SDR OFDM WAVEFORM DESIGN FOR A UGV/UAV COMMUNICATION SCENARIO

Christian Bluemm[1], Christoph Heller[1], Robert Weigel[2]
[1]EADS Innovation Works, Munich, Germany
[2]University of Erlangen-Nuremberg, Erlangen, Germany

ABSTRACT

In the course of a national research project, EADS IW has developed a waveform on a self-designed hybrid Software Defined Radio (SDR) platform, consisting of an FPGA (Xilinx Virtex 5) and a GPP (Intel Atom). The waveform realizes a video link between an Unmanned Ground Vehicle (UGV) and its base station. This link is established indirectly with an Unmanned Aerial Vehicle (UAV) acting as a relay, in order to enable non-line-of-sight (NLOS) communication and to increase the communication range. Additionally, a direct video link from the UAV to the base station is set up simultaneously as well as multiple low data rate control channels between the individual link partners. To cope with diverse operation areas, accompanied by a heterogeneous set of requirements, the waveform must offer outstanding adaptability and flexibility to maximize data rates in each scenario, while maintaining link robustness. The developed waveform is based on OFDM with freely customizable modulation parameters. Time Division Multiple Access (TDMA) is implemented on medium access layer to switch between the different users in the scenario (UGV, UAV, base station). In this paper, we give an overview of the waveform, its implementation on a hybrid platform and its validation for the intended field of application.

1. INTRODUCTION

Autonomous mobile robot systems with UGVs or UAVs are increasingly used for military purposes. For civil use, there is also a wide range of conceivable applications, where small unmanned platforms are more flexible, higher available and cheaper than traditional manned systems. Equipped with adequate sensors, autonomous systems could for instance detect hazardous substances at an early stage and monitor their spread. Other examples are Search and Rescue (SAR) activities, security services, image and video recording, environmental mapping and –monitoring, the surveillance of major sport events, etc. In combination with satellite navigation technology any captured information could be georeferenced exactly.

Typically, the UGV/UAV data is sent without much preprocessing to the base station. To therefore guarantee a reliable communication link, the special needs of UAVs/UGVs and their environmental conditions must be taken into account. This paper focuses on an appropriate self-designed waveform, which is based on an OFDM physical layer in combination with a TDMA medium access (MAC) protocol.

This work is part of the project SiNafaR (Safe navigation for autonomous robotic platforms), which was launched by the Bavarian ministry of state for economy, infrastructure, traffic and technology to develop methods and processes for the use of cooperating air and ground robots in civil applications.

2. THE PROPOSED COMMUNICATION SCENARIO

The waveform which is presented here can cope with a broad variety of communication scenarios. However, a specific set-up was defined for a proof of concept. It will be introduced in the following.

UGV communication in rough terrain is often hindered by a missing LOS data link between UGV and the base station. A promising way to overcome this problem is the use of a UAV as relay, optimized for acting as autonomously as possible. A second advantage of this approach beside the NLOS compatibility is the increased available communication distance between UGV and its base station.

Fig.1 depicts the proposed communication set-up. The UGV is equipped with scenario-specific sensors and a camera. The UAV is acting as a communication relay for the UGV and in addition, it carries another camera to monitor the UGV. For this set-up unidirectional video links are needed in parallel to bidirectional control links from the UGV to the base station (indirect link) and from the UAV to the base station (direct link). There will be no direct link between the UGV and the base station.

The main technical needs within this scenario are given as follows. For each video link, a minimum data rate of 3 Mbit/s is required, when low-quality MPEG 2 compression is chosen. [1] However, better video quality is desired, to be traded off against its need for higher bandwidth.

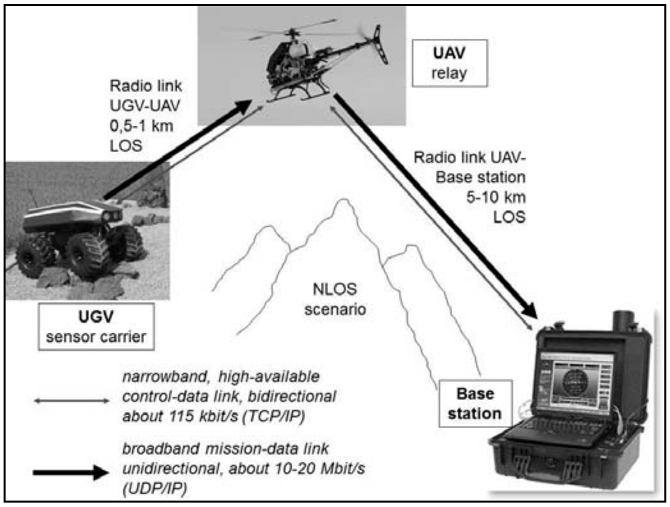

Fig.1 The UGV/UAV communication scenario

The control links are low-bandwidth data streams and thus negligible for throughput considerations. Another difference between the control link and the video link is the height of tolerable bit error rate (BER): Video stream errors lead to a decreased video quality, whereas the worst case of a defective control link would be a complete system failure.[1] The aspect of different reliability demands of the two link types must be kept in mind throughout the complete design process, starting with an adequate system interface: Both link types provide IP, but differ in the transport layer. For the video link, the minimal protocol UDP suffices, whereas the critical control link covers TCP to guarantee reliable message delivery. The difference is that UDP is based on continuous unidirectional transmission, no matter if the message reaches its destination or not. In contrast, TCP offers the concepts of message acknowledgment, retransmission and timeout. [2]

The set-up in Fig.1 is intended for heterogeneous operational environments. To comply with their inevitably varying demands, the waveform needs to behave differently for maximum performance. Hence, it must be customizable to allow different configuration parameters tailored for varying environments and varying channel characteristics. The video quality, for example, can be improved dramatically under good channel conditions, as soon as the waveform parameters fit the channel quality.

Scenario- and OFDM- specific major channel challenges include high relative speed between the communication partners and fast changing channels, e.g. in urban environments.

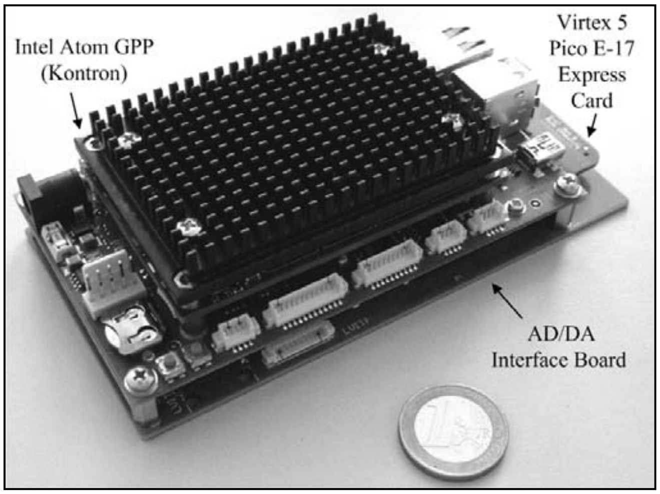

Fig.2 Photo of the hardware stack

3. HARDWARE PLATFORM

Beside the waveform, also the SDR hardware, on which the waveform is implemented, needs to account for the specific scenario requirements. The most obvious requirement for it is a small and lightweight form factor, suitable for mobile robots and flying platforms. According to the photo in Fig.2 and its block diagram in Fig.3, a compact three-staged hardware stack was developed and used in the same configuration for the UGV, the UAV and the base station. It combines a nanoETXexpress-SP Board from Kontron with a 1.6 GHz Intel Atom Processor Z530 [3], a Xilinx Virtex 5 FPGA and a self-designed 14 bit ADC/DAC interface board. As system interface, this platform features Gigabit Ethernet to connect to the mission control computers of UGV, UAV and the base station. Via this interface, video and control data streams are exchanged in an IP packet format. The Kontron GPP board serves as router here.

The front-end interface of the platform offers analog baseband I/Q signals, to be combined with any proprietary or commercial-off-the-shelf (COTS) RF transceiver hardware.

In order to achieve high signal processing performance, all the time-critical OFDM baseband processing is done within the FPGA. It comes as Express Card version from Pico Computing [4] to be inserted in a PCIe-based slot of the Kontron board. Beside baseband processing, another major function block of the FPGA is the TDMA MAC control, realized as a finite state machine (FSM). Moreover, there are two types of memory implemented in the FPGA. On the one hand there is a configuration RAM register, used to memorize all static and dynamic system settings and on the other hand there are multiple FIFO buffers for temporary IP packet storage. The latter is needed to decouple the data stream, as it passes from the GPP-based application layer to the FPGA-based MAC layer. As already mentioned, this

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[1] Even in case of a system failure, the UAV can be prevented from crashing by navigating it with a redundant remote control, as used for model helicopters

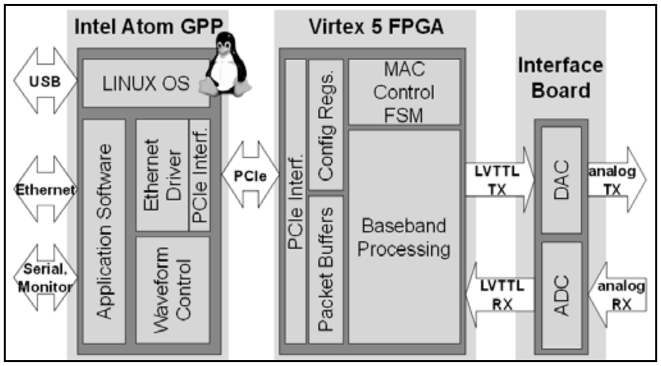

Fig.3 Hardware stack block diagram

interface is realized with PCIe. Since the GPP runs under Linux OS, any standard application software is easily applicable to the SDR platform. For this project, applications as the camera driver or video compression software could be integrated in the Intel Atom. However, since this is no primary focus of this paper, we will not go into details here.

Another major task of the GPP is the waveform control, which is primarily an easy-to-use handler for changing any waveform parameter on runtime. It was implemented in C language and connects to the relevant waveform settings in the FPGA's configuration register.

For the Ethernet interface, an adequate driver was implemented also in C language. It offers a standard Linux network interface for the IP data, with the opportunity to set priorities for the different ports, namely the video port and the control port. As a consequence, the complete data link is fully transparent to the application software. It does not even notice that a wireless link instead of a cable underlies.

4. OFDM WAVEFORM

Coming with the benefits of great spectral efficiency and robustness in multipath environments, OFDM is the communication scheme of choice when UAV systems require high data rates in heterogeneous outdoor scenarios. [5][6]

The decision to design a completely new OFDM waveform from scratch came up mainly for two reasons: The need for outstanding waveform flexibility and the need for two logical links at once (video/control). On the other hand, there was no claim for complying with any common OFDM wireless standard like DVB, IEEE 802.11a or WiMAX, so there was any freedom to pick up common ideas and disregard others. Just to name one example for an adoption from IEEE 802.11a, the synchronization algorithm and the Automatic Gain Control (AGC) setting was implemented according Fort's and Eberle's proposal. [7][8]

The broad parameter flexibility must not only apply to the waveform in general but for each logical link (video link, control link) independently of the other. So the idea is to have two sets of parameter settings, one referring to a robust channel with low throughput for the control data and one providing high throughput at the expense of reliability for the video data. Since subsets of subcarriers are freely assigned to the individual links (video/control), they can be transmitted simultaneously. This technique is commonly known as OFDMA (orthogonal frequency multiple access).

Fig.4 gives a simplified overview of the whole functionality of the FPGA part. Arrows for control signals are colored in light grey and those for data in dark grey. All function blocks are self-designed, except for the dark ones, which are standard Xilinx IP cores. As depicted on the top of Fig.4, the entire frontend configuration, namely AGC and transceiver setting, is done with simple FSMs.

There are two options for the waveform to choose its data source. During normal operation, the control and video data is exchanged via PCIe as described before. However, for the purpose of error testing, the system can be alternatively fed and evaluated with pseudo random bit sequences (PRBS). Of course, error testing is also possible with IP pinging, but this would only provide information about the IP packet loss rate and not about the bit error rate. The packet loss rate is less significant, because a packet will be discarded, no matter if there was only one false bit in the packet or multiple ones. Error testing is very important to determine the channel quality and the robustness of the data transmission.

Aside from the OFDMA aspect, a similar structure of what is shown in the lower right part of Fig.4 can be found as standard OFDM baseband processing chain in every OFDM book (see for example [9]). As already mentioned, the key difference to those traditional waveforms is the parameter flexibility. In the following, all the OFDM waveform parameters which are runtime-configurable are listed and explained. All of them have in common the trade-off between bandwidth and reliability.

4.1 Number of OFDM subcarriers / FFT length

An essential challenge of the presented scenario is the high speed the UAV is able to reach. The top speed depends on several aspects but theoretically, it can be as high as 120 km/h. With the UGV moving in the opposite direction, the relative velocity would be even higher. Specifically, in OFDM communication, high speed leads to much shorter coherence time and larger Doppler frequency spread. As a direct result, the orthogonality among subcarriers gets lost and inter-carrier-interference (ICI) degrades the performance. [10] The solution to this problem is to broaden

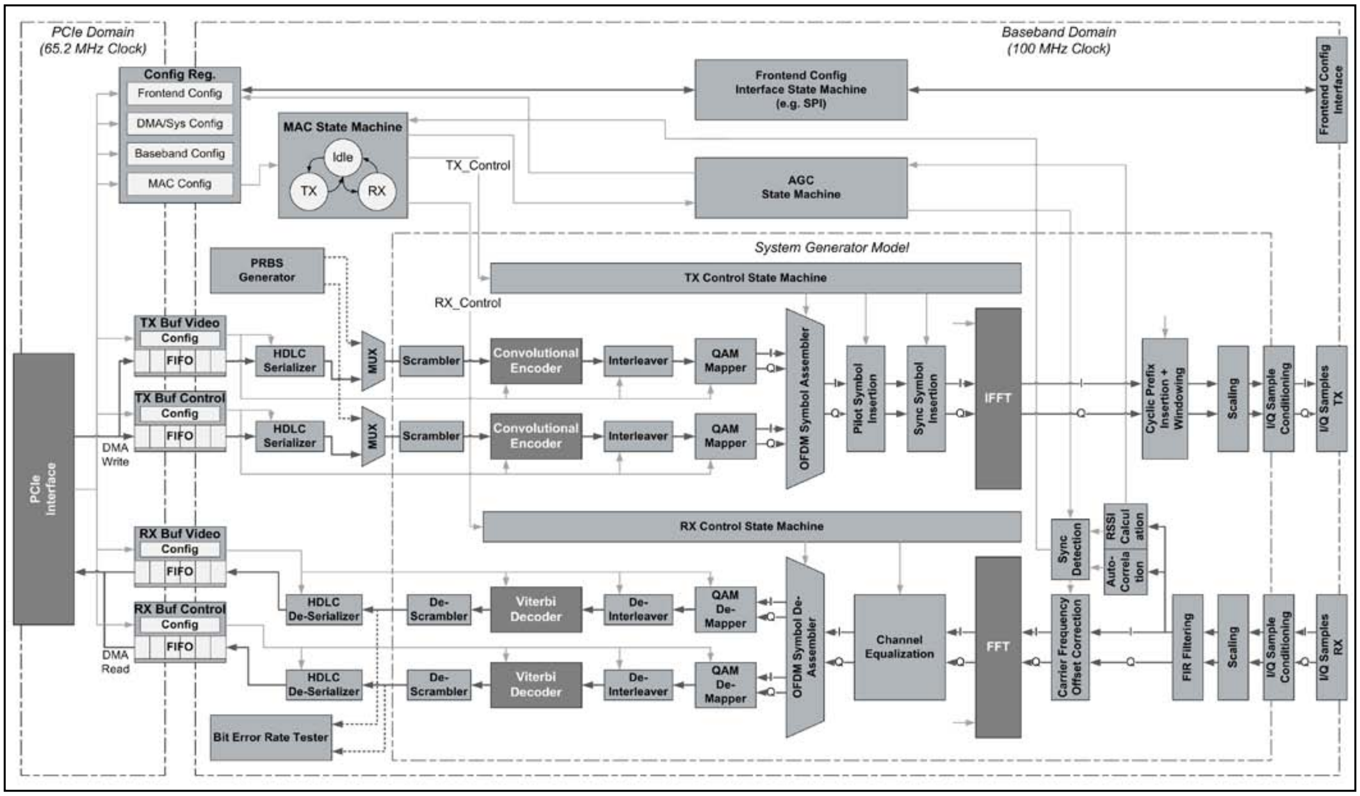

Fig.4 FPGA Processing

the frequency spacing between the subcarriers for increased tolerance against orthogonality loss. This can be achieved by decreasing the FFT length, because this parameter is indirect proportional related to the frequency spacing. So in order to strengthen against Doppler shift, an adequate FFT length out of the following can be chosen: 8, 16, 32, 64, 128, 265, 512 or 1024.

4.2 Modulation depth

Lowering the modulation depth and therewith the resolution of the I/Q constellation diagram is the traditional countermeasure against noisy channels at the expense of the bits per subcarrier ratio. The waveform presented here supports BPSK, QPSK, 16QAM and 64QAM. This spectrum is the state-of-the-art selection of modern OFDM based wireless standards like WiMAX, IEEE 802.11a or 3GPP Long Term Evolution (without BPSK).

4.3 OFDM frame layout

The video and control data is exchanged via Ethernet frames. However, during waveform processing, the data will be rearranged, causing a loss of this Ethernet frame structure. The new formation is the OFDM frame structure, comprising various OFDM symbols. (see Fig.5)

Regarding the layout of an OFDM frame, the presented waveform offers a variety of configuration possibilities:

4.3.1. Number of OFDM symbols

The option to freely adapt the number of OFDM symbols within one frame was basically included because of the scenario-specific problem of fast changing channels. The relationship arises from the simple method of channel estimation/correction applied: The first OFDM symbol of each OFDM frame is a pilot, which is a known data pattern to identify the transfer function of the system. The correction values calculated with this pilot are applied to all following OFDM symbols of this frame, assuming that the channel characteristics do not change meanwhile. Since this assumption applies less and less with fast changing channels, the pilots must occur more often in the data stream in order to update the correction values frequently. This implies a smaller number of OFDM symbols per frame.

4.3.2. Subcarrier usage

All subcarriers can be fully flexible occupied either with video data, control data or they are just left open. This has basically two advantages. On the one hand, the throughput of the video link can be dynamically adjusted at the expense of the control link throughput and vice versa, which allows further prioritization. On the other hand, each RF transceiver offers a specific bandwidth to be usable for transmission. To maximize throughput, the waveform must fill all subcarriers lying within this bandwidth up with data and leave the rest open as guard bands. With other words, any given transceiver bandwidth is supported with this option. Of course, this parameter is strongly related to the FFT length. Changing one of both parameters requires changing the other one as well.

4.3.3. Cyclic Prefix length

Without cyclic prefix, transmitting OFDM symbols over a fading multipath channel leads to ICI and inter-symbol-interferences (ISI). The reason is the spectral discontinuity between OFDM symbols which disperses into the payload part of the symbol and thus causes a loss of carrier orthogonality. However, the OFDM symbol can be cyclically extended by copying the last portion of the symbol and appending it as cyclic prefix to the front of the symbol. This way, the discontinuity still remains, but is no longer present within the payload part of the symbol.

For the receiver, the cyclic prefix is useless and will be discarded. Consequently, it should be set as short as possible, but at least as long as the channel impulse response.

4.3.4. Windowing length

Thanks to the cyclic prefix, the spectral discontinuity between OFDM symbols is no longer an obstacle for correct data transmission. Nevertheless, this spectral blurring is still existent and poses a problem for using adjacent frequency channels. A solution is windowing, which denotes simply cross-fading between consecutive OFDM symbols. To attain a sharp spectral edge of the OFDM signal, the fading must be as smooth as possible, which means long windowing.

Just like the cyclic prefix, also the windowing portion of the OFDM signal is discarded without being used by the receiver and thus it should be short, too.

4.4 Code rate of convolutional encoder/Viterbi decoder

A convolutional encoder is typically used by the sender to enrich the payload with redundancy. This is done in a way that allows the receiver to identify and to correct transmission errors with the aid of a Viterbi decoder, completely without further inquiry.

For the presented waveform, a Viterbi decoder IP core from Xilinx was applied. [11] Its code rate, meaning the ratio of payload to redundancy, is flexible from 1/2 to 1/7. With puncturing, the code rate can be increased up to 3/4 or 7/8.

5. TDMA

The channel access of the different users (UGV, UAV and base station) is organized with TDMA. As depicted in Fig.5, the top layer is made up of a periodically repeated superframe, which is sub-divided into 64 slots or less, all of the same length. Once the traffic demand of the different users is identified, the slots can be portioned accordingly: The more traffic a user requires, the more slots are reserved for him to transmit.

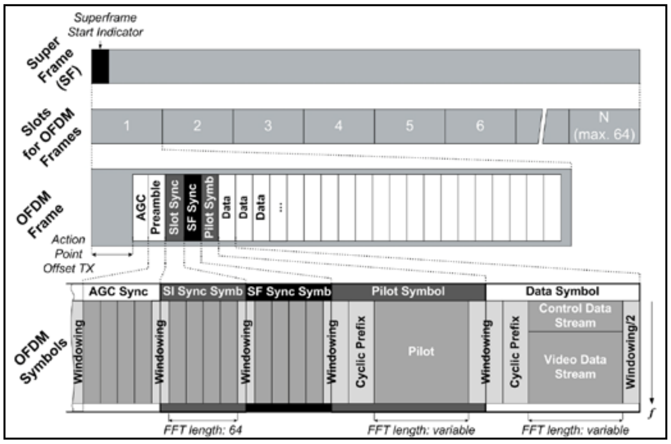

Fig.5 OFDM frame structure and TDMA

The users are not equal. One master node must be chosen to set the timing of the superframe by inserting a superframe start indicator in the first slot of the schedule. Since the master node must be directly visible for all other users, it must be the UAV in our scenario. When the UGV or the base station join the network, they must wait for the superframe start indicator to come, before they can synchronize and actively participate. Besides synchronizing, this first slot is also used to spread information about important TDMA settings like the number of slots currently in use and their occupancy.

At the start of each slot, a short idle time is hold to ensure that all users are listening. (Action Point Offset TX in Fig.5)

6. DESIGNING AND TESTING THE WAVEFORM

The process of developing the waveform can be divided into three major steps.

At first, the FPGA design was done with a hybrid approach of pure VHDL and a model driven design environment based on MathWorks Matlab/Simulink including the System Generator for DSP from Xilinx. This approach allows at a very early stage elaborated simulations, e.g. with the Simulink multipath Rayleigh or Rician fading channel models.

Second, testing on the SDR hardware was performed within a predefined environment. More precisely, the fading simulator R&S AMU200A was deployed to stress the waveform with a set of specific static and dynamic fading scenarios, as well as Doppler and AWGN noise real-time simulations.

The final step for the waveform to pass is the test with the UGV, the UAV and a base station in the open field. There are two types of UAVs in use, on the one hand a self-designed one with the maximum speed of 70 km/h and on the other hand a Swiss UAV, NEO S-300 series, which flies with up to 120 km/h. [12] The applied UGV is the rover MERLIN, which was designed for robust operations in harsh outdoor environments. Its maximum speed is 12 km/h.

7. CONCLUSION AND OUTLOOK

In this paper, we gave an overview over an OFDM-based waveform, designed for communication links among autonomous robotic platforms.

Though the waveform is applicable to a broad spectrum of scenarios, a specific communication set-up was defined for validation. Its participants are a UGV, a UAV and a base station, all accessing the channel by means of TDMA. In this scenario, the communication focus is on a unidirectional video link from the UGV to the base station, which is established indirectly, utilizing the UAV as relay. In addition, further direct and indirect links for video and control data among the communication partners are needed.

The waveform perfectly accounts for the challenges of this set-up, as it offers two separated logical links for video and control data concurrently in OFDMA manner. Furthermore, it provides outstanding flexibility according its waveform parameters. The user is able to freely optimize for throughput or for reliability and even more specific problems like fast changing channels or Doppler spread can be systematically and efficiently fought with the right parameter setting. All adaption is done dynamically on runtime and not just for the waveform in general but specifically for each logical link independent of the other.

The SDR hardware is also ideal for autonomous robotic platforms, since it features a very small form factor. Moreover, with TCP/IP and UDP/IP over Ethernet, it offers a universal system interface.

As soon as the waveform is fully tested, the next big goal is to improve the system with adaptivity features. Up to now, the broad set of waveform parameters is freely adjusted by the user, who must know about current channel characteristics. In future releases, the waveform itself is supposed to measure, to analyze and to adapt to changing channel characteristics automatically.

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