BROADBAND HIGH DATA RATE SIGNALS IN SPACE FOR MILITARY APPLICATIONS WITH CODED OFDM

Dr. Thomas Kuhwald, Dr. Andrew Schaefer, Thorben Detert, Dr. Thomas Nicolay
(Rohde & Schwarz, Munich, Germany; Thomas.Nicolay@rsd.rohde-schwarz.com)

ABSTRACT

We describe an OFDM based high data rate signals in space (SiS), designed specifically for use in military applications. This means that the system is optimized for operating units with long multi-path delays and relatively high speeds. The aim of such a SiS is to enable high data rate transmissions, in the order of tens of Mbps within the framework of an internet protocol (IP) based mobile ad-hoc network (MANET).

1. INTRODUCTION

Consider the example of a WLAN within the context of the internet. Such a system has important features for future military communications systems. Firstly, within certain physical constraints (e.g. transmission distances and relative speeds) the members of the network can communicate with each-other directly with high data rates. Secondly, given a suitable gateway and that an IP is used, the operators in this network can communicate almost anything, e.g., contents of web-pages, video or voice over IP, to almost any other operators who are also connected to the global network of the internet.

In a military scenario we want to use the same ideas. We have a LAN with which units, e.g., a group of advancing tanks, can directly communicate with each-other. In addition, if there is a connection to a gateway and if we use IP, then this advancing group can communicate with anyone else in this military internet. An obvious example is a communication back to a command centre. By using a mobile ad-hoc network (MANET) in the higher protocol layers, communication within the LAN itself is free of infrastructure such as base stations. The network also recognises automatically new or no longer active members and reconfigures itself automatically.

In military terminology a standard such as WLAN is called a signals-in-space (SiS). Within a military framework, we can envision that many different SiS must be designed for different purposes. For example, the SiS which we describe in this paper is optimised for transmission of high data rates over relatively large distances. In a situation where an enemy is attempting to disrupt communication, an anti-jam SiS would be used. In this case, the SiS would have a lower data rate but would be much more difficult to disrupt. A further example is a low probability of intercept (LPI) SiS.

As stated above, the aim of a high data rate SiS is to provide a fast connection to the military internet. It is possible to imagine a wide range of services which are enabled. These include, for example, transmission of maps, co-ordinate updates or instructions. In addition digital photos or even video can be transmitted by drones or advancing soldiers. A high data rate link can also be used as a type of backbone in a higher-level network and of course, with voice over IP, voice transmissions are also possible.

Our choice of modulation to achieve these high data rates is orthogonal frequency division multiplexing (OFDM). OFDM is a broadband transmission technique which has the advantage of a high spectral efficiency. Given an appropriate design, it also has a very simple equalisation technique for dealing with multi-path channels.

In section 2 we discuss possible use cases and derive from these the physical constraints which need to be taken into account in the design of our SiS. In section 3 we review OFDM and describe the design of the system based on the physical constraints from section 2. In section 4 we describe the channel coding / error correction coding which is used to make OFDM robust against fading and noise. Finally, we describe the implementation of the SiS in section 6 and provide our conclusions in section 7.

2. USE CASES AND COMMUNICATION ENVIRONMENT

We can best explain some of the features of our waveform by making a comparison with the example of WLAN and its physical layer characteristics.

The guard interval of WLAN is very short (<1µs for data) [1], allowing compensation of multi-path delays corresponding to distances of around only 300m which is adequate for the typical 'at home' scenario. In a military scenario we aim to transmit over several kilometres. Additionally, WLAN performs channel estimation only at the beginning of a group of OFDM symbols (further pilots only track the phase) meaning that transmission time must be relatively small or otherwise the channel will have changed too much for reliable transmission. Our custom design continuously tracks the channel since it is expected that operating units will be travelling with high speeds during transmission and we do not wish to limit the transmission time. Our channel estimation is optimised to be as efficient and robust as possible by interpolating between known pilots in frequency and time. Further, the FFT (fast Fourier transform) length of WLAN is 64 allowing for relatively simple hardware components but resulting in a loss of spectral efficiency. In our case we are able to deploy high quality hardware to allow for much larger FFT lengths (which is not the only advantage of high quality hardware). Finally, in designing our own system we are able to deploy state of the art turbo-codes for high forward error correction capabilities.

We now consider a scenario where an armoured brigade uses a MANET for communication between units within an area of approximately 30km x 30km for example. The brigade contains infantry units, armoured units and other vehicle units as well as airborne units such as drones or helicopters.

In order to enable fast and reliable communications between the various units of the brigade the channel characteristics need be known. The channel is defined as everything between the transmitting and receiving antennas. Thus, in wireless scenarios, the channel includes everything in the environment such as trees, mountains and other vehicles, resulting in a multi-path channel where various copies of the sent signal arrive at the receiver with different strengths and delays. A further important feature of the channel is that it changes with time depending on the relative speeds of the units which are communicating with each other. A maximum relative speed of 400kmph between any two operating units is assumed. This corresponds for example, to two helicopters performing tasks relevant to the brigade.

3. HIGH-DATA-RATE SIGNALS-IN-SPACE BASED ON OFDM

Our choice of modulation is OFDM since it can provide the data rates required within an acceptable bandwidth with an acceptable complexity. If we consider briefly the alternative of a single carrier technique for transmitting at a rate of 10Mbps in a mobile channel with a maximum path delay of 5us (corresponding to a distance of 1.5km), we see that such a system would need an equaliser with 50 taps. Such a technique has a prohibitive decoder complexity which excludes its use in this system. We now proceed by summarizing the main characteristics of OFDM.

OFDM is a multi-carrier technique where many sub-carriers are packed densely together and each sub-carrier is modulated separately with a linear modulation such as PSK (phase shift keying) or QAM (quadrature amplitude modulation). Due to rectangular pulse-shaping on the sub-carriers, the spectrum of each sub-carrier has well defined zero-positions. Dense frequency multiplexing is achieved by placing neighbouring sub-carriers in exactly these zero positions. Thus we have a dense frequency multiplexing without inter-carrier interference and a high spectral efficiency. A group of sub-carrier spectra are shown as an example in Figure 1.

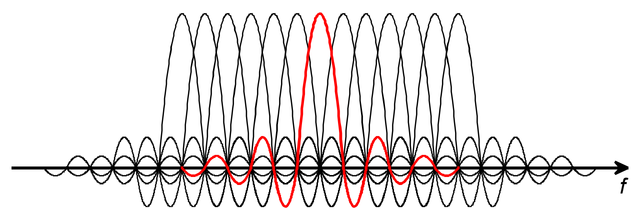

Figure 1: Spectra of a group of sub-carriers in an OFDM signal.

In OFDM, the echoes of the channel (multi-path) are used constructively through the use of a guard interval which is simply a cyclic repeat of the last portion of the symbol (which is often called a 'cyclic prefix'). This is shown in Figure 2. Since the demodulation of the data bits is performed with a FFT, the echoes of the channel simply result in an additive superposition of phase shifted signals at each sub-carrier position. Thus as long as the guard interval is longer than the maximum multi-path delay, equalisation in an OFDM system is relatively simple. All that is required is to estimate the channel which can be done by using some of the sub-carriers as 'pilots' as described later in this section.

Orthogonal sub-carriers are only guaranteed if the channel remains constant over the symbol duration. If this is not the case then inter carrier interference occurs. The interference can be quantified as an equivalent noise given by [2],

$$\sigma_{fad}^2 \approx \frac{\pi^2}{6} \cdot \left(f_D T_{data}\right)^2 ,$$

where f_D is the maximum Doppler frequency in the channel and T_{data} is defined as shown in Figure 2.

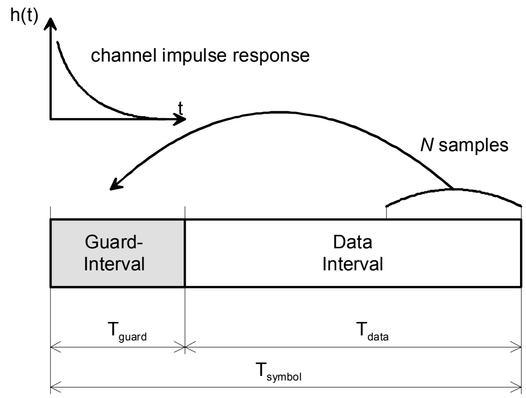

Figure 2: Structure of an OFDM Symbol in time.

Taking the above discussions into account and making use of the guidelines given in [3], we dimension the system as shown in Table 1.

Table 1: Dimensioning of the OFDM system: Bandwidths and signal lengths.

Type	T_{symbol} in µs	Bandwidth in MHz	T_{data} in µs	$1/\sigma^2_{fad}$ in dB
1	100.3	10	85.3	27.8
2	100.3	5	85.3	27.8
3	121.6	2	106.6	25.9
4	201.6	1	186.6	21.0

By taking into account the bandwidth, the length of the guard interval and filter implementation constraints, the following values, as shown in Table 2, were chosen for the FFT length, N_{FFT}, and the number of used sub-carriers, N_{SC}. Note that η_{SC} is defined as the ratio of N_{SC} to N_{FFT}.

Table 2: Dimensioning of the OFDM system: FFT lengths and useful sub-carriers.

Type	N_{FFT}	N_{SC}	η_{SC}
1	1024	850	83%
2	512	425	83%
3	256	212	82.8%
4	256	188	73.4%

For each type of our high data rate SiS, we have set a guard interval length of 15µs which corresponds to a multi-path delay over a distance of 4.5km (as a comparison, the guard interval for WLAN is less than 1µs).

As state above, channel estimation is necessary in order to accurately demodulate our data. This can be done by inserting pilots into our transmitted signal, as described for example in [4]. A pilot is a signal, sent on a particular sub-carrier, which is known by the receiver. Specifically, placing pilots at regular sub-carrier intervals in an OFDM symbol achieves a sampling of the channel in the frequency domain. It is possible to estimate the response of the channel at the remaining sub-carrier frequencies by using interpolation.

Further, the OFDM symbol duration is designed such that the channel does not change significantly over one symbol. It is obvious that the channel estimates from one symbol to the next must be correlated in time. This correlation is exploited by inserting pilots not into every OFDM symbol but only at regular intervals. Channel estimates for the 'pilot-less' symbols are obtained by interpolating in time. This adds to complexity in the receiver but allows the transmission of a larger amount of useful data.

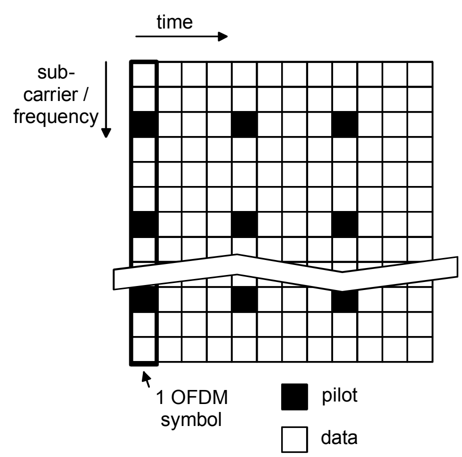

Figure 3: Placement of pilot symbols used for channel estimation in an OFDM transmission.

The concept of our channel estimation is illustrated in Figure 3. Each square represents a sub-carrier and one column therefore represents one OFDM symbol. The horizontal direction is time. Sub-carriers which contain pilots are represented by filled squares and sub-carriers carrying data are left blank. Channel estimates for the pilots are obtained directly from the received power at that frequency. The aim is then to obtain channel estimates for all other sub-carriers. This is possible as long as the sampling theorem is obeyed in both frequency and time (i.e., care must be taken to have enough black squares). In the setup of Figure 3, an interpolation in time requires that the symbols without any pilots are saved until the next symbol with pilots is received. Table 3 shows the proportion of sub-carriers used for pilots in each SiS type averaged over frequency and time.

Table 3:Proportion of data Sub-carriers

Type	1	2	3	4
N_P/N_{SC}	6%	6%	5%	8%

4. ADAPTIVE CHANNEL CODING AND MODULATION

Error correction coding (or channel coding) is an essential part of almost every communications system. This is especially the case in a broadband transmission over a mobile channel using OFDM since the channel is almost certainly frequency selective. This means that in addition to noise at the receiver, a certain proportion of sub-carriers are received with a negligibly small amount of power and the information is effectively lost. Using channel coding over a block of bits being sent over one or more OFDM symbols, these lost symbols can be efficiently recovered thus making OFDM a 'communications weapon'.

The channel coding theorem, [5], states that every channel has a particular capacity and that as long as the transmission rate is lower than the channel capacity, it is theoretically possible to achieve arbitrarily low transmission error rates. In a mobile communications environment, many different channel realisations are possible, each correspondingly with different capacities. The designed system must therefore be able to adapt to a range of conditions.

This is achieved by adjusting the coding rate, R, and modulation type used. Table 4 lists the MC (Modulation and Coding) types used. Note that for a particular MC type, each sub-carrier uses the same modulation and has the same coding rate. If a fast feedback channel is available in future systems, each sub-carrier can also be loaded independently according to the current channel estimate. Thus more information is transmitted on sub-carriers with a strong frequency response and little or no information is transmitted on those sub-carriers where the frequency response is weak. In other words, power is not being wasted on the weak sub-carriers and it is possible to increase the overall transmission rate.

Using the tables presented in this paper, it is possible to determine the range of useful bit rates U_B which this system provides. It is possible to write,

$$U_R = \frac{N_{SC}\left(1 - N_P / N_{SC}\right)B_S}{T_{data}}.$$

It can be seen that useful information bit rates at the physical layer ranging from around 300kbps up to 36Mbps are possible. These figures depend on the bandwidth used and the channel conditions.

Table 4: Code rates and modulation types offered.

MC Type	R	Modulation	Bits per sub-carrier, B_S
1	0.33	BPSK	0.33
2	0.5	BPSK	0.5
3	0.5	QPSK	1
4	0.5	16QAM	2
5	0.5	64QAM	3
6	0.75	64QAM	4.5

Regarding the coding itself, we make use of capacity approaching serially concatenated (turbo) codes, [6], to achieve near-optimal bit error rates for given signal to noise ratios. The encoder for such a code is shown in Figure 4. The sequence of information bits *u* is encoded first with an outer code before being interleaved and then encoded again with an inner code. Finally the bit sequence *x* is mapped onto complex symbols *z* which are transmitted on sub-carriers of one or more OFDM symbols over the channel.

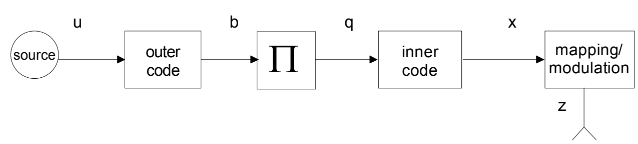

Figure 4: Encoder structure for a serially concatenated code.

The corresponding turbo decoder is shown in Figure 5. The first component decoder receives a vector of complex symbols *Z*. The inner and outer codes are then alternately decoded, making sure that only new (extrinsic) information is passed on to the next decoder. This aspect is shown in the figure with the subtraction signs. This process is iterated until the decoder converges to a decision or until a fixed number of iterations have been performed.

One of the challenges in the design of the channel code is to find a capacity approaching code with an acceptable implementation complexity which can also offer variable code rates. One of the tools used to design such a system is the well known extrinsic information transfer (EXIT) chart [7]. Using EXIT charts it is possible to predict the behaviour of a turbo decoder by knowing only the behaviour of each of its components. Thus it is possible to find components which fit well together.

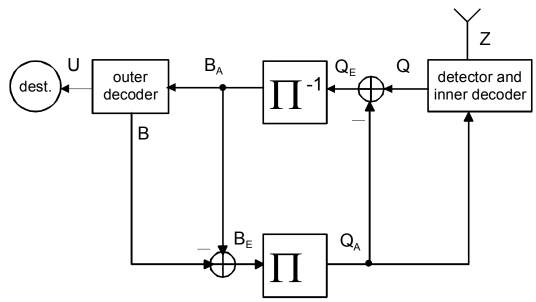

Figure 5: Turbo decoder for a serially concatenated code.

5. SYSTEM BLOCK DIAGRAM AND IMPLEMENTATION OF THE SIS

Figure 6 and Figure 7 show the structures of the transmitter and receiver and where each of the sub-blocks is implemented. In both cases, configuration, control and data flow tasks are performed in a DSP which also interfaces with the higher layers of the communications system. Both transmitter and receiver also use a custom ASIC to perform base-band processing. All other tasks are performed in an FPGA. An FPGA provides us with more speed than a DSP and more flexibility than an ASIC in case it is required to implement different signals in space for example.

The structure of the transmitter is as follows. Data is written into a buffer which is first sent through the channel coder. The bits are then modulated and mapped onto the OFDM sub-carriers before performing an IFFT to determine the time signal of the OFDM symbol. Finally the guard interval is inserted before the base-band processing is performed and the signal is sent to the RF front end.

The receiver performs the same steps as the transmitter but in reverse. After base-band processing, the first task is to perform coarse timing which has the aim of determining where the data interval of the OFDM symbol is. Note that a small timing offset is only detrimental if the guard interval is completely filled by the impulse response of the channel since this would result in inter-symbol interference. Otherwise such an offset results only in a phase shift of the FFT.

It is also necessary to correct a frequency offset which can result either from different carrier frequencies in the transmitter and receiver or also through Doppler effects in the channel. Before performing the FFT, an initial frequency correction is performed such that the remaining offset is a multiple of the sub-carrier frequency spacing. This is the so-called fractional frequency offset correction which is performed by a simple phase rotation.

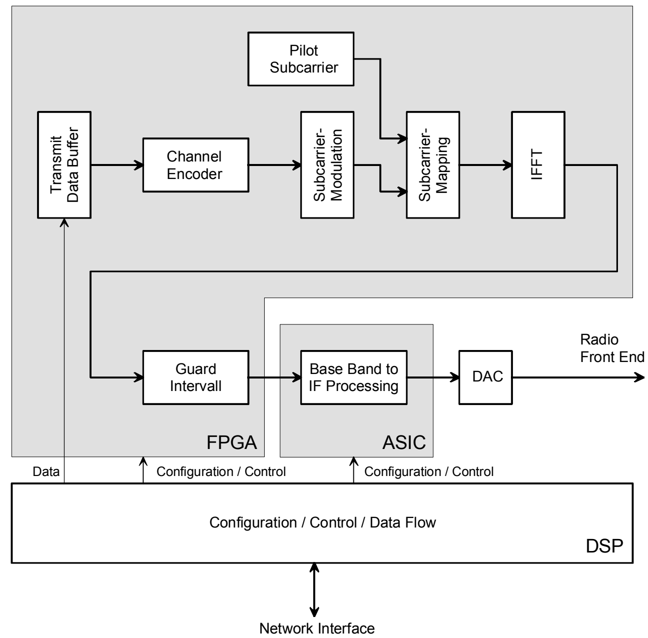

Figure 6: Transmitter structure including which processing element performs which tasks.

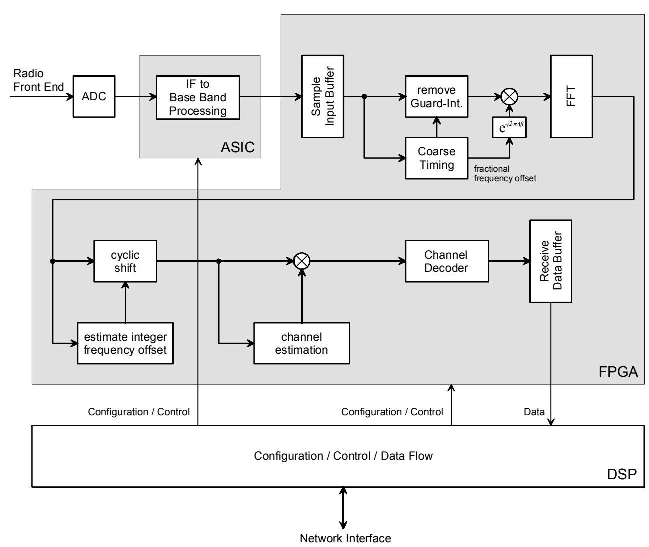

Figure 7: Receiver structure including which processing element performs which tasks.

It is also necessary to correct a frequency offset which can result either from different carrier frequencies in the transmitter and receiver or also through Doppler effects in the channel. Before performing the FFT, an initial frequency correction is performed such that the remaining offset is a multiple of the sub-carrier frequency spacing. This is the so-called fractional frequency offset correction which is performed by a simple phase rotation.

Once these operations have been performed, we can perform the FFT to return the signal to the frequency domain where we see the channel distorted complex symbols sent on each sub-carrier. After the FFT, we perform the remaining frequency offset correction with a simple shift of the sub-carriers. This is due to the fact that the remaining offset was set to be a multiple of the sub-carrier frequency spacing.

In the next step the channel is estimated using the pilot structure defined earlier in the paper. The equaliser is trivial and simply inverts the channel. The output of the equaliser, which is a sequence of complex values, is passed onto the channel decoder which uses these values to reconstruct the information sequence.

6. CONCLUSIONS

In this paper we have described a ‘custom made’ high data rate communications system which is specifically designed to be used as a SiS for future military communications systems. Our system uses OFDM and is designed for multi-path delays of up to equivalent distances of 4.5km and relative speeds of up to 400kmph. Using state of the art modulation and channel coding techniques, reliable communication is possible for a wide range of channel qualities by using more robust coding schemes for bad channel conditions and correspondingly by reducing the redundancy to enable faster transmissions for good channel conditions. Depending on the transmission bandwidth used, which can range from 1MHz to 10MHz, bit rates up to 36Mbps can be achieved at the physical layer. Our implementation is primarily based on an FPGA structure where a DSP performs control and configuration operations and a custom made ASIC performs operations directly after the RF front end.

7. REFERENCES

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