Performance Analysis of Mobile Radio for Automatic Control in Smart Grids

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Abstract—In the context of a "Smart Grid" research project, together with industrial partners, the OTH-Regensburg realized an intelligent medium-voltage grid in the local area. Goal was to improve the current voltage regulation and to counter the problems with inconsistent energy feed-in of decentralized renewable energy producers. In this paper we discuss the possibilities of using 3rd generation (3G) cellular networks (UMTS) as basic technology to communicate the voltage-levels within a medium-voltage grid. We build an experimental hardware setup to generate data-traffic as specified for the smart grid. By analyzing the performance of 3G cellular networks in terms of transmission latency and rate of failure, we tried to evaluate the usability of this technology for such critical data exchange. Though mobile communication in its structure is not specified for the use of transmitting such infrastructure critical data, the results show a promising high reliability with low transmission latency. The experiments served just to test a fragment of the conditions of use in a real scenario. An expanded test scope is needed to further analyze the performance of mobile radio for automatic control in smart grids. In the end the results discussed in this paper led to a successful prototype of an intelligent medium-voltage grid with mobile radio as communication technology. *(Abstract)*

Keywords—mobile radio, cellular data transmission, 3G, 4G, Smart Grid, communication (key words)

I. Introduction

Mobile communication technology is nowadays a common way to exchange data and connect mobile devices. It is highly available in most countries and provides high data-rates. Since the mobile communication network infrastructure is well-developed in urban areas [1], it also provides a cheap way to connect distributed sensors in these areas. This is particularly true when there is no infrastructure for a cable based connection via technologies like Digital Subscriber Line (DSL) or the range and bandwidth limitation of other radio technologies are not acceptable [2] [3]. For these reasons the technology seems to be well suited to be used in the construction of an advanced electrical grid with intelligent self-management capabilities [4], [2].

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In this so called Smart Grid it is important to gather and exchange the data about supplier and consumer behavior to increase reliability and efficiency of a power grid with more and more decentralized and inconsistent energy feed-in [5]. Within the context of a "Smart Grid" research project, together with industrial partners, the technical university of applied sciences of Regensburg (OTH-Regensburg) worked on realizing an intelligent medium-voltage grid. We decided to use the cellular network infrastructure to establish the connection between several distributed power-measuring devices (located at different medium-voltage transformers throughout the city of Regensburg) and a central server (located at the preceding high-voltage transformer station). This decision was based on a comprehensive communication study of the OTH Regensburg. For this use case, 3 requirements were specified and evaluated:

1) For a reliable voltage regulation, the data transmission must be highly reliable [6] [2].

2) For a responsive voltage regulation, the grids status-data transmission latency must be highly responsive [6] (less than 10 seconds).

3) The authenticity and integrity of the transmitted grid data must be ensured to avoid cyber-attacks [2].

The system setup will be further described in section **Error! Reference source not found.**. In order to evaluation a process is introduced consisting of an experiment under laboratory conditions. Therefore a small test scenario was set up to simulate the data transmission between measuring-devices and the server. The used components and test procedure of the simulation setup are explained in section **Error! Reference source not found.**. Section **Error! Reference source not found.** of this paper presents the results of our experiments and an interpretation in terms of our requirements. In conclusion (Section **Error! Reference source not found.**) we give a statement about the usability of mobile radio for smart grid applications based on our test results as well as the known shortcomings of our experiments. Thereby we also show fields of interest for further work in this area.

II. Motivation

The current way to regulate the power grid and thereby guarantee a stable line voltage works by using Automatic Voltage Regulators (AVR) to alter the transformer ratio of the high- to medium-voltage transformers. For this purpose high- to medium-voltage transformers have built in On Load Tap Changers (OLTC). AVRs with conventional control algorithms measure the medium-voltage grid to decide, whether to raise or lower the transformer ratio based on the local voltage level. Problem is, that through the expansion of

decentralized renewable energy generation technology like photovoltaic- or wind-power, there is an increasing divergence of the voltage levels within the different areas of a medium-voltage grid [7]. Without considering this diverging voltage levels in the voltage regulation, it will probably soon be impossible to keep the voltage-level of each network-substring within the mandatory band limits of ±10% [8] [9]. One approach to solve this problem is to use smart control algorithms for the AVR at the high-voltage transformer stations in which the voltage deviation between the different medium-voltage grid-substrings is taken into account. For these smart algorithms to work, the current voltage-levels of the underlying substrings must be known by the AVR [10]. Since the infrastructure of cable based communication technology is not generally available at each medium- to low-voltage transformer stations and due to the current distance limitations of technologies like Power Line [11] [12], the easiest way to gather the remote data needed for the control algorithms is by using the cellular network infrastructure. This approach was used in the "Smart Grid" research project of the OTH-Regensburg. This required the analysis of the performance of mobile radio with regards to the usability for the automatic control of smart grids.

A. *Smart Grid Architecture*
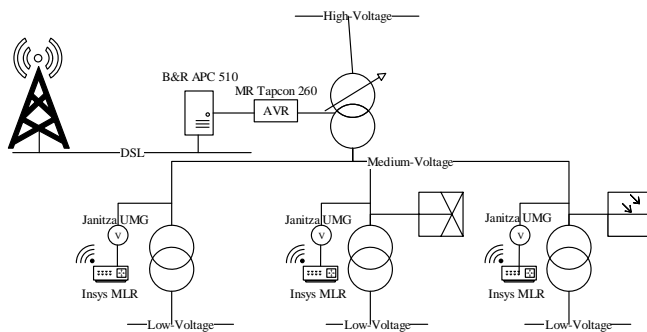
Figure 1: Smart Grid scenario overview

The OTH-Regensburg (Dep. of Electrical Engineering, Dep. of Computer Sciences and Mathematics) works in collaboration with the local power supplying company REWAG and the Maschinenfabrik Reinhausen (MR), to build an intelligent medium-voltage grid with smart power regulation [10]. For this project, 10 power measuring devices were installed on 10 medium- to low-voltage transformers in the urban area of Regensburg to determine the power levels at the corresponding network-substring. The measured values of each device are send to a central server, located at the preceding high-voltage transformer station. This server gathers the data of all measuring devices and determines the voltage fluctuations within the medium-voltage grid which are caused by the energy feed-in of photovoltaic-power plants and energy consumers. This information is provided to the AVR which then uses a smart control algorithm, to adjust the high-voltage transformer ratio when needed. Since the transformer-sites did not provide the necessary infrastructure for a cable based connection it was decided to focus on mobile communication technology for the data exchange between the measuring

devices and the server. Figure 1 illustrates the basic concept of the Smart Grid scenario.

1) Power-Measuring Devices

The local energy-supplier REWAG has installed Janitza UMG-96RM energy measuring devices [13] at 10 medium-voltage transformer stations within the urban area of Regensburg to determine the voltage-levels of the different substrings. The chosen transformers representing network-substrings with either high- or low energy feed-in to achieve a maximum transparency of the grid. The installed measuring devices meter the medium-voltage substrings voltage levels of each phase. The measured data is provided to a data-transmitter via a Modbus/TCP interface. This data-transmitter than sends the measuring data to the central server.

2) Clients

For the data transfer, each of the power measuring devices is connected to an industrial mobile communication router via its Modbus/TCP interface. The used Insys MLR 3G 2.0 devices, which provide this needed Modbus/TCP interface, also provide the option to run self-developed C/C++ applications. Therefore the project team of the OTH-Regensburg developed an application to gather the measuring data from the Janitza UMG-96RM devices, serialize them and then send them to a server for further processing. The application performs this actions cyclic every 3 seconds. For the connection to the server the embedded router devices where set up with a Congstar Subscriber Identity Module (SIM) to establish a connection to the D1-Telekom cellular network and to connect to the internet.

3) Data Transfer

For the data transmission, the routers read the measuring-values from the Janitza UMG-96RM devices and serializes them to generate a single data package. This data package is then extended by a time-stamp as well as the transformer-station ID. The data-packages are send to the server using a User Datagram Protocol (UDP) connection over the Internet. Due to the missing infrastructure at the medium- voltage transformer stations the internet connection is established by the routers using a cellular network connection. For the purpose of ensuring the authentication and integrity of the data, every package is further extended with a SHA1 hash value over the entire dataset and a key value. [14] This hash value will be evaluated by the server before accepting the data for further processing. The key values, used to seed the hashing-algorithm, are exchanged between server and clients once every 24 hours and have a validity duration of 72 hours. The key exchange is performed via a Virtual Private Network (VPN) connection. This procedure results in a total package length of about 150 byte.

4) Server

In the project, a B&R – APC 510 industrial personal computer (IPC) was installed at the high-voltage transformer station site. Task of the server is to establish the communication with the clients for the exchange of measuring data, to serve as data logger and to handle the communication with the AVR. This is handled by a single server application. The application gathers and logs the data from the industrial

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mobile communication routers (here called clients) installed at the medium-voltage transformer stations. This data is then evaluated by the application in a 10 second cycle to generate the information about the grid-status that is needed by the AVR's controlling algorithm. In every cycle the server application uses only the newest data available from each station and provides them to the AVR connected via a RS232 serial interface. The AVR then uses the data for the smart controlling algorithm to balance the different medium-voltage grid substring voltage levels to keep them within the set bandwidth. Since the clients provide the most recent measuring data to the server every 3 seconds, the server should have updated information about the grid status in every 10 seconds update interval of the AVR. If the server does not get new data from any station within the 10 second interval, the last available dataset from this station is used. If the age of the dataset of one station exceeds 60 seconds, the smart control algorithm will be suspended by the AVR automatically and the conventional control algorithm will take over the regulation.

This constrain lead to a real-time requirement for the data transmission between the routers (clients) and the server. Using the scenario described above, each data transmission must have a latency below 10 seconds to reach the server within one evaluation cycle. Though the server software can compensate a package loss, the control algorithm of the AVR requires a high reliability of the data transfer for an accurate regulation.

III. Simulation Setup

For the experiments to test the responsiveness and reliability of the 3rd Generation (3G) mobile communication technology a simplified test-scenario was set up to simulate the communication behavior of the intelligent medium-voltage grid as described in section **Error! Reference source not found.**. Figure 2 shows an abstract illustration of the test-simulation architecture.
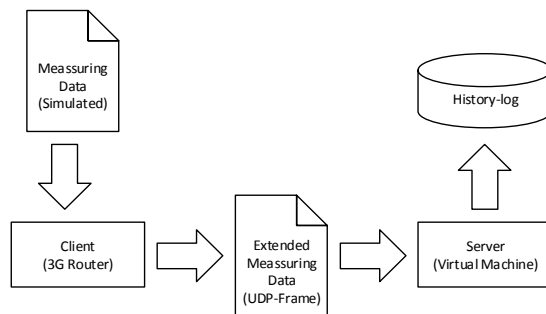
A. *Overview*

Figure 2: Test-Simulation Architecture

The test setup consisted of 3 mobile communication router from 2 different manufacturers and a Windows 7 virtual machine running the server application. The software used in the simulation setup equals the software used in the online Smart Grid Scenario.

Like in the online scenario the server has to evaluate the hash value of the package before processing it to prevent package modification. The key exchange has been disabled for the communication simulation to eliminate the possibility of package loss due to errors in the key exchange process. For this the keys where set manually before every test interval and the validity duration of the keys was set to infinite. To analyze the data transmission, the server has to calculate the transmission latency for each data package using the send-timestamp within the data package and the receive time of the server. Thereby if the transmission latency is higher than 10 seconds, the package is logged as invalid data by the server, because it did not satisfy the time requirements. Packages with a latency of less than 10 seconds are stored as valid data. Each client router as well as the server are synchronized with the same NTP-Server to achieve an accurate and comparable time between server and clients. The tests run about 4 weeks, while each device sent about 188,000 packages. The results of the test are shown below (See section **Error! Reference source not found.**).

B. *Hardware*

In the simulation setup we use two different device types from different manufacturers as client hardware. One is the MLR 3G 2.0 from the manufacturer Insys which were also used in the setup of the real scenario (Section **Error! Reference source not found.**). The other industrial mobile communication router is a C1500L from TDT. Furthermore we used two different network providers for the test. In addition to the D1 Telekom network we also used O2 to analyze the dependencies between transmission and network infrastructure.

1) **Clients**

We equipped two different devices (one MLR 3G 2.0 and one C1500L) with a SIM from the same provider (Congstar – D1) to analyze the performance dependencies between communication and devices. Further we set up an additional MLR 3G 2.0 device with a SIM from the provider O2 to analyze the performance dependencies between communication and provider. All devices were forced to use 3G technology only. If that technology was not available at any given time, the devices couldn't send any data. The devices were placed in a cluster inside the University of Regensburg. We didn't test any other technology, providers, devices or locations.

a) **Insys – MLR 3G 2.0**

The Insys – MLR 3G 2.0 [15] is an industrial mobile communication router supporting the 2nd and 3rd generation mobile communication standard. The routers run a Linux operating system which also offers the possibility to run self-developed applications in a sandbox environment. The

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Software used in the test scenario was developed and built on pc and then transferred to the router using PSCP (PuTTY Secure Copy). For further declaration of the program flow see section **Error! Reference source not found.**.

b) TDT – C1500L

The TDT – C1500L [16] is an industrial mobile communication router supporting 2nd, 3rd and 4th generation (LTE) technology. The Router comes with a Perl Script interpreter, but does not support to run custom software by default. For the test setup TDT provided a non-commercial developer firmware to develop and run the client application. This required to re-implement and compile the client software - used for the MLR 3G 2.0 routers - directly on the router. For further declaration of the program flow see section **Error! Reference source not found.**.

2) Server

The server is a virtual machine running a Windows 7 operating system. The server-sided test software was developed as a Java application. The server is connected to the university network to establish an internet connection needed for the data transfer. For details on the server software see section **Error! Reference source not found.**.

C. *Software*
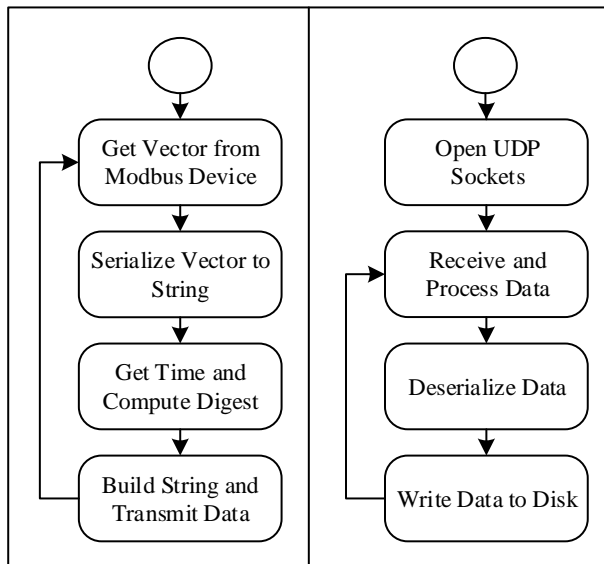
Diagram 1: Flow diagram Client

Diagram 2: Flow diagram Server

1) Client

After starting the client software, the router fetches the data from the built-in Modbus/TCP-Simulation in a 3 second interval. This was achieved by using a library from the device that supports the simulation of distinct Modbus device communication like the Janitza UMG 96RM devices. The result is a vector [Get Vector from Modbus Device]. This vector is then serialized into a string [Serialize Vector to String]. The string is prepended with the preset station ID and the local time stamp. For an accurate local-time the C1500L is set to synchronize with an NTP-Server every ten Minutes. The

MLR 3G 2.0 synchronization interval can only be set to one hour. To ensure the data authentication the string will be appended with a SHA1-128Bit HMAC digest over the entire content. [Get Time and Compute Digest]. The data-string now consists of the timestamp, station id, measuring data and digest. This string is then sent via UDP to the server IP specified in the router configuration file. [Build String and Transmit Data]. These steps are repeated every 3 seconds starting at [Get Vector from Modbus Device].

2) Server

The server opens up UDP sockets and prepares itself for the reception of data [Open UDP Sockets]. Then the server runs in an infinite loop waiting for packages. If a package is received it will create a received timestamp (The server is also synchronized via the same NTP-Server as the clients) [Receive Data and Process Data]. Therefore it de-serializes the data [De-serialize Data]. The timestamp and the received data will now be written to disk in a single text-file per 10 seconds (one line for each device) [Write Data to Disk]. Due to the sending interval of 3 seconds from the clients, up to three data-sets per station can be transmitted per logging interval. This takes into account that UDP is not reliable and packages can be lost. Only the newest data-set per station will be processed and written to disk.

IV. Results

Table 1 - Reliability of transmission latency

	MLR O2	TDT D1	MLR D1
[0 – 2] sec	99.63%	99.63%	99.08%
]2- 5] sec	0.11%	0.03%	0.30%
]5 – 7] sec	0.00%	0.00%	0.01%
]7 – 10] sec	0.00%	0.00%	0.01%
]10 – ∞[	0.25%	0.33%	0.61%

The test results consist of the data-log of around 188.000 data package transmissions. This equals a working period of about 1 month for each of the 3 test devices. Table 1 shows the percentage values of the package transmission latency for the time intervals [0s , 2s],]2s , 5s],]5s , 7s],]7s , 10s] and]10s , ∞[. Packages in the]10s , ∞[interval did not satisfy the specified time requirements and therefor where counted as lost packages. Overall the test results show that over 99% of all packages transmitted had a latency of less than 2 seconds (In fact, the total difference between C1500L – TDT / O2 with D1 and the MLR 3G 2.0 / O2 in packages transmitted in less than 2 seconds was only 4 packages). This satisfies the time requirements of the Smart Grid scenario. Only about 0.3% of all transmitted data packages arrived outside of the required time interval or did not arrive at all. Taking a closer look the Insys - MLR 3G 2.0 had the lowest overall package loss using the O2 network infrastructure and the highest loss-rate of 0.61% using the Congstar – D1 cellular network.

Figure 5 shows the ratio of packages loss (discussed in Table 1) divided into 7 segments for the 7 days of week. Taking a closer look at this data it can be recognized that,

while the device connected to the internet via O2 had nearly no fluctuation, the devices using the D1 service provider had a noticeable peak on Wednesday and its lowest package-loss rate on Sunday. While we have no data to further analyze this behavior, we assume that this could be caused by the different network utilization over the week. Since the router where placed at the campus of the University of Regensburg this seems to be in relation to the number of people at the campus over the days of the week. Because the small number of overall data packages lost, one other possible explanation for the peek on Wednesday would be a provider-sided maintenance interval, but we have no evidence that could prove or disprove that assumption.

In Figure 3 the dependence between responsiveness and the used devices become visible. The data packages transmitted from the TDT - C1500L had an overall latency of around 350ms while the Insys -MLR 3G 2.0 devices had nearly double the latency. Despite the different service providers used by the MLR devices the overall transmission latency was about 600ms. This led us to the conclusion that the transmission latency only depends on the used devices.

Breaking the data up into hours of the day, Figure 4 shows that while the C1500L (TDT) has nearly the same transmission duration during the whole day, the MLR 3G 2.0 devices transmission times are increasing over time when the system is up. As stated above the MLR 3G 2.0 devices
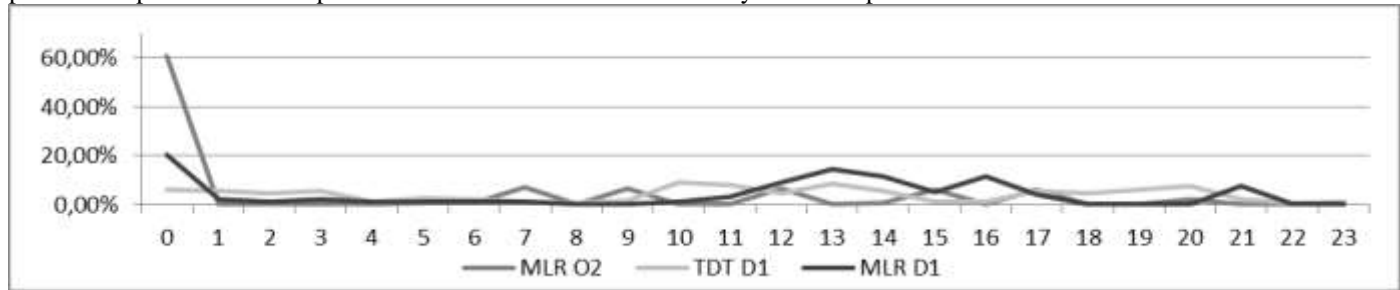

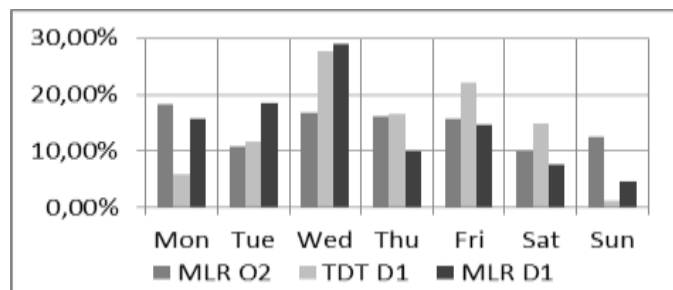**Figure 6: Packages lost per Hour of Day (ref. to lost total)**

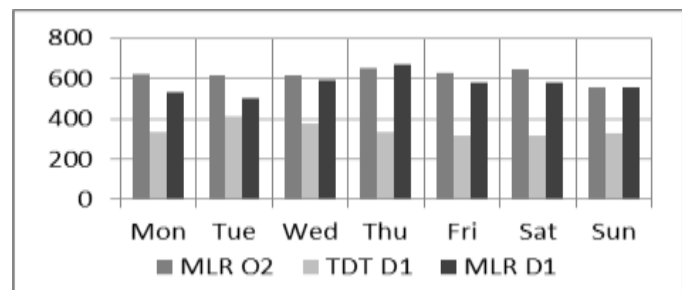**Figure 5: Packages lost per Days of Week (ref. to lost total)**

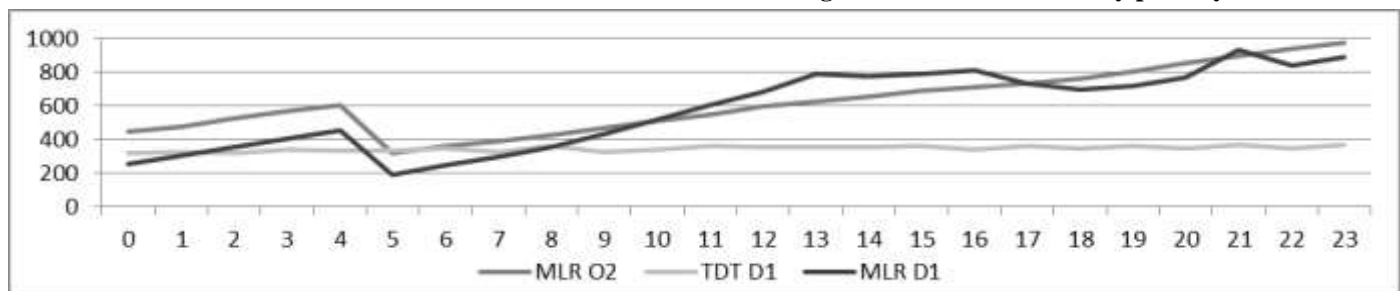**Figure 3: Transmission delay per Days of Week**

Figure 4: Transmission delay per Hours of Day

Figure 6 illustrates the distribution of packages lost per hours of a day. First noticeable is a huge spike between 0 AM and 1 AM for the MLR devices. We assume, this could be caused by a daily restart of those devices. The MLR device with the O2-SIM had about 60.0% of all its data-loss between 0 AM and 1 AM while for the MLR device using D1 only about 20.0% of its data-loss occurred at the same time. We assume that the device with the O2-SIM encountered some problems while restarting or dialing into the mobile network, because the device logs show that the downtime of the O2 Device was nearly three times longer than the same MLR device using a D1-SIM.

perform a system restart at 0 AM while the TDT does not have to restart at any given time. Also at the time between 4 AM and 5 AM the MLR devices reconnect with the internet service provider. Both, the system reboot and the internet reconnect seems to reset the increasing transmission latency. One possible assumption we came up to explain this behavior would be a problem with the router firmware but this is a matter of conjecture.

v. **Conclusion**

In our experiments we used a very simple method to simulate the same data traffic as used in the specific scenario

of the smart grid research project described above (Section **Error! Reference source not found.**). The gathered data were *Analyzed in Terms of the Performance of Mobile Radio for Automatic Control of the Smart Grid* in this specific scenario. Mobile communication technology in its structure is not designed for use cases like transmitting measuring-data for to control sensitive infrastructure like electricity power grids [17]. This is caused due to the complex structure of the cellular networks and high dependencies on different providers of infrastructure technology [18]. Still the test-results show promising values in terms of reliability and responsiveness. Overall the determined average data-transmission latency satisfies the communication requirements for the intelligent medium-voltage grid prototype.

One noticeable knowledge gained through the experiment is, that using different providers had up to no impact on the average transmission latency of the data packages. Despite this the results show that conventional UMTS and the underlying cellular network infrastructure of different service providers can have an impact on the reliability of the data transmission. This might depend on the network utilization or service restrictions due to maintenance intervals or the like. For an extensive use of this technology these problems must be countered. For example by adding a quality of service class for smart grid communication to the transmission protocol standards [19]. Also by way of a contractual agreement between the cellular network providers and power supply companies on the dependences between cellular network and electrical power grid an improvement could be achieved. This would enable the cellular network providers to take impact of network maintenances and high network utilization on the power grid into consideration. By doing so, the cellular service providers could guarantee increased uptime of their services for power grid regulation.

Another result of our research is that the devices used in the test had almost equivalent data transmission reliability. However, looking on transmission times, the test-data led us to the assumption that there is a dependency between transmission time and the used device type. The numbers show that the transmission time of the data packages sent by the devices from TDT was 50% lower than the transmission time of the Insys devices. Though we only used one TDT - C1500L and one MLR 3G 2.0 device with the identical cellular service provider to gain comparable data, more devices must be tested in order to confirm our assumption that the transmission latency partially depends on the used mobile communication router types.

A. *Known Issues*

One known issue is the mobile communication router behavior in the test setup. In comparison to the C1500L router from TDT, the Insys MLR 3G 2.0 routers need to restart itself every night at 0 AM and to reconnect to the internet at around 4 AM. These restarts take at least 30 seconds – so the server loses a minimum of 3 packages per night. As mentioned before, the MLR router using an O2-SIM took even two times longer to restart, resulting in a minimum loss of 9 packages

per night. The C1500L doesn't have to restart or to reconnect at all. This leads to a higher package-loss count for the MLR 3G 2.0 routers which is not caused by network dependent communication issues.

Another known issue is that due to the short test duration of about 30 days and the very low transmission failure rate, the number of lost data packages was not enough to statistically prove certain behavior. Therefore the interpretation of the test results could only be done through the assumption of logical reasons for a certain behavior. Further insight from the provider (like maintenance intervals and network utilization) and a larger dataset will support correct interpretation.

The test simulation setup scope did not contain the variety of issues that could occur because of low received signal strength indicator (RSSI) values. The tests were performed in an area with high network stability and good network signal strength. The influences of network utilization or low RSSI values due to shielding, interferences, electromagnetic disturbances or signal dispersion are of great importance for a more realistic interpretation of the usability of this technology in a scenario as described in this paper.

The reliability of the used hardware – not part of the test scope – had also an influence on the test runs itself. Sometimes the routers terminate the program without any reason or output. The reason for this behavior is still not clear. Even the timing of these errors is not predictable. For the duration of the entire test this happened once per device and we found no way to trigger this behavior on purpose. Further analyses by the device manufacturer are necessary in order to fix this error.

B. *Further Work*

Further tests must be done to better assess the usability of mobile communication technology for a data-transmission between different distributed transformer stations. Thereby one important test requirement must be to analyze the dependencies between the reliability and responsiveness of the data transmission and different network areas with different network utilization and different signal strength values. This is important since the use case of the underlying scenario is to install the mobile communication routers directly at the transformer stations were the routers are in different network areas and have to operate with a different quality of network connection.

The tests must also analyze the dependencies of the transmission results and all of the available network providers. This is required since the areas of the transformer stations where the routers are installed might not always be within the network areas of all providers. For example: to improve the network connection of a specific device, the switch to another cellular network can be the easiest way. Therefore the influences of the different networks must be further analyzed.

Since the results of this paper only discuss the usability of the 3G mobile communication networks, the improvements or limitations of using the router devices within 2G (GPRS/EDGE) or 4G (LTE) networks has not been researched. Therefore all of the tests must be repeated with

devices utilizing the different generations of network technology.

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