Surviving Disaster Events Via Dynamic In-Network Processing Assisted by Network Digital Twins

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***Abstract*—In post-disaster situations, search and rescue operations are actively supported by Unmanned Aerial Vehicles (UAVs) technology. As it is well known, UAV-based monitoring services require computational effort for in-network processing, which drones cannot easily support. This gives rise to the need to offload tasks to available and nearby network segments. However, the disruption caused by natural disasters often renders networks and services unavailable and unreachable. While some recent scientific contributions have already explored the idea of offloading computing tasks to support network elements in post-disaster situations, there is still a need to formulate a lightweight approach aimed at dynamically selecting suitable, trusted, and available network segments for in-network processing. In line with these premises, a novel service orchestration scheme for selecting the most suitable domain to offload processing tasks generated by drones is presented. Precisely, the conceived scheme addresses the domains affected by natural disasters and replaces them with available network segments for in-network processing, leveraging the Network Digital Twin representation. The adopted strategy employs a lightweight multi-criteria decision-making methodology to jointly consider the quality of service and trustworthiness parameters of the domains crossed by a drone. The effectiveness of the proposed solution is investigated through computer simulations. The obtained results demonstrate that the conceived approach offers up to 75.61% service availability for in-network processing compared to baseline techniques.**

I. Introduction

Thanks to their adaptability, agility, low cost, and ease of deployment, the employment of UAVs has become a compelling option for providing support services during natural disasters [1]. In particular, UAVs can acquire videos for disaster recovery and serve as countermeasures to track the regions affected by calamities and offload them to nearby and available supporting network segments for processing [2]. As it is well known, UAV-based monitoring services often cannot be performed onboard due to the required heavy computational capabilities, which drones themselves lack. Task offloading presents itself as a viable solution to address this challenge.

However, natural disasters inevitably disrupt users' coverage, service continuity, and availability, making the management of calamities and the quick restoration of network connectivity essential requirements [2]. The data offload and subsequent processing required to determine search and rescue interventions in such circumstances are significant tasks, as disruptions caused by disasters prevent network segments from being available and reachable. Therefore, it is critical to promptly identify the state and readiness of physical domains to efficiently offload tasks to the most suitable ones and proceed with disaster recovery steps.

A promising technology that actively supports the visualization of the ecosystem, as well as the management of services, network resources, and processing, is the Network Digital Twin (NDT) [3]. Through the virtual representation of a physical system, which involves the process of offloading tasks from one domain to another, it exploits the opportunity to analyze performances and make informed decisions, thus representing a key enabler for 5G and beyond.

Several works in the current scientific literature have defined architectures and platforms that employ drones to facilitate the communication between victims and rescuers [4]–[7]. At the same time, valuable works define Digital Twins (DTs) assisted task offloading strategies, formulated through complex optimization problems [8]–[11] or not providing a dynamic and prompt solution suitable for post-disaster and rescue operations [12], [13]. Indeed, to the best of the authors' knowledge, a lightweight approach aimed at dynamically selecting network segments for the network processing, leveraging the opportunities provided by DTs, is still missing.

To extend the existing scientific literature, this work proposes a lightweight scheme for selecting the most suitable domain based on availability and trust parameters to offload processing tasks from video captured by drones. In line with these premises, the proposed scheme is designed starting from the Intent-based network (IBN) 2030 framework proposed by ITU-T [14] and developed in [15]. Specifically, by leveraging the concept of DTs to describe the domains, the conceived scheme addresses the network segments affected by natural disasters, which are not viable offload destinations, and replaces them with available network segments for in-network processing. The adopted strategy employs a lightweight Multi Criteria Decision Making (MCDM) methodology (i.e., TOPSIS), which is commonly used to solve network selection problems in heterogeneous wireless networks. The dynamic selection process jointly considers the state, readiness, and trustworthiness parameters of the domains crossed by the drone to identify the most suitable network segment for processing, based on available resources and network reliability.

Simulation results demonstrate the effectiveness of the proposed scheme in terms of service availability, achieving up to 75.61% compared to other baseline techniques.

The remainder of this paper is organized as reported below. Section II reviews the state-of-the-art addressing the implementation of effective disaster management practices and network processing offloading procedures. In Section III, the proposed environment structure is presented, which encompasses both the system architecture and the implemented procedure. Section IV evaluates the performance of the proposed approach. Section V concludes the paper.

II. Related Works

Natural disasters like earthquakes, volcano eruptions, and flooding can cause building collapses, infrastructure damage, and economic losses in affected regions. The current communication networks are unable to effectively handle such unforeseen events, resulting in a widespread loss of mobile coverage. To enable timely rescue responses, computationally demanding tasks must be offloaded to nearby powerful network segments during post-disaster and rescue operations. As summarized in Table I, several studies in the scientific literature have been dedicated to addressing this concern, exploring the potential of promptly and efficiently supporting offloading operations after natural disasters.

On the one hand, extensive research works [4], [6], [7], [16]–[18] have been conducted on the applications of the UAV technology in natural disaster scenarios, and only a part of these [4], [16], [18] focuses on network processing task offloading. However, these studies highlight the difficulty of developing a strategy that takes into account the dynamic state of the system due to the heterogeneity of domains and the representation of their characteristics.

On the other hand, other studies [9]–[13] employ the DTs as a tool for data collection and modeling of the reference network domains. In particular, the authors of [9] and [13] explore the DTs as a useful tool for task offloading procedures in vehicular and urban scenarios. However, none of them fully exploit their potential in the context of natural disasters or incorporate a dynamic approach that addresses task offloading to assist in-network processing. Furthermore, to the best of the authors' knowledge, none of the valuable contributions mentioned above utilizes social attributes as support for selecting the suitable domain for network processing in order to increase the reliability of the offered service.

To advance in this direction, our contribution proposes an innovative strategy for selecting the suitable domain for task offloading using a lightweight approach that leverages the capabilities offered by DTs to represent the characteristics of heterogeneous network segments. Additionally, the IBN framework proposed by ITU-T [14] is extended by designing a Trust Management System (TMS) that computes a trustworthiness parameter into DTs. This parameter evaluates the trust among network segments, considering factors such as reputation and social relationships, as mentioned in [19]. This ensures a trust-based approach for in-network processing during task offloading.

III. The Proposed Solution

The envisioned scenario reflects a typical multi-domain network characterized by several network segments capable of supporting the provisioning of end-to-end services. Based on their capabilities, the sequence of tasks required to meet service demands, such as storing and in-network processing, is allocated to these inherently heterogeneous domains, which can range from terrestrial networks to non-terrestrial network (NTN), as well as integrated terrestrial-non-terrestrial network (TN-NTN). Moreover, the considered scenario involves a UAV encompassing the network segments of all crossed domains. Firstly, it is responsible for acquiring data in each crossed domain (i.e., videos of industrial and critical infrastructures) with the aim of assessing, inspecting, and monitoring targets that are often difficult to access for maintenance or are inaccessible.

Secondly, the UAV can offload the acquired data to the suitable network segment to facilitate their processing. With this in mind, the captured videos can effectively support recovery operations in domains affected by natural disasters. They enable swift interventions and rescue operations while also avoiding the loss of in-network processing capacity in circumstances where network coverage and services are unavailable and unreachable.

Figure 1 depicts the considered scenario and the IBN architecture, extending the solution proposed in [15] and the ITU-T specifications [14]. The heterogeneous segments are grouped into network domains, representing the physical infrastructure that handles requests for processing or storage services. Here, the end-to-end service requirements are modeled as an intent that, in turn, requires a specific performance level for enabling the provision of a service. This performance level is expressed through Service Level Agreements (SLA), formulated to ensure the compliance of network providers with these goals. Following the ITU-T specification [14], intents are processed and translated into a set of actions and policies implemented by the Intent and SLA management module.

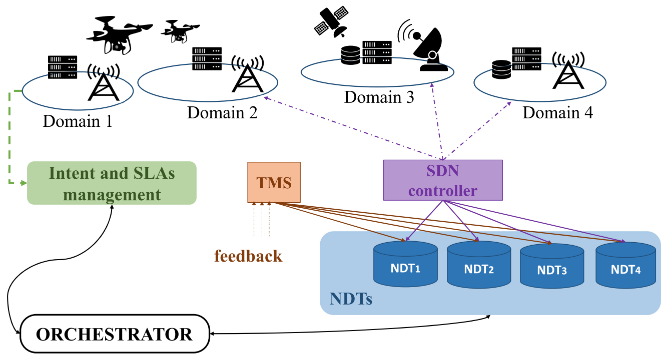

Fig. 1. Reference scenario and IBN-based network architecture.

In such a scenario, considering the intrinsically diverse nature and changing state of the network segments involved, DTs are exploited to represent the features and capabilities of

TABLE I
REVIEW OF RELATED WORKS

Features	[16]	[7]	[4]	[17]	[18]	[6]	[9]	[10]	[11]	[12]	[13]	**This work**
UAV technology	✓	✓	✓	✓	✓	✓						✓
Rescue operations		✓	✓	✓	✓	✓				✓	✓	✓
Task offloading	✓		✓		✓		✓	✓	✓			✓
Dynamic selection				✓		✓	✓		✓			✓
Trust and Social attributes												✓
Digital-twin							✓	✓	✓	✓	✓	✓

the domains. This enables network monitoring operations and prediction of maintenance needs. As abstractions of physical entities, the DTs support the selection of the most suitable domain for in-network processing by investigating the extracted features. To handle the abstraction of network resources, a Software Defined Network (SDN) controller populates and updates the performance features of DTs through appropriate APIs and modeling languages (e.g., YANG-CBOR, OMA lightweight M2M, and DTDL). This programmable controller supports the configuration of network functionalities as well as the implementation of intents.

Moreover, to assess and collect the trustworthiness feature, the TMS module calculates the behavior of network segments by evaluating their past history. Specifically, it utilizes an automatic mechanism based on feedback evaluation to compute the trust parameter, which determines the reputation of each involved network segment. This value is updated after each end-to-end service is provided, enhancing the overall reliability of the network for future intents by identifying trusted network segments for in-network processing.

Above all the aforementioned modules, the orchestrator oversees the overall multi-domain network architecture and handles both service and network orchestration functions. For each service demands, it evaluates the features of NDTs to identify the most suitable network segment supporting it. The orchestrator then allocates tasks, deploys intents, and monitors the adherence to SLA, service models, and descriptions. The algorithm determining the most suitable domain for in-network processing, which is implemented in the orchestrator, is detailed in Section III-B.

A. Network Digital Twins parameters

The primary function of the NDT component is to establish a network model that replicates the characteristics of the physical network. This approach enables the management of metrics and features through an abstracted network state description of a real-world. Leveraging this powerful tool, the orchestrator can monitor network segments to understand and counteract service disruption occasions, thereby facilitating the achievement of intents. In this context, the digital representation of network segments is explored to select the most suitable domain for task offloading and in-network processing, aiming to find the optimal configuration that satisfies the predetermined service requirements.

To construct an NDT, it is necessary to gather a dataset that contains relevant information about the network. Therefore, the conceived strategy involves extracting a combination of features from each network segment, which are related to the radio interface, network capabilities and reliability. Specifically, these features include bandwidth, CPU, RAM, storage availability, and trustworthiness.

1) Bandwidth: measured in [MHz], it assesses the minimum guaranteed value of available bandwidth for communication within the given network segment.
2) CPU: measured in [MHz], it indicates the processing capability of network resources in the domain.
3) RAM: measured in [KB], it represents the minimum guaranteed availability of RAM in the network segment.
4) Storage availability: measured in [GB], it calculates the available space for data storage in the domain.
5) Trustworthiness: it is a value ranging from 0 to 1, determined by the TMS, which represents the stated and proven reliability of a network segment. It is calculated as the product of two factors: the domain's reputation and the social tier between domains, as stated in [19].

B. Conceived decision-making algorithm based on the TOPSIS methodology

The conceived algorithm, employed to determine the suitable domain for in-network processing, is summarized in the pseudo-code reported in **Algorithm 1**. It takes into account the constraints of the UAV's battery and capacity as it acquires videos during its flight. With these considerations, the procedure can compute the number of traversable domains before the UAV's battery needs to be recharged. Additionally, if there is available free storage space in the UAV, it can acquire a video from the crossed domain.

The proposed strategy exploits the TOPSIS method, which is a commonly used Multi-Criteria Decision Making approach for solving network selection problems in heterogeneous wireless networks. It computes the ideal solution by selecting the network segment that can provide an affordable Quality of Service (QoS) in terms of availability, expressed by the highest values of CPU, RAM, free storage space, and trustworthiness among the monitored domains. Then, it quantifies the closeness of each network segment to the ideal solution through the evaluation of a parameter, namely Relative Closeness (RC). In this strategy, it is assumed that the UAV stays in each network segment for approximately 10 minutes, crossing domains with extensions ranging from 500m to 1km at speeds varying from 3 km/h to 6 km/h, respectively. Consequently, the DTs' parameters are updated every 10 minutes.

Considering all the traversable domains, the implemented TOPSIS function constructs a decision matrix. Each row of the decision matrix represents a domain described by its features, including CPU, RAM, free storage space and trustworthiness. Additionally, the decision function calculates the ideal solution and assigns an RC value to each potential target domain. The calculated solutions are then ranked in descending order based on their RC values. All the domains below an empirically evaluated RC threshold are not considered for the selection. Subsequently, a communication bandwidth check is performed to verify if data can be offloaded while the UAV passes through that domain. The final domain selection is based on the following reasons:

1) The domain allows data offloading, considering the available bandwidth.
2) The domain is considered optimal and trustworthy for data offloading, based on the RC value.
3) The domain satisfies the energy and data capacity constraints.

If there are no options for data offloading, the UAV will recharge if necessary and then move on to the next network segment. The entire procedure will be repeated after data acquisition in the next crossed domain. If the selected domain no longer corresponds to the ideal solution computed before, it is updated. This ensures dynamic decision-making that promptly reacts to significant changes in the network state. Indeed, if a natural disaster takes place, the framework modules supporting the digital representation of the network will notify this event. Thus, the features representing a disrupted domain will exhibit noticeable anomalies, signaling the possible occurrence of a disaster and triggering a new selection of a suitable offloading domain.

Algorithm 1 Pseudo code of the conceived decision-making algorithm

```
for Every domain do
    check_UAV_capacity()
    n ← n_traversable_domains()
    offloading_options ← TOPSIS(n)
    if !offloading_options then
        domain ← domain + 1
        update_time()
    else
        d ← domain_bw_avail(offloading_options)
        if decision = d and id = d then
            0 ← capacity_UAV                    ▷ Data offload
            domain ← domain + 1
            update_time()
        else
            domain ← domain + 1
            update_time()
        end if
    end if
end for
```

IV. Performance Evaluation

The performance of the proposed approach is investigated through computer simulations. A MATLAB script is used to model the DTs representation of domains crossed by UAV and implement the conceived decision-making algorithm detailed in III-B.

The analyzed scenario considers eight domains, each characterized by CPU, RAM, free storage space, and trustworthiness parameters that vary throughout the day. These values are updated every 10 minutes, which is the amount of time the drone stays in each domain. The employed UAV has a 650 MB storage capacity, and while crossing domains, it acquires a 130 MB video of the specified target for monitoring services. As the drone flies over a network segment, the orchestrator runs the conceived algorithm, considering the drone's storage capacity and battery. In this regard, the battery model takes into account the documented energy consumption reported in [20].

Figure 2 illustrates an example of the dynamic domain selection. In the time slot ranging from 00:00 to 00:10, the drone flies over domain 1. Once computing the traversable domains until the drone's next battery recharge, the orchestrator runs the implemented algorithm, identifying domain 4 as the most suitable one for the task offloading. The selection is computed through the implemented TOPSIS function, which evaluates features extracted through DTs representation. Indeed, the selected domain exhibits adequate level of CPU, RAM, and trustworthiness, as highlighted in Figure 2. From 00:10 to 00:20 the drone crosses domain 2. The TOPSIS function applied to the scenario confirms that domain 4 is the most suitable one for the data offload and in-network processing. In the third phase, specifically at 00:20, a disruption occurs in domain 4 while the drone is crossing domain 3. The representation of features through DTs shows noticeable anomalies triggering the TOPSIS function to recompute the selection of the suitable domain. In that case, the choice is updated, and the domain 6 is selected as the closest one to the ideal solution. Finally, in the time slot ranging from 00:50 to 01:00, the drone flies over domain 6 and it can successfully complete the data offloading for the in-network processing.

A. Simulation Results

Finally, the performance of the conceived approach is compared with two baseline approaches. In the former, a random network segment is chosen for offloading data and processing and the obtained results are averaged over 15 seeds. In the latter, the orchestrator runs the selection algorithm through a deterministic approach only when the drone's capacity is full.

Figure 3 shows the performance of the proposed approach against baseline solutions. The considered key performance indicators for the evaluation are:

- the amount of offloaded data;
- the number of domains in which the drone misses video acquisitions since it has not found opportunities to offload the stored data and, consequently, it has no more available space;

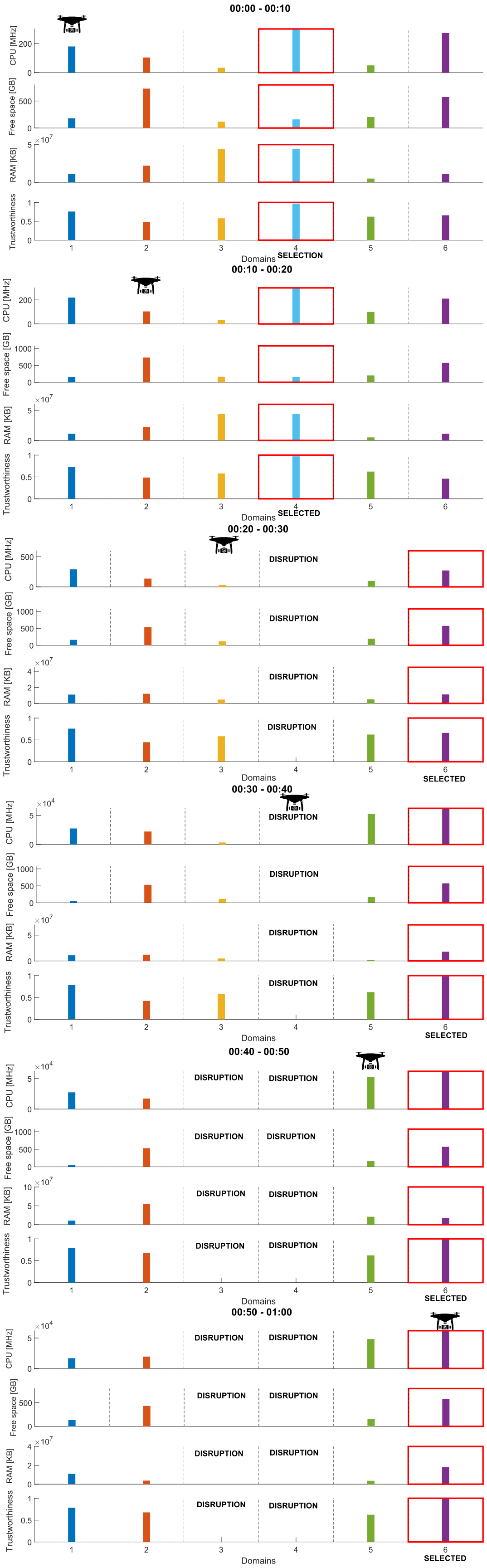

Fig. 2. Overview of the drone flight and domain selection.

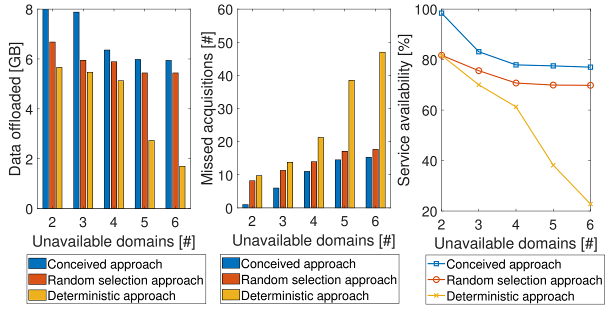

Fig. 3. Offloaded data, missed acquisitions and overall service availability for CPU SLA focus.

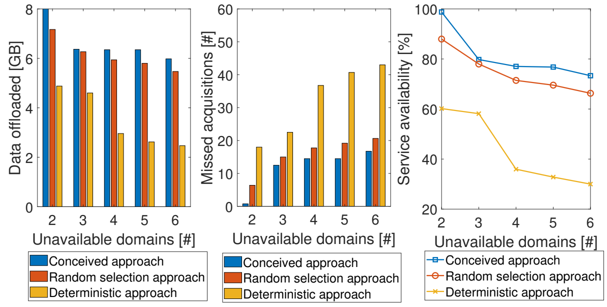

Fig. 4. Offloaded data, missed acquisitions and overall service availability for trustworthiness SLA focus.

- the overall processing availability, assessed by measuring the ratio of offloaded data to the total amount of data acquired by the drone, expressed as a percentage.

Moreover, Figure 3 highlights a use case that entails SLA requiring a high level of CPU. The graphs report the evolution of the three approaches, varying the number of unavailable domains due to disruptions (ranging from 2 to 6). Regarding the amount of data offloaded, the conceived approach outperforms the others in all situations of unavailable domains. Specifically, it allows to offload up to 2.41 GB more data with respect to the random selection approach (when 3 domains are unavailable), and up to 4.24 GB more data with respect to the deterministic approach (when 6 domains are unavailable). Regarding the number of missed video acquisitions, the conceived approach allows to miss up to 9 fewer domains with respect to the random selection approach (when 2 are unavailable), and up to 32 fewer domains with respect to the deterministic approach (when 6 are unavailable). Overall, this approach achieves a service availability of network processing up to 28.61% more if compared to the random selection approach and up to 75.61% more if compared to the deterministic one.

Figure 4, instead, shows the same performance evaluations considering SLA requiring a high level of trustworthiness. The difference in data offloaded is nearly unvaried, with about up to 3.51 GB more data when 6 domains are unavailable, compared to the deterministic approach, while up to 0.93 GB more data are offloaded when 2 domains are unavailable if compared to the random selection approach. Moreover, the number of missed video acquisitions is up to 6 less if compared to the random selection approach (when 2 domains are unavailable) and up to 27 less if compared to the deterministic approach (when 6 domains are unavailable). Last, the conceived approach achieves an availability of providing in-network processing of up to 32.38% more if compared to the random selection approach and up to 68.78% more if compared to the deterministic one.

The larger amount of data offloaded and the smaller number of missed video acquisitions, along with an overall higher service availability, confirm that the conceived approach is the most suitable solution for the in-network processing surviving natural disasters.

V. Conclusions

This work presented a lightweight approach to dynamically select, in post-disaster situations, the most suitable network segment to guarantee the in-network processing of videos acquired by a drone. Digital Twins were leveraged to identify the state and availability of physical domains. A decision-making algorithm, based on QoS and trust parameters, has been presented. Computer simulations show that the conceived approach resulted in a more reliable performance in terms of offloaded data and missed video acquisitions when the number of unavailable domains due to disruptions increases if compared to the baseline approaches. Future research activities will investigate the security aspects of the communication between network segments, particularly concerning the UAV authentication and the development of a sophisticated TMS taking into account social features.

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