Adaptive Software Modem Technolog

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Abstract

This paper presents a description of a new software modem technology. The standard modem technology is based mainly on different kinds of modulation methods and basically on hardware structures. The adaptive modem technology described here uses software algorithms for the modulation and demodulation process. A modem of this type can be designed with standard microprocessors and A/D and D/A devices or with special signal processors. We have developed a signal detection method, which uses the Discrete Fourier Transform (DFT). Our prototype modem can be used both in radio communication channels and in PSTN networks because of the free selection of the modulation method parameters and the bandwidth used. Thus we call it the adaptive software modem technology. The use of complex waveforms gives us the practical Shannon's capacity in different cases. Basically we use AM, FM and PM modulations adaptively, which means that we can select the best modulation scheme (MFSK, MPSK, QAM) for different channels. The number of symbols in a block, the number of transmitted bits in a symbol, symbol rate, bit rate, sampling frequency and symbol time or the number of samples in a received symbol are parameters in our adaptive modem. We explain here the use of DFT and show some simulation results. We have made several field tests with the modem prototype. We present our modem tests over radio channels. We will see how the data transmission adapts to the narrow bandwidth. The most important feature of the adaptive modem is the data throughput and bit/Hz superiority. The band-limited data rate is higher than the rate of standard solutions of ITU-T or some military radio applications in use. With this technology we can improve the GSM and GPRS data transmission considerably. We believe that it is an alternative for EDGE and UMTS. We expect that the use of this technology will be in mobile internet access (WLAN) and in tactical internet.

I. INTRODUCTION

In standard ITU-T [1] modems we have some interesting properties. We start with the following features of the modern hardware modems: carrier frequency, symbol rate, number of bits in one symbol. These parameters have fixed values associated with one carrier and a simple modulation scheme. Thus it is quite easy and not expensive to manufacture a modem as a hardware design. We found that they use in many cases the carrier frequency 1800 Hz, which is in the middle of the band. Symbol rates are 300 Bd, 600 Bd, 1200 Bd, 1600 Bd, 2400 Bd and 2800-3429 Bd. The number of bits carried by a symbol rate varies from one to six. The band-limited bit rate is developed from 4 bit * 2400 Bd = 9600 bit/s to 33.6 kbit/s analogy network modems or 8*8=64 kbit/s digital network ISDN-modem.

Next we focus on the evaluation in software modem technology based on the microelectronics expansion. This progress makes new things, such as waveform processing and soft waveform detection, reality in all future modems (software modems). In practise hardware detection of the complex waveforms is impossible. We have simulated and developed these waveforms for use in band-limited channels. We also designed an adaptive prototype modem and its test results are presented here. The adaptive modem technology uses microcomputers (dsp) and such high calculation speeds that we can use Discrete Fourier Transform (DFT) [2] in real time detection of waveforms. DFT is the solution, where as Fast Fourier Transform (FFT) is not suitable for the adaptive modem, because the adaptive use of any number of samples is not limited in DFT to powers of two. We set the balance between the number of samples and the sample frequency in detection. We used assembly language code generation tools in our algorithm and A/D and D/A devices [3] in the hardware design process. The team succeeded in the design of an adaptive modem prototype in 1998.

Table 1 explains the difference between DFT and FFT (Fast Fourier Transform) in calculation complexity and times. As we see, we cannot use all numbers of sample with FFT. DFT is very good with N=<32 in real time processing as we have noticed in our test program during 1998-2000. We don't need to use very large numbers of samples in detection let us say N>64. This reduces the heavy calculation task.

$$S_x\,[m\cdot\Delta(f)]=\sum_{n=1}^{160} x[n\cdot\Delta(t)]\cdot e^{-2\cdot j\cdot\pi\cdot m\cdot\Delta(f)\cdot n\cdot\Delta(t)} \qquad (1)$$

Samples N	Multiplications DFT	Multiplications FFT
13	169	-
16	256	32
26	676	-
32	1024	80
64	4096	192
128	16384	448
160	25600	-
256	65536	1024

Table 1. DFT vs FFT

Detection is based on the DFT Formula (1). It gives us the symbol detection from n samples, any of m frequencies with resolution Δ(f), and symbol time nΔ(t). In the formula an example setting of the number of samples is n=160. We can set both Δ(f) and nΔ(t) by adaptive modem software. You notice, that FFT uses n-values only as powers of two, Table 1. Thus it is not fully adaptive as a DFT-software solution. The next section will describe new waveforms with their expected or measured data rates and also some narrow-band field test results made in VHF and UHF range.

II. ADAPTIVE MODEM WAVEFORMS

As we have discussed earlier modems are still quite limited in their use of the bandwidth with only one carrier frequency. They effectively use the usual audio channel of the telephone network 300- 3400 Hz. However in radio communications, military HF, VHF and UHF tactical radio networks or in civil networks (GSM, CDMA, UMTS) we have different cases from very limited bandwidth to broad bandwidth. We have a large scale of channel types, modulation methods, bandwidths, bit error rate requirements etc. Thus we need different waveforms in data transmission to optimise bit error or throughput performance. To mention a few applications we have some different cases: low S/N tactical communication systems, multi-path radio propagation, delays in satellite communications etc. Channels many have many kind of distortions. For example in military radio channels we may have fading or jamming problems. With an adaptive software process we can minimise these problems. In the worst cases we may even change the waveform during the data transmission. We are going discuss the adaptive modem waveforms next.

The basic idea of the adaptive modem technology is to offer an adjustable range of bandwidths or different frequencies to optimise the use of the modem to different communication paths. It may be referred to as the software-defined radio (SDR) technology. Thus we have made the use of carrier frequencies selectable by software and we can adapt the bandwidth used just to the values of the communication link used. This adaptation will be made automatically according firstly to the principles by setting sample frequency, sample number and symbol time and then by selecting frequencies and their modulation method, for example, a suitable QAM number.

Generation and Detection of Complex Waveforms

To generate waveforms in a digital way we have a flexible method in software modem technology. It is easy to mathematically describe and detect in real time continuous or discontinuous waveforms. The latter waveforms were used in our adaptive modem prototype tests. We have the possibility to use any sample frequency f_S with any sample number N in the symbol transmission and detection. In the transmission of bits we select the symbol rate R_S and we set the associated number of samples in a symbol N together with a proper sample rate f_S according to the formula 2.

$$R_S = f_S / N \qquad (2)$$

The generated waveform of the signal is fully described by the discrete values of amplitude samples in reception. We have the following steps in transmission: (1) plain text in memory, (2) text or any other symbols represent M bits each, (3) conversion of all blocks of M bit symbols to discrete waveforms, (4) sending the waveforms to the line through an interface unit, and (5) transmission of the rf-signal from the radio to the antenna or sending the base-band signal over the existing wired transmission system. The blocks of bits are for example built according to the standard 7-bit set code M=7.

Step (1) Plain text in memory
Source random text (test value and ascii symbol):

17 31 14 11 25 11
Q 2 N K Y K

Q2NKY has the following 7-bit ascii presentation
Q 2 N K Y
0101000 00110010 01001101 01001011 01011000

Step (2) Ascii code conversion to f, A and P values for transmission

Tr f	615,38	1846,15	2461,54	1230,77	615,38	1230,77	1846,15
A	0,67	1,00	0,58	0,53	0,86	0,53	1,00
P	0,79	0,79	3,93	0,79	0,79	0,79	1,57

Every symbol presents a waveform. In Figure 1 we have the symbol "Q" presented in 26 samples.

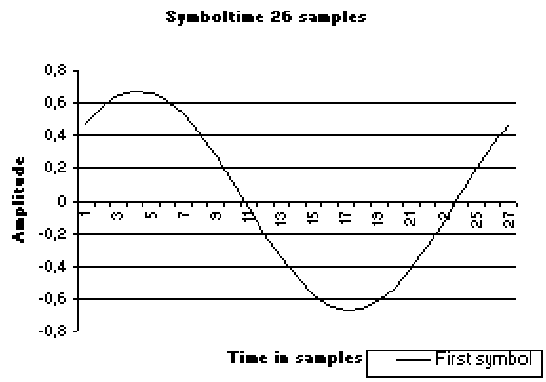

Figure 1. Symbol Waveform

Step (3) Transmitted continuous symbol waveforms are sampled in reception.

In Figure 2 we see the whole discontinuous block waveform Q2NKYK transmission. W call it a complex waveform because of its several different symbol frequencies, amplitudes and phases. We are able to select all these parameters quite freely. Thus we call this method the adaptive software modem technology.

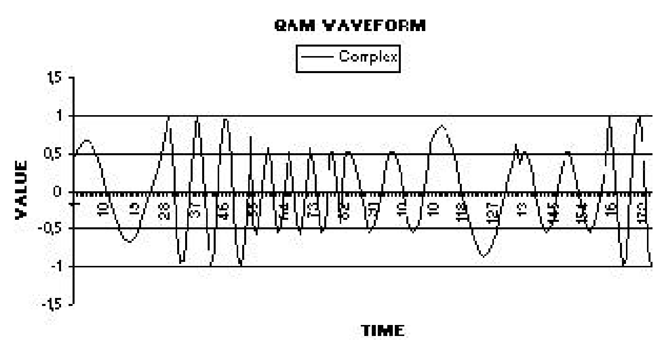

Figure 2. Complex Waveform of an Adaptive Modem

Simulator

We have demonstrated in the simulator the transmission and the reception of complex waveforms in Figures 1-2. Other examples of complex waveforms are in figures 3-6.

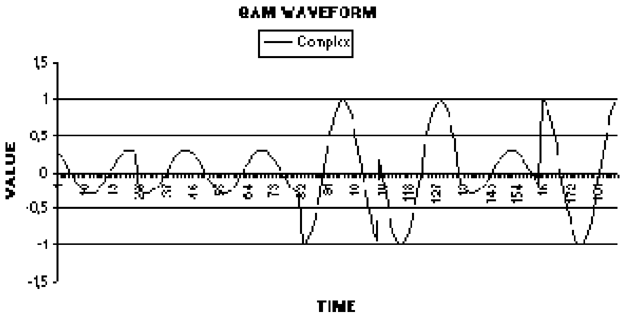

Figure 3. Complex Waveform 32QAM (A-bit and four P-bits)

Figure 3 presents a waveform, which has one amplitude bit and four phase bits and uses only one low carrier frequency. Figure 4 has the opposite: sixteen amplitude states and two different phase states but this waveform uses four carrier frequencies.

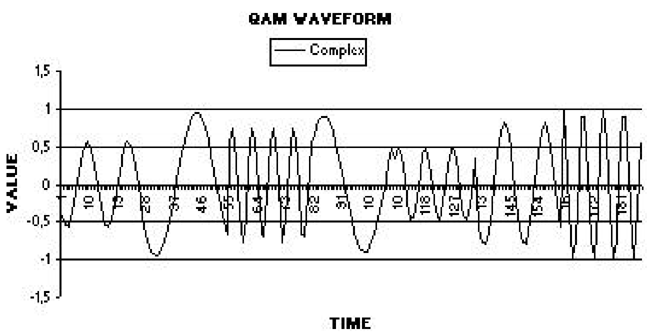

Figure 4. Complex Waveform 32QAM (four A-bits and P-bit)

In simulations we could easily calculate with the parameter values used (bits =5… 8, the symbol rate = 45000/26), so that we get the maximum bit rate 13846 bit/s. Still we used four channels (carriers) and thus we get 55385 bit/s in this system. However, the whole system occupies only a band-limited voice channel. It is quite easy to simulate the high data rates of the present wide band systems. We have, nowadays, Shannon's theory in partial use. Only the wide bandwidth gives us the high data throughput not the complexity of the waveforms. The adaptive software modem technology will correct this situation. Next we are interested in the real world throughputs the results we got in the field tests in summer 2000.

Complex Waveform Field Tests

With field tests we have demonstrated the adaptive use of different complex waveforms, Figures 5-8. We were able to use different combinations of frequencies, amplitudes and phases and decode them to ascii characters only by changing our software modem parameters. We used the following settings over the VHF radio channel:

- Symbol length 16, 20, 24, 48 and 64 samples.
- Symbol time 444 -1422 microseconds.
- Symbol rate 703-2250 Bd.
- Modulation 4QAM, 8QAM and 16QAM.
- Number of carriers 1, 2, 4, 5, 6 and 8.

The resulting bandwidth in all cases was in the range of 600-4800 Hz. The corresponding band-limited bit rates were 1406-22500 bit/s. This test result over 4 bit/Hz is quite good for an old-fashioned military VHF-radio. Some examples of these field test waveforms are in Figures 5-7 where in reception we used N=64 and f_S= 45000.

It is easy to calculate the bit rate for example a test case, where we used two carriers and 16QAM (M=4). If R_S is the symbol rate, we get the bit rate R_b in a general case with formula (3), where k is the number of carriers used and M is the number bits forming the QAM-states of the symbol.

$$R_b=k*M*R_S \tag{3}$$

The test result that we get with k=2, M=4 and R_S=2812,50 symbol/s is R_b = 22500 bit/s. This band-limited spectrum is presented in Figure 8.

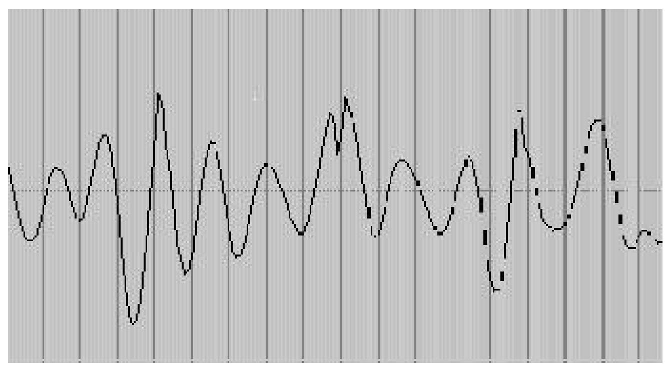

Figure 5. 5625 bit/s 4-QAM waveform with 4 carriers

This important test was made during the Finnish Army exercise in May 2000 in Hyrylä by the adaptive modem team. The radio communication equipment was the usual analogy VHF tactical radio connected with a Laptop computer using our adaptive modem software and hardware.

With our software algorithm it is easy to generate any kind of complex waveforms. These performed example waveforms are error free short test transmissions and they give us the idea of the adaptive software modem's performance in radio data communication systems. The old analogy channels of the military radios are thus very attractive for use in the tactical internet. The only modernisation needed is the adaptive modem card in the conventional military radios.

Detection of the adaptive waveforms

To detect the waveforms we have used the Discrete Fourier Transform (DFT). The steps are:

(1) Reception and saving of the continuous symbol waveforms.
(2) DFT calculation of the symbol waveforms with the selected right parameter values (m, n and f_S) in the software modem algorithm.
(3) Selection of the corresponding ascii symbols from the received calculated M-bit constellation (amplitude vs phase diagram).
(4) Saving and presenting the received plain ascii text.

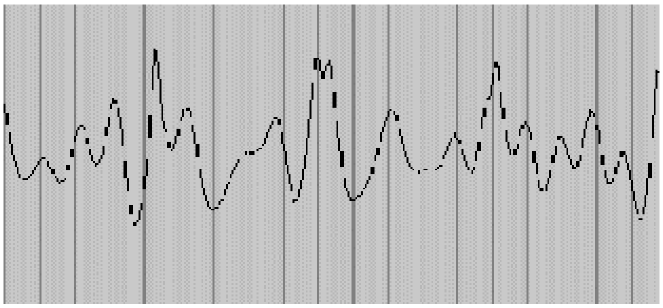

Figure 6. 8437,5 bit/s 4-QAM waveform with 6 carriers

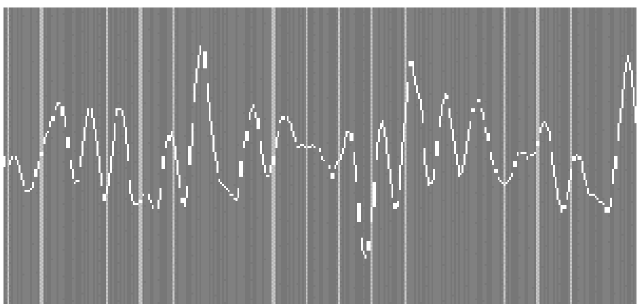

Figure 7. 11250 bit/s 4-QAM waveform with 8 carriers

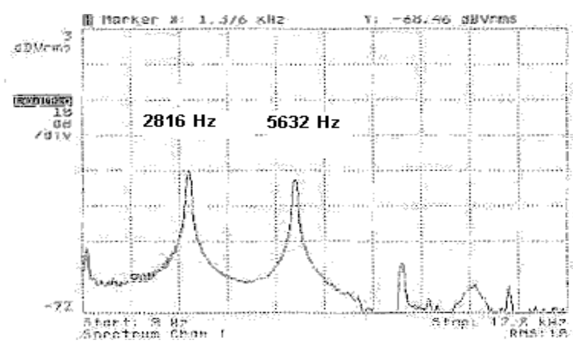

Figure 8. Spectrum of 22500 bit/s 16-QAM waveform

Starting from Formula (1) with N=64 we can develop the Discrete Fourier Transform with Euler's formula to real and imaginary parts. The real part of the Discrete Fourier Transform of the received and sampled signal $x[n\cdot\Delta(t)]$ at frequency $m\cdot\Delta(f)$ is

$$Re(S_x)=Re\{S_x[m\cdot\Delta(f)]\} \quad (4)$$

The imaginary part of the same signal is

$$Im(S_x)=Im\{S_x[m\cdot\Delta(f)] \quad (5)$$

We can now calculate the bit constellation with the amplitude (A) and the phase (P) values, which have the definitions $x = Re(S_x)$ and $y = Im(S_x)$.

$$A = \mathrm{sqrt}(x^2+ y^2) \quad (6)$$
$$P = \arctan(y/x) \quad (7)$$

All these parameters are well known in DFT theory. The frequency parameter is m and it is associated with the frequency selectivity $\Delta(f)$. This $\Delta(f)$ can be set with the sampling rate f_S and the number of samples N to a minimum value f_S/N, which is the symbol rate, formula (2). The importance of the adaptive change of N was also presented earlier [5]. The adaptive software filter can be made as narrow as needed and thus it can be adjusted to the adaptive waveform and the channel. The bandwidth used in the symbol transmission is given by the DFT calculation during each symbol time only. We should not calculate over any discontinuity points between symbols. Thus in theory we can use near zero bandwidths compared to the whole bandwidth, which is available for use. Then we can have multiple carriers very near each other. There are a few practical references for narrow-band multi-carrier frequency modems.

Discussion of Adaptive Modem Technology

We have tested and simulated earlier the use of adaptive waveforms in different channels of radio, telephone and tactical delta-modulated networks [4]. The performance of the adaptive modem was simulated before we went to the field test. The exercise proved the adaptive software algorithm value in practice. The adaptive process is now the best way we know to reach the Shannon's capacity limit. The importance of the adaptive change of the sample number N in the symbol detection was well understood during the field tests, where we changed the symbol length and the modulation method and balanced it with the radio channel in use.

We must have symbol synchronisation so that we know exactly the beginning of each symbol. But we only need a PC level crystal accuracy for timing in normal data transmission. In the field tests the timing was not any problem with a few minute long messages.

We only presented here an example set of effective waveforms. Starting from a simple 4-QAM-waveform with two carrier frequencies, two amplitude states and two phase states we could adapt our modem to 1024-QAM, a ten bit constellation. All these waveforms have been developed using 32 samples per symbol in D/A (digital to analogy) device. We sent the waveforms using, in most cases, a low 1406 Bd symbol rate process in our adaptive modem prototype. The pictures presented here are dumped from the PC memory. The waveforms present a block of ascii symbols. To get high bit rates we use several carriers (1...16 channels). For example, in transmission of ascii files a 1024-QAM symbol itself can carry ten bits of ascii characters or any other symbols. A block of symbols can be developed combining several channels (refer CDMA technology).

The adaptive modem connects the A/D or D/A device to the radio or telecommunication line. The most sophisticated part of the modem is its detection algorithm, which can decode the multiplex signal of the several channels and adapt itself to the waveform used in a band-limited data communication channel.

In theory we expect to get the following bit rates in the next developing cycle using the USB-bus of a PC and design the algorithm with DSP developing tools, Table 2.

Symbol Rate	QAM	Channels	MFC-code frequencies	Bit/s
1000	1*16	1	(1 1)	4000
1000	1*16	2	(5 2)	8000
2000	1*8	2	(4 2)	12000
2000	1*16	2	(5 2)	16000
2000	1*64	2	(24 2)	24000
3000	1*64	2	(17 2)	36000
3000	1*64	3	(65 2)	54000
3000	1*64	4	(513 2)	72000
3000	1*64	5	(514 3)	90000
3000	1*64	6	(285 4)	108000
3000	1*64	7	(803 4)	126000
3000	1*64	8	(640 5)	144000
3000	1*64	9	(572 6)	162000
3000	1*64	10	(541 7)	180000
3000	1*128	10	(685 8)	210000
3000	1*256	10	(836 9)	240000

Table 2. Channels or MFC code

In Table 2 we have two theoretical approaches to higher bit rates a) channels b) multi-frequency coding (MFC). In the adaptive modem prototype we use channels. Every frequency is a channel in the voice band or in the radio channel. We select the modulation methods (QAM) depending on the channel S/N available in practice. In our laboratory tests bit rates over 100 kbit/s are easily generated and decoded in a wired line channel. In Table 2 we have also compared the channel solution with the theoretical MFC waveform solution. The comparison is based on the equal number of signal states. The benefits of MFC is that we need some less frequencies than in a channel solution.

We have calculated in Table 2 some examples over 200 kbit/s bit rates with only ten carrier frequencies or channels. In practice some of these high-speed data transmissions may need more bandwidth than a regular voice grade circuit (300-3400 Hz). In modern military VHF radio systems we already have available about 30 kHz wide frequency bands. We believe that older VHF radio equipment, which have 30 kHz bandwidths, are easily modernised for data transmission. They may be then connected to the laptops in command posts of the digital battlefield. We point out here that the adaptive modem is designed for the best digital (speech, data, video) transmission throughput over any radio (hf, vhf, uhf, satellite etc) or other voice grade communications channels. The design principle in the channel solution is that the channels are adaptive to combine speech, data or video. We can choose the high data rate for example 16 kbit/s for speech, 16 kbit/s for data and the rest of 108 kbit/s for video in the case of six channels (carriers) of Table 2. This of course depends on the quality of the channel S/N available. These are now our main investigation areas.

We have discussed about the applications of the adaptive modem with some industry experts, telecommunication service providers, military professionals and university researchers. The expected use of this invention would be the basic data transmission system in different classical radio systems and the seamless interoperability with wired telecommunication networks. The data transmission is optimised in selectivity of frequency, amplitude, phase and time range in full respect of Shannon's theory. Generally speaking we have an extraordinary wide scale of different attractive applications for the adaptive data modem. A few most frequently discussed data communication needs are the following:

(1) Internet access at higher data rates than standard 33.6 kbit/s ITU-T modems or 64 kbit/s ISDN or 14.4 kbit/s gsm .
(2) Military tactical internet radio access.
(3) Military and other secure data.

We already have a prototype software radio modem for gsm-voice channel, hf, vhf and uhf radio communication frequencies. We have not yet demonstrated its functionality in a satellite communication system. We also have some application ideas for secure data communication waveforms using the adaptive modem technology. At the moment, we have the prototype briefly presented in this paper. We believe that the design cycle of the commercial products will be shorter than the two years, which we used with the first prototype design.

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