In-Car Communication based on Power Line Networks

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Abstract—**The number of electronic control units in today's cars is permanently increasing. As the demand for information exchange between these units is growing, the complexity of the in-car communication infrastructure also increases. In the past more and more bus-segments have been added to cope with the growing demands. In order to reduce the complexity and the costs for the future in-car communication infrastructure, the approach of using power line communication for the in-car communication has been analyzed. By using power line communication, the cabling can be reduced to the minimum. In this paper the challenges of today's and the requirements for future in-car systems are summarized. The HomePlug Green PHY standard, which has been designed for Smart Grid applications, is analyzed according to its applicability to the in-car communication. Additionally a proposal and its evaluation for the reduction of the protocol overhead is presented.**

I. INTRODUCTION

In the past decades, the demand for an information exchange between ECUs (electronic control units) in vehicles rapidly raised. Prior to the digital data transmission, mainly discrete electrical signals have been used for the information exchange. With the increasing number of safety and comfort functions, the demand for a data exchange between a huge number of ECUs is growing from vehicle generation to vehicle generation. Over the years different communication systems emerged for different applications.

In the 1980s the CAN-bus (Controller Area Network) [1] has been designed and released. The CAN-bus was one of the first widely spread communication buses in modern vehicles. With an increase in body and comfort functions, the wish for a cheap and simple communication system came up. For this purpose the LIN-bus (Local Interconnect Network) [2] has been defined. It is mainly used for the body and comfort functions where safety requirements are typically low and no high data rates are needed. In the beginning of the 21 century the requirement for a new in-car communication system came up. FlexRay [3] has been designed to provide a communication system for time-critical functions like safety functions.

In a today's upper class vehicle more than 40-50 of these communication buses can be found. This introduces challenges in planning, deployment and the maintenance of the harness. Additionally the high number of wires lead to higher costs and also weight, which directly translates into fuel consumption.

The highest rate of change is typically observed in the body and comfort area, where the LIN-bus is dominant. Upper class vehicles already contain more than 20 of these buses, which are distributed over the whole vehicle. If information has to be transmitted to a different LIN-bus, gateways have to be used.

One possibility to reduce the cabling of the ECUs is the usage of wireless communication. But with wireless communication additional challenges arise. The interference to and from other devices in the surrounding of the vehicle have to be considered. Measurements [4] show that the effective area of influence is quite large. The positioning of the antenna has to be chosen carefully and the transmit power should be as low as possible.

Another possibility is the application of Power Line Communication (PLC). With PLC the need for dedicated communication lines besides the power lines disappears. Thereby the cabling is reduced to the minimum - the power supply. Measurements [5] show that the physical transmission of PLC signals on a car body is feasible. But the EMC still has to be investigated in detail in order determine if it meets automotive requirements.

Various PLC standards for the in-house application like G.hn or HomePlug AV are available. In this paper, the latter one is investigated according to its applicability to the in-car communication. Starting from a today's vehicle, the challenges and requirements for the future in-car communication are stated.

In section II a short overview on a today's in-car communication infrastructure is given. In Section III requirements for a future in-car PLC protocol are stated. Section IV summarizes the main features of the HomePlug Green PHY standard and its applicability to the in-car communication is discussed. A proposal for the reduction of the overhead is given. In section V simulation results with the modified protocol are presented. A conclusion is given in section VI.

II. TODAY'S IN-CAR COMMUNICATION

Today's cars include highly interconnected ECUs covering a wide range of applications. Upper class vehicles - depending on the configuration of the features - may contain up to 50-100 ECUs. Besides these ECUs there are also sensors and actuators which have to be connected. The cabling needed for the interconnection of the ECUs easily reaches summed up length of more than 1-2 km. Widely spread bus-systems which can be found in modern vehicles are CAN, LIN and FlexRay.

Multiple buses of each type are typically deployed in a car and most of them are interconnected by a gateway.

As a high rate of change from vehicle generation to vehicle generation is in the body and comfort area where the LIN-bus is dominant, the focus of this paper is on the replacement of the LIN-infrastructure by a PLC-system. The low safety-requirements on the LIN-bus are another reason for choosing its replacement as a first step.

The LIN-bus is a comparatively cheap master-slave bus-system mostly used for non-safety-critical communication in the body and comfort domain. The maximum data rate is 20 kbit/s. However the possible savings of replacing the LIN-infrastructure by a PLC-system is quite high, because of the high number of LIN-buses in a car covering almost every part of the vehicle. A today's upper class vehicle already includes over 20 LIN-buses, which comes along with a high effort in wiring.

The high number of LIN-buses leads to various challenges. The increasing complexity enlarges the effort in planning, installation, management and the diagnosis of the harness. The weight is also increasing which directly translates into higher fuel consumption.

III. PLC FOR THE IN-CAR COMMUNICATION

The requirements for the in-car communication differ from typical Home Area Networks (HANs). Typical HANs consist of a small number of nodes interconnected by a network with comparably high data rate. For a high throughput, the frames typically carry some hundred bytes in order to reduce the overhead. For the in-car communication in contrast, a high number of nodes has to be connected while the exchanged information is typically in the range of only 1-8 byte. Thus a protocol for the in-car communication should be able to support a high number of nodes while minimizing the overhead for short payloads.

Most protocols for the home and wide area networks are non-deterministic. Regarding diagnosis, determinism is a desirable property for in-car communication systems.

Another point is the Quality of Service (QoS). Most protocols support a kind of QoS (i.e. prioritized queues), but for the in-car communication some functions have strict requirements regarding the latency. Functions like control loops often produce periodic traffic either continuously or at least for a period of time.

Thus a protocol should be suitable to transport periodic traffic on the one hand and support event based traffic on the other hand. In addition the costs have to be minimized. Costs can typically be reduced by using off-the-shelf components. For this reason the HomePlug Green PHY standard is analyzed in section IV.

The requirements for an in-car communication system can roughly be summarized as follows:

- Scalability: The protocol has to be able to handle a high number of nodes (one hundred or even more)
- The overhead has to be minimized; in case of the LIN-bus the payload is less or equal to 8 byte
- Support for periodic traffic and additionally support for event based traffic
- Determinism is a desired feature (at least for periodic traffic)
- Minimize costs: prefer the usage of off-the-shelf components

IV. IEEE 1901 AND HOMEPLUG GREEN PHY

The IEEE 1901 standard [6] has been defined to provide coexistence between different PLC standards. Thus IEEE 1901 includes the HomePlug standard. In the following, a brief overview on the HomePlug standard is given.

The HomePlug 1.0 standard has been released in 2001 by the HomePlug Alliance. HomePlug AV as an extension has been released in 2005. HomePlug AV currently supports data rates up to 500 Mbit/s. The new HomePlug AV2 standard already supports data rates of approximately 1 Gbit/s.

For Smart Grid applications the HomePlug Green PHY (HP GP) standard has also been released in 2005. HP GP is a subset of the HomePlug AV standard with the focus on a robust communication. The robustness is reached by using only QPSK (Quadrature Phase-Shift Keying) modulation and using the so-called ROBO (robust OFDM) modes. With the ROBO modes, multiple copies of the same signal are simultaneously transmitted over the OFDM (Orthogonal Frequency Division Multiplex) carriers.

A. MAC layer

For the organization and synchronization of a network, one node is selected to act as a Central Coordinator (CCo). The CCo periodically sends beacons to synchronize the network. In between the beacons, two medium access methods are defined. The first one is the mandatory CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) which uses a backoff-mechanism for collision avoidance. The optional TDMA is the second access method. The structure of the beacon period is depicted in figure 1.

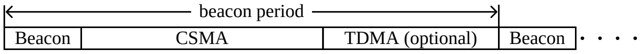

Fig. 1. HomPlug beacon period

For the CSMA/CA access, four Channel Access Priorities (CA0 to CA3) are defined. Before a stations starts a backoff, the priority resolution is performed. Two Priority Resolution Slots (PRS) are used to communicate the highest priority of a pending frame to all nodes in the network. Depending on the priority, a station either transmits a priority resolution signal or it listens on the channel. The states of the two Priority Resolution Slots (PRS0 and PRS1) for the four Channel Access Priorities are listed in table I.

After the priority resolution, every station in the network knows about the currently highest frame priority. Only stations with a frame of the highest priority are allowed to start a backoff afterwards.

The medium access is depicted in figure 2. After the priority resolution, the time-slotted random backoff procedure

TABLE I. HOMEPLUG CHANNEL ACCESS PRIORITIES

Channel Access Priority	PRS0 State	PRS1 State
CA3	1	1
CA2	1	0
CA1	0	1
CA0	0	0

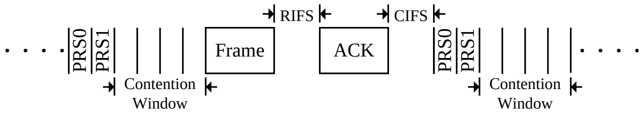

Fig. 2. CSMA/CA Medium Access

is started. The backoff procedure uses different counters and parameters: the Backoff Procedure Event Counter (BPC), the Backoff Counter (BC), the Deferral Counter (DC) and the Contention Window (CW). The BPC is set to 0 for the first transmission attempt. The CW and DC are set according to table II.

TABLE II. HOMEPLUG BACKOFF PARAMETERS

BPC	CA0 & CA1		CA2 & CA3	
0	CW=7	DC=0	CW=7	DC=0
1	CW=15	DC=1	CW=15	DC=1
2	CW=31	DC=3	CW=15	DC=3
>2	CW=63	DC=15	CW=31	DC=15

After CW and DC have been set, the BPC is increased by 1. The Backoff Counter is chosen uniformly in the range of [0, CW] and is decremented by 1 at every idle time-slot. When the BC is 0, the frame is sent out and the successful reception is acknowledged after a Response Interframe Space (RIFS). After a successful transmission the BPC is reset. If a transmission fails, new values for CW and DC are chosen according to table II. Afterwards the BPC is incremented by 1 and a new value for the BC is uniformly chosen.

Until now the procedure follows the backoff procedure known from IEEE 802.11. The only difference is the Deferal Counter. If a station senses the medium busy during its backoff, it freezes its counters. When the channel is idle for the duration of a Contention Interframe Space (CIFS), a priority resolution is initiated again. If the station is allowed to run a backoff afterwards (i.e. it has got a frame of the highest priority), it may resume its backoff depending on the value of the DC. If DC is not 0, DC and BC are decremented by 1 and the backoff resumes. If DC is 0, CW and DC are again set according to table II, BPC is incremented by 1, a new BC is uniformly chosen and the new backoff is started. The DC is used to extend the backoff when the contention is high, thus reducing the collision probability.

In the TDMA access period, stations can ask the CCo for a reserved transmission time. The reservation request is sent in the CSMA region. This may introduce an additional delay, because stations first have to wait for the CSMA region to be the active one. The CCo uses the beacon to communicate the reserved transmission time to all nodes. In the CSMA region collisions might occur. Sporadic in-car messages typically don't need a reserved TDMA slot. In this case the frame could already be transmitted in the CSMA region. For periodic frames in contrast, a static reservation would be the right choice in order to reduce the delay and overhead.

As a dynamic reservation of transmission time according to the HomePlug AV standard is not a suitable solution for the in-car communication, only CSMA is considered in this paper.

In table III the HomePlug Green PHY ROBO modes are listed. In the last column the Physical Block (PB) size is shown. PB136 denotes a Physical Block with 136 byte in length, PB520 corresponds to a PB with 520 byte. These PBs are the smallest amount of data which is transmitted on the channel. Each PB consists of a PB header and a PB check sequence (each 4 byte in length). For a PB136 this leads to a PB payload (PB body) of 128 byte. In the PB payload the MAC Protocol Data Unit (MPDU) is transported. A MAC frame consists of a 2 byte header and a 4 byte checksum. In the case of a PB136 this leads to a MAC payload of 122 byte per PHY block.

TABLE III. HOMEPLUG GREEN PHY ROBO MODES

mode	PHY rate	# copies	PHY block
Mini-ROBO	3.8 Mbit/s	5	PB136
Standard-ROBO	4.9 Mbit/s	4	PB520
High Speed ROBO	9.8 Mbit/s	2	PB520

Considering typical in-car frame length of up to 8 byte, even the usage of the smallest PB size of 136 byte introduces a huge overhead. In addition there is an overhead for the CSMA/CA medium access (backoff, interframe spaces and acknowledgment).

B. *Protocol overhead*

The Physical Protocol Data Unit (PPDU) is depicted in figure 3. A preamble is sent out, followed by a Frame Control (FC), which is either one or two OFDM symbols in length. After the FC, several OFDM data symbols are sent out which carry one or more PBs. The FC has got different tasks. The Delimiter Type field of the FC identifies the type of frame or the content of the data symbols (e.g. beacon, data or acknowledgment).

Fig. 3. HomPlug Green PHY PPDU structure

One option to reduce the overhead introduced by the size of the Physical Blocks could be the definition of shorter PBs. The length of one block could be chosen to fit into one OFDM symbol, thus reducing the transmission time. A drawback of this option is the fact, that it breaks the current standard.

In protocol design when defining headers, a common way is to reserve fields or IDs for future extensions. In other cases, fields designed for a specific function are later on used for a different purpose. One example is the Explicit Congestion Notification (ECT), which is an extension to the IP- and TCP-protocol. ECT is used for the end-to-end notification of network congestion and it uses 2 bit of the Type Of Service (TOS) field in the corresponding header.

Another option to reduce the overhead is described in the following. The IEEE 1901 standard defines two MPDU frame formats. The long MPDU consists of the Frame Control followed by the MPDU payload, which is transported in the OFDM data symbols as illustrated in Fig. 3. The short MPDU in contrast only consists of the Frame Control. One example for a short MPDU is the acknowledgement indicated by the corresponding value in the Delimiter Type field of the FC.

When having a look at the Frame Control fields, two Delimiter Types can be found as currently unused. In addition there is a Variant Field whose type of content is indicated by the Delimiter Type. One of the currently unused Delimiter Types can be used to identify the transmission of a payload in the Variant Field. The Variant Field in the FC is 96 bit in length. This is enough to transport a LIN payload of 8 byte plus additional management information like an address.

The transmission time for one frame with a PB136 is 353.08 µs (including the transmission of the preamble, Frame Control and data symbols for the transmission of the PB136) when all 1155 OFDM carriers are available and Mini-ROBO mode is used. Note that the shortest PHY block size (PB136) is only used with the Mini-ROBO mode. When transmitting the payload in the Frame Control, the transmission time can be shortened to 110.48 µs (transmission time for the preamble plus Frame Control). But this is only the transmission time of the frame. Additional protocol overhead such as the priority resolution, backoff, interframe spaces and the transmission of the acknowledgement has to be considered.

When using the default values for the RIFS (140 µs), the CIFS (100 µs) and the slot duration (35.84 µs), the additional overhead in a collision-free environment can be determined. As the Contention Window in the first backoff-stage is 7, the average backoff length is 3.5 slots. The acknowledgement is sent in a short MPDU, i.e. only a FC is transmitted. With these values the duration of the additional average overhead without collisions can be calculated:

$$\begin{aligned} T_{overhead} &= 2 \cdot T_{PRS} + 3.5 \cdot T_{slot} + T_{RIFS} \\ &\quad + T_{ACK} + T_{CIFS} = 547.6\,\mu s \end{aligned} \tag{1}$$

The total transmission time for a frame including protocol overhead and frame transmission sums up to 658.08 µs. This means more than 80% of the total transmission time is protocol overhead.

Regarding the requirements for the in-car communication, the transmission with the IEEE 1901 CSMA/CA protocol might be an option. The overhead can be reduced by using the FC for the payload transmission. The costs can be reduced when using standard HomePlug Green PHY hardware. But the protocol is non-deterministic and collisions might occur. In order to investigate this effect, simulations with the modified protocol are presented in the next section.

V. SIMULATIONS WITH THE MODIFIED PROTOCOL

In order to analyze the performance of the protocol, simulations are carried out. A framework for the OMNeT++ network simulator has been created which supports the IEEE 1901 standard. The simulation is modified for the payload transmission in the Frame Control. The scenario of the simulation is a network with 100 nodes. All nodes are transmitting frames with a configurable inter-arrival time with an exponential distribution.

The beacon period is set to 50 ms. On an AC line the beacon period is two line cycles in length (33.3 ms @60 Hz, 40 ms @50 Hz). On a DC line the beacon period has to be defined in the CCo. The Frame Control is used for the payload transmission, e.g. no OFDM data symbols are transmitted. The nodes are equally configured to generate frames with a given frame rate. For the arrival process an exponential distribution is used.

Figure 4 shows the simulation results when only frames of priority CA1 are sent. The results for priority CA0 are the same, because CA0 and CA1 are using identical backoff parameters. On the x-axis the number of total generated frames of all 100 nodes in the network is given. The green solid line corresponds to successfully transmitted frames. The dashed red line corresponds to collided frames. The number of collided frames/s can exceed the number of generated frames/s because collided frames are transmitted (and may collide) again. Vertical lines have been added to mark the traffic-values where 3% and 5% of the transmissions collide. At a frame generation rate of approximately 1075 frames/s the collision probability exceeds a threshold. From this point on the channel usage rapidly increases due to re-transmitted frames. This in return increases the collision probability, which is a self-amplifying effect.

The presented figures are the mean value of 500 simulation runs. The variation from run to run in the low load case is minimal, beacuse the collision probability is low. In the area where the collisions shoot up, huge variations can be observed because of the random backoff procedure.

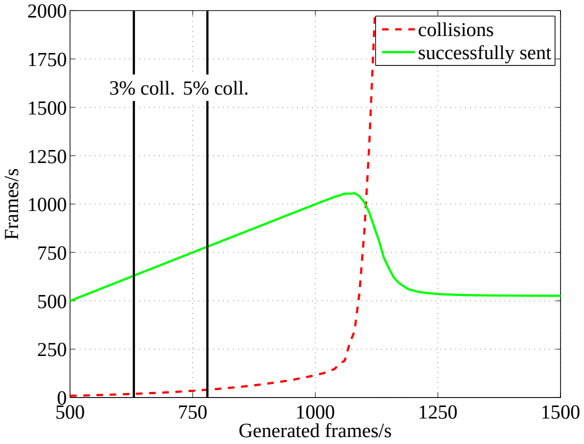

Fig. 4. Simulation results with priority CA1 only

Saturation is reached at a frame generation rate of approximately 1200 frames/s. From this point on stations always have frames in their TX queue. For the simulations the retry counter has been set to 7, e.g. after 7 unsuccessful transmission attempts a frame is dropped. When the offered load is increased further, the TX queue is filled more and more, but this has no observable effect on the channel usage. The system should be operated below a frame generation rate of 1000 frames/s, because otherwise the collision rate is way too high.

If a higher priority is used (CA2 or CA3) the average backoff length is shortened. This in turn increases the collision probability. One option to reduce the collision probability is the usage of all four priorities. The priority resolution ensures that only stations with a frame of the highest priority in the network start a backoff. For low loads this reduces the average number of stations simultaneously running a backoff, thus reducing the collision probability.

In figure 5 the simulation results are shown, when all four priorities are used. For every generated frame, a random priority is chosen with an uniform distribution, i.e. the probability of each priority is 25%.

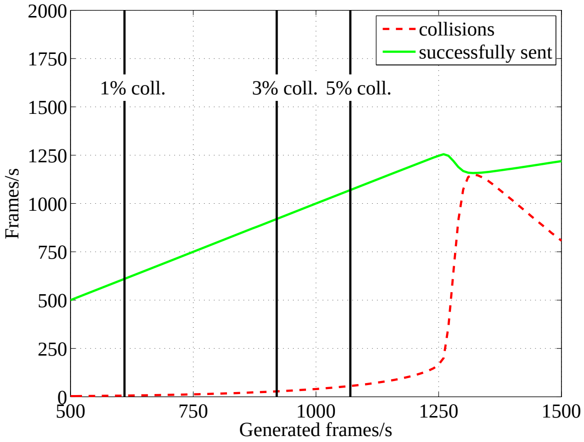

Fig. 5. Simulation results with uniformly distributed priorities

The overall number of collisions is lower and the throughput is higher when compared to figure 4. Using the priorities penalizes low priority traffic in favor of higher prioritized frames. This might be a desired behavior, but priorities have to be chosen with care.

VI. CONCLUSION

An overview on current in-car communication systems has been given. The requirements for a PLC protocol for the in-car communication have been summarized. These requirements commonly differ from the ones for example in Home Area Networks. A PLC standard designed for Smart Grid applications - the HomePlug Green PHY standard - has been analyzed regarding to its applicability as a replacement for the LIN-infrastructure. Even though the HomePlug Green PHY standard has been designed for Smart Grid applications, the minimum MAC payload is 122 byte when using the smallest Physical Block size (PB136). Currently the payload length of a LIN or a CAN frame is limited to 8 byte, which is far below the minimum payload of a Green PHY frame. In order to reduce the overhead, the transmission of the payload in the Variant Field of the Frame Control has been suggested. Thereby the transmission time of one frame can be reduced from 353.08 µs to 110.48 µs. Calculations show that the additional protocol overhead (backoff, interframe spaces and acknowledgments) is still huge.

Simulations have been carried out in order to analyze the protocol performance with a high number of nodes. The collision probability increases with increasing traffic load. The four Channel Access Priorities of the HomePlug standard can be used to lower the collision probability. But they have to be chosen carefully, because low priorities might starve when the load is too high. In addition the energy consumption has to be investigated. When using CSMA/CA, nodes have to listen on the channel most of the time. Thus using a pure CSMA/CA medium access might not meet the requirements for some applications. If this is the case, the combination of CSMA/CA and TDMA might be a solution, as defined in the HomePlug AV standard. A modification to the TDMA mechanism might be necessary to fit automotive requirements.

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