A Steiner Zone Approach for Mobile Data Collection in Partitioned Wireless Sensor Networks

Araştırma Makalesi/Research Article

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Abstract— Wireless sensor networks (WSNs) typically operate in harsh environmental conditions. Hardware constraints and external damage from inhospitable surroundings leave the nodes susceptible to node failures. Depending on the damage scale, the network can be subject to partitioning which segments the network into multiple isolated connected components. A prompt reactive approach to restore network connectivity is to employ a mobile data collector (MDC) that visits and collects data from partitions periodically. Availability of the wireless data communication through multi-hop routing in a partitioned network complicates designating the shortest possible route for data collection. This paper regards the mentioned data collection problem as the Close-enough Traveling Salesman Problem (CETSP) and employs Steiner zone approach to designate respective data collection points for corresponding partitions. We have assessed the proposed approach in terms of the number of points visited for data collection and the total travel distance of the MDC. Obtained results indicate that the proposed approach can reduce the number of data collection points up to 67% and total travel distance up to 42%.

Keywords—WSN, connectivity restoration, mobile data collection, Close-enough Traveling Salesman Problem, route planning.

Steiner Zone Yaklaşımı İle Bölünmüş Kablosuz Algılayıcı Ağlarda Hareketli Veri Toplama

Özet— Kablosuz algılayıcı ağlar genellikle zorlu çevresel koşullar altında faaliyetlerini sürdürürler. Donanımsal kısıtlar ve olumsuz kuşatanlar ağı oluşturan düğümleri kayıplara maruz bırakır. Ortaya çıkan hasarın boyutuna bağlı olarak ağ içerisinde, ağın geri kalanından yalıtılmış ayrık bağlı bileşenler ortaya çıkabilir. Bu tür durumlarda ağ bağlantısının hızlı ve tepkin şekilde onarılması için hareketli veri toplayıcılarından (HVT) faydalanılabilir. HVT, parçalanmış ağdaki bağlı bileşenleri belirli aralıklarla ziyaret ederek toplanan verilerin iletilmesine olanak sağlar. Çok-sekmeli yol atamanın mümkün olması, parçalanmış bir ağdan kablosuz veri iletimi ile veri toplayacak maliyet-etkin güzergahın tespiti problemini karmaşıklaştırmaktadır. Bu makale, belirtilen veri toplama problemini Yeterince Yakın Gezgin Satıcı Problemi (YYGSP) olarak ele alarak Steiner zone yaklaşımı ile her bir ağ parçası için ilgili veri toplama noktasını tayin eder. Önerilen yöntemin başarımının değerlendirilmesi için ziyaret edilen veri toplama noktalarının sayısı ve HVT'nin toplam seyahat mesafesi ölçülmüştür. Elde edilen sonuçlar, önerilen yöntemin, veri toplama noktalarının sayısını %67, toplam seyahat mesafesini ise %42 düşürdüğünü göstermektedir.

Anahtar Kelimeler— KAA, bağlantının onarımı, hareketli veri toplama, yeterince yakın gezgin satıcı problemi, güzergah planlama.

1. INTRODUCTION

Wireless sensor networks (WSNs) consist of small form factor sensors thanks to microelectromechanical systems (MEMS) [1]. Unless ambient energy harvesting is available [2], limited on-board batteries dictate conservation in terms of the transmission power. Low-power short-range wireless networks [3] require a base station (*BS*) to connect the network to the rest of the world. The BS is less resource restricted in terms of communication range, computational power, and battery [4]. The BS acts as a gateway between the network and the remote user. The BS uses one of the long-range communication means to forward data to the remote user. On the other hand, sensor nodes form a multi-hop network to reach the *BS* due their limited transmission range. Thus, sustainability of the overall network connectivity is very critical to ensure a certain degree of coverage. The lack of coordination among nodes due to node failures degrades fidelity of the collected data and may leave some areas uncovered [5].

Depending on the network topology and the scope of the failure, damage scale can vary. Single node failures can be tolerated partly through redundancy unless the failed node serves on an exclusive routing path (i.e., cut-vertex). However, large-scale node failures often partition the network [6]. To restore network connectivity, various recovery solutions exist in the literature [5]. Increased node redundancy is a proactive approach, however, it cannot guarantee a solution unless the failed node is not a cut-vertex. Another recovery scheme introduces additional nodes to the network in order to link the partitions. This approach fails to address the problem if the intervention to the application area is not feasible. Also, network-wide recovery will not be possible unless sufficient external nodes are available. Another class of connectivity restoration solutions assumes availability of inherent controlled mobility of the existing nodes and recovers the connectivity by restructuring the network layout. This recovery scheme assumes availability of the on-demand mobility for the whole network.

In this paper, we apply a reactive mobility-based solution to ensure network connectivity. We employ a mobile element to collect data from partitions and forward to the BS by visiting them periodically. The mobile element can be a mobile robot or a vehicle depending on the application and it is referred to as the mobile data collector (MDC). The main idea of mobility-based data collection schemes is providing intermittent connectivity to partitions by visiting them for data exchange periodically. The main drawback of this type of solutions is the extended data latency due to mobile data delivery. MDCs are typically equipped with limited batteries. Considering the energy cost of mobility and the data latency, this scheme is ideal as a temporary but prompt solution until a permanent solution is available.

The Traveling Salesman Problem (TSP) is a classic optimization problem, which requires a salesman to visit customers at their precise locations one and only once and then return to the initial location. The goal of the TSP is to designate the shortest possible route for the salesman. Several variations of the TSP exist in the literature [7] including the multiple TSP (mTSP) [8], generalized TSP (GTSP) [9], TSP with neighborhoods (TSPN) [10], Close-enough Traveling Salesman Problem (CETSP) [11], etc. In the mTSP, more than one salesmen are available. Cities are clustered and the salesman visits only one city from each cluster in the GTSP. The TSPN seeks the shortest tour that passes the given regions once. The CETSP, on the other hand, defines a service area that the salesman can visit for each city. Instead of visiting the exact location of the city, it is sufficient to approach the city close enough for the service. An intuitive application for the CETSP is the task of meter reading for a utility company [11]. In this application, meters are assumed to be equipped with radio frequency identification (RFID) for remote data collection. This paper formulates the problem of mobile data collection in partitioned WSNs as a CETSP and seeks the shortest possible tour for the MDC to relay data from partitions to the *BS*.

Proposed solution assumes availability of a MDC which is located next to the BS initially. MDC starts the tour at its initial location, visits each partition exactly once at each tour and returns to the original location to forward the collected data. MDC repeats the same tour until its battery is depleted. Considering the possibility of having multiple nodes at each partition, the main challenge that needs to be addressed is identifying the positions to collect data from each partition. For each node, a circular disk can be defined to denote the area for wireless communication. It should be noted that, disks can overlap. Following the approach proposed in [11], we consider the degrees of disk overlaps. Disk overlaps are regarded as Steiner zones and the number of disks overlapped in the respective region signifies the Steiner zone degree. We pursue an iterative approach as detailed in Section 3. At each iteration, we select the Steiner zone with the highest degree and determine the visiting point in that region. We consider connectivity with multi-hop routing and mark the covered nodes accordingly. We proceed with the next Steiner zone until all nodes are covered.

The rest of the paper is organized as follows. Related work is summarized in Section II. The proposed solution is discussed in Section III. Approaches are evaluated in Section IV. The paper is concluded in Section V.

2. RELATED WORK

The TSP is a well-known optimization problem with several applications in different fields including transportation, logistics, scheduling, etc. The TSP is an NP-hard problem even for points defined in the Euclidean plane [12]. The original Euclidean TSP assumes availability of edges between every pair of nodes if the network is modeled as a graph. Therefore, we have a complete graph with undirected edges associated with a positive weight. The intuitive solution is to follow a brute-force approach and try all permutations to find the tour with the minimum sum of the edge weights. However, this solution does not scale. While some exact solutions exist with dynamic programming [13] and linear programming [14], heuristics and approximation algorithms are also available.

In the CETSP, nodes are defined as a point in the plane similar to TSP. Unlike [15], movement is not restricted with the road network and all distances are Euclidean. The tours in the CETSP must pass within a certain distance d of each node. CETSP becomes TSP when d=0. CETSP can lower the cost of the solution compared to the TSP with the flexibility in visiting the nodes. However, this flexibility makes the problem more complicated than the standard TSP [16]. CETSP is applicable for certain applications involving sensors and wireless communication where remote data collection is possible. Thus, the route optimization problem of data collection in partitioned WSNs can be modeled as a CETSP.

CETSP is classified by [16] as a special case of the three combinatorial optimization problems, namely Covering Tour Problem (CTP), TSPN, and GTSP. CTP defines a discrete set of nodes (V) that can be visited and a subset of nodes ($T \subseteq V$) that must be visited and a set of nodes (W) that must be covered. A node is covered if it is within a certain distance of a node, which is part of the tour. In GTSP, k clusters are defined and each node is assigned to a cluster. GTSP seeks a solution, which visits at least one point in each cluster. If we define a disk to represent the communication area of a node and populate infinitely many nodes at the boundary of each disk, GTSP becomes CETSP when each disk is regarded as a cluster. In the TSPN, nodes can travel up to a certain distance to meet the salesman.

In WSNs, TSP is usually employed to find the best path for MDCs [17-22]. The typical approach is identifying a set of points to visit and collect data from nearby sensors and then applying TSP on the data collection points. [17] addresses the connectivity problems of WSNs with mobile data collectors. Unlike our work, [17] assumes availability of multiple MDCs and aims task balancing between them. Due to availability of multiple MDCs, the problem is modeled as mTSP. To find the solution, a multi-objective genetic algorithm is exploited to identify data collection points. Another mobility-based data collection solution is proposed by [18]. [18] regards the data collection points as sojourn points (SPs) so that the network data can be collected by upon visiting only the sojourn points. [18] considers both obstacle-free and obstacle-resisting environments for the mobility of the MDCs. If the application environment is assumed to be obstacle-free as in our work, the MDC can move through the shortest path between two data collection points. SPs are determined by defining circumcircles for equilateral triangles dividing the application area. The length of the triangles' sides is equal to the transmission range. The center of a circumcircle is identified as an SP if there are any sensors within the transmission range. [19] groups sensors into clusters and selects a cluster head from each cluster based on the distance to other sensors in the group. The sensor with the minimum distance is selected as the cluster head. MDC visits cluster heads according to the path obtained from the TSP solution. [20] assumes multiple MDCs and formulates the problem as the k-traveling salesman problem with neighborhood (k-TSPN). [20] considers two different scenarios to deliver collected data to the BS. In the fist scenario, MDCs have to visit the BS to forward their data. In the second scenario, MDCs are assumed to be able to connect to the BS from any location in the network. Our study assumes a common limited transmission range (TR) for both the BS and the MDC so that MDC is required to visit the BS to forward its data. In this work, visiting a node implies approaching close enough to establish communication. [21] is another work which employs mobile data collectors in WSNs. [21] first clusters sensors based on their degrees and then groups clusters by using a variety of the k-means algorithm.

3. THE PROPOSED SOLUTION – STEINER ZONE WITH PARTITIONS (SZP)

Wireless communication enables remote data collection from nodes in a given WSN. Based on the network topology and the employed routing type, data collection scheme can be complicated which needs to be managed carefully. In this paper, we assume a partitioned WSN where multi-hop routing is available. Partitioned network refers to a network comprised of multiple connected components. Each connected component consists of one or more nodes. Inter-node communication is possible within the same partition. Each partition is isolated from the rest of the network. In a partitioned WSN, the *BS* cannot collect sensor readings unless they are within the same partition. In the literature, various approaches are available to restore connectivity of a partitioned WSN [5].

This paper assumes availability of a MDC which visits partitions periodically to collect data and relay to the BS. This approach provides intermittent connectivity between partitions and the *BS*. Two major concerns regarding this approach are the increased data latency and the excessive energy cost of mobility. Therefore, it is crucial to minimize the total travel distance of the MDC. For the given set of nodes, designating the shortest possible route that visits all the nodes exactly once and returns to the initial location is regarded as the TSP. TSP is a classic optimization problem with several variations. The problem that we consider in this paper can be formulated as the CETSP [11]. The considered problem is TSP since we have a set of nodes that must be visited in order to collect their data. Also, in the network, we have a special node referred to as the *BS*. For our case, *BS* is regarded as the depot and the nodes become cities that must be visited by the salesman (i.e., MDC). On the other hand, the problem becomes CETSP when we consider the wireless communication area based on the employed transmission range.

Assuming an omnidirectional antenna, we can define a disk centered at the node location with a radius equal to the transmission range. MDC does not have to visit the exact node location and collect the sensor data upon entering the communication area of the respective node.

In this paper, we extended the Steiner zone approach presented in [11] considering some differences in our problem. First of all, we assume multi-hop routing. This complicates the problem due to the formation of partitions. Instead of considering only the nodes, we need to take partitions into account while designating the route of the MDC. Similar to the Steiner zone approach [11], we define a disk to represent the communication area for each node and evaluate the degree of disk overlaps while determining the position of super nodes (i.e., visiting points or data collection points). It is desired to select Steiner zones with higher degrees. Unlike [11], we also consider connectivity of the partitions while determining super nodes. A sample execution of the algorithm is given in Fig. 1. It can be noticed that there are two Steiner zones in *Partition*$_1$ and one Steiner zone in *Partition*$_2$ with a degree equal to three. On the other hand, the number of nodes is different in these partitions. Unlike [11], *SZP* considers multi-hop routing and eliminates redundant data collection points. Both zones of degree three can be selected in *Partition*$_1$ as the next data collection point for the MDC. Consequently, all the nodes within the partition will be marked as covered.

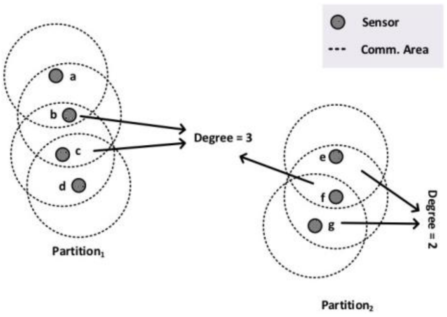
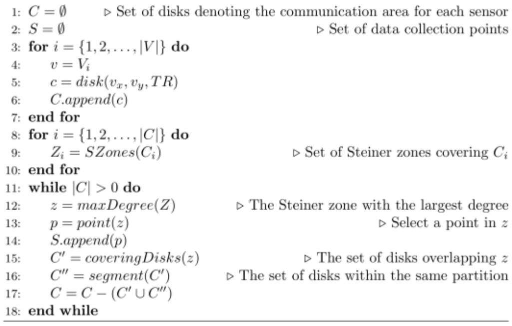


Figure 1. The network has two connected components. There are three Steiner zones with the highest degree, which is equal to three. *SZP* also considers multi-hop routing and identifies covered nodes accordingly.

A formal description of the SZP algorithm can be found in Fig. 2. The transmission range is used as the radius of the disks. Higher transmission range enables larger disks and increases the likelihood of disk overlaps.



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Algorithm 1 SZP(V, TR)
$C = \emptyset$    ▷ Set of disks denoting the communication area for each sensor
$S = \emptyset$    ▷ Set of data collection points
for $i = \{1, 2, \ldots, |V|\}$ do
    $v = V_i$
    $c = disk(v_x, v_y, TR)$
    $C.append(c)$
end for
for $i = \{1, 2, \ldots, |C|\}$ do
    $Z_i = SZones(C_i)$    ▷ Set of Steiner zones covering $C_i$
end for
while $|C| > 0$ do
    $z = maxDegree(Z)$    ▷ The Steiner zone with the largest degree
    $p = point(z)$    ▷ Select a point in $z$
    $S.append(p)$
    $C' = coveringDisks(z)$    ▷ The set of disks overlapping $z$
    $C'' = segment(C')$    ▷ The set of disks within the same partition
    $C = C - (C' \cup C'')$
end while
```

Figure 2. The formal description of the SZP algorithm. V denotes the set of nodes in the network. TR is the transmission range.

4. EXPERIMENTAL EVALUATION

4.1. Experiment Setup

We have evaluated the proposed approach through simulations. The simulations were carried out on the test platform implemented in Python. We assumed an application area of 800 meters × 800 meters and deployed wireless nodes randomly. The network size was changed between 50 and 200 nodes. A random node was selected as the *BS*. Transmission range was varied from 20 meters to 80 meters for the whole nodes. Due to random deployment and the limited transmission range of the sensors, we employed an MDC to collect data and ensure network-wide data collection. We have generated 30 different topologies for each test case and reported the average for significance. Proposed SZP approach identifies data collection points to be visited and therefore reduces the CETSP to TSP for partitioned WSNs. Afterwards, we employ OR-Tools library [22] to solve the TSP.

Table 1. The number of partitions in the network.

Transmission Range	Network size			
	50	100	150	200
20	47.70	91.83	130.57	163.17
30	45.33	81.27	108.13	125.27
40	41.70	69.07	82.63	86.3
50	37.63	55.23	58.33	52.3
60	33.27	41.10	37.67	27.1
80	23.27	17.70	9.73	4

Depending on the employed transmission range and the network layout, connected components can be formed. We regard these connected components as network partitions. Each partition can consist one or more nodes. We report the number of partitions with respect to transmission range and the network size in Table 1. It can be observed from Table 1 that the number of partitions is tightly aligned with the network size. For increased transmission ranges, the number of partitions declines which implies extended size of the partitions.

4.2. Performance Metrics

We have employed the following metrics to evaluate the performance of the proposed approach.

- The number of data collections points: This metric denotes total number of points to be visited in order to collect data from the network.
- Total travel distance: This metric measures the total distance traveled by the MDC.

4.3. Baselines

We have employed three different baselines to evaluate the performance of the proposed approach. The first baseline is the Steiner zone approach presented in [11]. The main idea of this heuristic is identifying a set of super nodes such that each node in the network will be within the communication area of at least one super node. The problem is regarded as the CETSP. CETSP is similar to TSP but the salesman does not have to visit the exact node locations but rather a zone defined by the disk representing the service area for the corresponding nodes. Assume a meter reading application for a utility company. In such an application, nodes represent meters. The service area for the corresponding meter represents the zone where the meter can be read remotely thanks to the RFID. RFID enables meter reading within a certain radius of each meter considering the communication area as a circular disk. Super nodes can be arbitrary positions in the network where the meter reading is performed. To minimize the complexity of the problem, it is desired to reduce the number of super nodes. Once the super nodes are identified, CETSP reduces to TSP on the super nodes.

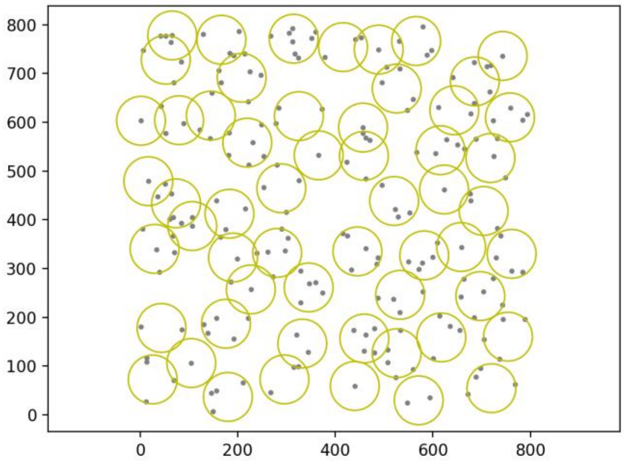

Figure 3. A WSN deployed in an application area of 800 meters × 800 meters. Gray nodes indicate sensors. The centers of circles denote data collection points determined by SZ.

Various approaches can be applied to determine the super nodes. Steiner zone heuristic defines disks to represent the service area for each node and regards the overlapping disk regions as Steiner zones. Also, Steiner zone degrees are specified which is equal to the number of intersecting disks as given in Fig. 1. In this approach, it is possible to collect data from n nodes if the Steiner degree of the visited super node is n. To minimize the number of super nodes, Steiner zone heuristic enumerates Steiner zones and selects the largest degree in a greedy manner. The heuristic proceeds with the next step until all nodes are covered with at least one super node. A sample network with 200 nodes and the resulting data collection points are given in Fig. 3. Transmission range is set to 50 meters. The same topology is also used in Figs. 4 and 5 to represent data collection points for different baselines.

The second baseline is a cluster head (CH) selection technique for MDC-based data aggregation in WSNs [19]. In this approach, sensors broadcast their coordinates and a CH is selected in such a way that the total distance from sensors to the CH is minimized. After CHs are identified, MDC visits CHs to collect data. The path of the MDC is calculated using TSP. This baseline is referred to as the distance-based heuristic in this paper. Distance-based heuristic selects one CH from each partition and applies TSP on CHs. The data collection points determined by this baseline can be found in Fig. 4.

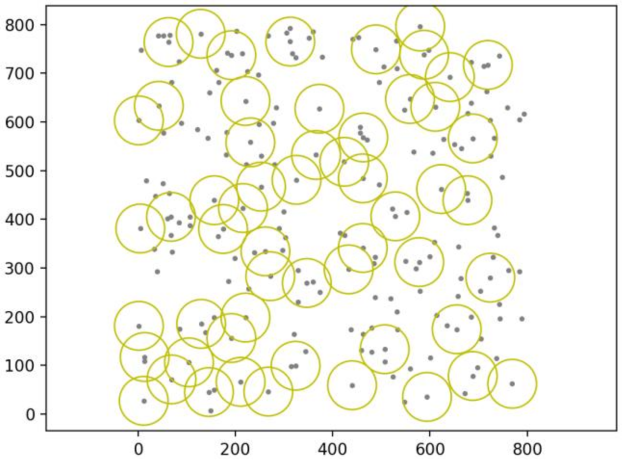

Figure 4. A WSN deployed in an application area of 800 meters × 800 meters. Gray nodes indicate sensors. The centers of circles denote data collection points determined by the distance-based heuristic.

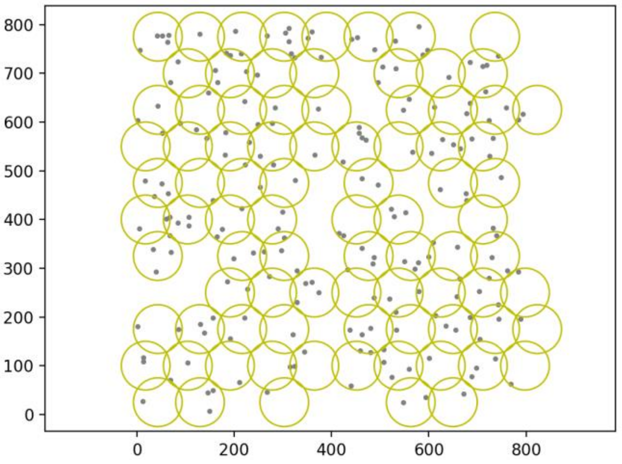

Figure 5. A WSN deployed in an application area of 800 meters × 800 meters. Gray nodes indicate sensors. The centers of circles denote data collection points determined by the circumcircle-based heuristic.

The last baseline follows a geometric property to determine sojourn points (i.e., data collection point) for MDCs in WSNs [18]. [18] divides the application area into triangles and defines circumcircles for the corresponding triangles. Obtained circumcenters are used as sojourn points to collect data from sensors within the transmission range. If there is no sensor within the transmission range of a circumcenter, this point is not included in sojourn points. The path of the MDC is calculated using TSP. TSP is applied on the sojourn points. This baseline is referred to the circumcircle-based heuristic in this paper. A circumcircle is a circle which passes through the vertices of a triangle. The circumradius of the circumcircle is equal to the transmission range.

4.4. Performance Results

In the rest of the paper, the proposed approach is denoted by *SZP*. Steiner zone, distance-based, and circumcircle-based heuristics are denoted by *SZ*, *Dist*, and *CC* respectively.

4.4.1. The number of data collection points:

Results are given in Fig. 6 and Fig. 7 for varying transmission ranges and network sizes respectively.

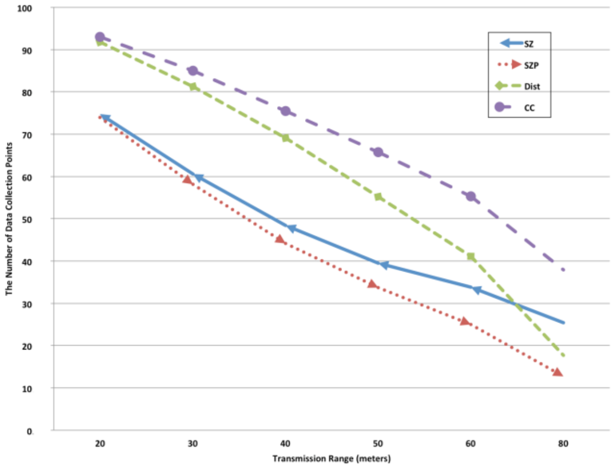

Figure 6. The number of data collection points with respect to transmission range. The network size is 100 nodes.

As can be observed from Fig. 6, the number of points to be visited in order to ensure full network coverage declines with the extended transmission range. This is expected due to the increased node redundancy in networks with a higher transmission range. Therefore, the number of data collection points for all approaches when the transmission range is increased.

Fig. 6 also indicates that *SZP* outperforms all of the baselines when different transmission ranges are employed. *CC* provides the worst performance among all approaches. Compared to *CC*, *SZP* decreases the number of data collection points 20% for TR=20. For extended TR, the gap increases even more and *SZP* reduces data collection points up to 67% compared to *CC*. Despite the poor performance of *Dist* in networks with limited transmission range, it can be noticed that *Dist* closes the gap and performs better than *SZ* when TR=80. Despite the reduced performance gap between *Dist* and *SZP* in networks with higher transmission range, *SZP* outperforms *Dist* in all cases.

Fig. 7 suggests that the number of data collection points tends to increase in denser networks. This is due to the increased demand for connectivity in larger networks. Considering the limited number of nodes within the direct access of the *BS*, most of the nodes depend on the MDC's intermittent visits to forward their data. However, despite the initial increase, the number of data collection points declines for both *Dist* and *SZP* after 150 nodes. The decline implies a threshold in network size. Considering the limited size of the application area, increasing the node count improves the node redundancy after reaching the threshold. Among all, *CC* provides the worst performance. Compared to *CC*, *SZP* decreases the number of data collection points between 37% and 64% for varying network sizes. For 50 nodes, *SZP* outperforms *SZ* 5%. In denser networks, *SZP* reduces the number of data collection points up to 41% compared to *SZ*.

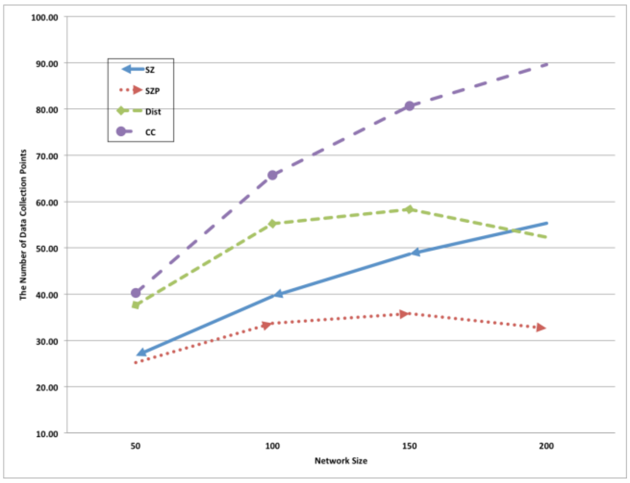

Figure 7. The number of data collection points with respect to network size. Transmission range is set to 50.

4.4.2. Total travel distance:

Results are given in Fig. 8 and Fig. 9 for varying transmission ranges and network sizes respectively. According to Fig. 8, increased transmission range alleviates the travel cost of the MDC. Declined number of data collection points is regarded as the major factor for the decreased traveling distance. Obtained results indicate that *SZP* outperforms all approaches and *CC* performs the worst. *SZP* reduces the travel distance around 5% when TR=20. The gap increases up to 42% when the transmission range is extended to 80 meters.

Fig. 9 also signifies the adverse effect of the network size on the total travel distance of the MDC. This is expected considering the increased number of data collection points in larger networks as denoted in Fig. 7. On the other hand, after reaching a threshold, the total travel distance decline for *Dist* and *SZP* in denser networks. Nevertheless, SZP outperforms all approaches in all cases.

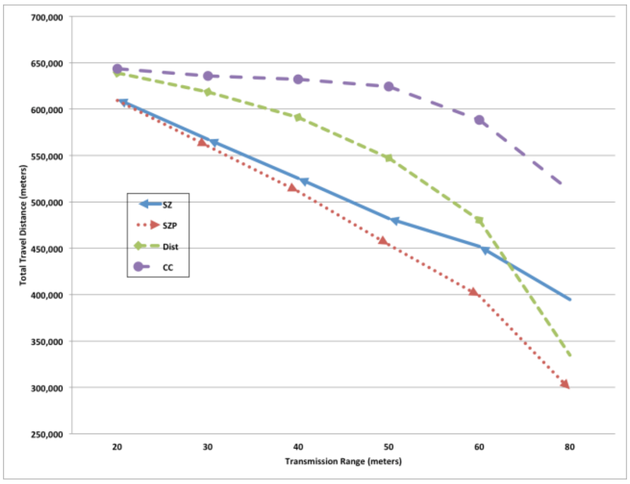

Figure 8. Total travel distance with respect to transmission range. The network size is 100 nodes

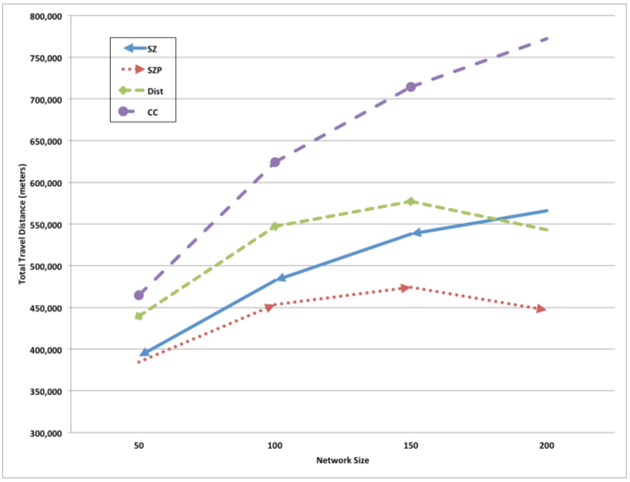

Figure 9. Total travel distance with respect to network size. Transmission range is set to 50.

CONCLUSION

In this paper we considered the problem of mobile data collection from partitioned WSNs. The lack of connectivity between the partitions and the *BS* hinders inter-node coordination and degrades network coverage. To address the connectivity problem, we employed an MDC that visits partitions and the *BS* periodically and relays data among them. Mobile data collection provides intermittent network connectivity, however, the route of the MDC must be carefully designated in order to decrease data latency and extend the MDC lifetime considering the limited on-board energy. Determining the shortest possible route that visits the given locations is a well-studied problem, which is known as TSP. However, we have a slightly different problem, which makes the NP-hard problem even harder. Given the availability of wireless communication and multi-hop routing within the partitions, MDC does not have to visit the exact location of each node. On the contrary, we can determine visiting points to collect data from as many nodes as possible. To minimize the number of visiting points, we followed a Steiner zone approach. We defined a disk for each node to denote the wireless communication area and considered the degree of disk overlaps. Pursuing an iterative approach, we selected Steiner zones with the highest degree at each step and marked the covered nodes considering the multi-hop routing accordingly. To assess the proposed solution, we conducted extensive simulations. The results show that the proposed solution can reduce the number of data collection points up to 67% and total travel distance up to 42%.

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REFERENCES

[1] I. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, “Wireless Sensor Networks: A Survey”, *Computer Networks*, 38(4), 393-422, 2002.

[2] W. K. G. Seah, Z. A. Eu, H. Tan, “Wireless Sensor Networks Powered by Ambient Energy Harvesting (WSN-HEAP) - Survey and Challenges”, **1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace Electronic Systems Technology**, 1–5, May 2009.

[3] J. A. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Mitter, B. Heile, “IEEE 802.15.4: A Developing Standard for Low-Power Low-Cost Wireless Personal Area Networks”, *IEEE Network*, 15(5), 12–19, 2001.

[4] M. A. Matin, M. M. Islam. “Overview of Wireless Sensor Network”, *Wireless Sensor Networks-Technology and Protocols*, 1-3, 2012.

[5] M. Younis, I. F. Senturk, K. Akkaya, S. Lee, F. Senel, “Topology Management Techniques for Tolerating Node Failures in Wireless Sensor Networks: A survey”, *Computer Networks*, 58, 254 – 283, 2014.

[6] I. F. Senturk, “Partition-aware Centrality Measures for Connectivity Restoration in Mobile Sensor Networks,”, *International Journal of Sensor Networks*, 30(1), 1–12, 2019.

[7] G. Gutin, A. P. Punnen, **The Traveling Salesman Problem and Its Variations**, Springer Science & Business Media, 12, 2006.

[8] T. Bektas, “The Multiple Traveling Salesman Problem: An Overview of Formulations and Solution Procedures”, *Omega*, 34(3), 209-219, 2006.

[9] C. E. Noon, J. C. Bean, “An Efficient Transformation of the Generalized Traveling Salesman Problem”, *INFOR: Information Systems and Operational Research*, 31(1), 39–44, 1993.

[10] A. Dumitrescu, J. S. Mitchell, “Approximation Algorithms for TSP with Neighborhoods in the Plane”, *Journal of Algorithms*, 48(1), 135–159, 2003.

[11] D. J. Gulczynski, J. W. Heath, C. C. Price, **The Close Enough Traveling Salesman Problem: A Discussion of Several Heuristics**, 271–283, Boston, MA: Springer US, 2006.

[12] C. H. Papadimitriou, “The Euclidean Travelling Salesman Problem is NP-Complete”, *Theoretical Computer Science*, 4(3), 237-244, 1977.

[13] R. Bellman, “Dynamic Programming Treatment of the Travelling Salesman Problem”, *J. Acm*, 9(1), 61–63, 1962.

[14] G. Reinelt, **The Traveling Salesman: Computational Solutions for TSP Applications**, Berlin, Heidelberg: Springer-Verlag, 1994.

[15] I. F. Senturk, G. Y. Kebe, “A Novel Shortest Path Routing Algorithm for Wireless Data Collection in Transportation Networks”, **2019 International Conference on Computer Science and Engineering (UBMK)**, 280-284, 2019.

[16] W. K. Mennell, **Heuristics for Solving Three Routing Problems: Close-enough Traveling Salesman Problem, Close-enough Vehicle Routing Problem, Sequence-dependent Team Orienteering Problem**, Ph.D. Dissertation, 2009.

[17] Z. Kang, Z. Hong, H. Hu, Q. Xiong, G. Xu, “Multi-objective Optimized Connectivity Restoring of Disjoint Segments Using Mobile Data Collectors in Wireless Sensor Network*”, J Wireless Com Network*, 65, 2017.

[18] N. Ghosh, I. Banerjee, “An Energy-efficient Path Determination Strategy for Mobile Data Collectors in Wireless Sensor Network”, *Computers and Electrical Engineering*, 48(C), 417–435, 2015.

[19] U. Sharma, C. R. Krishna, T. P. Sharma, "An Efficient Mobile Data Collector Based Data Aggregation Scheme for Wireless Sensor Networks”, **2015 IEEE International Conference on Computational Intelligence & Communication Technology**, 292-298, 2015.

[20] D. Kim, R. N. Uma, B. H. Abay, W. Wu, W. Wang, A. O. Tokuta, “Minimum Latency Multiple Data MULE Trajectory Planning in Wireless Sensor Networks”, *IEEE Transactions on Mobile Computing*, 13(4), 838-851, 2014.

[21] D. V. Le, H. Oh, S. Yoon, “A Novel Hierarchical Cooperative Data Gathering Architecture Using Multiple Mobile Elements”, **Sixth International Conference on Ubiquitous and Future Networks**, 522-527, 2014.

[22] Internet: OR-Tools, https://developers.google.com/optimization, 11.04.2020.