CMHN: Coverage Maximization of Heterogenous Network

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CMHWN: Coverage Maximization of Heterogenous Wireless Network

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***Abstract*—One of the main challenges in Wireless sensor network (WSN) is the connectivity and coverage. Connectivity is responsible of keeping the different nodes in the network connected and exchange data. Coverage impacts how efficient we are utilizing the operating sensors or mobile devices in the network. To provide a better performance to the connectivity in the network, one of the solutions is to maximize the coverage. This paper provides a novel resilient incremental algorithm which improves the coverage of connected mobile devices within a heterogeneous and homogeneous networks. Extensive simulations showed an improvement on the coverage up to 99% in homogeneous environments and 89% in heterogeneous environments.**

***Index Terms*—Internet of Things, Heterogenous and homogeneous environments, Coverage Maximization, Connectivity, Wireless Sensor Network.**

I. Introduction

The Internet of Things (IoT) is growing to become more promising in creating smart worlds, homes and cities by bridging the gap between physical and virtual objects. Everyday we are becoming more and more dependent on connectivity due to the emergence of smart cities applications: Installations of surveillance cameras, disaster management control and easy recovery, remote patient care, pollution and weather monitoring. With new rising subjects like Internet of Things (IoT), reliable connectivity and wider coverage are becoming a must. Coverage plays an important role in increasing the performance of the network [1]. One of the most important infrastructure for IoT is Wireless Sensor Network (WSN). It is very useful in emergency situations; like natural disasters; due to their mobility and the easy and rapid deployment. Mobile Ad hoc Network (MANET),Vehicular ad hoc networks (VANETs), Army tactical MANETs, Disaster rescue ad hoc network, and Hospital ad hoc network are some of the applications of wireless sensor network.

WSN is composed of thousands of sensors/ mobile devices deployed in an area to monitor specific events (war terrain, temperature, volcano activities, pollution, etc.). The deployment strategies of WSN are either deterministic (which means the position of deployed sensors is predefined) or random (e.g position of sensors is hazardous in the field of Interest) [2]. As the deterministic deployment is not feasible in most mission critical application areas like earthquakes, floods, wildfire, leakage of nuclear radiations, etc. Ensuring connectivity and coverage is the main challenge to keep the deployed devices cooperating together for the sake of monitoring and maintaining the desired area. Simply without connectivity, nothing will work.

Most of the work related to the coverage and connectivity was assuming homogenous devices in the monitored area, which means that the devices have the same characteristics such as energy consumption, processing capacity, and radio equipment. However, this option is not always valid in real case scenarios and thus, extra work focusing on the heterogeneous type of network should be considered [3].

Coverage is classified into three types, namely area coverage, point/target coverage, and barrier coverage [4], [5]. In this paper, we care for the area coverage and the corresponding connectivity. We focus on large mobile devices (sensors) networks, more specifically the case where devices are randomly deployed in a large field. We propose a resilient algorithm that serves both homogenous and heterogeneous environments in order to maximize the coverage of randomly distributed mobile devices. Our contribution can be summarized as follows:

- Maximizing the coverage of the whole network
- Maintaining the connectivity of the network

In this paper, we investigate the network connectivity and coverage problem. The rest of the paper is organized as follows: In Section II, we introduce the existing research efforts related to the various techniques in connectivity and coverage problems in WSN. In Section III, we introduce our solution for the coverage and connectivity problem. In Section IV, we present the simulations and the results of our algorithm. Section V concludes our paper.

II. Related Works

Coverage and connectivity (CC) has been studied extensively in recent years, especially when combined with energy efficiency [6], [7], [8], [9], [10]. CC requirements are known as three main groups: full coverage with connectivity, partial coverage with connectivity, and constrained coverage with connectivity. Full coverage with connectivity means that every location in the field is covered by at least one node. In many researches, K-coverage and K-connectivity are required since these helps offering higher accuracy and fault tolerance [11]. A network with partial coverage and connectivity requirements needs much less sensor nodes. In constrained CC, the maximum size of an area that an event can occur is bounded.

Many researches have concentrated on finding strategies for an optimal node deployment to achieve maximum area coverage with efficient connectivity control. In [12], authors review area coverage protocols, for both deterministic sensor nodes deployment and random sensor nodes deployment. As random deployment is not guaranteed to be efficient for achieving the required coverage, authors in [13] utilize the mobility feature of sensor nodes in order to maximize the coverage. Their proposed algorithm improves the network coverage and the redundant covered area with minimum moving consumption energy. The authors of [14] present a brief survey on k-coverage problems and protocols. The protocols were mainly classified, into two categories: k-coverage verification protocols and sleep scheduling protocols for k-coverage problems.

Many recent research works consider only homogeneous sensors which having similar technical characteristics and specifications (uniform circular sensing range and communication range.). Other works studied the coverage problem for heterogeneous wireless sensor network (WSN). In [15], authors focus on the connected target k-coverage (CTC k) problem in heterogeneous wireless sensor networks (HWSNs). They proposed a centralized and a distributed connected target k-coverage algorithms (CCTCk and DCTCk) algorithms for energy-efficient connectivity and coverage maintenance. In [16], authors studied the problem of coverage in planar heterogeneous sensor networks. They formulate the coverage problem as a set intersection problem. Sensors are deployed according to an arbitrary stochastic distribution; the sensing areas of sensors need not to follow the disk model but can have any arbitrary shape.

In this work we focus on area coverage and k-coverage connectivity. We study the behavior of our algorithm on homogenous and heterogeneous networks deployed randomly.

III. Maximizing coverage of heterogenous group of devices

In this section we will provide some mathematical formulas that will be used by our algorithm "Coverage Maximization of Heterogenous Wireless Network (CMHWN)"

A. Definitions

Let $\Omega = \{D_i\}_{i=1}^{n}$ be a set of n connected devices. Let (x_i, y_i) be the position of the device D_i which can be calculated using GPS or other RSSI techniques. Let r_i be the communication range of the device D_i. Two devices $D_i \in \Omega$ and $D_j \in \Omega$ are connected when:

$$d_{ij} = d(D_i, D_j) = \sqrt{(x_j - x_i)^2 + (y_j - x_i)^2} < r_i + r_j \quad (1)$$

d_{ij} is the Euclidian distance between the two devices $D_i(x_i, y_i)$ and $D_j(x_j, y_j)$. Each device D_i has:

- $Ready$ flag to indicate whether the area covered by the device is maximized or not.
- Two points $S_i(x_s, y_s)$ and $E_i(x_e, y_e)$ that are used to determine the sum of the intersected arcs with other devices as shown in the Fig.1. Assume t is the number of connected devices to D_i, then $|\widehat{S_i E_i}| = \sum_{j=1}^{t} \widehat{D_i D_j}$.

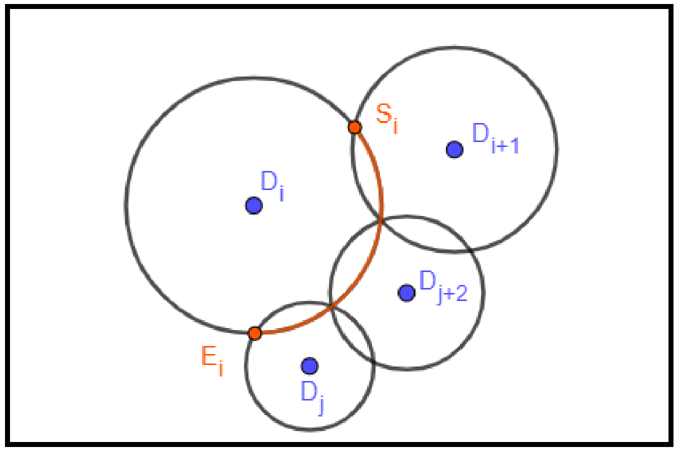


Fig. 1: Intersection between device D_i and D_j,D_{j+1}, and D_{j+2}

Let $\tau_{ij} = m_{ij} \cdot r_i + m_{ji} \cdot r_j$ be the optimal connection between two devices D_i and D_j with required minimum overlapping. We mean by $m_{ij} = m(i, j)$ the ratio function which defines the overlapping area between the two devices (Fig.2). This ratio is a user defined value $m \in [0, 1]$ such that:

$$m(i, j) = m_{ij} = \left\{ \begin{array}{ll} m, & r_i < r_j \\ \frac{m+1}{2}, & r_i = r_j \\ 1, & r_i > r_j \end{array} \right\} \quad (2)$$

Let u_i, w_i be the two intersection points between two devices D_i, D_j with $d_{ij} < r_i + r_j$.

B. Circle to Circle connection constraint

Our goal is to reduce the overlapping area between the devices to a small margin in order to ensure connectivity and to maximize the coverage. This margin is relative and depends on the network setup configuration. Therefore, we are using a user defined variable $m \in [0, 1]$. For example, when using $m = 0.9$ between the devices D_A and D_B, the value of τ_{AB} will be $\tau_{AB} = 0.9 \cdot r_A + r_B$ since the communication range of the device D_A is less than D_B range. As shown in Fig.2, since D_B doesn't satisfy the condition $d_{AB} = \tau_{AB}$, it has to move from its initial position (dashed orange device B) to the final position (green device B'). To generalize, the

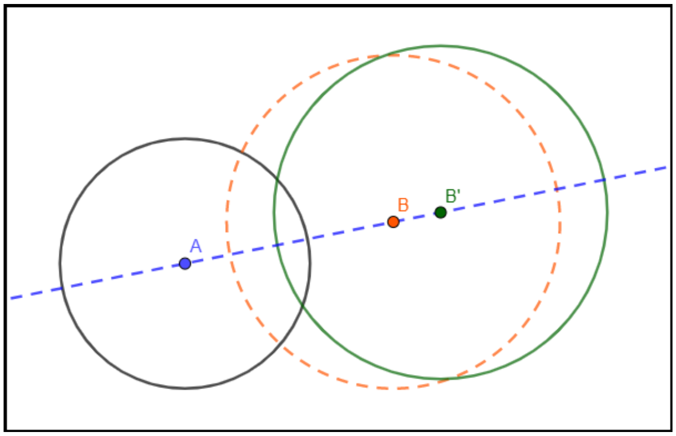


Fig. 2: Intersection between device D_A and D_B with m=0.9, $m(A,B) = 0.9$, $m(B,A) = 1$, and $\tau_{AB} = 0.9 * r_A + r_B = d_{AB'}$

displacement from B to B' is denoted as (d_x, d_y). B should move to B' far from or near to D_A along the line that joins the two centers (blue dashed line). For any two devices D_i and D_j the displacement is calculated as follows:

$$\frac{d_y}{d_x} = \frac{y_j - y_i}{x_j - x_i}, x_i \neq x_j \quad (3)$$

and the new distance of the device D_j after displacement with D_i can be represented as

$$d'_{ij} = \sqrt{(x_j + d_x - x_i)^2 + (y_j + d_y - y_i)^2} \quad (4)$$

combining equation (4) and (3) we get

$$\tau_{ij} = d'_{ij} = \sqrt{(x_j + d_x - x_i)^2 + (y_j + d_y - y_i)^2}$$

that is

$$\tau^2_{ij} = (x_j + d_x - x_i)^2 + (y_j + d_y - y_i)^2$$

by replacing d_y from equation (3) we can obtain

$$\frac{d^2_{ij}}{(x_j - x_i)^2} \cdot d^2_x + \frac{2 \cdot d^2_{ij}}{(x_j - x_i)} \cdot d_x - \tau^2_{ij} + d^2_{ij} = 0 \quad (5)$$

By solving the quadratic equation (5) we can find the roots of d_x. These roots represent two possible positions of D_j. The accepted root is the nearest position to the initial position of D_j. By substituting the accepted root of d_x in equation (3) we can obtain the value of d_y. Hence, the new coordinates of D_j is known.

For $x_j = x_i$, we have $d_x = 0$, by substituting in equation (4) we can obtain

$$\tau_{ij} = \sqrt{(y_j + d_y - y_i)^2} \quad (6)$$

that is

$$d^2_y + 2 \cdot (y_j - y_i) \cdot d_y + (y_j - y_i)^2 - \tau^2_{ij} = 0 \quad (7)$$

Again, by solving the quadratic equation we can obtain the value of d_y.

C. Circle to two connected Circles constraint

Fig.3 shows a device D_C trying to connect with two connected devices D_A and D_B. First step is to decide how these three devices are going to connect in a way to improve the coverage. Since devices D_A and D_B get connected using the method presented in the previous section III-B. The new position of D_C (circle with pink color) is C' will be collinear with $E(x_e, y_e)$ and $F(x_f, x_f)$, the intersection points between D_A and D_B, such that $C'(x_{c'}, y_{c'})$ (circle with blue color) satisfies $r_c = min\{d_{cf}, d_{ce}\}$. As illustrated in Fig.3, E is the nearest point to C. The updated value of used arcs become: Used arc for the device C' is the arc $\widehat{DE'} = \widehat{DE} + \widehat{EE'}$ and for the device B is the arc $\widehat{DF} = \widehat{DE} + \widehat{EF}$ and for A is the arc $\widehat{FE'} = \widehat{FE} + \widehat{EE'}$. In general, as long as the used arc length of D_i is less than $2\pi \cdot r_i$ where r_i is the range, D_i can accept more devices to connect with.

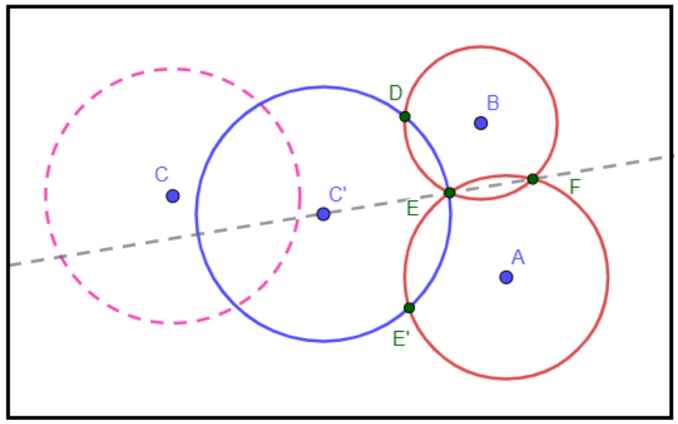


Fig. 3: Intersection between device D_1, D_2 and D_3

D. CMHWN Algorithm

This algorithm will iteratively adjust the coordinates of each mobile devices to maximize its coverage with the surrounding devices in the network.

The algorithm starts by finding the median of the network $\mathscr{M}(x_m, y_m) = \frac{1}{n}\sum_{i=1}^{n}(x_i, y_i)$. This step will reduce the average number of movements that each device will make in order to connect with the neighbors. The closest device D_i to $\mathscr{M}$ will move to $\mathscr{M}$ coordinates. For every closest device D_j to D_i, two possible cases exist:

- D_i is not yet connected to any other device
  In this case, The coming D_j obtains the new position coordinates based on the m-ratio function m_{ij} and the distance $d_{ij} = \tau_{ij}$. Both D_i and D_j will update $Ready$ to true. The used arc of D_i is represented by the two points S_i and E_i, the intersection points of the two devices.
- D_i is connected to t devices $\{D_k\}^t_{k=1}$
  In this case, the used arc of D_i has two ends S_i and E_i. The coming D_j will connect to D_i at distance r_j apart from the nearest point $min\{d(D_j, S_i), d(D_j, E_i)\}$.

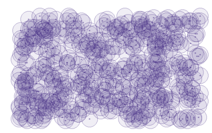
The device D_i continues to accept to connect with other devices as long as the new device D_j with range r_j satisfies the following condition : $\widehat{S_iE_i} + \widehat{u_jw_j} <= 2 \cdot \pi \cdot r_j$. Otherwise, Another device D_z to connect to D_j will be chosen with a condition $\widehat{S_zE_z} + \widehat{u_jw_j} <= 2 \cdot \pi \cdot r_z$. The pseudo code of our algorithm is presented below algorithm.

Algorithm 1: CMHWN algorithm

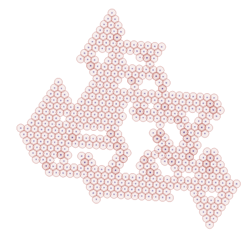
```
CMHWN(Ω : {D_i}_{i=1}^{n}, m: decimal)
Input: Ω set of all devices in the network
Input: m a user defined ratio
C ← φ
l ← φ
n ← Ω.length()
M(x_m, y_m) ← (1/n) Σ_{i=1}^{n} {(x_i, y_i)}
for i ← 1 to n do
    if C = φ then
        C ← min_i { dist(D_j, M) }
        MoveDeviceToPoint(C, M)
    else
        K ← min_j { dist(D_j, C) | D_j.Ready = false }
        if C.Ready = true then
            do
                p_t ← min{ dist(K, C.E), dist(K, C.S) }
                K' = CalculateNewPosition(K, P_t, I)
                G_t ← FindIntersectionPoint(K', C)
                if C.UsedArc ≥ Arc(P_t, G_t) then
                    K.MoveToCoordinateOf(K')
                    UpdateUsedArcs(K)
                    K.Ready = true
                    C.Ready = true
                else
                    C ← FirstCloseDevice(C, G_t, P_t)
                end
            while K.Ready=false

        else
            MoveNearDevice(K, C, m)
            UpdateUsedArcs(K)
            K.Ready = true
            C.Ready = true
        end
    end
end
```

IV. Validations and Results

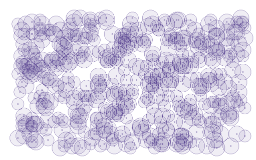
Different simulations were applied in order to measure the performance of our algorithm. For this study, we used different number of devices $N = 25, 50, 75, 100, 125, 150$ distributed randomly. The communication range of the devices varied between 3 units and 8 units for the studies on heterogeneous distribution, and 5 units for the homogeneous distributions. For a better study, we followed the statistical approach by taking a sample of 10 runs for each deployment. The area of interest was chosen to be a matrix of 1000×1000 $units^2$. In order to evaluate the performance of our algorithm, we studied the following indicators: The coverage maximization average rate, the displacement average for each device in heterogeneous and homogeneous scenarios, and the average of k-connected devices for each device.



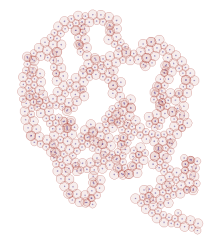
(a) Initial random deployment (Homogeneous)



(b) Coverage gain 99% by our algorithm



(c) Intial random deployment (Heterogeneous)



(d) Coverage gain of 89% by our algorithm

Fig. 4: Simulation results for 500 devices in both heterogeneous and homogeneous environment. The blew colored figures represent the deployment before applying our algorithm and the red colored figures represent the result after applying our algorithm

Fig.4(a) shows a random deployment of 500 devices in homogeneous environment and Fig.4(b) shows the result after applying our algorithm. The coverage gain was 89%, the average device displacement was 36.48 units, which is very short displacement compared to the area of interest length = $\frac{36.48}{1000\sqrt{2}} = 2.6\%$ of the device energy consumption. the average connected devices per each device was around 5 devices. Fig.4(c) shows a random deployment of 500 devices in heterogeneous environment. and Fig.4(d) shows the result after applying our algorithm. The coverage gain reached 99%, the average device displacement was 63.32 units, and the average k-connected devices for a given device was around 5 devices.

Fig.5 (resp. Fig.7) shows an initial deployment of a heterogeneous (resp. homogeneous) devices before applying our algorithm. The devices are connected but not in an efficient way in terms of coverage. Fig.6 (resp. Fig.8) shows the result after applying our algorithm.

Fig.9 (resp. Fig.10) shows the displacement of each device taken place after applying the algorithm. The results shows a small variation of the number which means that the displacement is more stable despite of the number of deployment size changes.

Fig.11 (resp. Fig.12) clearly depicts that when we increase the number of heterogeneous (resp. homogeneous) devices in the given network, the coverage area increases accordingly.

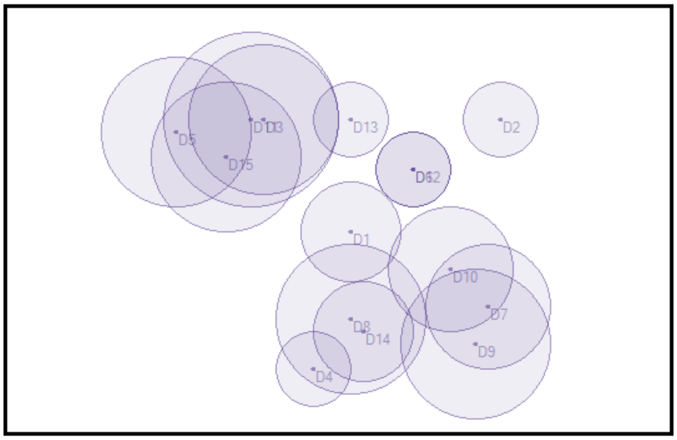


Fig. 5: Deployment of 15 devices randomly before applying the algorithm

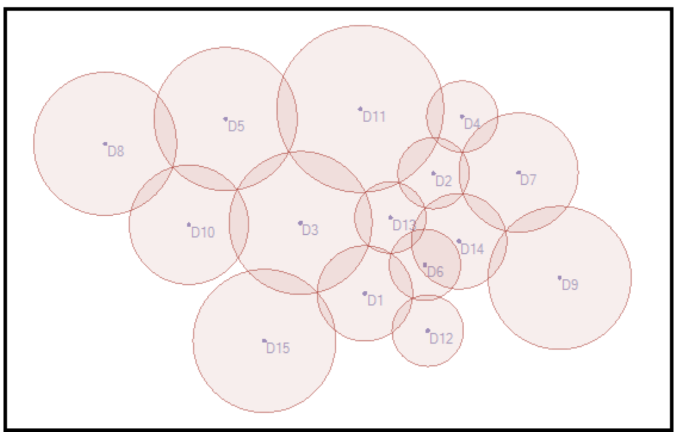


Fig. 6: The maximized coverage of heterogeneous after applying the our algorithm

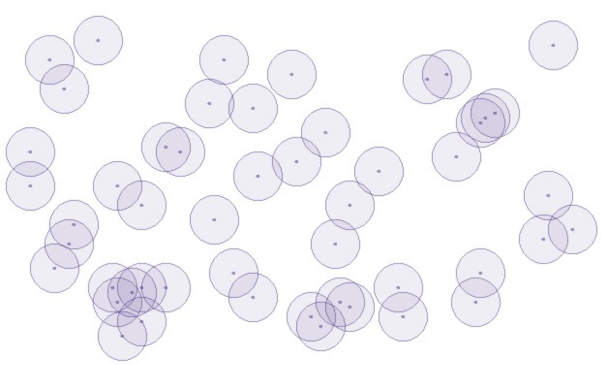


Fig. 7: Deployment of 50 homogeneous devices randomly before applying the algorithm

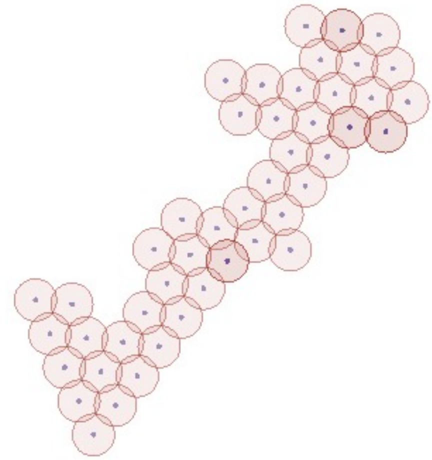


Fig. 8: The maximized coverage of 50 homogeneous devices after applying the our algorithm

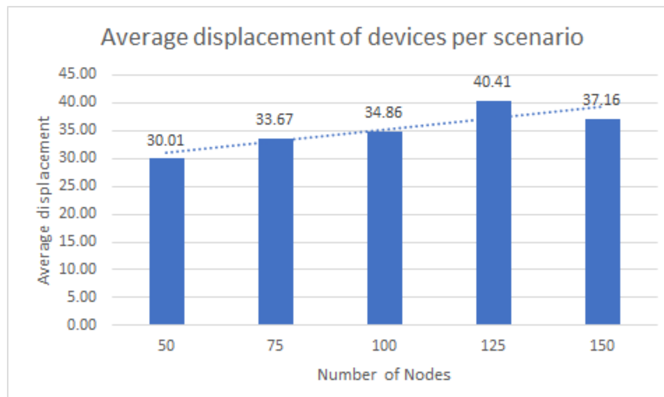


Fig. 9: The average displacement of each device per different deployment sizes in heterogeneous environment

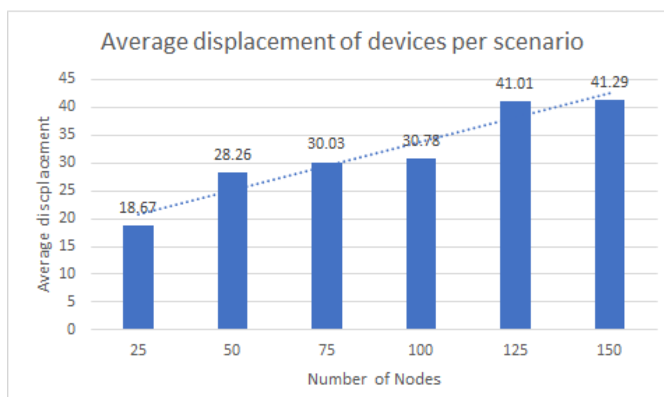


Fig. 10: The average displacement of each device per different deployment sizes in homogeneous environment

V. Conclusion and Future work

We presented a novel algorithm to improve the coverage of a network of mobile devices deployed randomly in the

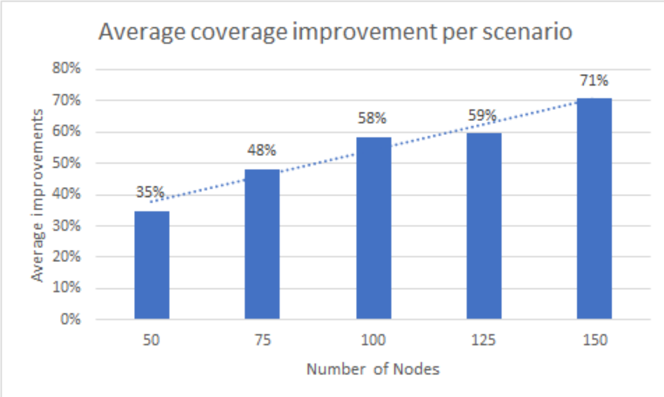


Fig. 11: The average coverage improvement of the network in heterogeneous environment

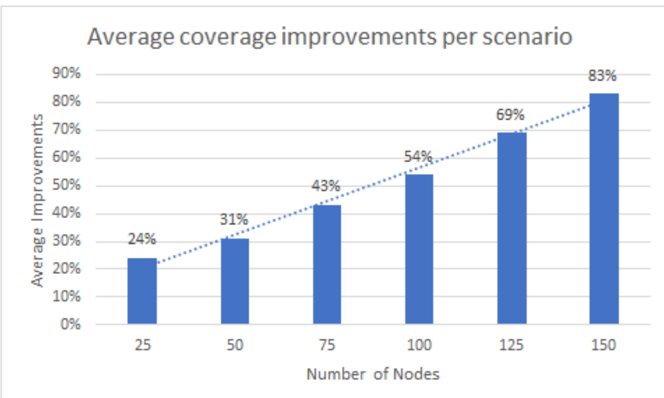


Fig. 12: The average coverage improvement of the network in homogeneous environment

field of interest. We examined the performance of our algorithm in different environments: heterogeneous and homogeneous devices. The algorithm showed a large gain in term of coverage up to 89% in heterogeneous and 99% in homogeneous for a sample of 500 devices. Also, the coverage gain increases as the deployment number of devices increases accordingly. This algorithm does not only improve the network coverage, but also maintain the network connectivity. As shown during the simulation, each device will be connected to at least 4-5 other devices which increases the reliability of the network by ensuring the system fault tolerance.

This algorithm does not take into consideration the gaps problem which might appear during the coverage maximization process in our algorithm. The reason of having these gaps is due to the fact that the way the devices are picked to connect to each other is random. In the future works, we aim to extend our work to cover the gap problem.

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