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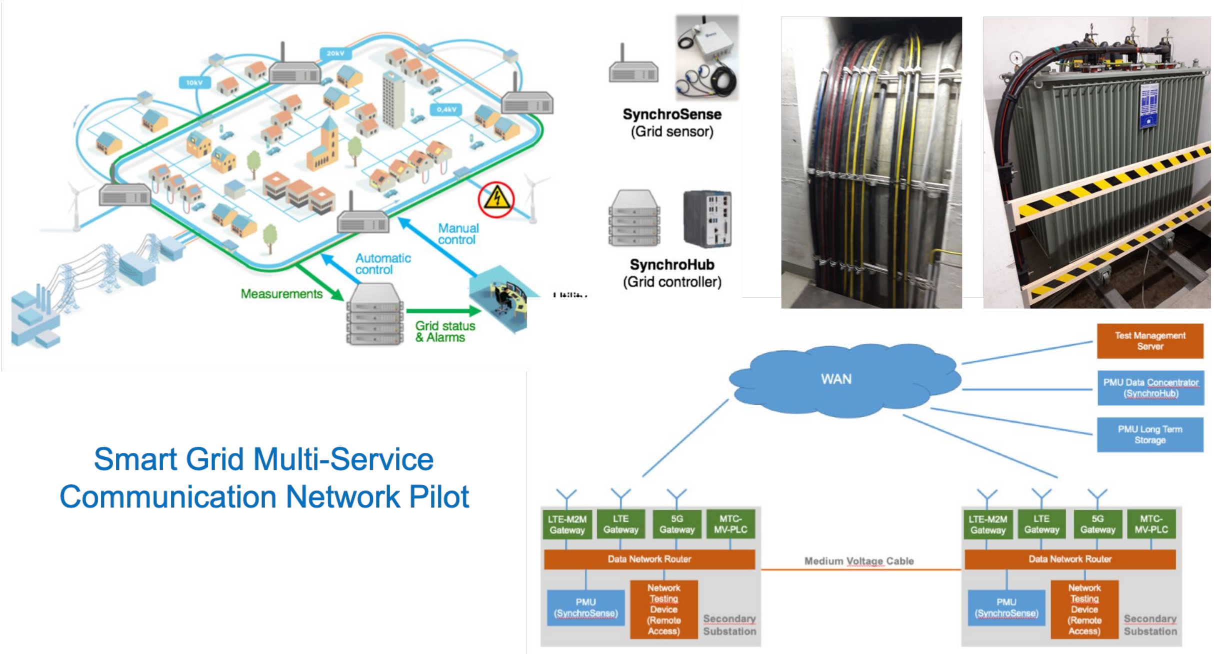
Smart Grid Multi-Service Communication Network Pilot



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Zusammenfassung

Ein vollständiges intelligentes Stromnetz (Smart Grid, SG) umfasst mehrere Anwendungsfälle, die von der automatisierten Zählerinfrastruktur (AMI) bis zur Überwachung, zum Schutz und zur Automatisierung (MPA) auf der Grundlage von Synchro-Phasenmessgeräten (PMU) reichen. Da nach dem Stand der Technik eine vollständige Abdeckung aller Szenarien bei gleichzeitiger Erfüllung aller erforderlichen Anforderungen nicht durch eine einzige Kommunikationstechnologie gewährleistet werden kann, erfordert ein SG die Verbindung der Netzelemente über ein Kommunikationsnetz (CN). Die Kosten und die Leistung des CN sind daher ein kritischer Faktor für den Einsatz des SG: ein Versorgungsunternehmen kann keine Verbundlösung anbieten, bei der jeder Dienst auf einem separaten CN betrieben wird. Daher ist eine Hybridlösung aus verschiedenen Technologien erforderlich.

In diesem Projekt wurde eine Methodik erweitert und in der Praxis validiert, die es ermöglicht, die optimale Mischung von Kommunikationstechnologien für eine Kombination von Anwendungsfällen zu bestimmen. Der Anwendungsfall mit den einfachsten Anforderungen (AMI) und der mit den schwierigsten Anforderungen (PMU-basierte MPA) wurden für das Pilotprojekt ausgewählt, implementiert und validiert.

Wie zu erwarten war, erwiesen sich die Anforderungen an die Latenz (< 20 ms) und die Verlustrate für die Anwendungen der PMU als die anspruchsvollsten. Die Analyse und Bewertung der verschiedenen in Frage kommenden Kommunikationstechnologien, die im "Smart-Grid Multi-Service Communication Network Pilot" zu testen waren, ergab LTE-NB1, LTE-M1, LTE-CAT3 und MTC-MV-PLC PLUS.

Das Pilotsystem wurde entwickelt und in einem Cluster von drei Ortsnetztrafostationen in der Region Wohlen bei Bern installiert. Die generische Pilotarchitektur bietet einen Rahmen für die Integration und den Test verschiedener Kommunikationstechnologien, die nicht unbedingt auf die in diesem Projekt getesteten beschränkt sind. Die Langzeitmessungen wurden von Oktober 2020 bis Mai 2021 durchgeführt. Die Ergebnisse zeigen, dass LTE-CAT3 und eine Kombination aus MTC-MV-PLC PLUS und LTE-CAT3 die am besten geeigneten Technologien für das Multi-Service-CN sind. Basierend auf den Testergebnissen ist zu erwarten, dass LTE-CAT3 die Anforderungen der meisten PMU-basierten Anwendungen (Latenz, Verlustrate und Durchsatz) bis auf wenige Ausnahmen erfüllen wird. Es wird erwartet, dass in Zukunft moderne Glasfasernetze oder 5G-Mobilfunknetze in der Lage sein werden, diese Anforderungen vollständig zu erfüllen. Die Resultate von MTC-MV-PLC PLUS zeigen, dass diese Technologie Anwendungen mit noch höheren Anforderungen ermöglichen könnte, insbesondere hinsichtlich der Latenz, da die gemessenen Latenzen im niedrigen einstelligen ms-Bereich liegen. Während aufgrund der Leistungsfähigkeit und Verfügbarkeit von LTE-CAT3 in Verbindung mit den regulatorischen Einschränkungen jeglicher PLC-Technologie über Freileitungen die Anwendung von MTC-MV-PLC PLUS für einen breiten Einsatz in einem SG ausgeschlossen werden kann, könnte diese Technologie für die Echtzeit-Datenkommunikation über unterirdische MV-Leitungen zwischen Sensoren und Aktoren innerhalb von zwei oder mehr Trafostationen interessant werden, z.B. für die Anwendung von Schutzsystemen mit höchsten Latenzanforderungen (u.a. Line Differential Protection). Die Tests zeigten auch den Einfluss von Rauschen auf der MV-Leitung, das die Leistung der MTC-MV-SPS PLUS einschränkt. Die HSLU hat über den Rahmen dieses Projekts hinaus weiterhin Zugang zu der Pilotinstallation und wird weiterhin Optimierungen untersuchen, die vorgenommen werden können, um eine Kommunikation ohne Datenverluste auch bei extrem hohen Störpegeln auf der Stromleitung zu ermöglichen.

Das Projekt hat auch gezeigt, dass die Einführung der PMU-Technologie im Verteilnetz dazu beitragen kann, die durch Störungen verursachten Schäden für die Endkunden erheblich zu reduzieren. Der Kapitalwert der Lösung wird bei einer Masseneinführung im Netz der BKW auf 11 Mio. CHF geschätzt. Diese Analyse beinhaltet nur die Kosten für die ungeplante Unterbrechungsdauer. Weitere Arbeiten können auch andere Arten von Vorteilen für die Endkunden einbeziehen, wie z.B. die Verringerung der Anzahl der Ausfälle durch die Vorhersage von Fehlern im Frühstadium. Andere Aspekte der Fehlerortung können ebenfalls berücksichtigt werden, wie z. B. die Sicherheit des Bedienpersonals und die Verlängerung der Lebensdauer der Anlagen, auch wenn sie als geringer Beitrag zu den Gesamtkosteneinsparungen eingeschätzt werden. Obwohl das Störungsmanagement eines der Hauptanliegen der Verteilernetzbetreiber in der Schweiz ist, wird es in naher Zukunft von anderen großen Problemen begleitet werden, die die Verteilernetzbetreiber zu bewältigen haben. Wenn die Schweiz ihre Ziele der Energiestrategie 2050 erreichen will, wird die Zunahme der erneuerbaren Energien zu neuen Herausforderungen für das Netzmanagement führen. Wie viele Studien nahelegen, wird eine Echtzeitüberwachung zusammen mit einer datengesteuerten Netzoptimierung und -planung notwendig sein, um exorbitante Kosten zu vermeiden und gleichzeitig einen zuverlässigen Betrieb aufrechtzuerhalten.

Résumé

Un réseau intelligent (Smart Grid SG) complet comprend plusieurs cas d'utilisation allant de l'infrastructure de comptage automatisé (AMI) à la surveillance, la protection et l'automatisation (MPA) basée sur des compteurs synchro-phasés (PMU). Étant donné que, selon l'état de l'art, la couverture complète de tous les scénarios tout en répondant à toutes les exigences nécessaires ne peut être garantie par une seule technologie de communication, un SG nécessite l'interconnexion d'éléments de réseau via un réseau de communication (RC). Le coût et les performances du RC sont donc un facteur critique pour le déploiement des SG: un service public ne peut pas offrir une solution d'interconnexion où chaque service fonctionne sur un CN distinct. C'est pourquoi une solution hybride associant différentes technologies est nécessaire.

Dans ce projet, une méthodologie a été étendue et validée en pratique pour déterminer la combinaison optimale de technologies de communication pour une combinaison de cas d'utilisation. Le cas d'utilisation avec les exigences les plus faciles (AMI) et celui avec les exigences les plus difficiles (MPA basé sur PMU) ont été sélectionnés, mis en œuvre et validés pour le projet pilote.

Comme prévu, les exigences en matière de latence (< 20 ms) et de taux de perte pour les applications PMU se sont avérées les plus difficiles. L'analyse et l'évaluation des différentes technologies de communication éligibles à tester dans le cadre du "Smart-Grid Multi-Service Communication Network Pilot" ont abouti à LTE-NB1, LTE-M1, LTE-CAT3 et MTC-MV-PLC PLUS.

Le système pilote a été développé et installé dans un groupe de trois stations de transformation du réseau local dans la région de Wohlen près de Berne. L'architecture pilote générique fournit un cadre pour intégrer et tester différentes technologies de communication, sans nécessairement se limiter à celles testées dans ce projet. Les mesures à long terme ont été effectuées d'octobre 2020 à mai 2021. Les résultats montrent que LTE-CAT3 et une combinaison de MTC-MV-PLC PLUS et LTE-CAT3 sont les technologies les plus appropriées pour le CN multiservice. D'après les résultats des essais, la norme LTE-CAT3 devrait répondre aux exigences de la plupart des applications basées sur les PMU (latence, taux de perte et débit), à quelques exceptions près. On s'attend à ce qu'à l'avenir, les réseaux modernes à fibres optiques ou les réseaux mobiles 5G soient en mesure de répondre pleinement à ces exigences. Les résultats de MTC-MV-PLC PLUS montrent que cette technologie pourrait permettre des applications aux exigences encore plus élevées, notamment en ce qui concerne la latence, puisque les latences mesurées sont de l'ordre de quelques ms à un chiffre. Si les performances et la disponibilité de LTE-CAT3 combinées aux limitations réglementaires de toute technologie CPL peuvent exclure l'application de MTC-MV-PLC PLUS pour une utilisation généralisée dans un SG, cette technologie pourrait devenir intéressante pour la communication de données en temps réel sur les lignes MT souterraines entre les capteurs et les actionneurs au sein de deux stations de transformation ou plus, par exemple pour l'application de systèmes de protection ayant les exigences de latence les plus élevées (notamment la protection différentielle de ligne). Les tests ont également montré l'influence du bruit sur la ligne MT, qui limite les performances du MTC-MV-SPS PLUS. Le HSLU continue à avoir accès à l'installation pilote au-delà de la portée de ce projet et continuera à étudier les optimisations qui peuvent être faites pour permettre la communication sans perte de données, même à des niveaux de bruit extrêmement élevés sur la ligne électrique.

Le projet a également montré que l'introduction de la technologie PMU dans le réseau de distribution peut contribuer à réduire de manière significative les dommages causés aux clients finaux par les perturbations. La valeur actuelle nette de la solution est estimée à 11 millions de francs pour une introduction massive dans le réseau FMB. Cette analyse ne comprend que les coûts de la période d'interruption non planifiée. Les travaux ultérieurs pourraient également porter sur d'autres types d'avantages pour les clients finaux, comme la réduction du nombre de pannes grâce à une prévision précoce des défauts. D'autres aspects de la localisation des défauts peuvent également être pris en compte, tels que la sécurité de l'opérateur et la prolongation de la durée de vie de l'équipement, même si l'on estime qu'ils ne contribuent que faiblement aux économies globales. Bien que la gestion des défauts soit l'une des principales préoccupations des gestionnaires de réseaux de distribution en Suisse, elle s'accompagne d'autres problèmes majeurs auxquels les gestionnaires de réseaux de distribution devront faire face dans un avenir proche. Si la Suisse veut atteindre les objectifs de sa stratégie énergétique 2050, l'augmentation des énergies renouvelables entraînera de nouveaux défis pour la gestion du réseau. Comme le suggèrent de nombreuses études, une surveillance en temps réel ainsi qu'une optimisation et une planification du réseau basées sur des données seront nécessaires pour éviter des coûts exorbitants tout en maintenant des opérations fiables.

Summary

A Smart Grid (SG) will include multiple use-cases ranging from Automated Metering Infrastructure (AMI) to grid Monitoring, Protection and Automation (MPA) based on Phasor Measurement Units (PMU) technology, all connected through a Communication Network (CN). According to the literature, a single communication technology cannot guarantee the necessary coverage nor the fulfilment of all the necessary functional requirements. At the same time a utility cannot provide a federated solution with each service operating on a separate CN. Therefore, a hybrid solution of different technologies is required.

In this project, a methodology that allows the determination of the optimal mix of communication technologies for a combination of use cases has been defined and validated in the field. The use case with the simplest requirements (AMI) and the one with the most difficult requirements (PMU-based MPA) have been selected, implemented and validated for the pilot. Multiple communication technologies have been tested in the pilot: LTE-NB1, LTE-M1, LTE-CAT3 and MTC-MV-PLC PLUS.

The pilot system has been designed and installed in a cluster of three Secondary Substations (SSs) in the Wohlen bei Bern region. The generic pilot test architecture offers a framework for the integration and testing of several communication technologies, not necessarily restricted to the ones tested in this project. Long-term measurements were performed from October 2020 to May 2021. The results show LTE-CAT3 and a combination of MTC-MV-PLC PLUS and LTE-CAT3 as the most suitable technologies for the multi-service CN. Based on the test results it can be expected that LTE-CAT3 will generally achieve with only few exceptions the requirements of most PMU based applications (latency, loss rate and throughput). It is expected that modern fiber networks or future 5G cellular networks will be able to fully meet these requirements. The results of MTC-MV-PLC PLUS show that this technology might enable applications with even higher demands regarding latency, as the measured latencies are in the low one-digit ms range. While the Swiss regulatory limitations on the use of broadband PLC technology on overhead lines may rule out the application of MTC-MV-PLC PLUS for widespread use in a SG, this technology could become interesting for real-time data communication over underground MV lines between sensors and actuators within two or more transformer stations, e.g. for the application of protection systems with the highest latency requirements (including Line Differential Protection). The tests also showed the influence of noise on the MV line limiting the performance of the MTC-MV-PLC PLUS. HSLU continues to have access to the pilot installation beyond the scope of this project and will continue to investigate optimizations that can be done in order to communicate without message loss even in the presence extremely high noise levels on the power line.

The project also demonstrated that the adoption of the PMU technology in the distribution grid can contribute to considerably reducing the economic losses caused by faults to the end customers. The Net Present Value (NPV) of the solution is estimated to be 11M CHF for a mass roll-out on BKW's grid. This analysis only includes costs related to unplanned interruption duration. Further work could include other type of benefits to the end customers such as reducing the number of outages by predicting early-stage faults. Other aspects of fault location can also be considered, such as operator safety and lifetime extension of equipment, although they have been estimated to be minor contribution to the total cost-savings. Despite being one of the major concerns for DSOs in Switzerland, fault management will be soon accompanied by other major problems for DSOs in the near future. If Switzerland were to reach its 2050 Energy Strategy targets, the increase of DER will lead to new challenges in the grid management. As many studies suggest, real-time monitoring along with data-driven grid optimization and planning will be necessary to avoid exorbitant costs while maintaining reliable operation.

Contents

Acronyms

AC	Alternating Current
ADC	Analog-to-Digital Converter
AFE	Analog Front End
AMI	Automated Metering Infrastructure
BPL	Broadband Power Line Communications
CAPEX	Capital Expenditure
CC ISN	Competence Center of Intelligent Sensors and Networks
CN	Communication Network
COSEM	Companion Specification for Energy Metering
DAC	Digital-to-Analog Converter
DC	Data Concentrator
DER	Distributed Energy Resources
DLMS	Device Language Message Specification
DMS	Distribution Management System
DN	Distribution Network
DNO	Distribution Network Operator
DSL	Digital Subscriber Line
DSO	Distribution System Operator
EMC	Electromagnetic Compatibility
FO	Fiber Optic
GPRS	General Packet Radio Service
GPS	Global Positioning System
GTW	Gateway
HES	Head End System
HSLU	Lucerne University of Applied Sciences and Arts
ICT	Information and Communications Technology
IP	Internet Protocol
ISM	Industrial, Scientific, and Medical
LAN	Local Area Network
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution (4G)
LV	Low Voltage
M2M	Machine to Machine
MPA	Monitoring, protection, and automation
MTC	Mission- and Time-Critical
MV	Medium Voltage
NB-IoT	Narrowband Internet of Things
NB-PLC	Narrowband Power Line Communication
NPV	Net Present Value
OPEX	Operating Expenditure

PDC	PMU Data Concentrator
PLC	Power Line Communication
PLUS	Power Line data bUS
PLUS-TimeSync	Time Synchronization Protocol for PLUS
PMU	Phasor Measurement Unit
PS	Primary Substation
PTP	Precision Time Protocol
RER	Renewable Energy Resources
RF	Radio Frequency
SCADA	Supervisory Control and Data Acquisition
SFOE	Swiss Federal Office of Energy
SG	Smart Grid
SM	Smart Meters
SS	Secondary Substation
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
VoLL	Value of Lost Load
VPN	Virtual Private Network
WAMS	Wide Area Monitoring System
WAN	Wide Area Network
WP	Work Package

1 Introduction

1.1 Background information and current situation

Worldwide pressure is increasing on the Distribution Networks (DN) with the rapid introduction of distributed generation from renewable energy resources (RERs), such as wind/solar farms, new type of loads, such as electric vehicles, and energy storage systems. Future grids must be kept robust to accommodate new energy flow patterns with a high time dynamic characteristic due to the vast amount of spatially distributed sources with time-varying generation.

Smart Grids (SGs) are seen as the most promising approach to address such challenges and reliably manage large amounts of RERs. A SG is based on the application of Information and Communications Technology (ICT) to the grid, meaning that a Communication Network (CN) infrastructure is required exchanging data between the elements of the grid. However, after many demonstration and pilot SG projects it became clear that CNs cannot be built on single but rather on a hybrid mix of different communication technologies, depending on the specific scenario provided by a Distribution Network Operator (DNO).

<u>*Multi-Service* Communication Networks</u>

In addition, due to economic reasons, a CN must not provide single- but multi-service functionality. Single-service oriented networks are only able to support one single service tailored to a single application (e.g. Automated Metering Infrastructure (AMI)) due to their origin, supported services, performance, or design constraints [1]. Single-service network vision is the traditional or federated approach. AMI is typically seen as the first step for a DNO to the smartification of his grid. However, more advanced Grid Monitoring, protection, and automation (MPA) services are expected to be implemented soon. Building up a separate CN for each service will be uneconomical. Thus, there is a clear economic rationale behind multi-service CNs.

Communication services needed for the SG are only economically feasible when provided by CNs that do not need to be upgraded whenever there is a need to add a new service. They need to provide flexibility and scalability by also considering the requirements of potential future use-cases. The investment associated to network development for a DN is huge as assets are usually spread all over the service area. Any duplication of communication network will lead to significant costs.

<u>*Hybrid* Multi-Service Communication Networks</u>

Complete coverage for all scenarios while at the same time fulfilling all the necessary requirements cannot be provided by a single communication technology [2] and a hybrid solution of different technologies is required. An optimum mix of the different communication technologies is essential as it is generally accepted that no single communication technology can provide 100% coverage of the network [3]. Therefore, the end-to-end path will consist of multiple technologies.

The optimum mix will depend on several factors

- Physical medium (available spectrum, spectrum licensing/usage, Electromagnetic Compatibility (EMC) regulations)
- Industry support (product availability, pilots, rollouts)
- Application support (TCP/IP support, IPv6, DLMS/COSEM support, multicast / broadcast support)
- Application performance (data rates, latency)
- Communications reliability (availability, interference sources/mitigation)

- Security (authentication, encryption)
- Network deployment (scalability, range, coverage, planning/management effort)
- Interoperability (standardization, industry association, interoperability certification)
- Costs (capital expenditure (CAPEX), operational expenditure (OPEX))

Determining the proper mix of CN technologies presents a significant challenge.

Use Cases

No single solution exists for the "smarter grid" CN due to

- the difference of requirements for different parts of the network
- the limitations on investments and expenditures
- the location of the premises to cover are so different that the mix of public/private and wireline/wireless networks is a must
- potentially many different devices, networks, and services to be monitored and managed
- technology availability is limited by a relatively small number of application device vendors.

Designing and developing multi-service networks requires

- understanding of the future services
- higher up-front investment
- managing in a uniform way the communication services provided by different combinations of technologies.

Therefore, different use cases including future applications have to be considered from the beginning in the design of a SG CN.

The spectrum of SG applications is broad, ranging from AMI with a short-term application perspective and low communication requirements to advanced future applications such as MPA with more demanding requirements. The AMI use-case is to transmit the metering data of the Smart Meters (SM) installed in each household to the DNO's Head End System (HES) for billing, monitoring, etc. and to transmit signals the other way, e.g. for load management. This requires bi-directional communication. Figure 1 shows the different communication path variants building a CN based on different communication technologies between the SMs and the head end system.

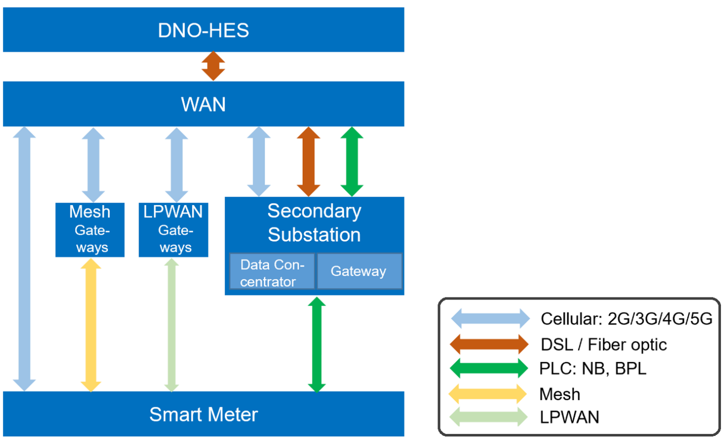

Figure 1: Communication paths and technologies for the AMI use case

A further use-case is Grid MPA services. The increasing integration of RERs in the DN is introducing frequent violations of operational constraints (e.g. overvoltage and line overloading), malfunctioning protection systems and thus increase in the number and duration of power outages. Phasor measurement units (PMUs) – nowadays employed at the transmission system level only – are seen to bear a substantial potential to revolutionize network operation and improve utilization also of the DN. However, they also bear the most challenging communication requirements – much higher than for AMI. To deploy a so-called “synchrophasor network”, synchrophasor data must be streamed from PMUs to one or more PMU Data Concentrators (PDCs) through a CN characterized by

- sufficiently high bandwidth mainly due to the higher refresh rate of such devices (up to 50 measurements/sec),
- low end-to-end latency and limited packet losses due to the criticality of the supported applications (e.g. fault management and real-time renewables control)

<u>CN Requirements</u>

Compared to other SG technologies, PMU communication requirements are thus more demanding, requiring Mission- and Time-Critical (MTC) CNs. This leads to very high CAPEX for the required CN which is currently one of the showstoppers for the broad rollout of such PMU-based MPA solutions into the DN.

Another hurdle to the adoption of PMUs in DNs is represented by their time synchronization requirements. PMUs currently require a sub-microsecond precise time-reference to properly operate. Normally, this is provided by the Global Positioning System (GPS), due to its good trade-off between performance and cost. However, GPS has 2 main drawbacks: (i) accessibility and (ii) security. With respect to (i), the applicability of GPS in DNs is limited, as a good visibility of the sky cannot be always guaranteed, particularly in high-density urban environments. Regarding (ii), recent works have demonstrated that GPS signals can be easily spoofed by superimposing a fake signal with a higher signal-to-noise ratio [4]. To overcome these limitations and enable a massive roll-out of PMUs in DNs, new communication technologies are required to enable PMU data transmission and time synchronization in medium voltage (MV) DNs.

Based on the previously described use-cases, a broad range of communication requirements has to be fulfilled by future multi-service CNs, e.g. for latency, bandwidth, etc. AMI and PMU-based MPA serve as the extreme ends of this broad range of requirements in terms of low- and high-criticality, respectively. However, their cost-effectiveness is also a must. The challenge comes in finding the correct balance between achieving the stricter performance requirements of MPA while at the same time providing a cost-effective and easy-to-deploy solution such that an economically feasible solution can be provided for the large number of SMs in the AMI use-case. Based on that the communication requirements for the selected use cases AMI und PMU-Based MPA are given in Table 1.

Communication Requirements	**Use Case AMI**	**Use Case PMU-enabled MPA**
Transmission Frequency	From once per day to every 15 min	Constant transmission of measurement values
Bandwidth	10 kbps per SS	61 kbps per SS
Latency	Not relevant (time-intolerant)	< 20ms
Bit error rate	No specific requirement	No specific requirement
Time synchronization Accuracy	No specific requirement	+-3.1µs for Transmission Network < 1µs for DN

Table 1: Communication requirements for the AMI and PMU-enabled MPA use cases

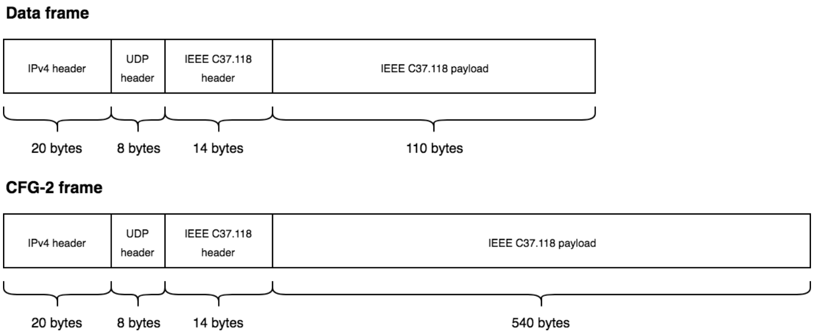

Figure 2: IEEE C37.118 frame format using UDP/IP

In the development of this project, a model of the overall data traffic was developed. The data traffic volume for AMI is shown in Table 1. For the transmission of the PMU data, the IEEE C37.118 in spontaneous mode over UDP/IPv4 is used [5]. The frame format is depicted in Figure 2, which results in total to 152 bytes for data frames (D_{CFG-2}) and 582 bytes for CFG-2 frames (D_{dp}). A CFG-2 frame is a configuration frame which contains information and processing parameters for a synchrophasor data stream. The CFG-2 data frame is transmitted at a reduced rate, typically once every minute. The actual synchrophasor data is contained in the data frames, sent at a rate of 50 frames per second. The actual size of the C37.118 frame may vary among application, especially with the number of transmitted measurement values. Our numbers assume 12 phasor values, 0 analog values and 1 digital status word per PMU [5]. In addition, UDP transmission protocol is considered. The total traffic per PMU or upload throughput (TP) amounts to:

$$TP = \frac{\left(n_{CFG-2} \cdot D_{CFG-2} + n_{dp} \cdot D_{dp}\ [\text{byte/min}]\right) \cdot \left(\frac{8\ [\text{bit/byte}]}{60\ [\text{sec/min}]}\right)}{1000} \quad [\text{kbps}],$$

$$TP = \frac{\left(1 \cdot 582 + 3000 \cdot 152\ [\text{byte/min}]\right) \cdot \left(\frac{8\ [\text{bit/byte}]}{60\ [\text{sec/min}]}\right)}{1000}\ [\text{kbps}],$$

$$TP \approx 61\ \text{kbps}, \qquad (1)$$

where n_{CFG-2} and n_{dp} are the number of CFG-2 and data packets send per minute, respectively.

<u>State-of-the-Art Communication Technologies for SG CN</u>

There are a number of communication technology candidates which are already used today in SG applications - mainly for the AMI use case - as shown in Table 2. For the MPA use case, for both security and reliability reasons, most of existing PMU deployments are based on private legacy wired networks to transmit data from PMUs to the PDC. Modern Wide Area Monitoring Systems (WAMS) of high-voltage transmission grids today rely on Fiber Optic (FO) lines due to their high speed and determinism (e.g. the PMU roll-out in the Lausanne DN). A further advantage of FO is the possibility of using the same communication infrastructure both for data transmission and PMU synchronization. However, still very few DNs are equipped with FO or any other wired infrastructure as their installation costs in both urban and rural DNs are usually prohibitive [6]. Consequently, a rapid wide-spread adoption of FO in DNs seems quite unrealistic.

Currently alternative commercially available communication technologies capable of supporting both data transmission and synchronization requirements of PMU-based MPA applications in a wide range of operating conditions do not exist. The main limitations are the high installation costs and/or poor performance (e.g. bandwidth, end-to-end latencies, and data losses) of existing technologies when deployed in considerably different operating conditions. It is currently unclear if further communication technologies might also provide an accurate time synchronization solution as this is typically not an inherent part of a communications solution.

Technology	Older Standards	State-of-the-art standards	Remarks
Narrowband PLC (NB-PLC)	Meters&More, P-LAN, OSGP	G3, PRIME	Mass G3 rollouts e.g. in France (LINKY) and G3 'mini-rollouts' of several Swiss DNOs, PRIME in Spain (STAR)
Broadband PLC (BPL)	OPERA	IEEE 1901, PLUS	Mainly on MV: OPERA-based rollout in Spain (IBERDROLA STAR) for connecting SS at MV level, pilot projects with using BPL at Low Voltage (LV) for AMI
Cellular	2G/3G	4G / 5G	Many releases in 4G/LTE covering M2M (Machine to Machine) requirements, widespread deployment by Enexis in the Netherlands
RF Mesh		Kamstrup, Zigbee, L+G Gridstream RF	Some pilot projects and rollouts (e.g. CKW [10]), large deployments in North America and Asia due to favourable wireless regulations
LPWAN		LoRa, Sigfox	Some pilots and mini deployments

Table 2 Communication technologies currently used for SG

- Narrowband Power Line Communication (NB-PLC) or Broadband PLC (BPL): Main benefit is that the communication takes advantage of the existing DNO infrastructure (communication directly over the electric grid cables/wires). Currently many DNOs all over Europe are testing or already deploying the NB-PLC standards G3 and PRIME. In Spain, the DNO Iberdrola has finalized in December 2018 their AMI rollout with 10.8 million SMs based on the PRIME standard (STAR project [1]). In Switzerland, different DNOs are currently testing and installing G3. HSLU developed and provided for this test a specialized PLC technology, called Power Line data bUS (PLUS), which has been designed for MTC applications, e.g. in avionics [7]. Regarding PMU time synchronization PLUS also provides a solution with an own developed Time Synchronization Protocol for PLUS (PLUS-TimeSync) [8].

- Cellular (2G/GPRS, 3G/UMTS, 4G/LTE, 5G): traditionally defined for Human-to-Human high-quality mobile voice and data services communications but also a good candidate for M2M communications. In particular, LTE has rapidly evolved with new features to form an attractive solution for emerging M2M applications. Therefore, the global 3GPP standard has promoted two technologies for low complexity devices to support M2M applications. LTE- Machine-Type-Communications and LTE-NB-IoT (Narrow Band Internet of Things). They operate on licensed spectrum. However, as SMs as well as secondary substations (SSs) are typically installed in-building in the basements/underground meaning a high attenuation for the radio waves their accessibility with cellular technologies is rather limited. On the other hand, the installation of an external antenna is often not optimum due to several reasons (missing public acceptance of antenna installations, security reasons). In addition, the OPEX of cellular technologies are rather high. The upcoming 5G cellular standard also seems to provide a promising solution, but technology development is ongoing.

- A Radio Frequency (RF) Mesh network is made up of radio nodes organized in a mesh topology. Wireless mesh networks often consist of mesh clients, mesh routers and gateways. The mesh clients are the end devices while the mesh routers forward traffic to and from the gateway which serves as the interface to the Wide Area Network (WAN). A RF mesh provides good potential, but the regulatory bodies in Europe limit the available spectrum and transmission power.

- Low-Power Wide-Area Network (LPWAN) wireless provides a solution in between that of a cellular and RF mesh technology. LPWAN has adapted the point-to-multipoint connectivity from cellular networks which provides more determinism and easier deployment planning. LPWAN uses unlicensed ISM (Industrial, Scientific, and Medical) bands allowing anyone to operate a LPWAN network as long as the technology adheres to the regulatory guidelines for operation in those ISM bands. A number of different LPWAN technologies exist such as LoRa, Sigfox, Haystack, NB-Fi, Symphony Link, Weightless, RPMA, etc. However, the two main technologies today which have the largest deployments are LoRa and Sigfox.

Table 3 shows the use cases selected for the "Smart Grid Multi-Service Communication Network Pilot", i.e. AMI and PMU-based MPA.

Use-Case Type	**Name**	**Description**
AMI	Domestic Meter Reading	The remote meter reading shall be done according to the requirements of the regulation [9]. The SM should measure the real and reactive power, compute consumption aggregates for intervals of 15 min and store them for 60 days. Also, power interruptions should be detected and logged. Data traffic volume is 4 kByte / 24h.
AMI	Industrial Meter Reading	Industrial meters are usually deployed at grid level 7 at "larger" consumers (manufacturer, bakery, etc.). Further, some meters are deployed at grid level 5 at the level boundaries, where the 16 kV outflow is measured by a measurement transformer. The inflow and outflow are measured every 15 min. Data traffic volume is 6 kByte / 24h.
AMI	Meter Reading On Demand	The remote meter reading shall be done according to the requirements of the regulation [9]. Additionally, a single SM shall be readable upon request of the provider to obtain instantaneous measurements. This selective reading shall be possible in pseudo-real-time, i.e. within seconds. Data traffic volume is 4 kByte / 24h.
MPA	Real-Time Monitoring	PMU data is collected and processed at PDCs and further provided upstream to the utility SCADA/DMS (Distribution Management System) as well as to a local long-term data storage server for offline analysis. Corresponding physical interfaces as well as the necessary communication protocols shall be implemented.
MPA	Protection	Measurement data from multiple PMUs is processed at PDC with a reliable centralized approach for fault detection. Upon fault detection an automatic line tripping mechanism is triggered.
MPA	Fault Location	PMU data is processed at PDC to detect faults. Upon fault detection a message is sent to a SCADA/DMS system, where an operator takes appropriate actions. Alternatively, the message can be directly sent to the remote terminal unit controlling the remote controllable switches.
MPA	Grid Control (e.g. voltage and frequency control, power quality monitoring)	PMU data is processed at PDC to determine system state. State information is used to trigger automatic or manual (executed by an operator) control actions.

MPA	Islanding detection	PMU data is processed to detect islanding situations of a portion of the grid caused by a change in network topology. This guarantees safe grid operation and eventual reconnection.
MPA	Grid model validation	PMU data is processed by algorithms, such as state estimation, that are able to detect and identify grid model errors and estimate network parameters. This method can validate existing network models, ultimately improving the result of state estimation, fault location, load flow analysis, and grid planning.
MPA	Real-time state estimation	PMU data is combined with the grid model to provide real-time insight on the grid's operating conditions (voltage, currents, power flows) at all the grid nodes.
MPA	Condition-based maintenance	PMU data can be used to diagnose equipment malfunctions or miss operation, by evaluating suspicious transient events (such as intermittent faults) or abnormal network state.
MPA	Post-event analysis	PMU data can be stored and analysed offline, enabling precise reconstruction of faults and other events. This improves diagnostic results and allow DSOs to gain experience from previous events.

Table 3: “Smart Grid Multi-Service Communication Network Pilot” – Use-Cases

1.2 Purpose of the project

As previously described, complete coverage for even a single service use-case while at the same time fulfilling all the necessary requirements cannot be provided by a single communications technology. Therefore, a hybrid solution of different technologies is required. Determining the optimal mix of communication technologies including estimations of their costs fulfilling the requirements regarding functionality and performance as well as costs presents a significant challenge.

CC ISN and BKW have developed an innovative systematic methodology for determining the optimal mix of communication technologies for the AMI use-case, capable of supporting a widespread deployment of SMs.

At the core of the methodology are:

- The development of a deployment planning tool (CommTech-Planner), integrating geographical and grid information, simulation, and lab test results as well as a cost analysis allowing the current version to estimate the CAPEX and OPEX for the BKW AMI rollout. The tool already includes all required BKW LV DN data (e.g. substations, topology, cabling information, etc.) and it is currently being enhanced to integrate the grid information data bases of any DNO (not just BKW).
- Testing of the different technologies (modems, gateways, etc.) as well as relevant grid elements (e.g. SMs, data concentrators (DCs)) from different vendors in the Smart-Grid-CommTech Lab which has been specifically designed and installed for that purpose at the CC ISN.

The developed methodology is based on a funnel-like evaluation and selection of communication technologies based on different scenarios (see Figure 3). Different network constellations, representing mixtures of communication technologies, channel conditions, etc. can be first simulated and then tested in the lab in a controlled manner. The results of the testing are continuously fed back into the CommTech-Planner tool. The methodology will be published, and the CommTech-Planner tool will become a tool suitable for use by any DNO. This methodology is shown in Figure 4. In fact, the methodology including the CommTech-Planner tool and the test installation in the Smart-Grid-CommTech Lab has attracted the attention of further Swiss DNOs (Romande Energie, Groupe E, City of Lausanne, City of Basel, Swisspower).

A field pilot test to validate the methodology including different technology scenarios integrating the relevant communication technologies is seen by HSLU and BKW as the 'natural' next step in the selection process for the single-service AMI communication technologies.

The purpose of this project was therefore to validate the methodology in the field for a CN not only fulfilling the single use case AMI requirements but a range of further use cases, thus representing a multi-service CN. This includes the selection, implementation, and testing of new communication technologies for a hybrid multi-service CN, fulfilling the requirements regarding functionality and performance as well as costs. Focus was thus on the definition of a cost-effective and flexible solution based on a mix of different communication and synchronization technologies for different use-cases.

To cover a broad range of use cases the use case with the less challenging communication requirements (AMI) and the one with the most challenging communication requirements (PMU-enabled MPA) were selected. It can be expected that a hybrid CN fulfilling such requirements (Table 1) will also fulfil those with intermediate requirements, e.g. less critical MPA applications.

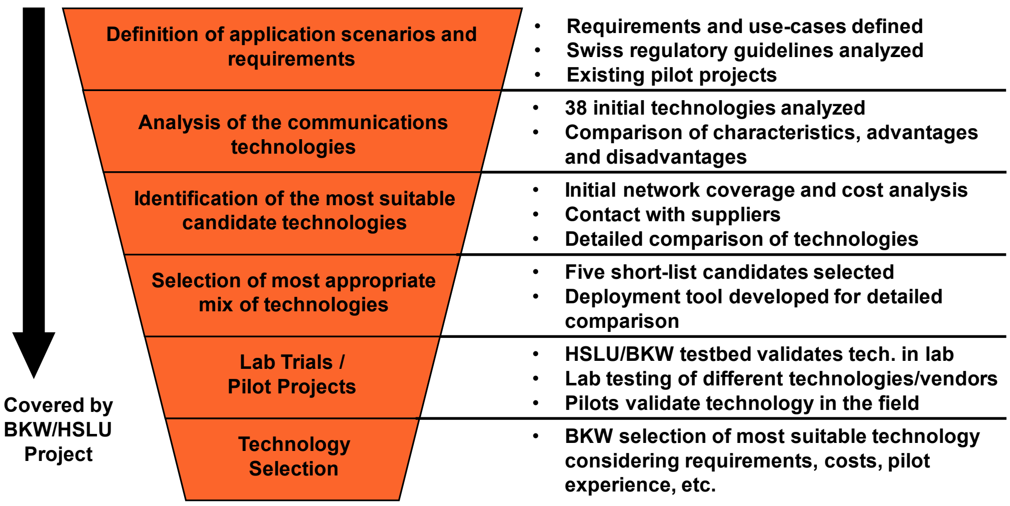

Figure 3 Evaluation and selection process for the optimal mix of communication technologies

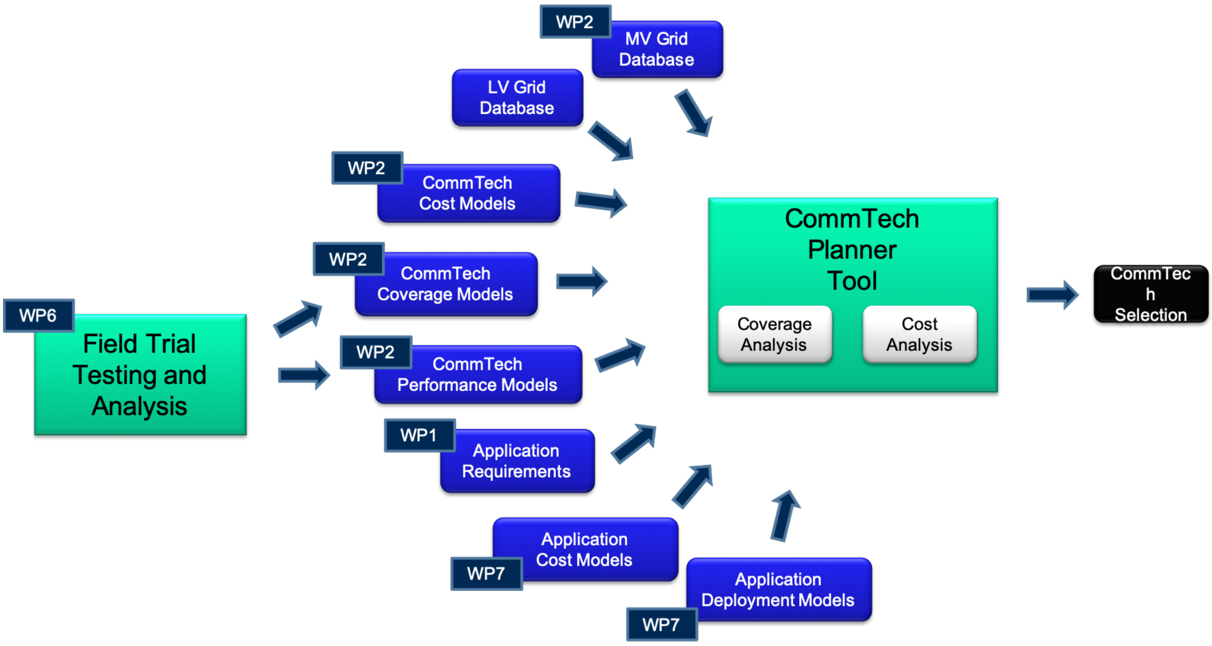

Figure 4 Methodology for the evaluation of communication technologies using the CommTech-Planner Tool

The resulting definition was based on a detailed evaluation of use-cases provided by the Swiss DNO BKW. However, especially regarding PMU-enabled MPA applications, the project consortium also considered the use-cases from former projects / applications of Zaphiro Technologies with other Swiss DNOs within the context of Swiss Federal Office of Energy (SFOE)-funded project (e.g. Romande Energie, Services industriels de Lausanne, Services industriels de Genève) as well as those of BKW within the context of the Gridbox project.

The CommTech-Planner is unique in allowing the design and deployment planning of a hybrid CN architecture, optimally adapted regarding performance and costs for different national and international DNOs. Through the application and enhancement of the methodology and the CommTech-Planner tool, reliable results were derived also regarding the scalability of the pilot tests for a future mass rollout project. This also includes deployment aspects of the CN. Results have shown that network deployment plays a fundamental role in guaranteeing service coverage, performance and meeting the cost budget. For a utility with hundreds of thousands of SMs a scalable deployment strategy is crucial.

The resulting CN scenarios were tested against the functional communication requirements AMI and PMU-based MPA service. Therefore, the results of this project are also valuable for further applications with a broad range of communication requirements. The pilot system was installed in a representative suburban/urban DN section of BKW (Wohlen bei Bern) with a representative size and number of elements so that reliable statements can be drafted for scalability to larger DN portions or even to the DN as a whole. The same approach can also be used to define the optimal technology mix for hybrid CNs tailored to the specific scenario provided by any other DNO.

For Zaphiro Technologies, this pilot project represents an opportunity to test and enhance its PMU-based solution in a realistic grid environment provided by BKW. By integrating novel and cost-effective communication & synchronization technologies into Zaphiro's sensing devices, this project was also expected to increase the flexibility and applicability of Zaphiro's solution to areas with no FO connectivity and with reduced sky visibility to receive a proper GPS signal.

This project also delivers a business case for the economic viability of mass implementation of PMUs into the DN. As previously described, the mass implementation of PMU-based MPA is highly dependent on the costs, which means CAPEX/OPEX for both the PMU equipment / devices as well as the required infrastructure for MTC communication and time synchronization. The business case yields a reliable answer regarding the question if and how PMU-based MPA applications can be realized with bearable costs.

1.3 Objectives

The following outcomes were targeted within this project:

- Validation of the methodology with a pilot system for the determination of the optimal mix of communication technologies for a hybrid CN architecture for a combination of different use cases / services.
- Enhancement of the simulation tool CommTech-Planner's methodology and software for integrating further communication technologies. Results from the pilot tests to the simulation performance / accuracy for the deployment planning of the CN.
- Results regarding the scalability for extension into larger CN installations and mass rollout, including network deployment issues like configuration etc.
- Determination of the optimal mix of communication technologies based on a mix of state-of-the-art and emerging technologies for the use-cases AMI and PMU-enabled MPA. Determination of the optimal time synchronization technology for the PMU-enabled MPA.
- Enhancement of PMU devices from Zaphiro Technologies with new hardware and software modules implementing the selected communication/synchronization technologies. This will improve the flexibility of Zaphiro's solution and its widespread adoption.
- Evaluation of the economic viability / business case for mass implementation of PMUs into the DN.

2 Activities and Results

2.1 Overall project plan

"The Smart Grid Multi-Service Communication Network Pilot" project has been broken down into eight different Work Packages (WP) with different deliverables as shown in Figure 5. The project began in January 2019 and ran through June 2021. The grey highlighted bars indicate the originally planned duration of each of the WPs. Green indicates WPs/deliverables that have been completed. During the last period, the WP for testing (WP6) began later than planned due to development delays and component availability (described later in this report). Nonetheless, the project ran on track and we were able to perform extensive testing.

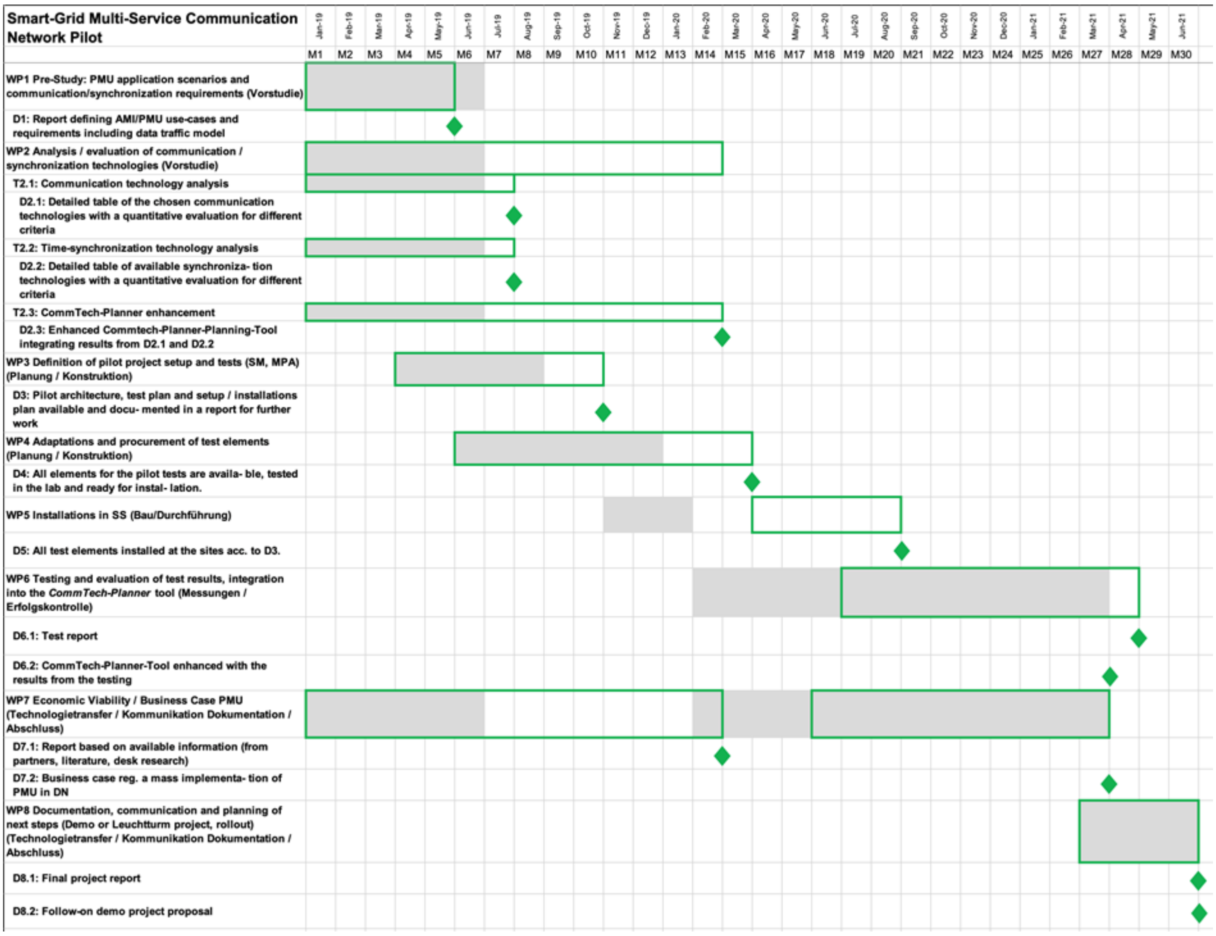

Figure 5: Project Plan for “The Smart Grid Multi-Service Communication Network Pilot”

2.2 System Architecture for the Test Setup

Together with BKW and Zaphiro different use-cases were defined for both AMI as well as MPA. These use-cases are outlined in Table 3. In addition, a system architecture was defined which depicts the setup of the pilot and the main components (actors) involved (see Figure 6). The actors involved in the AMI use-cases are depicted in blue: SMs are located at the consumer’s premises (residential or industrial), DCs are located within SSs and the HES is located at a central control center. The actors involved in the PMU use-cases are depicted in green: PMUs are located at SSs and PDCs are located at primary substations (PSs). Further, PDCs are connected to co-located long-term data storages for offline processing and analysis, and to a central SCADA or a DMS system, which are existing systems operated by the utilities.

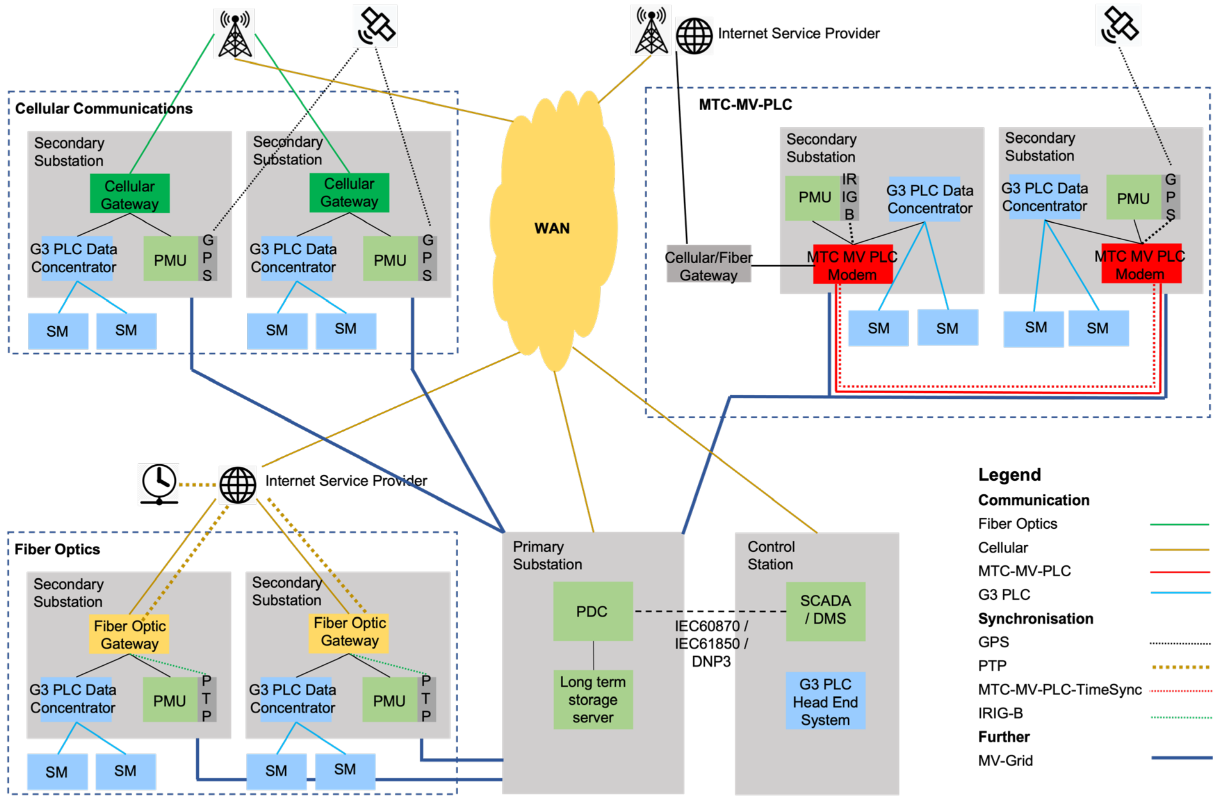

Figure 6: System architecture of an AMI and MPA infrastructure

2.3 Analysis and evaluation of candidate communication technologies

In this section, an analysis of different communications and synchronization technologies has been performed. It considers several criteria including application support, communications reliability, security, network deployment, interoperability, and costs. Each of these criteria were evaluated and weighted resulting in a quantitate “score” to be determined for each of the evaluated communication technologies. Table 15 in the Appendix provides a complete list of all the communications technologies which were evaluated as well as the resulting analysis score for each application and a summary of the results.

For the synchronization technologies a similar analysis was performed for several synchronization technologies. An overview is provided in Table 16 in the Appendix. Within the synchronization technology analysis, a quantitative score was not applied to the analysis, but the technologies were grouped according to the following three criteria:

- Green: the technology fulfils the requirements and will be available during the next years.
- Yellow: the technology has some limitations, or its market situation isn’t predictable for the next years.
- Red: the technology does not fulfil the requirements or will not be available on the market during the next years.

The grouping is based upon the colour coding of the conclusion column in Table 16.

The final task in the analysis and evaluation of candidate technologies was to extend the available CommTech-Planner tool in order to support the following features:

- Integrate new (not yet supported) communication technologies from the technology analysis which included the FO and MTC-MV-PLC PLUS technologies.
- Integrate the PMU-based MPA application. Support for different PMU deployment use-cases and the PMU application cost-analysis.
- Integrate the MV grid infrastructure. Previously only the LV grid had been integrated into the tool. The MV grid was necessary in order to support the MTC-MV-PLC PLUS communication technology and the PMU application.
- Adapt the CommTech-Planner tool to support a generic interface to a utility's grid database so that further databases beyond BKW could be supported. This feature has been tested by integrating the databases of the Swiss utilities Onyx and AEK into the tool for the AMI application.

A screenshot of an example PMU deployment is shown in Figure 7. In addition to these aspects, a cost model and analysis for the PMU application has also been developed. This cost model is based on a model which has been developed for the AMI application for a widescale rollout of the AMI application. It has been adapted to provide a cost analysis for the widescale rollout of the PMU application. Costs for the PMU specific equipment and the communications equipment are separated in the tool. The cost model includes the following components:

- Material Costs (CAPEX)
    - Communications modules including antennas for wireless technologies
    - PMU
    - PDC
    - Current/voltage sensor
- One-off expenses (CAPEX)
    - Communications module installation costs
    - Communications module setup costs
    - Communications network planning per module
    - PMU installation costs
    - Current/voltage sensor installation costs
    - Deployment service per PMU
- Running costs (OPEX)
    - Flat-rate costs per communications technology (falls applicable)
    - PMU software license
- Maintenance (OPEX)
    - Maintenance costs per module and year (based on the device lifetime)
- Reinvestment (OPEX)

The cost model also takes into consideration a rollout duration and Weighted Average Cost of Capital. More information about the results of the cost analysis with the PMU application is provided in section 3 below.

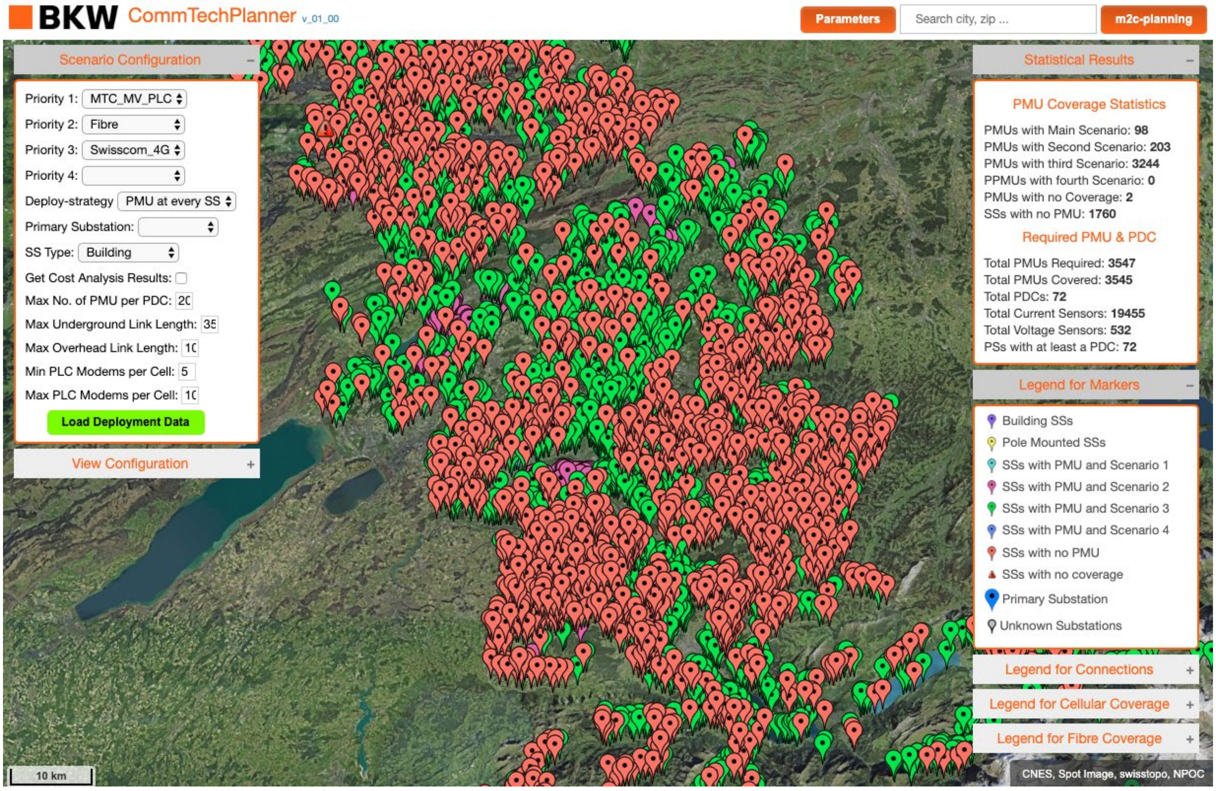

Figure 7: Example of a deployment scenario for PMU application with the CommTech-Planner Tool

2.4 Definition of the pilot project setup and tests

To select the SSs which could potentially be used for the pilot, BKW provided a list of 47 SSs in the region Wohlen bei Bern (see Figure 8). The list was created based on the plan for future renovations of SSs and/or cables/wires between the SSs. As long-term tests are planned in this project it was necessary to ensure that the targeted SSs and MV infrastructure will be available during the complete testing period. Therefore, SSs targeted for renovation within the project duration were excluded from the list. From the list of available SSs three different clusters were identified which would provide a suitable grouping of SSs for the pilot. These are shown in the boxes in Figure 8. The availability of the different communication technologies requiring a connection from a service provider was then clarified with Swisscom and Sunrise with the support of BKW for providing key points-of-contact with Swisscom and Sunrise. The resulting availability is summarized in Table 4.

Unfortunately, a FO connection is not available at any of the targeted SSs for the pilot – neither through the public nor the business FO networks. Due to the lack of a FO network to the SS buildings, both Swisscom and Sunrise said they could not offer us a FO connection.

5G is also only partially available from Sunrise in the targeted region and exact coverage would have to be determined through measurements. According to Swisscom coverage maps, 5G is available in that region. Swisscom provides coverage for LTE-M and LTE-NB-IoT in that region, however exact coverage would also have to be determined through measurements. Therefore, on August 21, 2019 measurements for the availability of the different LTE technologies and 5G were made at the different clusters of SSs. The results are summarized in Table 4.

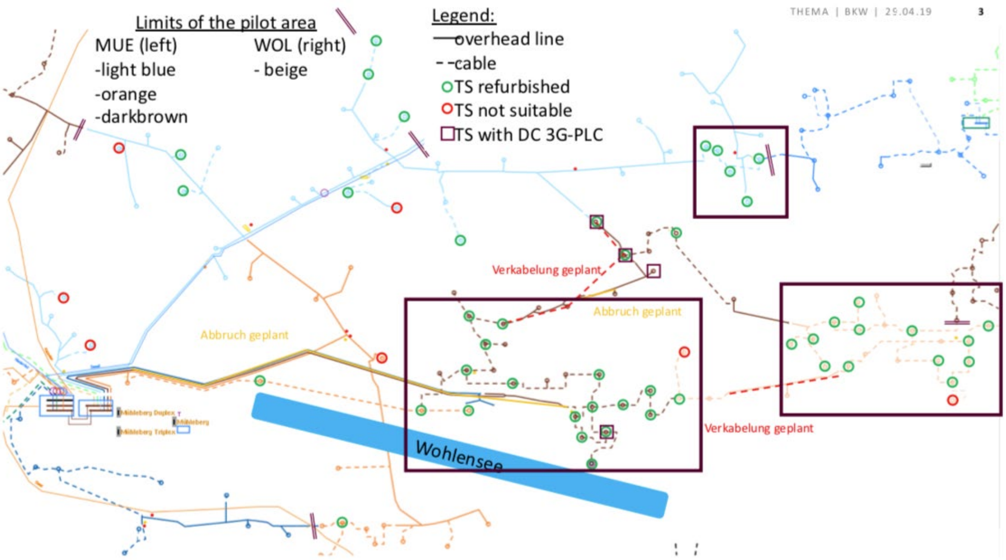

Figure 8: Potential SSs for pilot in Wohlen bei Bern region

Several 5G routers were found available in the Swiss market (e.g. Huawei 5G CPE PRO 2, Netgear Hotspot Nighthawk M5, Zyxel NR2101, HTC 5G router), however, none of them had a configuration option to force a connection to a 5G network. There was also no means to remotely monitor the connection that was selected (e.g. 4G, 5G). This made it impossible to use those routers for the pilot testing as there was no way to guarantee that 5G was actually being used during tests. The availability of suitable 5G routers was monitored throughout the duration of the pilot testing, however no routers became available as March 2021.

Additionally, the 5G rollout in Switzerland has found since its beginning major detractors who concern about the adverse effect of wireless radiation for people's health. This has caused social and political disputes and to some extent, it has slowed down the progress of 5G in Switzerland, in particular of 5G Plus. For instance, committees like "STOP 5G" carry out intense campaigns against the installation of new antennas and the mass rollout of 5G. The disagreements continue to the present day.

Based on the availability provided by Swisscom and Sunrise and the availability measurements a decision has been made on which technologies to include in the pilot which is shown in the final column of Table 4.

Communication Technology	Swisscom	Sunrise	Measured Availability on 21.08.19	Included in Pilot Testing
MTC-MV-PLC PLUS	N/A	N/A	N/A	Yes
Public FO Network	No	No	N/A	No
Carrier Line Service FO Network	No	No	N/A	No
Carrier Ethernet Sensing FO Network	No	No	N/A	No
LTE-CAT3	Yes	Yes	Yes	Yes
LTE-M1	Yes	No	Indoors at most of the SSs within cluster	Yes
LTE-NB-IoT	Yes	No		Yes
5G	No	Partial	No indoor availability. Sporadically available outside the SS.	No

Table 4 Summary of communication technology availability in the targeted pilot location

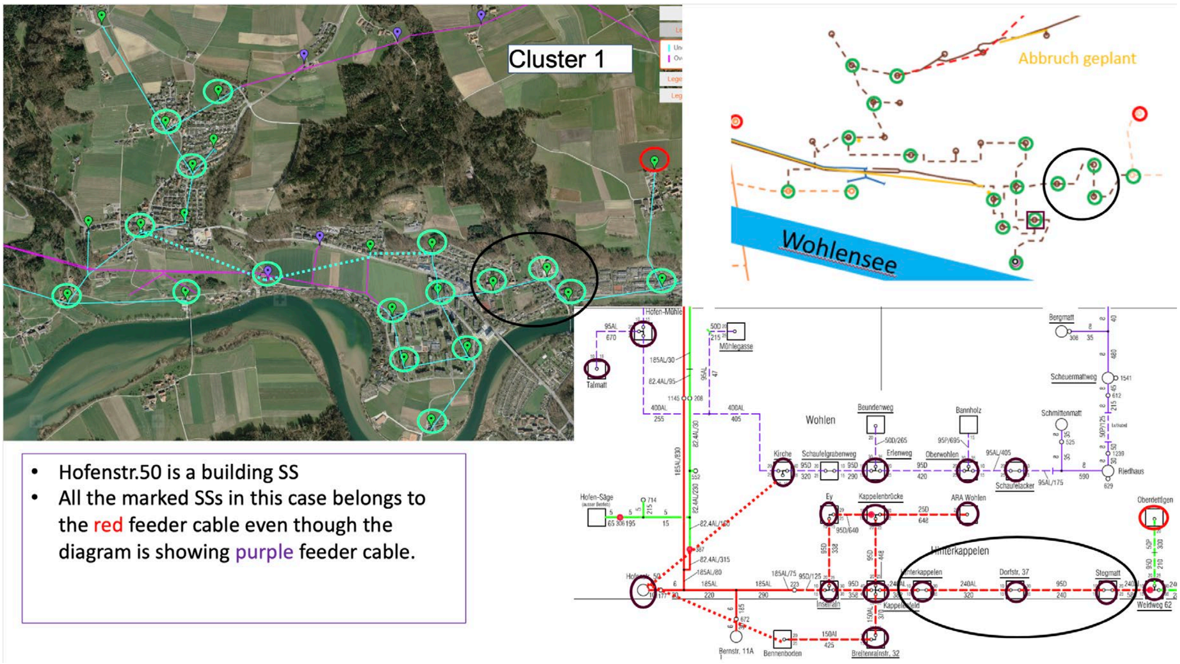

Figure 9: Selected test environment and SSs

Figure 9 shows the test environment and the SSs selected for the pilot in Wohlen bei Bern. The 3 SSs are along a MV feeder in Hinterkappelen, with the SSs Hinterkappelen, Dorfstrasse and Stegmatt. They are connected with underground MV cables of 320 m length between SSs Hinterkappelen and Dorfstrasse and 240 m length between SSs Dorfstrasse and Stegmatt. This feeder connected to the PS Mühlerberg until 17.03.21.

A detailed architecture for all the equipment which have been integrated in each SS for the pilot was defined and is shown in Figure 10. It takes into consideration all the communication technologies targeted for integration in the pilot shown in Table 4. A test plan for long-term testing to be performed has also been defined. This directly includes the PMU devices for testing the PMU application. A decision was made that enough AMI data exists through existing pilots and deployments within BKW's networks, that the existing measurement data can be used for the analysis of the AMI application.

The different hardware elements purchased, developed, and integrated in the pilot test are shown in Figure 10.

- At the time the pilot test architecture was designed there was only one 5G router available (HTC 5G Hub). This router is mainly targeted for consumer internet service and provides very limited network configuration options which has made it a challenge to integrate into the pilot networking concept. Also, there is no support to install an external antenna so it will need to be placed outside the metal cabinet. There is also no way to force a 5G connection or observe the actual connection technology (i.e. 3G, 4G, 5G) remotely. This currently severely limits the test capabilities of 5G. We have also tested a 5G router from ZTE – ZTE MC801. Similar to the HTC 5G router, we found that the router did not work reliably when trying to remotely force a 5G connection.
- The GPS antenna has been mounted on an external wall of the SS. In order to provide a sufficiently accurate time synchronization (comparison) it was found that an antenna with a clear view of the sky should be used.

- Inductive couplers were selected for MTC-MV-PLC PLUS. Originally capacitive couplers for gas insulated switchgear were targeted for use, however it was found that the usage of these couplers is highly dependent upon the switchgear manufacturer as the switchgear must provide enough space for integrating the coupler. The switchgear in the targeted SSs for the pilot do not provide enough space for these couplers. Therefore, inductive couplers from the company Arteche are used.

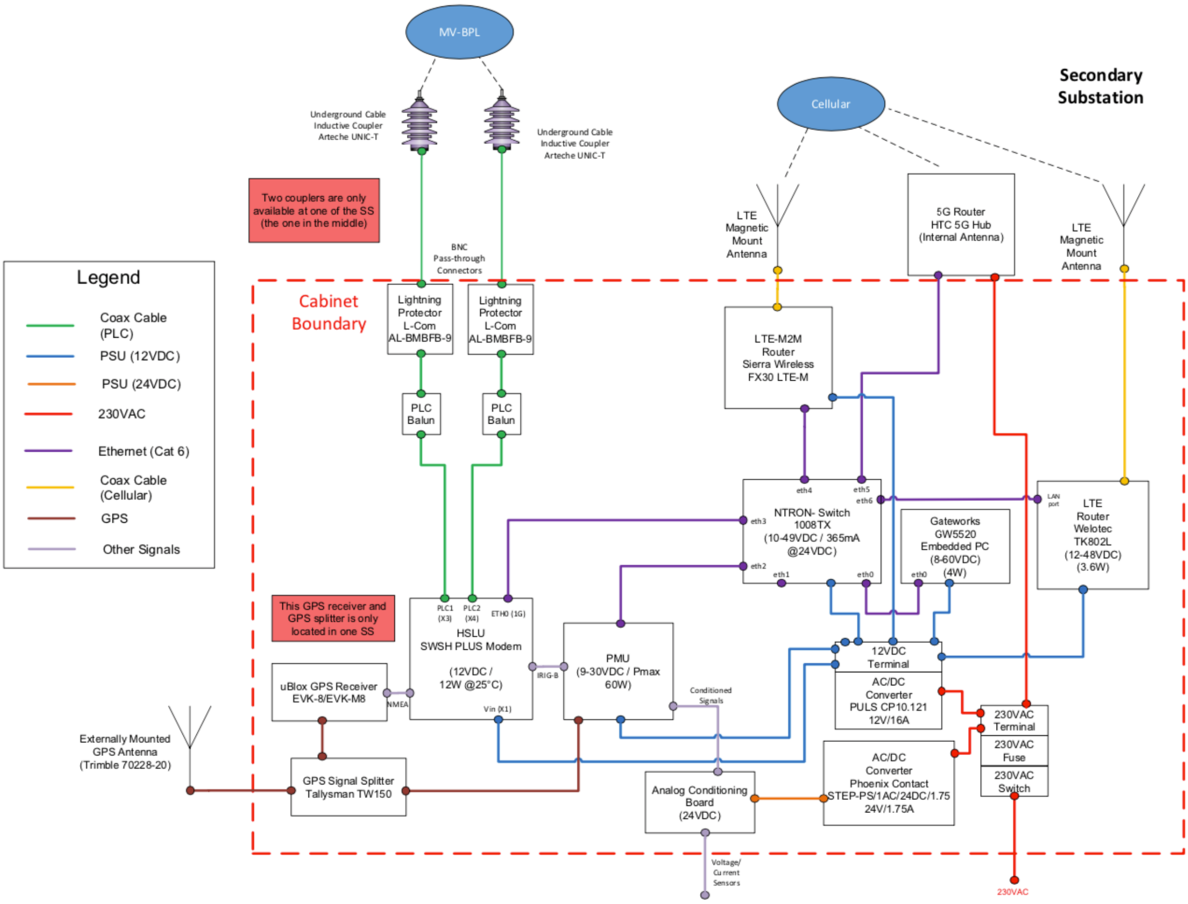

Figure 10 Pilot test equipment installation architecture

Additionally, the MTC-MV-PLC PLUS modems and the PMU have been adapted to support the proper time synchronization interface. An interface using the IRIG-B standard has been selected. IRIG-B is used to provide the PMU the time synchronization from the PLUS modem prototypes which synchronize the time over the MTC-MV-PLC PLUS network using the PLUS-TimeSync protocol [8]. The adaptation was completed in February 2020 and integration testing with the MTC-MV-PLC PLUS modems and the PMU was performed in March and April 2020.

The performance of communications technologies can be time-variant due to changes in environmental conditions, congestion, etc. Therefore, long-term measurements were planned to be performed to provide a sufficiently large dataset for analysis. Access to SSs is not readily available due to safety and security reasons which means the required access to SS during testing should be limited as much as possible. A solution for remotely accessing the test equipment as well as automation of the testing has been developed. Taking into consideration the previous point as well as the fact that multiple communications technologies were to be tested, a means for automatically switching between different technologies has been defined. The hardware for all technologies can be switched during testing to only use one technology under test at a time.

A significant challenge in the evaluation of the performance of different communications technologies is that a realistic data traffic is required for testing. The data traffic can then be used to evaluate the network performance in terms of availability (e.g. packet error rate and bit error rate), throughput (achieved bandwidth) and latency. However, testing becomes difficult if communications technologies are used within an operational application environment due to the following reasons:

- Traffic generated by the application may not be sufficient to test the performance limits of communication technology. It is often the case that it is not possible to place the application equipment in a mode in which higher data traffic could be generated as this is not relevant for the application. Especially considering that the target is a multi-service CN it will likely be necessary to generate additional traffic to best emulate multiple services.
- Even if suitable data traffic would be generated for testing the limits of the technology, it is often the case that the application equipment does not measure the performance or provide an interface to access these measurements.
- Additional data traffic could negatively influence the normal application traffic if it is not sent at the proper time.

For these reasons a two-step approach was implemented when testing:

- Application equipment would be used to test and validate the functionality of the application with the communication technology under test.
- Additional test devices would be installed together with the application equipment. These network test devices would be used to generate additional traffic to test the performance limits of the communication technologies.

Figure 11 shows a simplified architecture of the testing architecture for the three SSs. Devices in blue are the application equipment, while in green are the communication technology devices. Devices in orange are specialized equipment provided for testing. As can be seen multiple communications technologies were installed in parallel[1]. The application devices are connected to the communication technologies through the data network router. This router ensures that the application traffic is routed to the correct communications technology interface depending upon which technology is currently being tested. In addition, a network testing device was installed at each SS. This device is used to measure application device traffic, generate / measure dedicated data traffic for performance limit testing and enable remote access to the devices within the SS. Remote access is provided over a secure LTE link to the test management server, which not only serves as the centralized control for all testing but acts as a traffic endpoint for measurements.

[1] The technologies shown are the result of the analysis of candidates for our pilot. However additional technologies may also be tested by the same generic pilot architecture.

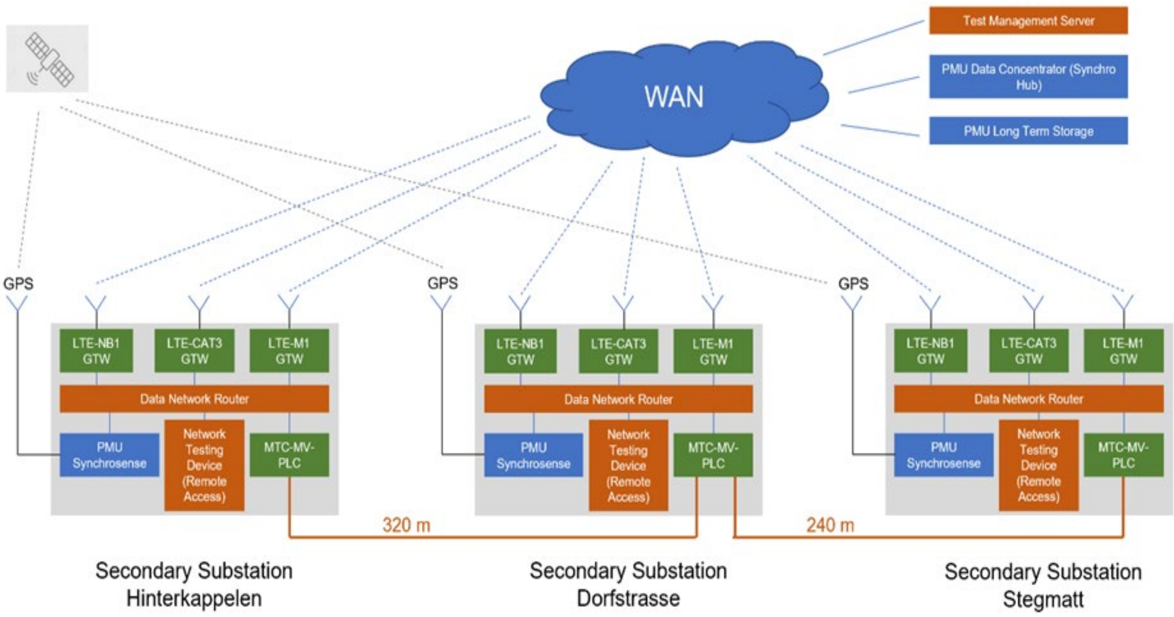

Figure 11 Generic pilot architecture

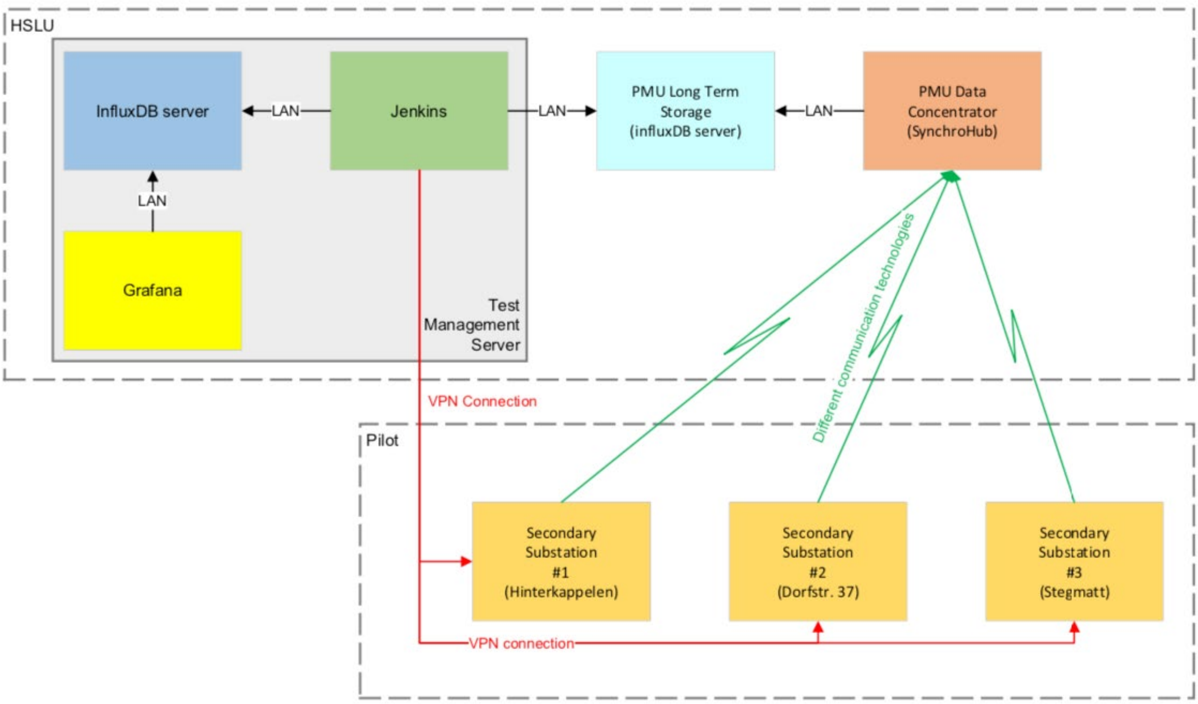

Figure 12 Remote access and testing – detailed server architecture

A more detailed server architecture is shown in Figure 12. Remote access to the demonstrator is provided through a secure Virtual Private Network (VPN) tunnel to the CC ISN (HSLU) LAN. Furthermore, an embedded personal computer from Gateworks (GW5520) is installed at each enclosure, which serves as the network testing device. GW5022 provides up to two Ethernet interfaces and runs an embedded Linux operative system. Different network test applications are installed on each GW5520. An instance of a Jenkins continuous integration server is used to control the test automation. Test results and data are stored on one side on a InfluxDB server with data made available for visualization through an instance of Grafana. On the other side the PDC (SynchroHub) stores PMU data into a separate instance of InfluxDB which is available to Jenkins for further analysis.

The installation of the pilot was originally planned to begin in November 2019; however, it was delayed due partially to component unavailability as well as development delay in previous stages. The equipment for the pilot was installed at the three different SSs shown in Figure 12. A single cabinet was installed in each SS. The equipment in each cabinet is shown in Figure 10. The installation was performed in three different phases as summarized in Table 5. The PMU voltage and current sensors were not available for the first installation date due to delivery delays. This allowed initial tests to be performed with all the communications equipment. Initial tests with the MTC-MV-PLC PLUS equipment showed that a PLC link was not available between two of the three SSs. This was identified to be an issue with the installation of the PLC coupler. The PMU voltage sensors were installed on June 23, 2020. The PLC coupler issue was also fixed during that installation. This allowed initial PLC channel measurements to be performed in July which are described in next section. Finally, the PMU current sensors were installed on August 31, 2020 which completed the pilot installation. Figure 13 shows some example photos from the pilot installation. The photo in the upper left shows the MV PLC inductive coupler installed around one of the three phases in the MV underground feeder cable. The picture in the upper right shows the GPS antenna installed outside of one of the SSs. A bracket was constructed for mounting the antenna to ensure that good line-of-sight to the satellites is available to improve GPS accuracy. The picture on the bottom shows the test cabinet installed on the inside wall of one of the SSs.

Date	Installed Elements
April 23-24, 2020	Test cabinets with PMUs, MTC-MV-PLC PLUS modems, LTE-CAT3 gateways, LTE-M1 gateways, LTE-NB1 gateways, GPS antennas, PLC couplers
June 23, 2020	PMU voltage sensors / Fix PLC coupler issue
August 31, 2020	PMU current sensors

Table 5: Pilot installation phases

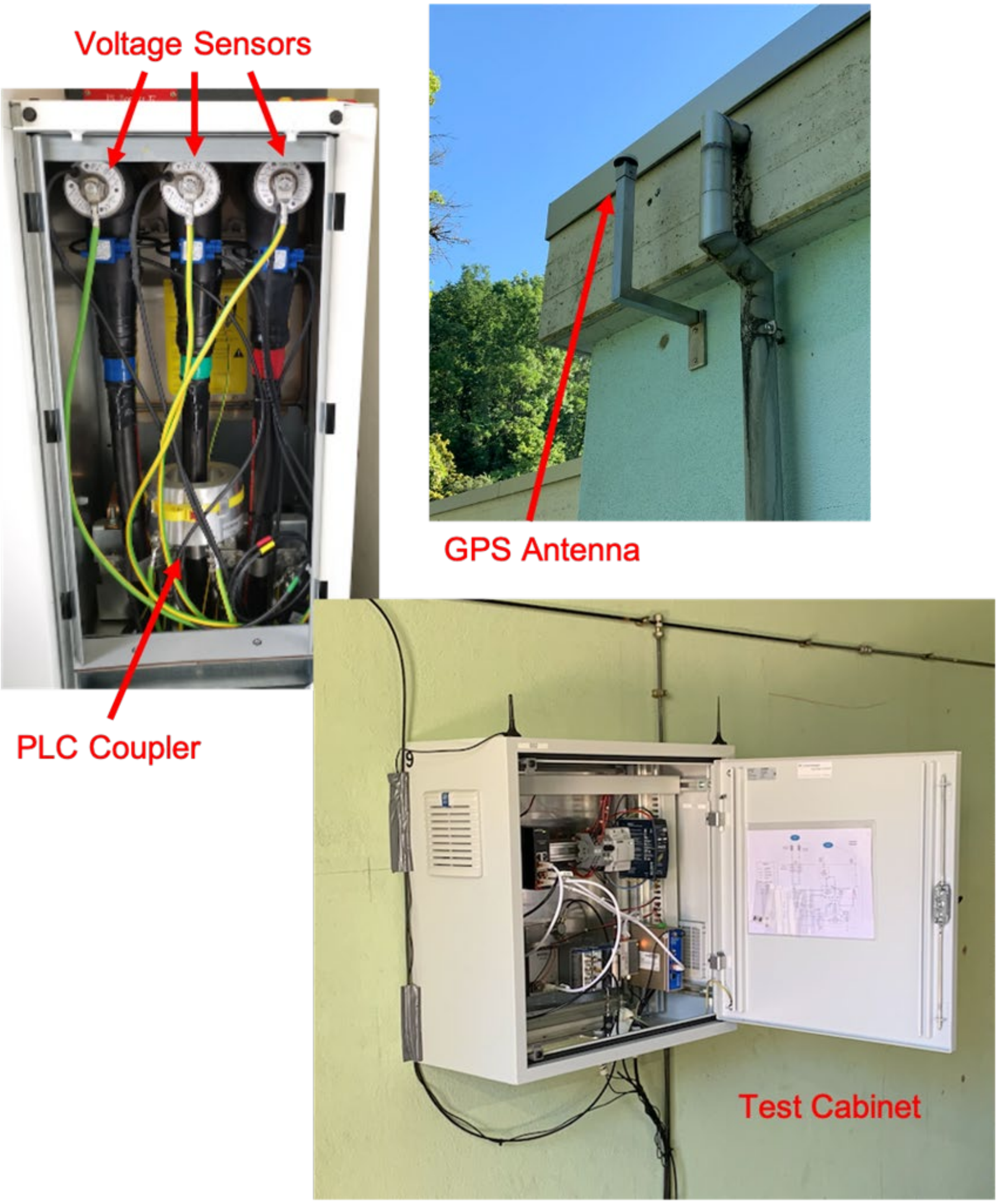

Figure 13: Pilot installation pictures

2.5 Analysis of test results

2.5.1 Communication Technologies

As an important part of this project, extensive functional and long-term performance testing of each communication technology has been carried out. Time synchronization performance has been compared against a GPS receiver-based solution. Latency, data loss and throughput measurements have been made with each communication technology. The CommTech-Planner-Tool has been enhanced with the results of the tests.

Functional tests were started on the different communication technologies after the second installation campaign, as discussed in previous section. Tests began by verifying the availability of the communication link with the different technologies. After that a PLC channel measurement campaign was performed from July 6-13, 2020. The PLC channel attenuation was measured between all SSs. Also, noise measurements were performed over the course of a week. Initial communications testing with the MTC-MV-PLC PLUS technology showed a time-dependence in the link quality. The goal of this measurement campaign was to verify that observation with low-level signal measurements using a spectrum analyser. The channel attenuation measurement results are shown in Figure 14 and the noise measurement in Figure 15. The results depicted in Figure 14 show that the channel attenuation is low enough to support reliable communications up to about 20 MHz which is in line with previous measurements and modelling on MV underground cables. On the other hand, the noise measurements show higher noise in the evening between about 19:00-21:00. A potential source of this noise could not be determined, however time-variant behaviour of the PLC channel was expected which is why long-term measurements were planned to be performed.

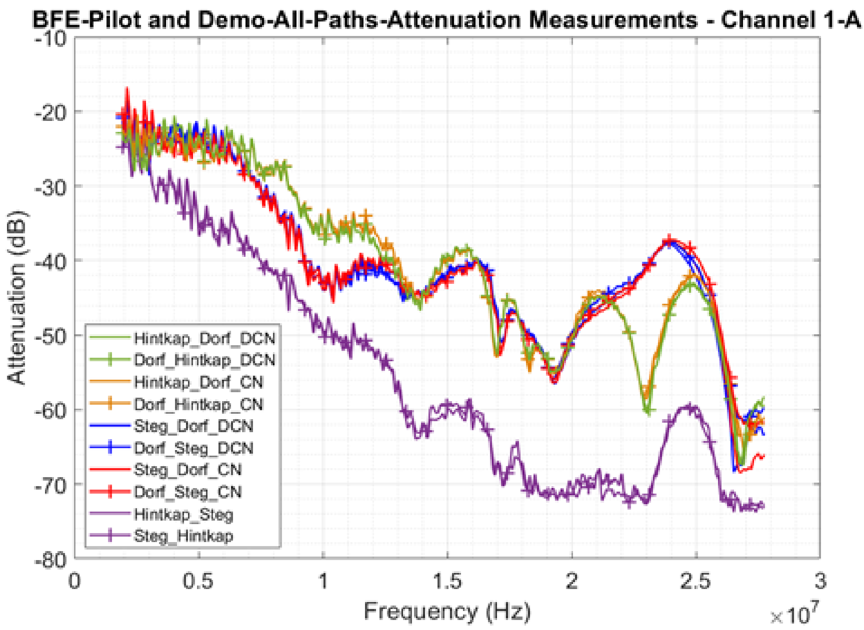

Figure 14: Measured PLC channel attenuation between different SSs

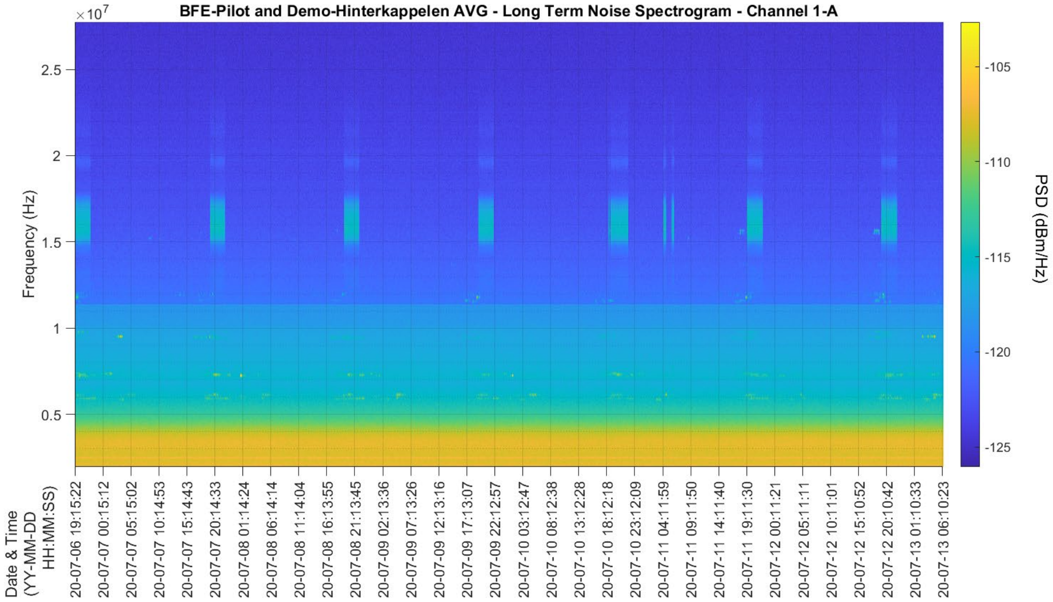

Figure 15: Measured long-term noise spectrogram on the MV power line

After successful installation of the PMU current sensors on August 31, 2020, full functional measurements of the PMU application were performed. Also, the complete long term automation test concept was finalized and verified. Long term testing was officially started on October 1, 2020. A schedule was defined for testing each of the communication technologies that has been integrated into the pilot. Each of the technologies was tested for approximately 24 hours by transmitting all traffic between the PMUs and the PDC over that technology. Each PMU generates a message every 20 ms and the message includes a timestamp. The periodic nature of the traffic allows message loss to be determined and the timestamp allows one-way latency value to be accurately measured. There is a short period of time for collecting results and performing some additional testing before switching to a different communication technology. The lowest time resolution represented (i.e. a measurement point) for loss rate values is calculated by averaging 5 min of measurements taken with the same technology. For the latency, three points were stored for every 5 min of measurements, i.e. maximum, average, and minimum value.

An example of the test schedule for testing between 01.10.2020-11.11.2020 is shown in Figure 16, where the green bars represent the technology being measured vs. time. The following encoding was used: LTE-NB1 = 1, LTE-M1 = 2, MTC-MV-PLC PLUS + LTE-CAT3 = 3, LTE-CAT3 = 4, and MTC-MV-PLC PLUS-TimeSync = 5, e.g. 3 on the y-axis means that MTC-MV-PLC PLUS + LTE-CAT3 has been measured but not LTE-NB, LTE-M1, LTE-CAT3 or MTC-MV-PLC PLUS-TimeSync. The testing of the LTE-NB1 technology has been limited due to issues with the LTE-NB1 gateway device.

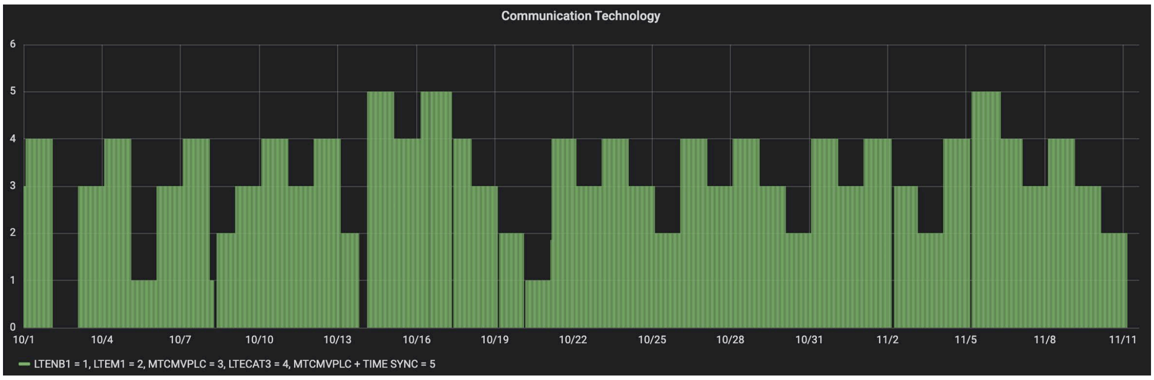

Figure 16: Communication technology test schedule between 01.10.2020-11.11.2020

The scheduling of LTE-M1, MTC-MV-PLC PLUS + LTE-CAT3 and LTE-CAT3 is summarized in Figure 17. The plot represents the total number of intervals of 5 min measured per month at each SS. For instance, LTE-CAT3 was measured 3’000 times in February, which is equivalent to 15’000 min / 250 h.

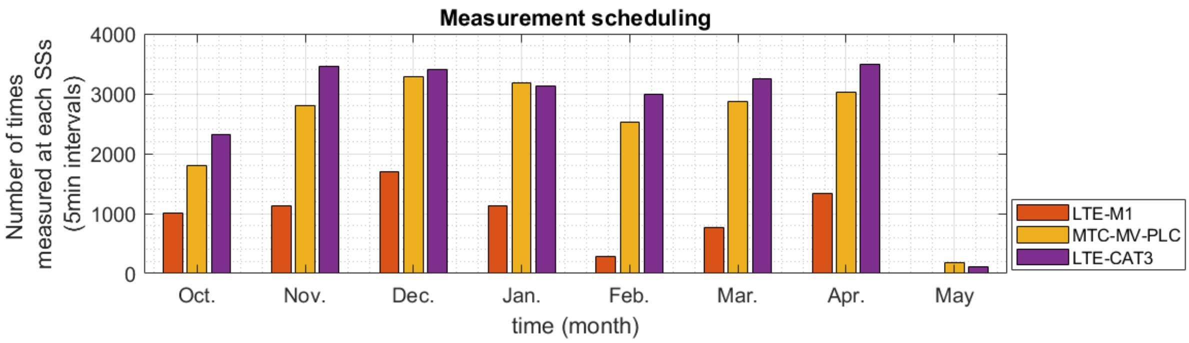

Figure 17: Communication technology test schedule between 10.10.2020-01.05.2021

As shown in Figure 12, measurement results are stored in InfluxDB and can be visually displayed using Grafana. The measurements were planned so that when one technology was tested, the others were not. The end-to-end connection between the PMUs in the SSs Dorfstrasse and Stegmatt and the PDC when using MTC-MV-PLC PLUS consists of the PMU measurements being transported over MV power line to the SS Hinterkappelen and from there to the PDC over LTE-CAT3. In other words, the end-to-end connection uses two different communication technologies in a row. For this reason, additional performance measurements were made over just the MTC-MV-PLC PLUS technology, i.e. only between SSs.

To process the data to draw conclusions, we calculate three metrics out of each measured parameter, i.e. loss rate, latency, and throughput. These metrics are defined as the maximum, average and minimum value. The way we calculate them is explained below. The metrics for the latency are obtained differently from those for loss rate and throughput, because of how the measurements were stored. As was previously explained, for the latency measurements only the maximum, mean, and minimum value over the 5 min blocks have been stored, not the whole set of measurements.

Maximum, average, and minimum value of the loss rate / throughput: The maximum value is calculated as the 99% percentile[2]. This metric is used to leave outlier values out of the analysis but to include most of the samples in the measurement set. Likewise, the minimum value is calculated as the 1% percentile, while the average, as its name indicates, is calculated as the average.

Maximum, average, and minimum value of the latency: For every 5 min blocks three values of latency were measured and stored, i.e. “Latency max.”, “Latency mean”, and “Latency min.”. Out of those measurements, the maximum value is calculated as the 99% percentile of “Latency max.”, the average is obtained as the average of “Latency mean”, and the minimum is derived as the 99% percentile of “Latency min.”. We decided to calculate the minimum latency as the 99% percentile of “Latency min.”, instead of the 1% percentile as for the loss rate and throughput, because the set of measurements stored in “Latency min” already contains only minimum values (i.e. the minimum values of the measurements taken over 5 min). Therefore, the 99% percentile of this set is more representative of the minimum value of the latency than the 1% percentile.

Figure 18 shows the signal paths from the PMU in the SS Hinterkappelen over the different communication technologies to the PDC. The MTC-MV-PLC PLUS is not involved as this SS acts as the MTC-MV-PLC gateway from the MV-PLC network to the WAN through the LTE-CAT3 gateway.

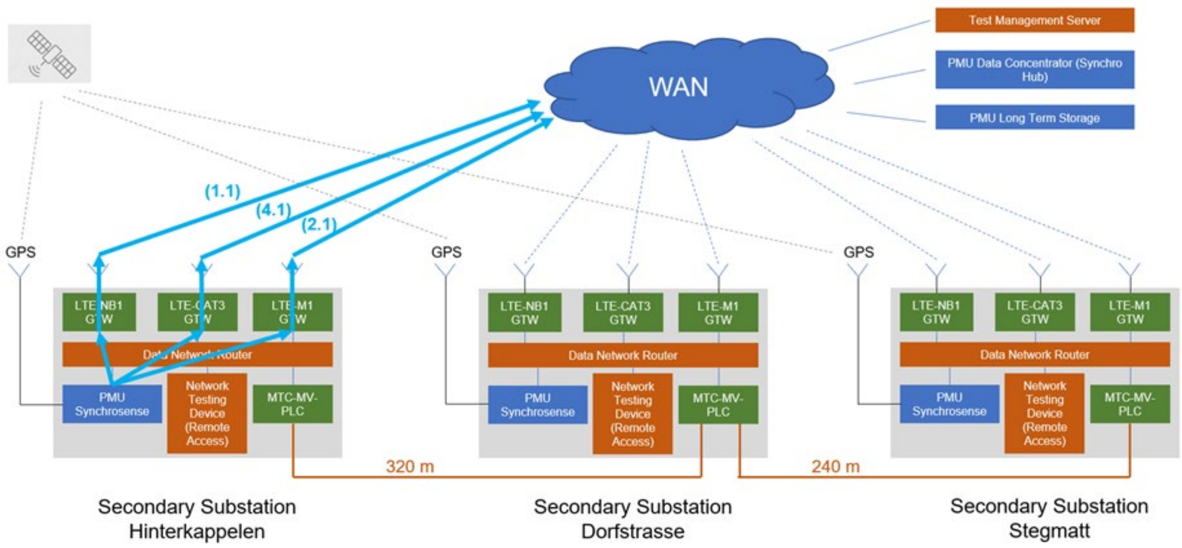

Figure 18: Different signal paths from the PMU in SS Hinterkappelen to the PDC

Figure 19 and Figure 20 show the signal paths from the PMUs in SSs Dorfstrasse and Stegmatt, respectively. For instance, path (3.2) is via the MTC-MV-PLC link to the SS Hinterkappelen and from there via the LTE-CAT3 path to the PDC, and path (3.3) goes along two hops to SS Dorfstrasse and then to SS Hinterkappelen over the LTE-CAT3 link to the PDC, with a whole distance over the underground MV cable of 560 m.

[2] The percentile describes the distribution of the observations. A given percentile X% (e.g. 99%, 95% or 1%) is the value where the X% of the samples fall below.

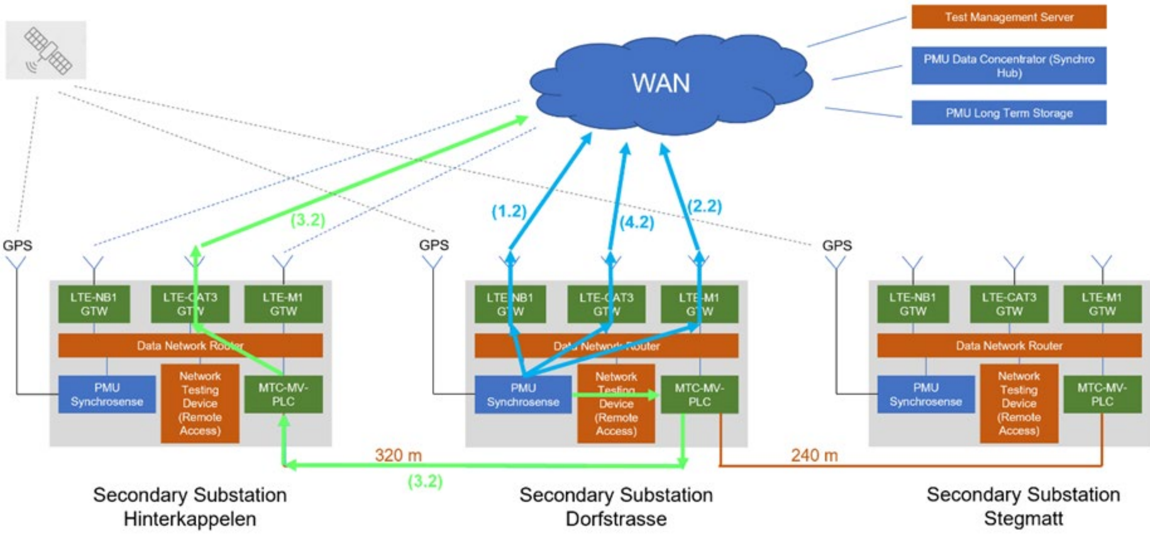

Figure 19: Different signal paths from the PMU in SS Dorfstrasse to the PDC

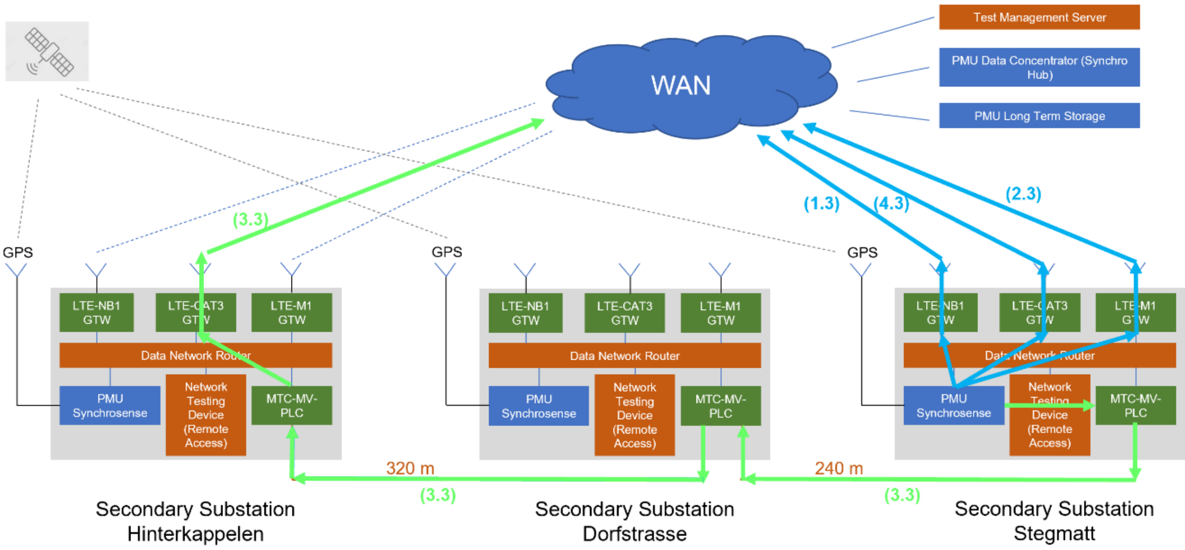

Figure 20: Different signal paths from the PMU in SS Stegmatt to the PDC

Table 6 shows the results of the performance of the four communication technologies over the 11 links of the test scenarios, for the entire time duration over which the measurements were performed. Such results must be compared to the requirements set for the PMU use case:

- Latency < 20 ms
- Throughput > 61 kbps (1)

Regarding the reliability / availability there were no quantitative requirements initially set for the data loss rate. However, as a result of the test procedure, it turned out that this is another important performance criteria. A limit of 1 % has been therefore assumed. A simple colour legend is used to colour in green or orange those values that do or do not meet the requirements.

ss Hinterkappelen			(1.1) LTE-NB1	(2.1) LTE-M1	MTC-MV-PLC PLUS + LTE-CAT3	(4.1) LTE-CAT3
	Loss rate (%)	max.	95.67	13.79	NA	0.10
		avg.	94.15	0.41	NA	0.03
		min.	91.86	0.00	NA	0.00
	Latency (ms)	max.	70'765.17	2'307.90	NA	652.27
		avg.	43'617.49	56.20	NA	17.68
		min.	51'950.70	13.80	NA	13.80
	Upload Throughput (kbps)	max.	40	540	NA	5'140
		avg.	20	200	NA	4'890
		min.	0	0	NA	0
SS Dorfstrasse 37			(1.2) LTE-NB1	(2.2) LTE-M1	(3.2) MTC-MV-PLC PLUS + LTE-CAT3	(4.2) LTE-CAT3
	Loss Rate (%)	max.	97.75	0.84	1.80	0.11
		avg.	94.93	0.09	0.12	0.03
		min.	89.07	0.00	0.00	0.00
	Latency (ms)	max.	130'605.71	1'516.04	616.77	741.88
		avg.	56'385.48	44.35	19.99	16.40
		min.	89'870.24	15.90	16.20	11.10
	Upload Throughput (kbps)	max.	40	520	2'990	5'160
		avg.	20	290	2'400	4'970
		min.	0	0	2'180	4'640
SS Stegmatt			(1.3) LTE-NB1	(2.3) LTE-M1	(3.3) 2 hops MTC-MV-PLC PLUS + LTE-CAT3	(4.3) LTE-CAT3
	Loss Rate (%)	max.	95.81	51.00	1.95	0.10
		avg.	93.02	1.58	0.09	0.02
		min.	89.05	0.00	0.00	0.00
	Latency (ms)	max.	62'047.01	6'599.60	616.22	666.09
		avg.	39'053.12	86.22	20.14	17.58
		min.	53'938.67	1153.69	16.60	12.40
	Upload Throughput (kbps)	99%	40	550	2'310	5'170
		avg.	20	220	2'140	4'950
		min.	0	0	1'800	4'540

Table 6: Test results for the different paths from 10.10.2020 – 01.05.2021

The following conclusion can be drawn from the results in Table 6:

- LTE-NB1: very high loss rates of about 90% and more, and latencies of several tens seconds with throughput of 20 kbps mean that this technology does not only fail to fulfil the requirements of PMU, but also those of most applications with lower requirements, even for the AMI use case. This is because the bandwidth is not sufficient which leads to high loss and high latencies. Therefore, this technology has been taken out of any further analysis.
- LTE-M1: Throughput is in the range of several 100's of kbps but with average latencies in the range of 40 - 90 ms does also not fulfil the latency requirements of the most demanding PMU use case, but probably for use cases with less stringent latency requirements this technology could still be considered. At SS Stegmatt also the loss rate is quite high, therefore not fulfilling the reliability requirement.
- LTE-CAT3 fulfils all requirements for the PMU use case, in particular throughput and loss rate. Latency requirements are met for the average case, but not for the maximum case.
- MTC-MV-PLC PLUS + LTE-CAT3: For signal paths with a transmission between the SSs via MTC-MV-PLC PLUS (paths (3.2) and (3.3)) similar performance results as for LTE-CAT3 are observable. The latency figures are slightly higher than for LTE-CAT3 alone (and in one case the requirement is not met for the average). However, it can be observed that most of the latency seems to be produced by the LTE-CAT3 part of the end-to-end transmission. To validate this assumption, Table 7 displays in more detail the data as shown in Table 6 for the MTC-MV-PLC PLUS transmission between the SSs only (single hop between SSs Hinterkappelen and Dorfstrasse as well as SSs Dorfstrasse and double hop between SSs Hinterkappelen and Stegmatt). From that table we can see that LTE-CAT3 contributes to about 75% of the overall end-to-end latency. It can further be observed that the maximum loss rates of paths (3.2) and (3.3) are beyond the required limit when considering the overall test duration. Therefore, the results have been split into three different time periods for the results analysis. The reason for that was that during the monitoring of the tests some problems started to occur after 17.03.21 and it was found out that the MV feeder for the SSs Dorfstrasse and Stegmatt was then switched from the PS Mühlerberg to the PS Worblaufen. Up to then the test results looked very positive but then after they became somewhat worse. So, for the analysis the test period was divided in a first one which starts with the beginning of the tests on 10.10.20 and lasts until 17.03.21, and the second one from 18.03.21 till 01.05.21 (end of the tests). It is apparent that the period after 17.03.21 mainly contributes to the higher loss rate and latency figures.

Table 7 shows that

- as already assumed above most of the latency on the paths (3.2) and (3.3) is contributed by the LTE-CAT3 but not the MTC-MV-PLC PLUS technology, whose contribution is in the lower one-digit ms range, far below the 20 ms set as the latency requirement for the PMU use case.
- The throughput is over the whole test period at an average of about 2 Mbps.
- maximum latency and loss rates were generally higher after the switch of the feeder which happened on 17.03.21

Besides the overall statistical test results the time-dependence of the performance indices is important. Therefore, the overall analysis of the measurements was broken down into weeks to try to identify trends and isolated deviations, which could have been caused by specific situations. Such outliers may strongly influence the global measurements analysis even though they rarely occur. Figure 21 to Figure 32 depict the results for the weekly data loss, latency, and throughput for the whole period.

	SS Dorfstrasse 37 – SS Hinterkappelen (1 hop)								
	Loss Rate (%)			Latency (ms)			Throughput (kbps)		
	max.	avg.	min.	max.	avg.	min.	max.	avg.	min.
10.10.20 - 01.05.21	3.00	0.15	0.00	14.70	4.92	2.83	2’990	2’400	2’170
10.10.20 - 17.03.21	0.00	0.00	0.00	14.42	4.78	2.82	2’560	2’290	2’170
18.03.21 - 01.05.21	10.00	0.45	0.00	28.59	5.20	2.83	2’990	2’700	2’250

	SS Stegmatt – SS Hinterkappelen (2 hops)								
	Loss Rate (%)			Latency (ms)			Throughput (kbps)		
	max.	avg.	min.	max.	avg.	min.	max.	avg.	min.
10.10.20 - 01.05.21	3.00	0.20	0.00	17.15	5.61	4.18	2’310	2’140	1’800
10.10.20 - 17.03.21	0.00	0.01	0.00	15.34	5.24	3.20	2’310	2’210	2’050
18.03.21 - 01.05.21	17.00	0.60	0.00	19.18	6.36	4.29	2’200	1’940	1’800

	SS Dorfstrasse 37- SS Stegmatt (1 hop)								
	Loss Rate (%)			Latency (ms)			Throughput (kbps)		
	max.	avg.	min.	max.	avg.	min.	max.	avg.	min.
10.10.20 - 01.05.21	1.00	0.05	0.00	616.06	5.20	2.95	2’310	2’140	1’810
10.10.20 - 17.03.21	0.00	0.00	0.00	14.50	4.89	2.95	2’310	2’210	2’040
18.03.21 - 01.05.21	5.00	0.15	0.00	1’223.36	6.02	2.95	2’180	1’930	1’800

Table 7: Summary table of the MTC-MV-PLC PLUS (SS-SS) measurements for three time periods

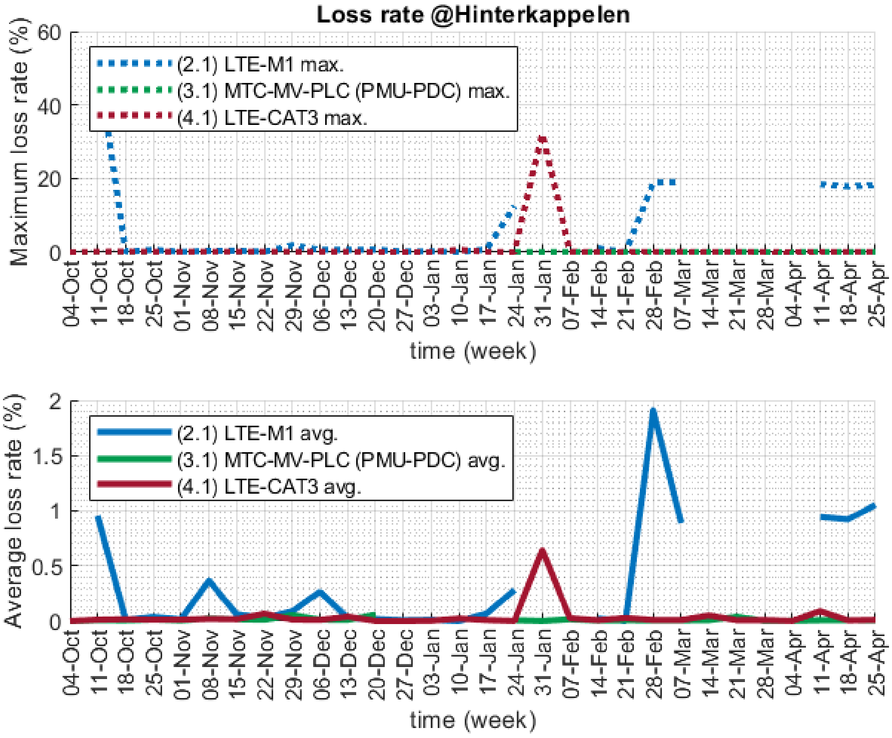

Figure 21: Maximum (top) and average (bottom) loss rate per week at SS Hinterkappelen (signal paths (2.1) and (4.1))

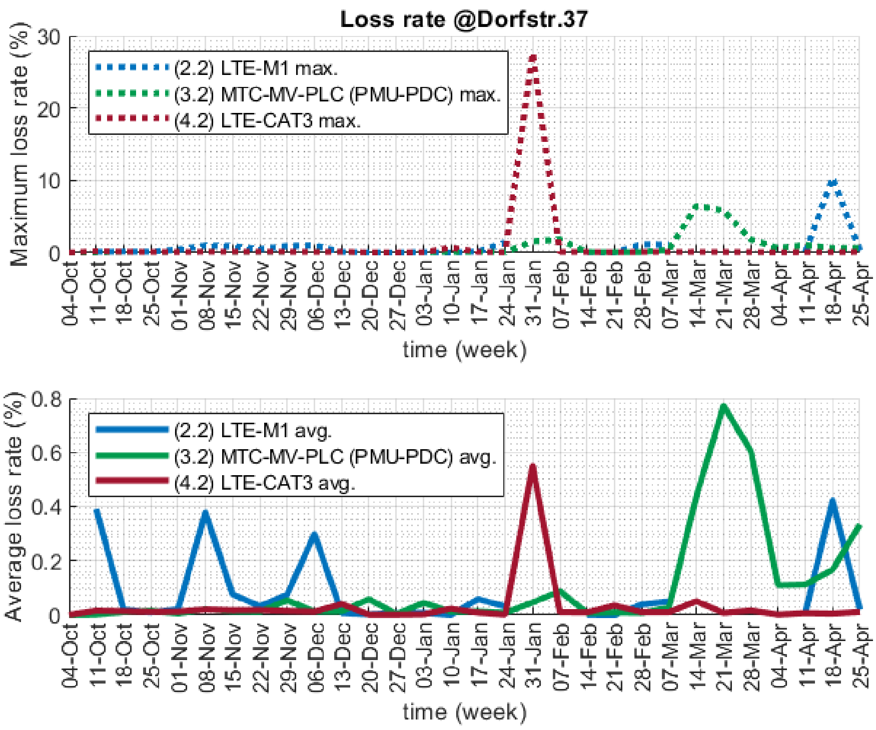

Figure 22: Maximum (top) and average (bottom) loss rate per week at SS Dorfstrasse (signal paths (2.2), (3.2) and (4.2))

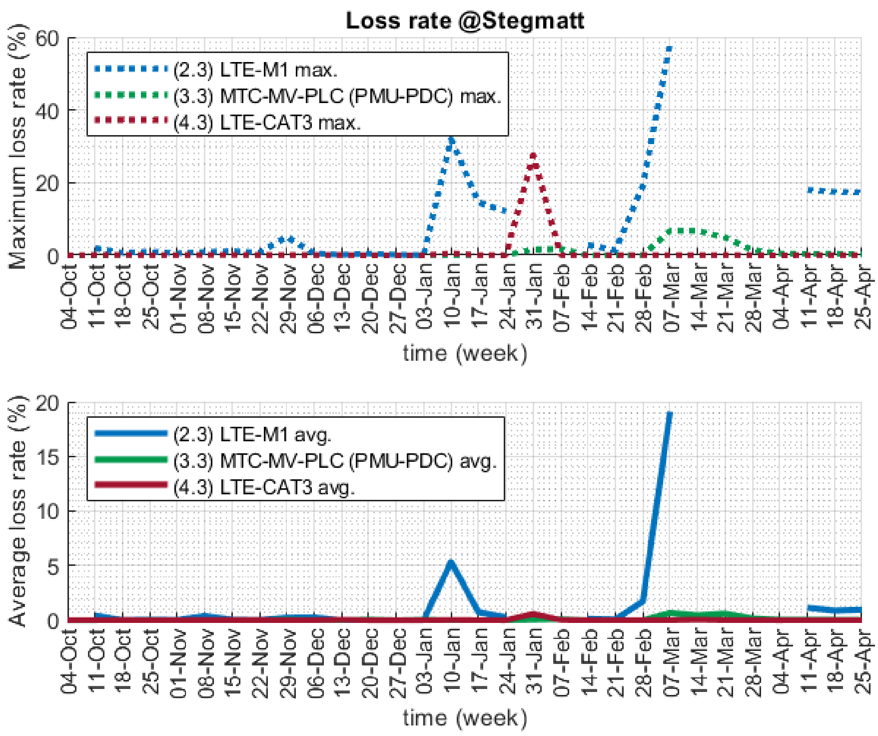

Figure 23: Maximum (top) and average (bottom) loss rate per week at SS Stegmatt (signal paths (2.3), (3.3) and (4.3))

Figure 21 shows data loss peaks higher than the 1% limit for both LTE-M1 as well as for LTE-CAT3 max. Likewise, Figure 22 shows data loss peaks for all three technologies. The increased loss rate of MTC-MV-PLC PLUS appeared around 17.03.21 when the MV feeder was switched from PS Mühlerberg to PS Worblaufen. After 11.04.21 there is another increase in loss rate. This will be further analysed below. There are peaks in the loss rate for all three technologies in Figure 23 as well. For MTC-MV-PLC PLUS it increased after 17.03.21 but came back down afterwards to low levels where it remained through the end of the testing. The data loss peak shown at the three SSs for LTE-CAT3 on the week of the 31st of January, is due 1h of high packet loss on the 5th of February.

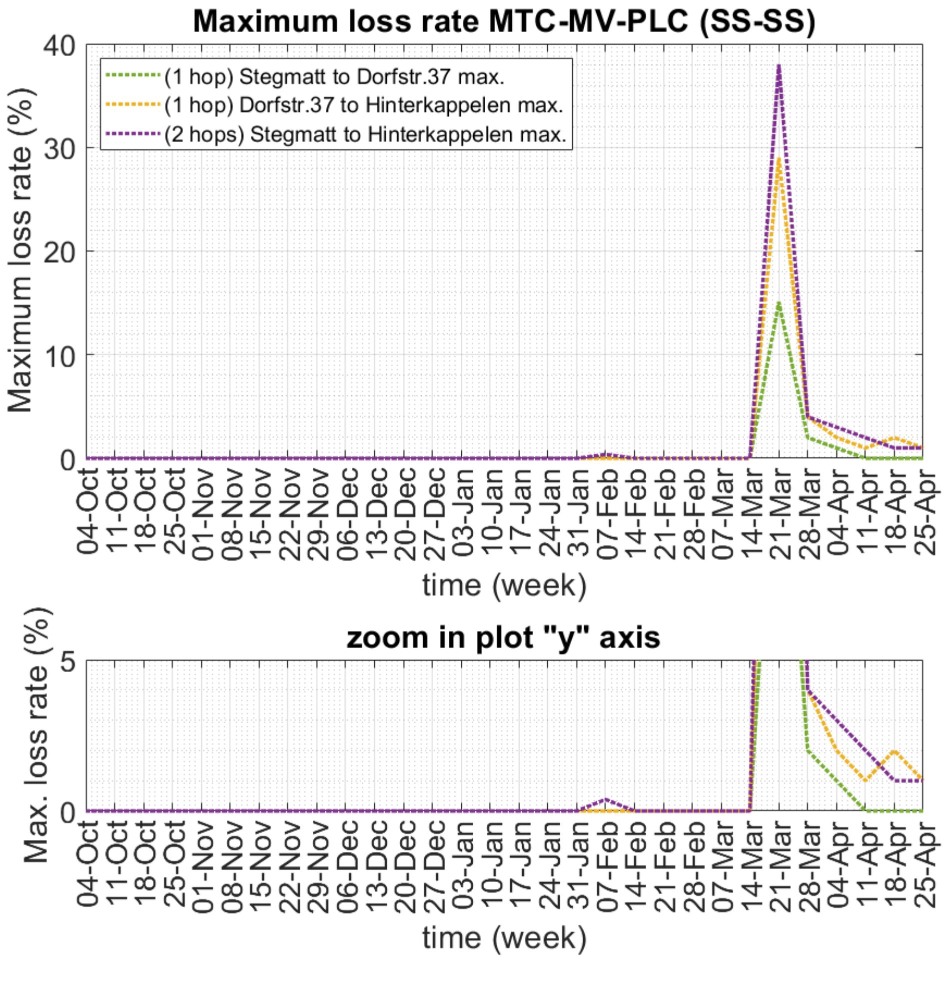

Figure 24: Maximum loss rate per week, MTC-MV-PLC PLUS (SS-SS)

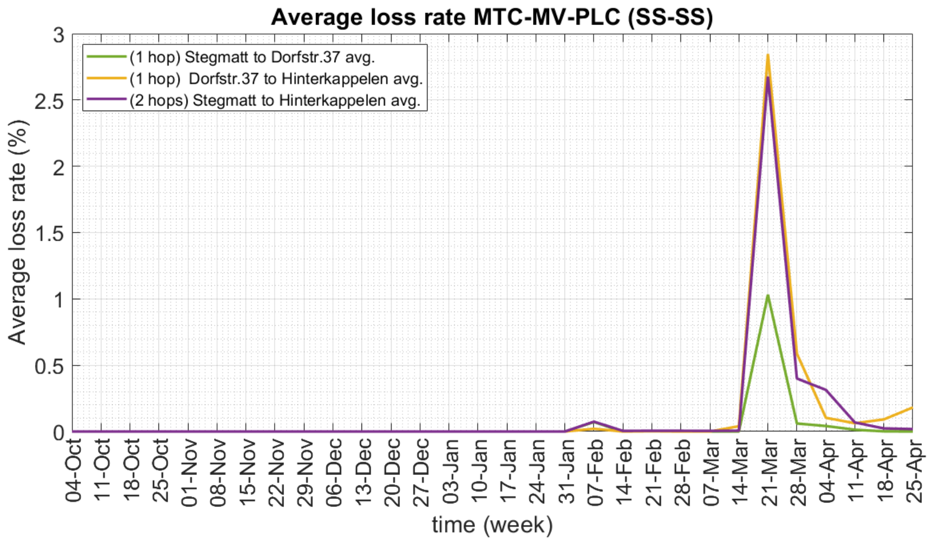

Figure 25: Average loss rate per week, MTC-MV-PLC PLUS (SS-SS)

The loss rate increase described before at the SSs Dorfstrasse and Stegmatt is clearly visible and is attributable to the loss rate in the PLC path between the SSs.

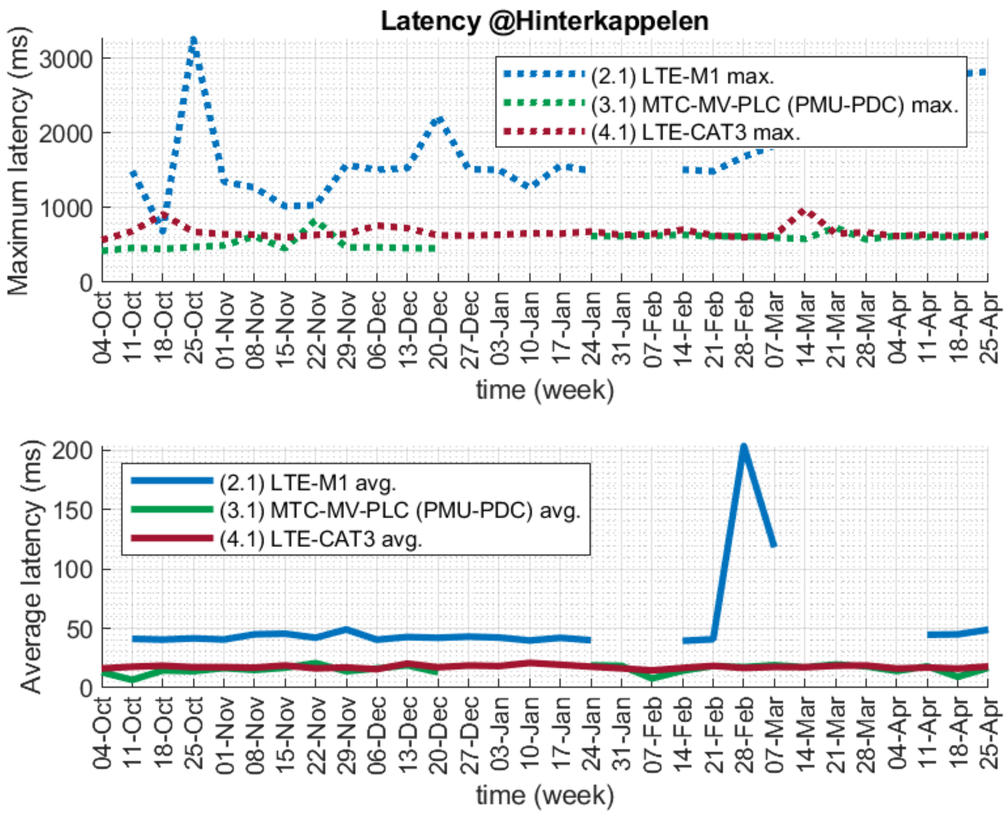

Figure 26: Maximum (top) and average (bottom) latency per week at SS Hinterkappelen (signal paths (2.1) and (4.1))

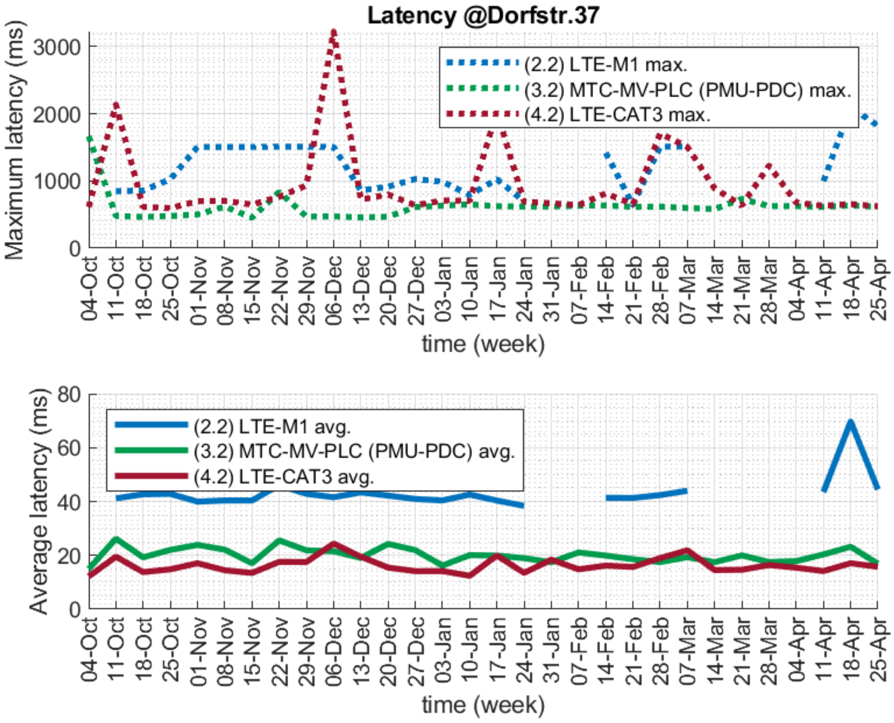

Figure 27: Maximum (top) and average (bottom) latency per week at SS Dorfstrasse (signal paths (2.2), (3.2) and (4.2))

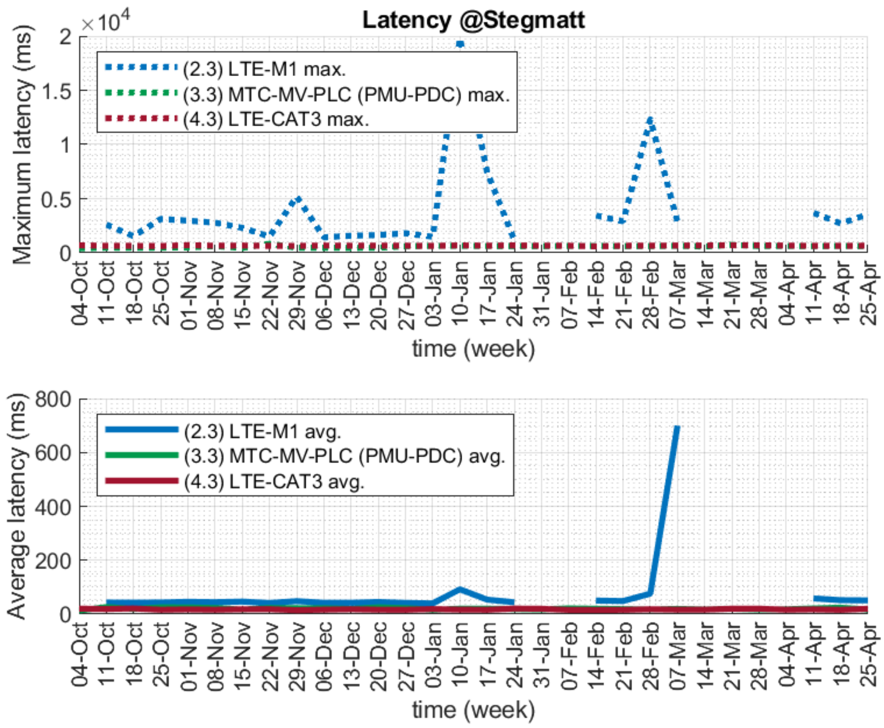

Figure 28: Maximum (top) and average (bottom) latency per week at SS Stegmatt (signal paths (2.3), (3.3) and (4.3))

The latency values for LTE-CAT3 (paths 4.1, 4.2, 4.3) and MTC-MV-PLC PLUS + LTE-CAT3 (paths 3.2 and 3.3) are in the same range and rather stable, which underlines the overall results as shown in Table 6. Therefore, the latency on the PLC parts of paths (3.2) and (3.3) were analysed separately, as shown in Figure 29.

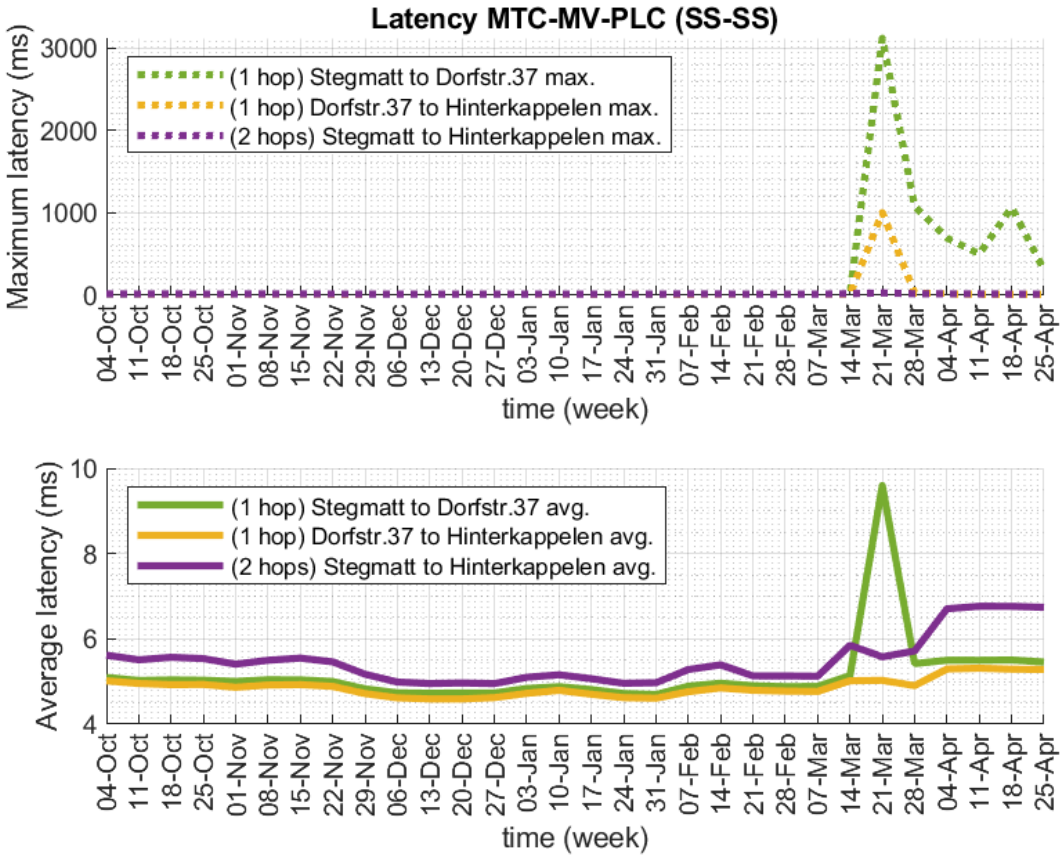

Figure 29: Maximum (top) and average (bottom) latency per week, MTC-MV-PLC PLUS (SS-SS)

The latency values are rather stable at about 5 ms. The switching of the feeder and its effects also resulted in a slight increase of the latency on the MTC-MV-PLC links.

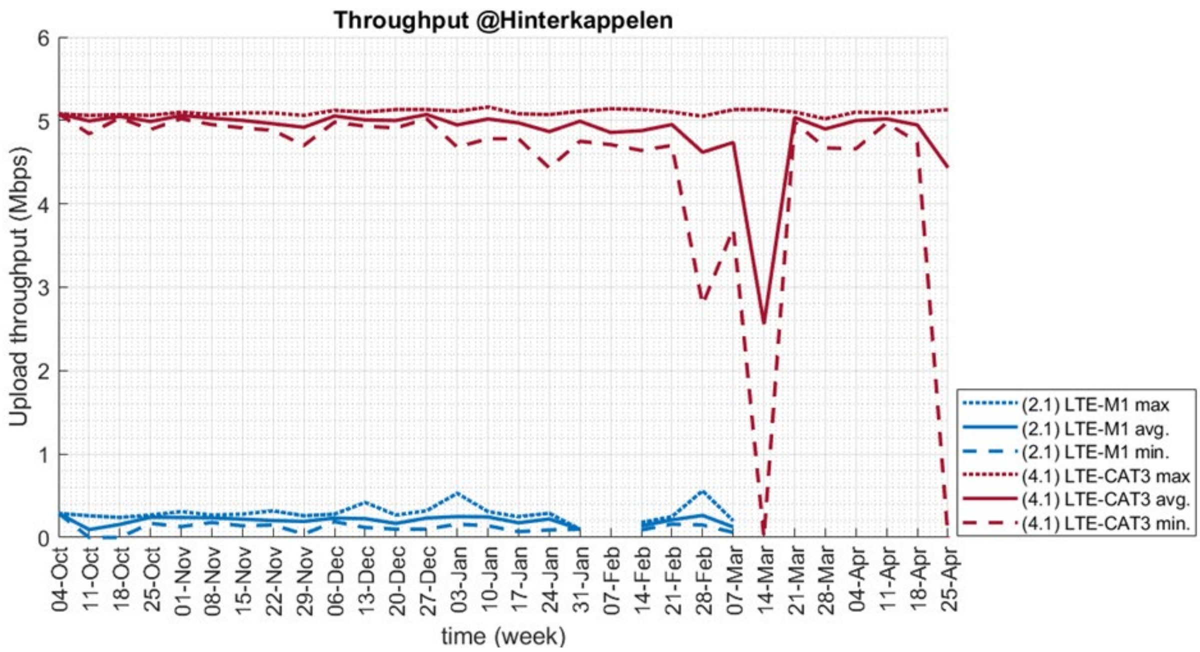

Figure 30: Upload throughput per week at SS Hinterkappelen

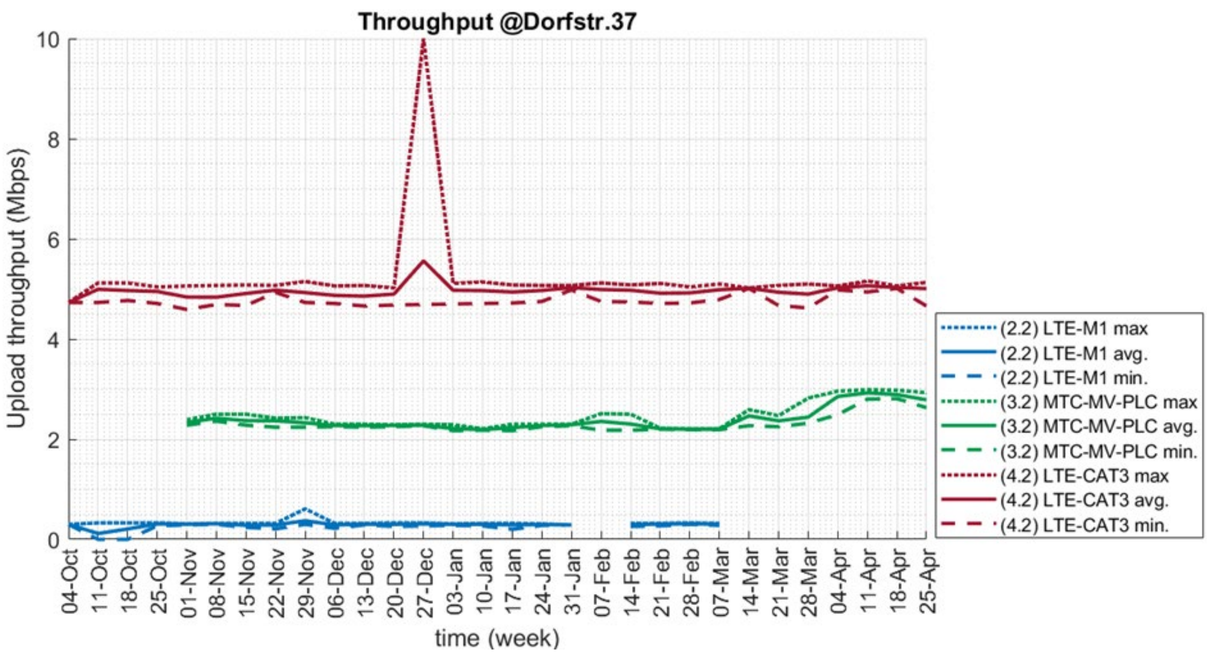

Figure 31: Upload throughput per week at SS Dorfstrasse 37

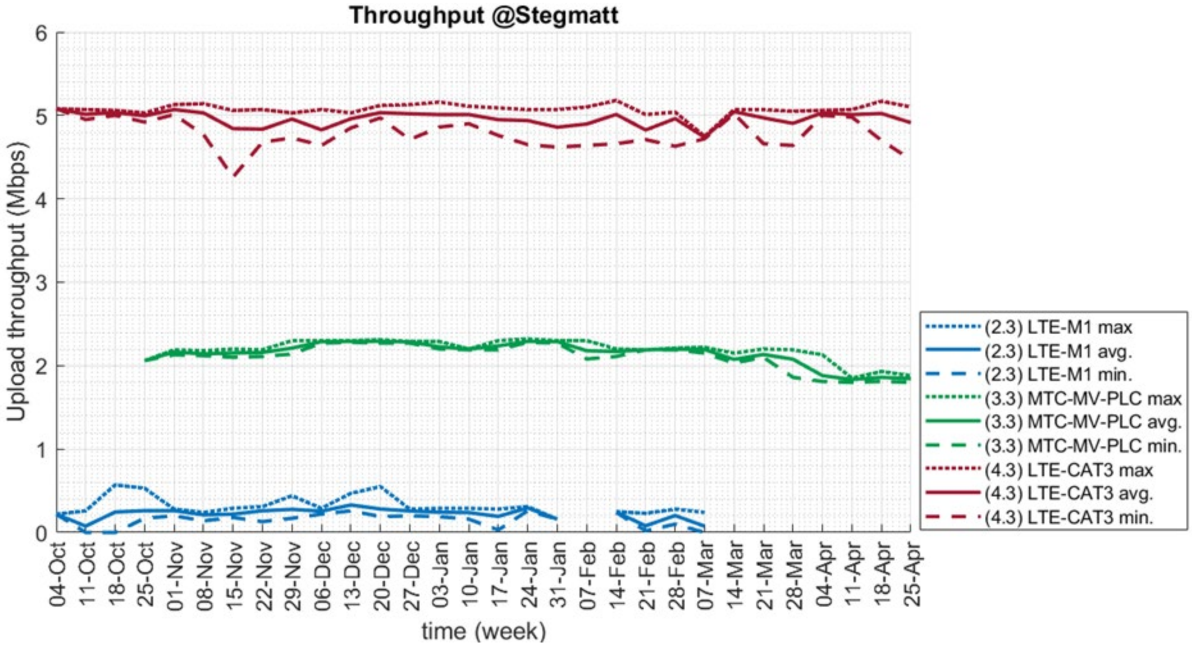

Figure 32: Upload throughput per week at SS Stegmatt

The throughput is rather stable for both LTE-CAT3 (signal paths (4.1), (4.2), and (4.3), around 5 Mbps) and MTC-MC-PLC PLUS +LTE-CAT3 (signal paths (3.2) and (3.3), about 2 Mbps).

We believe the visible impact after 17.03.21 can be clearly attributed to the switch of the MV feeder cable from PS Mühlerberg to PS Worblaufen. Unfortunately, the detailed reason could not be identified clearly, but the assumption is that with the switching new and possibly more noise has been introduced to the MV feeder line and the corresponding loads on that line. High-frequency noise on the MV feeder cable would reduce the signal-to-noise ratio and explain the reduced performance.

To better understand the origins of the additional noise the influence of time of the day in data loss for LTE and MTC-MV-PLC PLUS has been analysed (see Figure 33 and Figure 34). For LTE, there is no apparent correlation between time of day and data loss. However, for MTC-MV-PLC PLUS there is a clear correlation between the peak in the loss rate and the higher noise encountered in the evening hours, in particular after 17.03.21: the loss rate increases by a factor of 10 and is for these hours also beyond the required 1%.

It is well known that a higher noise level decreases the performance of PLC in general, and MTC-MV-PLC PLUS in this case, regarding longer latencies, less throughput and higher loss rates. However, as can be seen in Table 7, MTC-MV-PLC PLUS (SS-SS) also fulfils all requirements of the PMU use case, with a stable latency in the 5 ms range and a throughput of 2 Mbps.

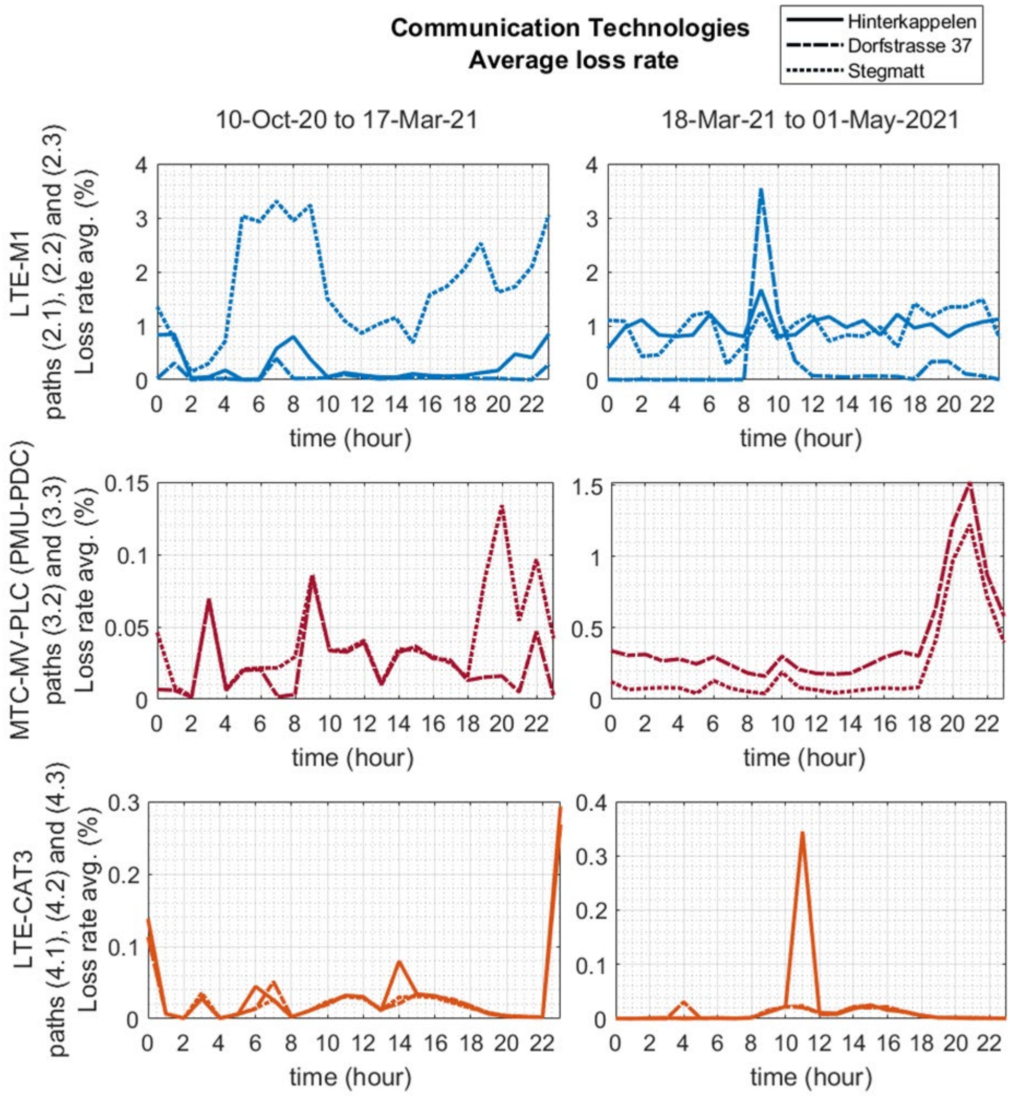

Figure 33: Influence of the time of the day on the average loss rate for the communication technologies

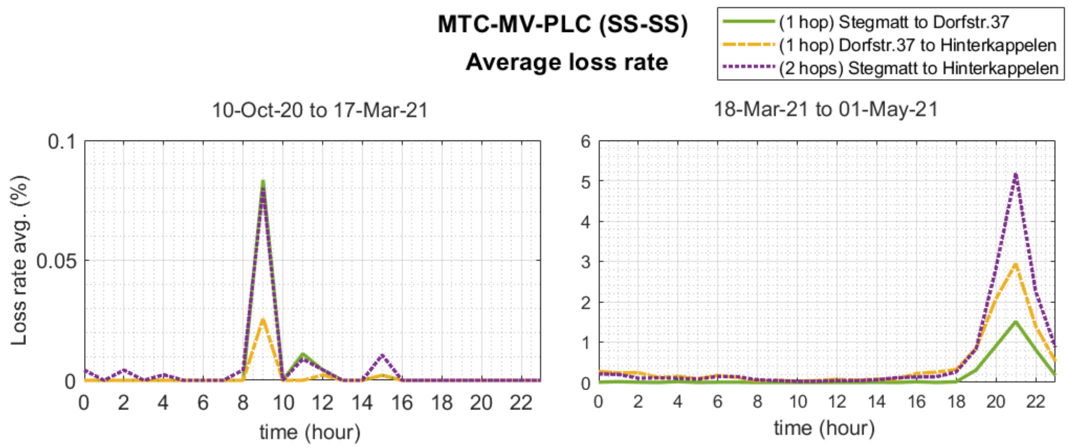

Figure 34: Influence of the time of the day on the average loss rate for MTC-MV-PLC PLUS (SS-SS)

2.5.2 Time Synchronization

In addition to the testing of the communication technologies, time synchronization is also being tested as accurate time synchronization is a key requirement for the PMU application. As mentioned in Table 1, a time synchronization with an accuracy smaller than 1 µs is required. MTC-MV-PLC PLUS is the only communications technology that provides a time synchronization feature. Therefore, time synchronization testing focusses on comparing the accuracy of the PLUS-TimeSync solution provided by the MTC-MV-PLC PLUS technology against the time synchronization accuracy of GPS. Figure 35 shows an example of the deviation of the MTC-MV-PLC PLUS time synchronization versus the GPS time synchronization over a period of approximately 24 hours. The variation comes from the fact that the time provided by PLUS-TimeSync will drift over time until is surpasses a threshold and a new synchronization will occur.

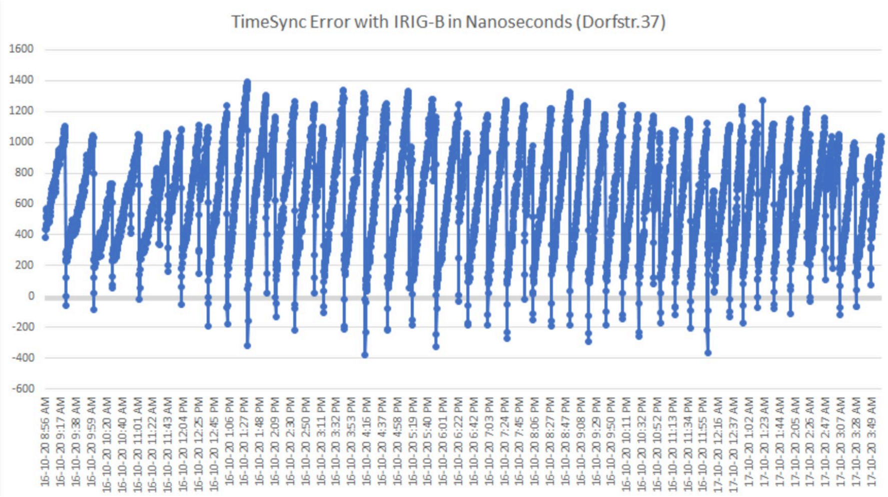

Figure 35: Measurement example of MTC-MV-PLC PLUS time synchronization deviation vs. GPS over one day

Table 8 summarizes the latency error measured between the PLUS-TimeSync and GPS from October 10, 2020 to May 1, 2021. SS Hinterkappelen represents a special case as the PMU time is synchronized directly from GPS at that station. SS Hinterkappelen acts as the time master for PLUS-TimeSync and SS Dorfstrasse and Stegmatt synchronize to SS Hinterkappelen over MV-PLC using PLUS-TimeSync. Therefore, the error at SS Hinterkappelen represents the variation in the GPS input time from the current clock running on the PMU. It essentially shows the variation in the GPS time. At SS Dorfstrasse and Stegmatt the error shown is measured as the difference between GPS (also available at those stations) and the time provided by PLUS-TimeSync. It is therefore the error between GPS and PLUS-TimeSync. The average values provided by PLUS-TimeSync are below the required 1 µs at the SSs Dorfstrasse and Stegmatt, but the maximum values are above the requirement. However, during the test phase an error was detected in the implementation of the PLUS-TimeSync algorithm which could not be addressed during the test phase due to the difficulties of debugging the issue in a field installation. This error will be addressed in a future project.

	Latency max.	**Latency avg.**	**Latency min.**
SS Hinterkappelen (GPS reference)	44.00 ns	24.91 ns	5.00 ns
SS Dorfstrasse 37	4'510.02 ns	827.41 ns	23.00 ns
SS Stegmatt	4'291.00 ns	668.71 ns	8.00 ns

Table 8: MTC-MV-PLC PLUS time synchronization latency error deviation with respect to GPS (IRIG-B) from 10.10.2020 – 01.05.2021

2.5.3 Conclusions regarding the performance of the communication and time-synchronization technologies

Regarding communication technologies, the following conclusion can be drawn from the results as described above.

- LTE-NB1: Very high loss rates of about 90% and more, and latencies of several tens s with throughput of 20 kbps mean that this technology does not fulfil the requirements of PMU-based MPA but also most other applications with much lower communication requirements, even for the AMI use case. This is because the bandwidth is not sufficient which leads to high loss and high latencies.
- LTE-M1: Throughput is in the range of several 100 kbps but with average latencies in the range of 50 ms does also not fulfil the latency requirements of the most demanding PMU-based MPA use case, but probably for use cases with less stringent latency requirements, including less demanding MPA applications. At SS Stegmatt also the loss rate is quite high/below the requirements' fulfilment.
- LTE-CAT3 fulfils all requirements for the PMU-based MPA use case, in particular throughput (~ 5 Mbps) and loss rate. However, the latency requirements are only just met without any margin (~ 15-20 ms) and for certain time spans the loss rate is beyond the limit.
- MTC-MV-PLC PLUS technology fulfils all requirements for the PMU-based MPA, including throughput (~ 2 Mbps). The latency figures are in the lower one-digit ms range (~ 5 ms) and thus much lower than the required 20 ms. The well-known sensitivity to increased noise levels has been seen also in the tests with an increased data loss rate during short time spans, however, there are principally additional measures like re-transmission schemes to address such impacts.

  Regarding time-synchronization technologies: PLUS-Time-Sync achieves an average time-synchronization accuracy of below 1 us.

  In combination with the ultra-low latency the PLUS technology is a promising technology candidate for the demands of PMU-based point-to-point MPA applications like Line-Differential Protection [11].

Table 9 shows an overview of the applicability of the different communication technologies for SG Hybrid Multi-Service CNs.

Candidate communication technologies	LTE-NB	LTE-M1	LTE-CAT3	MTC-MV-PLC PLUS
Communication requirements				
Latency / ms	Several 10'000	~50	~ 15- 20	~ 5
Throughput / kbps	~ 20	200 - 300	~ 5'000	~ 2'000
Loss rate / %	> 90	mostly < 1	On average far below 1 but some peaks	On average far below 1 but some peaks when high noise levels on the MV
Applications				
Lowest				
Medium				
Highest				
Further				
Advantages	- Low CAPEX	- Low CAPEX	- Low CAPEX	SSs clusters can be built based on PLC with only one LTE-CAT3 access point to the WAN, saves OPEX
Disadvantages	- External antenna required in inhabited area - Low OPEX	- External antenna required in inhabited area - Medium OPEX	- External antenna required in inhabited area - High OPEX	In Switzerland only applicable / allowed on underground MV cables

Table 9: Overview of the applicability of the different communication technologies for SGs Hybrid Multi-Service CNs

3 Economic viability of PMUs for mass-rollout

In this section we analyse the suitability of PMUs for mass-rollout in distribution system operators (DSOs) MV distribution grids by evaluating the economic viability through the development of a business case.

The distribution grid is going through an unprecedented transition—from a passive grid that connects consumers to electricity, to an active grid integrating DERs from solar/wind, energy storage and electric vehicles. To cope with such increased complexity and regulatory compliance, power utilities are required to invest in grid digitization and automation.

Such solutions should 1) Increase the visibility on grid assets both for real-time operations as well as for optimal grid planning and maintenance; 2) Automate fault location and service restoration process to reduce the duration and undelivered electricity during blackouts; 3) Efficiently integrate DERs into the existing grid infrastructure with minimum disruption by guaranteeing continuous grid stability.

In such a context PMUs represent a very promising technology to provide full grid visibility and implement control strategies to guarantee the stability of the distribution grid. The high-speed measurements allow for capturing fast events, including faults and renewables intermittency. The accurate time-synchronization guarantees that measurements are taken exactly at the same time, therefore greatly enhancing the performance of various grid functions, such as fault location or state estimation accuracy.

PMUs can be applied for several use cases. We identified and reported the main use cases/functionalities in Table 10, including their associated benefits:

- **CAPEX** represents any investment in the form of a tangible asset.
- **OPEX** represents any other cost that does not include tangible assets (wage, software license, etc.).
- **Societal** benefits due to increased reliability and quality of supply. They sometimes translate into OPEX if regulations provide such incentive schemes.
- **Intangible** benefits that accrue to the DSO but do not have a direct monetary value, such as personnel safety or experience.

Functionality	CAPEX	OPEX	Societal	Intangible
Fault location		x	x	x
Voltage control			x	
Frequency control		x	x	
Power quality monitoring	x		x	
Automation		x	x	
Islanding detection				x
Grid model validation	x			
Real-time state estimation	x	x	x	
Condition-based maintenance	x	x		
Post-event analysis				x

Table 10: Benefits of using PMU data for various functionalities

In the following subsections we focus our analysis on the Fault location use case as it is the major concern of many DSOs today in Switzerland. Indeed, the Swiss grid is, as of now, seeing little penetration of intermittent renewables; this could change rapidly in the future as nuclear power plants are phased out.

3.1 Improving the fault location process with PMUs

By leveraging high-speed and time-synchronized measurements (via GPS or equivalent technologies), PMUs can be used to record fault events from multiple points of the grid and triangulate this information to automatically derive the fault location. Such an information can be immediately communicated to the utility control center where the faulted area can be immediately isolated to restore the energy in the healthy part of the grid.

In addition, if the fault is a short-circuit fault characterized by a fault current amplitude much higher than the typical load current, it is possible to further estimate the distance of the fault along the cable from the closest PMU. In BKW's case, the grid is isolated from ground, so in case of ground fault the faulted area can be detected and located by PMUs, but the fault distance inside the area cannot be determined. According to BKW statistics, short circuit faults represent about 60% of the faults that occur in BKW grid.

Thanks to the PMU technology, unplanned outages can also be avoided, by detecting incipient/intermittent faults before they evolve into permanent and disruptive faults (such transient events can only be captured by the high sampling rate of PMUs).

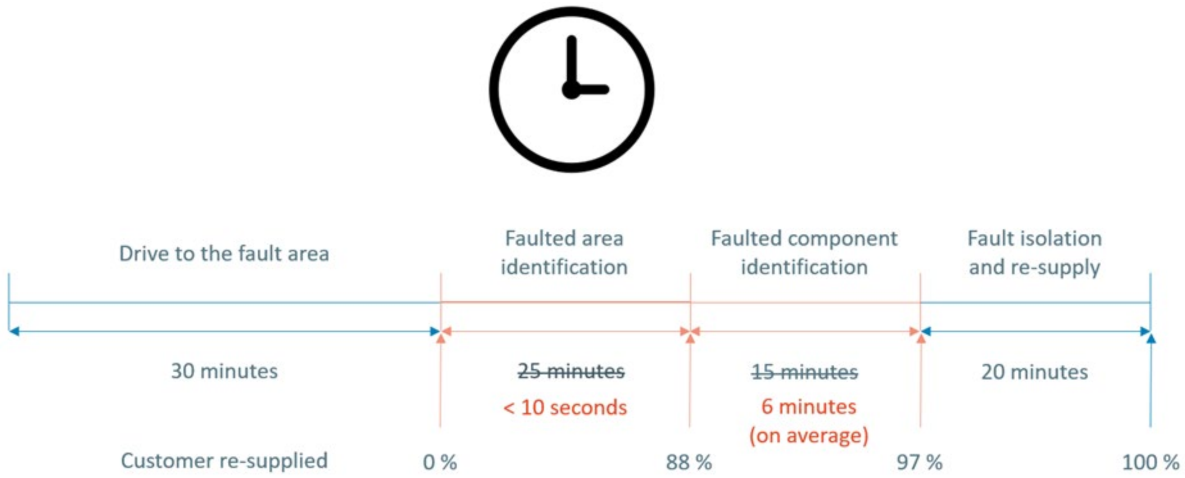

Figure 36: Typical fault location process in BKW distribution grid with average durations of each fault location step

Figure 36 shows the typical fault location process, PMUs can affect the fault identification process, but not the initial driving nor the power restauration process without automation. For this purpose, remotely controllable switches potentially combined with protection devices would be required, adding a benefit on their own or in combination with PMUs. However, they were not considered as the following analysis focusses on PMUs and not on fault location.

The reduction of component identification down to 6 min is due to the fact that PMUs can estimate the fault distance for short-circuit faults, which represents 60% of faults on BKW's grid. We conclude that PMUs save on average 34 min out of a 90 min fault location, isolation, and service restoration process, or 34 min out of a 40 min fault location process. The resulting lost load saved represents typically 25%-30% of total energy not delivered during the interruption.

At BKW (as many other utilities worldwide), the fault search process is mainly based on a trial-and-error approach where the field crew, using consecutive switching based on a certain logic and experience, identify the faulted area by a process of elimination. It generally takes them between 30 and 60 min to complete the search process, excluding power restoration and initial driving time. This method becomes highly inefficient when the grid becomes more complex, when the distance between substations becomes larger, or when the clients present on the feeder are sensitive to repeated short interruptions caused by switching (traders, paper industry, etc.).

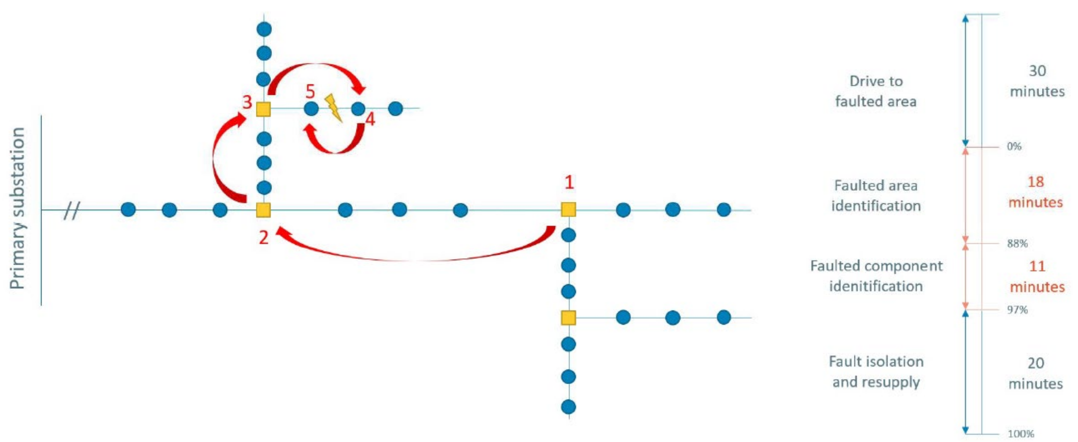

Figure 37: Illustration of a typical fault location process (source: Zaphiro Technologies 2020)

Thanks to PMUs, such a process can be considerably improved by automatically identifying the faulted area/component without the need of switching operations. The benefits of such an application are multiple including:

- CAPEX: extended switchgear lifetime due to less switching operations
- OPEX: reduced cost of labour
- Societal: shorter interruption duration for end customers
- Intangible: increased personnel safety

Still, in this analysis we have decided to focus on the end-customer benefits, as this represents the major contribution compared to other benefits.

3.2 VoLL analysis

To estimate value of a shorter/less frequent interruptions for the end clients, we use the concept of **Value of Lost Load (VoLL)** as an indicator of the cost of interruption for end customers. VoLL is widely accepted worldwide, but it is not easy to determine. VoLL is defined as the monetary value of 1 kWh not supplied and is expressed as [CHF/kWh]. Based on the results of several studies for various countries, regions, and DSOs, VoLL can be widely variable.

We chose to take a VoLL study from New Zealand as reference, commissioned by Transpower, the national Transmission System Operator, and performed by the consulting firm PwC. We decided to use this study as it is recent (2018), it is one of the most complete studies, and it is based on customer surveys (considered by most other studies the most accurate method to estimate the VoLL). The economy of New Zealand is also quite similar to that of the Canton of Bern in term of sectorial composition, thus we believe it represents a representative value. The GDP per capita of Switzerland is twice the GDP per capita of New Zealand, and the average VoLL for a PS in New Zealand is 25 NZD/kWh, equivalent to 16 CHF/kWh. By transposing this VoLL to Switzerland, we expect a VoLL of 32 CHF/kWh. To be conservative, we decided to use a VoLL value of 27 CHF/kWh.

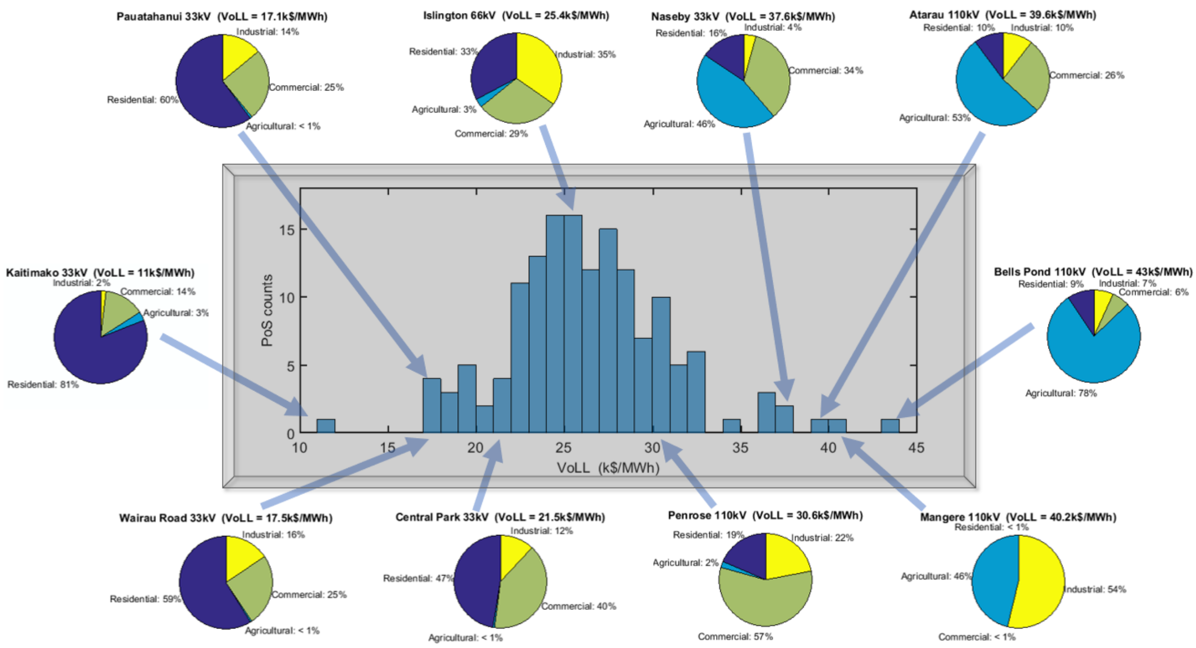

Figure 38: VoLL by Point-of-Supply, PS, in New Zealand [12]

In the following, we present 3 different case studies and their results in term of economic value for society. We will first study the case of a real fault on BKW's network, then generalize the findings through the study of a reference feeder; finally, we attempt to extrapolate the findings to the whole BKW grid.

3.2.1 Hinterkappelen feeder

On March 14th, 2021, a fault occurred in the Hinterkappelen feeder from BKW that was instrumented with the PMU technology. At the time of the fault the feeder was supplying 40 SSs with an average installed capacity of 513 kW per SS. As in this feeder only 3 PMUs were installed in a limited portion of the grid for other purposes than fault location, we assumed a typical scenario where 5 PMU devices are installed in each critical substation (i.e. having 3 or more number of departing lines), and we evaluated the benefits. From BKW's detailed fault data, it was possible to directly add-up the lost load at every step of the outage management process, by assuming that each substation was loaded at 15% of its installed capacity (based on BKW's experience). By comparing BKW traditional fault location approach with a PMU-based one, we estimated that 421 kWh would have been saved by automatically locating the faulted area with these 5 PMUs had been installed, which is equivalent to 26% of the total lost load due to the interruption. The total economic value saved for all end customers affected is equivalent to 11'300 CHF for this fault. Based on BKW data, such kind of fault occurs around 0.94 times per year in such a feeder. Over a theoretical 15 years of PMU lifetime, the PMUs could potentially save a total of 170'000 CHF for all the end customers of that feeder, while the installation and operational cost combined would amount to 90'000 CHF (including hardware and software license costs).

3.2.2 Reference medium-voltage feeder

To scale the results to the entire BKW grid, we first performed similar calculations with a "reference feeder", namely a feeder which is representative of most of BKW's MV grid (see Figure 39). The reference feeder contains 31 SSs with 4 intersections, which are average numbers derived from the topology data on BKW's feeders. We assumed that the intersections (i.e. substation with 3 or more departing lines) are equally distributed along the feeder and we derived the reference topology provided in Figure 39.

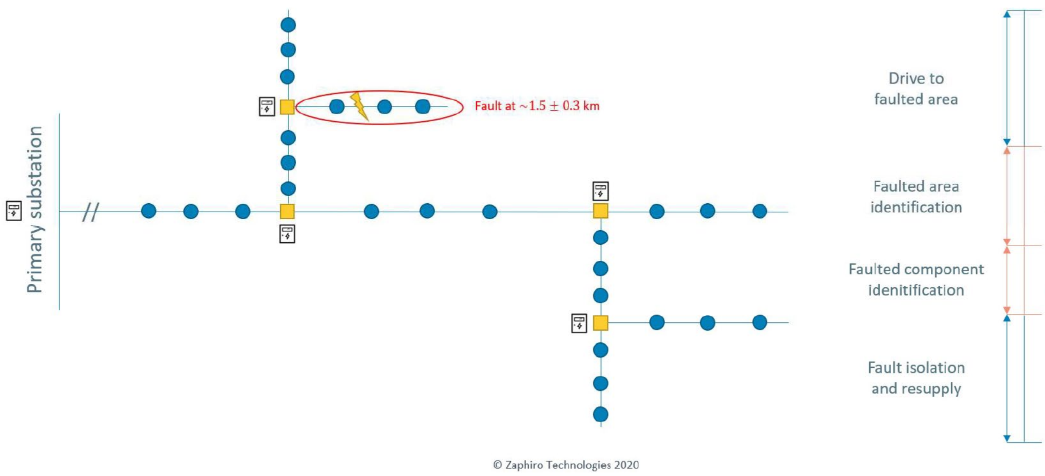

Figure 39: Reference feeder representing a typical feeder of BKW's grid. (source: Zaphiro Technologies 2020)

Like the previous case, PMUs are assumed to be installed in substations with 3 or more departing lines (yellow squares). Then, we applied assumptions derived from the Hinterkappelen case study, which include the numbers of minutes spent for switching operations and travel time between substations. This results in a theoretical saving of 18 min for a single-phase-to-ground fault, and 29 min for a short-circuit fault (2 or 3 phase fault), out of a total fault location time of 29 min and interruption time of 49 min. The benefits for the end customers in this case were estimated to be 115'000 CHF, and the total installation and operational cost of 75'000 CHF over 15 years.

3.2.3 Large scale roll-out on BKW grid

Based on these results, we estimated the value of Zaphiro's fault location solution for the entire MV BKW grid. Here below some statistics about BKW grid which includes more than 6000 MV-LV substations.

To analyse the costs of different deployment scenarios, we used the CommTechPlanner tool developed by HSLU in collaboration with BKW (Figure 40) to simulate 3 different scenarios:

1. **Base deployment strategy**: installation of PMUs at every PS and every indoor (i.e. we ignore pole-mounted substations) SSs with 3 or more departing lines.
2. **Advanced deployment strategy**: installation of PMUs at every PS and every SS (indoor/pole-mounted) with 2 or more departing lines.
3. **Full deployment strategy**: installation of PMUs at every PS and every SS (indoor/pole-mounted).

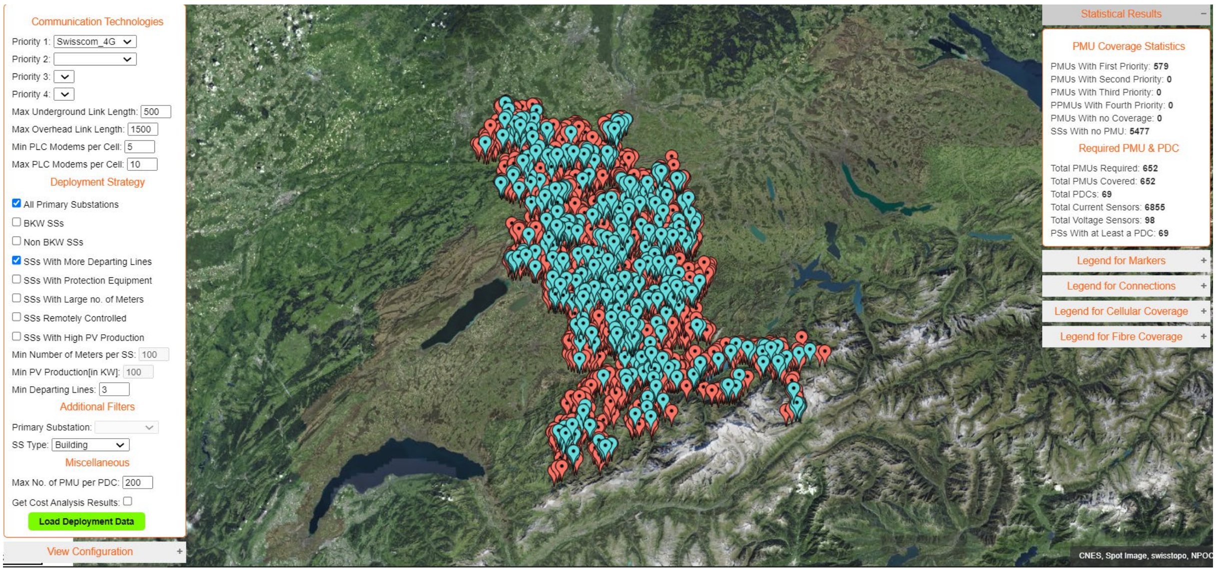

Figure 40: CommTechPlanner tool, example with the base case.

It is worth pointing out that the base scenario is the one which makes the most sense for an initial roll-out. The other two scenarios have been analysed for the purpose of anticipating the cost of future deployment given their necessity.

It is also worth pointing out that for each one of these scenarios we decided to adopt the Swisscom LTE technology for the data communication. The reasons for this choice are multiple:

- LTE technology has demonstrated, both in the analysis and evaluation of candidate communication technologies in section 2.3 and in the test results in section 2.5., to satisfy most of the requirements of the PMU technology (latency, packet losses, throughput). Also, it is extremely cost effective as it relies on an already available infrastructure with a typically wide geographical coverage.
- MTC-MV-PLC PLUS technology only makes sense in the scenario named "Full deployment strategy" where PMUs are deployed in every single node. In more common scenarios where

PMUs are installed in a limited subset of SSs (e.g. 10% in the Base case scenario) MTC-MV-PLC PLUS is economically not viable as it would still require the installation PLC modems also in substations that are not equipped with a device.

- LTE-NB1 and LTE-M1 technologies were disregarded, since they do not meet the performance requirements of PMU applications, as shown in section 2.5.

The results of the CommTechPlanner tool are shown in Table 11, the main cost assumptions are presented in Table 12. SynchroGuard is Zaphiro's PMU-based technology for grid monitoring and automation.

Deployment strategy	Base	Advanced	Full
Number of PMUs	652	3143	6048
Present value of the hardware (communication)	447'892 CHF	2'374'766 CHF	4'358'326 CHF
Running and maintenance cost (communication)	2'398'411 CHF	13'019'353 CHF	25'052'832 CHF
Present value of the hardware (SynchroGuard)	3'986'312 CHF	14'783'185 CHF	26'495'737 CHF
Running and maintenance cost (SynchroGuard)	7'090'500 CHF	34'974'000 CHF	66'565'875 CHF
Total costs over 15 years	13'923'115 CHF	65'151'304 CHF	122'472'770 CHF

Table 11: Cost of the roll-out plan, separated between communication equipment and SynchroGuard

In the Full deployment strategy scenario we compared the LTE-CAT3 with the MTC-MV-PLC PLUS technology and verified that with a mix of PLC (at 64% of the substations) and LTE (at 36% of the substations) technologies the overall costs were reduced by around 6% (115 million CHF vs 122 million CHF).

Category	**Cost item**	**Unitary cost**
Communication/ Synchronization	Combined GNSS-LTE Antenna	150 CHF
	LTE Cellular gateway	350 CHF
	Flat-rate LTE SIM card (per gateway and per year)	200 CHF
SynchroGuard	SynchroSense (Zaphiro's PMU)	3450 CHF (<=800 units) 2950 CHF (>800 units)

	Current sensor	100 CHF (<=800 units) 90 CHF (>800 units)
	Phasor Data Concentrator	7000 CHF
	Software license	750 CHF per year, per PMU
Installation	Labour expenses of a crew of four (2 technicians, 1 electrician, 1 administrator) for installation	2304 CHF per day
	Number of installed PMU sets (including communication/sensor equipment) per day	6

Table 12: Cost components breakdown, the largest contributors have been selected while the rest are not presented here

For the benefit calculations we based our extrapolation method on statistical assumptions about feeder data provided by BKW, and on educated assumptions about the two cases we have analysed previously. We evaluate the benefit for the base case scenario, where PMUs are installed at all building SSs with 3 or more departing lines (hereby called "intersection"), and all PSs.

The base case scenario distinguishes two types of feeders: those with a PMU somewhere in the feeder, and those without (i.e. they have only a PMU at the PS because they have no intersections). For the feeders without intersections, we can only use fault distance estimation. Table 13 summarizes the difference between the two categories of feeders and the average saving with PMUs. Finally, using the VoLL, we can estimate the societal benefit for the entire BKW grid.

	Feeder with intersections	Feeder with no intersections
Average number of SS	23	8
Share of total network length	82%	18%
Annual loss of one feeder[3]	400 kWh	140 kWh
Lost load saving with PMUs[4]	29%	19%
Total annual loss saved	60'340 kWh	3'037 kWh

Table 13: Fault location savings with PMUs for the two categories of feeders

From our analysis, we estimate that a large-scale roll-out of Zaphiro's PMU solution in the entire BKW grid (base deployment strategy) would bring a cost-saving of 25 million CHF for electricity customers over 15 years by only considering the fault location functionality, against an investment of 14 million CHF for the SynchroGuard system. The net present value (NPV) is thus 11 million CHF over 15 years. We also note that using a mix of PLC (3896 substations) and LTE (2154) as communication technologies for the full deployment strategy, we lower the costs to 115'884'695 CHF. The detailed cost breakdown for the base deployment strategy is available in Figure 41 and Figure 42 in the Appendices.

However, it has to be noted that this considerable enhancement of the grid performances is not yet sufficient to justify an investment by a DSO in Switzerland. Indeed, with the current regulation the

[3] Annual loss due to faults is calculated based on the fault data provided by BKW, where we assumed that 82% of the yearly faults occurred on feeders with intersections, and 18% on feeders without intersections.

[4] Lost load saving with PMUs is based on calculations done by using BKW real feeder case (with intersections) and a heuristic case on a reference feeder that has 8 SSs and no intersections. This reference feeder is built using BKW's grid topology data.

savings are mainly achieved by the end customers whereas the investment has to be paid by the DSO. It is not yet clear how the customers could contribute to the cost.

3.2.4 Summary of the results

Table 14 summarizes the cost-benefit analysis carried out in this report, we conclude that PMUs have a positive NPV with respect to value provided to the end-customers, considering the capability of fault location only. Further analyses could be entertained including the benefits of enhanced grid visibility for massive DER integration.

	Hinterkappelen	Reference feeder	Large scale roll-out (base scenario)
Costs	90'000 CHF	75'000 CHF	14'000'000 CHF
Benefits	170'000 CHF	115'000 CHF	25'000'000 CHF
NPV	80'000 CHF	40'000 CHF	11'000'000 CHF

Table 14: Summary of NPVs for the analysed scenarios

4 Conclusions and Outlook

The need of multi-service CN for SG is justified on economic grounds. According to the state of the art, complete coverage for all scenarios while at the same time fulfilling all the necessary requirements cannot be provided by a single communication technology. Therefore, a hybrid solution of different technologies is required. To establish the requirements of a multi-service CN, we considered the requirements of AMI and PMU-enabled MPA use cases as examples of one of the least and one of the most restrictive requirements. The analysis and evaluation of the different candidate communication technologies to be included in the “Smart-Grid Multi-Service Communication Network Pilot” has yielded LTE-NB1, LTE-M1, LTE-CAT3 and MTC-MV-PLC PLUS as the technologies to be tested.

A pilot system has been designed and installed in three SSs in Wohlen bei Bern region. The proposed generic pilot architecture offers a frame for the integration and test of several communication technologies, not necessarily restricted to the ones tested in this project. Long-term measurements were performed from October 2020 to May 2021. The results show LTE-CAT3 and MTC-MV-PLC PLUS + LTE-CAT3 (PMU-PDC) as the most suitable technologies for the multi-service CN. However, for both technologies, the maximum measured latency does not allow to apply the PMU technology to implement innovative protection schemes that typically require latencies <20ms. It is expected that modern fiber networks or future 5G cellular networks will be able to meet these requirements. Looking at the results of MTC-MV-PLC PLUS (SS-SS), we may conclude that before the switch of the UST all the metrics meet the requirements of data loss, latency, and throughput. After March 18, data loss and latency considerably deteriorated presenting a peak on the week of the switch although it again improved a few weeks later. We believe this is caused by an increment of the noise coupled to the PLC network at SS Stegmatt coming from the feeder cable. The specific source of this noise could not be identified also after consultation with BKW. It does highlight the challenge in using PLC in an environment in which all devices attached to the power network are not strictly regulated. HSLU continues to have access to the pilot installation beyond the scope of this project and will continue to investigate optimizations that can be done in order to communicate without message loss even in the presence extremely high noise levels on the power line.

We have also demonstrated that the adoption of the PMU technology in the distribution grid might contribute to considerably reduce the damage caused by faults to the end customers. The NPV of the project is estimated to be 11M CHF for a mass roll-out on BKW's grid. This analysis only includes costs related to unplanned interruption duration. Further works can include also other type of benefits to the end customers, such as reduction of outage number by predicting early-stage faults. Other aspects of fault location can also be considered, such as operator safety and lifetime extension of equipment, although they have been estimated to be minor contribution to the total cost-savings. Fault management, despite being one of the major concerns for DSOs in Switzerland, will be soon accompanied by other major problems for DSOs in the near future. If Switzerland were to reach its 2050 Energy Strategy targets, the increase of DER will lead to new challenges in the grid management. As many studies suggest, real-time monitoring along with data-driven grid optimization and planning will be necessary to avoid exorbitant costs while maintaining reliable operation [13], [14], [15].

Last but not least it is worth mentioning that currently, there is a lack of incentives in Switzerland, which could hinder such projects with positive NPV. Indeed, if BKW or other DSOs are unable to capture value from solutions which contributes to society as a whole, it is difficult to justify economically the investment in said solution without regulatory support.

5 National and international cooperation

Time synchronization technologies

To use PMUs in high-density urban environments, synchronization methods alternative to GPS have to be found, due to limited sky accessibility within so-called urban canyons. The knowledge accumulated within the context of this project has allowed Zaphiro Technologies to accelerate the integration of Precision Time Protocol (PTP) into their PMUs. In this respect, today, 2 clients are already leveraging the solution developed by Zaphiro for wide are synchronization using the IEEE 1588 protocol:

- CLP - China Light and Power (Hong Kong): since more than 2 years two PMUs installed in 2 remote substations, connected together via fiber links, will be synchronized together using PTP for the first time worldwide. Such an achievement still does not guarantee full coverage of the Hong Kong DN, due to the limited fiber roll-out. In this respect, the alternative solution proposed by HSLU (PTP PLUS) becomes extremely interesting as it can allow sub-microsecond synchronization without the need of a dedicated fiber roll-out.
- EPFL: the EPFL campus has been recently equipped with Zaphiro proprietary PMU technology. Providing accurate synchronization to PMU devices using the GPS technology in such a context becomes challenging, due to the underground nature of many electrical substations at EPFL and the impossibility to easily connect to the GPS antenna. In this respect, the solution that has been implemented at EPFL solely relies on the PTP solution developed by Zaphiro: 3 PMUs connected to dedicated GPS antenna act as PTP master for the rest of the devices (48) that are connected to them via the EPFL fiber network. The achieved phase measurement accuracies are in line with those achievable with GPS but without the hurdles of deploying GPS antennas and cables, therefore simplifying the entire deployment process.

Data communication technologies

The experience accumulated in the course of this project has allowed to improve the specifications of Zaphiro PMU device that now can optionally integrate multiple communication modules, including a 4G LTE module, a fiber to copper media converter and 2 direct Ethernet interfaces. This flexibility has allowed Zaphiro to onboard an increasing number of clients that set different type of requirements on the communication technologies to be used for data transmission. As an example, Romande Energie has started since few years the rollout of fibers in 70% of their SSs. Such a rollout is expected to advance relatively slow, therefore, where available fiber communication is preferred, where unavailable 4G LTE technology is considered. In other words, we have further demonstrated that a proper mix of communication technologies is key to achieve high reliability and scalability of a PMU system. At the same time, the pilot project in Rolle with Romande Energie, due to the extremely high coverage of fiber links in SSs, is extremely well suited to further tests required to compare the performance of HSLU PTP PLUS solution and standard methods based on PTP over fiber or GPS.

6 Publications

None

7 References

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8 Appendices

Technology	AMI Analysis Score	PMU Analysis Score	Summary
NB-PLC G3 (CENELEC-A)	89	N/A	G3 in the FCC band provides sufficient performance for the AMI use-case. Coverage is good, as well as technology suppliers. A risk is given for the FCC band in Switzerland, as regulation does not permit it yet. The performance of the CENELEC band is not problematic from regulation's point-of-view, however, in some areas performance might not be sufficient.
NB-PLC G3 (FCC)	89	N/A	
MTC-MV-PLC PLUS	N/A	72	PLUS technology provides good performance for the aimed use-cases. Additional advantages are the integration of a network time synchronization solution, as well as the independence of a 3rd party network provider. The costs are rather low. A risk is the single supplier, but also regulation for broad-band PLC.
3G (HSDPA/HSPA+)	83	75	3G and 4G offer good performance for most use-cases. There is a risk with respect to latency for time-critical applications. This issue might be addressed in the future; however, a certain risk remains due to the wireless nature. Network coverage may also be a limiting factor. Costs are moderate.
LTE Cat. 1	83	78	
LTE-M (Cat. M1)	74	80	LTE Cat.M1 may provide better coverage, but at the cost of data rates. The AMI use-case seems feasible. There are certain risks w.r.t. the PMU use-case regarding latency and data rates. Coverage may also be a limiting factor. Costs are moderate.
LTE NB-IoT (Cat. NB1)	74	70	LTE Cat.NB1 may provide better coverage, but at the cost of data rates. The requirements of the PMU use-case are not met, the AMI use-case is feasible with a risk regarding the data rates. Coverage may also be a limiting factor. Costs are moderate.
Private LTE	58	66	Private LTE is a sparsely tested technology operating in unlicensed spectrum, which are both factors of high risk.
5G	74	82	5G is a good candidate within the cellular category. It seems to fill the gap between existing 4G capabilities and the needs for the use-cases. However, it is a very new technology with the associated risks.
FO – Ethernet	69	76	A dedicated FO network offers the best performance among all technologies with enough headroom for future applications. The possibility to integrate PTP (time synchronization) is also advantageous. The CAPEX, however, are significant.
FO – SDH	N/A	61	SDH is a very robust technology with very good performance. The costs are significant.
Carrier Line Service	61	67	The Carrier Line Service solution does not provide any benefits over Carrier Ethernet Sensing for our aimed use-cases and has higher costs.
Carrier Ethernet Service	73	83	The Carrier Ethernet Sensing solution provides the necessary performance for our use-cases. The throughput even provides sufficient headroom for further applications. The costs, however, are significant and may be a limiting factor, although OPEX are expected to get lower in future.

Table 15 Summary of communication technology analysis

Category	Technology	Description	Conclusion Green: The technology fulfils the requirements and will be available during the next years. Yellow: The technology has some limitations, or its market situation isn't predictable for the next years. Red: The technology does not fulfil the requirements or will not be available on the market during the next years.
GNSS (Global Navigation Satellite System)	GPS L1 Only	US Air Force operated Medium-Earth Orbit (MEO) satellite system of 24 to 32 satellites. Broadcast signals from a medium earth orbit (MEO) constellation of satellites providing synchronization information directly to each User Equipment	Standard GNSS solution with very precise synchronization under optimal receiving conditions but prone to disruptions due to the weak signal power, to natural disturbances or to intentional and unintentional interferers.
	Multi-source GNSS L1 systems	GPS-similar GNSS-services operated by: GPS: US Air Force Galileo: European GNSS Agency (GSA). Glonass: Russian Roscosmos. BeiDou: China National Space Administration	GNSS solution with better protection against disruptions compared to the GPS-only solution.
	Multi-band GNSS	GNSS-services of bands L1, L2 and/or L5	GNSS solution with improved ionosphere error correction and better protection against unintended jamming.
Other satellite-based synchronization	SBAS	Additional GPS L1-signal from geostationary earth orbit (GEO) Satellite Based Augmentation System (SBAS) or quasi-zenith positioned (QZSS) satellites with correction data and integrity information of standard GPS-signals.	GNSS similar solution with improved and constantly stable receiving conditions given by a directional antenna in the direction of the geo-stationary satellite, but at the same time dependent on a continuously reliable signal transmission from this satellite.
	Iridium STL	Satelle's solution of high power synchronization signals transmitted from the low earth orbit (LEO) constellation of 66 Iridium satellites. The satellites send bursts of encrypted time and location data within spot beams to earth. The receiving signal power is ~30dB higher than for GPS signals. However, except for polar regions with higher coverage, there is generally only 1 Iridium satellite in the line-of-sight from the earth's surface.	Limitations in continuity, costs and the dependency on a unique service provider make this technology not a suitable synchronization solution.
	Starfire GPS Receivers	John Deere's solution of differential GPS-receivers, estimating the ionospheric delay besides the public L1 signal the carrier phase (but not the encrypted data) of the L2 signal and using correction data from ground references being broadcast by Immarsat III	Proprietary solution providing a very high accuracy out of the GPS signals and correction data but supporting only localizing and navigating but no time synchronizing applications.

Terrestrial broadcast radio signals for synchronization	LF radio station	Longwave standard-frequency and time-signal radio stations. The LF-signal can be considered to propagate as a ground-wave, only.	Standard synchronization solution of the area before GPS, with planned and unplanned transmission outages, limitations in precision and which will sooner or later disappear in the future.
	HF radio station	Shortwave standard-frequency and time-signal radio stations. The signal propagates as ground-wave and/or a skywave, resulting in inaccuracies due to changing ionospheric conditions	Synchronization solution with same disadvantages as the signals transmitted by the LF radio stations but with even lower precision due to variations in the transmission delay of the HF-signal.
	eLoran	Enhanced Long Range Navigation System (eLoran). Longwave signals from different world-wide transmitters used for two-dimensional location, especially (but not exclusively) for maritime navigation. The LF-signals can be considered to propagate as ground-waves, only. Transmitted correction data allow correction of weather-dependent propagation behaviour of the ground-wave resulting in an accuracy similar to uncorrected GPS.	Technology designated as a backup solution for GPS which seems to completely loose the remaining financial support in the future.
	FM radio / DAB+	Synchronization to timing messages of audio and video broadcast signals. FM radio stations provide UTC time information in RDS-messages with a resolution of seconds, only. For DAB+, the similar information is transmitted as a date-and-time string in the fast information channel (FIC) of the DAB+ signal. The accuracy of these timing information is in the range of 100ms.	Synchronization solution for radio receivers but not designated for professional synchronization solutions.
Synchronization Service from Cellular Base Station	4G LTE	4G LTE base stations are synchronized to reduce interferences between neighboured base stations. Every user equipment receives timing-advance (TA) information, to synchronize time-division duplex (TDD) of any involved user equipment at the receiving input of the base station. Transfer of absolute timing information is implemented but limited to the high granularity of 1ms within the system-information block (SIB) over the broadcast control channel (BCCH) [1].	Very precise synchronization information for the 4G LTE protocols is not provided as a synchronization solution for user equipment.
	5G	Transfer of precise timing information is actually similar to 4G LTE. 5G synchronization services for user equipment outperforming the possibilities of 4G LTE are not defined, yet [1].	Very precise synchronization information for the 5G protocols might be provided as a synchronization solution for user equipment in the future.
Data-network based synchronization-protocols	PTP IEEE 1588v2	UDP based IP-protocol where a client exchanges timestamps with a master clock. Acquisition of timestamps is supported on Layer 1 by 1588-capable physical layers. Assuming symmetrical network delays, any round-trip delay can be compensated	Protocol over IP-networks with a high market share for very precise and professional syntonization and synchronization solutions but with an accuracy depending on the symmetry of the transmission path delays.

	SDH	Network built up of typically a double ring of synchronous SDH/SONET nodes, with its timing controlled by a clock master named Primary Reference Clock (PRC, ITU-T G.811). The timing of the PRC is distributed over the whole Network. Each network node creates a synchronized timing with an SDH equipment slave clock (SEC, ITU-T G.813). As a synchronization output, a PDH E1 interface (2.048 MBit/s, ITU-T G.703) can be provided.	Syntonization but no synchronization solution. At the same time, an ideal legacy transport network for the IP-packets of the PTP IEEE 1588 protocol.
	Synchronous Ethernet SyncE	Network built up of exclusively synchronous Ethernet switches, which all derive the timing and exact data rate of transmitted from an incoming reference port. The hierarchical timing distribution is independent of traffic and should be traceable to a Primary Reference Clock. Jitter and Wander is filtered in a similar way as in SDH/SONET networks.	Syntonization but no synchronization solution. At the same time, an ideal modern transport network for the IP-packets of the PTP IEEE 1588 protocol.
	WLAN IEEE 802.11 with 802.1AS	PTP IEEE 1588 like protocol between time-aware WLAN bridges according to 802.1AS with timestamping according to the optional timing measurement procedure of IEEE 802.11(-2012). Timestamps have a granularity of 10ns. Synchronization is distributed point-to-point between the bridges by a tree with the grandmaster clock at its root and the clock clients at its leaves.	Synchronization solution with an unknown future market penetration convenient for a very limited local area and prone to many legitimated interferers.
	WLAN IEEE 802.11az (~2021)	Improved Fine Timing Measurement (FTM) with hardware timestamps defined in the future standard IEEE 802.11az (~2021)	Synchronization solution with an unknown future market penetration convenient for a very limited local area and prone to many legitimated interferers.
	PTP PLUS (PLC)	PTP IEEE 1588 like protocol between PLUS power-line communication modems.	Proprietary synchronization solution over the existing MV short- and medium-range cables especially adapted for harsh environments with limited wired and/or wireless communication capabilities providing a low-cost solution.
Combined Protocols	Assisted Partial Timing Support	Lower cost primary reference time clock (PRTC) deriving the time synchronization from a GNSS receiver calibrates an incoming unicast stream of PTP IEEE 1588 packets from a central ePRTC. In the case of a loss of the GNSS signal, the synchronized timing is maintained by the PTP stream.	Very precise synchronization solution designed for protection against GNSS signal disruptions having a maximum duration which depends on the accuracy of the backup clocks.
	White Rabbit	Protocol resulting from CERN's White Rabbit project. Combination of synchronous Ethernet for syntonization and PTP IEEE 1588 for synchronization.	Extremely precise synchronization solution with high-end network equipment actually not suited for low-cost solutions.

Table 16 Time synchronization technology comparison

Costs per Year in CHF*

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Material	144 750	144 750	0	0	0	0	0	0	0	0	0	0	0	0	0
Installation	83 376	83 376	0	0	0	0	0	0	0	0	0	0	0	0	0
Setup	4 342	4 342	0	0	0	0	0	0	0	0	0	0	0	0	0
Netplanning	8 685	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Investments	241 153	232 468	0	0	0	0	0	0	0	0	0	0	0	0	0
Asset Value	223 310	420 961	386 144	351 327	316 510	281 693	246 875	212 058	177 241	142 424	117 247	100 842	84 437	68 032	51 627
Depreciation	17 842	34 817	34 817	34 817	34 817	34 817	34 817	34 817	34 817	34 817	25 176	16 405	16 405	16 405	16 405
Interest	8 552	16 122	14 789	13 455	12 122	10 788	9 455	8 121	6 788	5 454	4 490	3 862	3 233	2 605	1 977
Depreciation + Interest	26 394	50 939	49 606	48 272	46 939	45 605	44 272	42 938	41 605	40 271	29 666	20 267	19 638	19 010	18 382
Running Costs	31 362	89 262	115 800	115 800	115 800	115 800	115 800	115 800	115 800	115 800	115 800	115 800	115 800	115 800	115 800
Maintenance Costs	26 634	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268	53 268
Running + Maintenance	57 996	142 530	169 068	169 068	169 068	169 068	169 068	169 068	169 068	169 068	169 068	169 068	169 068	169 068	169 068

*The number format is depending on the web browser language settings.

*The numbers are rounded downward to its nearest integer.

Total Costs in CHF

Total Present Value:	447 892
Total Running + Maintenance:	2 398 411
Total Material:	289 500
Total Installation:	166 752
Total Setup:	8 685
Total Netplanning:	8 685
Total Investments:	473 622

SynchroGuard

Costs per Year in CHF*

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Material	1 708 950	1 708 950	0	0	0	0	0	0	0	0	0	0	0	0	0
Installation	150 336	150 336	0	0	0	0	0	0	0	0	0	0	0	0	0
Deployment Service	489 000	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Investments	2 348 286	1 859 286	0	0	0	0	0	0	0	0	0	0	0	0	0
Asset Value	2 170 422	3 722 881	3 416 054	3 109 226	2 802 399	2 495 572	2 188 745	1 881 918	1 575 090	1 268 263	1 025 370	797 510	569 650	341 790	113 930
Depreciation	177 863	306 827	306 827	306 827	306 827	306 827	306 827	306 827	306 827	306 827	242 893	227 860	227 860	227 860	227 860
Interest	83 127	142 586	130 834	119 083	107 331	95 580	83 828	72 077	60 325	48 574	39 271	30 544	21 817	13 090	4 363
Depreciation + Interest	260 990	449 413	437 661	425 910	414 158	402 407	390 655	378 904	367 152	355 401	282 164	258 404	249 677	240 950	232 223
Running + Maintenance Costs	244 500	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000	489 000

*The number format is depending on the web browser language settings.

*The numbers are rounded downward to its nearest integer.

Total Costs in CHF

Total Present Value:	3 986 312
Total Running + Maintenance Costs:	7 090 500
Total Material:	3 417 900
Total Installation:	300 672
Deployment Service:	489 000
Total Investments:	4 207 572