

1 Article

# 2 Co-Simulation of Smart Distribution Network Fault 3 Management and Reconfiguration with LTE 4 Communication

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12 **Abstract:** Simulation tools capturing the interactions of communication and electrical system  
13 operation represent a powerful support for fully assessing the potential benefits and impacts of ICT  
14 in future smart power distribution network. A strong interest is upon the possibility of exploiting  
15 the last generation communication systems for supporting the transition of distribution network  
16 towards a smart grid scenario. Having in mind the above, the authors propose a numerical  
17 co-simulation tool useful to thoroughly understand the impact of the communication networks on  
18 the performance of whole power system dynamics. The co-simulation tool has been purposely  
19 developed to simulate the highly time-critical smart grid application of fault management and  
20 network reconfiguration and permits reproducing and evaluating the behavior of the public mobile  
21 telecommunication system 4G Long Term Evolution (LTE), as communication technology for smart  
22 grid applications. Results of the paper demonstrates that LTE provides good performances for  
23 supporting the data communication required to perform fault location, extinction and a subsequent  
24 network reconfiguration in smart power distribution networks.

25 **Keywords:** Smart Grid, Cyber Physical co-simulation, Information and Communication  
26 Technology, 4G Long Term Evolution - LTE, Network Reconfiguration, Fault Management  
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## 28 1. Introduction

29 The development of the future energy system in accordance with the smart grid (SG) paradigm  
30 requires a radical change in the management of the electricity distribution network, which needs to  
31 become intelligent and adaptive. Smart distribution networks (SDN) have systems in place to  
32 control a combination of distributed energy resources (DERs). Distribution system operators (DSOs)  
33 have the possibility of managing the electricity flows using a flexible network topology [1,2]. The  
34 transition towards SDN involves software, automation and controls, to ensure that the power  
35 distribution network not only remains within its operating limits (e.g. node voltages and branch  
36 currents within the acceptable limits), but it is also operated in an optimal way. In the SDN context,  
37 therefore, Information and Communication Technologies (ICT) are not a simple add-on of the  
38 electrical system, but their availability and efficiency are essential to the operation of the entire  
39 power distribution system. In fact, the electric system will be managed and controlled through the  
40 ICT network, which will allow a bidirectional exchange of large amount of data creating a keen  
41 interdependence between electric system and ICT system. In the ICT system, the communication  
42 between the SDN components is characterized by non-idealities such as latencies and packet losses  
43 that may reflect upon the power system operation; furthermore, components such antennas, routers,  
44 modems, etc. are subjected to faults and malfunctioning that may cause system reliability reduction,  
45 or service interruption [3].

46 With the recent enhancements in wireless solutions, which guarantee a reliable low-cost  
47 communication, a strong interest is upon the possibility of exploiting the last generation  
48 communication systems for supporting the transition of distribution network towards a Smart Grid  
49 scenario. However, the best option for the communication technology solution to fit SG applications  
50 is still not clear, even though LTE technology is considered one of the most promising. LTE, with its  
51 widespread distribution, broad coverage, high throughput, device to device (D2D) capability,  
52 despite not being originally designed for smart grid applications, represents a valuable candidate for  
53 the usage in a SG communication system [4,5]. A comprehensive analysis of an LTE-based smart  
54 grid operation analysis with a co-simulation approach is still missing in Literature. In [6] the  
55 communication challenges when choosing a technology supporting distribution automation  
56 applications are investigated with the communication software OPNET. LTE performances are  
57 analyzed in terms of coverage, delay and reliability with variable real-world deployment  
58 constraints, but the impact on distribution network is only analyzed in terms of requirements, and  
59 no interrelation between communication network and distribution network is analyzed in a joint  
60 way. A similar approach is adopted in [7], where an OPNET simulates the use of LTE for  
61 transmitting Phase Measurement Unit (PMU) packets in a fault monitoring system. Performances in  
62 terms of latencies, channel utilization and response with variable load are examined. An analogous  
63 methodology is applied in [8], where LTE is analyzed in an OPNET environment in order to  
64 investigate on the impact of SG communication on a public shared LTE networks. Finally, in [9] LTE  
65 latencies are theoretically investigated based on the requirement documents released by NIST and  
66 the traffic distribution of smart grid distribution automation, considering a smart grid application  
67 reserved bandwidth. All these valuable publications miss at catching the cyber-physical behavior of  
68 smart grid, where electric and communication systems are strictly interdependent. A joint  
69 simulation platform where both domains are contemporarily simulated is fundamental in order to  
70 correctly analyze the smart grid behavior providing test platforms for smart grid applications that  
71 can be used for engineering smart grids from use case design to field deployment [10].

72 In this context, this article aims at providing a co-simulation based assessment method for the  
73 performance evaluation of LTE as communication technology for smart grid application,  
74 considering a highly time-critical application like the fault location, isolation and system  
75 reconfiguration (FLISR).

76 The paper is organized as follows: section 2 reviews the challenges and objectives in developing  
77 co-simulators of SDN and provides the details of the co-simulator developed by the authors for the  
78 assessment of communication technologies for smart grids applications. Section 3 describes the  
79 smart distribution network reference scenario, the innovative protection schemes and the fault  
80 management approach co-simulated. Section 4 presents a case study analysis with discussion of the  
81 results. In the final section the conclusions are provided.

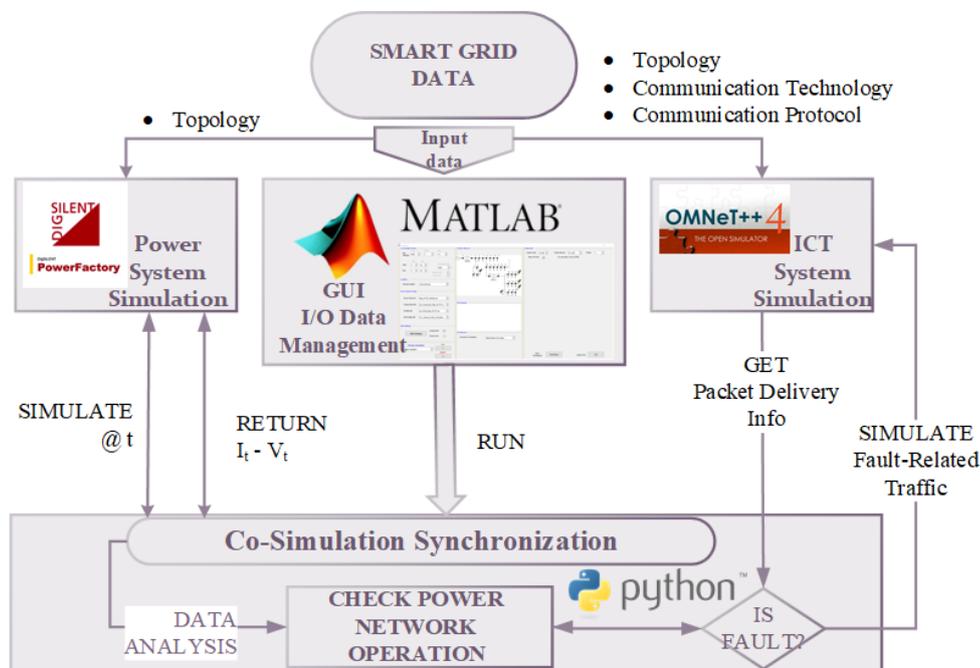
## 82 **2. Co-simulation of Smart Grids**

83 Smart Grids simulators may be classified according to their modeling capabilities of power and  
84 communication systems. Three alternative approaches have been proposed in literature to tackle this  
85 kind of studies: the co-simulation, the comprehensive simulation and the hardware-in-the-loop.

86 The co-simulation usually involves the integration of two or more simulators to capture the cyber  
87 physical interdependency of a process or system. By co-simulating conventional power system  
88 simulation with communication and automation systems, the impact and dependencies of  
89 communication on the system can be investigated [11],[12]. In co-simulation, each system is  
90 analyzed by its own dedicated simulator, and all simulators are executed simultaneously by  
91 appropriately designed run time interfaces (RTI) and coordinated simulation management. Various  
92 solutions for realizing a co-simulation tool may be found in the Literature, that differ for the targeted  
93 field in the research on the smart grids, and consequently in architectural choices, e.g., software  
94 components, time synchronization strategy, and scalability. Among them, for instance, EPOCHS is  
95 recognized to be one of the first co-simulation tools for power systems [13]. It was developed with  
96 the integration of three different commercial software: PSCAD/EMTDC and GE Power Systems

97 Load Flow Software (PSLF) simulating the power grid, and ns-2, which simulates the  
 98 telecommunication network. PSCAD/EMTDC is dedicated to simulate electromagnetic transients,  
 99 whilst PSLFs to simulate the electrical system for long-term scenarios. Another important pioneer  
 100 platform for co-simulation is GECO [14]. It exploits the event driven method for synchronizing the  
 101 simulation of the power system (with PSLF) and the communication network (modeled with ns-2).  
 102 In this tool, each iteration of the numerical solution of the power flow is an event. All events are  
 103 integrated in the event scheduler of ns-2, allowing a perfectly integrated simulation and the  
 104 minimization of the synchronization errors. If compared with time step synchronization, event  
 105 driven synchronization permits reducing the simulation time and simulating large power systems  
 106 with reduced computational burden. An alternative approach is the comprehensive simulation, that  
 107 combines power system and communication network simulation in one environment. In this case,  
 108 the main concept is to bring together both system models and solving routines which leads either to  
 109 integrate power systems simulation techniques into a communication network simulator or vice  
 110 versa. A comprehensive simulation approach has been adopted for instance in [15], where the  
 111 authors present a modular simulation environment based on OMNeT++ exploiting the existing  
 112 models for the communication network but purposely developing extra models for the electrical  
 113 network. Finally, co-simulation could be realized with hardware in the loop (HIL) with software  
 114 simulators and hardware components integrated in a real test bed, often used for testing control and  
 115 protection systems in power systems [16]. HIL approach allows a perfect correspondence with a real  
 116 system but with higher investment costs. A detailed state-of-the-art review of appropriate tools for  
 117 simulating both domains of power system and ICT processes in the evolution of smart grids is  
 118 presented in [17].

119 The architecture proposed in the paper for co-simulation coordinates two software packages,  
 120 i.e. OMNeT++ for the ICT system and DIGSILENT PowerFactory for the power system with a Python  
 121 script. A Matlab Graphical User Interface (GUI) has been developed, which allows the user to  
 122 personalize the input data and to interact with the simulation, as illustrated in Figure 1.  
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125 **Figure 1.** Schematic representation of the Co-Simulation tool

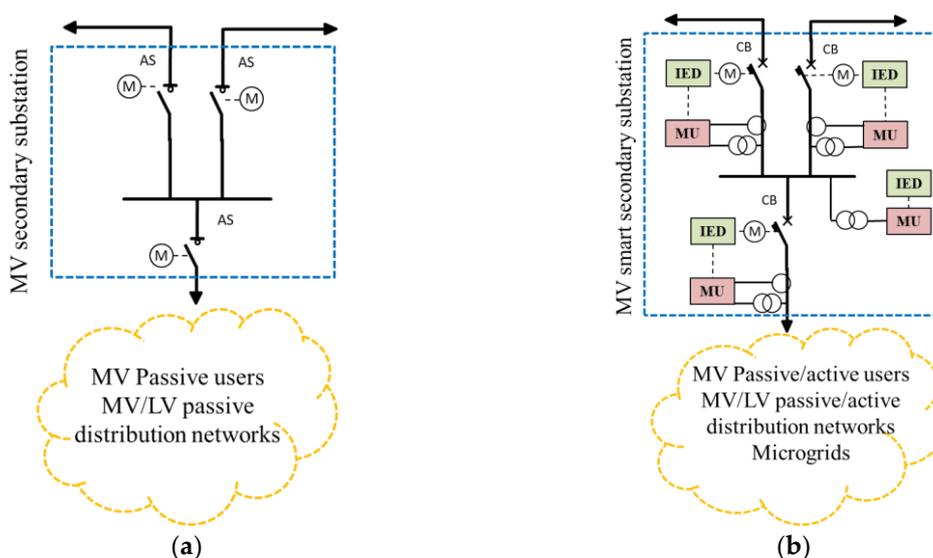
126 The co-simulator uses the electromagnetic transient analysis capabilities of PowerFactory, and  
 127 the wide choice of libraries for communication systems analysis that are offered in the OMNeT++  
 128 open source environment. Specifically, in this paper, a system-level simulator for LTE and  
 129 LTE-Advanced networks (SimuLTE) has been used [18].

130 The Python script coordinates both dynamic simulations and allows data exchange between  
 131 software packages through dedicated interfaces. PowerFactory provides a Python API that allows  
 132 accessing to the software functionalities, element parameters, simulation results, etc. The integration  
 133 of OMNeT++ in the co-simulation framework is obtained with a TCP socket connection programmed  
 134 in C++. The Python script is the Run Time Interface (RTI) of the co-simulation tool. For each  
 135 time-step,  $\Delta t$ , the script calls PowerFactory for solving the differential algebraic equations that  
 136 describe the electric network analyzed during the time interval, and contemporarily calls OMNeT++  
 137 that executes the simulation during the subsequent time sample. The scheduler is the heart of the  
 138 simulation in the OMNeT ++ environment, as its purpose is to handle the event list and run the  
 139 scheduled event for the instant immediately after the current time. A customized scheduler has been  
 140 purposely developed in the RTI to properly coordinate the OMNeT++ simulation. In the proposed  
 141 application when a short circuit condition is detected in the electric network, a new event is  
 142 scheduled in OMNeT++ that simulates the communication among the distributed devices involved  
 143 in the FLISR.

### 144 3. Protection system for Smart Distribution Networks

#### 145 3.1 Smart distribution network structure

146 In distribution systems, supervised control and data acquisition (SCADA) are typically  
 147 positioned at feeder level, and the majority of the distribution secondary substations are not  
 148 extensively monitored or controlled. Each secondary substation is equipped with manually or  
 149 automatic sectionalizer (AS), or load-break switches, used in conjunction with source-side circuit  
 150 breakers, such as reclosers or circuit breakers, positioned at the origin of the MV distribution feeders  
 151 or in critical points, to automatically isolate faulted sections of electrical distribution systems with  
 152 support of SCADA systems. The power to operate the control circuitry and the mechanism is  
 153 obtained from the line through the sensing-current transformers (Figure 2a). No auxiliary power  
 154 supply, external connections, or external equipment is required. The AS, when the source-side  
 155 circuit breaker opens to de-energize the circuit, permits disconnecting a portion of the distribution  
 156 system or a single MV user (typically passive).  
 157



158 **Figure 2.** Schematic representation of: (a) conventional secondary substation (b) smart secondary  
 159 substation.

160 In SDN, the secondary substations will be transformed into smart secondary substations (SSS)  
 161 with a pervasive use of digital communication and intelligent electronic devices (IEDs) to enable  
 162 local and/or remote sensing and control of substation equipment [19] (Figure 2b). The IEDs,

163 microprocessor-based controllers of power system equipment such as circuit breakers, transformers  
164 and distributed generation, can be used for protection purposes, power quality analysis, network  
165 monitoring, energy metering, and so on. Real-time control of each network component will be  
166 requested, and the network will be equipped with smart meters and communication devices as well  
167 as with faster protection devices and controls for power flow monitoring, distributed generation  
168 management and network automation [20]. Distribution system operators (DSO) are already  
169 developing a significant refurbishment activity of secondary substations with new solutions for  
170 technological improvement of MV and LV equipment, MV/LV transformers, protection system,  
171 remote control devices and auxiliary components [21,22], in order to create the SSS. The SSS will be  
172 equipped with reliable power components, high performance protection schemes, efficient flow  
173 monitoring system and reliable communication infrastructures, organized in order to:

- 174 • manage energy flows
- 175 • contribute to voltage regulation,
- 176 • ensure fast reconfiguration after a failure,
- 177 • identify and pursue efficiency opportunities.

178 With SDN, the radial operation of the network could be abandoned with significant benefits.  
179 Indeed with a closed-loop or weakly meshed network, the reduction of power losses, improvement  
180 of voltage profile, and a greater flexibility with reconfiguration, as well a superior ability to cope  
181 with the load/generation growth with less need of network upgrades [23–25]. SDN will allow the  
182 change between radial and meshed operation enabling the exploitation of the advantages of both  
183 schemes.

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### 185 *3.2 Fault detection and reconfiguration scheme for smart distribution networks*

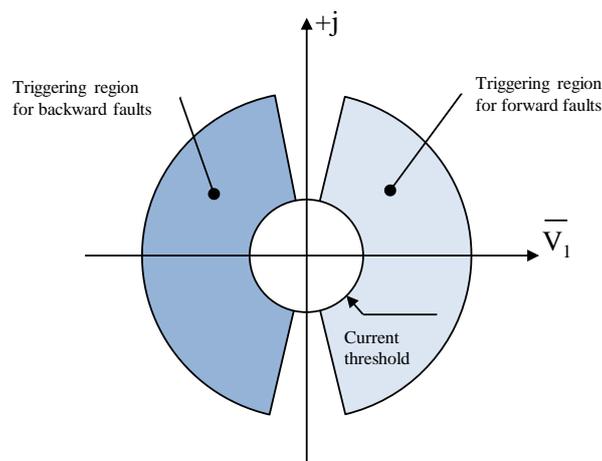
186 In distribution systems, network automation and protection systems are designed to minimize  
187 the number of power interruptions and to limit the outage duration. With the smart grid  
188 enhancement, the number and outage time of interruptions is expected to be further reduced  
189 compared to current situation.

190 The operation of the circuit breakers is highly time critical, since it is necessary to guarantee an  
191 instantaneous trigger on the breakers in order to assure an efficient intervention during or after a  
192 fault extinction. The implementation of such systems requires a smart grid infrastructure that allows  
193 the fast location of the area of the fault and the interruption of the short circuit current as well as  
194 automation systems to reduce the outage duration with automatic reconfiguration and strongly  
195 relies on the performance of the communication system. Compared to wired solutions, such as PLC  
196 or Fiber Optics, the paper wants to investigate to the use of wireless technologies for smart grid  
197 applications. In fact, they may provide communication abilities with lower cost of equipment and  
198 installation, quicker deployment, wide access and flexibility [26].

199 In the paper the communication systems analyzed is the LTE architecture used in public  
200 communication networks. The SSS are connected to the communication network through LTE user  
201 equipment (UE). A distribution management system (DMS) with  
202 supervision/protection/reconfiguration capabilities is also used on the same communication system.  
203 Under the proposed protection scheme each SSS is equipped with two measurement units, and IEDs  
204 able to detect the direction of the fault currents and to communicate with DMS besides the adjacent  
205 IEDs. This scheme configures a DMS with decentralized architecture able to provide more flexibility  
206 and rapidity of intervention [27,28].

207 The fault management and the strategy in opening of the breakers differs according to the  
208 network configuration, meshed or radial. Three phase short circuit faults are the simplest to be  
209 identified and handled. If the network is managed in radial configuration, and no distributed  
210 generation (DG) exists, the fault will be fed only from the primary substation. In this case, the nodes  
211 that are located downstream the fault will not detect any fault current. This fault condition is  
212 unambiguous and enables fast fault localization. Whether a reclosing branch is installed in the SSS,  
213 the IED will be alerted for reconfiguring the network in order to minimize the impact of the fault. In

214 case of meshed networks, the operating characteristic of the directional relays for a three-phase short  
 215 circuit fault can be depicted as shown in Figure 3. Depending on the phase of the current is easy to  
 216 find the position of the faults analyzing the module and phase of the current.



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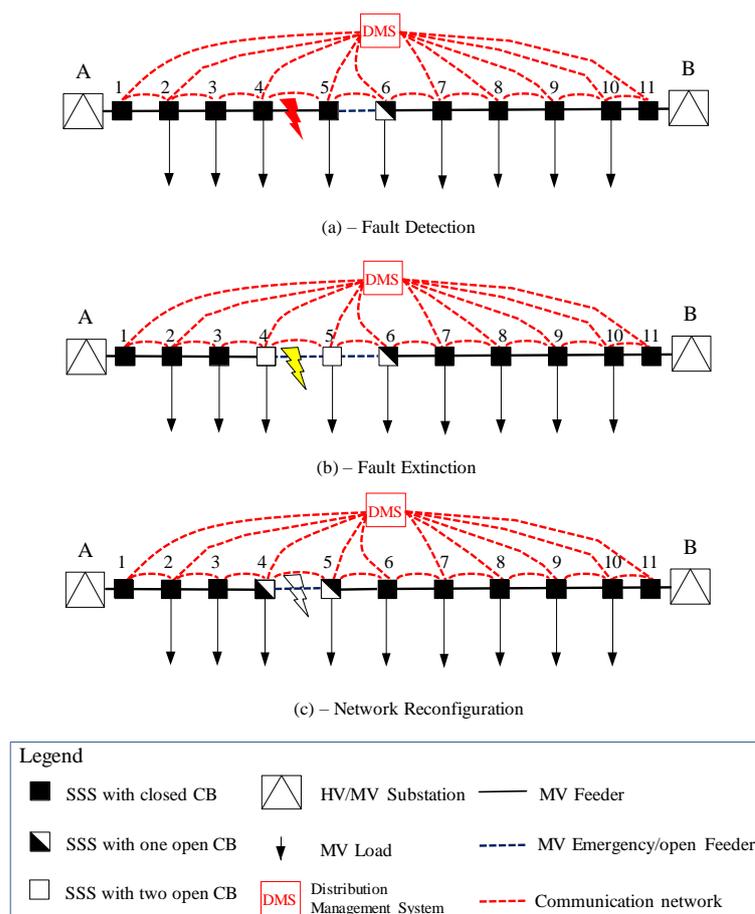
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**Figure 3.** Operating characteristic of the directional criteria for three phase short circuit faults

219 In this proposed application a smart selectivity scheme is assumed for three phase  
 220 inextinguishable faults. Those faults, even though are the less frequent, are the most critical in  
 221 distribution networks. In fact, the resonance grounding (neutral grounded with arc suppression  
 222 coils - Petersen coil), currently used in many European countries, permits choking the fault current  
 223 below the level of self-extinction ( $< 35\text{-}50\text{ A}$ ) by compensating the capacitive fault current of the  
 224 network. By this action all transient faults can be cleared without feeder tripping.

225 Considering an example of radial network as the one represented in figure 4, in case of  
 226 three-phase short circuit located between nodes 4 and 5 the fault current will flow from the feeding  
 227 HV/MV substation A.

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**Figure 4.** Radial distribution network reconfiguration managed with emergency tie

In case of fault on branch 4-5 of Figure 3a, the DMS, subsequently to the processing of information exchanged with the IEDs deployed in the SSS, has to:

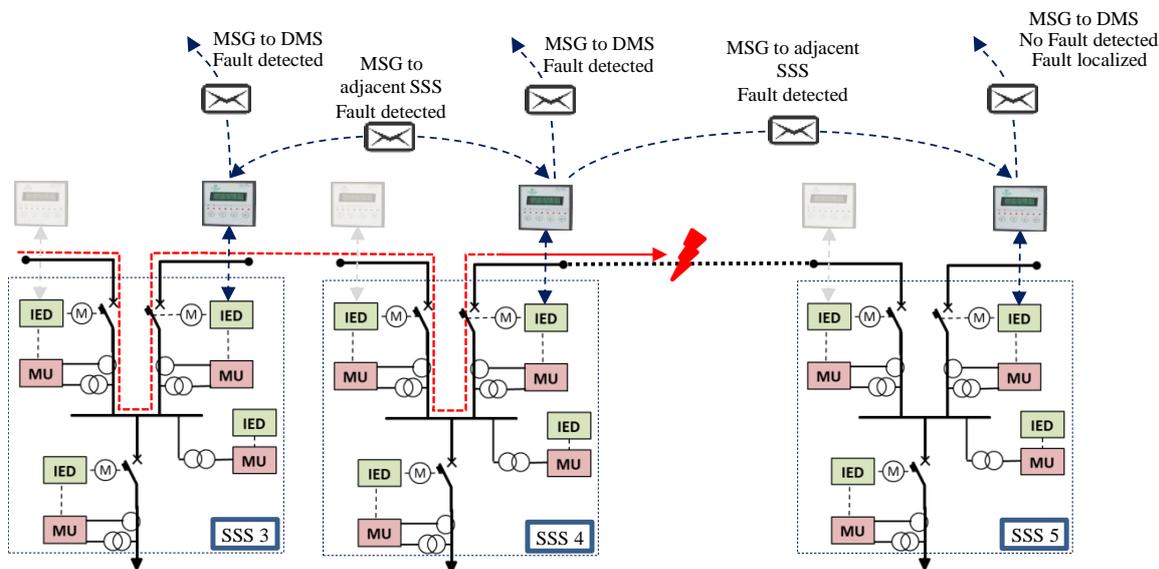
- 1) locate the fault (branch 4-5);
- 2) open the first circuit breaker upstream the fault (SSS 4) in order to extinguish the fault, providing selectivity (Figure 3b); the load at node 5 is unserved up to the network reconfiguration is completed.
- 3) operate the emergency tie (5 and 6, in order to minimize the out of service area. The opening of the circuit breaker on node 5, on the side of the fault, guarantees that the second HV/MV substation does not feed the fault, and the fault is cleaned (Figure 3c).
- 4) operate the closing of the circuit breaker on the node 6 permits the reconfiguration of the network and restoring the service to the load at node 5.

In case of fault, when the fault current exceeds the threshold, the IEDs of the SSS are activated and send to the neighboring IEDs positioned in the adjacent SSS the current measured (module and phase) (Figure 5) in order to provide a fast localization of the fault.

Each IED that measures the outbound short circuit current will provide a message, e.g. a Generic Object Oriented Substation Event (GOOSE) message using IEC 61850 standard protocol, of fault recognized to the DMS, and another message to adjacent IED. The IED receives a waiting signal from opening the corresponding CB, the selectivity is obtained and the location of the fault is reached where the IED downstream the fault does not receive any waiting message. After that, sequentially the DMS has to communicate with peripheral units do the following actions:

- a. opening of the CB (e.g. the outbound CB of the SSS4 in Figure 5) at the SSS upstream the fault;
- b. opening of the CB (e.g. the inbound CB of the SS5 in Figure 5) at the SSS downstream the fault;

257 c. closing of the CB that permit the reconfiguration of the network.  
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**Figure 5.** Short circuit current direction during three-phase fault in radial network

In case of meshed (closed loop) network as the one represented in Figure 6, when a short circuit fault occurs between nodes 4 and 5 the fault current will flow from both HV/MV substations A and B. In this case each IED that measures the outbound short circuit current from the SSS will provide a message of fault recognized to the DMS, and another message to adjacent IED. Itself receives a wait signal from opening the corresponding CB, and the location of the fault is reached when two adjacent IEDs register currents with opposed phases. After that, the IEDs send the message to the DMS to order the opening of the two CB (e.g. the outbound CB of the SSS 4 and the inbound CB of SSS 5 in Figure 7) on both sides upstream the fault.

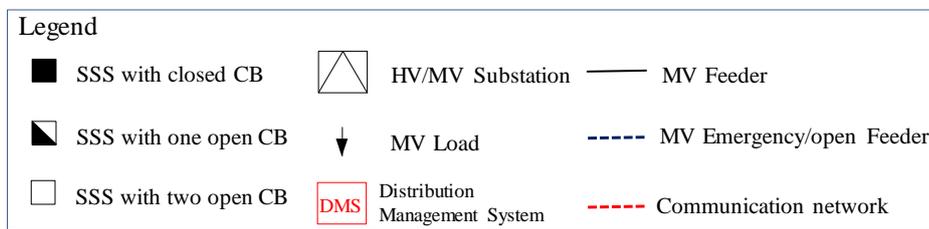
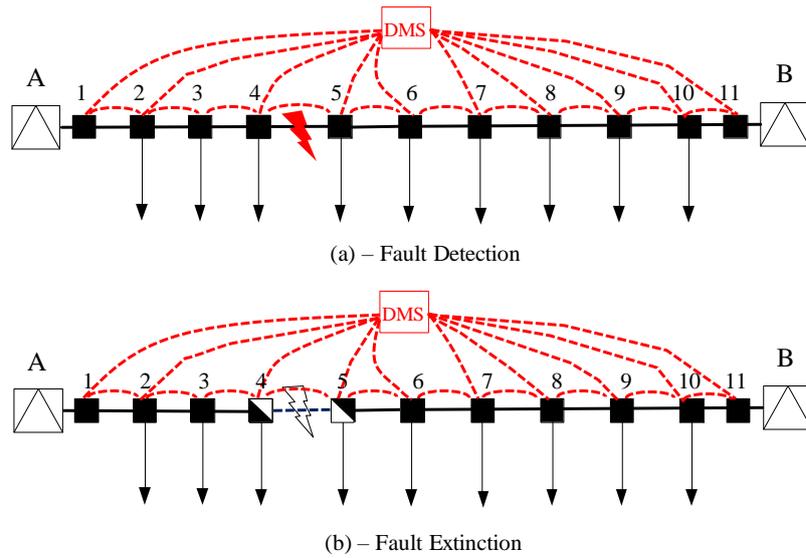


Figure 6. Fault detection and extinction in meshed distribution network

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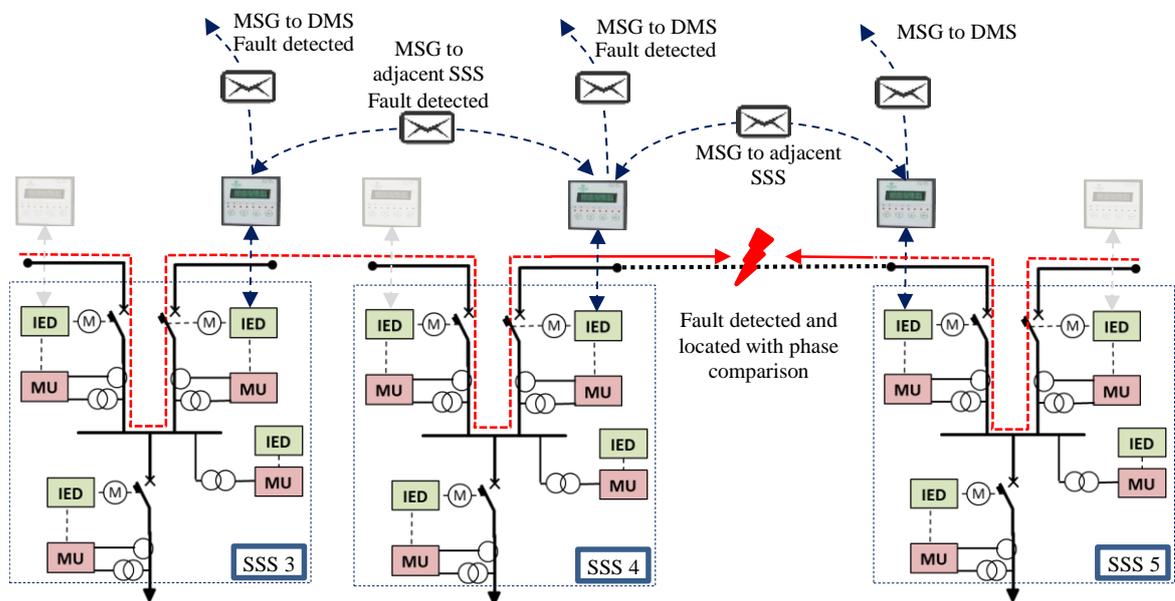


Figure 7. Short circuit current direction during three phase fault with meshed network

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### 283 3.3 LTE communication technology for smart grid operation

284 The smart grid concept requires flexible communication architecture that allows power  
285 network devices such as sensors, smart meters, IEDs, protection relays, to exchange data in order to

286 achieve an efficient operation of the electrical distribution system. A wide range of communication  
287 technologies, both wired and wireless, is nowadays available for building the communication  
288 infrastructure that will support the smart grid data exchange. Peculiar features characterize each  
289 technology, for example data rate, coverage, installation and maintenance costs, reliability, exposure  
290 to cyber-attacks, etc. The technology choice is therefore crucial. Wireless technologies appear as key  
291 candidates in building the Smart Grid communications network due to their low installation costs  
292 and ease of deployment. The spreading of mobile telecommunication devices has stimulated a  
293 committed research over existing communication technologies. GSM, GPRS, EDGE, UMTS are part  
294 of this continuous evolution that has led to LTE, which represents one of the fourth-generation  
295 mobile technologies (4G). According to the ITU, 4G technologies requires certain characteristics to be  
296 complied with, among others [29]

- 297 • Ability to inter-work with other radio technologies;
- 298 • High quality of service;
- 299 • Data rate of 100 Mbps in motion and 1 Gbps with fixed installations;
- 300 • Sharing of network resources, allowing multiple users per cell;
- 301 • scalable bandwidth from 1.4 to 20 MHz;
- 302 • Packet switching IP networks;
- 303 • Connection spectral efficiency of 15 bps/Hz in downlink and 6.75 bps/Hz in uplink;
- 304 • Operating modes: TDD and FDD.

305 Currently LTE is the technology that most efficiently meets all these requirements permitting  
306 broad coverage, high throughput, device to device (D2D) capability, and the most recent  
307 LTE-Advanced release (LTE-A) provides the users with performances that are comparable with the  
308 wired DSL technology [4,5]. Finally, the main features that enable LTE for supporting Smart Grid  
309 communication are [4]:

- 310 • use of licensed bands: the communication network is robust against cyber-attacks and possible  
311 stealing of confidential data and permits a better handling of interferences if compared with  
312 technologies that operate on license-free bands.
- 313 • mature and ubiquitous coverage: the communication network span over vast areas, thus  
314 permits to integrate even remote endpoints to the main power grid.
- 315 • high performance: high data rate, low latency, and high system reliability enable critical  
316 automation tasks within the distribution grid that are often associated with demanding QoS  
317 requirements, such as severe time constraints.
- 318 • third-party operation: it relieves DSOs from having to run and maintain a dedicated  
319 communication infrastructure.

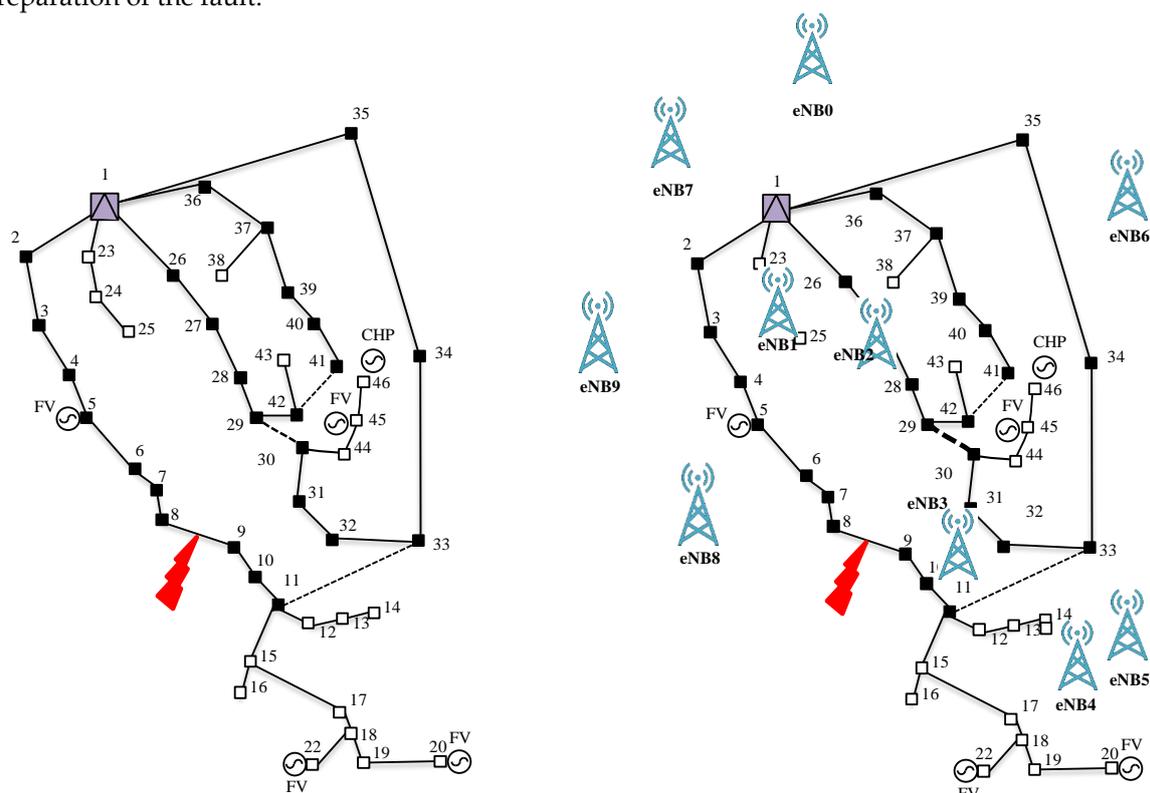
320 For the abovementioned reasons, the smart-grid operation considering the 4G LTE communication  
321 system, assuming to use the existing public mobile communication system has been chosen.

#### 322 4. Case study, results and discussion

323 The objective of the study is to analyze the performances of LTE as a communication carrier for  
324 supporting the data communication required for FLISR in SDN, permitting fault location, isolation  
325 and service restoration in an acceptable time. For example, in Italy, the regulation of distribution  
326 systems includes output-based incentives to DSOs related to the quality of service, and, in particular,  
327 the short interruptions from 1 second up to 3 minutes [30] can be targets of penalties or incentives.  
328 The DSO then, in order to avoid a worsening of its power quality indices, has to limit during faults  
329 the maximum interruption time under 1 second; for this reason he needs tools for the assessment of  
330 communication technologies for smart grids applications like the one presented in this paper.

331 The proposed FLISR has been tested on a real distribution network formed by 5 feeders, supplied by  
332 a HV/MV primary substation, and interconnected with emergency ties that can be used for changing  
333 the network reconfiguration. The network under study extends for about 10 km and supplies,  
334 through 46 secondary substations, a mix of residential and commercial loads in an urban scenario  
335 (Figure 8). The area is assumed being served by LTE mobile public network, and the distribution of  
336 towers/antennas (e.g. eNB nodes in Figure 8b) follows realistic georeferenced data. A three-phase

337 permanent fault in assumed in the branch 8-9, the fault is detected by the protection system of the  
 338 network and then the network can be reconfigured for permitting the DSO crews to perform the  
 339 repair of the fault.



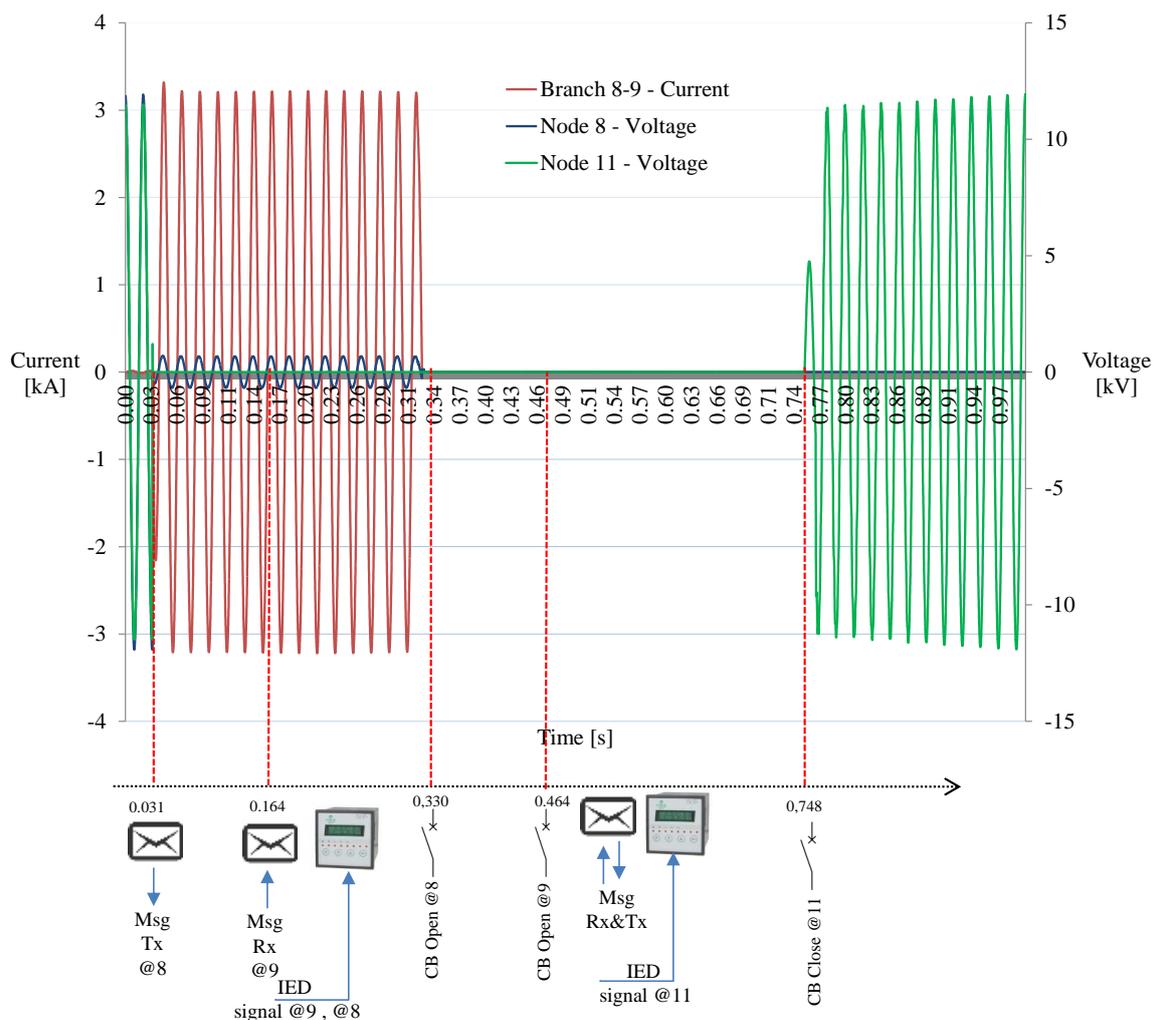
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341 **Figure 8.** Case study: a) Distribution network, b) Superimposed mobile LTE communication network

342 For the sake of simplicity, but without loss of generality, the simulations showed in the  
 343 following examples does not consider the fully implementation of IEC 61850 data model and  
 344 parameters in IEDs and DMS simulated [19].

#### 345 4.1. Radial network operation

346 In the radial operation of the network the emergency tie between nodes 11 and 33 in Fig. 8 is  
 347 normally open. The co-simulation platform permits simulating the detection and clearing of the fault  
 348 condition, as well as the procedure for reconfiguring the network by closing the emergency for the  
 349 minimization the network area out of service. This case study is of interest, for instance, for DSOs  
 350 interested to know how much time is necessary to reconfigure the distribution network using LTE  
 351 communication systems in a smart grid scenario.  
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**Figure 9.** Voltage/Current Profiles: a) Voltage profile at node 8, and current profile in branch 8-9

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The transient caused by a fault is depicted in Figure 9. At node 8, after 164 ms from the fault, the IED triggers for opening the breaker, and extinguishing the fault current. The mechanical opening of the breaker is simulated by a time delay, which is randomly extracted from a Gaussian distribution (with mean 0.2 s and standard deviation of 0.05 s) and the fault is extinguished after 330 ms. A message to the adjacent SSS (node 9) is sent for opening the switch and isolating the faulted network section. The node 11 will wait for the confirmation of the circuit breaker 9 opening that, due to the mechanical delay in the CB, arrives with a feedback packet at 464 ms. Afterwards, the DMS sends a message to IEDs at nodes 11 and 33 for closing the terminals of the emergency tie. The voltage profile at node 11 shows that the network is reconfigured after 748 ms.

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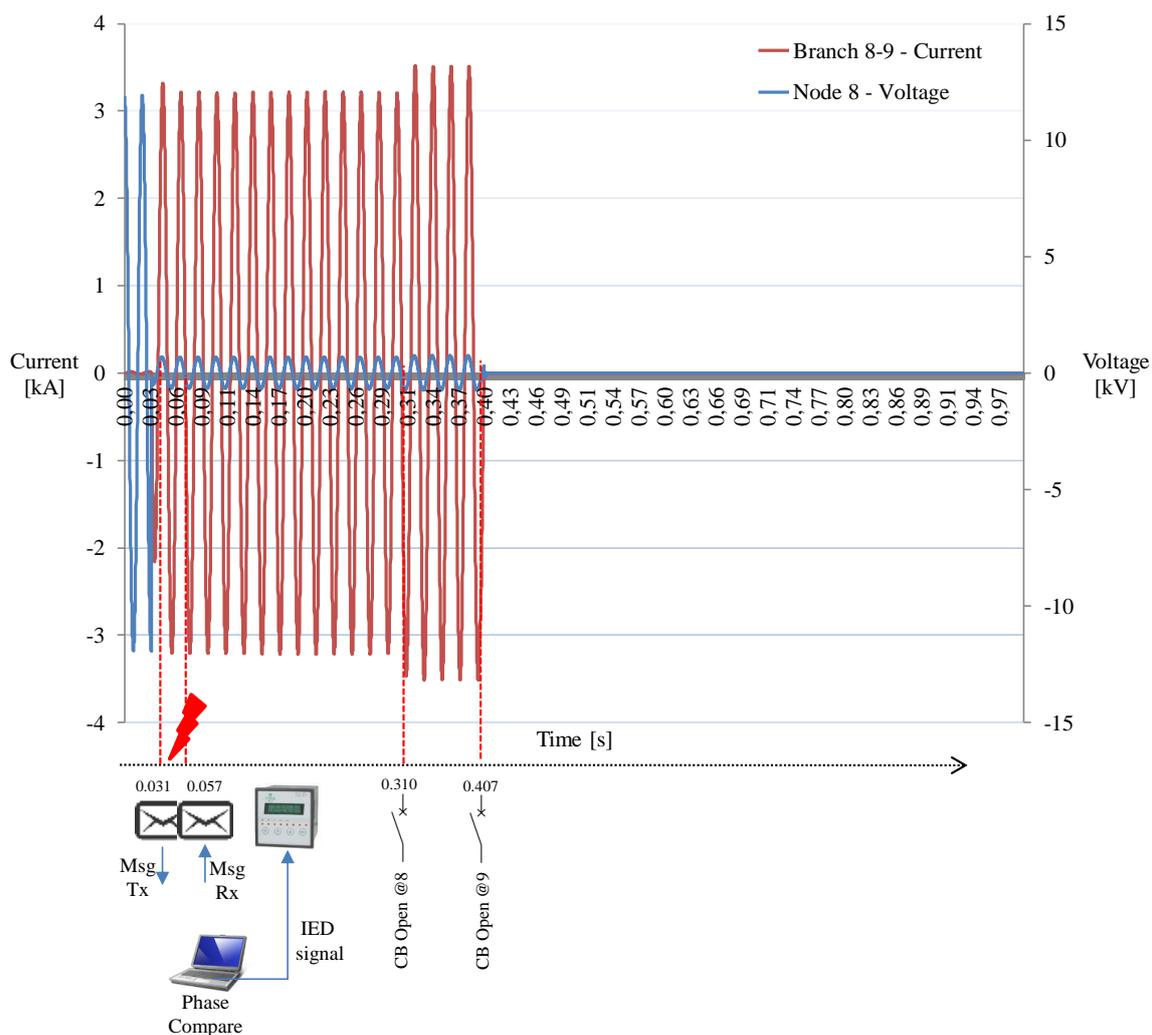
#### 4.2. Meshed network operation

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The second case analyzed considers a closed loop network operation. It means that the network is operated with the switches at the substations 8 and 9 normally closed, and the short circuit is fed by two sides.



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**Figure 101.** Voltage profile at node 8, and current profile in branch 8-9

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Figure 10 shows the voltage at node 8, and the current that flows in the branch between nodes 8 and 9. At 31 ms the overcurrent caused by the short circuit is detected by the IED in the SSS at node 8 that sends a message to the neighbors with current and phase measurement:

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**Table 1.** Node 8 current module/phase measurements

|         | Current<br>[kA] | Phase<br>[rad]                   |
|---------|-----------------|----------------------------------|
| Infeed  | 1.772           | 2.920 ( $\cos\varphi = -0.976$ ) |
| Outfeed | -1.786          | 0.220 ( $\cos\varphi = 0.976$ )  |

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At 56 ms, the substation 64 receives the message from the SSS at node 61, at 57 ms it receives the message from the SSS in node 67.

381 **Table 2.** Node 9 received current module/phase measurements

|                            | Time Rx | Current | Phase                        |
|----------------------------|---------|---------|------------------------------|
|                            | [ms]    | [kA]    | [rad]                        |
| Preceding SSS<br>(node 8)  | 56      | -1.057  | 0.077 ( $\cos\phi = 0.997$ ) |
| Following SSS<br>(node 10) | 57      | -1.433  | 0.259 ( $\cos\phi = 0.967$ ) |

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The DMS performs a phase comparison between the local measurements received allowing the location of the fault. The opening of the two CB is completed in 377 ms. The communication takes 27 ms, and 350 ms of mechanical delay are also considered. The network is reconfigured after 407 ms.

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#### 4.3. Background traffic analysis

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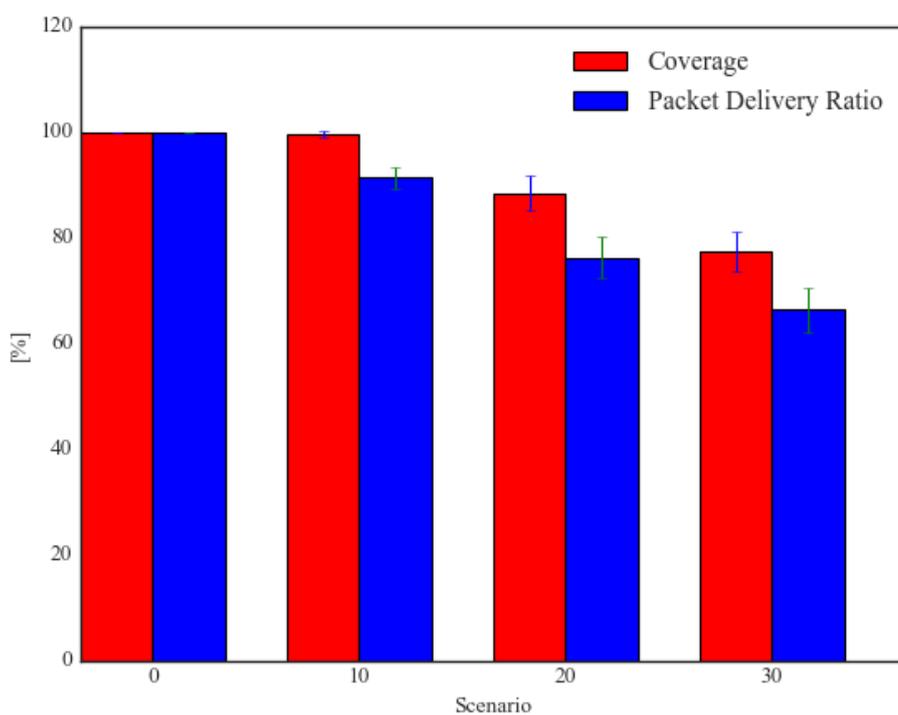
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The simulations have been executed in a more realistic situation considering the same network but different background conditions, in order to verify the LTE performances when a number of user are contemporarily connected to the same communication network. The first case considers a variable number of generic Mobile Broadband Users that are contemporarily active in the LTE network (MBBU). Four cases were considered with 0 (ideal case), 10, 20, and 30 MBBU per cell.

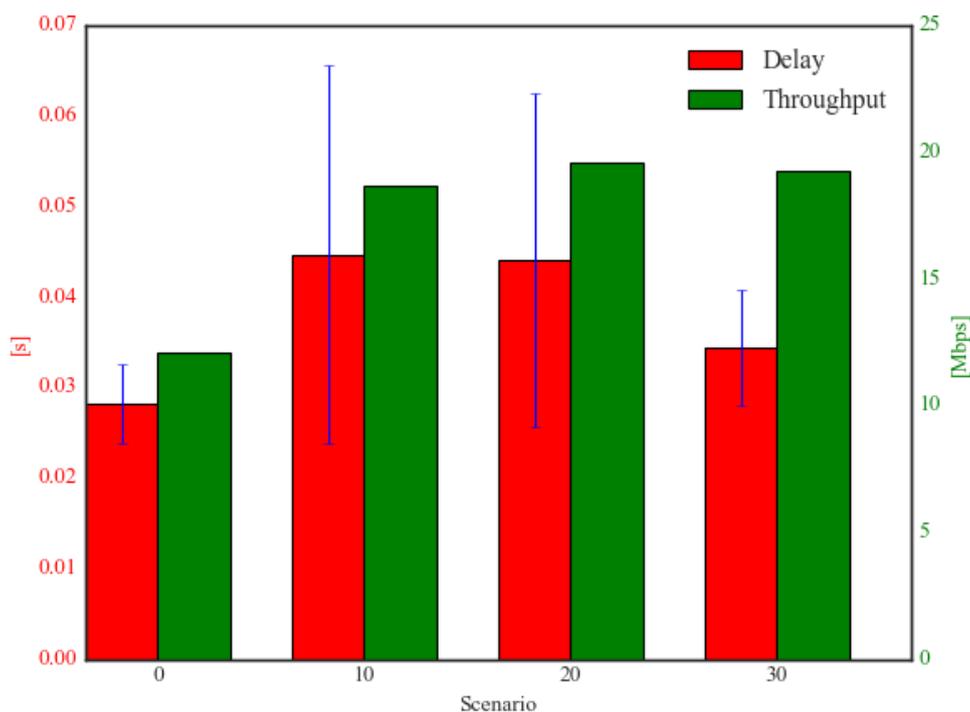
From Figure 11, it can be noticed that the system shows good performances in terms of delays and coverage with 10 active users per cell. This situation is currently considered a typical LTE usage in a dense urban scenario with optimal exploitation of LTE network [31]. With an overcharging situation of the LTE network with 20 active users per cell shows a reduction in the total coverage that decreases to a figure of 90%, and a slight increase of the transmission delay of the packets between the substation. The coverage further decreases with 30 users per cell, that clearly shows the congestion of the network and the poor performances of the UDP protocol in terms of packet loss. In the simulation, a slight improvement in the average communication delay is also observed in this scenario, due to the reduction of the users served by the LTE network.



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**Figure 11.** Coverage and Packet Delivery Ratio in background traffic scenario



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**Figure 12.** Communication delay and throughput in background traffic scenario

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Finally, in Figure 12 the performances variation of LTE in terms of delay and throughput are reported with a variable number of background traffic due to contemporary served MBBU. The delay increases on average from 0.028 seconds up to a 0.045 s (with a maximum value observed during the repetitions of the scenario of 0.067 s) in the scenario with 10 MBBU per cell. In the

410 scenarios with 20 and 30 MBBU per cell the delay decreases. This behavior is due to the reduction of  
411 the coverage because the LTE eNB effectively serves a less number of active users. The saturation of  
412 the throughput for 20 up to 30 MBBU per cell demonstrates that the volume of data exchanged with  
413 the LTE network does not increase when charging the network over the number of 10 MBBU per  
414 cell.

## 415 5. Conclusion

416 The implementation of an automatic fast reconfiguration scheme of the distribution network  
417 strongly relies on the performance of the communication system. Compared to wired solutions, such  
418 as PLC or Fiber Optics, wireless technologies offer many benefits for smart grid applications. The  
419 numerical simulations are performed in a context of realistic power distribution network, served by  
420 LTE public communication service with different traffic background conditions, in order to verify  
421 the LTE performances and quality of service provided to the smart grid, when a number of user are  
422 contemporarily connected to the mobile communication network. According to those first results  
423 presented in the paper, LTE communication technology is adequate for FLISR applications related to  
424 Smart Grid implementation.

425

426 **Acknowledgments:** This work has been partly financed by the Research Fund for the Italian Electrical System  
427 under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development – General  
428 Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency in compliance with the Decree of  
429 March 8, 2006.

430 **Author Contributions:** F.P., G.C., E.G. and S.C. conceived the idea behind this research, designed the  
431 simulations and wrote the paper; M.G. developed the software, performed the simulations and wrote some  
432 parts of the manuscript; all the authors analyzed the data and proofread the paper.

433 **Conflicts of Interest:** The authors declare no conflict of interest

## 434 References

- 435 1. D'adamo, C.; Abbey, C.; Baitech, A.; others Development and operation of active distribution networks:  
436 results of CIGRE C6.11 working group. In: Frankfurt, 2011; Vol. 6.
- 437 2. Mauri, G., Pilo, F. et. Al. Technical Brochure JWG C6.25/B5/CIREED. Control and automation systems for  
438 Electricity Distribution Networks (EDN) of the future Available online:  
439 [https://e-cigre.org/publication/711-control-and-automation-systems-for-electricity-distribution-networks-](https://e-cigre.org/publication/711-control-and-automation-systems-for-electricity-distribution-networks-edn-of-the-future)  
440 [edn-of-the-future](https://e-cigre.org/publication/711-control-and-automation-systems-for-electricity-distribution-networks-edn-of-the-future).
- 441 3. Garau, M.; Celli, G.; Ghiani, E.; Soma, G. G.; Pilo, F.; Corti, S. ICT reliability modelling in co-simulation of  
442 smart distribution networks. In *2015 IEEE 1st International Forum on Research and Technologies for Society and*  
443 *Industry Leveraging a better tomorrow (RTSI)*; Turin, Italy, 2015; pp. 365–370, doi:10.1109/RTSI.2015.7325125.
- 444 4. Kalalas, C.; Thrybom, L.; Alonso-Zarate, J. Cellular Communications for Smart Grid Neighborhood Area  
445 Networks: A Survey. *IEEE Access* **2016**, *4*, 1469–1493, doi:10.1109/ACCESS.2016.2551978.
- 446 5. Garau, M.; Celli, G.; Ghiani, E.; Pilo, F.; Corti, S. Evaluation of Smart Grid Communication Technologies  
447 with a Co-Simulation Platform. *IEEE Wirel. Commun.* **2017**, *24*, 42–49, doi:10.1109/MWC.2017.1600214.
- 448 6. Patel, A.; Aparicio, J.; Tas, N.; Loiacono, M.; Rosca, J. Assessing communications technology options for  
449 smart grid applications. In *2011 IEEE International Conference on Smart Grid Communications*  
450 *(SmartGridComm)*; 2011; pp. 126–131, doi:10.1109/SmartGridComm.2011.6102303.
- 451 7. Brown, J.; Khan, J. Y. Key performance aspects of an LTE FDD based Smart Grid communications  
452 network. *Comput. Commun.* **2013**, *36*, 551–561, doi:10.1016/j.comcom.2012.12.007.

- 453 8. Markkula, J.; Haapola, J. Impact of smart grid traffic peak loads on shared LTE network performance. In  
454 2013 *IEEE International Conference on Communications (ICC)*; 2013; pp. 4046–4051,  
455 doi:10.1109/ICC.2013.6655193.
- 456 9. Cheng, P.; Wang, L.; Zhen, B.; Wang, S. Feasibility study of applying LTE to Smart Grid. In *2011 IEEE First*  
457 *International Workshop on Smart Grid Modeling and Simulation (SGMS)*; 2011; pp. 108–113,  
458 doi:10.1109/SGMS.2011.6089018.
- 459 10. Andrén, F. P.; Strasser, T. I.; Kastner, W. Engineering Smart Grids: Applying Model-Driven Development  
460 from Use Case Design to Deployment. *Energies* **2017**, *10*, 374, doi:10.3390/en10030374.
- 461 11. Stifter, M.; Kazmi, J. H.; Andrén, F.; Strasser, T. Co-simulation of power systems, communication and  
462 controls. In *2014 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES)*; 2014; pp.  
463 1–6, doi:10.1109/MSCPES.2014.6842400.
- 464 12. Li, W.; Ferdowsi, M.; Stevic, M.; Monti, A.; Ponci, F. Cosimulation for Smart Grid Communications. *IEEE*  
465 *Trans. Ind. Inform.* **2014**, *10*, 2374–2384, doi:10.1109/TII.2014.2338740.
- 466 13. Hopkinson, K.; Wang, X.; Giovanini, R.; Thorp, J.; Birman, K.; Coury, D. EPOCHS: a platform for  
467 agent-based electric power and communication simulation built from commercial off-the-shelf  
468 components. *IEEE Trans. Power Syst.* **2006**, *21*, 548–558, doi:10.1109/TPWRS.2006.873129.
- 469 14. Lin, H.; Veda, S. S.; Shukla, S. S.; Mili, L.; Thorp, J. GECO: Global Event-Driven Co-Simulation Framework  
470 for Interconnected Power System and Communication Network. *IEEE Trans. Smart Grid* **2012**, *3*, 1444–  
471 1456, doi:10.1109/TSG.2012.2191805.
- 472 15. Mets, K.; Verschueren, T.; Develder, C.; Vandoorn, T. L.; Vandeveld, L. Integrated simulation of power  
473 and communication networks for smart grid applications. In *2011 IEEE 16th International Workshop on*  
474 *Computer Aided Modeling and Design of Communication Links and Networks (CAMAD)*; 2011; pp. 61–65,  
475 doi:10.1109/CAMAD.2011.5941119.
- 476 16. Cintuglu, M. H.; Ma, T.; Mohammed, O. Protection of Autonomous Microgrids using Agent-Based  
477 Distributed Communication. *IEEE Trans. Power Deliv.* **2016**, *PP*, 1–1, doi:10.1109/TPWRD.2016.2551368.
- 478 17. Mueller, S. C.; Georg, H.; Nutaro, J. J.; Widl, E.; Deng, Y.; Palensky, P.; Awais, M. U.; Chenine, M.; Kuch,  
479 M.; Stifter, M.; Lin, H.; Shukla, S. K.; Wietfeld, C.; Rehtanz, C.; Dufour, C.; Wang, X.; Dinavahi, V.;  
480 Faruque, M. O.; Meng, W.; Liu, S.; Monti, A.; Ni, M.; Davoudi, A.; Mehrizi-Sani, A. Interfacing Power  
481 System and ICT Simulators: Challenges, State-of-the-Art, and Case Studies. *IEEE Trans. Smart Grid* **2016**,  
482 *PP*, 1–1, doi:10.1109/TSG.2016.2542824.
- 483 18. Viridis, A.; Stea, G.; Nardini, G. Simulating LTE/LTE-Advanced Networks with SimuLTE. In *Simulation*  
484 *and Modeling Methodologies, Technologies and Applications*; Springer, Cham, 2015; pp. 83–105.
- 485 19. Alvarez de Sotomayor, A.; Della Giustina, D.; Massa, G.; Dedè, A.; Ramos, F.; Barbato, A. IEC 61850-based  
486 adaptive protection system for the MV distribution smart grid. *Sustain. Energy Grids Netw.* **2017**,  
487 doi:10.1016/j.segan.2017.09.003.
- 488 20. Dedè, A.; Giustina, D. D.; Massa, G.; Cremaschini, L. Toward a New Standard for Secondary Substations:  
489 The Viewpoint of a Distribution Utility. *IEEE Trans. Power Deliv.* **2017**, *32*, 1123–1132,  
490 doi:10.1109/TPWRD.2016.2622006.
- 491 21. Coppo, M.; Pelacchi, P.; Pilo, F.; Pisano, G.; Soma, G. G.; Turri, R. The Italian smart grid pilot projects:  
492 Selection and assessment of the test beds for the regulation of smart electricity distribution. *Electr. Power*  
493 *Syst. Res.* **2015**, *120*, 136–149, doi:10.1016/j.epsr.2014.06.018.

- 494 22. Botton, S.; Cavalletto, L.; Marmeggi, F. Schema project-innovative criteria for management and operation  
495 of a closed ring MV network. In *22nd International Conference and Exhibition on Electricity Distribution*  
496 (*CIREC 2013*); 2013; pp. 1–4, doi:10.1049/cp.2013.0811.
- 497 23. Wolter, D.; Zdrallek, M.; Stötzel, M.; Schacherer, C.; Mladenovic, I.; Biller, M. Impact of meshed grid  
498 topologies on distribution grid planning and operation. *CIREC - Open Access Proc. J.* **2017**, *2017*, 2338–2341,  
499 doi:10.1049/oap-cired.2017.0708.
- 500 24. Hadjsaid, N.; Alvarez-Hérault, M. C.; Caire, R.; Raison, B.; Descloux, J.; Bienia, W. Novel architectures and  
501 operation modes of distribution network to increase DG integration. In *IEEE PES General Meeting*; 2010;  
502 pp. 1–6, doi:10.1109/PES.2010.5589803.
- 503 25. Celli, G.; Pilo, F.; Pisano, G.; Allegranza, V.; Cicoria, R.; Iaria, A. Meshed vs. radial MV distribution  
504 network in presence of large amount of DG. In *IEEE PES Power Systems Conference and Exposition, 2004.*;  
505 2004; pp. 709–714 vol.2, doi:10.1109/PSCE.2004.1397664.
- 506 26. Jiang, J.; Qian, Y. Distributed Communication Architecture for Smart Grid Applications. *IEEE Commun.*  
507 *Mag.* **2016**, *54*, 60–67, doi:10.1109/MCOM.2016.1600321CM.
- 508 27. Matos, M. A.; Seca, L.; Madureira, A. G.; Soares, F. J.; Bessa, R. J.; Pereira, J.; Peças Lopes, J. Control and  
509 Management Architectures. In *Smart Grid Handbook*; John Wiley & Sons, Ltd, 2016 ISBN 978-1-118-75547-1.
- 510 28. D'adamo, C.; Valtorta, G.; Consiglio, L.; Cerretti, A.; D'orazio, L.; Malerba, A.; Marmeggi, F. Smart fault  
511 selection: new operational criteria and challenges for the large-scale deployment in e-distribuzione's  
512 network. *CIREC - Open Access Proc. J.* **2017**, *2017*, 1475–1478, doi:10.1049/oap-cired.2017.1330.
- 513 29. *LTE, WiMAX and WLAN Network Design, Optimization and Performance Analysis*; Korowajczuk, L., Ed.; 1  
514 edition.; Wiley: Chichester, 2011; ISBN 978-0-470-74149-8.
- 515 30. AEEGSI, A. per l'Energia E., il Gas ed il Sistema Idrico *Testo integrato della regolazione della qualità dei servizi*  
516 *di distribuzione e misura dell'energia elettrica*; 2014;
- 517 31. Auer, G.; Giannini, V.; Desset, C.; Godor, I.; Skillermark, P.; Olsson, M.; Imran, M. A.; Sabella, D.;  
518 Gonzalez, M. J.; Blume, O.; Fehske, A. How much energy is needed to run a wireless network? *IEEE Wirel.*  
519 *Commun.* **2011**, *18*, 40–49, doi:10.1109/MWC.2011.6056691.

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