Performance Evaluation of Large-Scale Charge Point Networks for Electric Mobility Services

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***Abstract*—Today's public charge points for Electric Vehicles (EV) are equipped with numerous ICT components for communication with vehicle and back-end systems for authentication, billing and invoicing. The rollout of EVs will inevitably lead to a higher demand for charging infrastructure and will increase the operational and management costs for operators. In order to minimize costs, this paper evaluates applicable local networking technologies for large scale charge point scenarios and takes into account IEEE 802.11g, IEEE 802.3 and Homeplug GreenPHY, which is currently discussed in the ISO/IEC Joint Working Group for defining the Vehicle 2 Grid Communication Interface where TU Dortmund is an active member. A Web-Service based Charging Process Protocol for data exchange between all involved entities is presented to determine the data rates for XML and EXI encoded packet transmission. The V2G communication between EV and charge point is analyzed as well as the goodput for back-end communication. For this, hubs including data concentration are proposed to minimize billing data amount for the clearing center. For examination of the possible charge point network size, an overview of current predictions for EVs is given and the proposed system is evaluated within a parking area at TU Dortmund, where we expect the installation of 61 charge points by 2030. With optimization of the presented load coordination service, the data rate in the charge point network could be reduced by 99.8 %.**

***Index Terms*—Electric Mobility; Charge Point Networks; Powerline Communications (PLC); IEEE 802.11g**

I. Introduction

The market penetration of electric vehicles will raise to approximately 1 million in 2020 and 2 million in 2030 in Germany [1]. Based on this prediction that is aimed by the German government for the next years, a charging at work application scenario is examined in this paper. This scenario is described in detail in Section II. To include important services like *load coordination* to prevent local substation blackouts and the possibiliy to feed back energy into the smart grid communication between EV and Electric Vehicle Supply Equipment (EVSE) is inevitable. For coordinated charging processes in parking areas a network beetween EVSEs and a Load Coordinator (LC) needs to be considered. The connection needs to be cost-effective, integrable in existing infrastructures and reliable. Hence, we propose the IEEE 802.11 standard due to high market penetration. If new parking areas are planed IEEE 802.3 is an alternative due to low costs and high data rates, which is sufficient for the next years regarding possible value added services. Section III introduces prEVail, a simulation environment for evaluation of the ICT for EV connectivity. The charging process communication protocol is presented and packet sizes for an XML based communication and an EXI encoded message exchange are determined using the MORE middleware [10]. With these measured packet sizes, Section III-A analyses the V2G communication based on the charging process protocol regarding the Powerline Communications standard Homeplug GreenPHY. After this the inter charge point communication is analyzed including back-end communication with data concentration for an effective transfer of clearing data. Afterwards a worst-case scenario including a fair load coordination is introduced, and the realization of the charging at work scenario can be verified regarding the predictions in Section I and Section II.

II. Charging at Work Scenario

The central scenario for charging an electric vehicle will be charging at home. 90 % of the people in Germany drive less than 50 km per day. These distances can be covered by most of todays EVs with a night charge. Hence, charging at public charge points is not inevitable. For commuters with a long travel to work, charging at work is the second major charging scenario. This scenario is discussed in the following chapters. The Federal Motor Transport Authority (KBA) of Germany published a study for January 2011 [3] where Germany currently has 42,3 million registered private vehicles. In [4], a slow increase of prices for transportation and hence a slow behaviour modification of the population is predicted, which results in an increasing number of vehicles in Germany.

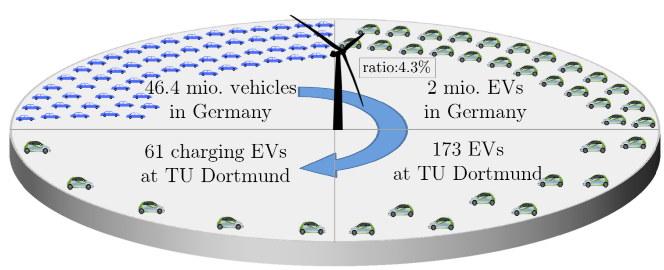

Fig. 1. Estimated number EVs at TU Dortmund in 2030

Therefore, 46.4 million vehicles are assumed on german streets in the year 2030, which include 2 million EVs (ratio

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of 4.13%). Figure 1 shows the calculation for EVs at TU Dortmund depending on the predictions before. With 4000 available parking spaces and an EV percentage of 4.13% a maximum of 173 EVs are available at TU Dortmund. Although the range of today's EVs is sufficient for 90 % of the german inhabitans, in future it will be important to plug in the EV to provide an operating reserve. In peak times pluged in EVs can help to stabilize the grid because renewable energy sources like wind parks and solar collectors are not reliable energy sources at all times. Indeed, not all of the cars need to be recharged at work and also not everybody wants to provide an operating reserve because of the anxiety that the battery gets damaged. Hence, we assume that in the year 2030 35% of the 173 EVs need the opportunity to plug in considering enhancements in the battery technology and EV owners who want to provide an operating reserve. Hence, we propose the installation of 61 charge points at TU Dortmund until 2030.

III. ICT Simulation environment prEVail

prEVail is an ICT validation environment for different communication technologies and is based on the simulation environment presented in [2] using OMNeT++ 4.0 [5] and the INET Framework [6]. For electric vehicle charging processes, the four main entities EV, EVSE, Emobility Hub (EMHub) and the optional LC are integrated (see Figure 2).

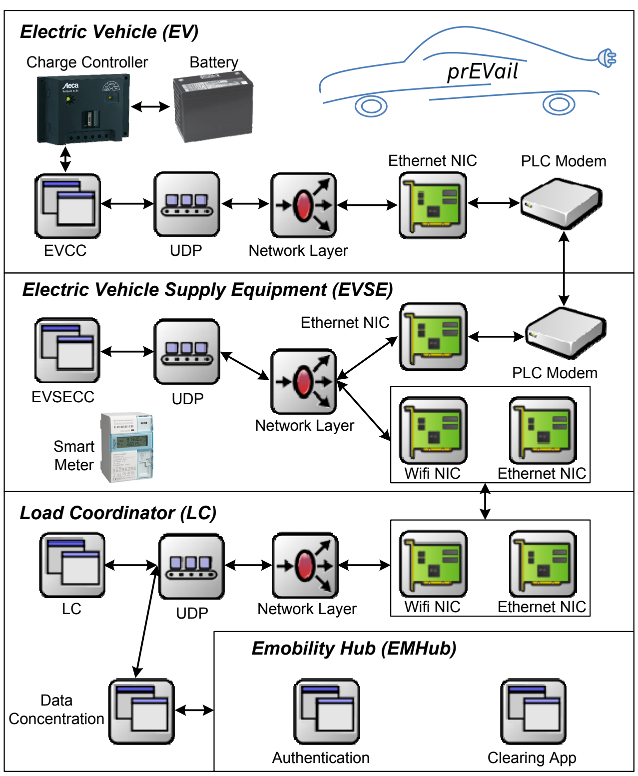

Fig. 2. prEVail, simulation environment for electric vehicle charging infrastrucutres

The modules UDP, network layer, ethernet nic and wifi nic are integrated within the INET framework and all other modules have been implemented by the authors. The *Electric Vehicle* (EV) consists of a full adjustable battery model, which is configured to act as a lithium ion battery, a charge controller and the Electric Vehicle Communication Controller (EVCC), the central communication module of the EV. It mediates between the internal modules of the EV and the charging infrastructure. The other modules of the EV (battery and charger) are implemented as traffic generators for the communication processes. Current EVs typically use high performance lithium ion batteries with charging characteristics shown in Figure 3. Before a deep discharge threshold is reached, the battery will be charged with a minimal current (a preconditioning charge). From this point the battery can be charged with a constant current until it reaches its maximum cell voltage. In the third stage the battery will be charged with a constant voltage leading to a decreasing charge current. The gradients of the voltage graphs in stage 1 and 2 are constant, although a saturation curve will be expected. In stage 3 the charging current is modeled as discrete saturation curve. These assumptions are made because it has no major effect on the characteristics of the modules with respect to traffic generation.

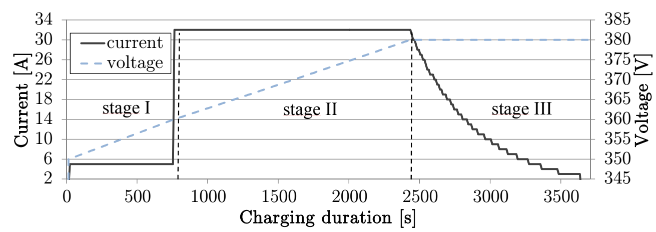

Fig. 3. Simulated charging characteristics of a lithium ion battery

The EVSE and the EV are connected via Powerline Communications (PLC). Due to current discussions in the ISO/IEC Joint Working Group for defining the V2G Communication Interface [8] Homeplug GreenPHY [7] was choosen for evaluation with prEVail. Results are shown in Section III-A. The Electric Vehicle Supply Equipment Communication Controller (EVSECC) is modeled as a gateway and only forwards messages from EV to LC and back. The smart meter generates meter readings for the charging process regarding parameters of the EV's battery, which will be needed for the clearing. The clearing data are send to the *Emobility Hub* (EMHub), which is responsible for authentication and clearing.

The *Load Coordinator* (LC) is parametrized by only one parameter, the total capacity, which is available for the whole parking area. This capacity is fairly assigned to all charging vehicles. To arrange multiple EVSEs in a local network, the EVSEs and the LC can be connected with different communication technologies. In this work Ethernet (IEEE 802.3) and Wifi (IEEE 802.11g) will be evaluated. For higher layer communication a web-service based protocol is discussed including XML and the Efficient XML Interchange (EXI) encoding format [9]. The charging process protocol including authentication, start of the ChargingPprocess (CP), clearing and optional capacity updates for the load coordination is presented in Figure 4.

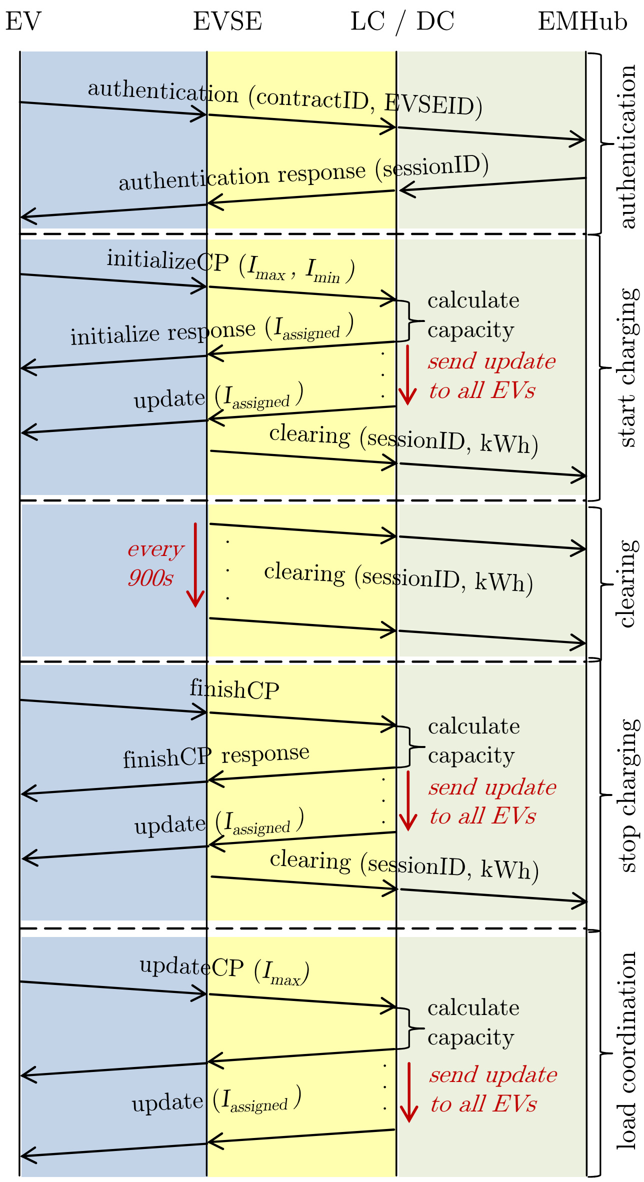

Fig. 4. Charging Process Protocol

For authentication the EV sends an *authentication* message with a contractID and the EVSEID via the LC with integrated Data Concentrator (DC) to the EMHub. The EMHub replies with an *authentication response* containing a sessionID for the new charging process, which is needed for the clearing later on. After successful authentication the EV initializes the CP by sending an *initializeCP* message containing I_{max} and I_{min}. With these information, the LC calculates new capacity assignements and sends updates to all charging EVs. After receiving the assigned capacity from the LC the EVSE sends a first clearing message including the initial meter reading to the EMHub. Afterwards the clearing will be done by the EVSE every 900s (15 min.) using the sessionID from the authentication process and the meter reading. When CP is finished the EV notifies the LC, which calculates new capacities for the other charging EVs and the EVSE initiates the last clearing message. The same recalculation of capacities is done during the load coordination. Every time the EV does not need the whole assigned capacity anymore it sends *updateCP* messages with the currently used power to the LC, in order to deallocate the excess power for use in other charging processes. Subsequently the LC recalculates the power allocation and replies with an *update* to all other active EVs.

For an estimation of packet sizes for authentication and clearing on the one hand and load coordination on the other hand, a web-service was developed using the MORE Middleware [10]. Table I shows the measured packet sizes for messages within the charge point network.

Type / Name	XML [byte]	EXI [byte]
Clearing Message		
authentication (P_{auth})	865	475
authentication response ($P_{authRes}$)	898	493
clearing ($P_{clearing}$)	960	550
Load Coordination		
initialize CP (P_{init})	883	477
initalize response / update ($P_{initRep}$)	829	448
update CP (P_{update})	867	461
finish CP (P_{full})	875	471

TABLE I
PACKET SIZES FOR AUTHENTICATION, BILLING AND LOAD COORDINATION MESSAGES IN THE CHARGE POINT NETWORK

These packet sizes provide a basis for further analyses.

A. Vehicle 2 Grid Communication

In this section, the V2G communication between EV and EVSE is analyzed based on the charging process protocol presented before. Due to the fact that EV and EVSE are generally connected with the charging cable (except inductive charge), this communication medium can be used with a PLC communication technology.

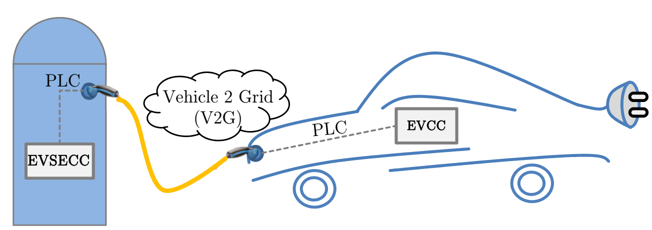

Fig. 5. Vehicle to Grid Communication Overview

Homeplug GreenPhy standard [7] is currently discussed in [8]. The advantage is the compatibility with Homplug AV and the reduction of cost and power consumption to 25% of Homeplug AV. Hence, the complexity is decreased, and e.g., TDMA mode was removed and the dynamic channel adaption was limited. The result is that only one subcarrier modulation format is supported (QPSK) as well as only one Turbo Code with rate 1/2 for Forward Error Correction and a limited PHY rate of 10 Mbps maximum. The number of 1155 subcarriers

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and subcarrier spacing of 24.414 kHz is unmodified to support the compatibility to Homeplug AV and hence the compatibility with in-house PLC networks. For further analyses the *MINI-ROBO_AV* mode with a PHY Rate of 3.7716 Mbps and a Physical Block (PB) size of 136 bytes and the *STD-ROBO_AV* with PB size of 520 Byte and a PHY Rate of 4.9226 Mbps are evaluated. An overview of the GreenPHY PB format is given in Figure 6.

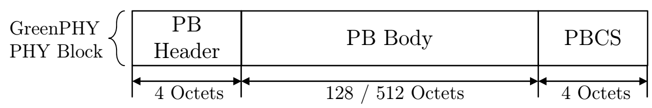

Fig. 6. Homeplug GreenPhy Physical Block format [7]

Each PB consists of a 4 octets *PB Header* containing e.g., a Segment Sequence Number (SSN). Depending on the PB size, data have to be padded to either 512 or 128 octets to fit exactly into the *PB Body*. The PHY Block Check Sequence (PBCS) contains a 32-bit CRC and is computed over the PB Header and the encrypted PB Body.

Based on this standard, the V2G communication is analyzed. Figure 7 depicts the occurence of messages during a whole fast charging process without getting influenced by the LC due to other charging vehicles and recalculation of the capacity assignment. The measurement was made with EXI encoding right before the encapsulation into the PB Body to see, if the messages fit into one PB Body. It can be determined that all sent messages and the *authentication response* do not fit into the PB520 Body of 512 octets (see dottet line in Figure 7). Hence, the messages are fragmented into 2 PBs with size of 520 octets each due to the needed padding.

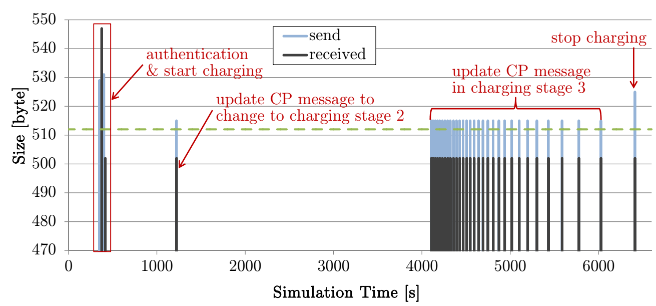

Fig. 7. Message occurence of charging process protocol in V2G communication using EXI encoding in a fast charging scenario

The CP begins at approximately 400s simulation time with the authentication and the response. After that, the charging process is initialized by the *initializeCP* message and the corresponding response. The next *updateCP* message at 1200s is the change over to charging stage 2 of the battery where the EV requests more capacity from LC. The third charging stage starts after approximately 4100s. In this stage the EV deallocates the excess capacity $\mathrm{N}_{\mathrm{CPupdates}}$ times.

$$\mathrm{N}_{\mathrm{CPupdates}} = (I_{\max} - I_{\min} + 2) \tag{1}$$

With $I_{\max} = 32$ and $I_{\min} = 3$, 31 CP updates are initiated by the EV before the CP finishes with a *finishCP* and corresponding response message. Figure 8 shows the XML and EXI data rate for HP GreenPHY PB sizes of 136 and 520 octets as a function of simulation time.

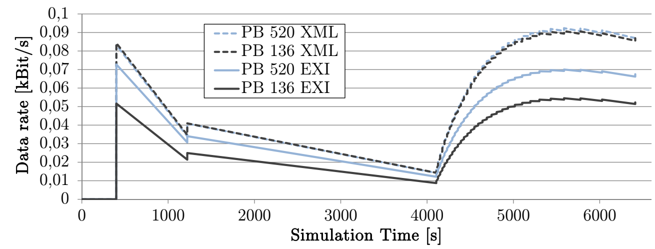

Fig. 8. Average data rate for V2G communication with XML and EXI encoded XML as a function of simulation time

It can be seen that the average data rate correlates with the message occurence in Figure 7. Because of the padding, in EXI transmision 2 PBs need to be transmitted and the data rate for PB520 is much higher, although PB136 has more fragments. With ongoing time when the CP goes over to stage 3, PB136 data rate is still a bit lower and PB520 data rate increases until the end of the CP. The last result is also the average data rate for a full CP. Using PB136 for the presented charging process protocol will save 23% of the needed data rate when using EXI encoding.

As stated in Table I, all XML messages including protocol overhead fit into 2 PB520 Bodys and the utilization of the PB Body gets more effective in comparison to EXI and the data rates for both modes are more or less equal. Nevertheless the data rate can be reduced from 87 Bit/s to only 51 Bit/s by using EXI and PB136 mode. This corresponds to an enhancement of 41 %.

B. Inter Charge Point Communication

For communication with EV and back-end, today's charge points are equipped with numerous ICT components, which increases the prices for the infrastructure. Especially the contracts for mobile radio for the back-end communication are very expensive and can be saved when organizing multiple EVSEs into a local network. Figure 9 gives an example for connecting EVSEs in a network using IPv4. This network includes one EVSE acting as a data hub for back-end communication, which concentrates the clearing data in one message and transfers it to the EMHub. Hence, protocol overhead can be reduced. In future work IPv6 will be integrated into prEVail to support analyses of larger networks.

$$d_{CSN/BE} = x \cdot \left[P_{auth} + P_{authRes} + \left(2 + \left\lfloor \frac{t}{900s} \right\rfloor \right) \cdot P_{clearing} \right] \cdot \frac{8}{t} \tag{2}$$

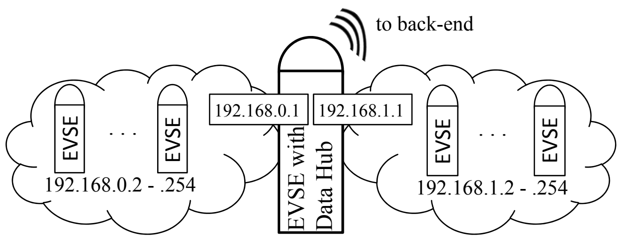

Fig. 9. Design of large-scale charge point networks using multiple IPv4 subnetworks

Considering the packet sizes of Table I, the goodput in the charge point network without load coordination $d_{CSN/BE}$ can be calculated with (2) for x charging process. In this context the goodput is defined as the data rate within the presentation layer. Thus protocol overhead is excluded. The goodput includes the authentication P_{auth} and the corresponding authentication response $P_{authRes}$, the clearing messages at the beginning and at the end of the charging process and periodic clearing messages every 15 minutes. For a charging process with $t = 3h$ the needed data rate is 6.42 *Bit/s* for EXI communication. This goodput is also valid for the communication link to the back-end. In order to reduce the needed data rate for this link, the clearing messages can be concentrated at the data hub, so that only one message is periodicaly sent to the back-end including the clearing data of all ongoing charging processes.

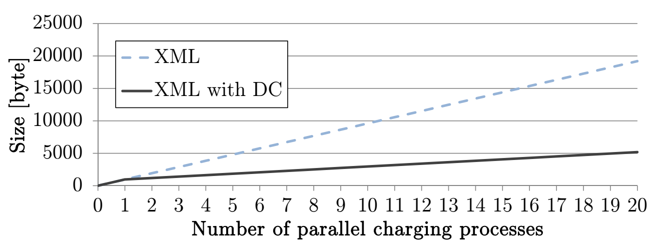

Fig. 10. Data Concentration (DC) with XML for back-end communication

A comparison between the concentrated messages using XML and XML with EXI encoding is shown in Figure 10 and Figure 11.

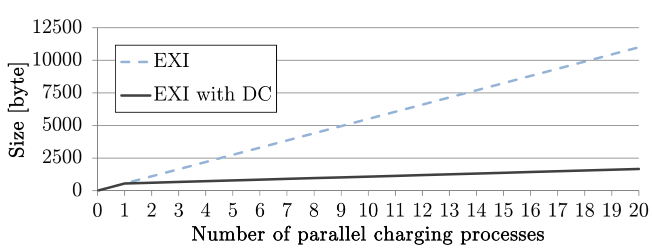

Fig. 11. Data Concentration (DC) with EXI encoded XML for back-end communication

When XML is used for sending clearing information to the back-end it can be seen that the data concentration is very effective and 73% of the transmitted data can be saved. If this XML stream is encoded with EXI the data can be reduced by a factor of one third. Because of the efficient encoding of information repeatedly used in the same message [9], only 8.6% of the clearing data need to be transfered to the EMHub in comparison to XML without data concentration. Formula (3) calculates the goodput for the concentrated back-end communication link d_{CBE} depending on the number of parallel charging processes and the *clearingSize* shown in Figure 10 for XML and in Figure 11 for EXI.

$$d_{CBE} = \left[(P_{auth} + P_{authRes}) \cdot x + \left(2 + \left\lfloor \frac{t}{900} \right\rfloor\right) \cdot clearingSize(x)\right] \cdot \frac{8}{t} \qquad (3)$$

An exemplary result for the back-end communication goodput is indicated in Figure 12 with 20 parallel charging processes for XML and EXI communication with and without data concentration.

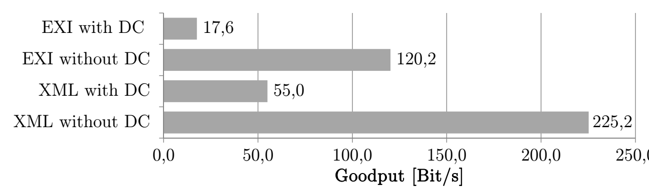

Fig. 12. Comparison of the goodput for data concentration mechanisms

If the clearing data of 20 charging processes are merged into only one message, the goodput for XML concentration can be reduced to 24% and for EXI Schema concentration to 14%. The concentration will be even more effective by increasing the parallel charging processes.
For estimation of a worst-case data rate for a charge point network, the LC is integrated into the parking area [2]. The LC coordinates all charging processes on the parking area to reduce the risk of local substation blackouts. The maximum power for the parking area can be defined depending on the scenario and is allocated equitably to each charge point.

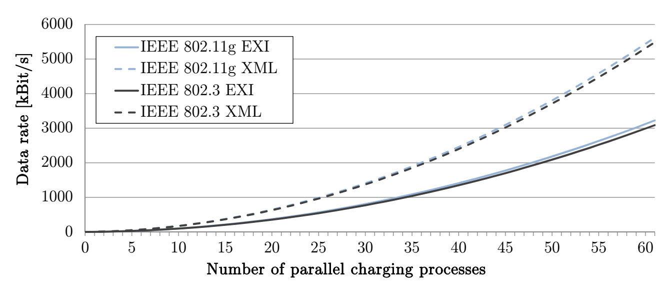

Fig. 13. Overview of the data rate for inter charge point communication using IEEE 802.3 and IEEE 802.11g with unoptimized LC

To analyze the data rate for communication between the EVSEs and the LC containing the data hub, a scenario for 61 expected EVs at TU Dortmund is created. To measure a

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worst case data rate, all EVs charge in the third stage to get a maximum of data traffic in the simulation. Figure 13 shows first results for an unoptimized load coordination message exchange where the *updateCP* messages in the third charging state were sent in periodic time intervals $t_{akt} = 5s$ instead of a fixed number shown in formula (1). This time interval guaranteed an optimal power allocation for all EVs.

IEEE 802.3 and 802.11g are analyzed regarding communication with pure XML and EXI encoded XML. The data rate of IEEE 802.11g is marginal higher for XML and for EXI communication than the one of IEEE 802.3 due to protocol overhead. Hence, a maximum data rate of 5.5 MBit/s for XML and 3.1 MBit/s for EXI encoded data traffic is needed. Figure 14 depicts the data rate for inter charge point communication after optimization of LC service without losing functionality.

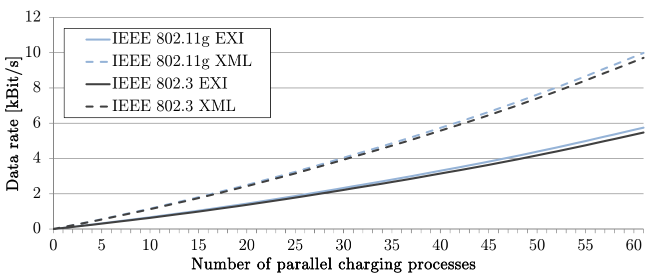

Fig. 14. Overview of the data rate for inter charge point communication using IEEE 802.3 and IEEE 802.11g with optimized LC

It can be seen that 99.8 % of inter charge point data traffic can be saved using the optimized load coordination. Only 5.7 kBit/s are needed for EXI encoding. Because of the low data rates, no packet errors occur in this scenario. In future work higher scale networks are analyzed e.g., for the year 2050 where we expect a maximum of 502 charge points regarding predictions of [11].

IV. Conclusion

This paper analyzed an application scenario for charging electric vehicles at work. At the beginning predictions of the German Government on the market penetration of EVs are presented. Based on these predictions a parking area at TU Dortmund was determined for installing a charge point network with a sufficient number of charge points supporting fast charging. For evaluating the ability of IEEE 802.11g, IEEE 802.3 and Homeplug GreenPhy for this scenario, the simulation environment prEVail based on OMNeT++ was presented. After that an optimized Charging Process Protocol was introduced, which supports communication between EV, EVSE, LC and EMHub. After that the V2G communication between EV and EVSE using Homeplug GreenPHY and the charging process protocol was analyzed and enhancements are presented for XML and EXI transmission. 41 % of data could be save using EXI and the small PB Size of 136 octets. For the communication link to the back-end a data concentration mechanism was presented showing an optimized data volume of factor 7 with 20 parallel charging processes. The data traffic within the charge point network was determined for authentication, billing and a worst case scenario enabling load coordination was introduced. With 61 charging EVs a data rate of only 5.7 kBit/s is needed for optimized load coordination and clearing, where the data traffic can be reduced by 99.8 %. Hence, no packet errors could be detected in this large scale application scenario for the year 2030.

In future work wide area communication technologies can be integrated into the simulation environment in order to calculate the data rates for the back-end communication depending on the physical layer. Also an integration of IPv6 is useful for higher scale charge point networks to simulate charging infrastructures for the year 2050. Furthermore the optimal position of a data-hub at the parking area at TU Dortmund will be determined using a raytracing environment for an estimation of the radiowave propagation of mobile communication networks. An analysis of a charging at home scenario would also lead to interesting results.

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