Coordinated Activation and Reporting for Energy-Efficient Target Intrusion Detection, Tracking, and Reporting in Wireless Sensor Networks

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Abstract— **Wireless sensor network (WSN) is a network consisting of several nodes equipped with sensors that cooperatively monitor physical conditions. WSNs are being used in many monitoring applications. In this paper, we present a new approach to perform coordinated activation and reporting (CAR) for energy-efficient target monitoring (detection, tracking, and reporting) in WSNs. Our approach aims to minimize the response-time by activating sensors (from sleep-mode) that are along the target's path, and then forwarding the information to be reported to the base-station from these sensors along the same coordinated path. If we are unable to meet the response-time deadline using a coordinated path, we split the tracking path and the reporting path in to independent paths, so that the base-station is reported within the response-time deadline. We perform extensive simulations on different sample target-paths, and compute average response-time and network lifetime for each scenario. We also investigate the problem of optimal base-station placement, so as to improve the average response-time in the network.**

Keywords: Wireless sensor networks, target monitoring, and response-time.

I. INTRODUCTION

A wireless sensor network is comprised of a group of specialized microcomputers intended to monitor and record conditions at diverse locations. The network consists of multiple detection points called sensor nodes, each of which is small, inexpensive, lightweight, and portable. Every sensor node is equipped with a transducer, microcomputer, transceiver, and power source. The power for each sensor node is usually derived from a battery. The transducer generates electrical signals based on sensed physical phenomena. The microcomputer processes and stores the sensor output. The transceiver receives commands from a central computer and transmits data to that computer [1]. The following are the characteristics of a sensor network:

- Sensor nodes are limited in power, computational capacities, and memory [2].
- Sensor nodes are densely deployed.
- Sensor nodes are prone to failures.
- Sensor network topology changes frequently.
- Number of sensor in a sensor network can be much higher than nodes in an ad hoc network.

Target monitoring involves detecting an object by its particular sensor signature, tracking its path over a period of time and then submitting the recorded information to a central computer. Target monitoring is one application that can benefit from the characteristics of sensor networks [3].

The rest of the paper is organized in the following manner: Section II outlines the problem description and Section III describes the related background work on target-tracking. Section IV discusses the real-time target monitoring framework. Section V analyzes the response-time for different base-station placement scenarios. Section VI presents the simulation results and Section VII concludes the paper.

II. PROBLEM DESCRIPTION

There has been a lot of research on target-tracking in WSNs [4], [5], [6], [7]. Most research papers focus on developing prediction algorithms for accurate tracking of the target's path. While some papers focus on developing selective node-activation algorithms that awaken sensors along the predicted path of the target from their sleep-mode, wherein all the nodes in the network are in sleep-mode except the active boundary sensor-nodes. Target tracking algorithms mostly concentrate on optimizing accuracy of the target positions by reducing the difference between the actual path of the target and the estimated positions based on the computations. The primary motivation behind our work is to develop a framework for real-time target monitoring, an approach that not only tracks the target accurately, but also keeps the response-time to the base-station minimal. To the best of our knowledge, there is no research work on performing target monitoring with a strict response-time deadline. In this work, response-time is defined the difference between the initial detection-time and the (first) reporting-time at the base-station.

III. RELATED WORK

There have been several different approaches to perform accurate target-tracking using WSNs. The following are some of the representative works on target-tracking.

A. *Tracking Moving Targets in a Smart Sensor Network [8]*

The goal of this protocol is to track and to predict the movement of a target and eventually alert the sensors that are close to the predicted path of the target. Hence, each individual sensor node is equipped with appropriate sensory device(s) to be able to detect the target as well as to estimate its distance based on the sensed data. The sensors that are triggered by the target collaborate to predict its course. Then the sensor nodes that lie close to the predicted course of the target are alerted. This alert is meant to serve as a trigger to activate additional on-board sensors.

B. *Co-operative Target-Tracking with Binary-Detection [3]*

This is a simple distributed tracking algorithm that records the time instances when each sensor detects the object and then performs line-fitting on the resulting set of points. Instead of looking at a single position measurement, the algorithm considers the path of a moving object composed of a sequence of positions over a period of time. The only requirement for this protocol is that the density of sensor nodes be high enough for the sensing ranges of several sensors to overlap. The outline of this cooperative tracking algorithm is as follows:

1. Each node records the duration for which the object is in its range.
2. Neighboring nodes exchange these durations and their locations.
3. For each point in time, the object's estimated position is computed as a weighted average of the detecting nodes locations.
4. A line-fitting algorithm is run on the resulting set of points.

In this paper, we adopt the co-operative target-tracking with binary-detection algorithm presented in [3].

IV. REAL-TIME TARGET MONITORING

The current research literature focuses primarily on target detection, accurate estimation of the target's path over a period of time, and performing *non-real-time reporting* to the base-station. Non-real-time reporting occurs when the base-station is not along the path of the target, and hence enormous time overhead is involved to report the data to the base-station. Real-time target reporting critical in real-time applications, such as missile defence and other environment monitoring applications, is ignored in most of the existing algorithms. Our goal is to implement real-time target reporting instead of non-real-time target reporting. We achieve real-time target monitoring by meeting a preset response-time deadline. This implies that given a response-time deadline, target monitoring should not exceed the deadline. To accomplish this, our algorithm performs *coordinated activation and reporting (CAR)* as long as data can be sent to the base-station within the response-time deadline, after which target tracking and reporting to the base-station are done independently in real-time. Coordinated activation and reporting aims to minimize the response-time and energy overhead by activating only sensors that are along the target's path [9], [10], [11], [12].

We develop a framework to model real-time target monitoring. The following are the important parameters and assumptions.

A. Parameters

1) Network Parameters:

- 6×6 grid network topology with 36 nodes.
- Nodes are static.
- Nodes are equidistant from each other, i.e., distance between any pair of nodes n_{ij} and n_{kl} is given by, $d(n_{ij}, n_{kl}) = \sqrt{(k-i)^2 + (l-j)^2}$, where $0 \leq (i,j) \leq 5$ and $0 \leq (k,l) \leq 5$. This implies distance between any pair of nodes on the same row/column is d meters and those diagonally opposite is $d\sqrt{2}$ meters.

2) Transmission Parameters:

- R: sensing range of any node in the network, i.e., an object at any Point p_i in $(x_i - r_x, y_i - r_y) \leq p_i \leq (x_i + r_x \pm R, y_i + r_y \pm R)$, where $0 \leq r_x, r_y \leq R$ and (x_i, y_i) are the coordinates of the sensor Node $n_{i,j}$, is detected.
- $R\sqrt{2}$: transmission range of any node in the network.
- t^t: Packet transmission delay given by, $t^t = \frac{L}{t_R}$, where L is the packet length and t_R is the transmission rate.
- $t^p_1(n_{ij}, n_{kl})$: propagation delay between any pair of nodes n_{ij} and n_{kl} on the same row/column is given by, $\frac{d(n_{ij}, n_{kl})}{c}$, where $0 \leq (i,j) \leq 5$ and $0 \leq (k,l) \leq 5$ and c is the transmission speed.
- $t^p_2(n_{ij}, n_{kl})$: propagation delay between diagonally adjacent nodes n_{ij} and n_{lk} is given by, $\frac{d(n_{ij}, n_{kl})\sqrt{2}}{c}$, where c is the transmission speed.
- $t^p_3(B_i, n_{ij})$: propagation delay between the reporting node n_{ij} and base-station B_i, where a *reporting nodes* is any node one-hop distance away from the base-station and is responsible for reporting data to the base-station.
- $t^d(n_{ij})$: initial-detection time at first boundary node n_{ij}.
- $t^r_{B_i}$: is the response-time, i.e., time at which the base-station B_i detects the target.
- r: target speed (in meter/second).
- t_i: target sensing interval (in second).

B. Assumptions

- All nodes in the network know their locations and have their clocks synchronized.
- Sensing range of adjacent nodes along the same row/column in the grid overlap.
- Target sensing interval is assumed to be greater than or equal to the propagation delay between any pair of adjacent nodes, $t_i \geq max(t^p_1, t^p_2, t^p_3)$.
- All target paths assumed to be straight lines at some angle, θ.
- A node after sensing and detecting, forwards its constructed data packet to at most one, amongst all of the neighboring nodes.
- Queuing delay is negligible.
- Activation delay is negligible.

Based on the framework parameters, the response-time ($t^r_{B_i}$) can be optimized for different base-station positions. We now evaluate ten different base-station placement scenarios for the 6×6 network.

V. BASE-STATION PLACEMENT SCENARIOS: NUMBER AND LOCATION

Fig. 1 represents three base-stations, one at northwest corner, one at the mid-west and one at the center of the network. In this section, we analyze the impact on the response-time by considering different scenarios for single base-station placement. Then we increase the number of base-stations to further evaluate the impact on the response-time. We consider 10 different scenarios for using one through five base-stations in the network. In a single base-station network, we analyze three scenarios. First scenario by placing the base-station at the northwest corner, second scenario by placing at the mid-west and third scenario by placing at the center of the network. We also analyze three scenarios in a two base-station network. The first scenario is placing them at the northwest corner and mid-west, second scenario is placing them at the northwest corner and southeast corner and third scenario is placing them

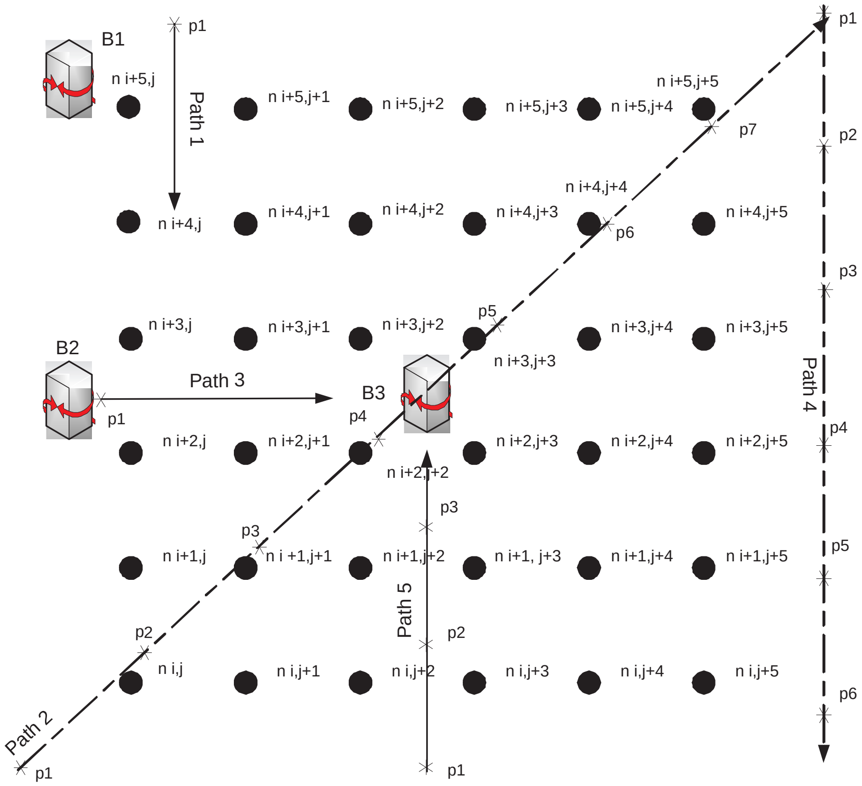

Fig. 1. Base-station placements in the grid.

at the northwest corner and center. For three base-stations case, we consider two scenarios. First scenario is placing them at the northwest corner, mid-west and southeast corner and second scenario is placing them at northwest corner, center, and southeast corner. We also consider a single scenario for four base-stations by placing one at each corner of the network and then a single scenario for five base-stations with one at each corner and one at the center of the network. Also due to the symmetrical placement of base-stations, we eventually evaluate 31 scenarios. We describe the analysis by considering specific target paths as indicated in the Fig. 1. Each point (p_i) on the path represents sampling of the target after a defined sensing interval.

Consider a scenario where we have a single base-station at the northwest corner (B_1) of the grid. We can observe that for the Path 1 taken by the target, the response-time is very less as the target originates near the base-station (B_1). The response-time can be given by the following equation,

$$t^r_{B_1} = t^d(n_{i+5,j}) + t^p_3(n_{(i+5,j)}, B_1). \qquad (1)$$

On the other hand, we observe that for target Path 2 the response-time is very high if we perform non-real time reporting to send the data to the base-station. Evaluating the equation for the Path 2 of the target,

$$t^r_{B_1} = \begin{array}{l} t^d(n_{i,j}) + \sum_{k=0}^{4} t^p_1(n_{i+5,j+k}, n_{i+5,j+k+1}) + \\ \sum_{k=0}^{4} t^p_2(n_{i+k,j+k}, n_{i+k+1,j+k+1}) + t^p_3(n_{(i+5,j)}, B_1). \end{array} \qquad (2)$$

Thus, for an uniform set of target paths we can observe that for most of the target paths, not originating near the base-station, the response-time is very high. The upper bound on the response-time duration is proportional to the length of the diagonal of the grid for tracking and further increases due to non-real time reporting to the base-station. There are only few target paths that originate near the base-station and yield a low response-time. We obtain the same analysis by symmetrical placement of base-stations (at Northeast, Southwest, and Southeast corner). In the second scenario, we place the base-station at the mid-west (B_2) instead of northwest corner. As can be seen in Fig. 1, Path 3 taken by the target provides for a low response-time. But Path 4 of the target results in a high response-time as non-real time reporting has to be performed. Thus, we can intuitively say that this kind of an organization does not provide significant improvements on response-time as compared to a single base-station at northwest corner. By symmetry we obtain the same response-time performance for base-station placements at Mid-east, Mid-north, and Mid-south of the grid. In the third scenario, we place the base-station at the center (B_3) instead of mid-west of the grid. We can observe that for Path 5 taken by the target the upper bound response-time is less as compared to the previous two organizations. As the base-station is in the center of the network, it lies in the path of the target, and hence we can reduce on non-real time reporting. Thus, for an uniform set of target paths the upper bound on response-time is equal to half the length of the diagonal of the grid and the lower bound on the response-time increases to the number of hops required to reach the base-station placed at the center. We also analyze seven base-station placement scenarios for two, three, four, and five base-stations in the network. The performance characteristics for all these scenarios are simulated in the next section VI. Also, it is intuitive to observe that as we increase the number of base-stations the response-time decreases. It is also oblivious that the cost factor increases as the number of base-stations increases. Due to page limitations, we have restricted the detailed analysis in this section to the three different single base-station scenarios. For a detailed description and evaluation of all the 31 scenarios refer to the technical report [13].

VI. SIMULATION RESULTS

In order to evaluate the real-time target monitoring we create a grid topology framework described in Section V. For the simulations, we have taken a grid network of 36 sensors placed at a distance of 100 m from each other. The transmission range is $100\sqrt{2}$ m and sensing range is 100m. The sensing interval is 0.1 second and target speed is 1250m/s. Transmission time is 0.1 second. Activation and propagation delays are assumed to be negligible. We compute the average response-time, average energy overhead and average blocking probability using 36 uniform target paths. The 36 target paths are composed of the 16 possible directions Fig. 2 with slight variations of the target originating point and the slope θ.

- Average response-time is defined as the ratio of the response-time required for the target paths to the total number of simulating paths.
- Average energy overhead is defined as ratio of the energy utilization for all the target paths to the total number of simulating paths. The energy utilized per hop is proportional to $d(n_{ij}, n_{kl})^2$, where $d(n_{ij}, n_{kl})$ is the distance between nodes n_{ij} and n_{kl}.
- Average blocking probability is defined as the ratio of the number of target paths that cannot be tracked within the response-time deadline to the total number of simulating paths.

Fig. 3 represents the best-case and worst-case paths of the target when non-real time reporting is performed. The graph indicates the response-times for the best-case and worst-case target paths for each base-station organization scenario. X-axis label in the graph indicates the placement of base-stations in the network. As seen in Fig. 3, the value of best-case for response-time is highest when a base-station is at the center as compared to all the other cases. This is because for any path taken by the target a minimum number of hops (two or three) are required to send the data to the base-station as the center. However, the worst-case response-time is low whenever at least one of the base-stations is at the center of the network. This is because the center base-station lies along the path of any target, and hence reporting of data can be done before the target reaches the boundary of the network.

Fig. 4 represents the average response-time for 36 different target paths simulated for each base-station organization scenario. We have simulated 36 different target paths by considering all the target directions stated in Fig. 2 at some angle. We observe from the graph that non-real time reporting has the highest response-time as compared to real-time reporting. Also, as the response-time deadline decreases the average response-time also decreases.

Considering the same plot from the perspective of the number of base-stations used in the wireless sensor network. We can see that placing a base-station at the center provides substantial reductions on the response-time. Increasing the number of base-stations further reduces the average response-time. Consider the graph for response-time deadline of 0.4 seconds, we see that the average response-time for a single base-station at the center is lower than placing two base-stations (one at the northwest corner and other at the mid-west of the grid). This indicates that merely increasing the number of base-stations does not necessarily reduce the response-time, we also need to intelligently place the base-stations in the network. We observe that for response-time deadline of 0.8 seconds, Point Q is 14.72% less than Point P and Point R is 12.5% less than Point Q. This clearly indicates that having a single base-station at the center provides for maximum reductions on response-time and additional base-stations provides further reductions. Similarly, Point S is 10.5% less than Point R. Having five base-stations (one at each corner and one at the center of the grid), provides the best response-time.

Fig. 5 illustrates the average energy overhead involved at each node for non-real time reporting, real-time reporting and the different base-station organizations.We observe that non-real time reporting results in increased average energy overhead per node as compared to real-time reporting with a response-time deadline of 0.8 seconds. This is because the target paths that do not have a base-station along their path incur substantial energy overhead for independently sending the data to the base-station. This overhead is reduced by performing real-time reporting where sending of data to the base-station can happen before the target actually reaches the boundary of the network. However, it is interesting to note that the energy overhead keeps on increasing as we further reduce the response-time deadline. This is because as we reduce the response-time deadline, the time to cooperatively tracking and reporting data to the base-station reduces. This clearly indicates that we need to perform coordinated tracking and reporting of the target until a break-way point after which target sensing and data reporting are performed independently. Also, we can observe that having optimal base-station organization and increasing the number of base-stations help substantial reduce the average energy overhead, resulting in increase network lifetime. However, increasing only the number of base-stations without their optimal placement increases the energy overhead, as seen in Fig. 5. It is interesting to note that, except for a response-time deadline of 0.2 seconds, the energy overhead is high for a network having four base-stations at the boundary of the network as compared to having three base-stations with one of them at the center. This is because, in the former case, most target paths report data to the base-station using more hops as the base-stations are placed at the network boundary. Moreover, decreasing the response-time deadline beyond a certain point (say 0.2 seconds) increases the energy overhead even when a base-station is at the center of the network.

Fig. 6 illustrates the average blocking probability. For the different base-station scenarios average blocking probability is defined as the number of failed paths to the total number of simulating target paths where failed paths are those target paths that could not be tracked within the specified response-time deadline. The total number of paths simulated for each

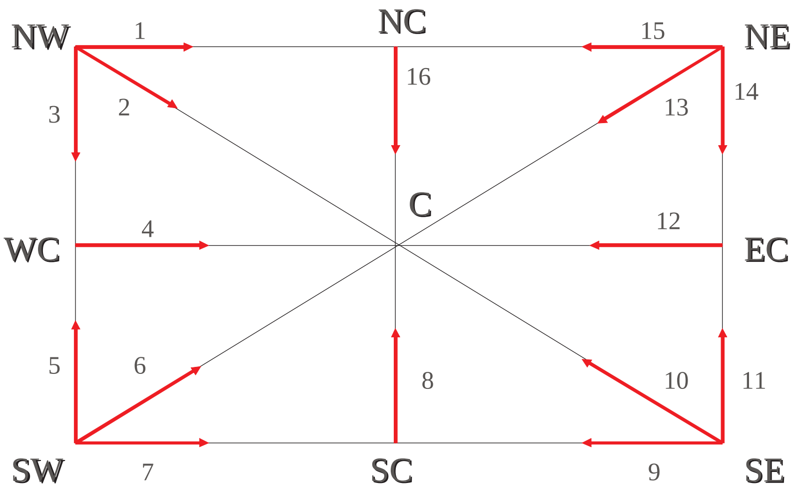

Fig. 2. 16 Target Directions.

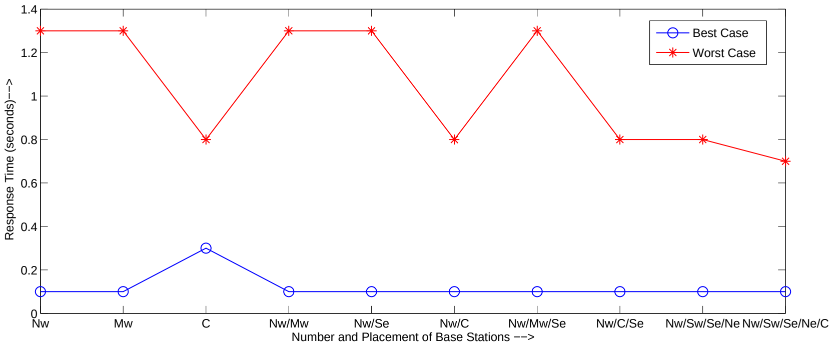

Fig. 3. Non-real time reporting best-case and worst-case for the 10 different base-station scenarios.

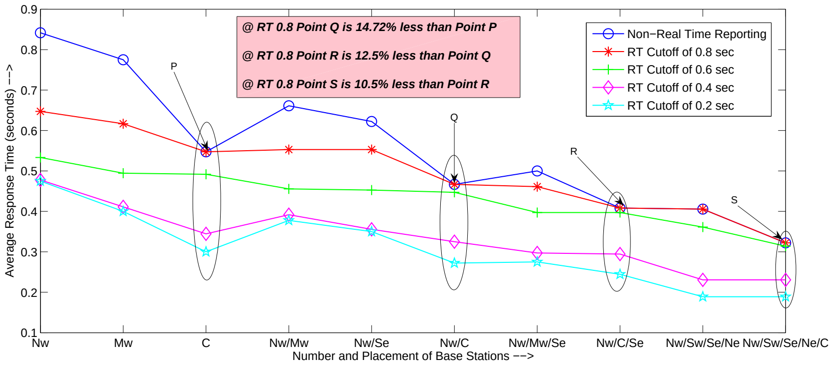

Fig. 4. Average Response Time for the 10 different base-station scenarios.

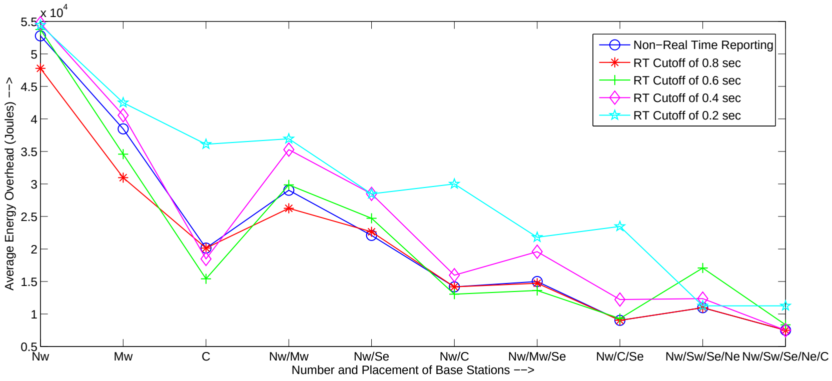

Fig. 5. Average Energy Overhead for the 10 different base-station scenarios.

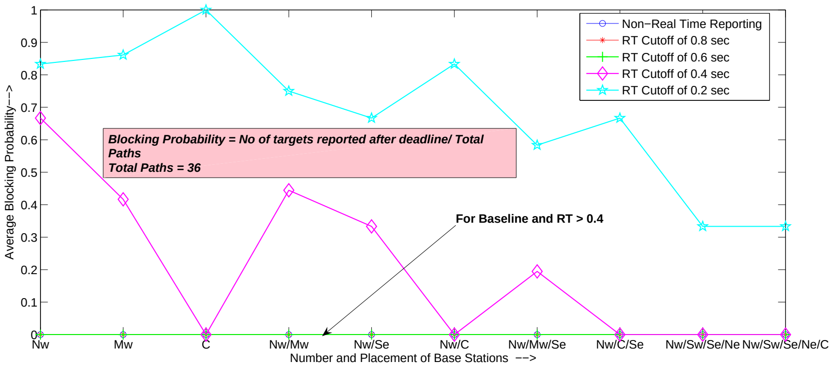

Fig. 6. Average Blocking Probability for the 10 different base-station scenarios.

base-station organization were 36. From the Fig. 6, we observe that all target paths get tracked for non-real time reporting, response-time deadline of 0.8 seconds, and response-time deadline of 0.6 seconds, for all base-station organization scenarios. But as the response-time deadline decreases there are certain paths that cannot be tracked for specific base-station organizations. The graph for response-time deadline of 0.4 seconds indicates that blocking ratio is high for non-optimal base-station placement and the average blocking probability decreases with optimal placement of base-stations. We observe that we can avoid blocking of any target path by having a base-station at the center of the network. Interestingly for the response-time deadline of 0.2 seconds, the blocking probability is highest when we have a single base-station at the center since any target path requires a minimum hops to reach the base-station, which are greater then the response-time deadline (0.2 seconds). In general, the blocking probability keeps decreasing as we keep increasing the number of base-stations and placing at least one base-station at the center of the grid.

In general, we can reduce on the response-time by placing a single base-station at the center of the network. We can further add base-stations depending on the cost factor. Also performing real-time target monitoring results in increased network-lifetime as compared to non-real time target monitoring.

VII. CONCLUSION

In this paper, we proposed coordinated activation and reporting to provide real-time target monitoring in wireless sensor networks. Simulation results show that response-time is highest when non-real time reporting is performed, i.e., data is send to the base-station only when the target reaches the boundary of the network. We have observed that non-real time reporting not only increases the response-time but also increases the energy overhead per node. By incorporating the real-time target monitoring using CAR, we can reduce the response-time and also the energy overhead per node. By carefully selecting the number and the location of base-stations, we can provide minimal blocking probability. We have observed that reducing the response-time deadline beyond a certain point increases the energy overhead substantially and results in a high blocking probability. This is due to the fact that tracking and reporting are no longer performed coordinately. Hence we should be careful in selecting the response-time deadline.

An important area of future work is looking at additional energy-efficient target monitoring. This can be achieved by having only alternate boundary nodes in the network to be active. As nodes are arranged in a grid pattern and have overlapping sensing range, the target always gets detected as soon as it enters the network even with alternate boundary nodes active. Also, in this paper we do not consider medium access layer issues and further energy reductions can be achieved by using S-MAC [14].

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