Population-Aware Relay Placement for Wireless Multi-Hop Based Network Disaster Recovery

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***Abstract*—Network recovery is one of the greatest concerns for Mobile Network Operators (MNOs) and first responders during large-scale natural disasters such as earthquakes. Wireless multi-hop relaying has been a promising technique to quickly and efficiently recover the network coverage in these scenarios. In this paper, we address the relay placement problem in such multi-hop networks that how to optimally deploy limited relays to extend network coverage as much as possible to most of the population after a disaster occurs. Given the hardness of this problem, our proposed solution is constructed in two steps. In specific, we first determine the *Steiner locations*, where the relays could be shared by more than two nodes. Then, we provide an integer programming based formulation and solve it by exploring the similarity of existing algorithm of classic Prize-Collecting Steiner Tree (PCST) problem. To evaluate the proposed solution extensively, we present numerical results on both real-world and random scenarios, which confirm the performance of proposed solution outperforms the existing one.**

I. INTRODUCTION

During natural disasters, timely and smooth communication between governments, communities and humanitarian organizations is essential for disaster relief [1]. Mobile communications is supposed to play an important role in such disaster situations as it has become the most convenient and common way for communication in our modern life. However, because of damages on the telecommunication infrastructures during disasters, the disruption of mobile networks may spread to a large geographical area and continued for a relatively long period of time, further magnifying chaos and hampering the rescue and disaster recovery processes in the affected area.

Since the repair of the damaged network infrastructure usually takes weeks or even months, fast and efficient emergency network recovery technologies are urgently needed in the first several days, which are the most critical time period for disaster relief. To this end, multi-hop wireless relaying has been proposed as an appealing technique to deal with disruption of communications during disasters for fast network recovery without or with less network infrastructure involved.

The studies [2]–[4] consider using users' mobile devices to build a multi-hop wireless network, which can rapidly extend the network coverage to a large disaster-affected area without network infrastructure. However, they do not consider a practical scenario that there are naturally occurring groups of survivors gathered at shelters, or evacuation sites in the aftermath of a disaster [5]. For example, in the most recent case of 2016 Kumamoto earthquake, it was reported that over 100,000 people had to evacuate away from their homes to different shelter facilities, e.g. local community centers or schools [6]. The shelters are supposed to be safe in terms of food, water and other necessities to support living for a certain time period but large part of them probably get disconnected due to the aforementioned damages of communication infrastructure. The study [7] has investigated the problem of multi-hop relaying in such a scenario at central Tokyo area, and demonstrates that a multi-hop relay network that purely consists of user mobile devices is not efficient to recovery the network coverage to those shelters. Based on the above key observation, it is difficult to have a reliable network connection to interconnect shelters purely rely on user devices due to sparse distribution and high mobility of population outside shelters.

The study [7] also identified that the performance can be greatly improved if some dedicated fixed relays can be deployed between shelters and still-alive base stations (BSs). In fact, from the point of view of mobile network operators (MNOs), it is quite promising to build a fast disaster recovery network based on a similar concept of multi-hop relaying. In study [8], a prototype of Movable and Deployable Resource Unit (MDRU) is experimented to quickly re-construct the network infrastructure in a disaster area with a vehicle-mounted base station and many dedicated low-cost wireless relays. The field test in this study shows that it can provide satisfying network coverage to a large area for a certain period of time. In addition, this technology can be complemented with user device based multi-hop relaying technique in static and high populated areas such as shelters. Therefore, in the scenario of wireless multi-hop based network disaster recovery, a naturally raised challenge is, how to properly deploy a limited number of relays to recover the mobile network services to the shelters where most of the people are gathered.

Relay placement has been an active research topic in wireless multi-hop networking in the past few decades. A lot of researches have been done in the context of wireless sensor networks [9]–[13]. The study [9] surveys various node placement problems as effective optimization means in designing wireless sensor networks (WSNs) for achieving the desired performance goals, such as throughput, latency, and data integrity while coping with the computation, energy and communication constraints. The study [10] investigates the minimal relay node placement when sensor and relay nodes have different communication ranges. The study [11] further investigates the fault-tolerant relay node placement to maintain certain coverage with minimal relay nodes. There are also a few other studies on relay node placement for performance enhancement in mobile networks. For example, the study [14] investigates the relay placement problem that deploys the minimum number of relays to meet system requirements such as user data rate requests, signal quality and network topology. However, all these relay placement solutions are optimized for the specific requirements of their focused scenarios, which can not be easily applied to the scenario of network disaster recovery.

In this paper, we focus on the relay placement problem for the wireless multi-hop based network disaster recovery, where the mobile network infrastructure (i.e. BSs) are partially damaged. The placement of limited number of relays can be optimized to extend the coverage of still-alive BSs to shelters in term of maximizing total recovered population. In our previous work [15], we formulated this problem directly as a Prize-Collecting Steiner Tree (PCST) problem on a complete graph consisting of BSs and shelters, and an approximation solution is thus adopted to achieve population-aware cost-efficient network recovery. However, in the previous work, the relays are only considered to be placed on the straight lines connecting shelters or BSs, which does not consider the sharing of relays for more nodes at any locations in order to reduce the number of required relays. In addition, PCST problem does not explicitly consider the relay constraint, it is not clear in previous work that how to properly set parameters for the bisection search processes, which would lead to a lower performance and higher time complexity. In order to overcome these shortcomings, we provide a clear and complete formulation of this problem based on an improved graph model in this paper. The contributions are summarized as follows.

- We formulate the problem based on the graph model incorporating the potential shared relay locations, which gives us a better solution than previous work.
- We present a clear and complete formulation of the studied problem, which provides more insight on how to properly determined the parameters for bisection search and thus maintains an acceptable running time.
- We evaluate our solution both in the real-world and random scenarios, which provides comprehensive results on the performance of proposed solution.

The remainder of this paper is organized as follows. We introduce the considered scenario of multi-hop based network disaster recovery and define the relay placement problem in Section II. In Section III, an improved solution is presented by incorporating shared relays and properly selected parameters. Simulation results are provided in Section IV, which is followed by the conclusion of this study in Section V.

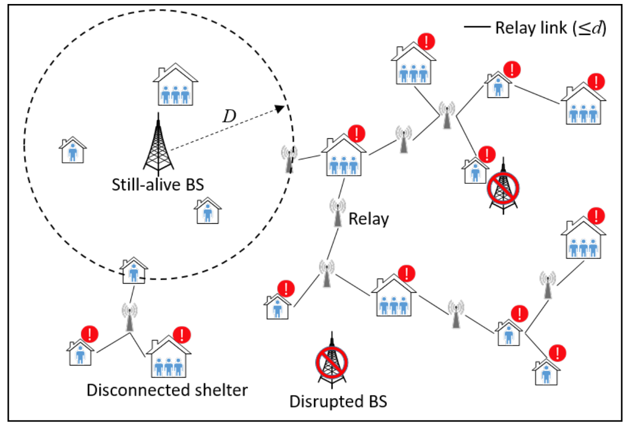


Fig. 1: A wireless multi-hop based network disaster recovery.

II. Network Model and Problem Statement

In this section, we first introduce the considered scenario of wireless multi-hop based network disaster recovery. Based on it, we then define the relay placement problem accordingly.

A. Wireless Multi-hop Based Network Disaster Recovery

In a post-disaster scenario, there are many geographically distributed shelters such as schools and community facilities, where people are tend to be gathered after the disaster occurs, and some surviving BSs which are still in service but can only cover a few of shelters in the whole affected area. In this case, the MNOs or first responders try to deploy limited number of mobile base stations and relays to extend the network coverage as much as possible to those disconnected people gathered at shelters, which is illustrated in Fig. 1. It is also observed that the shelters vary dramatically in terms of population capacity and density. For instance, in Tokyo area, the capacity vary from 18 people to 43,900 people, and the distance between two nearest shelters ranges from $50m$ to $26,000m$ [16]. Note that the mobile base stations are very limited in number, and mostly deployed near the sites of damaged BSs for the sake of facilities reuse, thus we neglect the placement issue of mobile BSs in this paper. Without loss of generality, the surviving BSs and mobile BSs are homogeneously interpreted as still-alive BSs in the considered network disaster recovery scenario. Contrary to mobile BSs, the relays are low-cost and with much smaller size, which can be deployed arbitrarily. For instance, in [8], a movable Wi-Fi relay module is just as small as a suitcase. Therefore, in such scenario, the relay placement can be optimized to maximize the population coverage. We denote the set of disconnected shelters as $S = \{s_1, s_2, \cdots, s_N\}$, and their corresponding population capacity as $P = \{p_1, p_2, \cdots, p_N\}$, where $N = |S|$. The set of still-alive BSs is denoted as $B = \{b_1, b_2, \cdots, b_M\}$, where $M = |B|$. According to the field test in [8], we consider all links from/to BSs are using cellular radio access interface, whose communication range is denoted as D, while the rest links, i.e. relay to relay and relay to shelter, are all using short range radio such as WiFi, whose communication range is denoted as d, where $D > d$.

B. Problem Statement

Previous studies [7], [17] compares different relay placement strategies that minimize the number of relays while cover all shelters. However, in practice, the MNOs or first responders are usually face a problem that how to recover the service coverage as much as possible with limited relays resources. Therefore, the accommodated population of shelters and budget of relays should be taken into account in the relay placement problem, which are largely neglected in the previous studies. We attempt to address these issues in this research, and we formally define our problem as follows:

Definition 1. (Population-Aware Relay Placement (PARP) Problem) Given a multi-hop disaster recovery network with a set B of still-alive BSs, a set S of disconnected shelters with corresponding population P. The communication ranges of BS and the other nodes are restricted within D and d, respectively. A set R of K relay nodes is placed to connect the shelters to BSs. The goal of this problem is to find an optimal placement of relays, i.e. set R, such that the total population of connected shelters is maximized.

III. Solution for PARP problem

To find an optimal solution of PARP problem is not straightforward. Hence, we consider a similar problem, i.e. Single-Tiered Relay Placement with BSs (RPwB), which is first defined in the context of sensor networks [13]. In the RPwB problem, there are a set of sensors, a set of BSs, and the communication ranges of sensor and relay are within certain distances respectively. It seeks to connect all the sensors such that the required relays are minimized. Let R^*_{opt} be the optimal solution of PRwB problem, we can easily see that R^*_{opt} is always a feasible solution for PARP problem when $K \geq \left|R^*_{opt}\right|$. This implies that the RPwB problem is actually a special case of PARP problem. Therefore, our PARP problem is NP-hard as the RPwB problem is known to be NP-hard. Given the hardness of the problem, it is not practical to find a polynomial time optimal solution for PARP problem unless $P = NP$ [18]. For the PARP problem, the biggest challenge is the placement of a relay that could connect three or more nodes. We call such kind of locations as *Steiner locations*. Therefore, to solve the PARP problem efficiently, we propose a solution with two steps. We firstly try to determine the *Steiner locations* in advance. Then, based on a graph constructed with such *Steiner locations*, we focus on placing limited number of relays to connect shelters that maximizes the total population coverage. We explain each step in detail in the following subsections.

A. Step I: Steiner Locations Determination

In this step, we consider to determine the *Steiner locations*, at which a single relay will be more likely deployed to connect three or more nodes. In fact, we could directly use the algorithm for RPwB problem to find these possible

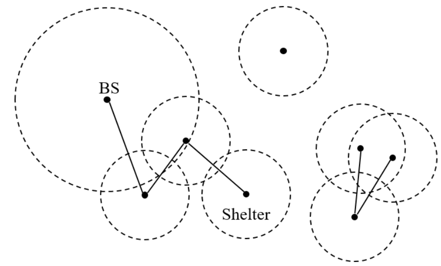


Fig. 2: An illustrative example of constructed disk graph.

Steiner locations as well as other relay locations. However, fixing all potential relay locations could result in a lower performance in the final results. The basic idea of the algorithm determining *Steiner locations* is based on the following observations. First, to connect an isolated shelter, it is obvious that a relay needs to be deployed on a range disk centered at the shelter with radius d. Second, for any two or more nodes, if their range disks all intersect with each other, then they can be connected by one relay in the intersected area. We denote the set of these nodes as a *cluster*, and a shelter could be belonging to multiple clusters. Third, there is no extra benefit for a shelter to be connected with multiple BSs in terms of reducing number of relays and maximizing connected shelters, which means the optimal solution should be multiple independent trees that are rooted at each BS. Based on above observations, to determine the *Steiner locations*, we can construct a disk graph $G_d = (V_d, E_d)$, where vertices are consists of all shelters and a virtual BS such that $V_d = S \bigcup \{b\}$, where all still-alive BSs are equivalently treated as one virtual BS b according to the third observation. As a result, the Euclidean distance from a shelter to the virtual BS corresponds to the distance to its nearest BS. An edge between any two vertices $u, v \in V$ only exists if their range disks are intersect with each other and u, v are both outside of the disk intersected area as shown in Fig. 2. In other words, an edge exists if any two shelters need only one relay placed at the intersected area for connection. Based on the above analysis, we present a simple algorithm to determine the *Steiner locations* in Algorithm 1.

Depending on the geometric relationship of intersections and area formed by the edges in a cluster, there are three different cases we need to consider to find the *Steiner locations*. We use examples in Fig. 3 to illustrate our algorithm. We assume the locations of shelters are given as (x_i, y_i), where $1 \leq i \leq 5$ as the maximum number of intersected disks are 5 in a planar space [13]. The *Steiner locations* are denoted as (x, y), which is computed as follows.

CASE I: The cluster consists of two intersected disks. The *Steiner locations* are selected at the two points that the circles are crossed, which is shown as red square dots in Fig. 3a, and can be calculated as

$$\begin{cases} x = \frac{x_1+x_2}{2} \pm \sqrt{\frac{d^2-((x_1-x_2)/2)^2-((y_1-y_2)/2)^2}{1+(\frac{x_1-x_2}{y_2-y_1})^2}} \\ y = \frac{y_1+y_2}{2} \pm \sqrt{\frac{d^2-((x_1-x_2)/2)^2-((y_1-y_2)/2)^2}{1+(\frac{y_1-y_2}{x_2-x_1})^2}} \end{cases} \quad (1)$$

Algorithm 1 Steiner Location Determination (S, B)

Construct sets $R_s, V', R_s \leftarrow \emptyset, V' \leftarrow \emptyset$;
Construct the disk graph $G_d = (V_d, E_d)$;
for each edge e **do**
  for each cluster V' containing edge e **do**
    if V' is marked **then**
      break
    end if
    Mark V' as a considered cluster;
    if $|V'| = 2$ **then**
      Choose the locations r_s according to Eq. (1);
    else if $|V'| = 3$ & $d^* \le d$ **then**
      Choose the location r_s according to Eq. (2);
    else if $|V'| = 3$ & $d^* > d$ or $|V'| > 3$ **then**
      Choose the location r_s according to Eq. (3);
    end if
    $R_s = R_s \bigcup \{r_s\}$;
  end for
end for
return Steiner location set R_s.

where the plus-minus sign is obtained reversely in cases $(x_1 > x_2, y_1 > y_2)$ and $(x_1 < x_2, y_1 < y_2)$.

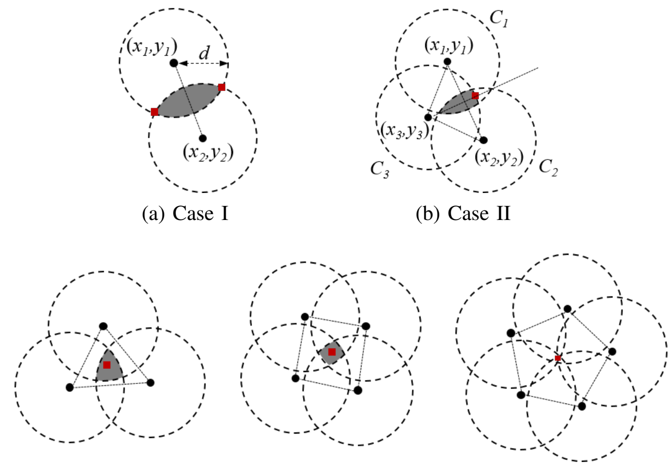
CASE II: The cluster consists of three intersected disks and the intersection area are partially outside the triangle area that three nodes formed, which is depicted in Fig. 3b. Assume the longest edge is between (x_1, y_1) and (x_2, y_2), and let d^* denote the distance between node (x_3, y_3) and the longest edge. Therefore, we can identify this case if $d^* = \frac{|(y_2-y_1)x_3+(x_1-x_2)y_3+x_2y_1-x_1y_2|}{\sqrt{(y_2-y_1)^2+(x_1-x_2)^2}} \le d$. In this case, the Steiner location is selected at the cross point of circle C_3 and the line that determined by points (x_3, y_3) and $(\frac{x_1+x_2}{2}, \frac{y_1+y_2}{2})$, which is located at the edge of intersection areas as well. The location can be calculated as

$$\begin{cases} x = x_3 \pm \dfrac{d}{\sqrt{1+(\frac{\frac{y_1+y_2}{2}-y_3}{\frac{x_1+x_2}{2}-x_3})^2}}, & \text{'+' if} \frac{x_1+x_2}{2} > x_3 \\ y = y_3 \pm \dfrac{d}{\sqrt{1+(\frac{\frac{x_1+x_2}{2}-x_3}{\frac{y_1+y_2}{2}-y_3})^2}}, & \text{'+' if} \frac{y_1+y_2}{2} > y_3 \end{cases} \tag{2}$$

CASE III: The cluster consists of three or more intersected disks and the intersection area are within the area that the edges formed, which is depicted in Fig. 3c. In this case, the Steiner location is determined at the middle point of these nodes, and can be calculated as

$$\begin{cases} x = \frac{x_1+\cdots+x_I}{I} \\ y = \frac{y_1+\cdots+y_I}{I} \end{cases} \tag{3}$$

Note that in cases I and II, we intentionally select the *Steiner locations* as far as possible from the shelters. It is because that these locations are most likely to be used by the nodes outside the cluster. If we want to connect a cluster, we always connect the nearest node in the cluster. If a Steiner location is determined inside the area of edges, this location is less likely to be connected with relays from outside nodes. In the next, with these *Steiner locations*, we consider how to solve PARP problem that connects population as much as possible with a budge on number of relays.



(a) Case I (b) Case II

(c) Case III

Fig. 3: Illustration of *Steiner locations* in three different cases

B. Step II: Integer Programming Formulation for PARP

In the second step, with predetermined *Steiner locations* R_s, we are ready to solve the PARP problem by constructing a undirected graph $G = (V, E, P)$, where vertices are $V = S \bigcup R_s \bigcup \{b\}$ and have non-negative penalty P that are population for shelter nodes and 0 for the other nodes. The edges exist as a complete graph except that the edges in clusters are replaced with edges via *Steiner locations*. A non-negative cost c_e for edge $e \in E$ is defined as the minimum number of relays it required for connection, which means if the edge is chosen in the final solution, the corresponding number of relays will be evenly deployed on this edge. For any two vertices $u, v \in V$, it can be calculated as

$$c_e(u,v) = \begin{cases} 0, & \text{if } \|u,v\| \le d \\ \lceil \frac{\|u,v\|}{d} \rceil - 1, & \text{if } \|u,v\| > d, \text{and } u,v \in S \\ \lceil \frac{\|u,v\|-D}{d} \rceil - 1, & \text{if } u = b \text{ or } v = b \end{cases} \tag{4}$$

Based on the constructed graph G, the goal of PARP problem is to find a vertex set $C \subseteq V \backslash \{b\}$ and a tree $T \subseteq E$ rooted at the virtual BS b. The tree T spans the vertices of $V \backslash C$ so as to minimize the weights of the vertices in C. For a feasible solution, vertex set C is the nodes that not connected, and tree T is where the relays are deployed. Maximizing the total population coverage is equivalent to minimizing the weights of unspanned vertices within the relay budget, therefore, the problem can be formulated as the following integer programming as

$$minimize \sum_{C \subseteq V \backslash \{b\}} w(C) z_C \tag{5a}$$

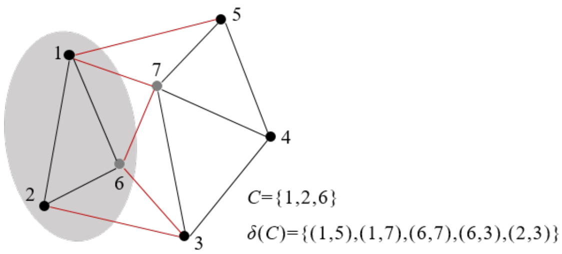


Fig. 4: An illustrative example of cut-set.

subject to:

$$\sum_{e \in E} c_e x_e \le K - N_s, \qquad \forall e \in E \tag{5b}$$

$$\sum_{e \in \delta(C)} x_e + \sum_{U: U \supseteq C} z_U \ge 1, \qquad \forall C \subseteq V \backslash \{b\} \tag{5c}$$

$$x_e \in \{0, 1\}, \qquad \forall e \in E \tag{5d}$$

$$z_C \in \{0, 1\}, \qquad \forall C \subseteq V \backslash \{b\} \tag{5e}$$

where $w(C) = \sum_{i \in C} w_i$ is the total weights of vertex set C, $N_s = |V(T) \cap R_s|$ is the number of *Steiner locations* included in T, $\delta(C)$ is the cut-set of C, i.e. the set of edges with exactly one endpoint in C. A simple example for the relationship of vertex set C and the corresponding edge cut-set $\delta(C)$ is illustrated in Fig. 4. The binary variable $x_e = 1$ indicates that the edge e is included in the solution, and binary variable $z_C = 1$ indicates that any vertex in the set C is not spanned by the tree T. Thus the constraint (5b) enforces that at most K relays are required. The constraint (5c) enforces that for each $C \subseteq V \backslash \{b\}$, either a edge e is selected from cut-set $\delta(C)$ or the set C is contained in the set U of all unspanned vertices. Collectively, it ensures that all vertices not in any C such that $z_C = 1$ will be included in a tree that rooted at b. If we apply Lagrangian relaxation to the constraint (5b), we obtain the following for a fixed Lagrangian variable $\frac{1}{\lambda} \ge 0$ as

$$minimize \quad \lambda \sum_{C} p(C) z_C + \sum_{e \in E} c_e x_e - (K - N_s) \tag{6}$$

subject to:

Constraints: (5c), (5d), (5e).

For a given λ, it is easy to see that the relaxed problem (6) is equivalent to the PCST problem [19] in terms of integer programming formulation since there is only an extra constant item $(K - N_s)$ in the objective function. It means any feasible solution for PCST integer programming is also feasible for our problem, thus we can easily use an existing 2-approximation PCST algorithm [19] to find a solution in case of a fixed λ.

For an arbitrary value of λ, we can use a straightforward bisection search procedure consisting of many PCST subroutine calls, which is presented in Algorithm 2. To have an efficient bisection search, the initial values for lower and upper boundary λ_1, λ_2 and the search stop threshold is key parameters for the performance of the algorithm, which

Algorithm 2 Population-Aware Relay Placement (S, R_s, B)

```
Construct sets T, T ← ∅;
Construct graph G = (V, E, P);
Initialize variable λ1 = 1/(Σ_{V\{b}} p), λ2 = Σ_E c_e;
repeat
    λ = (λ1 + λ2)/2;
    (T, N_s) ← PCST(G, λ);
    k = Σ_{e∈T} c_e + N_s;
    if k < K then
        λ2 = λ;
    else if k > K then
        λ1 = λ;
    end if
until k = K or λ2 − λ1 ≤ 1/(Σ_{v∈V\{b}} p_v) & k < K
return A tree T.
```

need to be carefully selected. From the objective function, we can easily see that the variable λ actually plays a role of weighting the penalty and cost in the final decision. In this sense, based on the physical meanings of penalty as population and cost as required relays, we can safely set the initial lower bound as $\lambda_1 = \frac{1}{\sum_{V \backslash \{b\}} p}$, which implies the cost dominated the decision process, and results in a solution with less relays. While, the initial upper bound $\lambda_2 = \sum_E c_e$ implies the penalty dominated the decision process and results in a solution that connecting all shelters regardless how many relay required. The bisection search will find a proper value of λ, which meets the requirement of relay budget. In specific, the algorithm terminates either when it found a solution with exactly K relays, or a solution with less than K relays and sufficiently small searching interval $\lambda_2 - \lambda_1$. Once we obtain the solution tree, the relays are placed on the *Steiner locations* and edges of the tree T with the constraints of communication distance.

C. Time Complexity Analysis

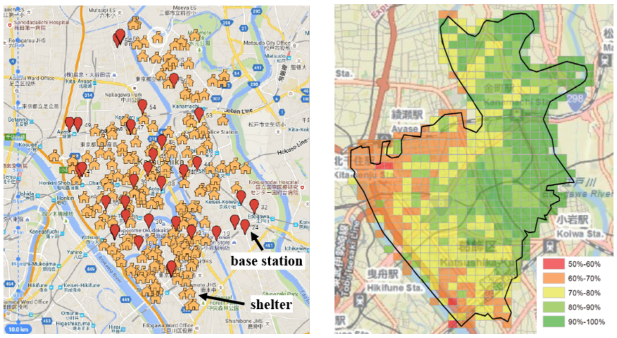
In the first step, the running time is trivial since it loops all clusters whose number is usually much smaller than the number of shelters. In the second step, the worst-case time complexity of a bisection search is $\mathcal{O}(\log \sum p \cdot \sum c)$. The GW-algorithm [19] we adopted for PCST subproblem runs in $\mathcal{O}(n^2 \log n)$, thus the total running time of our PARP solution is $\mathcal{O}(n^2 \log n \log \sum p \cdot \sum c))$. Note that $n = |V|$ is the cardinality of the set of all nodes, which is $|S| + |R_s| + 1$ for the proposed solution. The total penalty $\sum p$ varies linearly with the number of shelters $|S|$, and $\sum c$ varies with the number of edges in a complete graph as $n(n-1)/2$.

IV. Evaluation Results

In this section, we evaluate the proposed PARP solution by comparing with the previous solution in both real-world and random scenarios.

A. Simulation Scenarios

For the real-world scenario, we adopted the same instance of Katsushika ward as in [15] for comparison, which is one



(a) Locations of shelters and BSs (b) Network avilability

Fig. 5: A real-world scenario

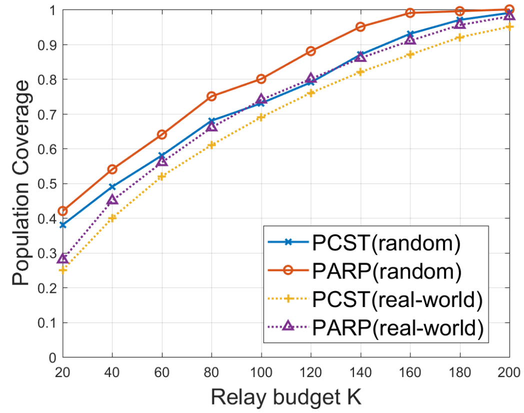


Fig. 6: Population coverage vs. relay budgets.

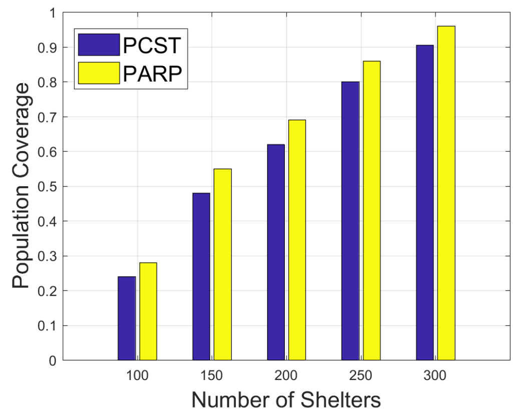


Fig. 7: Population coverage vs. number of shelters. ($K = 100$)

of the central 23 wards in Tokyo with an area of $34.8km^2$. As shown in Fig. 5a, there are approximately 190 shelters and 30 mobile BSs of a major MNO in this area. Based on the study of data-driven network availability analysis [20], we could obtain a mesh grid in $250m \times 250m$ resolution with respective network availability in percentage as demonstrated in 5b, which is estimated for the time 24 hours after the earthquake occurred. It is shown that in this scenario, the network availability ranges from 52% in the southwest part to 98% in the northeast part. Based on it, the evaluation results are obtained by averaging from 100 samples of still-alive BSs patterns. For the random scenario, we considered a square area of $5000m \times 7000m$ for comparison with the real-world instance. The still-alive BSs and shelters are uniformly generated within this area so that the results are averaged from 100 samples of random geographical distribution. For convenience, we simply adopt the communication rages in the field test [8] for the relay $d = 100m$ and BS $D = 500m$ respectively in our evaluation. Note that, to keep a constant number of disconnected shelters for each evaluation settings, the random generated shelters are only in the area of outside the coverage of BSs. We denote our solution as PARP and the previous one in [15] as PCST in the following figures.

B. Performance Analysis

We first evaluated the population coverage with different relay budgets for PARP and PCST in both the real-world and random scenario, which is depicted in Fig. 6. For each sample of evaluation, we set the numbers of shelters and still-alive BSs in the random scenario the same as the real-world scenario. The population coverage is defined as the ratio of total population of connected shelters by the relays and total population of all shelters. The results show that PARP algorithm always outperforms the previous PCST algorithm in both the real-world and random scenario with different relay budgets.

In order to have a comprehensive understanding of PARP solution in different scenarios, we leverage the number of shelters and number of still-alive BSs to further investigate the performance of population coverage based on the random scenario. We fix the relay budget as 100, the results in different number of shelters and number of still-alive BSs are shown in Fig. 7 and Fig. 8 respectively. The area of random scenario is the same as previous evaluation, therefore, changing the number of shelters or BSs only affects their distribution densities. As more shelters are located in the same area, the population coverage is increased even under the same relay budget. As expected, our algorithm outperforms the PCST algorithm due to the use of *Steiner locations* to improve the relay utilization. As the increase of still-alive BSs, the same performance increasing trend can be identified but in an exponential manner. The main reason is that more still-alive BSs in the same area makes shelters not only close to the BSs, but also easier to be interconnected due to increased density.

At last, we show the computation time fo both solutions as in Fig. 9. The running machine is with Intel Xeon E3-1241 CPU at 3.5 GHz and Windows 10 operating system. We implemented both algorithms in MATLAB R2017a. We ran them in the same software/hardware environment for 100 times for the averaged performance. Although our solution uses a longer time than PCST solution due to the enlarged scale of the problem with extra *Steiner locations*, it is still within the same order of $\mathcal{O}(n^2 \log^2 n)$.

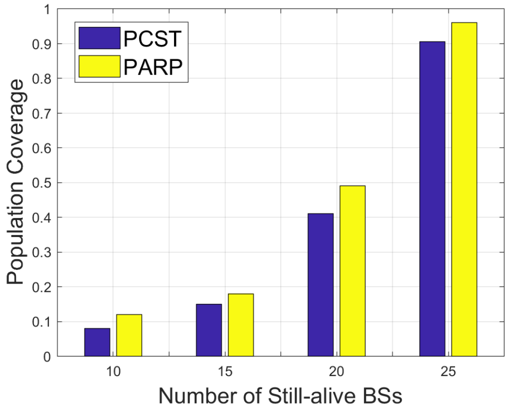


Fig. 8: Population coverage vs. number of still-alive BSs. ($K = 100$)

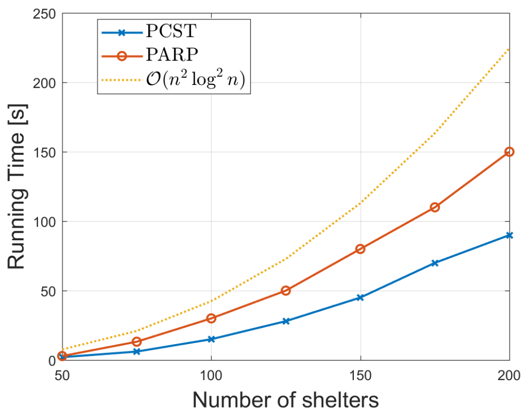


Fig. 9: Running time vs. number of shelters. ($K = 100$)

V. Conclusions

In this paper, we have studied a population-aware relay placement solution that maximizes the connected population with a limited number of relays. The proposed solution is based on a new graph model that takes into account of Steiner locations, i.e. potential shared relays. We also presented a clear and complete formulation of the studied problem, which provides more insights on how to properly determined the parameters for bisection search and thus maintains an acceptable running time. Finally, we evaluate the proposed algorithm by comparing with previous work in both real-world and random scenarios. The results demonstrate that the proposed solution outperforms the previous work with an affordable increase in the running time.

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