link.

3.2 Coding / Decoding

A pure (55,71) Reed-Solomon coder is used in the MEDIAN demonstrator PHY. This selection was mainly driven by hardware constraints caused by the high net data rate of 150Mbps. With every ATM cell coded separately, the achievable code rate is 0.7746 (L64710 codec). More sophisticated coding schemes like concatenated or TURBO codes are investigated for use in the future MEDIAN system.

Whereas often applied to OFDM systems, no explicit crest factor reduction coding is included in MEDIAN due to the relatively high number of OFDM subcarriers (286 used of 512).

3.3 Subcarrier Modulation / Demodulation

Before general OFDM modulation every OFDM subcarrier is DQPSK modulated. Unlike DAB, differential encoding is done between adjacent subcarriers within the same OFDM symbol. For this reason, 2 phase reference subcarriers are included in every symbol (see Figure 3).

Differential detection with hard decision is applied to the demodulator branch of the MEDIAN demonstrator. Coherent detection or more sophisticated soft decision techniques could not be foreseen for hardware complexity and high data rate reasons.

3.4 OFDM Modulation / Demodulation

After DQPSK subcarrier modulation the coded bit stream is OFDM modulated performing a 512 point IFFT (transmitter) or FFT (receiver) operation, respectively. With the 512 point FFT every extended

ATM cell (424 net + 16 MAC overhead + 128 code redundancy bits) is assigned to one OFDM symbol. So, 284 of the 512 QPSK modulated subcarriers are used for information transmission. Additional 2 subcarriers are for phase reference and 3 around DC are kept unused. The rest outside is also not used to simplify anti-aliasing filtering in the D/A converted analog signal. The OFDM subcarrier allocation is illustrated in Figure 3.

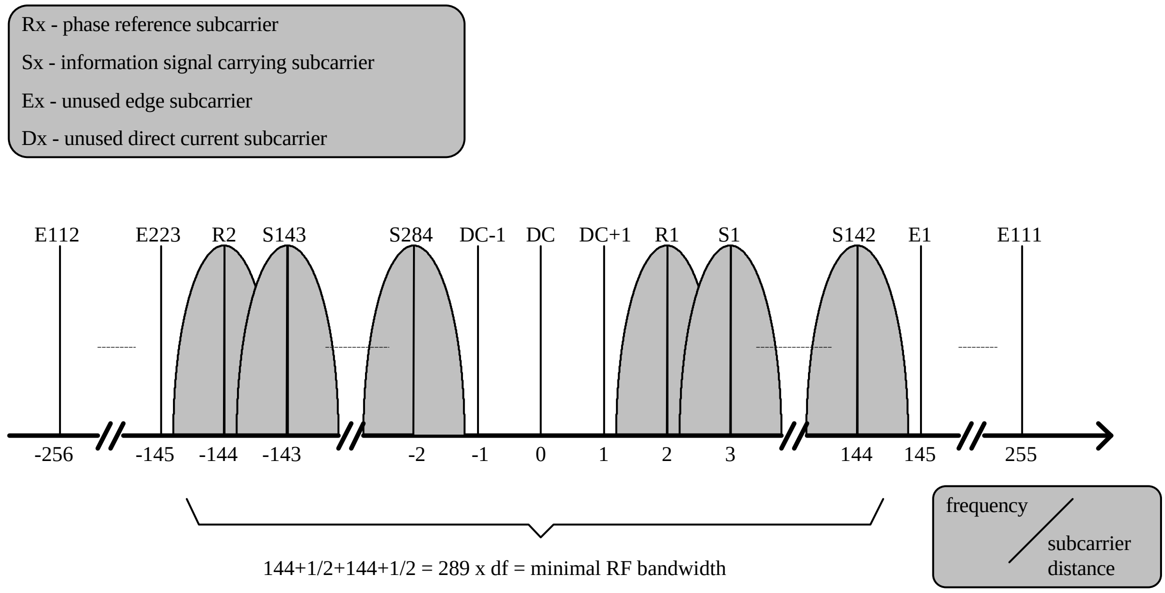

Figure 3: OFDM subcarrier allocation (frequency spectrum) in the equivalent lowpass domain.

3.5 Guard Time Insertion / Deletion

The 512 IFFT/FFT points form the main period of the OFDM symbol. 64 preamble and 24 postamble samples are added to the main period according to Figure 4 to fight multipath, ISI and group delay variations. The duration of this 600 sample OFDM symbol on air is 2.667µs.

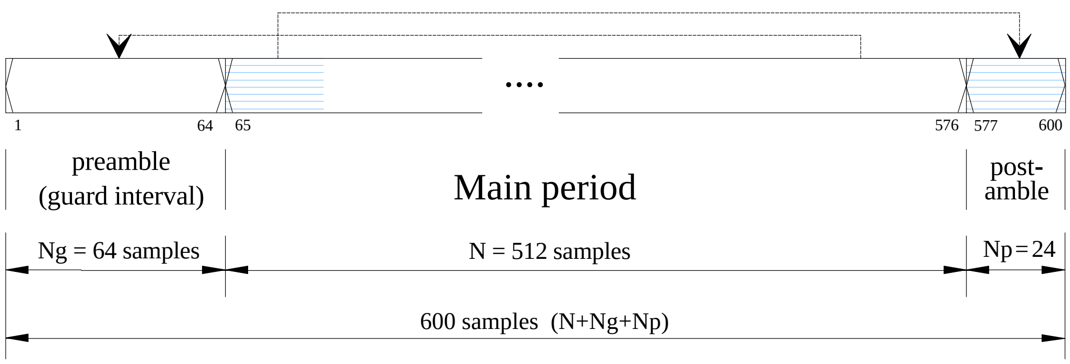

Figure 4: OFDM symbol structure. Samples of the main period are repeated for pre- and postamble.

Tx-windowing with raised cosine roll off shape in time domain was partly applied in simulation to decrease spurious spectral emissions in adjacent channels (see results below). 24 on each side of the

600 samples were used to ramp down the signal in that case. Tx-windowing is planned to be used in the future MEDIAN system, but not in the demonstrator.

Both pre- and postamble are removed in the receiver before FFT demodulation.

3.6 Synchronisation Principle

Both physical layer frame time and frequency synchronisation are based upon defined autocorrelation properties of a known sequence. This known sequence is inserted as one separate OFDM symbol, called reference symbol, at the beginning of each new TDD frame (see Figure 5).

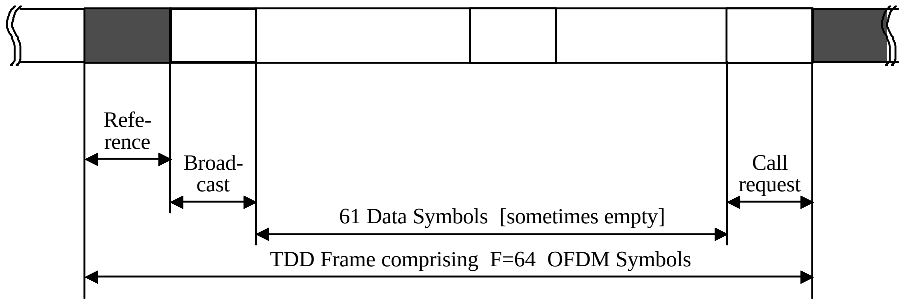

Figure 5: TDD-frame structure with one reference symbol per frame for synchronisation purposes.

The reference symbol consists of a signal pattern (SP) in time domain which is repeated 18 times within the reference symbol. An autocorrelation of type

$$\mathbf{R}(i) = \sum_{m=1}^{17SP} \left[y(i-m) \cdot y(i-m-N_{SP})^{*} \right]$$

to be applied to the incoming data stream founds the basis of all synchronisation processing (N_{SP}=32 is length of signal pattern SP). The maximum of $|\mathbf{R}(i)|$ determines the first signal sample of the reference symbol which is the frame start. The phase $\arg\{\mathbf{R}(i)\}$ gives a measure for the phase and finally the frequency error to be corrected by the loop.

After time and frequency acquisition where about 300 frames are needed to calculate the initial time and frequency error values by DSP, further time and frequency correction in the tracking period is done once per TDD frame. This is feasible for the short frame duration of 170.6µs and required by hardware constraints. Due to the TDMA/TDD approach in MEDIAN, all synchronisation correction is done in the portable stations alone, i.e. there is no extra physical layer synchronisation in the base station of the MEDIAN demonstrator cell. The sample clocks in the portable stations are free running. Frequency correction loop structure is feedback in digital domain.

3.7 A/D - D/A Conversion

D/A and A/D conversion is done with 8 bit resolution at 225.0 MHz sample rate. The influence of quantisation and clipping effects will not be discussed here.

3.8 IF/RF front end

Among others, IF/RF belongs to the most challenging subsystems due to its large analog signal bandwidth (127.5 MHz double sided RF-bandwidth) and the 61.2 GHz radio centre frequency.

Whereas the general IF/RF subsystem structure is mentioned in section 3.1 and assumed to be well known, only the significantly system performance degrading parts shall be highlighted here again. To these belong

a) I/Q-mismatch (ADC/DAC, BB-filters, attenuators, I/Q-mod/demod)
b) RF-front-end high power amplifier (HPA) nonlinearity
c) RF oscillator phase noise
d) Filter ripples & DAC-sinc-effect

The mismatch between I and Q branches near IF2 unit close to the baseband processor interface is critical and was found to be most performance degrading with standard tolerance components. The problem will be overcome with special selection of the baseband filters and I/Q-modulator/demodulator components having impairments of 0.1dB in magnitude and 1deg in phase. Main anti-aliasing filtering is done in the lowest IF for that reason.

The RF-front-end high power amplifier (HPA) is always a critical component in linear transmission systems due to its nonlinearities. AM-AM and AM-PM conversion was measured for an available 60GHz amplifier and a conversion model was generated from those measurements (see Figure 6). The amplifier's 1dB compression point of 14 dBm is relatively low and reflects today's technology limitations in 60GHz RF components. The restriction to pure LOS in the demonstrator radio link is established for that reason.

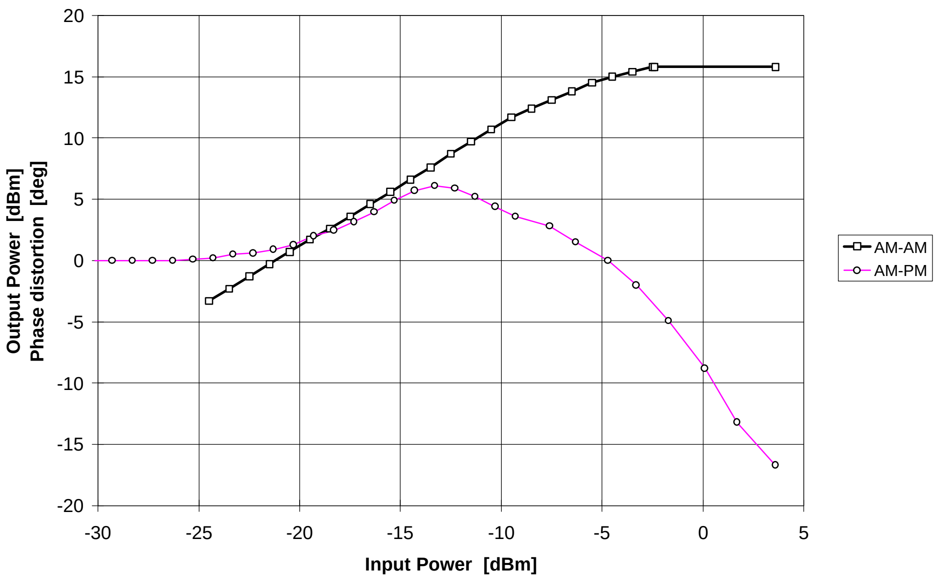

Figure 6: AM-AM and AM-PM conversion of 60GHz high power amplifier (HPA) to be used in the MEDIAN demonstrator (model based on measurements by Dassault Electronique)

RF oscillator phase noise is of significant influence to the system performance because of a very large system bandwidth in MEDIAN. The phase noise mask shown in Figure 7 is used for performance prediction simulations and represents real component behaviour. Noise contributions above the frame rate of about 5.8kHz cannot be coped with by the synchronisation circuit and degrade the performance. With present residual ‘noise floor’ of -130dBc/Hz the overall performance degradation is predicted to be below 1dB.

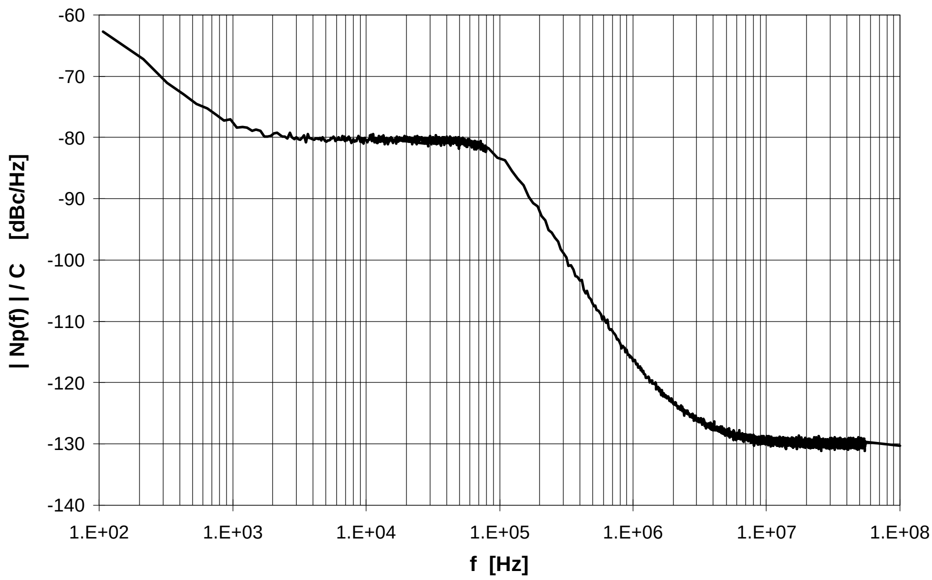

Figure 7: Phase noise mask of 56GHz local oscillator to be used in the MEDIAN demonstrator (approximated PSD curve based on measurements by Dassault Electronique)

Filter ripples and DAC-sinc-effect as above last mentioned source of performance degradation shall not be matter of simulation and prediction. Those changes in the frequency band are measured and digitally compensated in the demonstrator hardware setup.

4 Physical Layer Performance

MEDIAN performance predictions were accomplished by system analysis and simulations. For below described simulation results following parameters are applied:

Coding:	case a: none
	case b: Reed Solomon RS(55,71)
OFDM-FFT points:	512
Used OFDM subcarriers:	286 (=284+2), see Figure 3
Guard samples:	64 preamble, 24 postamble, see Figure 4
Subcarrier modulation:	DQPSK
Differential encoding:	adjacent subcarriers, 2 reference carriers per symbol
Subcarrier demodulation:	differential detection with hard decision
Subcarrier distance:	439.45kHz
OFDM symbol duration:	2.667µs
TDD frame duration:	170.667µs
Tx- symbol ramping /windowing:	case α: ideal rectangular (applied to all BER curves below)
	case β: RC shape with 24 samples on each side (PSD only)
Tx-Amplifier:	nonlinear incl. AM-AM and AM-PM, see Figure 6
	OBO=5dB (with respect to 1dB compression point @ 14dBm)
Tx-filtering:	ideal rectangular
Indoor channel:	case 1: AWGN
	case 2: NLOS channel model based on static 60GHz indoor measurements, FIR-filter approach, delay window 70ns, see [**Error! Reference source not found.**]
Oscillator phase noise:	56GHz Farran-LO model, see Figure 7
Rx-filtering:	ideal rectangular
Rx-DSP-Resolution:	infinite (floating point)
t-sync algorithm:	tracking based on time domain correlation (acquisition value as initial input)
f-sync algorithm:	tracking based on time domain correlation (acquisition value as initial input)
Power control:	not included

Both demonstrator and the future MEDIAN system are covered with those parameters. The main difference lies in the channel environment. Whereas the demonstrator works with a pure line of sight (LOS) radio link coming close to an AWGN channel, the future MEDIAN system is designed for more complicated non line of sight (NLOS) conditions.

Power spectral densities (PSD) as well as bit error rates (BER) of the overall MEDIAN physical layer shall be presented in this document.

PSDs of the OFDM modulated and amplified transmit signal are shown in Figure 8 and Figure 9. Figure 8 contains graphs for linear amplification to allow comparison with other sources. Two curves for two types of Tx-windowing, rectangular (i.e. no windowing) and raised cosine roll off with 24 of 600 samples ramp duration on both symbol ends, are shown in both pictures. For linear amplification (Figure 8) both curves look as expected. Without Tx-windowing there is relatively much energy outside the transmission band, whereas good suppression of spectral spurious emissions can be achieved with raised cosine Tx-windowing.

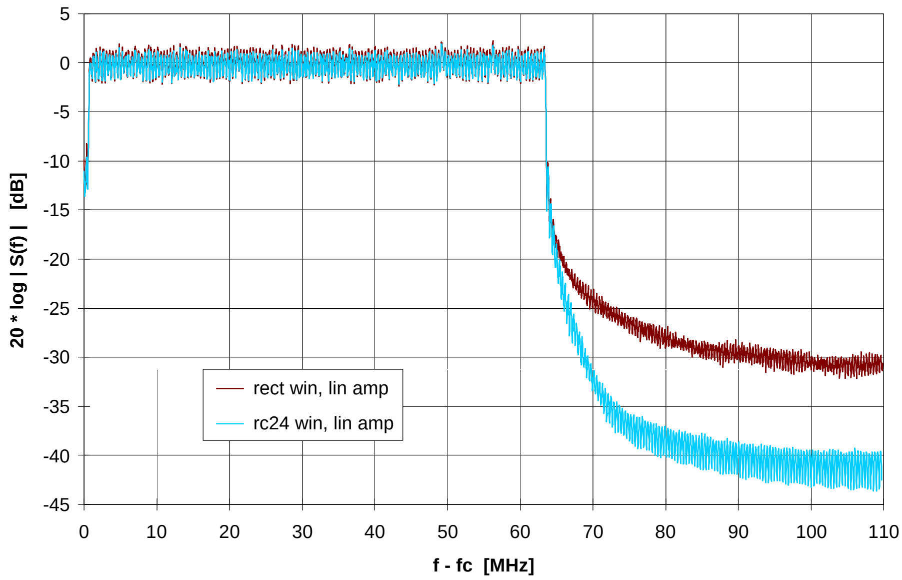

Figure 8: Power spectral density of OFDM modulated transmit signal for 2 types of Tx-windowing (rectangular and raised cosine roll off, see sect 3.5) after linear amplification.

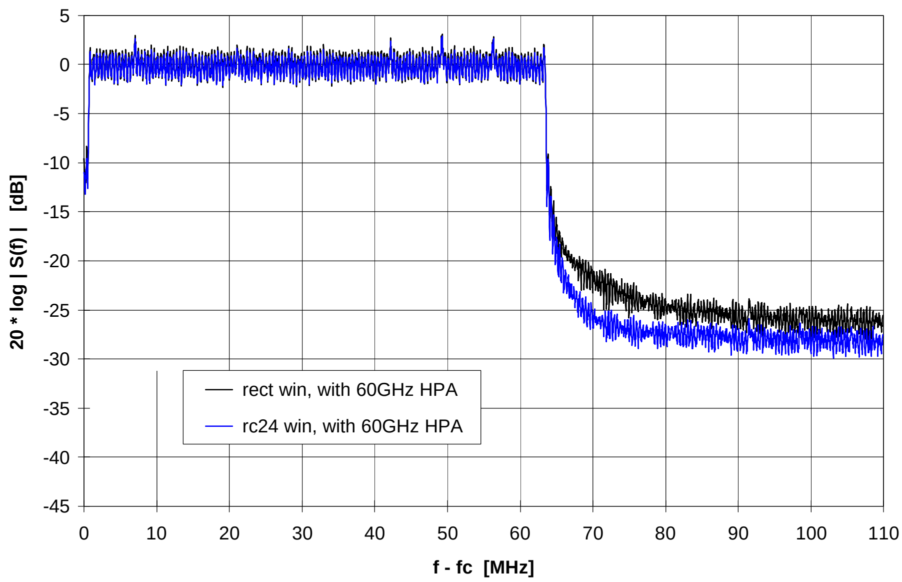

Figure 9: Power spectral density of OFDM modulated transmit signal for 2 types of Tx-windowing (rectangular and raised cosine roll off, see sect 3.5) after 60GHz high power amplifier (demonstrator HPA, Figure 6, 5dB OBO with respect to 1dB compression point).

However, the situation changes after insertion of a realistic 60GHz HPA (Figure 9). There is significant spectral restoration for both types of windowing at 5dB output backoff (OBO) what is the figure for demonstrator setup. The PSD curves show a significant influence of the 60GHz HPA nonlinearities even at that high OBO (difference to [2]). This is one of the reasons not to use Tx-windowing in the MEDIAN demonstrator. A combination of an amplifier linearisation technique and RC Tx-windowing is envisaged for the future system.

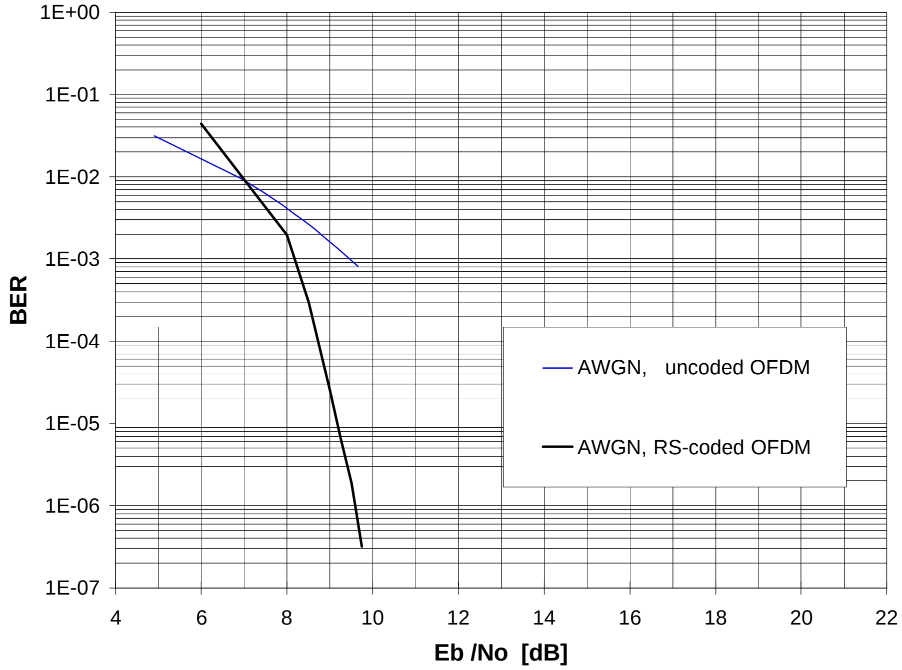

Figure 10: Uncoded and coded bit error rates of the overall MEDIAN physical layer in AWGN (comparable to demonstrator). HPA nonlinearities, LO phase noise, synchronisation are included.

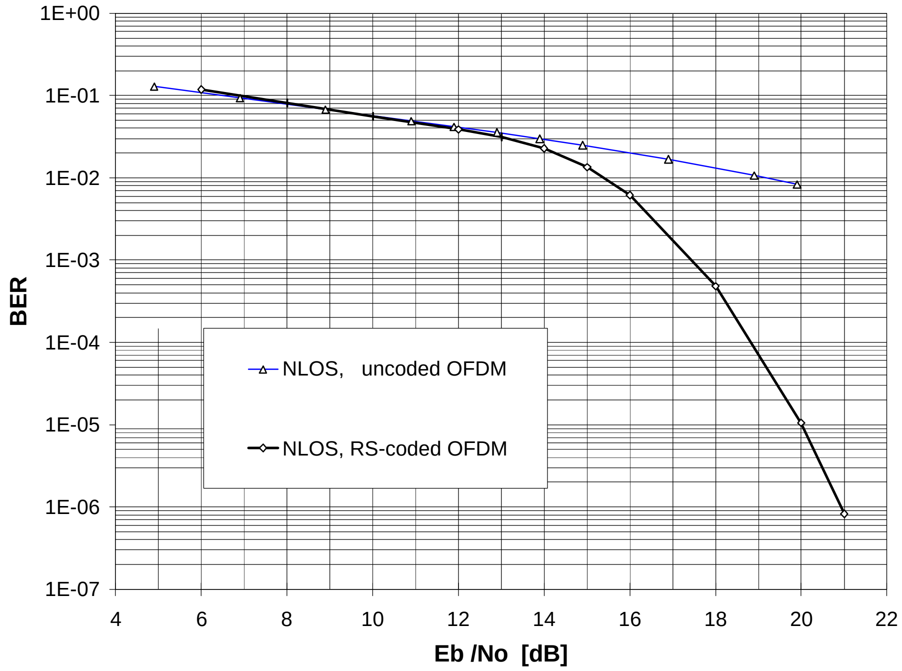

Figure 11: Uncoded and coded bit error rates of the overall MEDIAN physical layer for a Non Line of Sigth (NLOS) multipath channel (target environment for future system). HPA nonlinearities, LO phase noise, synchronisation are included.

BERs of the overall MEDIAN physical layer including RS(55,71) coding are depicted in Figure 10 and Figure 11. No Tx-windowing is applied here. The curves in Figure 10 are simulated for AWGN what comes close to the demonstrator channel, results in Figure 11 are obtained for a static 60GHz NLOS model [3] what represents the environment of a 60GHz W-ATM LAN system with omnidirectional portable station antennas in first approximation. All other simulation parameters are as indicated above.

A reliable physical layer with less than 10^{-6} BER at 10dB Eb/No is predicted for the MEDIAN demonstrator. Similar performance could be achieved with a single carrier modulation system in AWGN or LOS with a strong direct path (see [4]). However, more interesting is the omnidirectional antenna NLOS environment as the target scenario of the future MEDIAN system. 11dB more Eb/No (21dB) have to be guaranteed here to achieve a BER of 10^{-6} (see Figure 11). Regardless of this significant degradation, there is the same clearly decreasing qualitative slope in the coded BER what was not necessarily expected from the uncoded BER curve with major system nonlinearities (static multipath NLOS channel, 60GHz HPA, 56GHz Farran-LO phase noise) included. Once again, these results prove the advantage of OFDM in a multipath radio environment where a system can work without channel equalisation even at very high data rates.

5 Acknowledgements

This document is composed of consortium internal design notes and public project deliverables. New simulation results were added by the authors.

It shall be emphasised that, like all other project work, the physical layer design is based on results of the overall MEDIAN consortium. The project work is carried out by all partners: IMST, DTAG, Motorola, TNO, Dassault Electronique, VTT, Elektrobit, K-Net, North-West-Labs, Screenphones, Adimec, University of Dresden, University of Rome, University of Southampton, University of Eindhoven.

6 References

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