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### WIGWAM: system concept development for 1 Gbit/s air interface

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**Abstract**— The WIGWAM<sup>1</sup> research project (Wireless Gigabit with Advanced Multimedia) is aimed at designing a 1 Gbit/s system concept for the home/office, public access and high velocity scenarios. The cross-layer project covers PHY & MAC, integration into existing infrastructure and RF, BB and Dirty RF hardware and algorithm development. The current stage of the system concept is presented in this paper.

#### Introduction

THE WIGWAM research project (Wireless Gigabit with Advanced Multimedia) is aimed at designing a 1 Gbit/s system concept for the home/office, public access and high velocity scenarios. The cross-layer project covers the physical up to the protocol layer, and integration into existing infrastructure. Furthermore, RF, BB and Dirty RF hardware and algorithm development are addressed, since the availability of mass-market components is key to the success of a system concept and standards based on it. The project overview was given at WWRF10 in 2003 [1] and in [3]. The application scenarios: home, office, public access and high velocity (broadband access for trains and highways) are described in [2]. The aim of this paper is to present the current status of the system concept, which is taking shape now.

<sup>1</sup> The WIGWAM project is a collaboration of 27 partners from industry, research institutes and universities. It is supported by the German ministry for education and research (BMBF), and lead by TU Dresden. For further details see [www.wigwam-project.de](http://www.wigwam-project.de)

#### System Concept Development

Figure 1 shows the data rate development at the example of WLAN-type networks. IEEE 802.11a/g equipment with 54 Mbit/s PHY data rate has entered the mass market. Currently, in IEEE 802.11n a standard supporting 250 Mbit/s (PHY data rate) (or 100 Mbit/s goodput including MAC overhead) is taking shape. The WIGWAM system concept is looking beyond, at data rates of 1 Gbit/s, which are required for high quality audio and video applications.

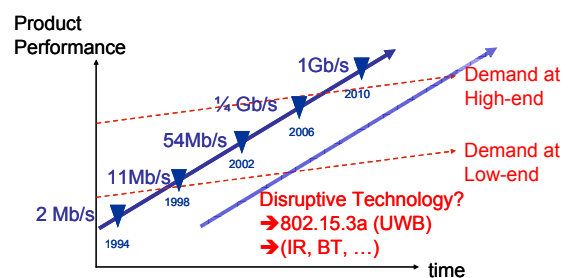


Figure 1: Data rate for wireless LAN networks

The following frequency ranges are considered for the WIGWAM system concept:

- **5 GHz:** This is the main WIGWAM frequency band. The World Radio Telecommunication Conference (WRC-03) agreed in July 2003 to allocate a total of 455 MHz in the bands 5.150-5.350 GHz and 5.470-5.725 GHz for wireless access systems including RLANS.
- **17 GHz:** In Europe, there is a band of



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200 MHz bandwidth at 17 GHz dedicated to RLANs to be used on a non-protected and non-interference basis. This is an extension band for the WIGWAM system concept.

- **24 GHz:** There is an unlicensed band at 24.0-24.25 GHz with 250 MHz bandwidth available in Europe and the USA.
- **38 GHz:** In Europe, there is a band at 38 GHz dedicated to directional communication links. For example, the communications link for special high velocity train system TRANSRAPID is operating at 38 GHz.
- **60 GHz:** This mm-wave band has attracted a lot of attention recently, e.g. in the IEEE 802.15.3c Millimetre Wave Interest Group. There is large bandwidth available in the range of 59-64 GHz. The limited propagation range, and therefore high interference isolation, makes this band especially attractive for home and office environments. The design of low-cost integrated transceivers at 60 GHz is extremely challenging. Only recent technological progress has made 60 GHz realistic for mass-market applications.

## Development of PHY

OFDM (orthogonal frequency division multiplexing) is chosen as modulation format. To support IEEE 802.11g/n devices in the same frequency range, bandwidth is kept flexible in  $n \times 20$  MHz steps, up to 100 MHz. Multiple antennas at the transmitter and the receiver can be used for spatial multiplexing or link quality enhancement. The concept adapts the transmission scheme in a flexible way to the amount of channel state information (CSI) available at the transmitter. Thus scenarios without CSI, with long-term statistical or no CSI at the transmitter are supported. With four transmit and four receive antennas, four parallel MIMO (multiple input – multiple output) data

streams can be transmitted. However, a spatial equalizer is necessary at the receiver. The challenge is to provide sufficient performance in terms of packet error rate with a reasonable computational complexity. Among the suitable MIMO receiver algorithms are linear processing, successive interference cancellation and sphere decoding (SD) [5].

Advanced coding concepts, like LDPC-Codes (Low Density Parity Check) or multi-level coding are considered (see [4] and references therein). They provide a performance gain compared to conventional convolutional codes, and have the potential to require a lower complexity. However, since convolutional codes are used for a long time in many standards, highly optimized hardware solutions exist now for them. Within this project, hardware solutions for LDPC codes are developed.

Another design option for OFDM systems is the length of the guard interval. For that, channel measurements for the WIGWAM bandwidth and carrier frequency were conducted by MEDAV and TU Ilmenau. Delay window, delay spread, coherency time, angular spread and spatial correlation are determined in various environments and with several antenna configurations [6].

The subcarrier spacing, FFT size and symbol length are other design parameters. It is advantageous, to fix the subcarrier spacing to a multiple or fraction of the 802.11a/g values for easier reuse of hardware components.

The resulting PHY data rate is:

$$\text{Data Rate} = \text{spatial streams} \cdot \frac{\# \text{ data subcarriers}}{\text{FFT size}} \cdot \frac{\text{coded bits}}{\text{subcarrier}} \cdot \frac{\text{info bits}}{\text{coded bits}} \cdot \frac{1}{\text{total symbol length}}$$

guard band overhead      constellation size  
code rate

What are the degrees of freedom to increase the data rate of an OFDM system?

- Bandwidth, and hence the ratio of FFT size and symbol duration, scales the data rate significantly. At 100 MHz, the data rate compared to 20 MHz increases at least by a factor of



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- five, and the relative guard band overhead gets also smaller.
- The number of spatial streams has a significant impact. With 2x2 MIMO, the data rate can be doubled, and with 4x4 MIMO quadrupled. However, the necessary SNR for the same constellation size depends strongly on the used MIMO detection algorithm
- The constellation size is also important. Going from 64-QAM to 256-QAM, a factor of 8/6 can be achieved. However, phase noise and other dirty RF effects may become dominant.
- The ratio of data subcarriers to the number of overhead subcarriers (pilots, zero subcarriers) also determines the bandwidth efficiency.

There are additional degrees of freedom to increase the system efficiency, but their impact is not so visible at the first place:

- Pilots are necessary for synchronization and channel estimation. In MIMO configurations, orthogonal pilots have to be transmitted from all antennas for channel estimation purposes. There are two main concepts for pilots: preamble-based pilots and superimposed pilots [8]. The first method has no interference problem, but spectral efficiency is wasted for short packets. With interference cancellation, superimposed pilots may have capacity advantages. Furthermore, superimposed pilots might shorten the delay due to the preamble.
- Signaling information and other applications have very short data bursts, like acknowledgements and “web-browsing mouse-clicks”. If frame aggregation can not be applied, the exploitation of large OFDM symbols is very poor. Tailored OFDMA packets or superimposed MC-SS (multi-carrier spread-spectrum) signaling are two methods to increase the efficiency.

- Scheduling, link adaptation, bit loading and power allocation for multiuser MIMO systems are extremely important. They have to be considered right at the beginning of a system concept development [9].

### WIGWAM PHY Parameters

In the current release of the WIGWAM system concept [12] a PHY is proposed which can be adapted to the user requirements and the environmental conditions. Table 1 shows the achievable data rate per spatial stream for the WIGWAM home/office scenario in the 5 GHz band. The bandwidth is 100 MHz in this example of the flexible WIGWAM n x 20 MHz approach. The subcarrier spacing is 156.25 kHz (e.g. 1/2 of legacy IEEE 802.11a/g devices), and the sampling time is 6.25 ns. 596 carriers are used effectively for data transmission; hence the FFT size is 1024 with an FFT bandwidth of 160 MHz. The symbol duration is 6.4 μs, and the guard time is 0.4/0.8/1.6 μs, depending on the channel conditions. The guard time is based on 100 MHz bandwidth channel measurements of Medav, TU Ilmenau and Siemens within the WIGWAM project. The guard overhead ranges from 6 % to 20 %, and 20 subcarriers are dedicated to pilots. Table 1 shows different modulation and coding schemes.

	596carr./ $T_u = 6.4\mu s$
BPSK, $R = 1/2$	41.4 Mb/s
QPSK, $R = 1/2$	82.8 Mb/s
16-QAM, $R = 1/2$	165.6 Mb/s
16-QAM, $R = 3/4$	248.3 Mb/s
64-QAM, $R = 2/3$	331.1 Mb/s
64-QAM, $R = 3/4$	372.5 Mb/s
256-QAM, $R = 3/4$	496.7 Mb/s

**Table 1: Home/office scenario data rates per spatial stream**



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The home/office scenario and the 5 GHz air interface is used here as an example to show the system concept development. For 60 GHz, a different approach is taken, since much more bandwidth is available, and MIMO is not used in the first place.

## PHY Simulation Results

Figure 2 shows the simulation results for a set from the WIGWAM parameters (home/office scenario, 5 GHz, SISO mode, QPSK, Convolutional Coding Rate 1/2). Without considering any guard band/time overhead, the performance is comparable to legacy 802.11a/g. However, taking into account the cyclic prefix and the pilot subcarriers, the effective bit energy is changed, and hence a 1 dB gain is achieved over the conventional 802.11a/g standard. Note that for both WIGWAM modes, a transmission bandwidth of 100 MHz is used. At the FFT bandwidth of 160 MHz, only 596 out of 1024 subcarriers are used.

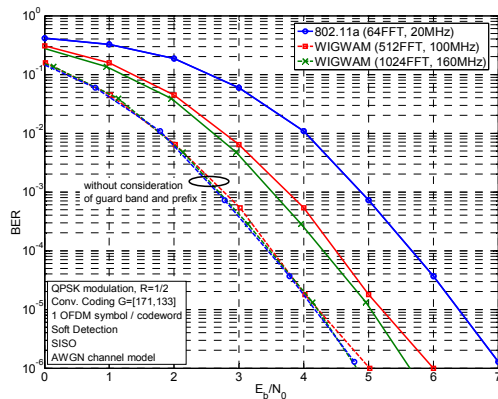


Figure 2 WIGWAM PHY Simulation Results (SISO, AWGN)

Figure 3 shows the SISO frame error rate in the 802.11n D channel scenario (NLOS) with the comparison of convolution codes (CC) and LDPC codes. In this simulation, the LDPC codes proposed by TGnSync are used as an example, and a soft detector is applied in the receiver. The gain of LDPC codes over CC codes is 1...4 dB, depending on the modulation scheme.

The results for 4x4 MIMO are shown in Figure 4. As receiver, an MMSE SQRD soft detector is used. Alternative receiver

algorithms are currently investigated within the WIGWAM project. The gain of LDPC codes is higher for MIMO (Figure 4) than in the SISO scenario (Figure 3).

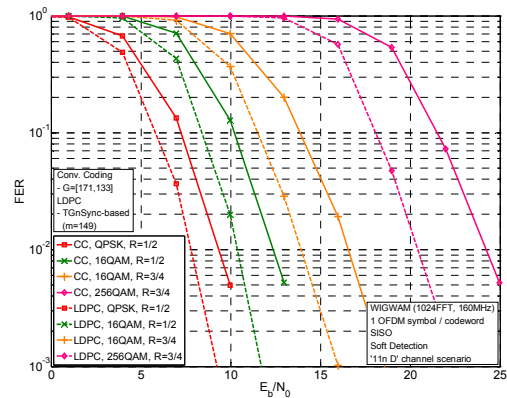


Figure 3 WIGWAM SISO results with convolutional codes and LDPC codes in IEEE 802.11n D channel environment

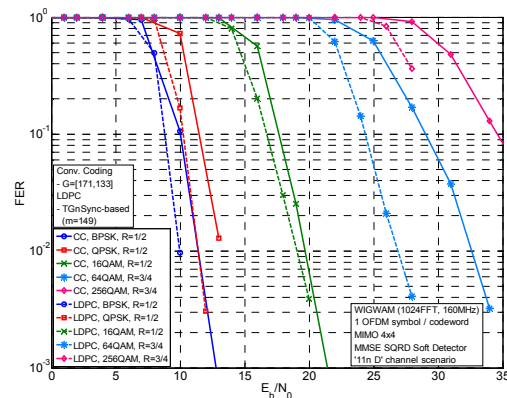


Figure 4 WIGWAM 4x4 MIMO results with Convolutional codes and LDPC codes in IEEE 802.11n D channel environment

## MAC and Mobility Support

For the home scenario, the focus is on a decentralized approach with self-configuring consumer equipment, where Multi-carrier-Code Division Multiple Access (MC-CDMA) basic Medium Access Control is one suitable option. For the high speed and the public access scenarios a centralized OFDMA based solution is required and the main focus is on providing seamless mobility support by means of handover mechanisms. The



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challenge in the high speed scenario is to deal with a very high mobile speed of up to 600 km/h. For the public access scenario, the challenge is to provide generic solutions for mobility support in future heterogeneous mobile communication networks.

As can be proven by the diversification of standardization bodies and industry consortia, the different scenarios can not and should not be covered by a single highly complex one-serves-all protocol, but rather the WIGWAM MAC protocol should be a combination of a decentralized and a centralized concept, with carefully engineered interfaces for coexistence and cooperation. The high-mobility scenario is unique in the sense that specific security and dependability assumptions have to be fulfilled, potentially requiring a separate and proprietary MAC and PHY level.

The multiple access schemes is developed to suit best the user scenario. Thus, both centralized and ad-hoc options are considered. As multiple access schemes, both OFDMA and MC-CDMA are suitable.

### Hardware enabling Gigabit Wireless

The success of wireless standards depends to a large amount on the availability of cheap high-volume hardware components in the right market time window. Therefore, the development of analogue and digital hardware components enabling data rates beyond 1 Gbit/s is in the focus of the largest working package within WIGWAM. Basically, three main points are considered:

- Hardware demonstrators showing the feasibilities of WIGWAM system concept modules
- Concepts and algorithms for analogue front-end impairment correction by baseband algorithms [7]. Phase noise, I/Q-imbalance, nonlinear power amplifiers, antennas and packaging are considered.
- Baseband processing to enable high data rate wireless communications with low-power mobile devices.

### Demonstrators

Within WIGWAM work package 2, hardware demonstrators showing partial WIGWAM features are built, and concepts for RF and baseband processing are investigated. The demonstrators are developed by Philips, MEDAV, IHP, DaimlerChrysler, Infineon and TU Dresden, respectively. Since the WIGWAM project will finish in March 2007, the demonstrators available now at project mid-term will be further enhanced to show the feasibility of 1 Gbit/s hardware and software components.

#### Easy and Secure Network Setup

One problem of current WLAN system in home environments is the insecure visibility of networked devices to neighbours, and the threat of external control of ones resources. Using RF-ID tags or NFC devices, a secure membership of a device to a network is established, and privacy protection and security are bootstrapped. This easy and secure network setup was demonstrated at Wireless Connectivity World Conference in London in spring 2005 [9].

#### Ultrawideband mm-wave channel sounder architecture

For the development of a wireless system concept, knowledge of the properties of the wireless channel is essential. The flexible channel sounder architecture supports currently a bandwidth of 7 GHz at frequencies up to 10.5 GHz. This is currently extended to mm-waves (56.5-63.5 GHz) [11]. The highly integrated design is based on ultra fast SiGe:C BiCMOS RF circuits with transit frequencies up to 200 GHz. Directional resolution is achieved using multiple Tx and Rx antennas.

#### 60 GHz OFDM Demonstrator

The 60 GHz demonstrator consists of an analogue front-end, an FPGA/baseband processor module, an ASIC board mainly for FFT and channel coding, a MAC processor and interfaces. The 60 GHz receiver front-end incorporates an integrated LNA and mixer [12]. The 60 GHz demonstrator implements the WIGWAM system concept for



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the home/office scenario at the 60 GHz extension band. The typical range is 5-10 meters. The FFT bandwidth is 400 MHz, and the subcarrier spacing 1.5625 MHz. For the transmission of data, 192 subcarriers are used. With 64-QAM modulation and rate  $\frac{3}{4}$  convolutional codes, the achievable data rate is 1080 Mbit/s. Multiple MIMO data streams are not feasible in this LOS (line of sight) dominated scenario.

### Six-Port Receiver for mm-Wave

Six-port receiver structures are among potential architectures for mm-wave and sub-mm-wave front-ends. Six-port receivers use simple power detectors to realize a direct conversion or a zero-IF receiver. The RF characteristics and boundary limitations show that the six-port receiver is an interesting alternative to existing mixer based architectures. The demonstrator developed within the WIGWAM project [13] shows that almost error-free reception is possible in the 24 GHz ISM band.

### 5/24 GHz Multiband/Multimode Front-End in CMOS

For the 5 GHz WIGWAM system concept and the higher frequency extension bands (e.g. 24 GHz ISM band), a receiver front-end was built in 0.13  $\mu\text{m}$  CMOS. The 5 GHz direct conversion receiver is reused as IF for receiving 24 GHz signals. LNAs and down mixers are suitable for digital frequency tuning. The multi-mode channel filters support 802.11a/g/n and 100 MHz WIGWAM channels.

### Vector Baseband Processor

For mobile applications, power efficient baseband processing is essential. Additionally, more than 1 Gbit/s have to be processed, including advanced MIMO receiver algorithms, LDPC decoders and other components of the WIGWAM system concept. The framework for the generation of communications-DSPs by an automated design flow includes code generation, hardware generation and development tool generation [14]. Currently, a floating-point DSP with 8 SIMD-parallel data paths is available. The modular DSP architecture will be used to show the feasibility of the

WIGWAM system concept and the according baseband algorithms by the end of the project.

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