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PREDICTIVE SINK MOBILITY FOR TARGET TRACKING IN SENSOR NETWORKS

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Abstract— **In sensor networks, the information is generated by sensors deployed in a geographic area, and sent to a node called "sink" (or gateway). Since the node's energy source is a battery, an efficient management of this resource affects the network's lifetime. Our work presents a new approach called RPL (Repositioning, Prediction, Localization), that aims to extend the lifetime of the sensor network for a target tracking application. This is realized by switching sensors between active/sleep states and moving the sink close to the target's future position. The movement of the sink reduces the energy needed for a packet transmission, and minimizes the number of hops between the sink and the emitting sensors. The proposed scheme is validated trhought simulations.**

Keywords: sensor network, target tracking, sink movement

I. Introduction

Recent advances in electronics allowed the development of tiny sensors at low prices, capable of communicating for small distances. However, numerous constraints are still imposed on these devices and especially on their energy. Sensors are randomly deployed in an area of interest. They use incorporated protocols and algorithms allowing them to auto-configure and form a network. The information (temperature, humidity, vibration, etc.) captured by the sensors, is relayed to the sink (or gateway) using a hop-by-hop routing. Many applications exist for such networks (civil, medical and military domains), justifying the numerous research effort in this area.

The sensor's operational time is limited, since it uses a battery as an energy source. This fact makes the proposal of an energy optimization mechanism important, to extend the lifetime of a sensor network. Several approaches deals with this issue. The first approach considers the optimization at the MAC layer, where sleeping modes are considered to save energy ([8], [9], [10]). The second approach acts at the network layer where efficient routing protocols help conserving the energy ([11], [12], [13]). The last approach is based on data aggregation, which exploits data correlations to reduce the size of transmitted information. In our work, we focus on routing mechanisms combined with a new approach, based on the concept of sink mobility. In [6], the notion of sink mobility has been introduced. The sink (gateway) is a mobile node with unlimited energy. The sink moves toward the zone of sensors generating most of the data, and sends the collected information to a central computing server. The sink could be a moving robot, a human with a laptop, etc. The sink's movement reduces the routing cost of the packets, by reducing the number of hops between the source sensor and the sink. This also conserves the remaining energy of the relaying nodes by reducing the number of sensors that participate in packets routing. Furthermore, the sink relocation can also be beneficial in real-time traffic applications. In such applications, the sink movement allows the use of shorter routes, which reduces end-to-end delay.

In the network, every sensor detecting a target generates a packet and forwards it to the sink. When the motion of the target is random, we have a random packet generation, that does not derive from a static zone of sensors. Thus, the solution presented in [6] could not be implemented in target tracking, since it only considers a static traffic, and moves the sink close to the nodes with high traffic loads. Moreover, the network needs to react fast to track the movement of targets without the need to activate all the sensors. Having this in mind, we use a prediction method, that estimates the future position of the target, and allows:

- an early movement of the sink toward the zones, expected to generate packets in the future
- an activation of the sensors in the zone between the current and estimated target positions. The sensors outside this zone are kept in a sleep mode in case the target's velocity is low.

As a consequence, the prediction method will introduce another degree of optimization in network's lifetime (besides sink mobility), since it restricts the number of active sensors. Finally, we propose a new method for target positionning that uses the information of the sensors detecting the target, and localizes the target in the monitored area.

The paper is organized as follows. In the next section, we detail a review of the main related work. In section III, we present our RPL scheme. Section IV describes the detection method used for target tracking. Performance evaluation and results are presented in section V. Finally, section VI presents the conclusions and some future works.

II. Related Work

This section presents a general overview of the previous work done in the target tracking domain.

The ”Distributed Predictive Tracking algorithm” DPT [4] uses a distributed prediction to track moving targets in a sensor network. The protocol relies on a prediction method, that uses the old positions of the target, It activates only three sensors situated in the vicinity of the predicted position. The algorithm becomes inefficient if the target changes suddenly it’s velocity or direction.

In [2], the authors consider a sensor density that insures a minimum number of nodes near the target. The detection range of a sensor is rectangular. The position of the target in the network, is the intersection of the nodes’ ranges detecting the target. This approach lacks of precision when, the number of sensors detecting simultaneously the target, is small.

In [5], the sensors monitor the environment and communicate the data periodically to the server. The server localizes the position of the target (the authors assume that the target continuously transmits a constant signal), using the triangulation method and the data generated by the sensors. This approach relies on the strength of the signal emitted by the target. However, the presence of noise or obstacles may attenuate the signal, resulting in an inaccurate localization of the target.

The authors in [7] propose a target tracking mechanism called Dynamic Convoy Tree-Based Collaboration (DCTC). DCTC, is based on a tree structure called convoy tree. Each node in the tree, corresponds to a sensor near the mobile target. The tree is dynamically configured to add and delete nodes during the movement of the target. Based on the convoy tree, the root gathers information from the sensors, and refines it to obtain a complete and precise information about the target. DCTC becomes ineffective when the target movement is fast and random. Frequent tree updates are then necessary causing a significant increase in the sensor’s energy consumption.

In [3], the authors present three protocols based on the distance between two random nodes. If the distance is lower than the detection diameter 2R, the detection ranges of the two nodes intersect and form a detection region. The line, formed by the intersection of the detection ranges of the active sensors, is moved to detect the target. Every geographic point in the field is scanned at minimum once. It may happen that a target enters the field from one side, while the active line is on the opposite side making the target invisible to the network for a moment.

In the literature, the approaches proposed for target tracking give good results for the case they were build for. Changing the initial assumptions of the tracking approach, leads to a significant decrease in the performance. In our work, we present a global tracking approach since no restriction is made on the targets movements. Moreover, our solution optimizes the energy consumption in the network, by moving the sink mobility, and using a prediction approach for a better management of the sensors energy states (active/sleep).

III. RPL SCHEME

A. Assumptions

In our approach, we consider realistic assumptions independent from network’s state and target movement. Recall that the sink (a laptop, an on-board computer in a car for example), is not energy constrained, and can move in the field with a limited speed. We assume that the nodes’ positions are known at the sink level. This assumption does not present any particular constraint on the solution, since it is generally admitted that the nodes positioning can be solved [1]. Thus, the sink possesses a total view of the network and can use a centralized routing approach, allowing an efficient tracking of the target. Our approach can be considered as a virtual clustering approach, since the sink position is calculated for a specific zone of sensors. We assume that the sensors, at the borders of the monitored area, are always active. The target is detected once it enters the field and then, the tracking is launched. The network is capable of managing simultaneously several targets, and each time a new target enters the detection field, the sink associates to each target a single identifier.

B. Solution description

Our solution distinguishes from the approaches presented in literature ([2], [3], [5], [7]), by the dynamic adaptation of the network to different conditions: single /or multiple targets with low and high velocity movement.

To achieve a maximum energy optimization, our solution merges the benefits of two distinct concepts

- Relocate the sink by considering the remaining energy of the nodes in its vicinity (see next section centroid formula)
- Predict the target’s future position using previous positions, in order to activate a restricted number of sensors for the detection of the target

1) Optimal sink positioning: We can optimize the energy consumed in the network, by moving the sink toward the nodes with low remaining energies. This reduces the transmission distance, and preserves the energy consumed in the network, by reducing the number of sensors that participate in the routing of a packet.

Sink mobility has been introduced in [6] where a cost function is used to calculate the optimal position of the sink in the network but for applications different from target tracking. This fonction takes into account the state of the nodes balanced with the number of transmitted packets in the nodes close to the sink.

The cost function introduced in [6] gives good results if used in a network where events are localized in static zones. But, when it comes for target tracking it gives poor performance since when the target moves fast, packets are generated randomly from different zones. In this case, the sink will not have enough time to move toward the position calculated by the cost function and if it does, the target will already be far from this calculated position. This leads to a frequent change in sink positions and a very high packet loss rate. Therefore, we introduce an*Energy centroid* (1) formula that finds the optimal positions of the sink with a fast moving target by considering the remaining energy of the neighboring sensors belonging to a prediction region which we will define in section 3. For the best of our knowledge, this formula has never been used in this domain.

The energy centroid formula main goal is to move the sink closer to the nodes that will generate the traffic in the near future and more precisely toward the nodes with the minimum remaining energy. This movement is done with the help of the prediction method described in next section. The main advantage of moving the sink is the reduction of the packet's total power transmission: packets need less hops and less transmissions distance to reach the sink. This results in a reduction in the energy consumed per route and limits the number of sensors involved in the routing. Both results are beneficial to reduce the energy consumption in the network and hence increase its lifetime.

The formula of the energy centroid is given as follows:

$$(X_G = \frac{\sum_i \frac{1}{Energy_i} \cdot x_i}{\sum_i \frac{1}{Energy_i}} \; ; \; Y_G = \frac{\sum_i \frac{1}{Energy_i} \cdot y_i}{\sum_i \frac{1}{Energy_i}}) \quad (1)$$

where X_G and Y_G are the coordinates of the new calculated position of the sink. Index *i* represents the identifier of all the active sensors in the prediction region (see section 3). x_i and y_i are the coordinates of the active sensor *i* and $Energy_i$ it's remaining energy. As it can be noticed, the weight of the sensor position is inversely proportional to its remaining energy, which will make the centroid close to nodes with little remaining energy. Note that this formula requires the knowledge of the sensors' energy in the specific zone, the remaining energy of the nodes is simply updated by the sink upon packet reception. This is done using the routing table that identifies the sensors that participated in the routing.

2) Predict the future position of the target: Our prediction method is based on the kalman filter prediction which uses the former positions of the target to predict its future position. In our approach, this is done in order to activate only the sensors in the vicinity of the current and future target's positions, this region is called the prediction region (PR). The used model for target motion is linear and is as follows:

$$X(t_{n+1}) = \Phi X(t_n) + \Gamma w(t_n) \quad (2)$$

where:

$$X = \begin{pmatrix} x \\ y \\ x' \\ y' \end{pmatrix}$$

X is a state vector consisting of position and velocity which evolve at each time interval according to the model in (2)

$$\Phi = \begin{pmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Gamma = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{pmatrix}$$

where w is zero-mean gaussian white noise with zero mean and covariance Q

$$Q = \begin{pmatrix} qT & 0 \\ 0 & qT \end{pmatrix}$$

T is the time step and q is a constant.

3) Prediction implementation: In our solution, the velocity of the target is the key factor used by the network to allow an efficient detection of all the targets while reducing the energy consumption of the sensors. In case a single target enters the monitored area with a low speed, using the former position of the target, we can predict its future position. These two positions (current and future) enable us to define a rectangular zone called the prediction region PR contained in a circle of radius R, and all the nodes included in this zone are activated. The movement of the sink into the PR zone is made to (1) reduce the transmission power of the sensors. If the predicted position is in the PR zone, to avoid unnecessary updates of the sink position, we condition the sink movement to the following criteria:

$$(dist(Sink, pos_{pred}) > 2{*}Range) \wedge (min(Er(i)/i \in S_d) < \Delta) \quad (3)$$

where:

- S_d be the set of the nodes participating in the routing of the packets generated by sensors belonging to S1
- S_1 = set of sensors in the PR zone with a distance less than Range from the predicted position
- Range is the detection range of the sensor, Er(i) is the remaining energy of node i and Δ is an energy threshold (for example, 20% of the node's initial energy)

If the target increases dramatically its velocity, the sink becomes incapable of tracking efficiently the target and will not have enough time to reach the calculated optimal position. Therefore, we propose a solution to activate all the sensors in the network and place the sink according to the formula of the energy centroid (1). The energetic centroid will be updated periodically using parameter p according to the speed of the target. This approach can be generalized in the case of several moving targets.

IV. Target localization method

In a target tracking application, the aim is to localize the position of the target. The network uses the packets received from the sensors which detected the target to compute the target's position. As mentioned previously, the sink knows all the positions of the sensors and possesses a total view of the network. When the target is simultaneously detected by several sensors at the same time, these sensors send the data packets to the nearest sink. The sink transfers these data to the command node which localizes the position of the target using our "homemade" method.

A. Localization method description

The method's main goal is to simplify target localization when the number of nodes n detecting the target is high. It reduces the number of nodes participating in the localization process for the computation of the real target's position.

If we consider the detection range of a sensor to be circular, the location of the target is the intersection of all the detection ranges (circles) of the sensors detecting the target. Note at this step, that the final target localization is the minimal intersection area of the detection ranges but not an exact position.

For a network with a high sensor density, target's location would be the intersection of numerous detection ranges corresponding to all the sensors having detected the target. This leads to computational complexity if we proceed using an iterative calculation method. To solve this problem, we introduce a new approach which to our knowledge does not exist in the literature. This approach reduces the computation for target position, from an intersection of *n* circles to an intersection of four circles, where *n* is the number of sensors which have detected the target. We assume that all the nodes have a circular detection range of the same radius.

Let us consider the following notations:

- Let Z be the minimum area containing the target
- Let D be the set of all nodes detecting the target
- Let (c_i),(c_j) and (c_k) be the circles having as centers N_i, N_j and N_k respectively

The goal of our method is to *minimize Z*. The method is summarized by the following algorithm:

Target localization algorithm

1) $\forall N_i, N_j \in D$, compute (d_1) the line formed by the points T_1 and T_2 such that $\{T_1, T_2\}$ = $(c_i) \cap (c_j)$
2) For all nodes $N_k \in D - \{N_i, N_j\}$
   Find the circle(s) c_k that restrict(s) the zone between T_1 and T_2, T_1 and T_2 become the limit of this zone on (d_1)
3) Find nodes which detection ranges (circles) pass through T_1 and T_2

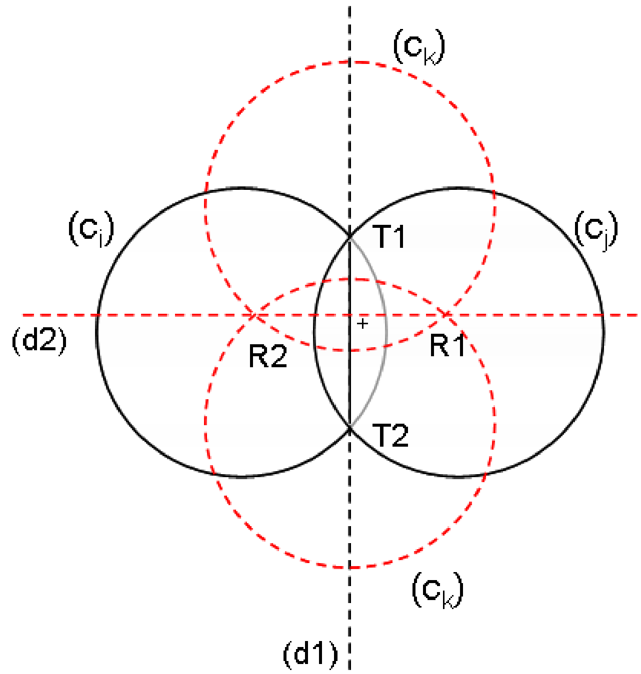

Fig. 1. The detection method

   3.1 If only one circle (c_s) passes by both T_1 and T_2 Then Z = $(c_s) \cap (c_i \cap c_j) \Rightarrow$ END
   3.2 Two circles (c_l) and (c_m) pass through T_1 and T_2
   - Compute points R_1 and R_2 such that ($\{R_1$,$R_2\}$ = $(c_l) \cap (c_m)$)
   - Compute line (d2) passing through R_1 and R_2
4) For all nodes which detection range ($\neq (c_l, c_m)$) intersects (d_2) and restricts $[R_1 R_2]$
   4.1 Execute (3.1) with $[R_1 R_2]$ substituting $[T_1 T_2]$
   - If two distinct circles exist passing by R_1, R_2
     Compute the intersection zone Z_1 of these two ranges Z = $(c_l) \cap c_m) \cap Z_1 \Rightarrow$ END
   - else (one circular (c_r) range pass by R_1, R_2)
     Z = $(c_r) \cap (c_i \cap c_j) \Rightarrow$ END

This method tries to compute the minimum zone in which the target is located. First, two nodes detecting the target are chosen arbitrarily in order to calculate the line (d_1). Then, in an iterative way the circles that intersect and restrict $[T_1 T_2]$ are found. After the second step, the method finds the circles passing by T_1 and T_2 and computes (d_2) which is the line formed by the points R_1 and R_2 resulting from the intersection of the circles passing by T_1 and T_2. The same method is used to restrict $[R_1 R_2]$. At the end, the zone in which the target exists is the intersection of (c_j), (c_i) and (c_k) (k can be 1 or 2) as shown in figure 1 ('+' in figure 1 represents the target).

V. Performance evaluation

The effectiveness of our RPL scheme with its repositioning, prediction and localization methods has been validated through simulations. In our experiments, we used Opnet simulator. The network is composed of 250 fixed nodes randomly distributed over a 100m x 100m square area. The detection range of a node is 20 meters and all nodes possess the same initial power estimated to 5000 unit (u). We consider that at any time only one event can occur in the network. Our simulation lifetime is considered as a series of rounds. A round represents the change of the target's position which is implemented by the routing of the packets generated by the sensors to the sink. A single event is generated per round of simulation which is fixed to every second. The target moves at a constant velocity of 1 m/s. The energy of the nodes in the network is updated after each packet routing. We considered two conditions to stop our simulations: the first is when 50 percent of the network nodes are depleted and the second is when the target becomes invisible to the network, i.e. all the packets generated by the sensors that detect the target are lost (do not reach the sink).

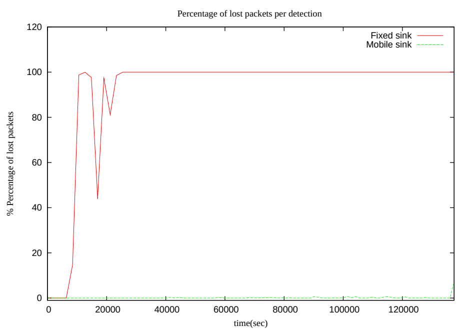

Fig. 2. Percentage of lost packets per detection

In figures 2 and 3, we consider that the simulation stops when 50 percent of the sensors are depleted.

In figure 2, we plot the percentage of packet loss per detection for the cases where the sink is fixed and mobile. The x-axis represents the number of rounds in the network and each round corresponds to a target detection. We can notice from figure 2 that between 0 and 8761 seconds, the network have the same percentage of packet loss for both cases. But, this tendency changes for the fixed sink case because of the depletion of the 1-hop neighbors of the sink. Since these neighbors are used in the routing of all the packets generated by the sensors, they are statistically the first nodes to die which results in the lost of all the packets generated by the sensors after 22969 seconds as it can be seen in figure 2. When the sink moves toward the position calculated by the energy centroid formula, we can clearly notice that the percentage of lost packets per detection is very low. This result was expected since the sink is positioned close to the zone that generate the most number of packets. Thus, the transmission distance between the source and the sink is reduced preserving the energy of the sensors. Moreover, the number of nodes participating in the relaying of the packet is reduced resulting in less overall energy consumption in the network.

In figure 3, we show the energy consumed per target detection. Between 0 and 20000 seconds, we observe that the energy consumption for target detection for a fixed sink is higher than the energy consumption when the sink moves. This results from the fact that the length of the routes in the first case (fixed sink) is always higher than the second case (moving sink) since the sink is always close to the zone generating the packets. We also notice that the energy consumed per detection is stable with a mobile sink but the behavior is different for a fixed sink. For moving sink, the sink is always in a zone where packets can be routed. On the contrary, in the fixed-sink case, the sensors detects the target but the routing uses less hops without reaching the sink since most of the sink neighboring nodes are depleted.

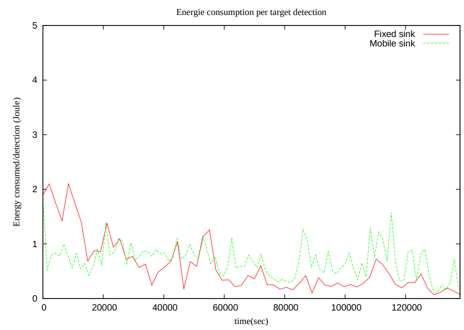

Fig. 3. Energy consumption per target detection

In figures 4 and 5, we consider the case where the simulation stops when all the packets generated from a target detection are lost.

Figure 4 shows a lifetime comparison between the case where the sink is fixed and when the position of the sink is changed according to the energy centroid formula. In figure 4, p represents the periodicity of updating the position of the sink using the energy centroid formula. The lifetime of the network is calculated in terms of the number of successful detections a network can perform. We can notice that the lifetime of the network when the sink moves outperforms the lifetime of the same network when the sink is fixed. This also results from the fact that most direct neighbors of the sink are depleted in case of fixed sink which results in an early packet loss. In fact, the use of the energy centroid formula depends also on the periodicity at which we update the sink position. We can clearly see, that if we increase this period, we will not react rapidly to the movement of the target which impacts the number of successful detections.

Figure 5, shows the lifetime of the network using a mobile sink for different R values. Recall that R is the radius of the circle containing the predicted zone PR. This means that only the nodes belonging to the PR area are used in the calculation of the energy centroid. This figure shows that the choice of the nodes that participate in the calculation of our formula is crucial to extend network's lifetime. The lifetime duration using a radius R = 1.5 * Range where Range is the detection range of a single sensor (here Range= 20m), is significant compared to the same network where the centroid formula is calculated using a larger R.

Finally, to evaluate the performance of our detection method, we use the same previous simulation parameters.

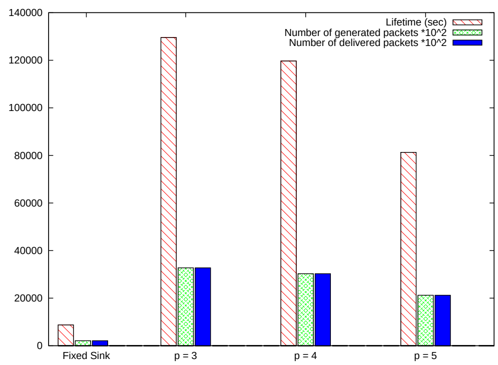

Fig. 4. Impact of updating parameter p

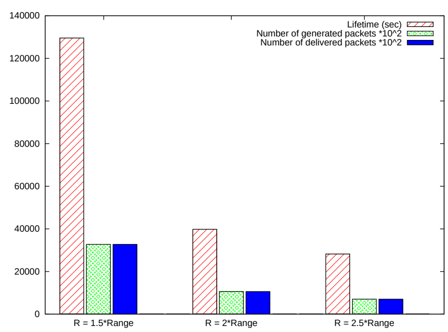

Fig. 5. Impact of updating parameter R

The obtained results are illustrated in figure 6. They show the difference between the real position of the target and the position computed by our detection method. This result proves the efficiency of our method since the mean difference between the real and calculated positions is around 3 meters with a peak value of 16 meters.

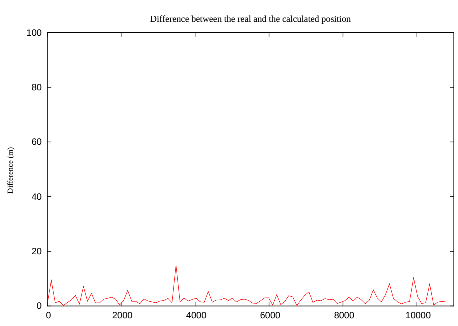

Fig. 6. Difference between the real and calculated positions

VI. Conclusion

In this paper, we introduced a new approach for target tracking in sensor networks. This approach joins and extends the research in the field of sink positioning and target tracking. Sink positioning increases the average lifetime of the network by decreasing the average energy consumed per target detection. Moreover, the network throughput is largely improved. For a better energy optimization, we also proposed a target prediction method which allows activation of only a subset of nodes in the vicinity of the expected target path. We finally proposed an efficient algorithm to reduce computational complexity for target localization estimation. Simulation results have demonstrated the effectiveness of our approach in terms of energy consumption and network throughput.

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