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Resilient Planning of PowerLine Communications Networks over Medium Voltage Distribution Grids

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Abstract— **In this paper a network planning problem aiming to enable underground Medium Voltage (MV) power grids to resilient PowerLine Communications (PLCs) is faced. The PLC network is used to connect PLC End Nodes (ENs) located into the secondary substations to the energy management system of the utility by means of PLC network nodes enabled as Access Points. An optimization problem is formulated, aiming to optimally allocate the Access Points to the substations and the repeaters to the MV feeders. A multi-objective optimization approach is used, in order to keep in balance the needs of minimizing the cost of equipment allocation and maximizing the reliability of PLC network paths. Resiliency and capacity constraints are properly modeled, in order to guarantee the communications even under faulted link conditions. As a byproduct, the optimization algorithm also returns the optimal routing. Simulations performed on a realistic underground MV distribution grid validate the proposed approach**

I. INTRODUCTION

Reliable communication in PowerLine Networks (PLCs) is a major concern for large scale deployment of Smartgrid applications at Low Voltage (LV) and Medium Voltage (MV) level. Such networks are of particular interest from the communication viewpoint as the Smartgrid concept concerns with the evolution of legacy distribution networks towards a fully automated distribution grid ([1], [2]). Hence, a reliable PLC system should enable new functionalities such as monitoring and control of Distributed Generation, real-time grid reconfiguration and Demand Side Management, just to mention few examples. Electric networks were not designed for such an extended purpose. Consequently, a PLC network suffers from many disadvantages compared to other wired communication networks, i.e., time varing channel properties due to impedance dynamical changes or significant signal attenuation.

The scenario considered in this paper aims at assuring reliable communication between a given PLC End Node (EN) and the Distributed Management System (DMS)/Supervisory Control And Data Acquisition (SCADA) through one or more PLC ENs equipped with Access Points (APs). So, the communication in question takes place in two runs: the former, via the PLC electrical network, between a given EN and an appropriate AP; the latter, via a proper telecommunication network (e.g. optical fiber), between the AP and the DMS/SCADA. This paper consider the former run in which redundant paths and signal repeaters are necessary in order to overcome the above-mentioned problems. As concerns redundancy, the placement of many APs (eventually some of them in standby hot mode) allows DMS to communicate with a given EN from different sites. Moreover, even if a distribution grid is electrically operated as a tree, physical meshed configurations can be considered from the PLC's point of view, since suitable bridges can be introduced where a feeder is interrupted. For instance, the simplest case is constituted by underground MV grids, where switches are located in the MV/LV substations only and PLC modems can work as bridge devices.

In this work, we are interested in guaranteeing that ENs are always connected to at least one AP even in case any link becomes unavailable, i.e. the network is (n-1)-resilient. However, resilience is still not enough to avoid interruption of communication. As a given transmission capacity is required over the available paths, we consider traffic requirements too. We then formalize a problem of network planning for an underground PLC-MV network, consisting in the optimal placement of APs and repeaters and in the optimal routing such that the PLC network is (n-1)-resilient with respect to the failure of any single link. Optimality is considered in terms of a proper trade-off between the need of (i) minimizing the PLC equipment provisioning and installation costs, and (ii) maximizing the average reliability related to the set of considered operating conditions.

It should be noted that a key novelty of the proposed approach is to *jointly* cope with two tasks, namely the optimal placement of the APs and the optimal routing, which, traditionally, have been dealt with as two independent (and hence uncoordinated) tasks; on the contrary, in this paper these two strictly related tasks are simultaneously addressed through a proper multi-objective optimization approach. This approach is fully in line with the concepts which are being developed in the Future Internet framework [3]: in particular, Future Internet intends to overcome the limitations coming from the incoordination among procedures belonging to different layers and/or to different planes (control/management) and/or to different heterogeneous networks, aiming at designing multi-objective procedures able to cope with, in a single shot, tasks traditionally dealt with in a separate fashion. In this respect, Future Internet offers several enablers (e.g. decoupling of the algorithms from the underlying technology, possibility

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to perform control decisions in a centralized elaboration unit and to remotely enforce the relevant decisions, etc.) which can be exploited even in the case dealt with in this paper.

The paper is organized as follows. After the State of the Art (Section II), the network planning problem is defined and formulated as a Combinatorial Optimization (CO) problem in Section III. Section IV presents the case study and the simulation results. Finally, we end up with conclusions and future researches in Section V.

II. STATE OF THE ART

A significant contribution to the optimal placement of APs and repeaters is given in [4], where a LV grid is considered. Optimality is guaranteed by a trade-off between costs and grid reliability, while resilience is not considered. Powerline failure problems have been widely studied in the field of Operations Research. Based on Bonnanss seminal papers ([5]-[6]) the problem of power transmission network design was originally formulated as a Mixed-Integer NonLinear Programming (MINLP) problem. A first attempt at defining a mixed integer disjunctive formulation was proposed in [7], where nonlinear constraints are avoided by means of a disjunctive form. Because of the combinatorial nature of the problem, sophisticated Combinatorial Optimization (CO) techniques have been adopted in order to cope with its complexity, e.g. Benders decomposition ([8], [9]). In [10], the mixed integer disjunctive formulation was extended in order to cope with contingent scenarios. A given set of scenarios was considered and in each one of them a subset of links was disregarded in the network. Following this approach, in this paper we consider a number of predefined scenarios, and verify that the network is connected and the routing is possible in each scenario.

The routing task for PLC is faced only at LV level in a dynamical way ([4]). The main problem is the high volatility of the link availability, because of fast changes occurring in the line impedance due to load variations operated by consumers at each connection points on the feeder. Since the resulting network topology is strongly non-stationary, statically routing approaches are not suitable. Such problem has been recognized to be similar to the Wireless Networks one and, consequently, a certain number of dynamical approaches, such as *Beacon Less Routing* [11], *Implicit Geographic Forwarding* [12] and *Beacon Based Routing* [13] have been adopted or are currently under investigation for the PLC case. A comparison among these methodologies can be found in [14].

When we consider PLC routing on MV grids, the effects of sporadic impedance changes occurring in LV power grids are statistically averaged at MV-LV substation level, resulting in a significantly smaller link quality variability with respect to LV power grids. Moreover, fast reactions to grid changes are needed to avoid loss of PLC connectivity. Proactive approaches, usually implemented as a static look up table during network planning, seems to be an attractive solution: pre-computed routing choices are triggered by the PLC Network Management System (NMS) as it senses any degradation of links performances. Then PLC nodes do not need to loose time and bandwidth to find the path to the desired end-node. Several proactive approaches for network recovery do exist such as *multitopology Routing* [15] and *Resilient Routing Layers* [16]. However, these approaches require a set of redundant paths to be available, i.e. a planning task must be performed before. In this work we propose an integrated proactive approach by means of a problem formulation modelling both network planning and routing.

Input:
- network topology with PLC ENs;
- APs and Links costs (equipment and installation costs);
- links reliabilities;
- minimum required path reliability;
- expected capacity of each Link and each AP;
- expected overall traffic generated by each EN.

Task:
- place an optimal number of APs in optimal locations;
- assign the optimal path to each EN in the *complete scenario*;
- assign the optimal path to each EN in every l^-*-scenario*.

Objective:
- minimize the installation and network equipment cost;
- maximize the network reliability.

Constraints:
- the network must hold the (*n*-1) resilience property;
- link and AP capacities;
- path reliabilities.

Fig. 1: problem description.

III. PROBLEM DEFINITION

A. Problem description

The network planning problem includes two different, but interrelated tasks.

Topology design. The first task consists in deciding the PLC network topology by placing APs and repeaters (which are required to enable long MV feeders to PLC communication) in order to assure connectivity (i.e. the presence of at least one path between each EN and the DMS) both in the so-called *complete scenario* in which all links are available, and in the so-called l^-*-scenario* in which link l is unavailable.

Routing. The second task, considering the topology made available in the first task, the link and AP capacities (yielding relevant constraints), and the expected traffic generated by each EN, consists in deciding, in each l^-*-scenario*, the routing between each couple (EN, AP) allowing to serve the whole demands of the ENs (i.e. to transmit all the traffic generated by the ENs).

In the former task, the paths must be found in each scenario. The latter task must verify that, in each scenario, at least one path per couple (EN,AP) satisfies the capacity constraints. The two tasks will be solved simultaneously by solving one Combinatorial Optimization (CO) problem. If both tasks are accomplished, i.e., if a problem solution is found, a (*n*-1)-resilient network is achieved. The overall network planning problem is summarized in Fig. 1.

We represent the electrical network as an undirected graph $G(K, \Lambda)$. The following definitions will be adopted for the set K of nodes, the set Λ of links and the set Π of undirected paths in G.

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1) Node sets: from the communications point of view, the network nodes can be simple switches, Access Points (AP) or End Nodes (EN). Correspondingly, the following sets of nodes are defined:

- K: set of nodes $k \in K$;
- Σ: set of ENs $s \in \Sigma \subseteq K$;
- A: set of candidate AP locations $a \in A \subseteq K$; hereafter, an AP located in node a will be referred to as AP a.

2) Link and path sets: in view of the node classification, the following sets are defined:

- Λ: set of the network links $l \in \Lambda \subset K \times K$;
- Π: sets of the paths p between the ENs and the candidate APs, where a path $p = \{l_1, ..., l_n\}$ of length n is an ordered set of n undirected links connecting an EN $s \in \Sigma$ to an AP $a \in A$; notice that, in our problem, we consider also degenerated paths of length $n = 0$, i.e., consisting of 0 links, defined whenever an EN is also an AP;
- Π^s: set of the paths p between a given EN $s \in \Sigma$ and all the candidate APs; note that $\Pi = \bigcup_s \Pi^s$;
- $\Pi^{s,a}$: sets of the paths p between a given EN $s \in \Sigma$ and a given AP $a \in A$, with $\Pi^{s,a} \subseteq \Pi^s$;
- Π^s_l: sets of the paths p between a given EN $s \in \Sigma$ and all the candidate APs, not containing the link $l \in \Lambda$; note that $\Pi^s_l \subseteq \Pi^s$;
- $\Pi^{s,a}_l$: sets of the paths p between a given EN $s \in \Sigma$ and a given AP $a \in A$, not containing the link $l \in \Lambda$; note that $\Pi^{s,a}_l \subseteq \Pi^{s,a}$.

Note that the set of the links of the complete scenario is Λ, whereas the set of the links of a given *l^{-}-scenario* is $\Lambda \setminus \{l\}$.

3) Link, paths, Access Points and End Nodes characteristics: link, paths, APs and ENs are characterized by costs and capacities which will be taken into account in the optimization. In particular, the following inputs are considered:

- $w^a \in R^+$: cost of placing an AP in location a;
- $w^l \in R^+$: cost incurred to enable link l;
- $r^l \in [0,1]$: link l reliability;
- $r^p \in [0,1]$: path p reliability;
- $c^l \in R^+$: capacity of link l;
- $c^a \in R^+$: capacity of AP a;
- $d^s \in R^+$: expected overall traffic generated by EN s.

Note that the cost w^a and w^l comprise all aspect i.e. equipments and installation cost, the number of needed repeaters and so on. The link reliability r^l is the probability that link l is available, in other words, it is computed as the percentage of time in which the link is available compared to the overall observation time (i.e. one year). The path reliability is computed as $r^p = \prod_{l \in p} r^l$. Finally the capacities c^l and c^a are the upper bounds on the amount of information that can be reliably transmitted, respectively over the link and by AP.

4) Restricted paths sets: firstly, the reliability constraint is dealt with implicitly in the problem formulation itself by defining restricted path sets, in which the unreliable paths are not considered. In particular, the new sets of paths only include the paths whose reliability is greater than the minimum required one, denoted with $r_{min} \in R^+$:

- $\underline{\prod}^s = \{p \in \prod^s \mid r^p > r_{min}\}$, $\forall s \in \Sigma$: restricted sets of paths between the EN s and all the candidate APs;
- $\underline{\prod}^{s,a} = \{p \in \prod^{s,a} \mid r^p > r_{min}\}$, $\forall s \in \Sigma$, $\forall a \in A$: restricted sets of paths between the EN s and the AP a;
- $\underline{\prod}^s_l = \{p \in \prod^s_l \mid r^p > r_{min}\}$, $\forall s \in \Sigma$, $\forall l \in \Lambda$: : restricted sets of paths, not containing the link l, between the EN s and all the candidate APs;
- $\underline{\prod}^{s,a}_l = \{p \in \prod^{s,a}_l \mid r^p > r_{min}\}$, $\forall s \in \Sigma$, $\forall a \in A$, $\forall l \in \Lambda$: restricted sets of paths, not containing the link l, between the EN s and the candidate AP a.

B. Problem formulation

As already mentioned in Section III-A, the optimization problem deals with two interrelated tasks, namely, planning and routing. Correspondingly, two kinds of unknowns are defined: *planning unknowns* and *routing unknowns*.

1) Planning unknowns: the first sets are used to indicate which candidate nodes are equipped with APs and which links will be used for communications:

- $x^a \in \{0,1\}$, $\forall a \in A$: $x^a = 1$ if node a is equipped with an AP; $x^a = 0$ otherwise;
- $y^l \in \{0,1\}$, $\forall l \in \Lambda$: $y^l = 1$: if link l is enabled to PLC communication; $y^l = 0$ otherwise.

2) Routing unknowns: the second sets of unknowns are used to indicate which paths will be used by the ENs to communicate with the APs, in the *complete scenario* and in each *l^{-}-scenario*:

- $z^p \in \{0,1\}$, $\forall p \in \underline{\prod}^s$, $\forall s \in \Sigma$: $z^p = 1$ if the traffic generated by s is routed on path p in the *complete scenario*; $z^p = 0$ otherwise;
- $z^p_l \in \{0,1\}$, $\forall p \in \underline{\prod}^s_l$, $\forall s \in \Sigma$, $\forall l \in \Lambda$: $z^p_l = 1$ if the traffic flowing from s is routed on path p in the *l^{-}-scenario*; $z^p_l = 0$ otherwise.

The generic unknown z^p defined above indicates if the path p should be used by the EN s to communicate whit an AP in the *complete scenario* (i.e., when all the links are available); the generic unknown z^p_l indicates if the path p should be used by the EN s to communicate whit an AP in the *l^{-}-scenario* (i.e., when all the links are available but link l). To achieve the problem objectives, on the ground of the definitions previously described, the following multi-objective function is considered:

$$
\begin{aligned}
min \sum_{a \in A} w^a x^a + \sum_{l \in \Lambda} w^l y^l + \\
- \lambda \left(\delta \sum_{s \in \Sigma} \sum_{p \in \underline{\prod}^s} r^p z^p + \sum_{l \in \Lambda} \delta_l \sum_{s \in \Sigma} \sum_{p \in \underline{\prod}^s_l} r^p z^p_l \right)
\end{aligned} \tag{1}
$$

The first and second terms compute the cost of the APs and of the links used by the planned network, respectively; the third term is composed by two parts: the first part, which depends on the routing unknowns z^p, computes the reliability of the paths selected to route the traffic in the *complete scenario*, whereas the second part, which depends on the routing unknowns z_l^p, computes the reliability of the paths selected to route the traffic in the *l^--scenarios*.

As customary in multi objective optimization, we introduce in (1) some weights balancing each component of the objective function; λ, δ and δ_l, for each $l \in \Lambda$. The parameter λ is used to decide the trade-off between the objective of minimizing the cost of the network (first and second member of equation (1)) and that of maximizing the network reliability (third member in (1)). The determination of a suitable value for λ is an operator choice.

The parameters δ and δ_l for each $l \in \Lambda$ specify the relevance of the different scenarios in the reliability term. A meaningful selection of the these latter parameters is to set δ equal to the probability that the network links are all available, and δ_l equal to the probability that the network links are all available but link l:

$$\delta = \prod_{l\in\Lambda} r^l \in [0,1] \tag{2}$$

$$\delta_l = (1 - r^l) \prod_{l' \neq l} r^{l'}, \forall l \in \Lambda \tag{3}$$

3) Constraints for the (n-1)-resilience property: The network is resilient to the failure of a link l if at least one path connecting every EN to an AP exists that does not contain l. In this work, we consider the (*n*-1)-resilience property as the network capability to sustain any single-link fault. The following constraints guarantee that one path is selected for each AP, for the *complete scenario* and for the *l^--scenarios*, respectively:

$$\sum_{p\in\underline{\prod}^s} z^p = 1, \forall s \in \Sigma \tag{4}$$

$$\sum_{p\in\underline{\prod}_l^s} z_l^p = 1, \forall s \in \Sigma, \forall l \in \Lambda \tag{5}$$

The existence of the selected paths is guaranteed by the capacity constraints (see the Section III-C).

4) Capacity constraints: As mentioned in Section III-A, besides placing APs and repeaters, the optimization problem must also guarantee that the planned network has enough resources to serve the source traffic. Therefore, the following constraints consider information about link and AP capacities to avoid congestions. Due to the desired (*n*-1)-resilient property, the capacity constraints must be verified both on the *complete scenario* and on all the *l^--scenarios*. The first constraints state that the traffic routed on a given link cannot exceed the link capacity:

$$\sum_{s\in\Sigma} \sum_{p\in\underline{\prod}^s : l\in p} d^s z^p \leq c^l y^l, \forall l \in \Lambda \tag{6}$$

$$\sum_{s\in\Sigma} \sum_{p\in\underline{\prod}_l^s : l'\in p} d^s z_l^p \leq c^{l'} y^{l'}, \forall l \in \Lambda, l' \in \Lambda \setminus \{l\} \tag{7}$$

The second constraints state that the traffic routed to a given AP cannot exceed the AP maximum capacity:

$$\sum_{s\in\Sigma} \sum_{p\in\underline{\prod}^{s,a}} d^s z^p \leq c^a x^a, \forall a \in A \tag{8}$$

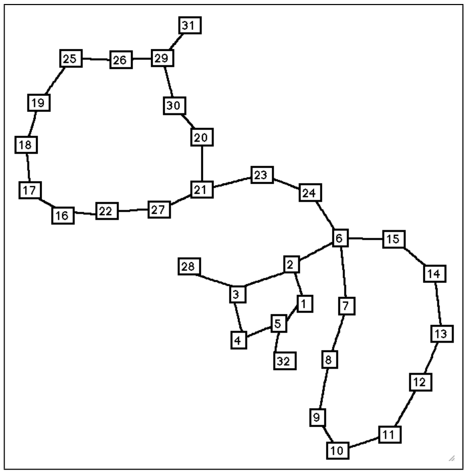

Fig. 2: example of MV underground grid.

$$\sum_{s\in\Sigma} \sum_{p\in\underline{\prod}_l^{s,a}} d^s z_l^p \leq c^a x^a, \forall a \in A, \forall l \in \Lambda \tag{9}$$

Note that these constraints guarantee the consistency among AP, link and path variables: in fact, constraints (6) and (7) force all links $l \in p$ to be enabled when a given path p is selected, whereas constraints (8) and (9) ensure that a given path $p \in \underline{\prod}^a$ can be enabled only if the AP a is enabled.

C. Solution Algorithm

The problem formulated in Section III-B is a Combinatorial Optimization problem because of decision variables (x^a, y^l, z^p, z_l^p) and the linearity of both constraints (4)-(9) and objective function (1). The problem is non empty. In fact, a trivial solution always exists, since enabling an AP on every EN ensures direct communication to the DMS from every EN, regardless of the status of the links. Solving the problem practically means exploring all possible $2^{|A|}$ configurations for APs in the graph G and, for each of them, selecting the optimal subset of links and paths among all possible subsets of Λ and Π. This requires an exponential time algorithm (e.g. Branch-and-Bound in worst case). In this paper we used a commercial implementation of the well known Branch-and-Cut algorithm with generic cuts to solve the Combinatorial Optimization problem (1)-(9).

IV. SIMULATION RESULTS

A. Case study

The proposed approach has been applied to the 32 nodes grid depicted in Fig. 2. The grid is a subset of one of the urban underground MV grids, that is proposed in the DLC+VIT4IP project because it is representative of the European scenario [17]. On each node $k \in [1, 32]$, a DLC node is placed. Data used for the simulations are listed in Table I. The traffic generated by each node is computed taking into account all the applications considered in the DLC+VIT4IP project for MV grids [18], including telecontrol, load and demand side management and many others.

Parameter	Value
Maximum Link Bit Rate c^l	100 Kbps
AP maximum throughput c^a	175 Kbps
Link reliability r^l	[0.9 – 0.99]
Nodes generated average traffic d^s	185 bps
Repeater cost w^l	200 €
AP cost w^a	1000 €

TABLE I: data used.

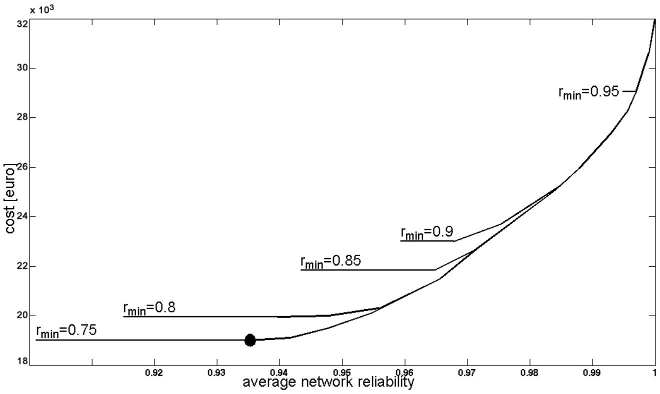

Fig. 3: efficient frontier for different value of r_{min}.

B. Results

Simulations have been performed using IBM ILOG CPLEX[1]. The optimization problem (1)-(9) was solved for different values of λ and r_{min}. We obtain the set of curves depicted in Fig. 3. These curves represent different efficient frontiers of the optimization problem for different value of r_{min}. According to the *Pareto efficiency principle* [19], the efficient frontier represents the optimal variables pairs equipment cost - average reliability and is represented by a piece-wise linear function depending of λ. The first flat zone corresponds to $\lambda = 0$. The distance among the frontiers vanishes as the requested average network reliability tends to 1, since it implies an increasing cost. Fig. 3 represents a tool helping utility in the preliminary step of the decision making process to choose the suitable working point.

We choose the working point characterized by $r_{min} = 0.75$ and $\lambda = 20$ (see black circle in Fig. 3). The optimal solution returns a level of average reliability of 0.936 and a cost of 19200 €. The Fig. 4 the related planned network is shown. Table II reports the probability of occurrence of each scenarios. Table III reports the optimal routing table for the *complete scenario*. Tables IV and V show an example of routing table changing when a link fault occurs.

The given problem formalization can not guarantee resilience when links are loss at the same time *a priori*. It is interesting to note that, in our case study, the probability of having two or more unavailable links at the same time is quite low (18%). The optimal solution is such that, in same cases of multiple link failure, the communication is still possible.

In order to identify which sets of links can be unavailable simultaneously, proper topological and traffic flow considerations have to be done. From topological point of view, it is necessary understanding if there is at least another path from all ENs to communicate with the APs, therefore it is necessary to verify that more than one fault does not occur in the same path between two APs. For example in Fig. 4, if (14-15) and (21-27) are faulted, the PLC communication can be still guaranteed because there are new paths from ENs 13,14 to AP 11 and from ENs 20,21 to AP 31 and to AP 24, respectively. Another way to examine this consideration is to compare the routing tables of the related (*n*-1)-scenarios: if the new lines (Tables IV and V) include faulted links then it is not possible to find a feasible routing table for the new scenario starting from the available ones. When the new paths share links or APs, it is necessary to verify that the traffic flows from all ENs do not exceed the capacity of APs and links. Considering the scenarios with (22-27) and (19-25) faulted, the topological condition holds, but both scenarios increase the throughput of AP 17. If AP 17 can provide the requested throughput, then the routing table for this (*n*-2)-scenario is given by combination of the related

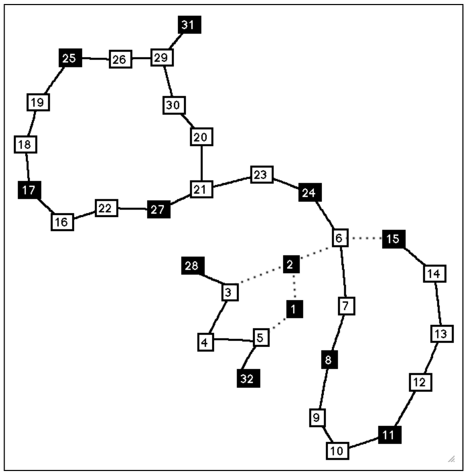

Fig. 4: APs allocation(dark square) and PLC enabled links (dark lines).

Faulted Link SN,DN)	Occurrence percentage [%]	Faulted Link (SN,DN)	Occurrence percentage [%]
None	63,72		
(1,2)	0,34	(17,18)	0,55
(2,3)	0,71	(18,19)	0,71
(3,4)	0,48	(20,21)	0,63
(1,5)	0,71	(16,22)	0,55
(4,5)	0,41	(21,23)	0,63
(2,6)	0,63	(6,24)	0,55
(6,7)	0,71	(23,24)	0,41
(7,8)	0,63	(19,25)	0,71
(8,9)	0,63	(25,26)	0,55
(9,10)	0,48	(21,27)	0,55
(10,11)	0,63	(22,27)	0,48
(11,12)	0,41	(3,28)	0,55
(12,13)	0,55	(26,29)	0,48
(13,14)	0,48	(20,30)	0,21
(6,15)	0,63	(29,30)	0,41
(14,15)	0,34	(29,31)	0,71
(16,17)	0,41	(5,32)	0,48

TABLE II: scenarios overview. Each link is between the Source (SN) and the Destination (DN) Node.

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[1] http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/

Path	Reliability	Path	Reliability
{1}	1	{17}	1
{2}	1	{18,17}	0,92
{3,28}	0,92	{19,25}	0,9
{4,5,32}	0,874	{20,21,27}	0,837
{5,32}	0,93	{21,27}	0,92
{6,24}	0,92	{22,27}	0,93
{7,8}	0,91	{23,24}	0,94
{8}	1	{24}	1
{9,8}	0,91	{25}	1
{10,11}	0,91	{26,25}	0,92
{11}	1	{27}	1
{12,11}	0,94	{28}	1
{13,14,15}	0,884	{29,31}	0,9
{14,15}	0,95	{30,29,31}	0,846
{15}	1	{31}	1
{16,17}	0,94	{32}	1

TABLE III: routing table for *complete scenario*. Each path shows the visited nodes between SN and EN.

Path	Reliability	Path	Reliability
{13,12,11}	0,865	{14,13,12,11}	0,804

TABLE IV: new paths of routing table for (14-15)-scenario.

Path	Reliability	Path	Reliability
{20,30,29,31}	0,821	{21,23,24}	0,855

TABLE V: new paths of routing table for (21-27)-scenario.

(n-1)-scenarios.

The proposed problem formulation does not guarantee resilience when links are loss at the same time *a priori*. In this case, we need to verify the existence of proper set up. Including additional resilience requirements at the problem formalization stage is possible, nevertheless it is not cost effective when working with typical MV distribution grids, being them characterized by simple loops. In fact, in the considered case study it is straightforward to verify that the (n-1)-resilience requirement would imply the leaf nodes and all the ones to be connected to the grid by means of two links to be equipped with an AP.

V. CONCLUSIONS AND FUTURE WORKS

In this paper the problem of developing a PowerLine Communications (PLC) overlaying a Medium Voltage (MV) power network is considered.

An optimal planning problem, formulated as a multi-objective Combinatorial Optimization problem.

As shown by the simulation results, based on realistic use-cases analyzed in the DLC-VIT4IP project, the proposed optimization algorithm can be used by the MV infrastructure owner as a decision tool to design reliable and cost-effective PLC network overlying the MV power network. On-going and future work is aimed at developing scalable algorithms to solve the defined optimization problem.

VI. ACKNOWLEDGMENTS

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