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A Novel Graph-based Topology Control Cooperative Algorithm for Maximizing Throughput of Disaster Recovery Networks

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***Abstract*—Deployment of portable access points (APs) in disaster affected areas has been heralded by many contemporary researchers as a key technique to formulate disaster recovery networks. However, existing research works do not effectively address one of its key problems, i.e., the low capacity of the backbone network (constructed by the APs) which is unable to satisfy the high user demands emanating from the users in the local network of each AP. We consider cooperative communications to be a promising candidate to alleviate this problem, and formulate the trade-off relationship between the gained throughput and the network complexity. Also, we propose a novel graph-based topology control algorithm to solve the problem by exploiting cooperative communications to increase the inter-AP throughput gain. We first model the network by using a logical graph, where any two nodes are connected by a logical link if they are within the transmission range of each other. After that, k best paths, in terms of throughput gain, via mobile terminals, are found to connect any pair of APs. The constructed topology based on the resulted paths is used for cooperative communications. An in-depth analysis of the effect of the value of k on the network complexity and throughput gain is presented. Also, by introducing cooperative throughput gain speed as the utility of our proposal, we prove that there is an optimal value of k that maximizes the utility. Furthermore, extensive simulations are conducted to validate the analytical findings and demonstrate the effectiveness of our proposal.**

I. INTRODUCTION

In recent years, disaster recovery networks have attracted a great deal of attention due to the frequent occurrences of natural disasters in the world. To formulate disaster recovery networks, a myriad of approaches have been introduced in literature that include the use of advanced technologies such as satellite networks [1]–[3] and unmanned aerial vehicles (UAVs) [4], [5]. Among these approaches, many prominent researchers heralded portable access points (APs) deployment in the disaster affected areas as the most practical technique to construct disaster recovery networks for providing wireless network access to the users [6], [7]. The advantage of these portable APs consists of their ability to operate on battery power, which can be replenished by energy harvesting technology using solar panels and/or other power generation methods. In addition, a portable AP can be connected to other APs using a mesh network paradigm to extend the service coverage. The deployment of portable APs in such a fashion to construct disaster recovery networks is, however, not without its shortcoming. For instance, since the number of portable APs is likely to be limited and it is difficult to deploy many APs in the disaster area, the APs are anticipated to be generally located far from each other. As a consequence, the capacity of the backbone network constructed by the APs becomes significantly low and not sufficient to deal with the high traffic originating from the local network of each AP.

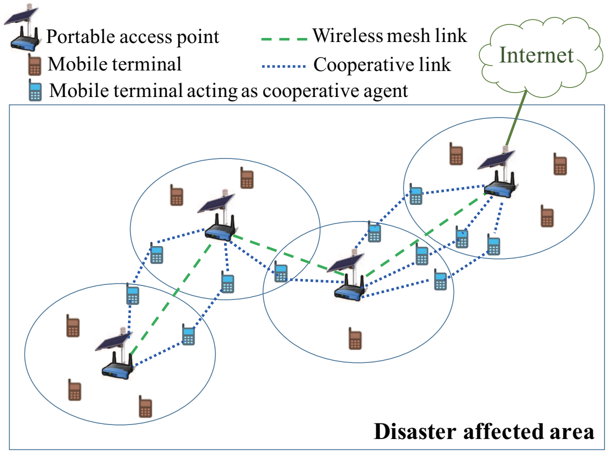

Fig. 1. Considered disaster recovery network constructed by portable APs and mobile terminals. Cooperative links connecting APs via mobile terminals, which also act as cooperative agents, are used to improve the throughput of inter-AP links.

On the other hand, cooperative communications have a noticeable feature in improving the network performance by exploiting each network node as both user and relay [8]–[10]. Therefore, in this work, we aim to utilize cooperative communications to improve the performance of the disaster recovery network. The considered network, as illustrated in Fig. 1, consists of portable APs and mobile terminals. Some mobile terminals can act as both user devices and cooperative agents that relay packets from an AP to another AP to achieve throughput gain of the connection between the two APs. However, if an excessive number of cooperative agents is used, it will lead to a significantly high network complexity. On the contrary, when only a few cooperative agents are used, the gained throughput may not be sufficient. Therefore, the problem in this trade-off relationship between the gained throughput and the network complexity needs to be solved.

In this work, we propose a novel graph-based topology control cooperative algorithm, that optimally decides the number of cooperative agents in order to maximize the throughput gain while guaranteeing the network complexity. The network is modeled by using a logical graph, where any two nodes, i.e., any AP or mobile terminal, are connected by a logical link if they are within the transmission range of each other. On the constructed logical graph, we find k best non-overlapping paths, in terms of throughput gain, via the cooperative agents, to connect any pair of APs. The topology constructed by the resulted paths is used for cooperative communications. We provide an analysis on the relationship between the value of k and the two main metrics, network complexity and throughput gain. Also, a metric named cooperative throughput gain speed serves as the utility in this work. Our analysis proves that there is an optimal value of k that maximizes the utility. Furthermore, extensive simulations are conducted to corroborate the analytical findings. Simulation results also demonstrate the effectiveness of our proposal.

The remainder of our paper is organized as follows. In Section II, we describe the motivation of this work and the challenges. Section III introduces our network model and the metrics to evaluate network performance. In Section IV, we describe our proposed topology control algorithm. The analysis of the trade-off relationship between the network complexity and the gained throughput is presented in Section V. We present the performance evaluation in Section VI. Finally, the paper is concluded in Section VII.

II. COOPERATIVE COMMUNICATIONS BASED DISASTER RECOVERY NETWORK: MOTIVATION AND CHALLENGES

In this section, we present our motivation for using cooperative communications in disaster recovery networks and discuss its challenges that need to be overcome.

A. Motivation

In disaster affected areas, if the cellular base stations are still remained, network service provisioning can be extended by using the device to device approaches such as in [11], which proposes an innovative resource allocation scheme by introducing the device freedom to multiplex multiple D2D and cellular users for increasing the spectrum efficiency. In contrast, when there is no infrastructure operating, deploying portable APs should be a more practical option. However, the previous works related to deploying portable APs mainly focus on accommodation and coverage [6], [7]. Even though the capacity in the local network of each AP is usually higher than the capacity of the connections between APs and the bottlenecks tend to occur at inter-AP links, the methods to gain the throughput of inter-AP links have not received desired attention. In a disaster affected area, the inter-AP links become even more important due to the fact that only few APs that are located next to the outside area may have connectivity to the outside world. This serves as our motivation to consider exploiting cooperative communications to improve the throughput of the inter-AP links. In order to do that, the mobile terminals are considered to be capable of acting as both users and cooperative agents that relay packets from an AP to another AP.

B. Challenges

In this work, we focus on improving network throughput and attempt to define the trade-off relationship between the gained throughput of inter-AP links and the network complexity. The throughput gained by exploiting cooperative communications is related to the number of cooperative agents used in the network. The higher the number of cooperative agents, the better the gained throughput. On the other hand, the network complexity is inversely related to the number of agents. The higher the number of cooperative agents, the worse the complexity. Therefore, finding the optimal number of cooperative agents for each inter-AP link constitutes the main challenge of our work that we deal with in the following sections.

III. NETWORK MODEL AND METRICS

Before delving into detail of our solution, it is important to discuss our considered network model and metrics. In this section, we first present how the network is modeled. Then, we introduce the metrics that are relevant to evaluating the effectiveness of the envisioned solution.

A. Network Model

To model the considered network, we define a graph $G(V, E)$, where V is the set of nodes, i.e., either AP or mobile terminal, and E is the set of links connecting the nodes. In this paper, we use an index number i to represent the node i and a pair (i, j) to represent the link connecting nodes i and j.

1) Cooperative Agent Availability: In order to relay traffic between two APs, a mobile terminal needs to be at the middle of the APs. However, due to its random mobility, there is a likelihood that the mobile terminal will move out of range of at least one AP, and hence cannot be the cooperative agent. We define the cooperative agent availability of node i, ρ_i, as the probability that the node i is available to be a cooperative agent between two given APs during a given time period. The probability ρ_i is considered to be related with the moving speed. Nodes with high moving speeds will easily move out of the APs' transmission ranges, and thus have low cooperative agent availability.

2) Path: A path p_{sd} from node s to node d is defined as a list of nodes $n_1, n_2, ..., n_l$ where $n_1 = s$, $n_l = d$, and $(n_i, n_{i+1}) \in E$ with any i that satisfies $1 \leq i < l$. We denote $\mathcal{A}$ as the set of all portable APs. The set of all paths between any two APs, $\mathcal{P}$, is calculated as follows:

$$\mathcal{P} = \{p_{sd} : s \in \mathcal{A}, d \in \mathcal{A}\}. \quad (1)$$

B. Metrics

In order to evaluate the performance of the considered disaster recovery network, we introduce the following metrics.

1) Cooperative Throughput Gain: We introduce the cooperative throughput gain of the connection between two APs s and d, $\mathcal{T}_{sd}$, as the throughput gained by using cooperative agents between them.

$$\mathcal{T}_{sd} = \sum_{p_{sd} \in \mathcal{P}} \left(\left(\min_{i \in p_{sd}} t_i \right) \times \prod_{i \in p_{sd}} \rho_i \right), \quad (2)$$

Procedure 1 Preliminary Phase

Input: Locations of APs and mobile terminals, mobile terminals' moving speed.

Output: $G(V, E)$.

```
V ← ∅
E ← ∅
for any node i in the network do
    V ← V ∪ i
    range(i) ← transmission range of node i
    if node i is mobile terminal then
        ρ_i is calculated by using the method in [12]
    end if
end for
for any pair of nodes i and j do
    if d_ij < range(i) and d_ij < range(j) then
        E ← E ∪ (i, j)
    end if
end for
return G(V, E)
```

where t_i is the throughput gain that node i can provide when it becomes a cooperative agent.

2) Cooperative Computation Time: This metric is used to evaluate the network complexity. The computation time needed to carry out the cooperative communications between two APs s and d, Δ_{sd}, is calculated as follows:

$$\Delta_{sd} = \delta_0 + \sum_{p_{sd} \in \mathcal{P}} \left(\delta_0^t + \delta_0^r + \sum_{i \in p_{sd}} \delta_i \right), \tag{3}$$

where δ_0 is the basic computation time of using cooperative communications; δ_0^t and δ_0^r are the additional computation times needed for an AP to transmit and receive data, respectively, if a path is added between the two APs; and δ_i is the time needed to relay data via the cooperative agent i.

3) Cooperative Throughput Gain Speed: Let $\mathcal{T}$ and Δ denote the total cooperative throughput gain and the total cooperative computation time of the network, respectively. The cooperative throughput gain speed, $\mathcal{S}$, is calculated as follows:

$$\mathcal{S} = \frac{\mathcal{T}}{\Delta}. \tag{4}$$

We consider (4) to be the utility function in this work.

IV. PROPOSED TOPOLOGY CONTROL ALGORITHM EXPLOITING COOPERATIVE COMMUNICATIONS IN DISASTER RECOVERY NETWORKS

In this section, we propose a novel topology control algorithm exploiting cooperative communications. Our proposed algorithm comprises three phases. In the preliminary phase, the graph-based network model is constructed. In the second phase, the backbone network is formed by portable APs and the direct links connecting them. In the final phase, topology formation for cooperative communications is carried out for each pair of APs (connected by a direct link) by finding suitable cooperative agents to connect the APs via cooperative links. In the remainder of the section, these three phases are discussed in detail.

Procedure 2 Topology Formation for Cooperative Communications Network

Input: $G(V, E)$, $\mathcal{B}(\hat{V}, \hat{E})$, and k.

Output: Cooperative communications network, $G^*(V^*, E^*)$.

```
V* ← V̂
E* ← ∅
for each (m, n) ∈ B do
    G′(V′, E′) ← G(V, E)
    for i ← 1 to k do
        Find the ith best path p^i_mn in G′(V′, E′)
        V′ ← V′ \ {j : j ∈ V′, j ∈ p^i_mn}
        V* ← V* ∪ {j : j ∈ V′, j ∈ p^i_mn}
        E′ ← E′ \ {(h, g) : (h, g) ∈ p^i_mn}
        E* ← E* ∪ {(h, g) : (h, g) ∈ p^i_mn}
    end for
end for
return G*(V*, E*)
```

A. Preliminary Phase

In this phase, we model the considered disaster recovery network by using a graph $G(V, E)$, where V is the set of all APs and mobile terminals. The set of links E consists of all logical links between nodes. A logical link between two nodes exists if the distance between them is less than the transmission range of each other. In this phase, the probability that a mobile terminal can be a cooperative agent to connect two APs is calculated based on the method introduced in [12], which uses the node moving speed to calculate the probability that a node moves out of the transmission range of another node. The detail of this phase is presented in Procedure 1.

B. Backbone Network Formation

This phase is to find the topology of the backbone network constructed by only APs. In many cases, the topology can be manually derived because the APs are deployed in the area and the locations of the APs are fixed. However, the topology can be also dynamically formed, which is beyond the scope of our current work. The resultant topology of the backbone network is denoted as $\mathcal{B}(\hat{V}, \hat{E})$.

C. Topology Formation for Cooperative Communications

This phase is based on the graph resulted in the preliminary phase and the topology of the backbone network derived in the backbone network formation phase. From the preliminary phase, we know all the nodes of the graph-based network model. On the other hand, from the topology of the backbone network, we know the pairs of APs that are connected by direct links. Based on the information of inter-AP links achieved from the backbone network, the cooperative agents are decided based on Procedure 2. The idea of this procedure is that for each pair of APs m and n that has a direct link connecting the two APs, k best non-overlapping paths, in terms of throughput gain, from m to n via mobile terminals are calculated. Nodes and links of the resulted paths together with the APs are used to form the topology of the cooperative communications network.

V. ANALYSIS ON THE OPTIMALITY OF k

In this section, we analyze the relationship between k and the metrics introduced in Section III-B. Based on the analysis, we discuss the existence of the optimal value of k that maximizes the performance of the proposal.

A. Cooperative Throughput Gain versus k

Lemma 1: Given a network $G(V,E)$ and the value of k, $G^*(V^*,E^*)$ is the resultant topology by applying Procedure 2 on $G(V,E)$. The total cooperative throughput gain calculated on $G^*(E^*,V^*)$ monotonically increases along with the increase of k.

Proof: Based on (2), the total cooperative throughput gain of the network, $\mathcal{T}$, is calculated as follows:

$$\mathcal{T} = \sum_{(s,d)\in\mathcal{B}} \mathcal{T}_{sd} \tag{5}$$

$$= \sum_{(s,d)\in\mathcal{B}} \sum_{i=1}^{k} \left(\left(\min_{j\in p^i_{sd}} t_j \right) \times \prod_{j\in p^i_{sd}} \rho_j \right), \tag{6}$$

where p^i_{sd} is the ith path connecting AP s with AP d. Since $0 \leq \rho_j \leq 1$ and $t_j > 0$, from (6) we can see that when k increases, $\mathcal{T}$ monotonically increases. ■

B. Cooperative Computation Time versus k

Lemma 2: Given a network $G(V,E)$ and the value of k, $G^*(V^*,E^*)$ is the resultant topology by applying Procedure 2 on $G(V,E)$. The total cooperative computation time calculated on $G^*(E^*,V^*)$ monotonically increases along with the increase of k.

Proof: The total cooperative computation time, Δ, is calculated based on (3) as follows:

$$\Delta = \sum_{(s,d)\in\mathcal{B}} \Delta_{sd} \tag{7}$$

$$= \sum_{(s,d)\in\mathcal{B}} \left(\delta_0 + \sum_{i=1}^{k} \left(\delta_0^t + \delta_0^r + \sum_{j\in p^i_{sd}} \delta_j \right) \right). \tag{8}$$

This equation proves that when k increases, Δ monotonically increases because δ_0, δ_0^t, δ_0^r, and δ_j are greater than 0. ■

C. Optimality of k

Let k_{max} be the value such that even if we make k greater than that, no more link is added to E^* in Procedure 2. Therefore, the value of k in Procedure 2 needs to satisfy $(1 \leq k \leq k_{max})$. As proved above, when k increases, both $\mathcal{T}$ and Δ monotonically increases. Therefore, based on (4), for each network scenario, there will be a value of k between 1 and k_{max} that maximizes the cooperative throughput gain speed, $\mathcal{S}$, which is considered as the utility. That value of k is the optimal value.

TABLE I
SIMULATION SETTINGS

Parameter	**Value**
Simulation area	500m × 500m
Number of APs	25
Number of mobile terminals	200, 500, 1000
ρ_i of mobile terminal i	0.0 - 1.0
Throughput that cooperative agent i (t_i) can share	1000 - 1500 [kb/s]
Transmission range of cooperative agents	65 [m]
Number of different scenarios	1000
δ_0	1.0 [s]
δ_0^t and δ_0^r	0.2 [s]
δ_i for any cooperative agent i	0.1 [s]

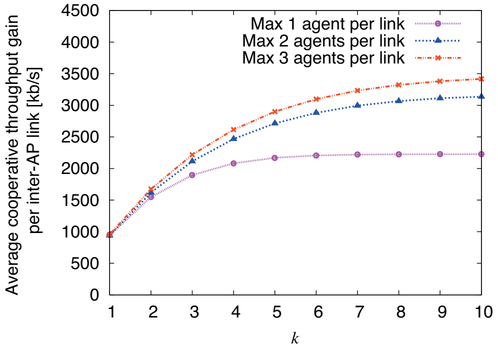

Fig. 2. k versus the average throughput gain per inter-AP link.

VI. PERFORMANCE EVALUATION

In order to validate the analytical findings and evaluate the performance of our proposed algorithm, we conduct extensive computer-based simulations. In this section, we present the settings of the simulations and the performance evaluation results.

A. Simulation Settings

The simulation settings are summarized in Table I. In an area of 500m×500m, 25 portable APs are deployed. The number of mobile terminals randomly deployed in the area is set to either 200, 500, or 1000. To simplify the relationship between the moving speed of mobile terminals and their availability to be cooperative agents, we randomly assign each mobile terminal i a value of ρ_i from 0 to 1. Each cooperative agent has a transmission range of 65m. The maximum number of agents per inter-AP link can be 1, 2, or 3. Each simulation is conducted with 1000 different scenarios generated randomly. Average values are used as result.

B. The Relationship Between Throughput Gain and k

Fig. 2 demonstrates the average expected throughput gain per inter-AP link when k changes. This metric takes into account both the probability that a mobile terminal is available to be a cooperative agent and the throughput it can share. The simulation results demonstrate that when k increases, the throughput gain for each inter-AP link also increases. Furthermore, the simulation is run with different maximum numbers of agents per inter-AP link, and the results elucidate that when we use multi-hop paradigm for cooperative agents, the throughput gain increases more rapidly.

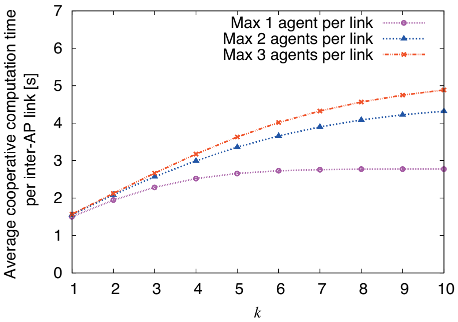

Fig. 3. k versus the average computation time per inter-AP link.

C. The Relationship Between Network Complexity and k

As mentioned in Section III-B, network complexity is evaluated by using Δ, the cooperative computation time. Fig. 3 demonstrates the computation time needed to carry out the cooperative communications. The results validate that when k increases, the cooperative computation time increases, and thus, the network complexity also increases.

D. The Relationship Between the Cooperative Throughput Gain Speed and k

Fig. 4 demonstrates the relationship between k and the utility, cooperative throughput gain speed. In this experiment, up to 2 agents are used for each inter-AP link. The figure shows that even though different network scenarios might lead to different results, there always exists an optimal value of k that maximizes the utility. In the generated scenarios, the optimal value of k is 3, 4, and 5 when the number of mobile terminals is 200, 500, and 1000, respectively.

These results prove that the trade-off relationship between throughput gain and complexity of the network can be optimized by finding the value of k that maximizes the cooperative throughput gain speed. From the optimal value of k, we can estimate the number of cooperative agents that should be used to improve the capacity of the backbone network.

VII. CONCLUSION

In this paper, we considered a disaster recovery network based on deploying portable APs in the disaster affected area. We addressed the problem that the low capacity in the backbone network constructed by APs cannot satisfy the high demand from the users in the AP local networks. Our proposed method utilizes cooperative communications to gain the throughput of inter-AP links. The proposal constructs the topology by finding k best non-overlapping paths, in terms of cooperative throughput gain speed, via cooperative agents to connect any pair of APs. We provided an analysis on the effect of k on throughput gain, network complexity, and the throughput gain speed, which is considered as the utility. We also proved that there is a value of k that maximizes the utility, and thus, optimizes the trade-off relationship between throughput gain and network complexity. Furthermore, we conducted extensive simulations to validate the analytical findings. The simulation results demonstrated that the proposed algorithm can help to maximize the throughput gain while maintaining the network complexity within a reasonable level.

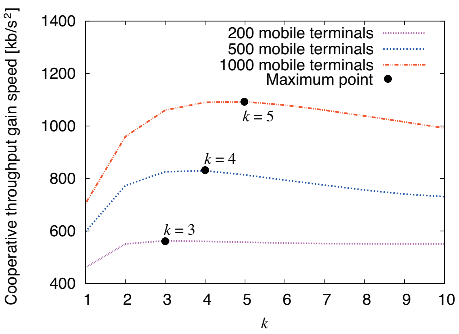

Fig. 4. k versus the cooperative throughput gain speed.

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