

5G NETWORKS ENABLING NEW SMART GRID PROTECTION SOLUTIONS

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ABSTRACT

Within the ongoing energy revolution, power distribution grid protection, control, and monitoring requires modern, advanced technologies to maintain safety and reliability of operation. If all devices could be interconnected through secure, reliable, and low latency communication infrastructure, a new dimension for design and operation of power distribution grids would be seen. Usually communication based protection and control schemes are built with wired communication technologies, which may be unavailable or difficult to arrange in retrofit scenarios. This paper introduces one of the most demanding communication-based protection principles - line differential protection including intertrip between circuit breakers, as a benchmark application for the evolved fifth generation (5G) wireless communication and an extensive test environment to validate its system and communication performance.

INTRODUCTION

The phase segregated line differential protection is used as feeder differential protection for distribution network lines and cables. The principle is to calculate differential current from currents entering and leaving the protection zone by utilizing the digital communication channels for data exchange. The differential currents are almost zero in normal operation. The differential protection is phase segregated and the differential currents are calculated at both ends separately. The communication link is expected to be highly symmetrical and synchronization is based on a ping-pong algorithm. However, this method is not suitable over the existing wireless communication links, since it usually introduces asymmetry and varying jitter, thus measurements must be sent with an accurate timestamp.

In stringent cases, faults should be cleared immediately and without time delay – within one cycle (about 20ms), for example. The isolation of a faulty section is secured by sending a tripping command to the circuit-breaker from the local end to the remote end over the protection communication, this scheme is called intertripping.

In this experiment, line differential is implemented on Routable-Sampled Values (R-SV) and intertrip on Routable Generic Object Oriented Substation Event (R-GOOSE) communication over User Data Protocol (UDP) according to IEC 61850-90-5. Applications are tested over wireless communication link.

POTENTIAL ROLE OF 5G IN SMART GRID PROTECTION SOLUTION

The fifth cellular generation (5G) technology is making a significant advance in the combination of latency reduction and reliability enhancement. This makes 5G an option for a replacement of fixed cable connections. Since the beginning of 5G, electricity distribution has been one of the major use cases for ultra-reliable low-latency communications (URLLC).

What is 5G, especially URLLC

Mobile devices have offered high quality connectivity over several generations. 5G is aiming to make a big difference in offering better connectivity between machines, especially when 5G is advancing towards low-latency with high-reliability communications by enabling URLLC. This addresses the demand from many vertical sectors for mission-critical machine-type communications (MTC), which are essential for new use cases and applications, such as industrial automation and intelligent transportation. The objective of the first version of 5G URLLC is to deliver a message in less than 1ms with 99,999% reliability [1]. Current standardization is working on how to improve this even further.

How does it help

The combination of low latency and high reliability makes 5G an option for replacing fixed connections. This obviously makes installations and especially retrofit scenarios clearly easier. Other expected benefits include cost savings achieved from wireless connections and network virtualization as well as increased reliability and improved response time, efficiency, flexibility and redundancy.

Required evolvment in protection devices and systems

According to the IEC 61850, SV and GOOSE services are utilized for the transfer of data in time-critical functions [3]. The SV is utilized for fast and cyclic transmission inside the substation and the GOOSE for event-based data transfer. Both GOOSE and SV are Layer 2 protocols, so they are not originally designed for data transfer outside the local substation network. To overcome this shortcoming, IEC 61850-90-5 defines enhanced SV and GOOSE protocols onto an IP based protocol with multicast UDP addressing to transfer e.g. synchrophasor data [3]. Since the routable UDP is utilised, these protocols over IP are called R-SV and R-GOOSE respectively.

Compared to Ethernet layer messaging, R-GOOSE and R-SV require more computing power. Therefore, it needs to be carefully considered whether routing should be implemented to a gateway or a protection device. Priority tagging and queueing are also required to ensure high priority in the network.

Communication supervision of gateway devices is a must, in order to achieve more accurate detection of failures. Whenever possible, such supervision should also be connected to a SCADA system.

In asymmetric networks, accurate timestamps are required. This is currently achieved by having a GPS or equivalent time source in every substation. In case of line differential protection, local measurements with timestamps are send to the remote end. Ideally, protection devices should be synchronized in a mobile network with the same time source.

Although VPN can be used in a 5G network to exchange messages, message authentication should also be considered to improve security. For R-GOOSE and R-SV, this requires the use of a key distribution centre (KDC) in both ends.

5G URLLC STANDARDIZATION STATUS

URLLC has been one of the three main 5G usage scenarios from the very beginning of the 5G system design. In 3GPP, the first official release for 5G is Rel-15 completed in June 2018. The major use cases considered in Rel-15 are coming from industrial automation and electricity distribution. The 3GPP Service and System Aspects (SA) working group has been investigating various use cases, their requirements and network architecture support for URLLC services. Furthermore, the 3GPP Radio Access Network (RAN) working group has specified radio level standards that are within our focus area.

In Rel-15, the system design target was set to achieve communication reliability corresponding to block error rate (BLER) of 10^{-5} for 32 bytes with a user plane latency of 1ms [1]. To achieve the goal of the reduced latency and increased reliability simultaneously, different technical enablers have been specified in Rel-15 [2]. The main features specified in Rel-15 are summarized in Figure 1.

Mini-slot	Reduced processing time	Data slot aggregation	Configurable reliability target
Short control channel format	Efficient multiplexing	Higher aggregation level for control	Multi-connectivity
Uplink grant free transmission		K-repetition	

Figure 1. Reliability (Green color) and latency (blue color) enhancements for the 5G New Radio (NR).

Currently, 3GPP is working on further enhancements in Rel-16. It also extends the supported services to cover time sensitive communications (TSC) e.g. vertical industries' widely deployed time sensitive networks (TSN). The desired target is to achieve communication reliability corresponding to the BLER of 10^{-6} with sub-ms latency. In addition, further communication requirements are considered such as:

- Enhanced uplink configured grant transmission;
- Improved control channel reliability;
- Mini-slot repetition to achieve high reliability;
- Enhanced PDCP layer duplication;
- Intra-/inter-UE multiplexing between different services;
- Enhance scheduling to support time sensitive communications;
- Accurate time synchronization among involved network nodes within the same synchronization domain.

TEST SETUP AND METHODOLOGY

A specific test setup was built to validate system and communication performance of two line differential relays that are connected with a fixed or wireless connection. The setup was designed so that separate one-way latencies across radio access and core networks, i.e. end-to-end connection, wireless links, and core network parts, can be measured at the same time. The measurement system is passive and does not interfere with the target system. However, the one-way measurement requires an accurate clock in both ends to measure latencies precisely. The developed test setup consists of four main parts:

- Grid components and applications to be tested;
- Communication components to provide wired and wireless communications capabilities;
- Measurement components used for synchronization and measuring latency, jitter, and packet loss; and
- Visualisation and analysis tools.

The test setup is built on a nation-wide 5G Test Network Finland (5GTNF) infrastructure, which is one of the outcomes in Finnish 5thGear programme to establish an integrated innovation platform for research community, industry, and the third parties. The test setup utilises the 5G test network implemented in Espoo, Finland. The core network and network cloud functionalities are located in

II Reference measurements with emulated traffic

The second set of measurements were performed using an active communication emulator over Ethernet connection (see Table 1). In the first configuration, an emulated wireless connection profile was used giving additional 11-23ms average delay in both directions. The test was repeated 100 times. The results indicated that the maximum operating time increased by 34.1ms and the average by 33.65ms, whereas the standard deviation decreased by 0.29ms. In the second configuration with the communication emulator, an additional 2ms of jitter was added to the previous traffic profile. The change increased the standard deviation by 0.18ms (as anticipated), but it also caused a 5.13ms increase in the average operating time. A 5.7ms increase in the maximum delay values was also seen. The reference results were well in line with the expectations.

III Measurements in commercial 4G network

Next, the measurements were performed several times in a commercial 4G network to assess possible performance gaps between the current network performance and the expected one, and to investigate how additional loads by other users affect the latency results. The results indicated that long measurements are important to include daily and weekly effects on traffic profiles. Average one-way latency may vary greatly during the day. In addition, the results revealed that even though current 4G networks in Finland in many cases fulfil the minimum latency requirement for line differential and intertrip protection, the issue is their variance of the latency. Figure 4 illustrates an example of the phenomena encountered in a commercial 4G network with the device presented in the Figure 3. Delay and jitter are on average within acceptable levels, but peaks occur with delays of over 200ms (averaged over a period of one second). More extensive (24 and 48 hour) measurements showed that these peaks occur frequently and there can be tens of them during a period of one hour. During a peak in the delay time, the line differential and intertrip messaging are directly affected by increasing the relays' operating time. Delays caused by wireless communication, other users' traffic, and network components may also accumulate and cause burstiness, which makes the implementation of protection applications quite challenging.

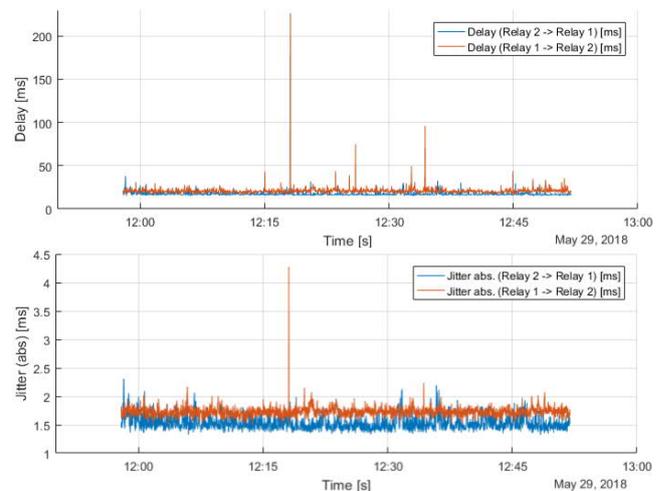


Figure 4. Communication delay (above) and jitter (below) between the two relays in a commercial 4G network. Each sample is averaged over 1s.

The analysis example of another 4G measurement, where the highest averaged delay samples were around 33ms, shows what is happening at the packet level (see Table 2).

Table 2. Time interval of successive arriving packets. Relay2 receiving R-SV packets in line differential case. Note that Min value can be 0, meaning two packets can arrive at the same time.

Variable	Time[ms]
Max	124.857
Min	0
Average	2.500
Median	2.001
Standard deviation	3.031
1st quadrant	0.155
3rd quadrant	3.148

Even though the relay sends packets with sizes of 205-212 bytes on a regular interval of 2.5ms, there are delays of more than 120ms between two successive arriving packets. This is detected by the receiving relay, which considers communication blocked and initiates a local backup mode of protection.

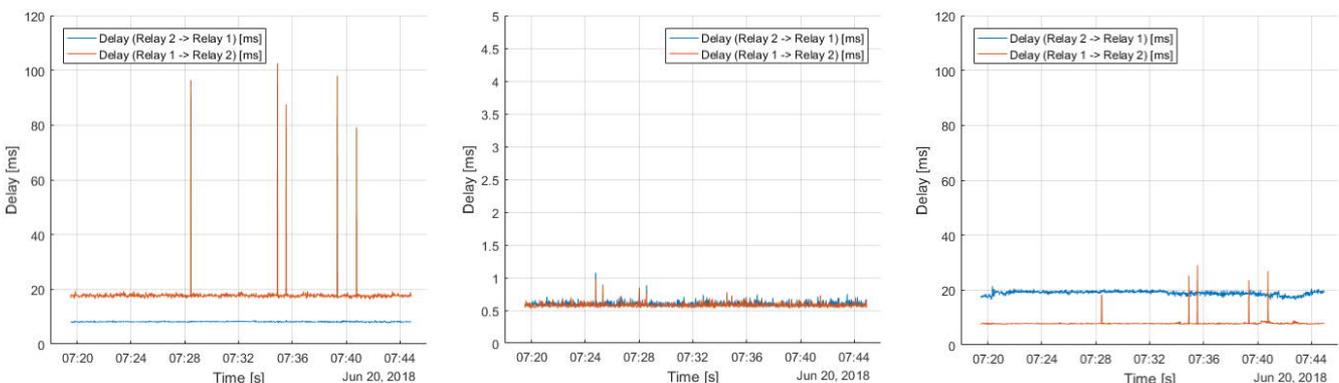


Figure 5. Delays in air interface 1, 5G packet core including connections to eNodeBs, and air interface 2, respectively.

IV Measurements in 4G/5G test network

As the next step following the results from the commercial 4G network, more tests were performed in a 5G test network. The network is still being constructed, but contains prototypes of 5G core network components. The same tests were performed as in the prior cases. This time 1000-2000 repeats were performed to get more statistical data of operating time measurements. The results indicated that extremely high maximum delay values were encountered, also in the test network. Further investigation was needed to see whether the degraded performance was due to the implementation of a network component or its parameterisation. Parallel latency measurements of radio access and core networks revealed that the delay is predominantly in the air interface, as can be seen in the following Figure 5 which represents delays in the two air interfaces including modem, radio channel, and 4G eNodeB and delays in the 5G packet core including connections to eNodeBs. It can be seen that delays in the core network are negligible compared to the over air interfaces' delays. This underlines the need for a true URLLC air interface emerging based on 3GPP Rel-15 and Rel-16.

Initial tests with a 5G URLLC base station and a user terminal prototypes operating at 2.6 GHz frequency were also conducted in lab environment. The 5G URLLC prototype is designed and implemented for a specific safety use case in mind. At the time of measurement, it supports only smaller packet sizes than used with R-SV and R-GOOSE protocols. The prototype supports asymmetric traffic with critical and miscellaneous data over a same or dedicated data links. For measurements, the traffic between 5G prototype terminals was made symmetrical to emulate the protection relay traffic.

According to the preliminary results, the one-way latency was very constant compared to the 4G traffic ranging from 1.7ms to 2.8ms in the DL direction and 1.6ms to 2.5ms in the UL direction. The DL direction experienced approximately 0.2ms more jitter than the UL direction. These results are easily fulfilling the defined requirements and thus leave a significant performance margin for bigger packet sizes, environmental effects, and larger network composition.

The measurements with the 5G URLLC prototype displayed the existing challenge pertaining to time accuracy, especially in distributed measurement setups. The faster the communication is the more important it is to ensure that errors caused by the measurement components, timestamping, and traffic generation stays within acceptable limits.

CONCLUSIONS

These preliminary results indicate that there is an evident need for a measurement setup that can differentiate latencies at E2E application, core network, and air interface levels. In addition to the challenges of building

the presented measurement system, accurate time plays an important role in wireless line differential protection scenarios.

The importance of extensive test environments cannot ever be underestimated. A good testing system provides quick, early, and transparent feedback for technology providers and improves mutual understanding of how these technologies should interoperate and evolve.

The technologies involved in wireless communication over public or private mobile networks and power distribution grid protection are not easy to merge. Depending on the practical deployment, a public 4G network in Finland is very close to providing reasonable latency, but it lacks reliability. This may be achieved, for instance, in dedicated installations of 4G, like private 4G networks. However, 5G technology with network slicing will enable application driven services where end-to-end virtual networks are built on public mobile networks according to requirements. One should also notice that neither 4G or 5G are monolithic technologies, but that there are different versions and practical implementations. While writing this paper, the first prototype implementation of 5G URLLC was available for preliminary measurements. Since the packet core was not found as the key source for delays, the new 5G radio interface is anticipated to bring overall latency and jitter to acceptable levels for protection applications. Reliability will be considered in future measurements after the latency requirements are met.

Indeed, 5G will provide a compelling platform for different grid applications, varying from IoT sensor and video streaming applications to ultra time critical applications like line differential protection presented in this paper.

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