SHORT TERM SCIENTIFIC MISSION (STSM) SCIENTIFIC REPORT

This report is submitted for approval by the STSM applicant to the STSM coordinator, the Host and the WG Leader

Action number: COST Action CA15127 – Resilient communication services protecting end-user applications from disaster-based failures (RECODIS)
STSM title: Impact of weather-based disruptions on interdependency between power grids and communication networks
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STSM start and end date: 05/06/2017 to 15/06/2017
Working group: WG2, Weather-based disruptions

PURPOSE OF THE STSM:

The interdependence between communication networks and power grids is a critical issue to be taken into account when designing and operating both systems. As a matter of fact, failures in one network may cause further failures into the other network and vice versa. This is due to the fact that nodes in power grids (i.e., power generators, loads or interchange nodes) are controlled and managed by telecommunication equipment, which, in turn, rely on the electricity grid for their power supply. Therefore, failures occurring on a limited portion of one network can cascade multiple times between these two networks, and a robust "*interdependency network*" (i.e., the reciprocal dependencies between nodes in the two networks) is needed. This is particularly true when considering large-scale network failures, i.e., disasters, such as those caused by bad weather conditions.
The purpose of the STSM is to define measures 1) to estimate the networks vulnerability (e.g., the risk of having such cascading disasters), and 2) to evaluate the efficiency of protection/recovery algorithms, in the context of interdependent power grid and communication network.

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

During the STSM, the work has been carried out with the aim of defining a set of measures to evaluate the performance of the *interdependency network* (i.e., the reciprocal dependencies between nodes in the two networks) from both resilience and cost points of view. To this end, the following main steps have been undertaken:

- we identified the relationship between equipment in the power grid and in the communication network as well as a set of requirements for equipment in the two networks;
- we identified a set of research problems which can be addressed in the context of the interdependency between communication network and power grid;
- we defined measures to evaluate the performance of the *interdependency network* in case of disasters;
- we defined specific measures related to the weather-based aspects of disaster-resilience, mainly exploiting the concept of *alert*, which has been identified in RECODIS WG2 as a main feature of weather-based disasters with respect of other types of disasters.

Funded by the Horizon 2020 Framework Programme
of the European Union

The present report has been developed also exploiting feedbacks from researchers of the University of Coimbra, i.e., Dr. Rita Girão-Silva, Dr. Alvaro Gomes, Dr. Teresa Gomes, Dr. Luísa Jorge, Dr. Lúcia Martins and Dr. Paulo Melo, who especially provided feedback about the requirements of the equipment in the power grid and the improvement of the interdependency network model.
The details of the work are explained in the following section.

DESCRIPTION OF THE MAIN RESULTS OBTAINED

1. Introduction

To introduce the problem of the interdependency between power grid and communication network we refer to Figure 1, where we schematically represent the two networks and their reciprocal relation.

Specifically, the communication network is represented at the top of the figure through a graph consisting of a set of nodes, representing generic communication equipment, such as IP-MPLS routers, optical nodes (i.e., Optical Cross Connects or Reconfigurable Add/Drop Multiplexers), and arcs, representing communication links (e.g., optical fibers).

Similarly, the power grid is represented at the bottom of the figure through a set of nodes, representing different types of equipment in the grid (e.g., generators, loads and substations), and arcs, which indicate transmission power lines. Although power grids can be considered at different levels (e.g., generation, distribution or transmission level), in the scope of this work, we refer to transmission systems. Note that any substation or load node in the power grid can only operate if it has at least one path towards to at least one generator.

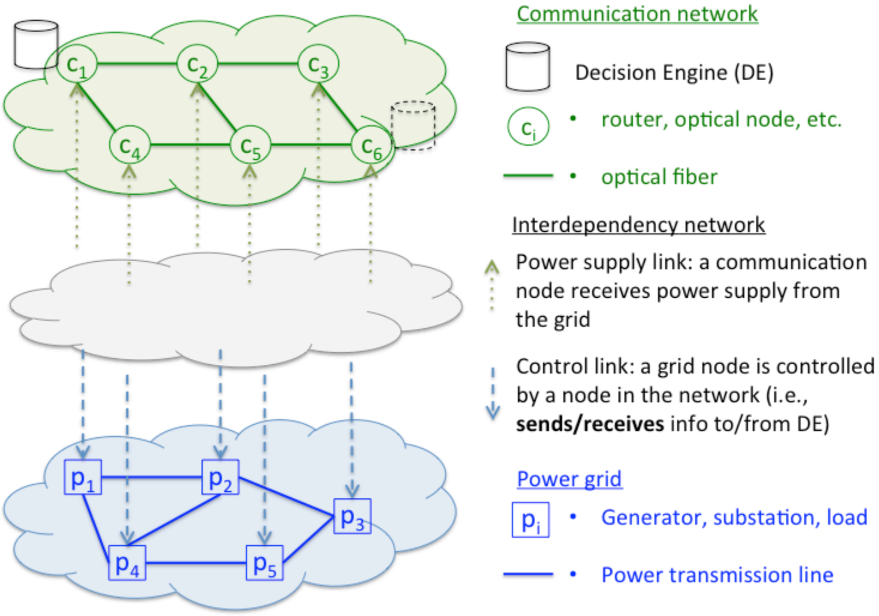

Figure 1: Interdependency between power grid and communication network.

In the figure, we also represent a set of directional links (vertical arrows in the figure), constituting what we call the *Interdependency network*. Vertical dotted arrows directed to nodes in the communication network represent power supply links, whereas links of the interdependency network, which are directed to nodes in the power grid (i.e., dashed arrows), represent control links. Namely, a power supply link, i.e., a directed link, e.g., originating in node p_1 and terminating in node c_1, indicates that communication node c_1 receives power supply from power grid node p_1. Conversely, a control link, i.e., a directed link, e.g., originating in node c_2 and terminating in node p_2 indicates that node p_2 is controlled through node c_2. Note that, the directionality of control links does not correspond to a directionality of data flows, that is, it represents the *bidirectional data exchange between power nodes and the communication network*. As a matter of fact, a power grid node collects information (e.g., on its current status, on the amount of load it is supplying, etc.) and sends it to the communication network. Moreover, it also receives instructions from the communication network, e.g., to power-on additional previously-inactive transmission lines or shut-down some devices in case their utilization is not necessary. Note that in Figure 1, we do not explicitly provide interdependency between the two networks (i.e., we represent the interdependency network as a “cloud”), as the design of a proper interdependency network is one focus of our work.

The model for the interdependency between power grid and communication network takes inspiration from ref. [1]. However, with respect to the model in [1], we also consider that the control of nodes in the power grid is not only performed through a single node in the communication network, but it also requires communication with a *specific* entity, i.e., the Decision Engine (DE), which is a dedicated management system located in the communication network (in Figure 1 it is assumed as co-located with node c_1), where all information is collected from the power grid. The DE is responsible for taking decisions on the activity of the power grid and for issuing commands to be forwarded to the power grid nodes. Therefore, with respect to [1], we consider that *at least one path* should be available from each node in the power grid towards the DE. This path is constituted by 1) an interconnection link with a node in the communication network (say node c_x)[1] and a path in the communication network connecting communication node c_x and the DE. As an example, for node p_3, different possible paths are the followings:

1. Path 1: c_1-c_2-c_3-c_6-p_3 (communication path: c_1-c_2-c_3-c_6; interconnection link: c_6-p_3);
2. Path 2: c_1-c_4-c_5-p_3 (communication path: c_1-c_4-c_5; interconnection link: c_5-p_3);
3. Path 3: c_1-c_2-c_3-p_3 (communication path: c_1-c_2-c_3; interconnection link: c_3-p_3);
4. Path 4: c_1-c_4-c_5-c_6-p_3 (communication path: c_1-c_4-c_5-c_6; interconnection link: c_6-p_3).

Note that, for resilience purposes the DE can be also replicated in the network (as shown in Figure 1, where a backup DE is represented with dashed lines and assumed as co-located with node c_6), although the replicated DEs are only utilized in case of failures, as we assume that the control over the power grid is always performed in a centralized manner.

As far as the power supply links are concerned, we assume that each communication nodes has *exactly one incident power supply link*, originated in a node in the power grid. This is in slight disagreement with [1], where more power supply links are allowed for each communication nodes, essentially for resilience issues. Our assumption is derived by the observation that, in realistic scenarios, lack of power supply in communication nodes is protected via local power supply, e.g., locally installed batteries or backup power continuity engines, which are able to provide power for a limited amount of time. As a consequence, we assume that a failure in one power grid node will propagate to the supplied communication nodes if the failure is not restored before a certain deadline.

2. Identification of research problems

After defining introducing the scenario, we identify research problems which can be addressed in the context of the interdependency between communication network and power grid under disaster scenarios. In fact, a proper configuration of the interdependency network should be performed in order to avoid the *zig-zag* cascading failure. An example of how such interdependency can propagate through the two networks is in [1], whereas real-life examples of disasters caused by cascading failures in interdependent networks are shown in [2] and [3].

At high-level, such research problems can be categorized into two main groups:

i. Planning phase problems: given the topology of the power grid and of the communication network, including the location of the DE (and possibly of the backup DE), we want to design the interdependency network (i.e., set-up interconnection links between power grid and communication network) to ensure robustness, i.e., to protect against cascading failures caused by an initial failure set. The initial failure set can be constituted by a set of nodes and/or links in the communication network and/or in the power grid. In this context, a proper design, should also take into account that every power node is connected with at least two paths towards the DE (and eventually with two additional path towards the backup DE).
ii. Restoration phase problems: given the topology of the power grid and of the communication network, the location of DE and backup DE as well as the interdependency network as provided by a preliminary design step, we want to design algorithms to perform network reconfiguration upon nodes failures or upon a disaster alert is issued, so as to minimize the amount of time required to limit the failure cascade and/or to reduce the cost required for the restoration.

For both classes of problems, to evaluate the performance of our design strategy or the efficiency of our restoration algorithms in the context of disasters resilience, a set of specific measures is needed. To this end, in the following we first introduce some notation useful for the definition of such measures.

3. Notation

In Table 1 we report some notation which will be used to define measures for the evaluation of the robustness of interdependency design and efficiency of restoration algorithms.

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[1] Note that, among all nodes in the communication networks, only a subset is "allowed" to control a power node, mainly due to proximity issues.

Table 1: Notation

Description	Comm. network	Power grid	Notes
Graph	$G_c(V_c , E_c)$	$G_p(V_p , E_p)$	
Set of nodes	V_c	V_p	
Sets of generators, loads, substations	-	V^g_p V^s_p V^l_p	$V^g_p \cup V^l_p \cup V^s_p = V_p$ $V^x_p \cup V^y_p = \emptyset$, $x, y \in \{g, l, s\}, x \neq y$
Set of links	E_c	E_p	
Number of nodes	$C=\|V_c\|$	$P=\|V_p\|$	
Number of links	$L=\|E_c\|$	$K=\|E_p\|$	
Interconn. links $m \in V_c$, $n \in V_p$ $s \in V_p$, $t \in V_c$	$x_{m,n}$	-	Control link; $x_{m,n} \in \{0;1\}$
	-	$x_{s,t}$	Power supply link; $x_{s,t} \in \{0;1\}$
Initial set of failed nodes	Z		$z \in Z$ is any set of nodes in $V_c \cup V_p$ INCLUDING the empty set
Number of surviving nodes	C_z	P_z	"Alive nodes" upon failure of nodes in $z \in Z$
Probability of occurrence of failure set z	π_z		s.t. $\sum_z (\pi_z) = 1$
Is node m (or s) alive after failure z? $m \in V_c$, $s \in V_p$	$y_{m,z}$	$y_{s,z}$	$y_{m,z}$ ($y_{s,z}$) $= 0$: node m (s) **does not** survives after z $y_{m,z}$ ($y_{s,z}$) $= 1$: node m (s) survives after z
Node "importance" degree	d_m	d_s	$0 \leq d_m \leq 1$ $0 \leq d_s \leq 1$ $m \in V_c$, $s \in V_p$
Deadline	D		When an alert is issued, D is the available time to react
Time-to-instruct	τ_i		Delay (e.g. propagation + transmission + queueing) between the DE and node i in $V_c \cup V_p$

4. Measures to evaluate resilience

The measures which have been identified, address the following main questions:

a) How much robust is the design of the interdependency network?
b) What is the minimum cost to obtain a desired level of resilience?
c) In case of an alerted (weather-based) disaster, what is the minimum time (or cost) to maintain a desired level of resilience?

In the following subsections we propose measures to evaluate the performance of design and restoration strategies by addressing these questions.

a. How much robust is the design of the interdependency network?

We start defining different flavours of resilience measures as follows:

- ***Punctual resilience, R_z*** : upon failure of nodes in a particular set $z \in Z$, it indicates the number of alive nodes[2].

$$R_z = C_z + P_z$$

- ***Strong resilience, ρ*** : it represents the number of alive nodes in the worst case.

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[2] We refer to an "alive node" to as a power node (respectively, a communication node), which is able to communicate with the DE and is connected in the power grid to at least one generator (respectively, which is supplied by a power node).

$$\rho = \min_z (R_z) = \min_z (C_z + P_z)$$

Strong resilience can be also defined in a per-network basis, e.g., to evaluate specific resilience of the communication network or the power grid, so that we can define:

- $\rho_c = \min_z (C_z)$ for the communication network, and
- $\rho_p = \min_z (P_z)$ for the power grid

- ***Weak resilience, ρ'*** : it represents the number of alive nodes in the best case.

$$\rho = \max_z (R_z) = \max_z (C_z + P_z)$$

Also weak resilience can be defined in a per-network basis, so that we define:

- $\rho_c = \max_z (C_z)$ for the communication network, and
- $\rho_p = \max_z (P_z)$ for the power grid

- ***Expected resilience, r*** : it represents the expected number of alive nodes after any failure $z \in Z$.

$$r = \Sigma_z (R_z \pi_z) = \Sigma_z [(C_z + P_z) \pi_z]$$

Note that not all the nodes, either in the communication network or in the power grid, have the same relevance. E.g., one power load can be relevant as it supplies a high number of users, or because it is used to provide electricity to critical loads, such as hospitals. Therefore, assuming we are able to identify nodes importance with a degree as in Table 1, we can weight all the (punctual, strong, weak, expected) resilience measures by applying the following replacements in the previous definitions:

- $C_z \rightarrow \Sigma_m (y_{m,z} d_m)$
- $P_z \rightarrow \Sigma_s (y_{s,z} d_s)$

b. What is the minimum cost to obtain a desired level of resilience?

In order to improve (punctual, strong, weak, expected) resilience, investments can be done at different levels, therefore, defining cost measures is not trivial. As an example, we can augment nodes resilience, i.e., reduce the probability of occurrence of an initial failure, that is, reducing π_z. In this case a cost measure can be defined as:

- $Cost1 = \Sigma_i$ *(cost of augmenting resilience of node i)*

In relation to weather-based disasters, this can be considered as the cost for preserving a node when an alert on a bad weather condition (e.g., hurricane, storm, etc.) is issued.

On the other hand, we can improve (punctual, strong, weak, expected) resilience by adding protection links in the interdependency network. In this case, a cost measure can be defined as:

- $Cost2 = \Sigma_{m,n} (x_{m,n})$

on the line of [1].

c. In case of an alerted weather-based disaster, what is the minimum time/cost to maintain a desired level of resilience?

Measures identified in the context of an alerted weather-based disaster, are mainly related to restoration phase problems, as identified in Section 2. In this context we can define two groups of possible measures, related to cost and time, respectively. In the former case, we can define a cost measure indicating the number of additional links in the interdependency network, i.e.:

- Cost3 = $\Sigma_{m,n} (x_{m,n})$ *for (m,n) pairs s.t.* $x_{m,n} = 0$ *before the alert.*

As far as time-related measures are concerned, we can identify the following measures:

- *Time To Protect (TTP)* : given a restoration algorithm which, upon an alert, reacts trying to maintain a certain level of (punctual, strong, weak, expected) resilience by, e.g., issuing commands from the DE to the power nodes indicating to activate additional communication links towards the communication network, *TTP* represents the time needed to propagate all these instructions to the involved nodes, i.e.,

$$TTP = \max (\tau_i)$$

- *Number of instructed nodes, S* : in case the alerted deadline *D* (see Table 1) is not met, the number of nodes which have correctly received the instruction from the DE is also a measure of the algorithm performance, and it can be expressed as:

$$S = \Sigma_i [(\tau_i \leq D) == TRUE]$$

FUTURE COLLABORATIONS (if applicable)

During the STSM, a wide set of potential issues to be addressed in future collaborations between research units in Politecnico di Milano and University of Coimbra have been identified. Taking inspiration from the work in [1] and exploiting the resilience measures defined during the STSM, as well as the improvements to the interdependency model which have been identified, the following research issues can be addressed in the future:

1) Perform the design of the interdependency network also considering the role of the DE, i.e., also ensuring that multiple paths are provisioned for redundancy purposes between power nodes and the DE.
2) Ensuring that the redundant paths are *geodiverse*, i.e., they are not only link/node disjoint, but also physically separated by a certain minimum geographical distance.
3) Performing the design of the interdependency network also considering the aspect of nodes relevance.
4) Perform multicriteria optimization, e.g., to find optimal trade-off between cost and resilience.

References

[1] Habib, F. *et al.*, “Cascading Failure Resilient Interconnection for Interdependent Power Grid–Optical Networks”, OFC 2015.

[2] S. V. Buldyrev *et al.*, “Catastrophic cascade of failures in interdependent networks”, *Nature Letters*, vol. 464, pp. 1025-1028, Apr. 2010.

[3] “Microgrids for disaster preparedness and recovery”, *IEC white paper*, available at http://www.iec.ch/whitepaper/microgrids (accessed June 2017).