A New Approach to Simulating Node Deployment for Smart City Applications Using Geospatial Data

Izzet Fatih Senturk
Dept. Computer Engineering
Bursa Technical University
Bursa, TURKEY
izzet.senturk@btu.edu.tr

Gaoussou Youssouf Kebe
Dept. Computer Engineering
Bursa Technical University
Bursa, TURKEY
kebegaoussou@gmail.com

***Abstract*—The rapid urbanization combined with the continuing growth of the world's overall population entails efficient provisioning of services and infrastructure in the cities. Some of the challenges of this gradual shift can be addressed by the global phenomenon of smart cities. Despite various definitions, the concept refers to data-driven solutions to operate cities more efficiently. As the infrastructure requires constant data collection, sensors and various wireless communication technologies are the building blocks of smart cities. In this paper, we consider a smart city application to monitor the road network obtained through one of the volunteered geographic information (VGI) systems. To analyze the impact of the employed wireless communication technology on the network connectivity, we have deployed sensors to the infrastructure according to the obtained geospatial data and varied the transmission range of the sensors. The results show considerable decline in the number of occurred partitions and the minimum number of relay nodes required to ensure network-wide connectivity when the transmission range is increased.**

***Index Terms*—smart city, sensor deployment, connectivity, volunteered geographic information, osm, osmnx**

I. Introduction

The world is undergoing the largest human migration in history. Today, 55 per cent of the world's population inhabits in urban areas [1]. This proportion denotes a staggering increase considering the urbanization rate of 30 per cent in 1950. Projections show that the proportion of the urban inhabitants to reach 68 per cent by 2050 [2]. The rapid urbanization along with the continued population growth pose a challenge against a sustainable world and the well-being of its inhabitants.

Cities must adapt digital technologies to make better decisions so that quality of life can be improved while ensuring the resource availability for present and future generations [3]. Digital intelligence can improve efficacy of the city operations including transportation, public safety, energy consumption, trash collection, and tourism [4]. According to McKinsey Global Institute, smart cities can save 25-80 liters water per person per day, reduce crime by 30-40 per cent and enable 20-35 per cent quicker response time for emergency services [5]. A study sponsored by Intel found residents can save 125 hours per year through improved efficiency in mobility, public safety, healthcare, and productivity [6].

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Intelligent transportation is a key component of a smart city which needs to deal with the mobility of people and goods. Considering its major contribution to greenhouse gas emissions, green means of transportation should be developed in order to improve mobility while decreasing congestion and the waiting times. In a smart city, different modes of public transportation can be offered and the service times can be coordinated in an adaptive manner based on the dynamic traffic pattern. To meet this challenge, traffic must be monitored with sensors and regulated with intelligent traffic signal controllers. Deploying sensors on the transportation infrastructure improves security and public safety as well through increased response capabilities for medical emergencies and disruptive events including strikes and violence acts.

Smart cities rely on data collection from a vast number of data points across the city. Thus, sensors and their connectivity are the main smart city technology enablers which feed the data platform for the analytics. While various sensors are available to detect events or changes in the environment, cameras can be installed to identify the number and speed of pedestrians and vehicles in the vicinity [7]. Designating data point locations for accurate data collection is another challenge though. In this paper, we assume a smart city application to monitor the road network and exploit one of the data elements of the employed VGI system, OpenStreetMap [8], to determine the locations for sensor deployment. OpenStreetMap (OSM), provides three basic components to model the physical world, namely node, way, and relation. While node denotes a particular point on the earth's surface with the respective latitude and longitude coordinates, way defines a polyline with an ordered list of nodes. In OSM, ways are used to represent roads. Therefore, we obtain strategic points for sensor deployment from the respective coordinates of nodes constituting the way. A sample road network with the defining nodes can be found in Fig. 1. Throughout the paper, we will use the terms sensor and node interchangeably.

Considering the availability of various wireless communication means, we evaluate the impact of transmission range on the network connectivity of the deployed sensors. Note that the range of a wireless technology is related to the employed transmission power as well as the receiver sensitivity and typically short-range communication is favored to

Fig. 1: Partial road network for the city of Bursa, TURKEY. From the city center, the nodes within a bounding box of 1000 meters are included. Red color denotes one-way traffic.

minimize the energy consumption. Depending on the network structure and the employed transmission range, network can be composed of multiple disjoint partitions isolated from the rest of the network. Consequently, sampled data from such partitions cannot be delivered to the data analytics platform and the fidelity of the collected data degrades due to uncovered regions.

To investigate the impact of the transmission range on the network connectivity, we identify the number of partitions to be occured with various transmission ranges. To link the partitions and enable data exchange among them, additional relay nodes can be introduced to the network. To minimize the deployment cost, we exploit a relay placement algorithm. This algorithm ensures connectivity while minimizing the number of relay nodes to be deployed. Both the road network obtained from OSM and the resulting wireless communication network are modeled as a graph structure and analyzed respectively. Obtained results signify that the number of partitions to be formed and the number of relays required to link them can be reduced up to 98 per cent by increasing the transmission range from 25 meters to 100 meters.

The rest of the paper is organized as follows. Related work is summarized in Section II. Deployment schemes are presented in Section III. Approaches are evaluated in Section IV. The paper is concluded in Section V.

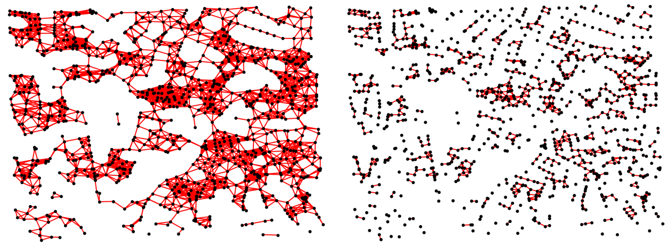
II. Related Work

Recent advances in microelectromechanical systems and the proliferation of smart devices have transformed the way the geospatial data is produced and disseminated. Abundance of user-generated geographic data collected and circulated voluntarily by the general public manifests itself in the increased availability of volunteered geographic information (VGI). Despite concerns over data quality, VGI has attracted much attention in the last decade and OpenStreetMap (OSM) has been repeatedly framed in the literature as one of the most successful examples. Besides data quality and reliability [9]–[11], OSM has been studied in a wide range of applications including route planning [12], vandalism detection [13], remote damage assessment [14], urban climate studies [15], network analysis and visualization [16], etc. In this paper, we have acquired the road network from OSM and employed OSMnx [16] for data visualization.

Data collection from wireless sensors is a well-studied area in the literature and a vast number of solutions exist for connectivity and coverage problems [17], [18]. Typically, sensors are constrained in terms of energy and employ short-range communication technologies such as Zigbee and 6LoWPAN. Due to the limited transmission range, nodes are expected to form a multi-hop network connected to a base station (BS). BS provides long-range wireless communication and acts as a gateway between the network and the remote user or the data analytics platform as in our case. Data exchange and coordination among nodes is crucial to sustain operations and ensure a certain level of data fidelity. Though, network can be subject to partitioning because of node failures or initial deployment. A node may fail due to various reasons including battery depletion, hardware malfunction, external damage, etc. In this paper, we assume partitioning after initial deployment.

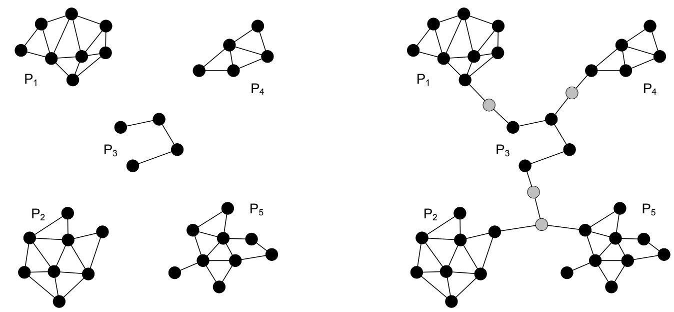
To recover connectivity in a partitioned network, different approaches can be applied. A proactive strategy is designating redundant nodes to avoid failures. The idea is to provide more than one routing path between every pair of sensors in the network. This idea is referred to as k-connectivity and tolerates up to k-1 node failures. Another approach is assuming controlled mobility for nodes and restructuring the network topology by relocating a subset of the nodes. Considering the excessive overhead of mobility, travel distances must be minimized. This paper does not assume node mobility and pursues another recovery scheme called relay placement. In this scheme, additional relay nodes are introduced to the network in order to link the partitions. In this paper, we employed CIST [19] relay placement algorithm to obtain the node locations to ensure connectivity. The goal is minimizing the required number of relays.

Internet of Things (IoT) refers to the network of everyday devices and it is considered as an essential part of the smart cities [20], [21]. The growth in connected devices is staggering and IoT endpoints is expected to reach 25 billion by 2021, according to Gartner [22]. Two emerging low-power solutions to enable wireless communication for IoT devices are 6LoWPAN and LPWAN [23]. LPWAN is a long-range non-cellular network protocol operating in the license-free spectrum. 6LoWPAN, on the other hand, enables short-range wireless IPv6 connectivity over IEEE 802.15.4 based networks. While LPWAN is typically deployed in a



(a) (b)

Fig. 2: Communication networks for the road network given in Fig. 1. Transmission range is set to 100 (a) and 50 (b) respectively.



(a) (b)

Fig. 3: An illustration of how CIST works. Initial topology (a). Resulting topology after employing CIST (b).

star topology, 6LoWPAN adapts mesh topology. The main drawbacks of LPWAN are the lack of IPv6 support and severe bandwidth and duty cycle constraints [24]. Considering the limitations of LPWAN, we assume a 6LoWPAN network in this paper and evaluate the network connectivity over large geographical areas with various transmission ranges.

III. Approach

We assume a smart city application to monitor the transportation infrastructure, more specifically, drivable public streets or the road network in other words. The spatial data was acquired from OpenStreetMap [8] by exploiting OSMnx [16]. Recall that a network can be modeled by using the graph data structure and analyzed by employing graph theory. Graphs are mathematical abstractions to model pairwise relations between objects. A graph is comprised of nodes connected with edges. In the obtained road network, edges represent street segments and nodes signify intersections. All the spatial characteristics including geographic and metric information is preserved. The edges are weighted based on the length of the street segment. The edges are directed. Self-loops and multiple edges between nodes are possible (i.e. multidigraph). Note that the resulting spatial network is not planar since the edges may not only intersect on nodes considering tunnels and overpasses.

Considering the importance of nodes in representing the characteristics of the road network, we assume sensor deployment on respective node locations. The sensors are assumed to be stationary. We considered different transmission ranges depending on the applied wireless communication technology and investigated the resulting wireless network topology. Fig. 2 depicts the communication network for the road network given in Fig. 1 considering two different transmission ranges. Depending on the employed transmission range, communication network may comprise multiple isolated partitions. To provide network-wide connectivity, we assume deployment of additional relay nodes to the network. To minimize the recovery overhead, we employ a relay placement algorithm, CIST [19], so that the number of relays to be added can be minimized. A sample demonstration of the solution is illustrated in Fig 3.

Relay placement is an NP-Hard problem [19] and therefore heuristics are employed. The goal is sustaining connectivity while reducing the required relay count. CIST uses partition representations at the boundary of the partitions and connects the partitions over these representative nodes. Basically, a Steiner Minimum Tree (SMT) is formed among these representative nodes as shown in Figure 3. The tree edges consist of relays that are deployed on a straight line depending on the transmission range of relays which is assumed to be equal to existing nodes.

IV. Experimental Evaluation

A. Experiment Setup

In the experiments, we assumed unit disk graph model for wireless communication. According to this model, two nodes can communicate if and only if the distance between them is at most R which is the common transmission range of the nodes. To assess the impact of the network size and the transmission range on performance metrics, we considered two different scenarios. In the first scenario, we fixed R and changed the size of the application area. In the second scenario, R is constant while the size of the application area changes. In order to control the size of the application area, we use the bounding box distance in each direction (north, south, east, and west) from city centers obtained from OSM. In the experiments, we considered 30 metropolitan cities in Turkey [25] and reported the average result for significance.

B. Performance Metrics

- *The number of nodes*: This metric measures the number of sensors deployed in the application area. Higher node count implies increased deployment cost.
- *The number of edges*: This metric indicates the number of links in the network and applies to both networks considered in the paper, namely road network and the communication network. Higher edge count signifies improved connectivity.
- *The number of partitions*: This metric denotes the number of disjoint segments in the communication network. Increased partition count refers to deteriorated connectivity and implies higher recovery cost.
- *The number of relay nodes*: Relay nodes are employed to link partitions and ensure network-wide connectivity.

Relay count is considered as the recovery overhead and it is more desirable to decrease the relay count.

C. Performance Results

Figs. 4 and 5 present the number of edges in the road network and the communication network with respect to bounding box distance and the employed transmission range respectively. According to Fig. 4, the number of edges increases for both networks with the increased bounding box distance. This is expected due to larger application area for the monitored region when the bounding box distance is higher. Despite staggering increase for both network types, road network widens the gap when the region to be monitored is extended. This can be attributed to the limited transmission range which becomes insufficient to link as many nodes as the ones added to the network.

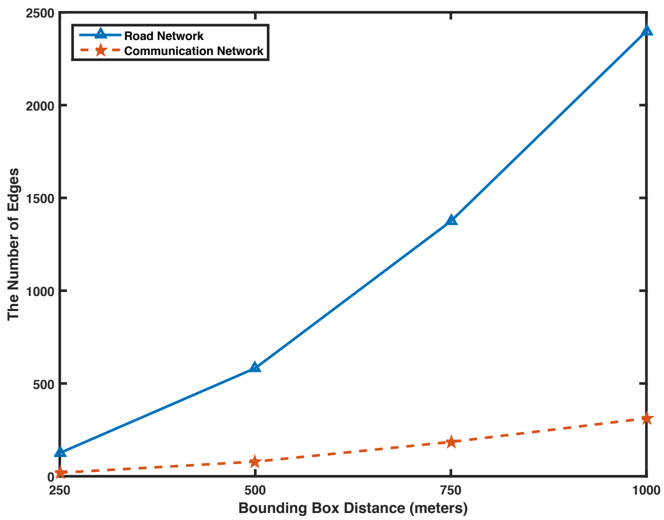


Fig. 4: The number of edges with respect to the bounding box distance. The transmission range is set to 25 meters.

Fig. 5 indicates steady increase in edge count for the communication network when the transmission range is extended. This is expected due to the improved wireless connectivity for the communication network. On the other hand, the number of edges is constant for the road network since the bounding box distance is constant and the transmission range does not affect the road network size.

Tables I and II present the number of nodes, the number of partitions and the number of relays with respect to bounding box distance and the employed transmission range respectively. It can be observed from Table I that the number of nodes increases when the bounding box distance is higher. This is expected since the area of the monitored region expands and additional roads are included into the network. Table I also suggests that the number of partitions increases with the increased bounding box distance. The main reason for the increase of the partition count is additional nodes in the network. Note that the ratio of the number of nodes to the number of partitions is around 1.4 for all cases. The last performance metric we report in Table I is the number of relays required

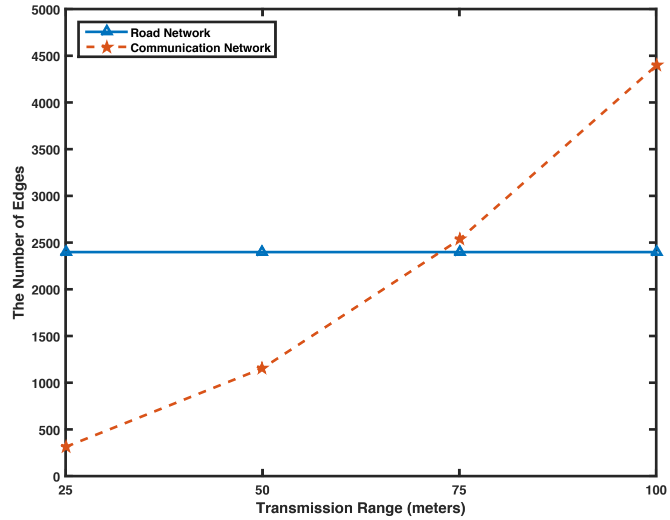


Fig. 5: The number of edges with respect to the transmission range. The bounding box distance is set to 1000 meters.

to link the partitions. According to obtained results, relay count increases when the bounding box distance is higher. The number of relays was found to be highly correlated with the number of partitions in the network. Considering the escalated demand for recovery when the number of partitions is higher, minimum number of required relays increase accordingly.

TABLE I: Total number of nodes, partitions, and relays with respect to bounding box distance. The transmission range is set to 25 meters.

bbox distance	***# nodes***	***# partitions***	***# relays***
250	56.37	40.87	56.90
500	231.37	167.07	221.90
750	527.17	378.27	496.70
1000	896.20	642.63	839.40

Table II suggests that the number of partitions declines with the extended transmission range. Considering the fixed size of the monitored region, higher transmission range improves wireless connectivity and the partition count declines consequently. Table II also signifies that the number of relays decreases with the increased transmission range. This is expected due to the reasons justified earlier. Improved connectivity reduces demand for recovery and the relay count declines as the recovery overhead. Table II also reports the number of nodes in the network. Since the area of the monitored region is constant, node count does not change as well.

TABLE II: Total number of nodes, partitions, and relays with respect to transmission range. The bounding box distance is set to 1000 meters.

TR	***# nodes***	***# partitions***	***# relays***
25	896.20	642.63	839.40
50	896.20	247.50	204.97
75	896.20	55.07	45.63
100	896.20	13.50	12.61

V. Conclusion

Digital intelligence can improve efficacy of the city operations including transportation, public safety, energy consumption, trash collection, and tourism. Considering the significant amount of time spent in traffic and its major contribution to greenhouse gas emissions, smart transportation systems are becoming one of the key components of smart city solutions which improve mobility while decreasing congestion and the waiting times. In order to collect data regarding the road infrastructure and the traffic conditions, wireless sensors must be deployed in the vicinity of the road infrastructure accordingly. However, determining the optimal locations for sensor deployment is a challenge considering the limited transmission range and the sensing coverage. In this paper, we employed one of the volunteered geographic information systems to obtain spatial data and deployed sensors at the road intersections. Then we investigated the wireless connectivity based on the selected transmission range. We have observed significant changes in the number of partitions formed in the network and the minimum relay count required to connect the partitions. Considering the availability of various low-power wireless communication technologies, obtained results can be used to determine the technology to be used in smart city applications.

Acknowledgment

Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org

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