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THE POTENTIAL OF EMERGING COMMUNICATIONS TECHNOLOGIES IN DISTRIBUTION GRID MANAGEMENT

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ABSTRACT

Increasing requirements for the dynamic performance of electric energy systems will necessitate expanded distribution automation, which in turn will require extensive connectivity solutions. This paper explores the relevance and potential use of the latest communication technologies in the evolving distribution grids of the 2030s. The results indicate that the most critical parts of the grid and the most vital applications will rely on optical networking, while the functionality provided by emerging industrial mobile communication technologies could provide a feasible and compelling option for addressing the automation needs of new distribution grids. However, the study also reveals concerns about the reliability, latency, cybersecurity, feature maturity, and realization of the mobile communications features specified by 3GPP.

1. INTRODUCTION

The electric energy system is facing a challenge in managing and controlling the power balance as well as adequate and continuous energy supply. Due to decreasing inertia and intermittent generation, the electric energy system is becoming more dependent on seamless co-operation between transmission and distribution grids. In distribution grids, intermittent inverter-based generation is likely to cause problems with voltage levels, power quality, and protection solutions, thus necessitating more extensive automation and connectivity. This paper contributes by evaluating the feasibility of applying the latest and anticipated new communication technologies in the distribution grids of the 2030s. For this purpose, the study uses the 76 Finnish distribution grids as a case example. The rest of the paper is organized as follows. Section 2 gives a summary of the applied Delphi method. Section 3 presents an overview of the latest communication technologies, followed by an expert-panel assessment of their significance and potential use cases in Section 4. Finally, Section 5 concludes the study by discussing and summarizing the findings.

2. METHODS

In this study, the significance of the communication technologies is estimated using a senior expert panel and a Delphi survey. The Delphi method [1] is a survey technique widely used to reach a common consensus without group bias. The panellists for the survey were selected based on their recognized expertise in the following domains: (1) **power grid** management, (2) information and communication technologies (**ICT)** integration, (3) mobile networks (**MNO**), (4) **cloud** computing, (5) network equipment (**NE**) provider business, (6) R&D in **academia**, and (7) technology and business **consulting**. The panel consisted of 29 senior experts, each of whom conducted a self-assessment to classify their degree of competence in the above-mentioned expertise domains into the following categories: *no expertise*, *basic*, *professional*, and *world-class* expertise. Figure 1 presents the number of *professional* and *world-class* experts in each of the expertise domains.

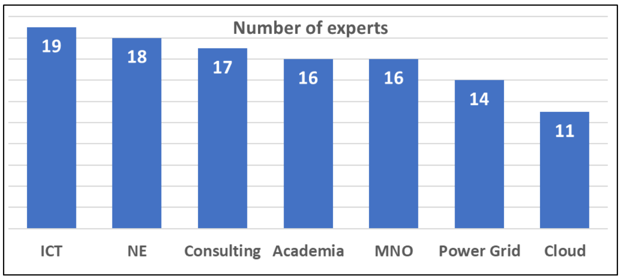

Fig. 1 The number of *professional* and *world-class* experts in each expertise domain among the panellists.

Panellists were asked (1) to describe the significance of different communication technologies in the management of the distribution grid of the early 2030s and (2) to give examples of use cases as well as the benefits and any concerns. The significance of each technology was categorised into four qualitative levels: (1) *not important*, (2) *moderately important*, (3) *important*, and (4) *very important*. The consensus between the panellists was measured as a standard deviation. The panellists could also choose to omit assessing a technology.

3. COMMUNICATIONS TECHNOLOGIES

For the purpose of this study, the field of communications was divided into seven generic communication technologies: **optical**, **mobile** (cellular), **wireless** local area networks (**WiFi**), ultra/very high frequency (**UHF/VHF**) private radio, **cloud computing**, **edge computing**, and **satellite** communications. While most of these technologies are evolving rapidly, the most
significant efforts have focused on mobile communications, due to work by the 3rd Generation Partnership Project (3GPP) to penetrate the industrial segment with 5th generation (5G) networks [2]. Currently, 5G forms the mainstream of 3GPP's specification work, though 4G has also been further developed in parallel with 5G. Furthermore, initial research aimed at 6G is currently ongoing, with the first 6G networks being expected to emerge in the early 2030s. 5G can be considered either revolutionary, due to its industrial focus, or evolutionary due to the similarity of the 4G and 5G air interfaces (differing mostly in their parametrization), as well as due to backporting of successful 5G features into 4G.

For electric power grid management, we identified 13 promising features (**bolded** in the following paragraphs) from currently published 3GPP releases (Releases 15 - 17) and ongoing specification work in Release 18 [3], [4]. Release 18 is branded as the first 5G Advanced release. As of 2022, many of these features have not yet been implemented nor deployed in commercial products. In order to understand the emergence of the 5G features, it should be noted that most features are gradually specified and enhanced over multiple releases.

A **5G network slice** forms a logical overlay network on top of the physical network for a certain communication need. This overlay network spans end-to-end across all three domains comprising a 5G network: (1) the Radio Access Network RAN, (2) the transport network, and (3) the Core (5GS). The RAN consists of base stations, gNBs, and the backhaul transport. A slice can be static or dynamic and can range from small-area (one gNB, in an extreme case) to countrywide overlay networks. Currently, in Release 17, 3GPP defines five Slice Service Types (SSTs): (1) enhanced Mobile Broadband (**eMBB**), (2) Ultra-Reliable Low Latency Communications (**URLLC**), (3**)** Massive Internet-of-Things (**MIoT**), and the more recent (4) Vehicle-to-X (V2X**),** and (5) High-Performance Machine-Type-Communications (HMTC) [3]. The eMBB, URLLC and MIoT slice types correspond to the initial three usage scenarios defined by the ITU-R in 2017 [5]. According to ITU-R requirements, eMBB should reach a downlink peak data rate of 20 Gbit/s and an uplink peak data rate of 10 Gbit/s. eMBB and URLLC have targets for user plane latencies of 4 ms and 1ms, respectively. In the MIoT usage scenario (called mMTC by ITU-R in 2017), the minimum requirement for connection density is as high as 1 000 000 devices per km^2, though no such stringent latency, availability or throughput requirements have been specified as in the newer HMTC. At the time of writing, the end devices on the market still appear to support only the eMBB slice type. Obviously, the expected performance and Service Level Agreements (SLAs) among different slices vary greatly, spanning from best effort eMBB traffic to URLLC and HMTC, requiring hard capacity, latency and reliability commitments. Consequently, URLLC and HMTC must have dedicated resources assigned to them and should be, at least partially, isolated from other slice instances of the same or different types. The 5G New Radio (NR) is designed to operate both on the conventional cellular spectrum (Frequency Range 1) and higher millimetre wave spectrum (Frequency Range 2, i.e. **mmWave**) in order to cover frequencies below 6 GHz and above 24 GHz, respectively. Higher frequencies enable higher capacities and lower latencies due to the wide spectrum range available. However, the range is limited, since higher frequencies require line-of-sight (LOS) unobstructed by obstacles such as foliage. Today, early deployments of 5G mmWave exist primarily in fixed wireless applications. **Edge computing** in the 5G context, also known as Mobile Edge Computing (MEC), enables services to be hosted close to user equipment (UEs) and 5G network attachment point to enable low latencies. **A 5G Non-Public-Network (NPN**), or private 5G network, is a network that is intended for private use, such as at a factory site. NPNs are typically used to enable guaranteed performance and confidentiality, as the user data stays on site. **5G Non-Terrestrial Networks (NTNs)** refer to the integration of a satellite radio into UEs in parallel with 2-5G, Wifi, and Bluetooth radios. A **5G Multicast Broadcast Service (MBS**) provides a point-to-multipoint (PTM) transmission from one central point to multiple UEs. **Time-Sensitive Networking (TSN**) is an Ethernet, i.e. Open Systems Interconnection (OSI) layer 2, set of standards aiming at providing deterministic, low latency communications within Local Area Networks (LANs). These features are of interest, for example, in industrial control applications. TSN standards have been developed by IEEE during the past decade, with many deployments of TSN networks being commercially available today. Time Sensitive Communications is a 3GPP term covering two aspects: the ability of the 5G network (1) to act as a TSN bridge and (2) to provide accurate timing information to end devices, also known as Time Synchronization Services or **Timing as a Service (TaaS)** [3],[4]. Time Synchronization Services can be provided by the TSN network, in which the mobile network plays the role of a TSN switch, or alternatively by conveying the gNB clock to the end devices. The latter is based on the fact that the RAN and its gNBs are always synchronized at microsecond accuracy by GPS or Precision Type Protocol (PTP) over the optical fibre to the gNBs. **5G LAN-type service** enables extension of a traditional LAN to include mobile network UEs, as well as layer 2 connectivity between these UEs and native terminals attached to the LAN [3]. 5G LAN-type service is based on Ethernet Packet Data Units (PDUs) instead of traditional IP PDUs. **5G Positioning** targets location services with an accuracy within meters, or even centimetres, primarily in factory environments. It should be noted that precise positioning requires wide bandwidths which are typically only available on higher frequencies, such as mmWave.

4. RESULTS

Figures 2 and 3 summarize the panellists' assessment of the future significance (in the early 2030s) of the seven generic communications technologies and the specific mobile communications technology features (bolded in Section 3), respectively. The significance of each technology is measured as the mean importance value calculated from the values given by the panellists on an ascending scale starting from 1 (*not important*) to 4 (*very important*), as explained in Section 2. Tables 2 and 3 summarize the panel's view on the use cases, benefits and concerns with respect to the generic communications technologies and the specific mobile communications technology features. Assessments are based on the context of the Finnish distribution grids. The consensus has been categorized into the following four qualitative levels based on standard deviation ranges: 0–0.34 Very High, 0.35-0.64 High, 0.65-0.94 Moderate, 0.95< Low.

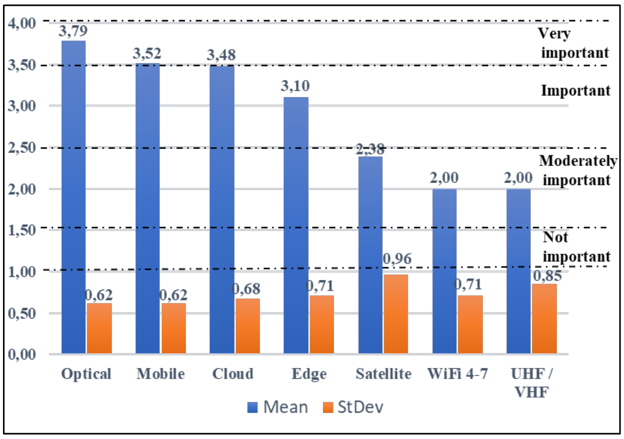

Fig. 2 Significance and consensus among the panellists on the features of each generic communications technology

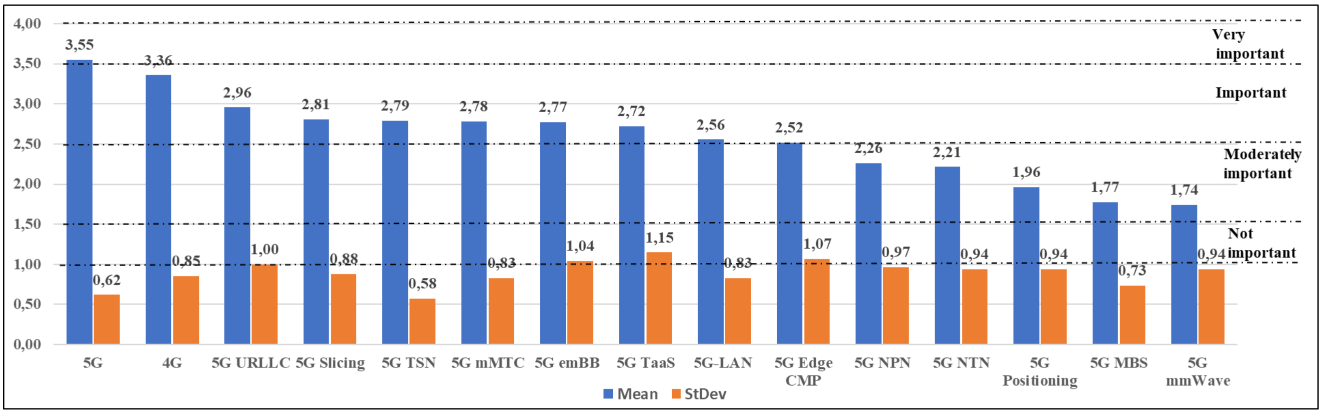

Fig. 3 Significance and consensus among the panellists on the features of each mobile communications technology

Table 1 Generic communications technologies: use cases, benefits and concerns (descending order of significance).

Technology	Use cases	Benefits	Concerns
Optical	Connectivity between the primary substation and both the cloud and management systems (SCADA), critical applications (e.g., line differential protection), wider deployments (e.g., for secondary substation connectivity).	Practically unlimited capacity, high reliability, inherent security due to clear separation, difficult to disturb.	Deployment more difficult than mobile connectivity deployment if the fibre is not laid down simultaneously with power lines.
Mobile	All except the most critical applications, secondary substation connectivity, broad distribution grid connectivity for IoT/sensoring, meter readings, backup to optical connections.	Easy to deploy and cost-efficient.	Capacity limitations, reliability/availability deficiencies (due to the unreliable physical channel), security deficiencies if using a public mobile network and public internet connectivity, vulnerable to disturbances.
Cloud computing	Platform for all control applications including SCADA	Cost-efficient, flexible, availability of applications, fast deployment, inbuilt security, mainstream technology, deployments outside of Finland can also increase reliability.	Reliability and trust issues if deployed based on services running outside of Finland.
Edge	Critical local application (e.g., frequency	Low latency	Increases complexity, added value vs.

computing	and voltage control).		increased cost.
Satellite	Backup (or backup of the backup) for optical and mobile communications, replacement for UHF/VHF.	Reliability during crises, wide coverage, evolving technology.	High costs, long latencies, limited bandwidth.
WiFi	Some primary substation applications, meter reading.	Easy to deploy, strongly evolving technology, potentially cost-efficient compared to mobile communications, alternative to mobile if using licensed spectrums.	Short range, security deficiencies compared to mobile communications and vulnerable to disturbances due to unlicensed spectrum.
UHF/VHF	Fault management and disconnector control along rural feeders, backup (although potentially replaced by satellite).	Proven technology, security and reliability/availability due to dedicated spectrum.	Security deficiencies due to legacy equipment having modest encryption capabilities.

Table 2 Mobile communications technology features: use cases, benefits and concerns (descending order of significance)

Technology	**Use cases**	**Benefits**	**Concerns**
5G	All except the most critical applications, mainstream by 2030.	More capacity compared to 4G, new features to support new power grid applications, obvious choice if non-wired technology is preferred, easy to deploy, cost-efficient.	Capacity limitations, reliability/availability deficiencies ultimately due to unreliable physical channel, limited coverage if no countrywide 700 MHz deployment, uplinks slower than downlinks.
4G	All except the most critical applications, still used in 2030, distinction between 4G and 5G will be somewhat vague due to support for both technologies by 5G UEs, air interfaces are fairly similar, and 5G features are backported to 4G.	Established proven technology, no need to change, extensive coverage, widely deployed, easy to deploy, cost-efficient.	Capacity limitations, reliability/availability deficiencies ultimately due to unreliable physical channel, uplinks slower than downlinks.
5G URLLC	Use cases requiring low latency and high reliability (e.g., for protection and other critical control).	Low latency in the air interface.	Does not yet exist in commercial applications (2022), high cost to achieve reliability, air interface latency is only a small part of end-to-end latency, doubts about commercialization by 2030.
5G Slicing	Critical applications requiring guaranteed performance (e.g., a URLLC slice for highly critical real time applications such as line differential protection and another slice for other control applications such as disconnector control).	Separation of different users, authentication of communicating parties.	Does not yet exist - so far promises have not turned into reality (2022), high costs expected due to dedicated resources and complexity, capacity is constrained by the number and bandwidth of base stations (gNBs), doubts about extensive commercialization by 2030.
5G TSN	Deterministic control at substation sites, time synchronization.	Determinism, accurate time synchronisation, expansion to 5G supported by industrial fixed TSN deployments, layer 2 (Ethernet) technology is a natural choice for geographically limited applications.	Does not yet exist in commercial applications (2022), lack of clarity concerning how layer 2 technologies function over a mobile network.
5G mMTC	Large-scale sensoring.	Low power consumption (New Radio Reduced Capability = NR RedCap, energy harvesting)	Low traction for 4G IoT, no essential progress in 5G IoT, required sensor density is ultimately not so high and data is also available via other means (e.g., smart meters), 4G-based solutions might be sufficient.
5G eMBB	A wide range of applications except the most critical ones, mainstream by 2030.	The only 5G feature widely deployed today (2022), lower latencies than in 4G.	700-MHz band needed in 5G to achieve coverage
5G TaaS	All applications requiring accurate time to synchronize data from the grid (e.g., state estimation, fault management, condition monitoring, and line differential protection).	An alternative to GPS for saving costs or as a backup.	Not yet implemented, though base stations (gNBs) already have the accurate time.
5G-LAN	Primary substation applications.	Layer 2 (Ethernet) technology is a natural choice for geographically limited automation solutions (compared to more complex layer 3 technologies).	No great need - layer 3 (IP) connectivity is the logical choice due to the wide area covered by power grids, lack of clarity concerning how layer 2 technologies function over a mobile network.
5G Edge computing	Local processing (e.g., for voltage control and protection).	Information generated locally should be processed locally if no particular need to transfer it to a central location, utilises 5G RAN computing platforms also for application computing,	Concerns about tying edge solutions to 5G networking technology, concept still unclear, cloud computing enables alternative non-5G dependent approaches.
5G NPN	Primary substation applications as replacement for local fixed wiring.	Licensed bands enabling security and congestion avoidance.	No great need due to wide distribution grid coverage - more applicable in factories, no moving or rotating devices (wireless would be an advantage) at primary substations.
5G NTN	Backup (or backup of the backup) of other connectivity solutions, means to ensure coverage.	Reliability during crises, wide coverage, evolving technology.	Mobile terrestrial networks and satellite networks are too different for meaningful integration.
5G Positioning	Backup for GPS positioning.	Provided as an add-on value service based on existing 5G infrastructure,	No great need due to static nature of power grid devices, accurate location is limited to

		no additional investment required.	only indoor deployments due to high bandwidths (enabled by only mmWave).
5G MBS	Controlling many flexible loads, software updates.	Possibly more efficient use of the mobile network.	Point-to-point connection is sufficient, unsuccessful track record in 4G.
5G mmWave	Applications needing high capacity in local deployments (e.g., within primary substation areas).	High capacity.	No obvious needs in electric power grids due to short range, requirement of line-of-sight (LOS) and sensitivity to disturbances, has so far been a disappointment.

Optical communication, mobile communication, and cloud computing were found to be the three most significance generic technologies (Figure 2) and are therefore expected to form the basis for the connectivity solutions in distribution grids. Although optical communications are deemed to provide superior performance in terms of capacity, reliability, and security compared to mobile technologies (Table 1), mobile technologies can provide sufficient performance for all except the most critical applications and have the advantage that they can rapidly and cost-effectively be deployed in geographically large distribution grids (Tables 1 and 2). Some panellists pointed out that some distribution system operators (DSOs) in Finland are actively laying down fibre for grid management purposes while renewing their medium voltage grid. The significance of Wifi is considered to be relatively modest in geographically large distribution grids (Table 1). Nevertheless, this might change to some extent if WiFi technologies in the future are deployed on licensed spectrum bands. Private UHF/VHF was considered a legacy technology having a clear downward trend (Table 1). Cloud technologies and commercial cloud platforms are widely seen as a very strong trend in most industries and are also assumed to gain further ground in power grid management, despite some concerns about the lack of direct control over dedicated physical servers (Table 1). As part of the cloud concept, aggregation edge computing in the primary substations or near the primary substation is considered important due to the increasing need for distributed computing (Table 1). However, the need for edge computing in secondary substations or near secondary substations is unclear, as it would also essentially increase complexity and costs.

As shown in Figure 3 and Table 2, URLLC, Slicing, TSN, mMTC, eMBB, and TaaS are considered to be most significant 5G features. At the time of writing, the mobile communications features listed in Table 2 are mostly limited to only initial trials or exists in product development laboratories, with widely deployed 4G and 5G eMBB being exceptions. Interestingly, even though there has been extensive communication and marketing around 5G for over 5 years, concrete understanding of the basic functionality of 5G industrial features is limited. For example, 11 panellists acknowledged that they do not have sufficient understanding of 5G-LAN to assess its significance. It is also noteworthy that none of the technologies reached a very high level of consensus, which is a sign that opinions were highly distributed, as can be seen in Figure 3. The study also showed clear disappointment among the panellists concerning the trials with some features (e.g., mmWave), materialization of some features (e.g., URLLC) and generic feasibility of other features (e.g., Slicing). A lack of clarity concerning 5G slices was demonstrated by the fact that the panellists had no clear common view on the range of the number of slice instances that would be in use by Finnish mobile network operators in 2030. With regards to the distribution grids, a typical perception was that there could be either one geographically constrained slice instance per DSO (or shared by some DSOs), or a nationwide slice shared by all DSOs for critical applications.

5. DISCUSSION AND SUMMARY

The latest 3GPP releases include a broad set of complicated features for the industrial market. Currently, we might in a way be facing - before a possible mainstream uptake - the death valley of product introduction [6], where after the initially high expectations, the industrial features still are mostly not available or have been disappointments. Disbelief in the development and commercialization of the analysed 5G technologies by 2030 was common among the panellists. There is also a lack of clarity concerning the techno-economic feasibility of the new industrial mobile technologies in terms of cost levels, and doubts concerning how network operators will be able to handle an industrial segment that has a greater number and variety of customer needs than traditional consumer businesses. Nevertheless, a need for increasing connectivity in distribution grids does exist. Mobile communications, even the consumer-oriented 4G or 5G eMBB would be sufficient for all except the most critical applications in electric power grids. Mobile communications also have the advantage that they can be flexibly deployed, particularly in retrofit cases. Optical communications are, on the other hand, technically straightforward and offer in practice unlimited capacity, as well as high reliability and availability.

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