Automotive Powerline Communications
-a new physical layer for CAN-

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Abstract

Due to the increasing replacement of mechanical components by mechatronic modules and the demand of cross-linked sensor and control elements the effort of cabling and networking of individual components in MPV's is also increasing.
Powerline communications (PLC) stands for integrated transmission of energy and information using supply lines. The advantages of PLC are reduction of wiring, resulting in reduced costs, weight and use of space; reduction of complexity (of harness) providing a better handling capability. Further advantages are easy retrofitting/ retrofit procedure (aftermarket systems), possibility of parallel transmission of several services (e.g. diagnosis) and protocols and the possible usage as a redundant system for safety related applications. The transmission onto the powerline is based on carrier transmission technique in general.
Due to this advantages PLC is of high interest for an application as a CAN/ TTCAN physical layer. Some specifications and limitations are necessary for the use of PLC based on CAN. Caused by the CAN-specific access technique and the error detection/ recovery procedure usable transmission technique based on carrier frequency transmission technique is restricted. The core of the developed transceiver is the synchronization set to achieve the essential synchronization of each carrier. Using a developed algorithm the "synchronizer-transceiver" can be determined in the "power on modus". CAN-PLC is a 100% CAN-compatible PLC-system. Only the physical layer has been changed (➔ changing the transceiver). In the first step it is used for low speed CAN-applications (≤ 125 kbaud).

1 Preamble

1.1 Introduction

Due to the increasing networking in motor vehicles as well as the synergy to new functional systems the requirements to the future network are also increasing. The network architecture will achieve an important contribution to the implementation of innovative automotive systems. Due to the increasing replacement of mechanical components by mechatronic modules and the demand of cross-linked sensor and control elements the effort of cabling and networking of individual components in MPV's is increasing too. Powerline communications, that means integrated transmission of energy and information using supply lines, is an interesting complement to existing network concepts for future automotive communication.

Some basic investigations are absolutely necessary for the development of communication systems. Knowledge about the transmission channel and EMC-aspects like the interference and disturbance onto the powerline are the basics for the development of PLC-systems. A lot of channel and disturbance investigations have been carried out in order to increase this knowledge. There are some harness modifications "recommended" (network design) which result from this investigations, depending on the used carrier frequency range.

Using the basic procedure as mentioned above some PLC-systems have been developed at Bosch. Due to the intention to use PLC in a wide automotive range every developed system use carrier transmission technique in general to be more resistant to noises especially to low frequency voltage swings caused by switching of high current loads.

1.2 Advantages of automotive PLC

The use of automotive Powerline communications has different advantages. One effect of PLC is the reduction of wiring. Considering especially the first three points of the following list of benefits of PLC a reduction of wiring is desirable, but besides this obvious aspect there are further advantages, too:

- reduction of wiring includes the effect of reduced weight, costs and use of space
- Reduction of failure risks; especially concerning moveable modules (e.g. door, mirror,...) there is a high mechanical stress on cables, which leads to an accelerated ageing and an increased failure risk.
- Reduction of complexity of harness provides a better handling capability
- easy retrofitting/ retrofit procedure for aftermarket systems
- parallel transmission of several services (e.g. diagnosis) and protocols are possible caused by frequency band sharing (frequency division multiplex)
- PLC can be used as a redundant system for safety related applications, e.g. X-by-Wire

Due to the advantages of PLC as mentioned above automotive Powerline Communications is very interesting as new physical layer for CAN/ TTCAN.

2 Requirements to PLC as new physical layer for CAN

Because of the access technique used for CAN and the CAN-specific failure detection mechanisms there are some restricting specifications of PLC using as a physical layer for CAN necessary. The developed CAN-PLC-system is 100% CAN-compatible. The main reasons of restriction are caused by the access technique CSMA/CD+CR, **C**arrier **S**ense

Multiple **A**ccess with **C**ollision **D**etection and **C**ollision Resolution, and the acknowledge of the receiver. Both are characterised by contemporaneous access of different nodes. At an event triggered bus system every node has the possibility to send a message at every time, assumed that the bus is idle (➔CSMA). The resolution of a collision is solved by using the bitwise arbitration. To guarantee 100% CAN-conformity of PLC, access and acknowledge using bitwise arbitration on the bus has to be realized on the powerline to support contemporaneous access of different messages.

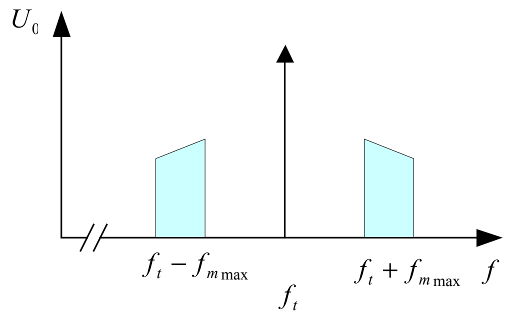

Fig.1: spectrum of OOK

As mentioned above the main requirement "bitwise arbitration onto the Powerline" restricts the usable carrier transmission techniques tremendously.

The possible access of different messages at the same time results in inevitable interferences between the carrier. In order to get evaluable signals using carriers in spite of this interferences the possible transmission technique is restricted to the ON-OFF-keying (short OOK), an Amplitude-Shift-keying, respectively using OOK-detection techniques. Using this transmission/ detection technique, the interference of carrier modulated by dominant or recessive bit have to result as following:

dominant X dominant ➔ dominant
dominant X recessive ➔ dominant
recessive X recessive ➔ recessive

This can be verified and evaluated. Thereby, dominant means carrier ON and recessive means carrier OFF. But using this transmission technique, it is not enough to apply a PLC-system as a physical layer for CAN. Because of the interference of carriers at the arbitrary phase it is essential to guarantee that the results of the interferences can be still evaluated as shown above at every time. In order to receive usable signals by "constructive" and deterministic interference the carriers have to be synchronized.

Another important communication requirement is the timing requirement and has direct consequences to the CAN-PLC system. First to the acceptable timing delay of a transceiver, second to the acceptable extension of the network and third to the possibility of error correction (forward error correction). The transmission delay is caused by transmitter, receiver and the transmission line. In case of CAN, the delay time of one bit must be half time shorter than the bit sampling point, because an acknowledge from a receiving node must be detectable within one bit by the transmitting node:

$$t_{delay} \leq 1/2 * t_{bit\_sampling}$$

equation 2-1

$$t_{delay} = t_{delay\_transmitter} + t_{delay\_receiver} + t_{delay\_line}$$

equation 2-2

This requirement causes a killing point for using any error correction code to improve the noise resistance of the CAN-PLC-system. The use of forward error correction codes is just possible in combination with collision-free protocols.

The Bosch-CAN-PLC-transceiver are specified by a maximum delay time of 2,3 µs at a data rate of 125 kbaud (dynamic data rate up to 125 kbaud). This delay time includes the delay of transmitter and receiver together. It corresponds to equation 2-2 without t_{delay_line}. Using a minimum bit sampling of 60% at least and a network with a maximum length of 20 metres the equation 2-1 is fulfilled. In comparison to the delay times of the transceiver the delay times of the lines can be neglected (with reference to the aspect as mentioned above).

However, the different delay times (depending on different locations and distances) of the line affects to the phase differences of the carrier. Besides the propagation delays onto the line, the phase difference depends on the carrier frequency, too. To receive detectable interfering signals with a sufficient signal to noise ratio the phase difference has to have an acceptable maximum. This maximum defines the maximum length of the network at a fixed carrier frequency (for more information look at 3.3 synchronization of carrier/ pilot-master-fight). Therefore, a limited network in dependency to accepted phase difference resulting from line delay and used carrier frequency is a further requirement.

Another, non technical, requirement is the financial aspect. The costs of a CAN-PLC-system must be lower than the costs of a CAN-transceiver plus two CAN-lines (CAN-high and CAN-low).

3 CAN-PLC-system

3.1 Network

As mentioned in chapter 1.1 a lot of channel and disturbance investigations have been made to achieve knowledge and experiences about transmission channel and specific EMC-aspects. In dependency to the used carrier frequency and the dimensions of the aimed PLC-network are some harness modifications useful or indispensable respectively. There are two ways of modifications. It is distinguished between low frequency systems and high frequency systems. With reference to the maximum line length in passenger vehicles [PV] the frequency range above 5 MHz has to be defined as quasi high frequency area. Reflections on impedance discontinuities lead to multi path propagation of data and noise signals. Through interference of different signals frequency selective fading occurs

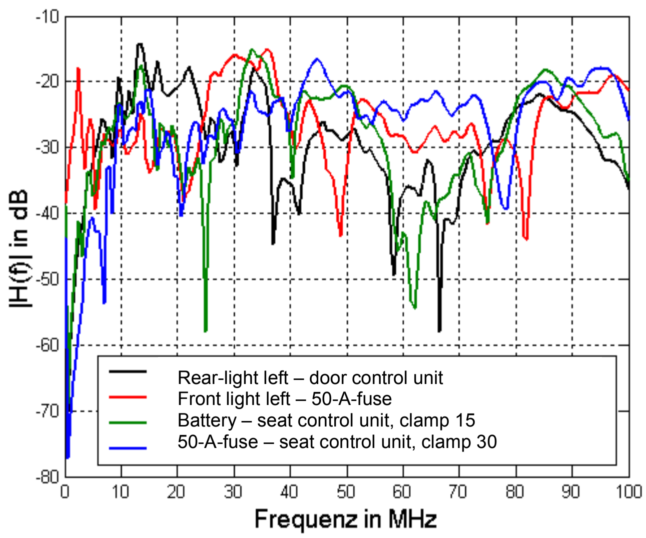

Fig.2: transfer function of standard on-board network (without modifications)

in the transfer function. Within a disturbed frequency band it is necessary to send data signals with higher power or to avoid this frequency range for use of data communication. In the high frequency area modifications of harness are indispensable without using expensive technology like channel estimator and self-adapting equalizer. Through modification of the structure of the harness as described above high frequency effects can be reduced. Furthermore with modification of the harness the channel is predictable. The main network-modifications in general are:

- using of twisted powerlines to support symmetrical transmission
- termination of lines by inductive elements
- *star topology with adapted passive and active stars recommended*

Referring to the mentioned point above the frequency range below 5 MHz or 3 MHz respectively is defined as the low frequency area (in reference to line length of PV). The modifications of the harness for transmission in the low frequency ranges are less extensive caused by the less high frequency effects. As shown in Fig.3 just a decoupling of the low impedance “supply input terminals” and the low impedance power source is recommended. In the low frequency range capacitive coupling elements are used to superimpose carrier information to the powerline. Using a low carrier frequency the unsymmetrical automotive supply network can be applied. The inductive elements take effects to terminate the lines. But due to the asymmetry, the lines have discontinuities and no constant characteristic impedances and therefor the termination has a high mismatch. This mismatch has neglectable effects using the low frequency range.

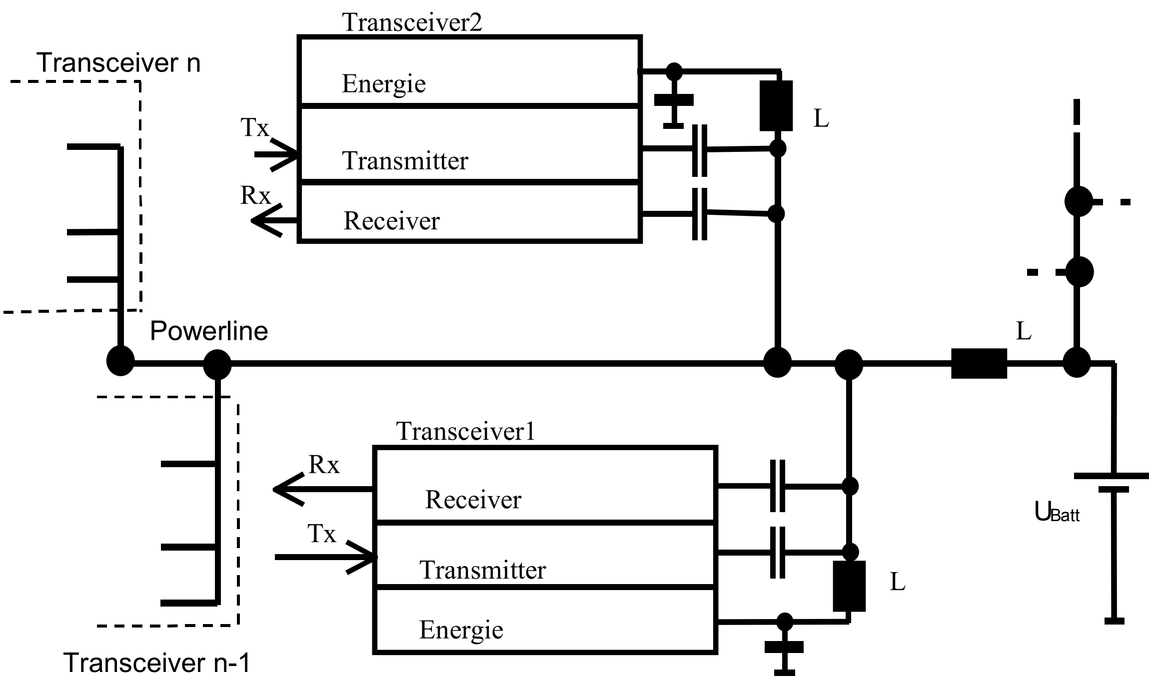

Fig.3: architecture of low-frequency PLC-system

In Fig.4 the transfer function of a terminated but inevitable mismatched asymmetrical door line harness is displayed. The door line has a length of more or less 2 metres. Below a frequency of 20 MHz the first notches in the function caused by reflections can be found.

The CAN-PLC-system is developed to use the asymmetrical supply network with the few modifications as mentioned. However, prototypes and future test-Asic's have the option to use symmetrical transmission. Symmetrical transmission in connection with twisted pair is useful and has positive effects to EMC-aspects and signal integrity. For collision-free systems it affects achievable data rate too, because of higher available bandwidth at higher carrier frequencies. Nevertheless, when using CAN it is ineffective to increase the

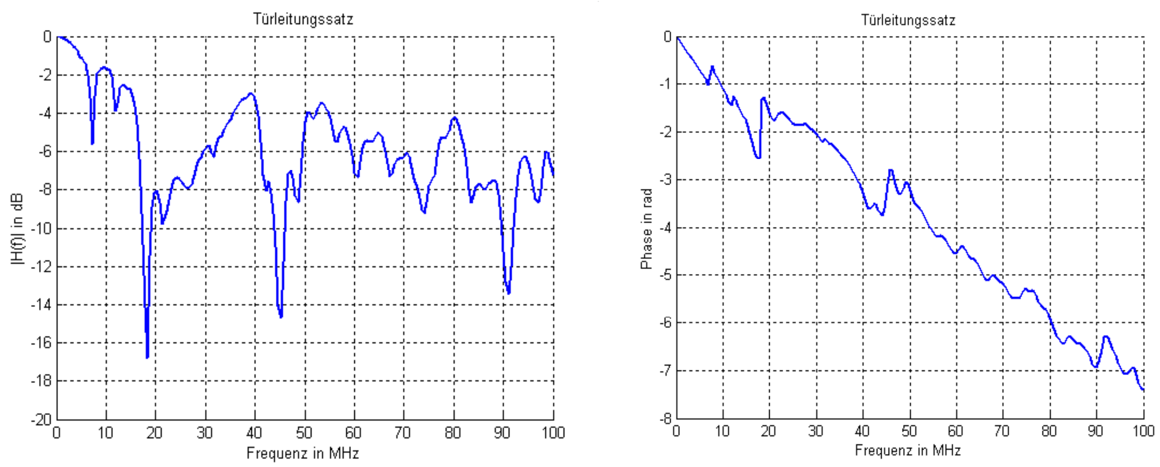

Fig.4: transfer function of door line harness (terminated with 150 Ohm)

carrier frequency because of the dependency of phase differences to line length and carrier frequency. Increasing carrier frequency means increasing phase differences at fixed line lengths. This results in reduction of maximum acceptable line length. Therefore, the phase differences do not go beyond the defined maximum values.

3.2 CAN-PLC-transceiver

CAN-PLC is 100% CAN-compatible. Besides the (described) recommended networking modifications only the physical layer has been changed as shown in Fig.5.

capacitive coupling elements onto the powerline and a receiver to detect the signals from the powerline with the functionality of the demodulator. Due to the reasons as mentioned above OOK is used, a very simple and cost efficient transmission technique. But OOK has the lowest noise resistance of the digital shift keying techniques, because of its sensitivity against amplitude interferences. The data carrier frequency is fixed outside of any radio band to 2,3 MHz. The carrier has an adjustable signal amplitude between 100 mV and 500 mV or 1V (for testing and evaluation) respectively. TxD is modulating the carrier and the

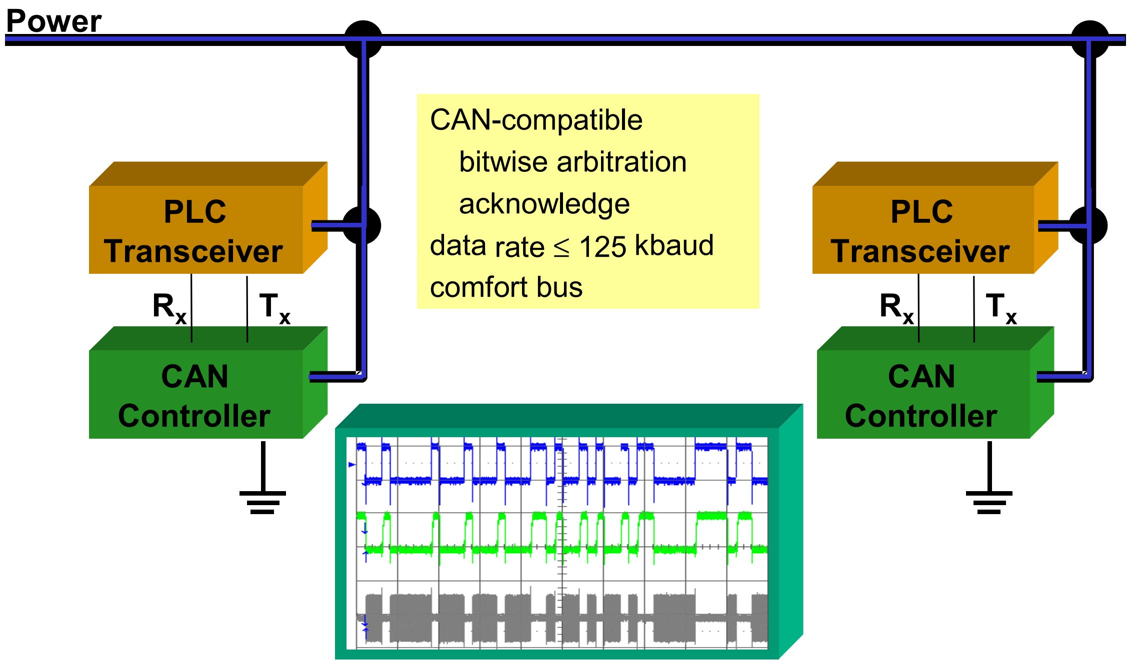

Fig.5: block scheme CAN-PLC-bus

Basically the CAN-PLC-transceiver consists of a modulator and demodulator to realize a carrier transmission. As shown in Fig.3, there is a transmitter including the modulator to send the information via

demodulated signal is represented by RxD. The transceiver has a sleep- and wake up-functionality. After a period of missing bus-communication the CAN-PLC-ASIC changes into sleep-mode and

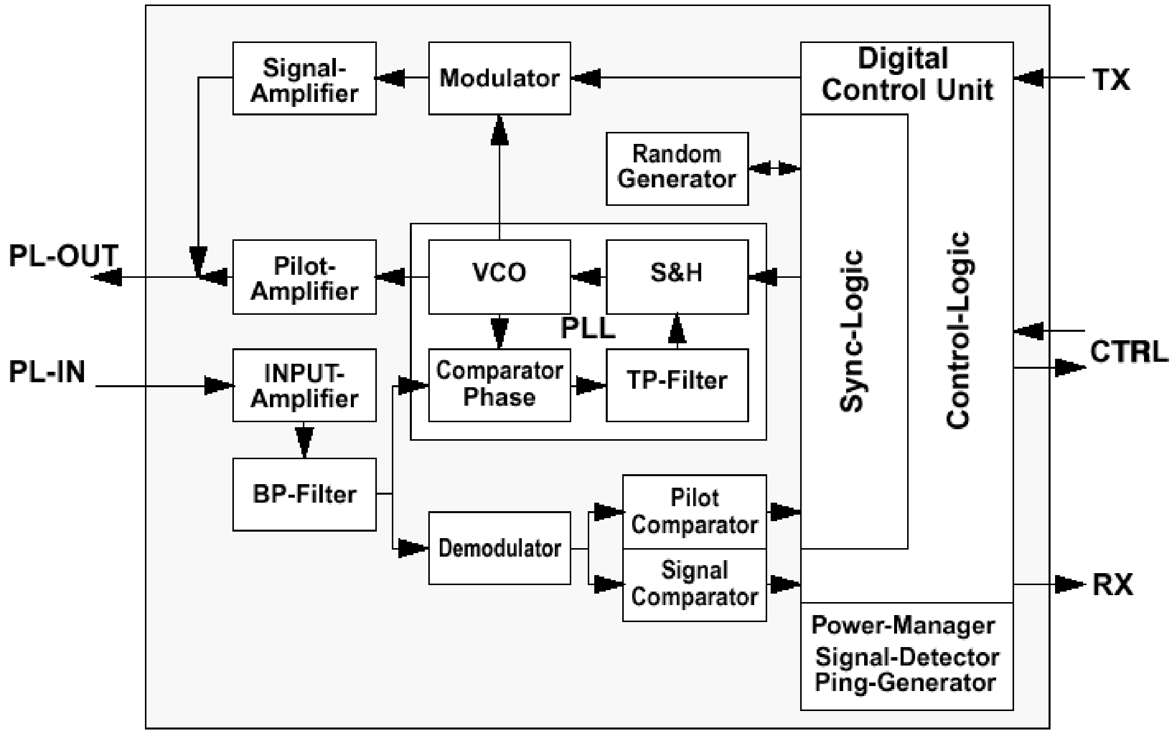

Fig.6: block diagram “one-frequency“-transceiver

can be awakened again by controller or bus communication.

The core of the transceiver is the synchronization set with synchronization- and control logic. The synchronization set is either generating the pilot carrier, which is used for synchronization of the data carriers or locking onto an external pilot carrier to synchronize their own data carrier onto the pilot; it depends on the state of the transceiver. Main task of the synchronization- and control logic is the running of the pilot-master-fight.

External there are four different modes selectable:

- Pilot-Master-fight
- Pilot-Master
- Pilot-Slave
- Node off

Furthermore, there is an error-interface to report a malfunction of the transceiver to the controller. Besides the SCI-interface (TXD, RxD) the transceiver has a Ready-pin to enable communication. As mentioned above, there is an interface for sleep and wake-up.

3.3 synchronization of carrier/ pilot-master-fight

In order to prevent destructive interferences at simultaneous access of different carrier pulses as shown in Fig.7 synchronization of carriers is indispensable. The phase lock of each carrier are realized by a synchronization set embedded into the developed CAN-PLC-transceiver. The single carriers can have phase differences among each other depending on differential propagation delays. The maximum acceptable phase difference defines the maximum extent of the network.

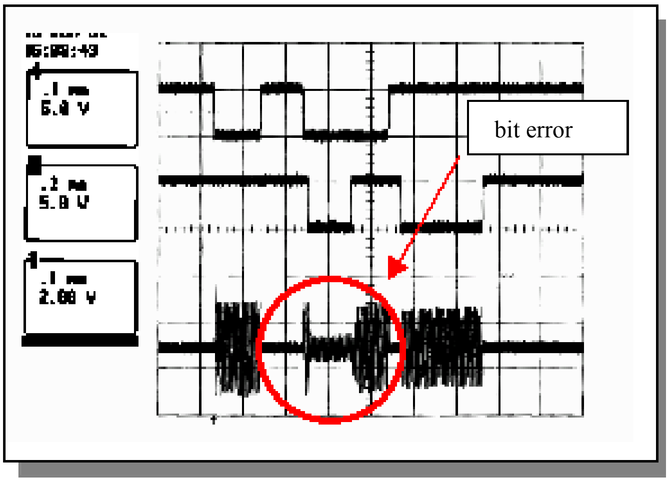

Fig.7: bit error caused by missing synchronization

The synchronization is accomplished by transmitting a pilot carrier. Every node can lock to this pilot carrier. The data carrier is derived from this pilot carrier.

In principle, every node can be pilot, respectively pilot-master and is able to send a pilot carrier. At start up of the network and in case of pilot errors, an algorithm is initiated, the so called pilot-master-fight. With the help of this master-fight the future pilot-master is determined. This pilot-master generates the pilot-carrier and transmits it to the powerline. The pilot-master-fight is mainly done by the embedded synchronization control unit according to the implemented algorithm.

Basically, there are different random distributed intervals to access to the bus (Fig.8). Every node tries to couple in their pilot carrier after random time (2) with a random duration (4). At the end of temporary transmitting time the pilot-carrier is switched off and the node is looking for other pilot carriers, so called external pilot carriers. A node will stop master fight, if it detects external pilot carrier (3) and will change to slave-mode. If a node does not detect any external pilot-carrier in its silent period, it will continue the master-fight, that means it will transmit it's own pilot-carrier after random time for a random duration, again. This procedure of transmitting and searching is repeated as often as implemented, provided that the node does not detect any external carrier in the time slot of searching.

At the end of the sequence the "remaining" node is sending the pilot carrier continuously, assuming that it is the real

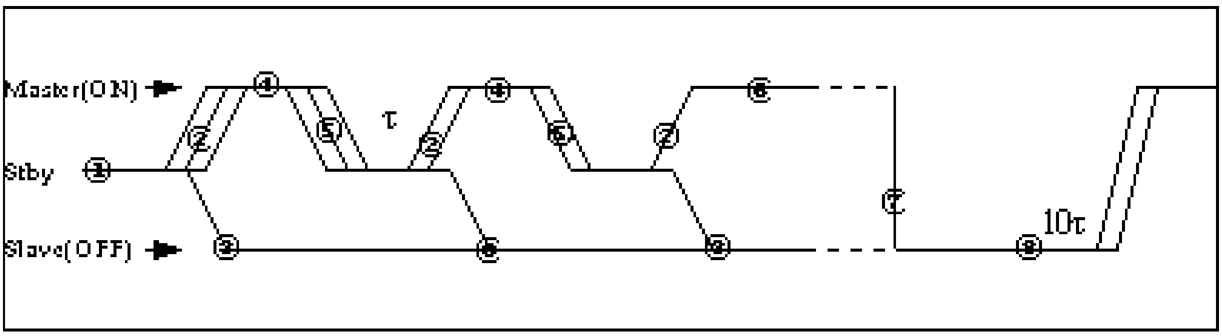

Fig.8: timing behaviour of pilot master-fight

pilot-master (6). Furthermore, this node sends out a ping, represented by a few periods of pilot carrier with increased amplitude. Pilot-master and pilot-slaves receiving this ping are setting a ready-bit at the interface of the controller to enable communication. The ping informs the other nodes that a pilot-master has been found and the pilot-master fight is finished. The temporary slaves have to change to the static slave mode and to enable the communication by setting the ready bit.

The failure of a pilot carrier can be detected by the slaves. After a period of time (8) and continuous pilot failure the pilot master fight is initiated again.

There are two different versions of synchronization developed using pilot carrier:

1. Pilot carrier and data carrier are using the same frequency but different amplitudes with the advantage of no effort of sharp channel separation.
2. pilot carrier and data carrier have different frequencies (factor 2) with the advantage of higher noise resistance than in version 1.

4 Status and outlook

First applications of the developed CAN-PLC-transceiver will be found in the domain of body electronics. At the end of the year 2003, a test-ASIC with specified maximum data rate of 125 kbaud for low speed CAN applications will be available. The modifications of the system are reduced to the physical layer and a few simple network conditions. This transceiver can also used for collision-free protocols, like LIN. Up to now there are some prototypes developed based on CPLD's. A PLC-subbus with this PLC-transceiver prototypes is already used in a test vehicle as subbus in the front door with four nodes: 3 LIN-slaves and 1 LIN-master with gateway-functionality (LIN ⇔ CAN).

By the first application of PLC in non safety-critical and low data rate domains like body-electronic the method and the system has to prove itself. With availability of the test-ASIC there are a vast number of tests and measurements scheduled. After successful operations of the test-ASIC's it has to be investigated the possibility to increase achievable data rate up to 500 kbaud for high speed CAN or 1 Mbaud for future TTCAN applications respectively. Furthermore there are investigations to improve the noise resistance of the PLC-transceiver necessary, especially for applications in more safety-critical domains than body electronic. In addition, PLC is investigated for data rate up to 10 Mbaud, a special transceiver (no CAN-compatibility) is under development.

5 Literature

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6 List of figures

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