Reliability Estimation of a Smart Metering Architecture using a Monte Carlo Simulation

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Abstract: The trend of connectivity dominates the technological progress. The number of networked devices is constantly increasing and the use of smart meters has become more societally relevant. For that reason, reliability is an important attribute of related architectures. To calculate reliability, it is required to do a specific analysis for the entire system. This paper describes a structured approach for calculating the reliability of smart meter architectures considering the limited data availability. For this, we combine Reliability Block Diagrams with a Monte Carlo simulation. The result is a realistic approximation of the system reliability, that can be used to evaluate optimization methods.

1 INTRODUCTION

The Internet of Things is the dominating megatrend in current social change (Kaufmann, 2021). The number of networked devices and the resulting volume of data is constantly increasing worldwide. Until 2025 there will be 75 billion networked devices worldwide (Statista, 2018) with a data volume of approximately 80 zettabytes (O'Dea, 2021). The Internet of Things has become a key technology for future-oriented scenarios. Driven by Murphy's Law – "*Anything that can go wrong will go wrong*", the reliability of computer systems is becoming even more important. The digitalization of civil infrastructure facilities in particular is becoming especially relevant to society (BSI, 2020). The services that are provided like the supply of water or electricity are increasingly dependent on available and operating information technology. Smart meters can record actual consumption data and forward it to the higher-level systems so that the resulting transparency can increase grid stability. A fault, an impairment, or even a complete breakdown can have a major impact on public safety or other dramatic consequences (BSI, 2020). The dependency of modern society on complex information systems, especially in the above-mentioned infrastructures, is growing steadily (BSI, 2021). The most significant part of this is accounted to smart meters. These are being implemented around the world, inter alia, to improve the efficiency of power grids for emissions control (Mordor Intelligence, 2020). The current trend of electromobility and the resulting increase in electricity consumption emphasize how important the digitalization of the energy transition is for society. Until 2023 the penetration rate of electrical smart meters in the European Union (EU) is expected to grow from 44% to 71% (Kochanski, Korczak,& Skoczkowski, 2020). In order to push that forward, the German Federal Ministry for Economics and Energy (BMWi) has published a roadmap for the ongoing digitalization of the energy transformation in Germany (BMWi, 2020). This includes a step-by-step rollout of smart metering systems for electricity, water, and gas.

The proposed smart metering architecture in Figure 1 shall being used as a standard for Europe, which is based on a set of technical and data protection requirements that are specified in various official documents (BSI, 2013; BSI, 2014; BSI, 2015; BSI 2016) of the German Federal Office for Information Security. The central concept in these specifications provides a separate unit called the

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smart meter gateway (SMGW) as a central communication medium. It provides the interfaces between the multiple domains and the smart metering system. Figure 1 shows the schematic architecture. Until 2032 all consumers in Germany should be equipped with these modern measuring devices (BMJV, 2016). The objective of digital data collection is a more efficient and transparent energy distribution as well as the sustainable control of energy production and the overall network utilization (EY, 2013; Huang, Grahn, Wallnerström,& Jaakonantti, 2018).

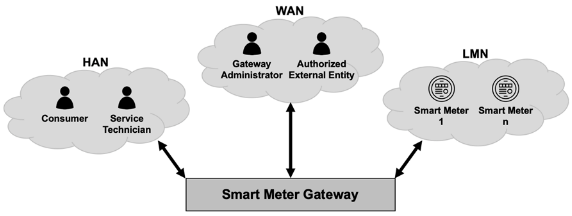

Figure 1: BSI Smart Metering Infrastructure (BSI, 2014).

Hence, the contribution at hand focuses on the reliability of smart metering architectures. The global number of smart meters is expected to be approximately 188 million in 2025 (Mordor Intelligence, 2020). In Germany, the number of smart meters is expected to increase to 53 million (BNetzA, 2021). To guarantee the required objectives of this ecosystem the reliability is a fundamental design goal (Müller, 2011). Basically, smart metering systems are more failure-prone than traditional metering devices, because of the more complex interaction between hardware and software components (EY, 2013). To obtain a validated value for the failure probability of SMGWs and smart meters we screened 5 publicly available databases and contacted 10 companies. These 5 companies submitted a response and 2 companies were interviewed on a detailed level. The investigations and interviews revealed that there are currently no validated data for the probability of failure or error. There is currently a lack of general data from the practice and field level, which can be explained by the delayed rollout (OVG NRW, 2020).

For the reason that analytical approaches of general reliability issues at component or system level were not available the approximative reliability methods respective Monte Carlo simulation (MCS) techniques became very popular (Wang, Broccardo,& Song, 2019). Compared to other reliability Methods MCS have the advantage of being accurate and easy to implement. This means that MCS is applicable for the reliability analysis of a smart metering architecture. It also enables the evaluation of the proposed reliability optimization by using different methods identified in a literature review (Altenburg, Bosse,& Turowski, 2020). Based on the previous argumentation we would like to answer the following research question: *"How could a valid reliability analysis on smart metering architectures with limited data be facilitated by using the Monte Carlo simulation?"*

To answer the aforementioned research question, in Section 2 the theoretical basis for reliability theory and analysis is presented. Then, in Section 3, the approach for the proposed reliability analysis is described. The process of reliability simulation and the presentation of the results are shown in Section 4. Concluding remarks are given in Section 5 that summarizes and illustrates the next steps to be taken.

2 FOUNDATIONS

This chapter presents the theoretical basis for the reliability analysis of a smart metering architecture that will be performed. The present paper use the Design Science Research (DSR). A key feature of DSR is solving social and real-world problems by constructing and evaluating a scientific artefact (vom Brocke, Hevner,& Maedche, 2020). Artefacts can be classified as concepts, models, methods, or realizations that contribute to a scientifically useful outcome. According to Pfeffers (2008), the design science process consists of 6 essential steps, namely *problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation and communication.* This paper describes a practical problem, which can be solved by a predefined reliability analysis based on RBD and MCS. This approach will be described and executed in the following chapters and the result will be interpreted as well.

2.1 Basics of Reliability

The research field of reliability was formed by Jean-Claude Laprié. He established a standard framework and general terminology for reliable and fault-tolerant systems (Laprié, 1995). According to Bertsche (2008) and Laprié (1995), Reliability R(t) is defined as "*the probability that a system will perform its functions satisfactorily and without failures under specified functional and environmental conditions over a specified period of time*".

According to a recently conducted literature review conducted by Altenburg et al. (2020), the design phase offers the highest potential for reliability optimization. In order to demonstrate that these identified methods (Altenburg et al., 2020) will increase the reliability R(t) of a smart metering architecture it is necessary to do a validated reliability analysis. Reliability analysis is a methodical approach to be able to determine the reliability of a system and the number of failures. The approach to calculating the system reliability starts with the design of the model and ends with the statistical calculation of the overall reliability (Yuan, Tang, Wang,& Li, 2019). In the literature, there are several techniques for quantitative and qualitative analysis of reliability (Niknafs, Faridkhah,& Kazemi, 2018). The basis for our approach is a combination of quantitative methods, because we have limited data as described aforementioned.

In quantitative methods the Reliability Block Diagram (RBD) (Bobalo, Seniv, Yakovyna,& Symets, 2019), the Network Diagram (Ridzuan, Rusli,& Saad, 2020), Markov Modeling (Aggarwal, Kumar,& Singh, 2015) and MCS (Wang et al., 2019) are the most important methods for reliability analysis. To perform the most exact calculation of reliability it is also possible to combine these techniques (Niknafs et al., 2018; Li& Zhang, 2011).

2.2 Reliability Block Diagram and Monte Carlo Simulation

Our selected evaluation approach, which is detailed in Section 3, uses RBD to model the overall system and an MCS to calculate the reliability per component. RBD is a schematic illustration of the main components in a system, which represents the hierarchy and mutual interaction to the overall function of a system (Niknafs et al., 2018; Raso, de Vasconcelos, Marques, Soares,& Mesquita, 2017). After that, we use MCS as a simulation technique. The execution of an MCS is based on repeated random sampling and statistical analysis to estimate results for complex system functions (Harrison, 2010; Mason et al., 2008). This approximation can be used to generate realistic results, that we will use for the reliability analysis of the smart metering architecture.

3 AN APPROACH FOR RELIABILITY ANALYSIS

To be able to perform a reliability analysis for the architecture in Figure 1, it is transformed into a simplified model as shown in Figure 2. The Data Layer is the equivalent of the Local Metrological Network (LMN; cf. Figure 1), which includes all the meters in a home or household and can be connected or read out by the SMGW in the Gateway Layer (Henneke, Freudenmann, Wisniewski,& Jasperneite, 2017). We have grouped the Home Area Network (HAN; cf. Figure 1) and the Wide Area Network (WAN; cf. Figure 1) into the Application Layer because meter information can be read or configured remotely in both domains (Henneke et al., 2017).

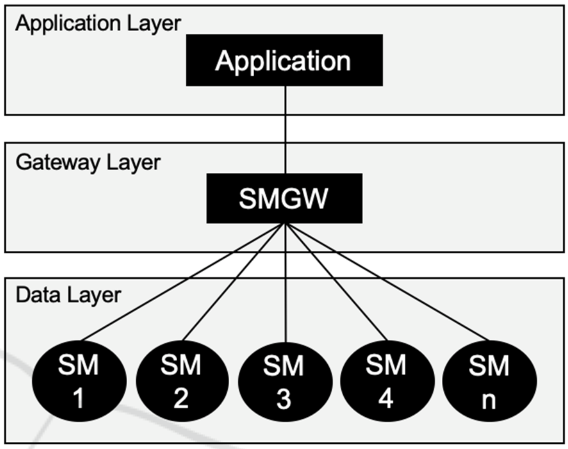

Figure 2: Simplified illustration of a smart metering architecture for reliability analysis.

Figure 2 shows the simplification of the overall system from Figure 1 into its basic components. We assume five smart meters in our reliability analysis, because in the future there will not only be smart metering for electricity there will be also smart metering for water or gas consumption. The next step is to convert the simplified model from Figure 2 into the logic of the RBD. Depending on the configuration the failure of any component can trigger the failure of the whole system, so that the required system functions are not fulfilled (Ahmeda, Hasana, Perveza,& Qadirb, 2016). An RBD design can include three basic component connections, which can be combined with each other - series connection, active redundancy or standby redundancy (Ahmeda et al., 2016). The following Figure 3 transformed into an RBD from the simplified architecture in Figure 2.

To be able to calculate the quantitative reliability of the overall system, the failure probabilities of each component are required. There are currently no validated data available for the failure probabilities and the characteristic lifetime of a smart meter or SMGW. For that reason, we use the failure probabilities per component and an MCS to simulate the different values.

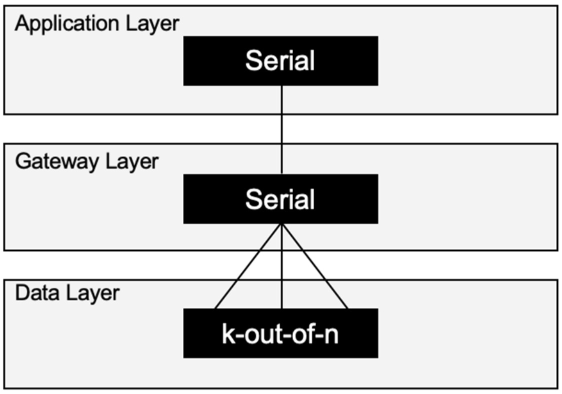

Figure 3: Simulation model based on RBD.

In addition to the architecture, the *Time t* is an important factor in the reliability domain, because it is directly related to the *Reliability R(t)* (Laprié, 1995). In many practical use cases the reliability level of an intact component depends mainly on the age that the component has already reached. The so-called bathtub curve shown in Figure 4 describes the generic time course of the *Failure Rate λ(t)* (Bonart& Bär, 2020). In the literature, the bathtub curve is divided into three phases - infant mortality, useful lifetime and wear out (Bonart& Baer, 2020; Alvarez-Alvarado& Jayaweera, 2018). Most studies focus on the useful life period (Li, 2014; Kim, Singh,& Sprintson, 2015; Li, 2013). In our evaluation, we also focus on the mid-period of the bathtub curve. In this phase, the *Failure Rate λ(t)* is constant, which means that the focus is on random failures. Furthermore, this is usually also the longest time phase in the overall lifetime of a system.

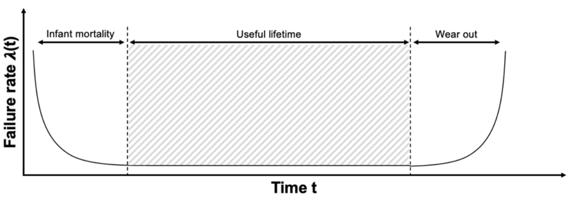

Figure 4: Bathtub curve (Neubeck, 2004).

4 EVALUATION

This section presents our incremental approach to reliability analysis of a smart metering architecture. Reliability distributions of systems must be modeled with suitable mathematical functions to capture the real world. The bathtub curve can be approximately described as a sum of Weibull distributions. The Weibull distribution is one of the most commonly used reliability techniques because of its versatility. Its distribution can be used to describe decreasing, constant and increasing *Failure Rates λ(t)* in technical systems. With this, it is possible to model different failure types and so all phases from the bathtub curve (Lienig& Brümmer, 2017). Depending on the life phase of a component, the Weibull distribution can be an exponential distribution or a logarithmic normal distribution (Härtler, 2016).

As described in Section 3, the focus of our reliability analysis is on the useful life phase where *Failure Rates λ(t)* are constant. For this case, the reliability distribution equals an exponential distribution. The exponential distribution is commonly used in the development of electronic systems, because it is sufficiently accurate for reliability calculations (Lienig& Brümmer, 2017). This is the foundation for the following Formulas for reliability calculations (Gelman, Martin, Malcolm,& Liew, 2021; Ram& Davim, 2018; Dey, Bhale,& Nandi, 2020):

$$\text{Reliability } \mathrm{R}(\mathrm{t}) = \mathrm{e}^{-\lambda \mathrm{t}} \quad (1)$$

4.1 Smart Meter and Smart Meter Gateway

For an overall reliability analysis, it is necessary to split the system into independent components. Because of the high technical similarities between smart meters and SMGW (EY, 2013; Gährs, Weiß, Bluhm, Dunkelberg,& Katner, 2021) it is possible to run a common reliability analysis of the components. The higher system complexity of smart meter architectures implicates a higher *Failure Probability G(t)* of the system. The typical average for this value can be set as 2% (EY, 2013; Zhou, Zonghuan,& Zhonghua, 2021). It serves as the basic for calculating the *Failure Rate λ(t)* and the *Lifetime t*:

$$\begin{aligned} &Failure\ Rate\ \lambda(\mathrm{t}) = \frac{1}{T} \\ &Lifetime\ t = T \times G(t) \end{aligned} \quad (2)$$

Afterward, the e-function can be used, which is an exponential function with Euler's constant (Humenberger& Schuppar, 2019) as basis to calculate the *Reliability R(t)* for the two components by Formula (1):

$$\text{Reliability } R(t) \approx \mathbf{98{,}02}\% \quad (3)$$

For a more realistic approximation of the reliability, we use the principle of MCS. The objective is to repeat the calculation of the *Reliability R(t)* many times and to approximate a realistic result using the law of Large Numbers (Hartbecke& Schütte, 2005). For this we use the following function (Ji, 2014):

$$Lifetime\ t\ (x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)}{2\sigma^2}} \quad (4)$$

$$x \in [0,1];\ \mu = 2081{,}52\ h;\ \sigma = 5256\ h$$

This function returns the percentile for a given mean and the standard deviation. The parameters for the reliability calculation are described below:

- The parameter x indicates the probability in the normal distribution and is created by a random number between 0 and 1.
- The parameter μ indicates the arithmetic mean of the distribution and is the *Lifetime* t_{MC} of our calculated *Reliability R(t)* in Formula 3.

It is calculated as follows:

$$Lifetime\ t_{MC} = 12\ a\ x\ 1{,}98\%$$
$$Lifetime\ t_{MC} \approx 2081{,}51\ h \quad (5)$$

The parameter σ indicates the standard deviation of the distribution, which is empirically defined as 5% (Zhou et al., 2021) and calculated into the corresponding *Lifetime* t_σ.

$$Lifetime\ t_\sigma = 12\ a\ x\ 5\%$$
$$Lifetime\ t_\sigma = 5256\ h \quad (6)$$

The next step is to run Formula 4 for 80.769 random samples each to simulate the *Lifetime* $t(x,\mu,\sigma)$. According to the law of Large Numbers (Hartbecke& Schütte, 2005) and the paper by Liu (2017), we assume that 80.769 random samples are an optimal number of trials for the purposed MCS. Each simulated *Lifetime* $t(x,\mu,\sigma)$ is now inserted into Formula 1, so that we obtain the reliability R_{SM} and R_{SMGW} for 80.769 smart meters and SMGW. In the end, we calculate the average of the results and we get approximately real reliability of the two components:

$$Reliability\ R_{SM}, R_{SMGW} \approx \mathbf{96{,}93}\% \quad (7)$$

Figure 5 shows the result of the reliability calculation based on the procedure described above and illustrates the smoothed *Reliability* R_{SM} and R_{SMGW}. Because of the large amount of samples only every 741st random sample is included in the diagram as these are exactly dividable and so a total of 109 measurements are presented. The red trend line represents the moving average of the random samples. As one can note, that the average reliability of the component varies strongly, because there are for example some early failures in the reliability sample or there are also samples without failures.

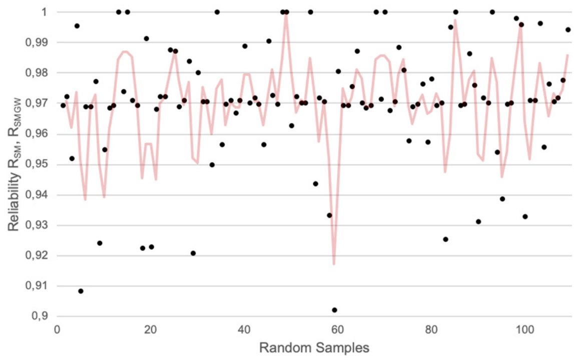

Figure 5: Smoothed calculation of reliability using an MCS of 80.769 samples.

4.2 Application

The WAN has the primary impact on system reliability because it provides the overall information that is needed to stabilize the grid. The services in the WAN are operated in a cloud environment (BSI, 2014). To approximate the *Reliability* R_{App} of the application that is operated in a cloud environment, we can use the characteristic availability of the three big cloud providers. This is at least 99.9% (Hauer, Hoffmann, Lunney, Ardelean,& Diwan, 2020; Wong, Zavodovski, Corneo, Mohan,& Kangasharju, 2021; Meinel, Schnjakin, Metzke,& Freitag, 2014) and is used in section 4.3. with the consolidation of the results.

4.3 Consolidation of Results

In this section, we will merge the *Reliability* R_{SM} and R_{SMGW} that we determined above from the RBD model defined in Figure 3 to get the *Reliability* R_{Total} of the overall system. For the smart meters we assumed a “k-out-of-n” dependency. The objective is that all of the five smart meters do not fail. Therefore, the Formula for the *Reliability* $R_{SM\text{-}Total}$ is as follows:

$$R_{SM-Total}(k, n, R_{SM}) = \sum_{k}^{n} \binom{n}{k} {R_{SM}}^{k} (1 - R_{SM})^{n-k} \quad (8)$$

$$k = 5; n = 5; R_{SM} = 96{,}93\%$$

$$R_{SM-Total}(k, n, R_{SM}) \approx \mathbf{88{,}35}\%$$

The following applies for this:

- The parameter x indicates the probability in the normal distribution and is created,

- n is the total number of units that are connected in parallel,
- and *Reliability* R_{SM} is the determined reliability of the smart meter.

The remaining components are connected in series (see Figure 3). Therefore, there is a multiplication of the determined reliabilities to calculate the *Reliability* R_{Total} of the entire system.

$$R_{Total} = R_{SM-Total} \times R_{SMGW} \times R_{App}$$
$$R_{Total} = 88{,}35\% \times 96{,}93\% \times 99{,}90\% \qquad (9)$$
$$Reliability\ R_{Total} \approx \mathbf{85{,}55}\%$$

Eventually past, we can summarize the calculations in Table 1 and compare them with each other. It can be seen that the simulated *Reliability* R_{Total} is about 5% lower than the hypothetical *Reliability R(t)*. Following the above definition of reliability according to Bertsche (2008) and Laprié (1995) the result means that about 15% of smart meter architectures could fail within the characteristic lifetime of 12 years. As an example, based on current forecasts for Germany of approximately 53 million smart meters (BNetzA, 2021) that would affect nearly 660,000 metering installations per year just for Germany in particular. In order to counteract this, it is necessary to increase the reliability of smart meters and smart meter gateways in particular. The design phase offers the greatest potential for reliability optimization (Altenburg et al., 2020). This is where the diverse methods for reliability optimization can already be implemented at the beginning and used with sustainable benefits.

Table 1: Comparison of hypothetical and simulated reliability.

	Smart Meter	Smart Meter Gateway	Application	Result by RBD model
hypothetical reliability R(t)	92,35%	98,02%	99,90%	**90,43%**
simulated reliability R_{Total}	88,35%	96,93%	99,90%	**85,55%**

5 CONCLUSION AND FUTURE WORK

This paper presented a structured reliability analysis. The theoretical foundations and the methodological approach were presented at the beginning. After that, we calculated the reliability of a smart meter architecture based on a limited data set using an RBD and an MCS. The result is a realistic reliability evaluation of the analyzed overall system. Our performed approximation demonstrates the need for reliability optimization in the context of smart meter architectures. Furthermore, the presented approach answers our aforementioned research question and verifies that the reliability of a smart metering architecture can be calculated with the help of an MCS for a limited dataset.

The largest optimization potential includes the design phase of a system (Altenburg et al., 2020). We will consolidate popular methods from the literature into efficient design strategies. This will provide a standard framework that can be used for reliability optimization. Based on our presented approach it is possible to validate the defined design strategies.

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