Drive-by-Wireless with the eCar Demonstrator*

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ABSTRACT

Drive-by-wire technology has been gradually adopted by the car companies in recent years to integrate active assistance systems in vehicles to increase comfort and safety. As an alternative to the wired case, we investigate the so-called drive-by-wireless, i.e., using a wireless network to control steering, braking, accelerating, and other functions within an automobile and focus on the discussion of the safety and latency properties of such a system. We use the commercial off-the-shelf ZigBee MSP-EXP430F5438 Development Board for wireless communication and demonstrate our drive-by-wireless prototype on a 4-wheel steering/drive electric vehicle.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication; C.3 [**Computer Systems Organization**]: Special-Purpose and Application-Based Systems—*Real-time and embedded systems*

General Terms

Drive-by-Wireless, Electric Vehicles, Safety, Latency

1. INTRODUCTION

In recent years, drive-by-wire technology has been gradually adopted by the car companies to integrate active assistance systems in vehicles to increase comfort and safety [4]. Complete new vehicle concepts are possible caused by the flexibility of drive-by-wire technology. In general, those techniques replace the mechanical and hydraulic connections between the driver and the associated vehicle actuators with electronic communication systems. These systems transmit electronic messages to direct a vehicle component based on the action taken by the driver of the vehicle, e.g., turning a steering wheel, depressing a brake pedal or accelerator pedal. The advantage of drive-by-wire is that safety can be improved by providing computer controlled intervention of the driver's commands with systems such as crash avoidance, brake assistance, and lane assist systems.

To further push the technologies for the electronic control systems of vehicles, we investigate drive-by-wireless, i.e., using wireless communication, rather than electronic cables, to control steering, braking, accelerating, and other functions within an automobile. The advantage of using wireless communication is multifold:

- Eliminating wired connections between sensors, actuators, and control modules so as to, in turn, eliminate associated design, installation and maintenance costs [1]. The possibility of the malfunction of wires and connectors may be eliminated through the use of a wireless network and the complexity of maintenance, problem solving, and repair may be reduced.
- In wired networks, all modules may share the same communication media. The capacity of the wired network may become congested, develop unacceptable latency and is hard to analyze. A wireless network for controlling vehicle functions may reduce the capacity limits by using different frequency domains for different types of communication.
- A wireless network may also increase the flexibility of design options because sensors, actuators, and control modules may be located regardless of wiring requirements [5]. The installation of sensor modules and control modules becomes easier.
- The integration of more safety functions increases the demand of inter-domain data transmission within the vehicle. The different domains of a car are connected via a central gateway which has to handle the cross-traffic of several bus systems with different technologies. Due to the availability of different channels for wireless communication, a node is not fixed to a specific domain and can be dynamically grouped with matching senders and receivers. This eliminates the bottleneck of a central gateway.

Although drive-by-wireless conceptually provides lots of advantages, it also faces practical challenges:

- The latency of a wireless network is higher due to used protocols and propagation delays. The wireless transmission of data demands a more complex technical re-

*This work is an extension of the technical report TUM-I1342.

CyPhy'14 April 14-17 2014, Berlin, Germany
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ACM 978-1-4503-2871-5/14/04$15.00.
http://dx.doi.org/10.1145/2593458.2593470

alization as the wired case which also contributes to an increased latency.

- Wireless communication can be distorted or interrupted by interfering transmissions or environmental effects. Especially a vehicle is an emitter of electromagnetic interference caused by components like the generator, electric engine, combustion engine or the inverters which has to be considered during the design of a wireless communication system inside a vehicle.
- As a wireless communication can be accessed without physical connection, it may be a target of hijacking or eavesdropping. This means a security concept has to be provided to protect the wireless channel.
- As a wireless system is complex, the costs of components using this technologies are significantly higher than the wired counterpart. On the other hand, weight and installation costs are saved as the cabling is removed.
- No transceivers nor protocols are available that are especially designed for the automotive in-vehicle communication. We expect that in the future more effort will be put into this point and that the trustworthiness of wireless communication is increased.
- We propose the usage of waveguides to shield the signals from external interference. An electromagnetic wave is neither able to exit nor enter a waveguide and forms a closed system. This concept only works if the waveguide, all interconnection points and all access points for antennas are sealed. This introduces mechanical challenges which are even increased inside a vehicle due to the harsh environment the components are exposed to.

In this work, we mainly address the safety and latency challenges. A wireless deployment environment is setup based on a drive-by-wire four-wheel steering/drive electric vehicle (Fig. 1). To verify the concept of drive-by-wireless, ZigBee-based communication is currently chosen to steer, accelerate, and decelerate one of the two axles. Commercial off-the-shelf MSP-EXP430F5438 Development Boards are used to integrate the wireless communication into the existing ICT infrastructure [2] of the eCar. To multiplex the communication between different in-vehicle ZigBee modules, a time division multiple access schedule is designed to provide temporal isolation. To increase transmission reliability, the beams of the eCar are used as a waveguide for the ZigBee communication. Our experimental results show a first proof that the communication latency and safety issues can be tackled and that drive-by-wireless is a promising concept.

The remainder of this paper is organized as follows: A short introduction of the fortiss eCar is presented in Section 2. Section 3 and Section 4 details our communication protocol and safety setup. Section 5 concludes the paper.

2. ECAR

The complete drive power of the eCar [3] is 8kW. Each of the in-wheel engines has 2kW and a maximum torque of 160Nm. The eCar is controlled with a sidestick connected to the human-machine interface unit. The current state of the evaluation platform is presented on a 10-inch touchscreen. The outline of the eCar is approx. 2.25 x 1.25 x 1.75 m (LxWxH) and its weight is about 600 kg. The eCar is constructed to carry one passenger. The ICT infrastructure of the eCar, shown in Fig. 2, consists of four nodes: Three Texas Instrument LM3S8962 evaluation boards for the control functions of the eCar and one Intel Atom computer for the management of the human-machine interface. The evaluation boards are interconnected via an in-house developed time-triggered Ethernet. FreeRTOS is used as the real-time operating system for the evaluation boards. The computer for the management of the human-machine interface runs Linux and shows an interface based on the Qt framework. The connection between the evaluation boards and the motor and steering controllers is realized via a CAN-Bus (Controller Area Network), running the CANopen protocol. The central evaluation board and the human-machine interface are connected via a serial link.

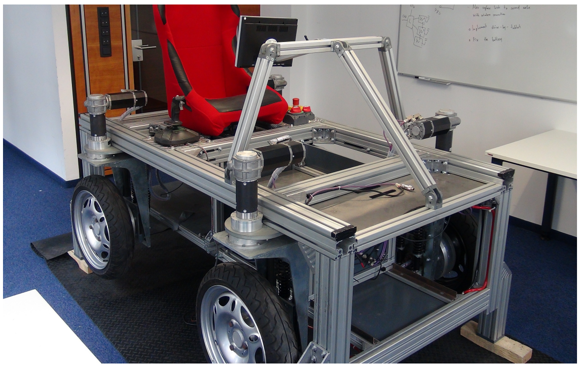


Figure 1: fortiss eCar demonstrator - an experimental platform for innovative ICT car architectures.

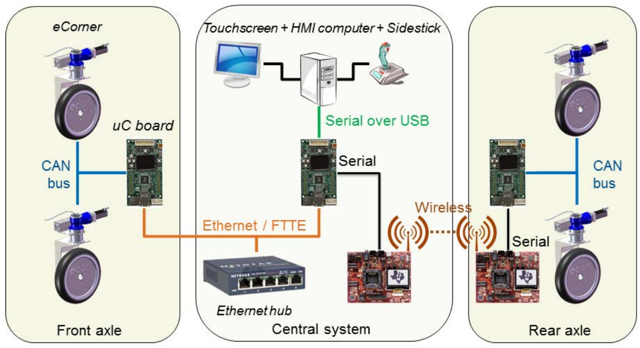


Figure 2: Information and communication architecture of the eCar with wired and wireless data transmissions.

3. COMMUNICATION LATENCY

The goal of our setup is to replace all the Ethernet cables in the eCar with ZigBee wireless communication and achieving a comparable performance to the wired case. In our first experiment, we replaced the cable to the rear axle with a wireless connection while leaving the setup of the front axle untouched, see Fig. 2. This allows us to compare the performance of the two different approaches.

The wireless nodes are connected to the central controller and to the rear axle controller via a serial connection. The connection between the wireless host boards and the daughter boards with the actual transceiver is realized via Serial Peripheral Interface (SPI).

While the controllers of the front axle and the central sys-

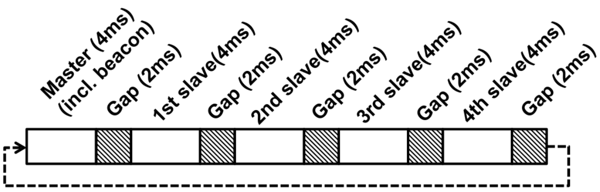


Figure 3: The used time division schedule for wireless data transmission.

tem are synchronized via a time-triggered Ethernet protocol (flexible time-triggered Ethernet, FTTE), the controllers of the central system and the rear axle are not, as the synchronization data is not forwarded via the wireless link. The wireless system itself is running a beacon-based communication schedule to guarantee collision-free communication. The schedule was designed to serve a maximum of five nodes. The master node sends a beacon every 30ms and the slave nodes respond after reception of the beacon and an individual delay, see Fig. 3. The transmission time of one packet is 4ms and after a silence phase of 2ms for the processing of the incoming data, the next node will send its data. Each packet has a size of 125bytes with 100bytes available for payload and is transmitted with 250kbit/s over the wireless media. In case of a corrupted transmission, the packet is lost and not re-transmitted.

Fig. 4 shows the latency caused by other components of the system in the complete chain from the sidestick to the actuator. The communication between the hardware units is realized via buffers. Incoming data is stored in a buffer until a periodic task processes this data and writes the outgoing data into an output buffer. The data stays in the output buffer until a sending task picks it up and sends it via wire or wireless. The period of tasks processing incoming data is labeled "d_in" in Fig. 4 while the period of tasks transmitting the output buffers are labeled "d_out". A value of 0 indicates that the data is processed event-based. The latency of the controllers of the actuators is unknown, thus no values are given. Note that this representation is not sufficient to calculate a tight end-to-end delay as the interaction of different tasks within one controller are not considered. First tests with this setup showed that the behavior of the system is equal to the wired case which means that effects caused by the increased latency were not noticeable during the operation of the eCar.

In the near future this setup will be extended to also allow a wireless transmission to the front axle and the battery system making the Ethernet based part obsolete. Also, we want to reduce the delay within the whole system to make it react faster to the driver's inputs. As the slave nodes only react on the beaconing signal, a loss of the master node causes the complete wireless network to stop. Therefore, we want to extend our protocol to support redundancy via multiple transceivers and to be able to detect the absence of a beacon. In addition, we are developing a formal model for our setup, trying to provide a theoretical bound for the worst case end-to-end latency.

4. SAFETY

The wireless transmission inside a vehicle is subject to electromagnetic interference. This can be caused by other

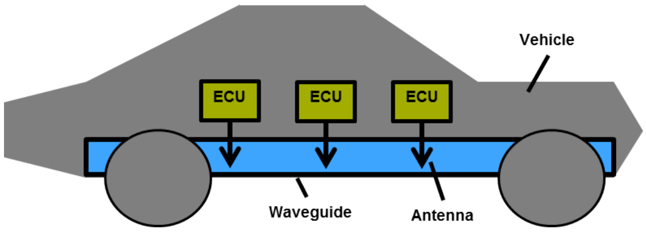
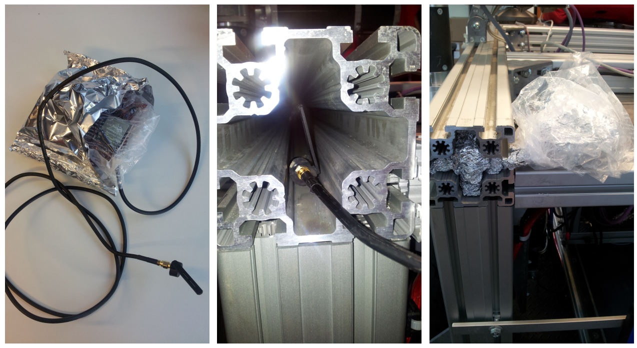


Figure 5: Utilizing compartments of the vehicle as waveguides.



(a) Antenna extension (b) Waveguide (c) Final setup

Figure 6: Using the beam of the eCar as a waveguide. As there is an on-board antenna, a simplified insulation pack is built to shield signals from the on-board antenna.

devices inside the vehicle, devices outside the vehicle or even by an external attack . The effect can reach from the degradation of the communication performance up to a complete loss of the communication ability. To increase the reliability of the system, we propose to use the internal compartments of the vehicle as a waveguide. This will hinder external signals to interfere with the wireless intra-vehicle communication. This concept is shown in Fig. 5. A waveguide and the antennas in it form a closed system, i.e., during normal operation, no electromagnetic signals can enter nor exit the waveguide. Additional nodes can easily be integrated into the system by installing an antenna in the waveguide. For our first experiments, we used the beams of the eCar as waveguides for the ZigBee communication, see Fig. 6.

The experimental scenarios are shown in Tab. 1. We recorded the data acceptance rate between two ZigBee modules under different combinations of: jammer on/off, antenna in/out of the beam, and end of the beam covered/open. During each experiment 1000 messages were transmitted. The ratio between transmitted and received messages defines the acceptance rate. Each experiment was repeated six times. The length of the beam is 204cm, width and height is 9cm. The material is eloxed aluminum with a minimum thickness of 3mm at each point. The impacts of the distance and allocation of the jammer to the signal source are measured as well. In Fig. 7, `j-c-2` represents that the jammer is two meters away from the signal source with the end of the beam covered with insulation materials (`u` represents an open end of the beam). `j-c-10-a` represents a 10cm distance between the jammer and the signal source. The postfix `-a`

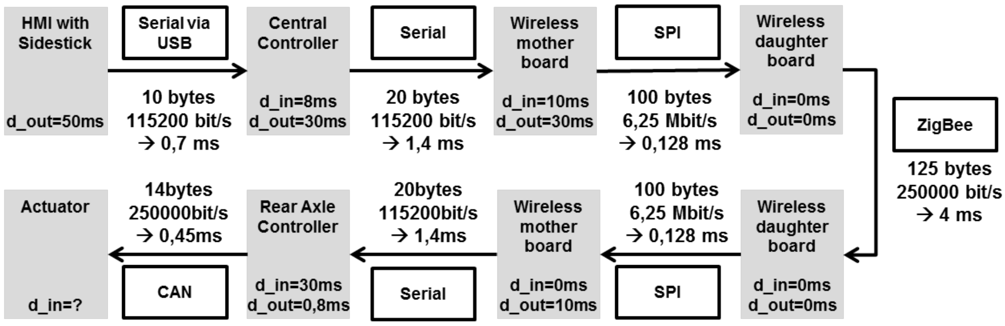


Figure 4: Timings for the transmission of commands from the sidestick to the eCorner. d_in and d_out refer to the periodicity of the tasks processing the incoming and outgoing buffers, respectively.

and -b indicates different allocations between the jammer and source. As a jammer, we used another ZigBee node that sends random data continuously on the same channel.

Table 1: Experiment scenarios and results. The numbers indicate the acceptance rate. One antenna was always left inside the beam with an insulated beam end. The position of the other one was changed according to the table.

configuration	beam end	jammer off	jammer on
both antennas inside beam	covered	100%	see Fig. 7
	open	100%	see Fig. 7
one antenna outside beam	covered	0%	0%
	open	100%	N/A

From Tab. 1, it can be seen that the beam can be used as an insulation media to protect the wireless signal from external interference for the scenario, where the open end of the beam is covered while the antenna of one device is outside the beam. The acceptance rate for this scenario is 0%, i.e., no message was received.

The results in Fig. 7 show that the jammer will affect the data acceptance rate in general. With the covering of the beam, the acceptance rate improved, which can be seen in the cases `j-c-2`, `j-c-10-a`, and `j-c-10-b`. However, the data acceptance rate did not recover to 100% for all cases with a closed-end beam. The reason is the onboard antenna on the wireless module which cannot be put into the beam nor were we able to properly shield it. Another phenomenon is that the relative position between the jammer and signal source affects the acceptance rate as well, which is subject of further investigation.

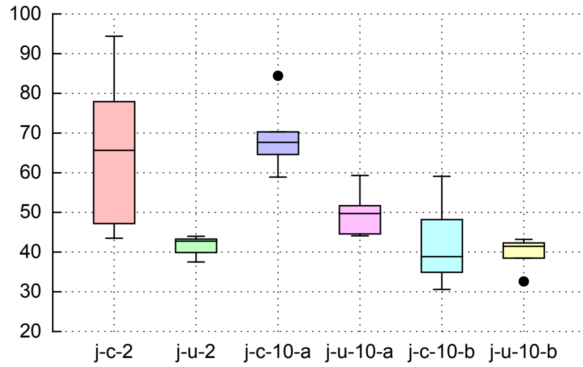


Figure 7: Detailed results for the acceptance rates in different scenarios. j=jammer active; c=end of beam covered; u=end of beam uncovered; 2=distance of 2m; 10=distance of 10cm; a,b=different positions of wireless nodes; the results are given as percentages.

5. CONCLUSION

We have shown a proof-of-concept with our experiments, that drive-by-wireless is feasible to control the eCar demonstrator. We addressed two of the main challenges towards a reliable drive-by-wireless concept: Latency issues by using a time-division protocol for the wireless communication and safety issues by utilizing the beams of our demonstrator as waveguides. The results suggest that the latency is low enough to control the eCar and the concept of waveguides greatly improves the packet acceptance rates between the communication participants in the case of external interference. In future work, we will investigate in the improvement of the shielding, a lowering of the latency to increase responsiveness and a comparison of suitable protocols for the in-vehicle use of wireless data transmission.

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