Dualistic Assessment of Communication Technology Performance for Control of Large-scale Smart Distribution Grids

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ABSTRACT

The integration of Distributed Energy Resources (DER) and functionalities such as Demand Side Management (DSM) or Automated Meter Reading (AMR) into the electrical grid is progressing with the move towards a more environmentally friendly, decentralized approach to power generation. As deployments of these Smart Grids become more pervasive, advanced monitoring and control schemes lead to an increased importance of communication infrastructures, as they are instrumental in achieving a manageable and stable distribution grid. Therefore the available choices in Information and Communication Technologies (ICT) have to be assessed regarding their capabilities to support the necessary control algorithms and thereby the overall use cases. In this work a dualistic approach employing simulations as well as physical testbeds is presented. This serves to achieve a comprehensive assessment of communication network performance supporting utilities in rollout decisions for large-scale Smart Distribution Grid deployments.

INTRODUCTION

The subject addressed in this paper is a dualistic assessment approach for analyzing the performance of different wireless and wireline ICT and their suitability for control functions in Smart Distribution Grid use cases, such as Customer Energy Management Systems (CEMS). First the developed methodology of assessing ICT and control performance via simulation and physical testbeds is presented. While the latter implement single instances of use cases, simulations allow the assessment of real world scenarios with thousands of devices ahead of deployment. Through combination of both approached it is possible to retain the high granularity in detail of practical implementations, while achieving the flexibility and large-scale analysis possible through simulation. Next the evaluation scenario and the employed use case are introduced. There parameters used for this paper are presented. Results and their discussion are given in the penultimate section and show how the adopted assessment approach allows the detailed evaluation of the different communication technologies under study. Effects which can only be observed on a large-scale are laid out and illustrate the benefits of the proposed dualistic assessment framework. Finally a conclusion is given.

SYNERGISTIC ASSESSMENT OF ICT AND CONTROL PERFORMANCE

Providing an assessment of ICT performance for control applications in large-scale smart distribution grids is associated with many challenges. While simulations allow a replication of infrastructures with even millions of entities, abstractions are necessary to limit runtime as well as effort for model creation. Evaluations based on physical testbeds meanwhile yield highly precise results as all functional aspects are implemented as they would be in a real deployment. Due to costs and the required effort however it is not possible to capture the extent of large scenarios. Thus scaling effects cannot be reproduced in full. Systems such as Smart Grids however require a precise modeling of small as well as large-scale effects. Therefore this paper proposes an approach which combines the benefits of both traditional assessment methods. Control algorithm traffic patterns are captured in a testbed which implements the respective use case, and are used as input for a simulation to support the analysis of ICT behavior on a large-scale. Figure 1 illustrates this.

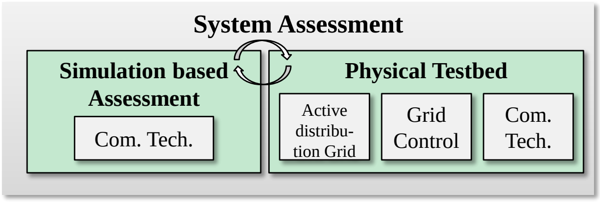

Figure 1: Dualistic Assessment Methodology

In order to facilitate this approach, first a cross-validation of testbed and simulation models is performed to increase confidence in the results. The required alignment of both these parts is achieved through multiple steps, including the matching of technological parameters. As the testbed is recreated in simulation (i.e. Riverbed Modeler) results need to match. In case of discrepancies, models need to be fine-tuned until the gap is closed. Subsequently the examined scenario is scaled up in size to replicate large deployments in simulation. Here the performance of different communication technologies is recorded and can be fed back into a network emulator embedded in the testbed. Thereafter the behavior of control functions affected by the previously captured performance data can be analyzed, thereby yielding crucial insights into the effect of diverse ICT on large-scale Smart Grid operation.

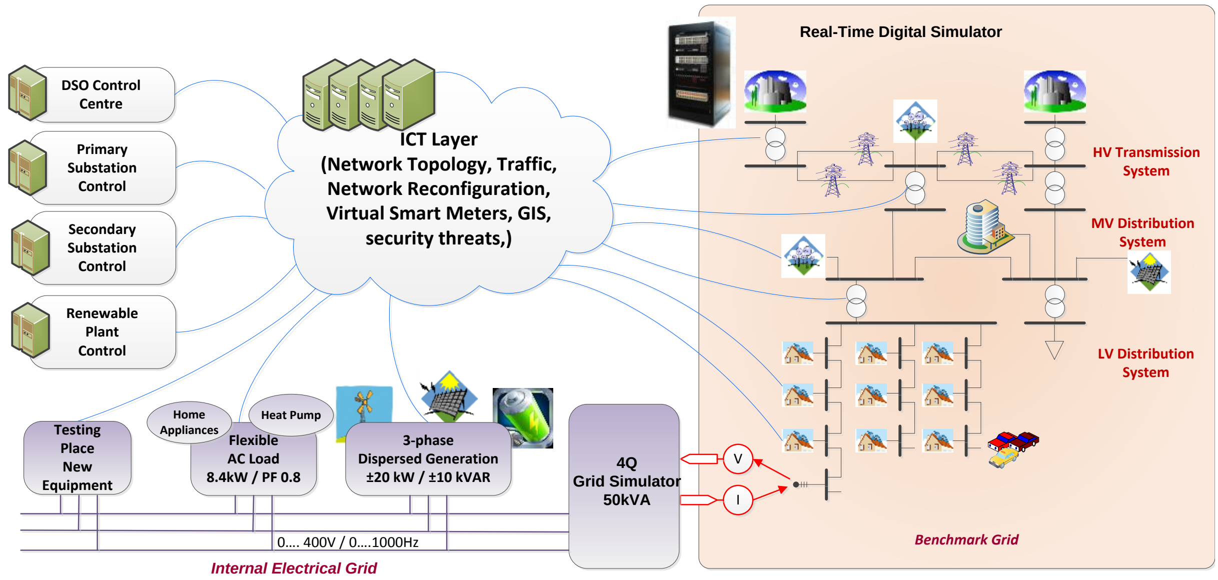

Figure 2: Architecture of the DSO control for active distribution grid testbed hosted at Aalborg University [5]

USE CASE AND EVALUATION SCENARIO

Distributed Energy Resources (DER) such as combined heating and power, wind turbines and photovoltaics are a central aspects of Smart Grids. Therefore this use case serves as a basis for the purposes of this paper. A detailed description of it and its architecture is given in [1]. An overview of the used testbed is given by Figure 2. Located at Aalborg University it implements an internal electrical grid complete with flexible loads, 3-phase generation, primary and secondary substation control as well as a DSO control center. It can be seen, that parts of the use case which require a means of communication are connected to a block called “ICT Layer”, which implements network emulation based on results from large-scale simulations.

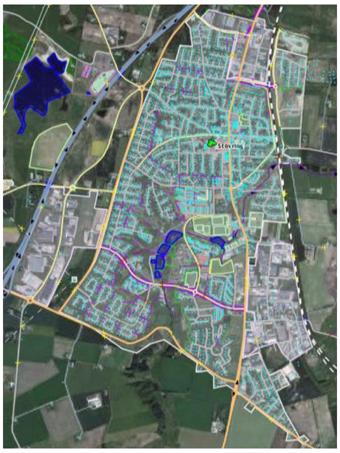

Figure 3: City in Simulator with DER shown as Dots

Furthermore a real-time digital simulator is utilized to recreate a benchmark grid, in this case the electrical grid of the town of Støvring in Denmark. It serves as an area whose characteristics, such as the topology, cell-tower locations and building placements are recreated within the simulation environment with the aim of providing a detailed and realistic deployment scenario. Figure 3 shows a high level view of this urban area [4]. Here the locations of deployed DER are indicated by markers overlaid on the satellite imagery.

Regarding the evaluation scenario the following aspects apply. A DER controller runs the appropriate control algorithms to optimize power generation and consumption with the aim of achieving grid stability in the face of unsteady energy demand and creation. Low and medium voltage grid controllers are included in the secondary and primary substation and are attached to a wide area network to simulate the effects induced in real-world layouts. Relevant set-points as calculated by the developed control algorithms and monitoring functionalities [3] are sent from low and medium voltage grid controllers to the different DERs, which then follow the configured profiles. The two main traffic flows are therefore the transmission of measurement values from the DER to the grid controllers and their response with the appropriate set-points in the inverse direction. Data sizes have a payload of typically 50 Byte per asset per transmission. Fully assembled packets (i.e. including protocol overhead) are at 340Byte for TCP based transmissions (e.g. set-points) and 196Byte for UDP packets (measurements). Given values are based on the implementation of control, monitoring and related functionalities as they are integrated in the physical test beds [5]. Control cycle length is set to 15 minutes and thus represents the upper bound for transmission of measured data as well as processing and the subsequent installation of new set-points. 600 DER are distributed within the benchmark area. End-to-end communication delay is a critical metric for the evaluation of ICT and their suitability for use in Smart Grid control as the value of information decreases as it ages [2]. It is therefore the key performance indicator of this work. Unsuccessful transmissions are repeated until messages arrive at their destination. Packet loss can thus be neglected but increases delay and thereby decreases ICT and control performance.

ANALYSIS RESULTS AND DISCUSSION

The impact of different scenario sizes on ICT performance can be seen from the results obtained for the deployment of CEMS in the benchmark area. Starting with 75 of such systems the simulation yields the results given in Figure 4.

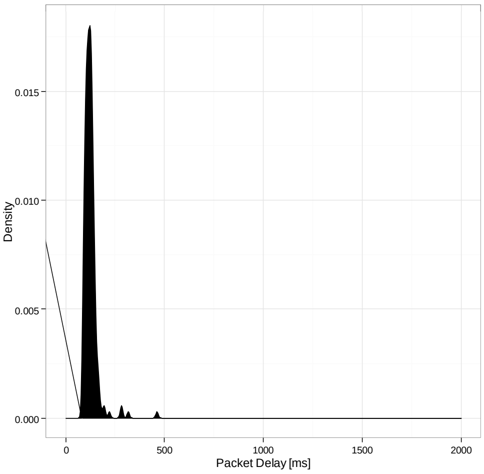

Figure 4: Communication Delay of 75 CEMS Systems in 3G UMTS

The delay distribution of UMTS (Universal Mobile Telecommunications System, 3G) stays mostly below 0,4 s when 75 instances of CEMS are active. Here one main peak at around 0,12s can be observed, with few results not grouped around this value. Therefore, if a testbed of such size would be used for assessment of the use case, 3G would be considered a solution fully suitable for the task. If the number of deployments however is increased to 200 (c.f. Figure 5), the delay distribution shifts to higher values and gains an additional peak at around 0,25s. Outliers reach close to 2s. This behavior is caused by more pronounced contention for access to the wireless channel, resulting from a higher probability of concurrent transmissions coming from more active CEMS. In this instance wireless 3G is still suitable for even advanced control schemes. Nevertheless the increased load placed on the technology can clearly be seen. Also the lack of background traffic, as it is found inside public communication infrastructures, needs to be taken into account in case such a configuration is desired.

Moving on to the main scenario of DER deployment, the results are given by Table 1. As outliers in communication delay can potentially affect Smart Grid operation, the 1st ($Q_{0,01}$) and 99th ($Q_{0,99}$) percentile are given, in addition to the average delay obtained by simulation. The lower percentile is indicative of the performance that can be expected in regions of the area under study with few DER, while the average gives a good indication of the respective technologies overall suitability within the scenario.

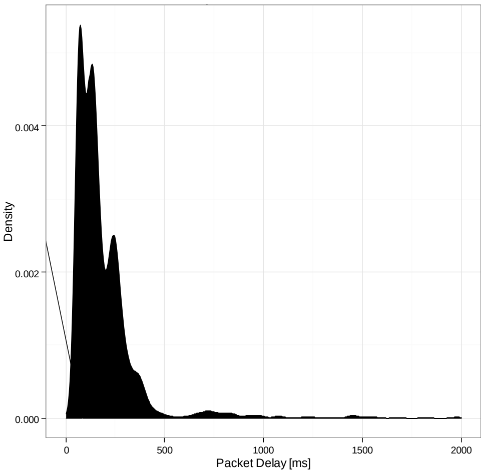

Figure 5: Communication Delay of 200 CEMS Systems in 3G UMTS

Starting with wireline communication, it can be seen how Digital Subscriber Line (DSL) averages just below 40ms. It shows a narrow delay distribution as upper outliers reach only about twice the average, while the $Q_{0,01}$ percentile is at 16ms. This constitutes a slight rise compared to an idle connection, as multiple active assets connect to the same DSLAM (DSL Access Multiplexer) due to the high number of DER deployed within the area. The second wired technology, fiber based Ethernet, however is less affected as a result of its different, more capable network topology. The average and the lower percentile are around 7ms while peaks reach up to approximately 14ms. This very narrow distribution highlights the substantial capabilities and potential of fiber based communication. A closer examination shows that delay variations are mostly caused by queueing at the ingress switch of the access network.

IEEE 802.11g, commonly known as WiFi, is the fastest wireless option studied. To achieve full coverage of the analyzed area, it is however necessary to have a densely placed infrastructure of base stations. This also increases the available capacity for the transport of information and is associated with increased financial costs. Peaks of about 2,4s are substantially higher than those of the wired alternatives and can be contributed to contention for access to the wireless channel, which causes collisions and retransmissions. An average transmission time of about 88ms is just slightly above the peaks of DSL. The same applies to the $Q_{0,01}$ percentile with ~44ms.

Moving on to the cellular technologies, 4G LTE (Long Term Evolution) is shown to have the best and most consistent performance characteristics with an average delay of ~370ms. Although this is factors above WiFi, the $Q_{0,99}$ percentile at 1,12s is less than half of WiFi's peak.

Table 1: Delay overview for the Distributed Energy Resource Use Case (unit: ms)

	DSL	Fiber	IEEE802.11g	2G (GPRS)	3G (HSPA)	4G (LTE)
$Q_{0,99}$ percentile	82,61	13,93	2381,52	12836,09	5034,18	1120,31
Average	38,42	7,01	87,56	2241,84	970,47	369,24
$Q_{0.01}$ percentile	16,01	6,73	43,63	362,74	216,84	55,68

LTE's predecessor technology 3G, with High Speed Packet Access (HSPA) enabled, is on average significantly slower in transmitting data with just under one second delay. The lowest observed value is around factor four slower compared to LTE while the peak is four and a half times as high. This larger delay spread is still acceptable for 15minute control cycles as used for this work. It could however become a problem in future, more demanding iterations of the use case with more complex monitoring and control algorithms or more DER.

The second generation of cellular communication, 2G General Packet Radio Service (GPRS) has the worst performance of the analyzed technologies. On average it needs 2s to transmit the Smart Grid messages. With 12,8s peaks are over twice are high as with 3G and eleven times higher than LTE. Considerations formulated for 3G thus apply even more strongly. As control algorithms need time for calculations, 2G is highly unlikely to operate stably within for example voltage control cycles with a length of e.g. one minute. In conclusion 2G cannot be considered a future proof option and should not be used on a large-scale. Also cross-traffic, when used in a shared public network, will increase delays further, which might limit additional functionalities like faster control cycles. Additional results as well as parameters are given in [4].

With regards to deployment options, all communication technologies studied in this paper can handle the requirements of the use case, although some delimitations have to be taken into account as no air interface contention from public wireless infrastructures is introduced. In this regard UMTS and more so LTE are the only cellular options capable to support future increases in requirements such as shorter control cycles. IEEE 802.11g outperforms both solutions, but requires a denser infrastructure for full coverage. Both wireline technologies are fast enough for the currently employed traffic patterns and have high untapped resources in terms of data-rate to support future requirements. Choosing the most suitable ICT therefore depends on factors such as cost and investment protection for long term infrastructure use. Here it is to be noted that 2G will, at least in some countries, be dropped by carriers around the year 2020 [6]. As cellular 5G, as an evolution based on 4G LTE, is currently scheduled to be available until then, UMTS is also likely to be replaced within the following years. Freed spectrum will be reused by public telecommunication companies to strengthen the spectrally more efficient 4G and 5G networks. For this reason a shared use of 2 and 3G communication infrastructures by DSOs and TelCos won't be possible in the long-term. In consequence only 4G is recommended as a future proof cellular technology. Wireline options such as DSL and fiber based Ethernet have the highest performance but suffer from comparatively high deployment costs. In this regard DSL has the advantage of functioning via traditional telephone networks, resulting in cost savings.

CONCLUSION

An analysis strategy via interaction between testbed and simulation is presented and used to show the performance of different communication technologies (e.g. cellular 2G to 4G) and their suitability for control functions in large-scale Smart Distribution Grids deployments. The results show how that LTE is a technology suitable for use in current and future Smart Grids, while 2G is not recommended for new and large-scale rollouts.

ACKNOWLEDGEMENT

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