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Optimal Allocation of Resilience Resources for Strategic Communication-aware Restoration of Smart Distribution Grids

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Abstract—Albeit power grids evolve to be smarter, major extreme events still pose reliability and resilience challenges, mainly at the distribution level due to increased vulnerabilities and limited recovery resources. Information and communication technologies (ICTs) introduce a new set of vulnerabilities, widely examined in the literature, like remote device failures, communication channel disturbances, and cyber attacks. However, very few studies explored the opportunity offered by communications to improve the resilience of power systems and move away from viewing power-telecom interdependencies as a threat only. This paper proposes a communication-aware distribution system restoration (DSR) methodology, which leverages power-telecom interdependencies to find optimal restoration strategies. The state of the grid-energized telecom points is tracked to inform the best restoration actions, which are enabled via resilience resources of repair, manual switching (MS), remote reconfiguration, and distributed generators (DGs). As the telecommunication network coordinates the allocation of those resilience resources due to their coupling, different telecom architectures are introduced to investigate the contribution of private and public ICTs to grid management and restoration operations. The system restoration takes as input the configuration after the remote fast-response to formulate the problem as a mixed integer linear program (MILP). Results from numerical simulations highlight the enhancement in the DSR process brought by telecom-aware recovery and co-optimization of resilience resources, while quantifying the existent disparity between overhead and underground power line configurations.

Index Terms—Smart Grid, Distribution System Restoration, Cyber-Physical Systems, Resilience, Co-optimization, MILP

NOMENCLATURE

Indices and Sets

c, e	Index of communication, electric service, resp.
N	Set of all power nodes (HV/MV SS, MV buses)
S	Set of HV/MV Substations (SS)
X, W	Set of fixEd, Wireless access points, resp.
U	Set of utility-owned access points
$n(j)$	Set of neighbor nodes of node j
$n_m(l)$	Set of neighbor manual lines of line l
L, L^u	Set of all lines and underground lines, resp.
L^m, L^r	Set of manual, remote switchable lines, resp.
L^{ar}, L^{cb}	Set of auto-reclosing, circuit-breaking lines, resp.
F	Set of failed power lines
F^o, F^u	Set of failed overhead, underground lines, resp.
DP	Set of depots
RC, MC	Set of repair, manual switching crews, resp.
GC	Set of DG placement crews

Parameters

M	Large number
r_{ij}, x_{ij}	Resistance, Reactance of line (i, j)
Res_l	Demand of repair resources from faulted line l
Res^{dp}	Repair resources available at depot dp
RT_l, MT_l	Repair, manual switching time of damage l , resp.
GT_g	DG placement time at bus g
TT_{lm}	Travel time from l to m (depot, line, or bus)
s_i	Binary parameter. 1 if i is a SS, 0 otherwise

Variables

$sw_{l,t}$	1 if switch at $l = (i, j)$ is closed at t , else 0
$sw_{ij,t}$	1 if directed switch (i, j) is closed at t , else 0
$p_{ij,t}, q_{ij,t}$	Active, reactive power flow of line (i, j) at t , resp.
$p_{i,t}^{ns}, q_{i,t}^{ns}$	Loss of active, reactive load at node i at t , resp.
$p_{i,t}^{dg}, q_{i,t}^{dg}$	Active, reactive DG power at node i at t , resp.
$v_{i,t}$	Voltage magnitude at node i
$d_{ij,t}$	1 if power flows from i to j at t , 0 otherwise
$a_{ij,t}$	1 if line $l = (i, j)$ is available at t , 0 otherwise
$a_{i,t}^e$	1 if bus i is available at t , 0 otherwise
$y_{i,t}^e$	1 if bus i is energized at t , 0 otherwise
$y_{i,t}^{dg}$	1 if a DG is connected at bus i at t , 0 otherwise
$d_{i,t}^{dg}$	1 if a DG is available at bus i at t , 0 otherwise
$u_{i,t}^e$	1 if telecom service (TS) from utility-owned access point i is available at t , 0 otherwise
$ss_{i,t}^c$	1 if TS of a SS i is available at t , 0 otherwise
$T_{i,t}^c$	1 if TS from the operator access point i is available at t , 0 otherwise
$T_{i,t}^e$	1 if electricity supply for the operator access point i is available at t , 0 otherwise
$E_{i,t}$	Energy storage of the battery at node i at t
$b_{i,t}$	1 if AP battery i is not empty at t , 0 otherwise
$r_{l,t}^{dp,k}$	1 if line l is under repair by crew k of depot dp at time t , 0 otherwise
$m_{l,t}^{dp,k}$	1 if line l is under manual switching by crew k of depot dp at time t , 0 otherwise
$g_{n,t}^{dp,k}$	1 if bus n is under DG-placement by crew k of depot dp at time t , 0 otherwise

I. INTRODUCTION

SMART grids abide by high standards of quality-of-supply and service continuity despite being challenged by extreme events such as natural hazards, cyber-physical

attacks, and human errors. Consequently, all involved stakeholders strive for increased grid reliability and resilience [1]. Resilience commonly encompasses proactive planning, robustness, damage assessment, and restoration [2, 3]. For resilience improvement, operational measures at the restoration stage are identified as a high opportunity compared to the expensive hardening measures [4, 1]. Smart grids restoration aims to get the system back to an acceptable level of performance as fast as possible, with minimized adverse impacts on society. Methods to achieve this objective evolved from rule-based expert systems to heuristics like genetic algorithms and fuzzy logic, then mathematical optimization and AI-based methods [3, 5]. Resilience-based optimization is introduced in many recent literature for grid restoration. The transmission network has drawn many efforts in this area given its high criticality by acting as the backbone of the electric system [6, 7]. Yet, increasing grid applications (renewables, electrical vehicles, smart-meters, etc.), pervasive ICTs, and inherent vulnerabilities in the smart distribution grid (SDG) prompted deep analysis of restoration optimization at this level [8]. Thereby, even if the insights from the present work apply well to transmission grids and other industrial cyber-physical systems, the model focuses on distribution grids as advanced operational aspects of radiality, switching, and power balancing are discussed.

For distribution grid restoration, literature-proposed approaches range from *single-resource optimization in the power grid* to *multi-resource co-optimization in interdependent systems*. Investigated resources include mainly reconfiguration switches, intervention crews, and mobile power storage. Authors in [4] focused on the fast response of the grid using remote-controlled switches (RCSs). A unified two-stage optimization model was constructed starting from proactive RCS allocation, followed by remote reconfiguration. A two-stage remote and manual switching is considered in [9], where an initial MILP formulation describes feeder reconfigurations with DG-assisted grid-forming, before seeking with a similar optimization method the optimal sequence of switching operations. For multi-resource DSR optimization, Ref. [10] models the routing and scheduling of crews to disrupted components by two MILPs that correspond to the cases of full-repair requirement before reconnection and possible partial operation, respectively. Some works discussed dynamic programming [11], markov decision processes [12], and reinforcement learning [13] as promising methods to overtake computation and scalability concerns related to models of large-scale real world systems. However, mixed integer programming (MIP) methods are this far dominant in co-optimization of multiple resilience resources for faster crew interventions with microgrid formation capabilities. The work in [14] coordinates resilience strategies of repair crew dispatch, DG placement, and reconfiguration. A MILP is formulated based on power flow, routing, and scheduling constraints to optimize the served load and the restoration time. With similar objectives and resources, but using vertex-wise routing instead of the edge-wise approach, [15] constructed a MIP to optimally recover the distribution system in minimum time. The problem was convexified

and linearized equivalently, then reduced by pre-assigning damages and DG candidates to depots. The co-optimization approach is extended by the authors in [16] to encompass damage assessment for comprehensive system restoration analysis. The designed framework brings forward crew schedules and reconfiguration to the damage assessment stage, resulting in a dynamic update of restoration schedules as failures are revealed. All these recent contributions to DSR analysis are comprehensive and already address many aspects related to restoration modeling for single-resource and multi-resources problems with various constraints, as well as scalability issues. However, none of them consider the omni-present power-telecom interdependencies.

The DSR invoke many power-telecom interdependent functions from outage management and wide-area monitoring, protection and control systems, e.g. volt/VAR control, fault location, isolation, and service restoration (FLISR), and intervention workforce management [17, 18, 4]. According to [19], this power-telecom coupling can be seized by extending the optimal power flow model to include information flow. The resulting integrated model is non-convex and highly non-linear due to prevailing event-driven communications. Alike complexity is observed in [20] that developed a cyber-constrained power flow model to evaluate and enhance the power system resilience, then used a bi-level linear programming exact reformulation to solve the problem. An attempt was conducted in [21] to investigate the status of the telecommunication service (TS) by coordinating repair and reconfiguration alongside the deployment of emergency communications. However, this work considers power supply effect on feeder terminal units (FTUs) only till the batteries are depleted, and does not look into prioritizing the recovery of nodes from which FTUs are initially supplied. An emergency deployment is conducted, looping back to only considering telecom impacts on the grid, missing the impact of the grid on communications. Authors in [22] present a fine-grained description of the power-telecom interdependence with a discrete-event evaluation methodology. However, back-up power supplies such as batteries in communication devices are not modeled, making the study of the impact on the restoration process incomplete.

Hence, reviewed state-of-the-art works consider no- or one-way power dependence on the telecom service. This reduces the telecom network to its cyber layer, whereas practical evidence strongly demonstrates the importance of telecoms' physical layer that can be affected either by a physical damage or a shortage in power supply [23]. In addition, no previous DSR contribution considered underground lines, which differ from overhead lines in terms of failure isolation [24]. To bridge these gaps, the present work considers both cyber and physical layers of the telecom network, allowing to capture two-way power-telecom interdependencies: the power distribution system depends on telecoms to control switches and communicate with intervention crews, while telecom assets depend on the power supply from the grid or back-up batteries to operate. A telecom-aware co-optimization is proposed to solve the DSR problem, with novel contributions outlined as follows:

- The model captures the two-way power-telecom interdependencies, as well as the coupling among restoration resources and within public-private telecoms;
- A DSR co-optimization is formulated to seek optimal restoration strategies by leveraging information on the availability of telecom assets and their power supply;
- Various grid architectures are accounted for by the two broad families of overhead and underground lines, demonstrating minimal model changes for configuration evolution;
- A simplified formulation is used for radiality conditions, and a realistic multi-feeder network is constructed to validate the proposed approach.

Section II introduces the system model and the proposed restoration approach; Section III presents simulations and numerical results; and the conclusion is drawn in Section IV.

II. SYSTEM MODEL

Distribution grids are meshed by design but operated radially to limit the propagation of faults by opening some switches in normal operation (called tie-switches). The term *failure* is used here interchangeably with fault, damage, outage, and incident to indicate an unavailability status of a component due to an exogenous event. Fig. 1 summarizes interactions among intra- and inter-domain components, with four main actions: power supply, telecom service, repair/isolation and DG placement (each arrow originates from an entity providing the action/service and ends at a targeted entity). After the outbreak of an extreme event, the fast response reconfigures the network by maneuvering RCSs, relying on prior knowledge about the structure and operation of the grid, as well as monitoring information. The whole process is conducted within few minutes of the surge and usually allows for a partial restoration. Topological, power flow, and zone isolation conditions are verified before any reconfiguration in the network. Interested readers can refer to [4, 9] for more details about the fast remote reconfiguration.

Following the initial response, the SDG attains a limited recovery that needs to be carried on by means of multiple resources: remote/manual switching, repair/MS crews, and DGs. A MILP formulation is proposed to co-optimize restoration resources, where the optimal combination of resilience resources is sought subject to topological, operational, and interdependence constraints. The co-optimization is motivated by tight coupling of considered resources. For instance, an intervention crew finishing a repair at a given line, would need to inform the control center that may execute some reconfiguration using switches, before commanding the crew to reconnect the repaired segment. Likewise, formed microgrids using DGs combine the tasks achieved by specialized intervention crews and reconfiguration in the network by manual and remote switches. There is also a complementarity between repairing and placing DGs, because zones that receive DGs are most likely to afford delayed repair, which allows prioritizing other zones, and vice versa. The inter-resource coupling is even more appealing when ICTs are acknowledged as the vector of coordination. Unlike

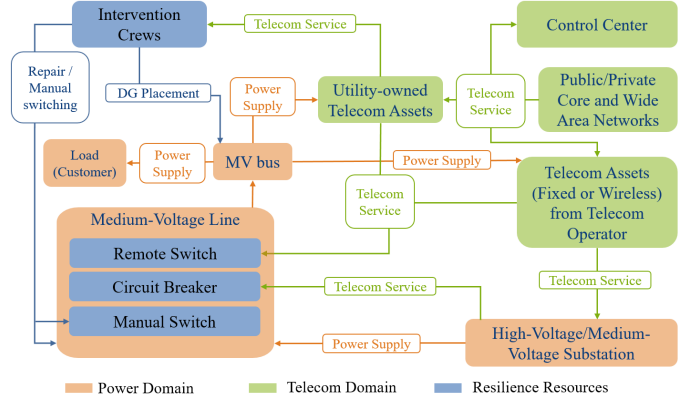


Fig. 1. Summarized interactions in the proposed model

the fast response, where telecom points are only affected by direct failures, power shortages affect important telecom points after depletion of their batteries. Therefrom, the DSR stage deals with the two-way power-telecom dependence, where ICTs are dependent on the grid for power supply, and the grid dependent on ICTs for both controlling field assets and coordinating restoration strategies. Information provided to the DSR stage ($t = 0$) includes remote reconfiguration from the first response and outage diagnoses. This is organized as a record of identified damages, an estimation of travel/repair time, and an indication of damaged sites' accessibility.

A. Zone Separation Constraints

Three zones can be distinguished during an event: i) *Damaged zone*: part of the grid containing the initial failure and subsequent damages due to failure propagation; ii) *Out-of-Service safe zone*: part of the network, at first included in the damaged zone, but could be isolated from the damage using switches. Elements in this zone wait for re-connection to the grid; iii) *Supplied safe zone*: parts that are safe from damages and energized. In overhead lines, only one switch is present at each line between two nodes (buses), then the tightest isolation could be made by opening switches of neighboring lines. However, in underground lines, a switch is often positioned at each side of a node, allowing for a better isolation by opening both sides for a damaged line.

$$a_{i,t}^e + sw_{l,t} - 1 \leq a_{j,t}^e, \forall l = (i, j) \in L, \forall t \quad (1)$$

$$a_{i,t}^e \leq a_{i,t-1}^e + a_{l,t}, \forall l = (i, j) \in F^o, \forall t \quad (2)$$

$$a_{i,t}^e \leq a_{i,t-1}^e + a_{ij,t} + (1 - sw_{ij,t}), \forall (i, j) \in F^u, \forall t \quad (3)$$

$$sw_{l,t} \leq sw_{ij,t}, \forall l = (i, j) \in L^u, \forall t \quad (4)$$

$$sw_{l,t} \leq sw_{ji,t}, \forall l = (i, j) \in L^u, \forall t \quad (5)$$

$$sw_{ij,t} + sw_{ji,t} - 1 \leq sw_{l,t}, \forall l = (i, j) \in L^u, \forall t \quad (6)$$

Constraint (1) ensures that damaged zones are not connected to safe (supplied or out-of-service) zones. This is guaranteed by requiring open lines between safe and damaged zones. Connection between supplied and out-of-service zones is possible. From (2)–(3), a power bus can be restored if no neighboring overhead or underground line is damaged ($a_{ij,t} = 0$), or isolated from neighboring underground line. The variable $sw_{ij,t}$ is directed, because it represents the switch

closest to node i and $sw_{ji,t}$ is the switch closest to node j in underground networks, while the undirected variable $sw_{l,t}$ is used when direction is not needed. Constraints (4)–(6) state that an underground line is closed only when both switches are closed, and open otherwise. Other than constraints (3)–(6), the undirected variable $sw_{l,t}$ is used throughout the model to represent the state of line $l = (i, j)$.

B. Radiality Constraints

A novel formulation is adopted to guarantee the radiality of the power grid

$$d_{ij,t} + d_{ji,t} \leq sw_{l,t}, \forall l = (i, j) \in L, \forall t \quad (7)$$

$$sw_{l,t} - (2 - y_{i,t}^e - y_{j,t}^e) \leq d_{ij,t} + d_{ji,t}, \forall l = (i, j) \in L, \forall t \quad (8)$$

$$d_{ij,t} + d_{ji,t} - (2 - y_{i,t}^e - y_{j,t}^e) \leq sw_{l,t}, \forall l = (i, j) \in L, \forall t \quad (9)$$

$$\sum_{\forall j \in n(i)} d_{ji,t} \leq a_{i,t}^e - s_i - y_{i,t}^{dg}, \forall i \in N, \forall t \quad (10)$$

$$\sum_{\forall j \in n(i)} d_{ij,t} \leq M \cdot \left(\sum_{\forall j \in n(i)} d_{ji,t} + s_i + y_{i,t}^{dg} \right), \forall i \in N, \forall t \quad (11)$$

Constraint (7) imposes unidirectional power flow, while capturing the existence of *unsupplied* closed lines in damaged zones. This fact is missed in all reviewed works as an equality sign in (7) would force energizing (de-energizing) a line to be equivalent to closing (opening) it. Then, (8) and (9) state that for all t , a line out of damaged zones is safely energized as soon as closed. Note that the damage in a line is represented by failing the direct connecting nodes, meaning that both *failed-open* and *failed-closed* events can be considered. Constraint (10) prohibits power flow into HV/MV substations or nodes with a DG source, while indicating that any other bus has at most one parent node. If this parent node is not supplying power to the considered node i , or i is neither a substation nor a DG, no downstream flow is possible from i as encoded in (11). The placement of DGs to form islanded zones (or microgrids) is anticipated by (10), and the resulting topology is a spanning forest similar to the case of multi-substation power system. This construction admits the formation of out-of-service islands.

C. Power Flow Constraints

The LinDistFlow model is used to represent the flow of power to all loads in the system.

$$\sum_{\forall j \in n(i)} p_{ij,t} + p_i^d = \sum_{\forall j \in n(i)} p_{ji,t} + p_{i,t}^{ns} + p_i^{dg}, \forall i \in N \setminus S, \forall t \quad (12)$$

$$\sum_{\forall j \in n(i)} q_{ij,t} + q_i^d = \sum_{\forall j \in n(i)} q_{ji,t} + q_{i,t}^{ns} + q_i^{dg}, \forall i \in N \setminus S, \forall t \quad (13)$$

$$\begin{aligned} -M \cdot (1 - d_{ij,t}) &\leq v_{i,t} - v_{j,t} - 2 \cdot (r_{ij} \cdot p_{ij,t} + x_{ij} \cdot q_{ij,t}) \\ &\leq M \cdot (1 - d_{ij,t}), \forall (i, j) \in L, \forall t \end{aligned} \quad (14)$$

$$0 \leq p_{ij,t} \leq S^{max} \cdot d_{ij,t}, \forall (i, j) \in L, \forall t \quad (15)$$

$$0 \leq q_{ij,t} \leq S^{max} \cdot d_{ij,t}, \forall (i, j) \in L, \forall t \quad (16)$$

$$v_i^{min} \leq v_{i,t} \leq v_i^{max}, \forall i \in N, \forall t \quad (17)$$

$$(1 - y_{i,t}^e) \cdot p_i^d \leq p_{i,t}^{ns} \leq p_i^d, \forall i \in N, \forall t \quad (18)$$

$$(1 - y_{i,t}^e) \cdot q_i^d \leq q_{i,t}^{ns} \leq q_i^d, \forall i \in N, \forall t \quad (19)$$

$$0 \leq p_{i,t}^{dg} \leq P^{dg,max} \cdot y_{i,t}^{dg}, \forall i \in D, \forall t \quad (20)$$

$$0 \leq q_{i,t}^{dg} \leq Q^{dg,max} \cdot y_{i,t}^{dg}, \forall i \in D, \forall t \quad (21)$$

Constraints (12)–(13) express the power balance at each bus. The difference in node voltages is given in (14) in terms of power and impedance quantities. Equations (15)–(16) limit the power capacity of closed lines, while (17) bounds the bus voltage. The non-supplied power is restrained by (18)–(19).

D. Telecom Constraints

The grid operators use public and/or private communications for DSR and other grid applications [25, 26, 27]. Public ICTs range from wired (fiber-optic, copper: PSTN, xDSL) to licensed (GSM, CDMA, LTE, 5G, etc.) and unlicensed (WiFi, LoRa, SigFox, etc.) wireless technologies [28]. DSOs subcontract telecom operators to provide and manage the access and core infrastructure that allows the connection of substations, field devices, and crews to the control center and other central functions (DSO datacenters, procurement centers, billing system, etc.). This has the advantages of reduced operational costs, wide coverage, and specialized support from experienced telecom teams. The alternative is to deploy a private network, managed by the DSO itself, to cope with privacy and congestion issues in public ICTs. Unfortunately, this imposes limitations like narrow bandwidth (i.e., reduced data rate), high OPEX, niche technology, and very restricted ecosystem. Such technologies encompass power line communications (PLC) for which the DSO already has the basic infrastructure, and private mobile radiocommunications (PMR), operated in a dedicated frequency band. A hybrid setting can offer a good compromise between the pros and cons of public and private communications, with great flexibility in selecting the technology that meets the requirements of a given grid application [25]. The constraints below show an example of a hybrid architecture that can be captured by the proposed DSR model combining utility-owned ICT infrastructure and telecom operator services. The hierarchical setup of telecom networks is illustrated by the wide area network (WAN) and core network that provide services to public and private access points (APs), which in turn serve grid assets. Therefore, in addition to connecting RCSs, crews, and substations, other communication components are modeled:

- Private or Utility-owned APs (U-APs): An important DSO asset equipped with large batteries. Each U-AP has a primary fixed (wired) and a secondary wireless link in case of a hybrid configuration. U-APs can provide RCSs and intervention crews with requested TS.
- Telecom operator fixed APs (F-APs): Serve the DSO assets (HV/MV SS and RCSs) in a public configuration, and can be a primary link for U-APs in a hybrid configuration. The battery can last some hours.
- Telecom operator wireless APs (W-APs): Serve the DSO assets (HV/MV SS and RCSs) in a public configuration,

and can be a secondary link for U-APs in a hybrid configuration. The battery can last some hours.

The upper layer that serves APs is called the *core network*, which collects, processes, and transmits data through technology-dependent aggregation points, location registers, gateways, etc. Some requests can be routed directly at the core level, while others resort to the grid's central functions, such as the control center in the case of the DSR. The core network connects to the WAN of the utility, which is a collection of routers, switches (communication switches), and various networking equipment granting access to grid functions and applications. The criticality associated with WANs pushed most power operators to deploy their own networks that may or may not be handed to a tier telecom operator for management [26]. The core network and WAN are admitted as perfectly operating in the present work to concentrate on the impact of the more vulnerable APs [29].

$$\begin{aligned} \frac{1}{M} \cdot \left(T_{k,t}^c + \sum_{\forall j:(j,i) \in W \times S} T_{j,t}^c \right) &\leq ss_{i,t}^c \\ &\leq T_{k,t}^c + \sum_{\forall j:(j,i) \in W \times S} T_{j,t}^c, \forall (k,i) \in X \times S, \forall t \end{aligned} \quad (22)$$

$$\begin{aligned} \frac{1}{M} \cdot \left(T_{k,t}^c + \sum_{\forall j:(j,i) \in W} T_{j,t}^c \right) &\leq u_{i,t}^c \\ &\leq T_{k,t}^c + \sum_{\forall j:(j,i) \in W \times U} T_{j,t}^c, \forall (k,i) \in X \times U, \forall t \\ T_{i,t}^c &\leq T_{i,t}^e, \forall i \in W \cup X, \forall t \end{aligned} \quad (23)$$

$$\begin{aligned} \frac{1}{M} \cdot (1 - f_i) \cdot (E_{i,t} + y_{i,t}^e) &\leq T_{i,t}^e \\ &\leq M \cdot (1 - f_i) \cdot (E_{i,t} + y_{i,t}^e), \forall i \in W \cup X, \forall t \end{aligned} \quad (24)$$

$$\frac{1}{M} \cdot E_{i,t} \leq b_{i,t} \leq E_{i,t}, \forall i \in W \cup X, \forall t \quad (25)$$

$$E_i^{min} \leq E_{i,t} \leq E_i^{max}, \forall i \in W \cup X, \forall t \quad (26)$$

$$E_{i,t} = E_{i,t-1} - p_i^{disc} \cdot (1 - y_{i,t-1}^e) \cdot b_{i,t-1}, \forall i \in W \cup X, \forall t \quad (27)$$

The notation using the cross sign between different sets is used to represent indexed sets, where only meaningful elements are evaluated. In other words, $W \times S$ does not contain all possible two-dimensional (j, i) combinations formed by elements of the two sets, but includes only the valid pairs formed by a substation $i \in S$ connecting to a W-AP $j \in W$. In (22), the summation over all W-APs associated to substation i shows the redundancy that can be offered by W-APs, obviously not found in fixed networks (dedicated wired link). The available TS to a HV/MV SS relies on the availability of either a F-AP or a secondary W-AP. Although quite common, this is a generic choice of connecting substations, and (22) is easily adaptable to other technologies. A hybrid public/private telecom architecture, where private assets are eventually sending and receiving data through public networks is stated in (23). Constraints (24) and (25) emphasize that the TS is at disposal only when power supply is guaranteed by the grid or back-up batteries. In that case, HV/MV SS and U-AP will not necessarily fail, but will operate in a blind mode. The binary variable $b_{i,t}$ is linked in (26) to the state-of-charge

(SoC) $E_{i,t}$ to indicate whether the battery of an AP i is empty ($b_{i,t} = 0$). Equation (27) bounds the SoC of the battery by min and max capacities. The discharge power is p_i^{disc} in (28) containing a quadratic component $y_{i,t}^e \cdot b_{i,t}$, which is easily linearized and replaced with a binary variable $w_{i,t}^1$.

E. Routing and Scheduling Constraints

Damage assessment is conducted by diagnosis crews, helicopter-transported teams, and airborne drones [8] to collect data and pinpoint damage locations, helping to estimate important parameters, e.g. repair time, travel time, and required resources. The DSO exploits gathered information to organize operations by allocating resources and providing a timeline and traveling paths. This is described by the well-known routing and scheduling problem [30]. For the DSR problem, depots and damaged lines are *nodes* connected with road paths seen as *edges*, and the aim is to find the sequence of locations for each crew to visit while minimizing the overall restoration time. The vehicle routing problem (VRP) is adopted in many recent works [16, 14] to model the dispatch of repair crews and/or DG placement. Since tasks (MS, repair, and DG placement) are conducted at damage sites and interdependencies of intervention crews with ICTs and switches arise at these same nodes, the edge-centred approach in VRP is less convenient for the DSR problem.

We adopt the node-centered approach proposed and demonstrated in [15] to bypass issues of transportation-grid coupling and their different timescales. Let c be a binary variable representing a crew k visiting node l at time t (a crew among repair (rc), manual switching (mc), and DG placement (gc) crews). Variable $c_{l,t}^k$ provides the same information in the present model as variables $c_{l,m}^k$, c_l^k , and AT_l^k used in [16, 14] to respectively represent crew k traveling the path (l, m) , crew k visiting node l , and the arrival time of k to damage l . Still, the number of variables is comparable between $c_{l,t}^k$ with $|C| \cdot |F^{dp}| \cdot |T|$ elements and the edge-centred approach necessitating $|C| \cdot |F^{dp}|^2 + |C| \cdot |F^{dp}|$ elements, where $|C|$ the number of crews, $|F^{dp}|$ the number of nodes (damaged lines + depots), and $|T|$ the number of DSR time steps. The square term indicates that the edge-centred approach grows fast with an increase in the handled failures, while the node-centred approach grows slower with the number of damages, and depends on the number of time steps that is usually limited from other parts of the global model. The form $c_{l,t}^k$ from [15] is extended here to $c_{l,t}^{dp,k}$ capturing the fact that each crew k is linked to a given depot dp , as well as integrating the widely used problem reduction techniques of pre-assigning damages and DG candidates to depots [14, 15].

$$\begin{aligned} \min(TT_{l,m}^c, T-t) \\ \sum_{\tau=0} \left(c_{l,t+\tau}^{dp,k} + c_{m,t}^{dp,k} - 1 \right) &\leq 0, \forall l \neq m, \end{aligned} \quad (29)$$

$$\forall (dp, k, l, m) \in DP \times C \times F^{dp} \times F^{dp}, C = RC \cup MC, \forall t$$

$$\sum_{\tau=t}^T \sum_{\forall (dp,k) \in DP \times RC} mc_{l,\tau}^{dp,k} \leq M \cdot \left(1 - \sum_{\forall (dp,k) \in DP \times RC} r_{l,t}^{dp,k} \right) \quad (30)$$

$$a_{l,t} \leq \frac{\sum_{\tau=0}^t h(\tau)^*}{RT_l + 2 \cdot \sum_{\forall m \in n_m(l)} MT_m}, \forall l \in F, \forall t \quad (31)$$

$$\sum_{\forall l \in F} a_{l,T} \cdot \text{Res}_l \leq \text{Res}^{dp}, \forall (dp, l) \in DP \times F \quad (32)$$

$$h(t) + a_{l,t} \leq 1, \forall l \in F, \forall t \quad (33)$$

According to (29), a crew is at a maximum of one node (damaged line or depot) at any given t , and it would take at least the traveling time TT_{lm}^{rc} for a repair crew and TT_{lm}^{mc} for a MS crew to get from l to m . From (30), no isolation crew can visit an incident $l \in F$ at any t after having been visited by a repair crew. Constraint (31) shows that a line is repaired when repair and MS crews have spent sufficient time at the node, starting by MT_l to manually isolate the damage site, then RT_l for the repair, before taking MT_l to reconnect the restored line. Repair crews are able to perform the MS. A depot can handle a limited number of damages (32). In (33), the damaged line is in one of the following states at any time step: not visited yet, under isolation, under repair, or resolved.

$$\min(TT_{m,0}^{gc} + TT_{n,0}^{gc} \cdot T - t) \sum_{\tau=0}^t (gc_{m,t+\tau}^{dp,k} + gc_{n,t}^{dp,k} - 1) \leq 0, \forall n \neq m, \forall (dp, k, m, n) \in DP \times GC \times CD^{dp} \times CD^{dp}, \forall t \quad (34)$$

$$\sum_{\forall \tau=0}^t \sum_{\forall n \in CD} gc_{n,t}^{dp,k} \leq \sum_{\forall \tau=0}^t gc_{0,t}^{dp,k}, \forall (dp, k, n) \in DP \times GC \times CD \quad (35)$$

$$a_{n,t}^{dg} \leq \frac{\sum_{\tau=0}^t \left(\sum_{\forall (dp,k) \in DP \times GC} gc_{n,\tau}^{dp,k} \right)}{GT_n}, \forall n \in CD, \forall t \quad (36)$$

$$\sum_{\forall (dp,k) \in DP \times GC} gc_{n,t}^{dp,k} + a_{n,t}^{dg} \leq 1, \forall n \in CD, \forall t \quad (37)$$

Unlike the routing of repair and MS crews, DG placement crews need to get back to the depot after each task completion. This comes from the assumption that considered DGs are truck-mounted, which are bulky and require a whole team for transport and installation. In (34), a crew is at a maximum of one node (DG candidate or depot) at any given time t . At least a traveling time $TT_{n,0}^{gc}$ is required between a node n and its depot (0 is used to indicate that a crew is coming from/heading to its depot). (35) enforces that no direct paths between DG candidates are allowed. A DG is placed after a crew spends at least a placement time GT_n at a site n as indicated by (36). From (37), a candidate node is either not visited yet, undergoing a DG placement, or has the DG installed.

F. Interdependence Constraints

The first power-telecom dependence is unraveled in (24) as the power system energizes APs, making the TS only available when the physical equipment is up and running. Executing received commands by grid assets depicts another

$$*h(t) = \sum_{\forall (dp,k) \in DP \times RC} rc_{l,t}^{dp,k} + \sum_{\forall (dp,k) \in DP \times MC} mc_{l,t}^{dp,k}$$

power-telecom dependence, where the flow of power is regulated by applied controls.

$$a_{l,t} \leq u_{k,t}, \forall (k, l) \in U \times L, \forall t \quad (38)$$

$$sw_{l,t-1} - u_{k,t}^c (2 - a_{i,t}^e - a_{j,t}^e) \leq sw_{l,t} \leq sw_{l,t-1} + u_{k,t}^c \cdot a_{i,t}^e \quad (39)$$

$$\forall l = (i, j) \in L^r \cup L^{ar}, (k, (i, j)) \in U \times L, \forall t$$

$$sw_{l,t-1} \leq sw_{l,t} \leq sw_{l,t-1} + ss_{k,t}^c \cdot a_{i,t}^e, \quad (40)$$

$$\forall l = (i, j) \in L^{cb}, (k, (i, j)) \in S \times L, \forall t$$

Before switching, a line needs to be available for connection, which is conditioned in (38) by the status of the communication AP. Constraint (39) implies the dependence of RCSs and ACRs on the TS from U-APs, and from (40) a CB is operated only when the TS from a substation is available. The non-linear square terms in (39)–(40) are easily linearized.

$$sw_{m,t-1} - \varepsilon - z^\dagger \leq sw_{m,t} \leq a_{l,t} + 2 - \varepsilon - z, \forall l \in F, \forall t \quad (41)$$

Interdependencies manifest also between resilience resources. Constraints (31) and (36) already expressed that a line and DG are not operable unless the missioned crews have finished their tasks. Also, closest manual lines are first opened for best isolation, then need to be closed after task completion (41). The dependence of U-APs on public ICTs is represented in (23), which can be built upon to model other dependencies based on chosen hybrid architectures.

G. Objective Function

During an extreme event, recovering power as fast as possible to the maximum number of clients is the utmost target of a utility. In this work, supplied power (or conversely non-supplied power) is adopted as a performance measure, and used in the objective function of the formulated MILP problem alongside costs related to deployed resilience resources.

$$\min_{p,d,sw,c,a,y,T,E,w} \left[\alpha \sum_{\forall t} \sum_{\forall i \in N \setminus S} C_i^{ns} \cdot P_{i,t}^{ns} + \beta \sum_{\forall t} \sum_{\forall l \in L} C^{sw} \cdot w_{l,t} + \gamma \left(\sum_{\forall (dp,k,l,t)} C_i^{rc} \cdot rc_{l,t}^{dp,k} + \sum_{\forall (dp,k,l,t)} C_i^{mc} \cdot mc_{l,t}^{dp,k} + \sum_{\forall (dp,k,n,t)} C_i^{gc} \cdot gc_{n,t}^{dp,k} \right) \right] \quad (42)$$

$$s.t. \quad (1) - (41), \quad (43) - (44)$$

Equation (42) poses the objective function with vectors of variables: c all intervention crews, a the availability of power buses, lines, or DGs, y the connectivity of buses to the grid or DGs, T the vector of electric and telecom status of public and private APs, E the SoC and $b_{i,t}$ the depletion status of batteries. C_i^{ns} , C_i^{sw} , C_i^{rc} , C_i^{mc} , and C_i^{gc} refer to non-supplied load, switching, repair, MS, and DG placement costs, respectively. DSOs do not spare efforts for restoration due to the pressure from governments, regulation bodies, and the public opinion, as well as the operator commitment.

$$\dagger z = (1 + \sum_{\tau=1}^{t-1} h(\tau)) / (1 + \sum_{\forall m \in n_M(l)} MT_m)$$

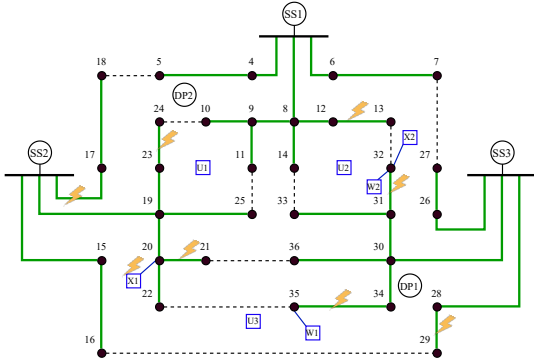


Fig. 2. Multi-feeder test network with serving telecom points

Thus, $\alpha \gg \beta$ and $\alpha \gg \gamma$, meaning that costs are only significant in cases of equivalently performing restoration strategies. The switching cost is introduced, as no change on the configuration is desired unless there is a gain in restored power or damage isolation. C^{sw} is considered the same for all operated switches, and variable $w_{i,j,t}$ results from the linearization of $|sw_{l,t} - sw_{l,t-1}|$.

$$sw_{l,t} - sw_{l,t-1} \leq w_{l,t}, \forall l \in L, \forall t \quad (43)$$

$$sw_{l,t-1} - sw_{l,t} \leq w_{l,t}, \forall l \in L, \forall t \quad (44)$$

From (43) and (44), $|sw_{l,t} - sw_{l,t-1}|$ equals 1 if the switch at line l is toggled (opened or closed) at t , and 0 otherwise.

III. SIMULATIONS AND RESULTS

Multi-feeder systems are constructed to validate the proposed approach. Per-phase analysis is run in 20kV balanced grids. We set: $\alpha = 10, \beta = 0.1, \gamma = 0.1, C_i^{ns} = 0.5, C_i^e = 1, C_i^{sw} = 0.1, C_i^{rc} = 3, C_i^{mc} = 1, C_i^{gc} = 1.5$. The model is implemented in Pyomo and solved using CPLEX on a computer with Intel Core i7 (2.5 GHz) and 32 GB RAM.

A. Distribution System Restoration in 36-bus system

Fig. 2 shows a 36-bus system with a total 1305 kW demand. Supplied buses by each feeder have a supply path from the associated substation (through green lines) and tie-switches (dashed dark lines) make the interconnections between feeders. This is the nominal configuration, from the grid planning stage, which is out of the scope of this work. We consider two configurations: full-overhead (all lines are overhead) and hybrid overhead-underground (some lines are underground). Nodes $SS1, SS2$, and $SS3$ represent the HV/MV substations, while the remaining nodes are MV buses energizing power loads, F-APs (X1 and X2), and W-APs (W1 and W2). A scenario of 8 damages is considered, with 7 affected power lines and 1 telecom AP (X1 damaged for the whole period).

After events occurrence, the total supplied power drops from a 100% at the initial phase to 29.5% after degradation, before an increase owing to RCS-based reconfiguration. As expected, hybrid overhead-underground grids perform better than full-overhead grid with 48.66% against 42.91% of supplied power, respectively. Still, both cases are away from an

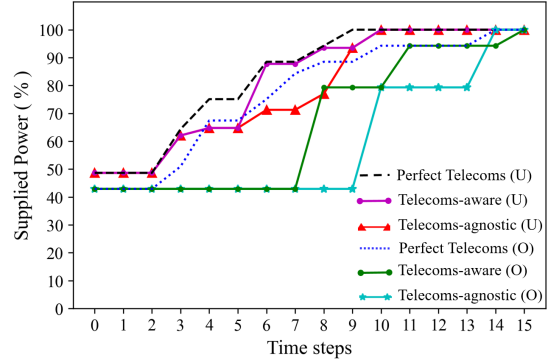


Fig. 3. Evolution of supplied power during the DSR stage

acceptable level of restoration due to the limited improvement brought by remote switches. Hence, distribution operators append other resources in next restoration steps.

The resulting grid configuration is taken as an initial state ($t = 0$) of the restoration process for which a time step of 1h is used. Damages 2–17, 20–21 and 23–24 are pre-assigned to depot 1 (DP1), whilst the remaining damages to depot 2 (DP2). Similarly, candidate buses for DG reception are set, for safety, to not be the directly connected buses to damaged lines, then, DP1: {36}; DP2: {14, 18, 22}. Repair crews (RC), MS crews (MC), and DG placement crews (GC) are initially located at depots. DP1 is set to have (RC,MC,GC)=(2,1,1), whereas DP2 has (RC,MC,GC)=(2,1,1). The travel time is proportional to the distance between a depot and a damage or between two damages, and MCs are twice faster as RCs and GCs. Repair, MS, and DG placement are chosen for all lines to last 2h, 1h, and 1h, respectively. All crews depart from depots. Without loss of generality, Utility-owned APs are assumed to possess large batteries, while possible supply shortage can be undergone by public communications despite the battery storage duration set here to 3h. The damage in the telecom AP should be handled by the telecom operator as the DSO repair strategy is limited to grid assets. RCSs and intervention crews connect to the closest U-AP, and CBs to their substations. U-APs and substations connect to the closest F-APs and W-APs.

A preliminary simulation is conducted to confirm the intuitive (and literature-well-verified) statement that co-optimization achieves better performance than non-cooperative approaches. Considering perfect communications (Case 1), we obtain gains of 12% and 9% in total supplied load using the proposed co-optimization, compared to a first case of separate optimization problems for reconfiguration and crew schedules [14], then a second case of co-optimization of reconfiguration and repair/MS crews (no DGs), respectively. Next, to quantify the criticality of TS in SDGs, a *telecom-agnostic* case is constructed (Case 2). This corresponds to the case where restoration decisions are made without special attention to the status of telecom points. To do so, the problem is solved first in case of *perfect* communications (Case 1), then the obtained solution of crew allocation (the sequence of dispatching crews) is used as a parameter to solve the formulated problem for

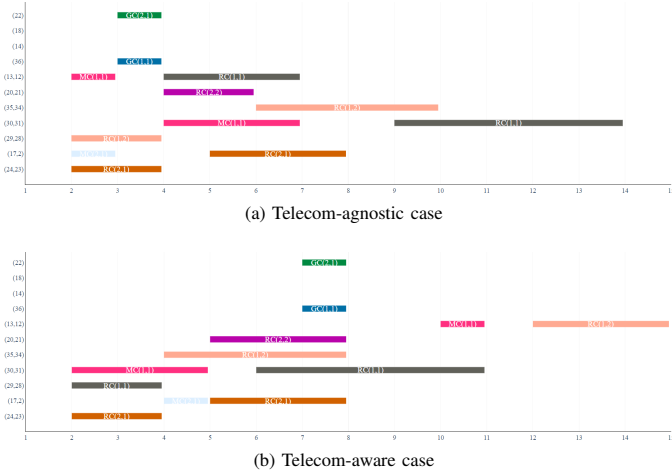


Fig. 4. Schedule of intervention crews for the overhead configuration

remaining variables of telecom and switch states as well as power quantities. Our approach that leverages the state of telecom points to find a restoration strategy is referred to as *telecom-aware* (Case 3).

The evolution of supplied power over restoration steps in the three cases is shown in Fig. 3 for both full-overhead (O) and hybrid overhead-underground (U) configurations. The co-optimization is solved within 1.25 seconds for Case 2, and 21 seconds for Case 3. Clearly, the hybrid configuration outperforms the purely overhead configuration in all three cases, due to advanced isolation capabilities in underground networks. This result should be taken carefully as the cost of MS and repair is assumed to be equal for underground and overhead networks in conducted simulations, which may not be valid given that underground interventions are complex and more time-consuming. Thus, a tight isolation surely helps to improve the level of restoration, but the cost of introducing enhanced isolation should be considered in the future. For the hybrid configuration, the ideal case of perfect communications achieves the best restoration compared to cases 2 and 3, but can be described as over-optimistic as the ICTs are not perfect and undergo many failures. Cases 2 and 3 are more realistic by including telecom failures, which are exploited in our proposed approach (Case 3) to orient restoration choices and attain a better recovery than Case 2, which does not link resource allocation to the state of telecom APs. A similar trend is observed in the overhead configuration as the curve associated with Case 1 dominates the telecom-aware and telecom-agnostic cases, while the importance of prioritizing supply restoration to some important telecom points (that will be useful for subsequent restoration) is demonstrated through Case 3, which outperforms Case 2.

Fig. 4 displays the schedules for all intervention crews in cases 2 and 3, exemplified in the overhead configuration. Unlike Case 2, interventions related to lines 30 – 31 and 34 – 35 are prioritized in Case 3, allowing earlier recovery of telecom points supplied by involved buses. For instance, although repair of lines 23 – 24 and 28 – 29 is finished at $t = 4$, their reconnection is delayed till $t = 8$ in 4b to be enabled by the recovered TS. MS crew MC1 of depot

TABLE I
TELECOM SERVICE AVAILABILITY FOR OVERHEAD CONFIGURATION

Telecom-agnostic				
	0 → 3	3 → 10	10 → 14	14 → 15
W1, U1, U3, SS2	TS up	TS down	TS down	TS up
X2, W2, U2, SS1, SS3		up	down	TS up
Telecom-aware				
	0 → 3	3 → 5	5 → 8	8 → 15
W1, U1, U3, SS2	TS up	TS down	TS down	TS up
X2, W2, U2, SS1, SS3		up	down	TS up

DP1 (MC(1,1)) isolated buses 32, 34, and 36 from damaged line 30 – 31 by opening 30 – 34, 30 – 36, and 31 – 32, allowing 34 and 36 to be restored at $t = 8$ after DG placement at 22 and 36, respectively. Hence, it is important to have fast-moving crews, which can better isolate damages prior to interventions from heavily equipped (and slow-moving) repair crews. The timelines show that repair crews operate manual switches after finishing their task as they are already on-site, in accordance with the control center instructions. The post-repair MS is depicted by retaining repair crews at the handled damage longer than the repair time, set here to 2 time steps. Further, knowledge about battery discharging of telecom APs is used in Case 3 to delay sending crews (GC(1,1), GC(2,1), RC(1,2), RC(2,2), RC(2,1), and MC(2,1)) to their respective tasks, because opportunities of reconfiguration are blocked by the absence of TS, and were carried out only following the restoration of a portion of the TS at $t = 8$. This intervention postponement can allow assigning another task to crews and avoid the cost of waiting at damaged sites until the TS recovery.

Table I summarizes the availability of the TS in both telecom-aware and agnostic cases for the full overhead configuration. The telecom-aware approach is able to restore supply to important telecom points faster, which accelerates later recovery operations.

B. Distribution System Restoration in 141-bus and 315-bus systems

Two case studies with 141 and 315 MV buses are constructed from a real MV grid to demonstrate the applicability of the proposed approach to larger networks (27 and 59 MW load power, respectively). A switch (remote or manual) is considered at each line, distinctive from most used bus systems where manual switches are ignored and very few remote switches are analyzed. A scenario of 10 failures is chosen, where 3 depots host restoration resources as follows: $DP_1 \rightarrow \{RC_{1,1}, RC_{1,2}, MC_{1,1}, GC_{1,1}\}$, $DP_2 \rightarrow \{RC_{2,1}, RC_{2,2}, MC_{2,1}\}$, $DP_3 \rightarrow \{RC_{3,1}, MC_{3,1}, GC_{3,1}\}$. For an overhead configuration, the DSR was solved in 225.3 and 267.4 seconds, respectively. Results from figures 5a and 5b confirm that the perfect telecom case achieves the best restoration in terms of cumulative supplied power. The telecom-aware approach succeeds in both usecases to outperform the telecom-agnostic case, following the same trend already observed in Fig. 3, where awareness about telecom points availability increases the restoration potential. The problem at hand is verified as *NP-Hard*, combining a

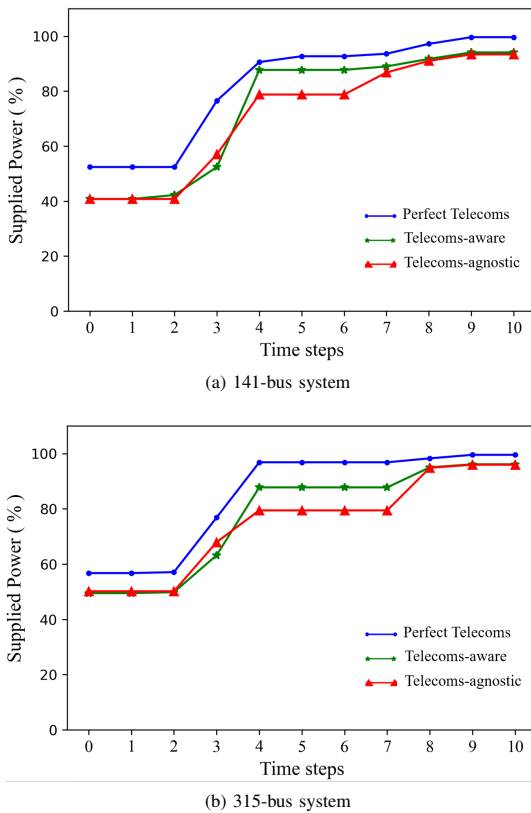


Fig. 5. Evolution of supplied power during DSR

routing combinatorial optimization problem (with exponential complexity) and SDG operation constraints. Obtained results remain important to confirm the validity of the proposed model, and allow to concentrate on a lower complexity solution in future works.

IV. CONCLUSION

The restoration process in distribution grids is modeled integrating power-telecom interdependencies and considering multi-resources. Reconfiguration switches, repair/MS crews, and DGs are coordinated by a telecom-aware MILP co-optimization yielding improved resilience strategies. The general cases of underground and overhead electrical networks are explored, revealing advantages of tight damage isolation. The proposed approach incorporates both the contribution of communication networks to DSR (by connecting remote switches and field crews to grid central functions) and power supply of telecom assets, for a comprehensive analysis of two-way power-telecom interdependencies. Results from case studies show that co-optimization of resource allocation and telecom-aware strategic interventions improve the DSR, enhancing the overall resilience of the grid. Results from the real distribution network, partially included due to space limit, validate the applicability of the model. The development of a lower complexity solution algorithm and extensions to capture telecom dynamics are identified for future works.

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