Implementation of a CAN Physical Layer on a Narrow Band Channel

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Abstract

This paper investigates the use of new alternative transport media for CAN, with specific focus on narrow band systems. Designing a physical layer for these kind of media implies using modulation techniques on a carrier wave. In an introductory study we give an overview of different digital modulation schemes and compare their performance. We identify the additional requirements imposed by CAN on the choice of modulation scheme and discuss some possible complications. As an application of the ideas and results following from this study, we present a concrete design of a new narrow band physical layer for CAN, using the mains[1] wiring as transport medium.

1. Introduction

As an answer to the growing needs for distributed real-time intelligence within the physical layer of present-day new emerging telecom systems, the Department of Information Technology at the University of Gent has designed a development environment for the implementation of distributed real-time embedded control systems, called FORTRESS [8] [11]. The backbone of this system is a Controller Area Network (CAN) with a physical layer implemented using plastic optical fibre (POF) in an active star topology [6] [7].

For the latter environment we are currently investigating the use of new alternative transport media, with specific focus on narrow band systems. Typically a narrow band channel is characterised by its limited relative bandwidth. According to the absolute channel centre frequency, the latter limits the absolute bandwidth that can be used to transport information. Examples of physical layers where this limitation applies are, in order of increasing relative bandwidth, ultrasonic communication, transmission on the mains network and RF wireless communication. Designing a physical layer for these kind of media implies using modulation techniques on a carrier wave.

In this paper we will start with an investigation into bandpass digital transmission, making a comparison between a number of digital modulation techniques. We will further identify the requirements that CAN imposes and elaborate on a number of possible complications.

After this introductory study, the paper will focus on one implementation in particular, i.e. communication over the mains network.

[1] The term “mains” refers to the public electrical supply system or the electrical supply installations within the consumers premises.

2. Bandpass digital transmission

2.1. Introduction

In order to match the requirements of the transport channel, be it radio, cable, or whatever, some kind of carrier modulation is needed. The aim of this modulation is to reduce the relative bandwidth and to adjust the centre frequency. Just as there are a multitude of modulation methods for analog signals, so too there are many ways of impressing digital information upon a carrier wave.

2.2. Modulation systems

Basically three degrees of freedom exist. A digital system can modulate the amplitude, frequency or phase of a sinusoidal carrier wave. If the modulating waveform consists of NRZ digital pulses, then the modulated parameter will be switched or keyed from one discrete value to another. Figure 1 illustrates the concept of binary amplitude-shift keying (ASK), frequency-shift keying (FSK), and phase-shift keying (PSK).

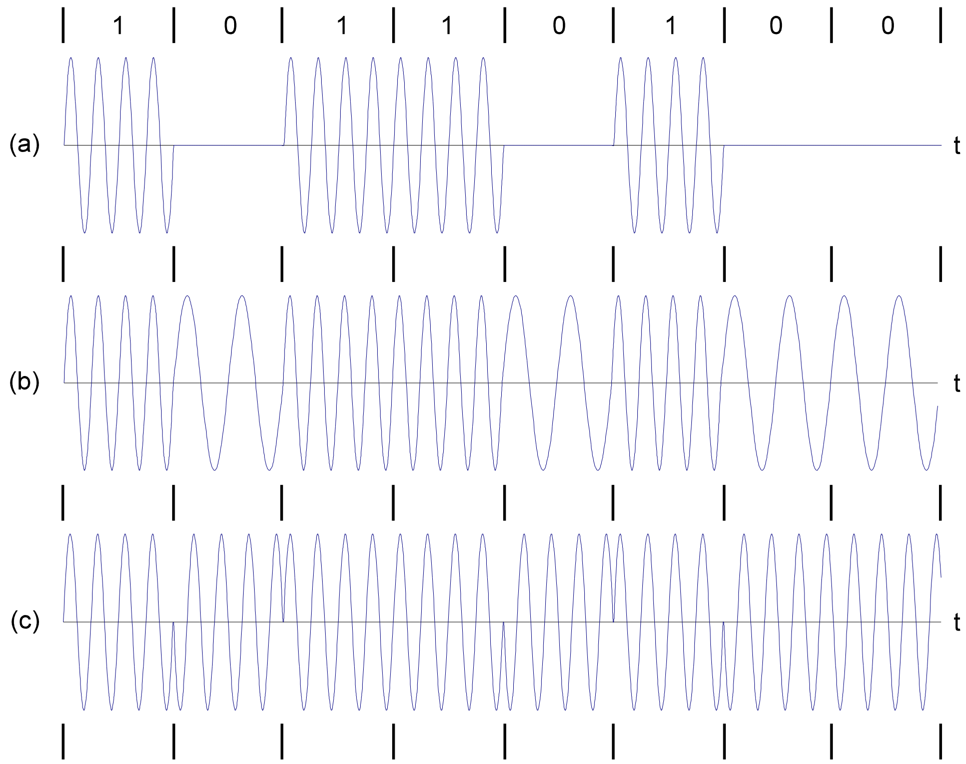

Figure 1: Binary modulated waveforms. (a) ASK; (b) FSK; (c) PSK

Whereas this figure shows the special case of a binary modulating waveform, in a more general case the latter may be an M-ary encoded waveform. In that case the modulator produces one of an available set of $M=2^m$ distinct signals in response to m bits of source data at a time. In the figure only a single feature of the carrier (i.e. amplitude, phase or frequency) undergoes modulation. In some cases a hybrid form of modulation can be more appropriate. For example, changes in both amplitude and phase of the carrier can be combined to produce amplitude-phase keying (APK).

At the receiver side, in order to extract the original digital data signal, we must perform demodulation. For this we basically have the choice of two approaches, coherent and noncoherent detection.

In the ideal form of coherent detection, exact replicas of the possible arriving signals are available at the receiver. This means that the receiver has exact knowledge of the carrier wave's phase reference, in which case we say that the receiver is phase-locked to the transmitter. The coherent detection is then performed by cross-correlating the received signal with each one of the replicas. In noncoherent detection, on the other hand, knowledge of the carrier wave's phase is not required. The complexity of the receiver is thereby reduced but at the expense of an inferior error performance, compared to a coherent system.

2.3. Comparison of digital modulation schemes

From the overview presented in 2.2, we see that a multitude of modulation/detection schemes are available for digital communication systems over narrow-band channels. Each scheme has its trade-offs and the final choice is determined by the way in which the available primary communication resources, transmitted power and channel bandwidth, are best exploited.

A good and complete performance comparison can be found in [1]. In this work both the binary as well as the more general case of M-ary modulation systems are discussed. Given the additional requirements imposed by CAN on the choice of modulation scheme, as will be discussed in section 2.4, we will here present only the simple case of binary modulation systems.

Table 1 gives an overview of the key characteristics of the most common binary modulation systems. These include the modulation speed r_b/B_T (or spectral efficiency) which is the ratio of bit rate to transmission bandwidth, the error probability P_{be} in function of the energy-to-noise ratio γ_b and the necessary energy-to-noise ratio to obtain an error probability equal to 10^{-4} - a common standard for comparison purposes. The various systems are listed here in order of increasing complexity and hence increasing hardware expense.

Table 1: Summary of binary modulation systems (by A.B. Carlson [1])

Modulation	Detection	r_b/B_T	P_{be}	γ_b in dB ($P_{be} = 10^{-4}$)
OOK[2] or FSK ($f_d=r_b/2$)	Envelope	1	$\frac{1}{2}e^{-\gamma_b/2}$	12.3
DPSK[3]	Phase-comparison	1	$\frac{1}{2}e^{-\gamma_b}$	9.3
PRK[4]	Coherent	1	$Q\left(\sqrt{2\gamma_b}\right)$	8.4
MSK[5], QAM[6] or QPSK[7]	Coherent quadrature	2	$Q\left(\sqrt{2\gamma_b}\right)$	8.4

The table omits coherent OOK and FSK, which have little practical value, but includes QAM and QPSK viewed as binary rather than quaternary modulation. Q is the Gaussian probability given by $Q(k) = \frac{1}{\sqrt{2\pi}}\int_k^\infty e^{-\lambda^2/2}d\lambda$.

From this comparison we learn that the minimum required energy-to-noise ratio is mostly influenced by the fact that the receiver can have knowledge of the carrier wave's phase and that doubled modulation speed goes hand-in-hand with coherent quadrature-carrier detection.

One characteristic not taken into account in the comparison is spectral spillover. This refers to the fact that the spectra for some modulation techniques (e.g. ASK, QAM,...) actually extend beyond the estimated transmission bandwidth. This "spillover" outside B_T becomes an important concern in radio transmission and frequency-division multiplexing systems when it creates interference with other signal channels. Bandpass filtering at the output of the modulator can control spillover in these cases. Some modulation techniques avoid spillover for example by applying Nyquist pulse shaping on the input signal (e.g. VSB[8]).

Now that we have a fair overview of the different modulation systems and the trade-offs between modulation speed, signal energy and complexity (i.e. hardware expense), we can take a closer look into the extra requirements that CAN imposes.

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[2] On-off keying (OOK)
[3] Differential phase-shift keying (DPSK)
[4] Phase-reversal keying (PRK)
[5] Minimum-shift keying (MSK), also known as fast FSK
[6] Quadrature amplitude modulation (QAM)
[7] Quadriphase-shift keying (QPSK)
[8] Vestigial-sideband modulation (VSB)

2.4. Requirements imposed by CAN

The basic requirements imposed by CAN on the choice of modulation system come from the fact that CAN uses the principle of priority-based bitwise contention to resolve bus access conflicts [5]. This technique introduces some constraints on the signal representation within the physical layer and on the maximum geometrical extension of the network. In order to have high-priority bits overrule low-priority bits during the arbitration faze, signals on the physical medium may either be dominant (energy) or recessive (no energy), as for example "light" versus "no light" in our optical physical layer mentioned in the introduction. When a dominant and recessive bit are simultaneously transmitted, the resulting state must be dominant.

Taking a second look at Figure 1, we can immediately see that from the three basic modulation types shown in this figure, only in the case of the binary amplitude-shift keying modulation scheme we are able to identify dominant and recessive bits. We can for example transmit a dominant and a recessive bit by respectively turning on and off the carrier (i.e. energy versus no energy). This simple form of ASK is also known as on-off keying (OOK). Since no energy is transmitted during a recessive bit, there is no crosstalk between the transmitted and received signal, and hence no duplex filter[9] is needed before the transmitter/receiver pair.

The second constraint following from the bitwise contention principle results from the fact that a bit must travel from one end of the physical medium to the other, before it can be detected and compared with the transmitted bit. This consideration results in a trade-off between the maximum geometrical extension of the network, the bitrate and the type of physical medium through which the data is transported, since the latter determines the velocity of propagation. Whereas the velocity of propagation for electromagnetic waves travelling through different types of media such as air, light-waveguides and copper-cabling falls approximately within the same order of magnitude (i.e. 3×10^8 m/s), the velocity of propagation for sound waves on the other hand is considerably smaller (i.e. 3×10^2 m/s), hence making for example ultrasonic transmission less suitable for CAN.

2.5. Conclusions

Based on the discussion presented in the two earlier sections we can conclude that OOK modulation combined with envelope detection is a suitable transmission scheme for CAN. Although it needs approximately 3 dB or more signal power to obtain the same error probability as other commonly used modulation systems and also has a small spectral efficiency, it has the benefit of a very simple implementation. The dominant/recessive bit concept is inherently present without the need for any additional hardware and/or logic. The strong error detection, signalling and correction features offered by the CAN protocol compensate to some extend this higher hardware transmission error probability.

There still remain however some complications, as we will present in the following section.

2.6. Possible complications

Possible complications arise from the relative signal levels within the system. Viewed from a certain receiver, two transmitters in the system can either be located at approximately the same distance from the reference point or in the opposite case one transmitter can be located very close to the receiver and the other very far from the receiver.

In the first case the signals received from both transmitters will have approximately the same signal levels at the receiver, and hence destructive interference of the carrier-waves[10] can become a problem when their phase difference becomes close to 180°. Two approaches can be taken in solving this problem.

The system can either be made fully coherent, applying phase synchronisation of the carriers in each node. This can be done for example by using some sort of master clock principle where the local clocks are periodically phase synchronised. In this approach the largest propagation time difference within the system must not be more than a fraction of the period of the carrier-wave. Another approach is to make the system deliberate incoherent, for example by adding some phase noise to the carriers. This technique does not suffer the before mentioned

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[9] A duplex filter, commonly used in for example cellular radio transceivers, is a directional device that directs the relatively high transmit signal power to the antenna and, at the same time, directs the relatively low receiver power to the receiver input.

[10] In reality the carrier-wave frequencies of the different transmitters will not be exactly the same. In this case the carrier-wave interference causes a kind of fading pattern.

restriction and is generally easier to implement (as will be discussed in section 3), but has the drawback that it requires additional bandwidth.

The second complication arises when the nearest transmitter sends a dominant bit, after which the far off transmitter also sends a dominant bit as the next bit. In this case the receiver will get desensitised by the preceding strong signal and fast receiver recovery is therefore needed. This means that the receiver must have a high dynamic range or fast automatic gain control (AGC).

3. Communication over the mains

3.1. Introduction

As an application of the ideas and results discussed in the introductory study given in section 2, we will now present a concrete design of a new narrow band physical layer for CAN, where we have chosen the mains wiring as transport medium. This medium is attractive to use because it is almost everywhere readily available without any installation cost. Most devices already have a connection to the mains for their power supply, they therefore can be connected to the “network” simple by plugging them into the nearest wall socket.

Since data communication over the mains network is subjected to regulations, we will start by giving a summary of, and references to the applying standards, before describing the actual physical layer implementation.

3.2. Standards

Standards that apply to data communication over the mains network are the European CENELEC EN 50065 standard [3] and the US FCC regulations.

The CENELEC document standardises signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz, either on the public supply system or within installations in customers premises. Its main objectives are the specifications of the frequency bands allocated to the different applications, limits for the terminal output voltages in the operating band and limits for conducted and radiated disturbance. It also gives the methods of measurement, but does not specify any signal modulation methods, coding methods or functional features of the communication system. Table 2 gives an overview of the standardised frequency bands and the usage and output level restrictions that apply within the respective bands. For the disturbance limits applying to frequencies outside the band in which the signalling equipment operates and any other information regarding the standard we refer to [3].

Table 2: Frequency bands, output level and usage restrictions according to EN 50065 standard

Frequency bands	Output level restrictions	Usage restrictions	
3 kHz - 95 kHz	Under consideration	3 kHz - 9 kHz	Restricted to electricity suppliers, can be used in special cases under authorised conditions
		9 kHz - 95 kHz	Restricted to electricity suppliers and their licensees
95 kHz - 148.5 kHz	For general use: 116dB (µV) For industrial use: 134dB (µV)	95 kHz - 125 kHz	For customer use, without any access protocol requirements
		125 kHz - 140 kHz	For customer use, standard access protocol required
		140 kHz - 148.5 kHz	For customer use, without any access protocol requirements

For the implementation, which will be presented in the next section, we have chosen to work in the 95 kHz - 125 kHz band. In this frequency range, the impedance of the mains line varies between 5 and 100 Ω, while the maximum allowable transmission level on the mains line is restricted to 1.78 Vpp (Class 116 equipment) according to the standard. The attenuation of the mains line in this frequency band ranges between 10 and 30 dB depending on the topology of the mains line [10].

3.3. Implementation

The block diagram of the physical layer that has been developed is shown in Figure 2. Three major sub-blocks can be identified, i.e. the transmitter, the receiver and the interface towards the mains network.

A digital signal modulates a carrier-wave using the on-off keying modulation scheme. This carrier is a 113 kHz square-wave obtained from a 455 kHz ceramic resonator oscillator after division by 4 using two flip-flops. Before being modulated the carrier is buffered and its duty-cycle is made adjustable using a pulswidth modulator (carrier driver block in Figure 2). At this point the modulated signal is still a digital signal. Using a class C amplifier we now transform the modulated square-wave to a modulated sine-wave with as little distortion as possible. Since the duty-cycle of the square-wave carrier determines the amplitude of its base-harmonic, we can adjust with it the level of the output signal put on the mains (max. 116 dB (μV)). A signal indicating the strength of the output signal, obtained from the envelope detector, can be used to control the duty-cycle. In order to have enough current to drive the line interface, the modulated sine-wave at the output of the class C amplifier is further amplified by a power amplifier. This power amplifier has a high input impedance and a low output impedance. It is switched off during periods where there is no output signal in order to minimise the load on the network. A filter is used to limit the bandwidth of the signal before it is put on the network by the line interface. This line interface is needed to isolate the rest of the interface from the power line and to protect it from possible spikes.

The receiver part of the physical layer is formed by the envelope detector and the comparator behind it. The envelope detection is performed by an NE/SA616 chip. This device is a low-voltage high performance monolithic FM IF system, widely used for example in portable communications applications. This device can however also be used to build an ASK data receiver, in which case only a portion of its functionality is used, i.e. the logarithmic received signal strength indicator (RSSI), the RSSI opamp used as voltage follower and the two limiting amplifiers. After lowpass filtering the output of the envelope detector to remove the small remaining carrier-wave ripple, the signal is compared to a reference value in order to obtain the digital demodulated signal.

In order to solve the problem of destructive interference of the carrier-waves, we have implemented both approaches presented earlier. The preferred approach is to make the system deliberate incoherent.

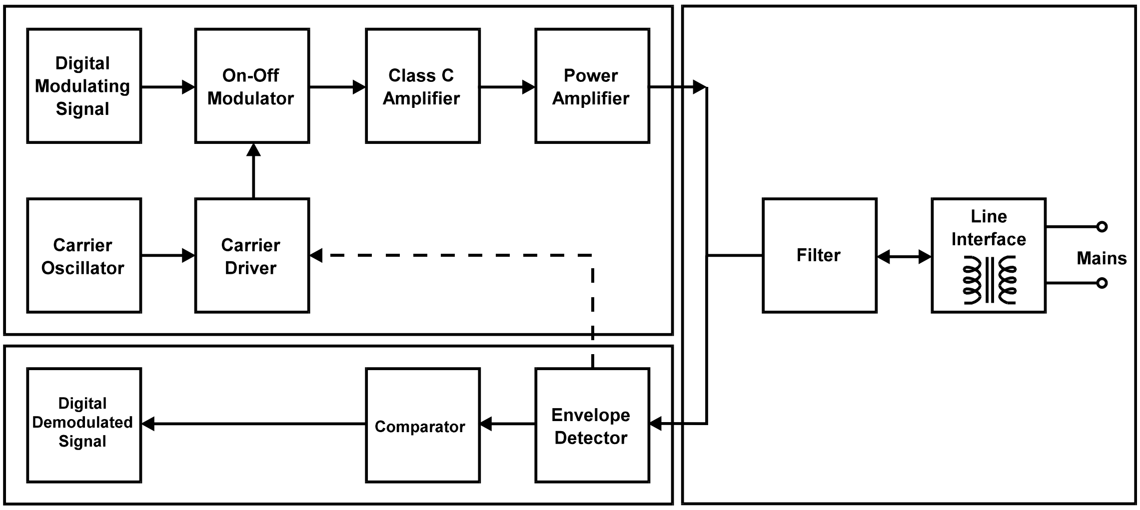

Figure 2: Block diagram of physical layer for communication over the mains

In this technique the phase of the carrier-waves is made random, so that the probability for destructive interference's to occur is also random. Since the build-in error handling features in CAN are able to cope with and recover from sporadic errors, message corruption due to occasional destructive interference's will be solved by the protocol, by simple retransmission of the message. A simple way to randomise the carriers phase is to use a noise source, such as for example a zenerdiode. If a zenerdiode is polarised backwards, somewhat above is breakdown voltage, a small current will start flowing through it. The larger the breakdown voltage of a diode the more noise it will produce. The small AC noise signal is amplified by a cascade of operational amplifiers. The 113 kHz square-wave carrier is fed into a phase locked loop (PLL), composed of a phase comparator and a voltage controlled oscillator (VCO). The amplified noise signal is added to the input of the VCO. The output of the VCO now gives the modified carrier-wave.

The design described in this section has been build using conventional of the shelf available components. To become cost effective however, a high level of integration must be achieved. For this reason, within our department, a CMOS IC has been designed which forms the main building block for a compact power line modem design [2].

4. Conclusions

Resulting from the introductory study on bandpass digital transmission and the additional requirements imposed by CAN, we have identified the OOK modulation scheme as a suitable technique for CAN communication over narrow band channels. Although its performance is not as good as other common used binary modulation schemes, it has the benefit that it supports the dominant/recessive bit principle needed for CAN, without any major modification to the modulation principle. Evenmore it is a fairly simple and easy to implement technique, which has been demonstrated in the implementation presented in the paper.

5. Acknowledgements

The power line interface presented in section 3 of this paper has been implemented within the framework of a one year graduation project performed by two last year students at our department, Steven Gabriëls and Tim Gyselings. The authors would like to thank both students for the enthusiasm and effort which they have put into their graduation project. Their work has contributed to the further extension of the FORTRESS development system. We would further like to thank Ir. Hans Van Parijs, who co-supervised the graduation project.

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