Biologically Inspired, Cooperative Target Tracking Framework for Wireless Sensor Networks

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Abstract: We introduce an energy-efficient Cooperative target tracking framework for Wireless Sensor Networks (WSN). A Biological Independent Task Allocation (BITA) algorithm is presented to execute an application using a group of nodes. BITA is inspired from biological behaviours of differentiation in zygote formation. Simulation results show that BITA leads to improved network performance in terms of the number of served targets and service time compared with other commonly used algorithms.

1 Introduction

Wireless Sensor Networks (WSNs) consist of small electronic nodes connected to each other via wireless communication protocols. Each node is equipped with embedded processors, sensor devices, storage, and radio transceivers. The nodes or sensors cooperate to sense, compute and transmit the information to the main controller. The sensor nodes have limited resources in term of battery-supplied energy, processing capability, communication bandwidth, and storage. WSNs have useful civil and military applications including healthcare, target tracking, monitoring, smart homes and surveillance [1]. Target tracking requires highly accurate estimation and prediction. Selecting suitable nodes from the nodes in the vicinity of an incident target improves the measurements accuracy. However, due to the unattended nature of sensor nodes, energy conservation and network lifetime remains a crucial issue [2].

This paper proposes a novel autonomic self-organising framework for biologically inspired Cooperative target tracking algorithm using fitness functions. The motivation of the proposed system is twofold. Firstly, concurrent processing in WSNs decreases the prevalence of gaps in the network caused from dying nodes and consequently increases the overall network lifetime. Secondly, a cooperative tracking algorithm facilitates the timely completion of real time applications by exploiting the speed-up resulting from concurrent processing. Moreover, the proposed selection algorithm improves the network lifetime and measurement accuracy because it allows the system to choose the best nodes in terms of resource availability and their locations, relative to the target. The biological [3] aspect of the proposed system is inspired from the zygote. When a zygote is formed, it comprises a collection of similar stem cells. Over time, the zygote cells start to specialize with different functionalities. This behaviour is called differentiation [4]. The same principle is be applied in the proposed system; the network nodes start equally in a default state and then exhibit some kind of differentiation to perform certain tasks according to their resource availability and location with respect to the target and other nodes. The nodes behave as if the target is a virtual chemical emitter. Their proximity to the target is used to influence the differentiation process.

2. Related Work

A number of researchers have already considered target tracking in WSNs. In [2], collaborative target tracking is proposed. The selection of the nodes used to track the target is based on the predicted target location. In [5], regular and irregular network topologies are proposed to track a target using mobile agents. The nearest nodes to the target are selected to track it. In [6], dynamic clustering for target tracking is proposed. However, in [5] and [6], all sensor nodes have to be in sensing mode all the times. To reduce the energy consumption, the proposed system adopts a hybrid architecture, in which static cells with Cell Heads (CHs) are in sensing mode all the time and dynamic tracking groups are formed when the target arrives. To prolong the network lifetime, the proposed algorithm adopts a fitness function to choose the nodes to track the target based on the target range and available resources. Unlike the proposed system, in [7] the cluster heads have its nodes information all the time. In [7] the nearest three nodes are selected from the current cluster. However, in the proposed system, the best three nodes in the vicinity of the target are selected and they may belong to different clusters.

The proposed system makes the following contributions: 1. It employs an energy-efficient framework. 2. Biologically-inspired self-organisation, including election and selection algorithms. 3. A Biological Independent Task Allocation (BITA) algorithm to decompose an application that can be divided into independent equal-weighted subtasks. 4. Meta-data migration to facilitate the configuration process. 5. Proactive handover to enable seamless target tracking. To our knowledge, this is the first research inspired from zygote biological behaviour, where differentiation is related to distances to the target and among the nodes

3. Framework and Algorithms Used

Assume, $S_{net}= \{ s_i, i=1,2\ldots,m\}$ are heterogeneous WSN. For sensor node "s_i", "NID" is the node ID, "E" is its remaining energy, (x, y) is its position and "p" is its CPU speed. As shown in Figure 1 (b), the sensor nodes are

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randomly deployed in the area of interest to track target(s). We assume that some of sensor nodes have advanced capabilities such as mobility, routing algorithms, additional resources and automatic power control.

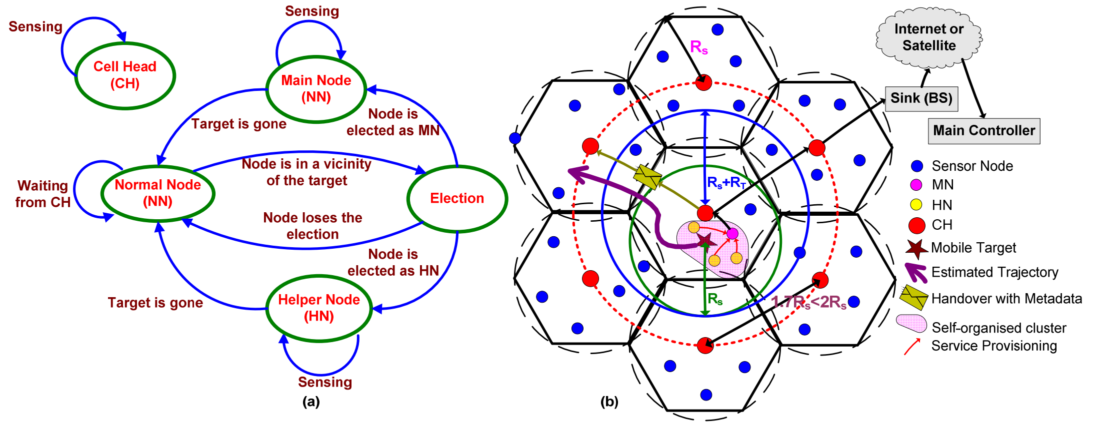

Figure 1 (a) Node State Transition Diagram, (b) System Architecture

We assume that after deploying the nodes, the advanced sensor nodes move to form a cellular-based network topology. In the centre of each cell is one of the advanced nodes and we refer to it as a Cell Head (CH). The cell radius equals to the sensing range (R_s). The radio range, R_r, is set to twice of the sensing range, R_s. Therefore, one-hop communication is employed to communicate between each CH with its six CHs neighbours and to communicate with the sensor nodes inside the sensed area. Multi hop communication is used to connect the CHs and the sink (i.e. the base station) using well-known table-driven routing protocols. However, CHs do not know any prior information about the sensor nodes. As shown in Figure 1 (a), CHs are always in sensing and communication modes, while all the remaining nodes are initially in communication mode alone, using ultra-low communicated channel. We assume a potential target can be regarded as a virtual chemical emitter that influences nodes to a degree called chemical diffusion gradient (*CDG*) that is determined by their proximity to the target. When the target arrives, the CH informs the nodes to go to sensing mode. Therefore, initially, all the wireless nodes inside the sensed area are assumed to be equal. After that, nodes within target's region of influence are organized by election into a group that specifies the nodes into Main Node (MN) and Helper Node (HN). This group cooperatively provides the target tracking and the network management functions according to the strength of the chemical and node available resources. There are three system operational phases, namely: group discovery, service provisioning and group management.

3.1 Group Discovery & Election Algorithm

When the CH(s) detects the target, it computes the range from it, R_T. If the received signal (i.e. acoustic signal) from the target is below a threshold value, the target will be in the Handover Region (HR), which is the intersection between cells. Therefore, a CH Selection (CHS) message is required to choose the nearest CH to the target. The selected CH broadcasts Target Detected (TD) message to its (R_T+ R_s) neighbours to inform them to go to sensing mode. The nodes (S_d) that detect the target compute the target's range, switch of the sensing range and broadcast it with their locations, remaining energies and processor speeds to the CH and their (S_d) neighbours through Selection and Election (SEEL) message. The CH computes and selection fitness function (f_S) as follows:

$$f_S(s_i,T_j,\beta,S_d)=\left[\beta*\frac{CDG(s_i,T_j)}{\sum_{\forall k\in S_d}CDG(s_k,T_j)}\right]+\left[(1-\beta)*u(s_i,\alpha,S_d)\right] \quad (1)$$

where the node utility (u) relative to a set of nodes "S" and $CDG(s_i, T_j)$ of the node(i) on the target (j) are:

$$u(s_i,\alpha,S)=\left[\alpha*\frac{E_{s_i}}{\sum_{\forall k\in S}E_{s_k}}\right]+\left[(1-\alpha)*\frac{p_{s_i}}{\sum_{\forall k\in S}p_{s_k}}\right] \quad (2) \qquad CDG(s_i,T_j)=\frac{Q(T_j)}{d_{s_iT_j}} \quad (3)$$

and 0 <= α and β <= 1, "d_{siTj}" is the distance to the target, $Q(T_j)$ is the target (j) importance or class and is used for multi target tracking to give priority to more important targets. The CH selects the set of "n_g" nodes(S_g) that have the greatest fitness function defined in (3), where 3 <= n_g <= q , "q" depends on the target importance $Q(T_j)$ and should be less than or equal number of the S_d set, n_d. After this, the CH performs the election algorithm to choose the MN as the node that has the maximum fitness function defined as follows:

$$f_E(s_i,\gamma,S_g)=\left[\gamma*\frac{C_{s_i}}{\sum_{\forall k\in S_g} C_{s_k}}\right]+\left[(1-\gamma)*u(s_i,\alpha,S_g)\right] \quad (4) \qquad C_{s_i}=\frac{1}{\sum_{\forall k\in S_g} d_{ik}} \quad (5)$$

where 0 <=γ<= 1, C_{si} is the node centrality which indicates how much it is in the group centre and d_{ik} is the distance between node (*i*) and (*k*). The CH sends to the MN the election results through election (ELE) message.

3.2 Service Provisioning & BITA Algorithm

Most of target tracking algorithms adopt dynamic systems to get the states of the target. Using a Kalman Filter (KF) is one approach for target tracking. A KF dynamic system uses matrix based equations, which need high computational power [2]. We assume the system uses one of the target tracking algorithms, which can be partially decomposed into "*N*" independent equal weight subtasks. The MN performs the BITA algorithm to distribute the tasks among the group (S_g) based on the nodes utility and their influences (*CDG*) on the MN. It computes the decomposed fitness functions (f_D) of the group nodes as follows:

$$f_D(s_i,\delta,S_g)=\left[\delta*\frac{CDG(s_i,s_{MN})}{\sum_{\forall k\in S_g} CDG(s_k,s_{MN})}\right]+\left[(1-\delta)*u(s_i,\alpha,S_g)\right] \quad (6) \qquad CDG(s_i,s_j)=\begin{cases}\frac{1}{d_{s_is_j}} & i\neq j\\ Z & i=j\end{cases} \quad (7)$$

Where 0 <= δ<= 1, $CDG(s_i, s_j)$ is the influence of node (*i*) on node (*j*) and *Z* is an integer number. To have load balancing and minimise the consumed resources, each group node is assigned a number of tasks, $n(s_i,N)$, so that:

$$\frac{n(s_1,N)}{f_D(s_1,\delta,S_g)}=\frac{n(s_2,N)}{f_D(s_2,\delta,S_g)}=.........=\frac{n(s_{n_g},N)}{f_D(s_{n_g},\delta,S_g)} \quad (8) \qquad \sum_{\forall k\in S_g} n(s_k,N)=N \quad (9)$$

$$n(s_i,N)=N*\frac{f_D(s_i,\delta,S_g)}{\sum_{\forall k\in S_g} f_D(s_k,\delta,S_g)} \quad (10)$$

The MN informs the HNs about their functionalities through the Function (FUN) message. The HNs send the results to the MN through Results (RES) messages and the MN sends the current and predicted target states to the CH through Target State (TSTA) message. The CH sends the current states to the sink and uses the predicted states to proactively form the next group.

3.3 Group Management

Advanced functionalities are achieved in this phase including proactive soft and hard handovers, recovery mechanism from unexpected target's trajectory and meta-data migration. In proactive soft handover, which occurs inside the current cell, the CH broadcasts a Target Prediction (TP) message to its (R_{PT}+R_s) neighbours to inform them to go to sensing mode, where R_{PT} is the predicted distance of the target to the CH. The selection and election processes described in Section 3.1 take place to form a group from the nodes (S_d) that has distances to the target's predicted location less than or equal the sensing range, R_s. When the target arrives in the vicinity of the predicted group, the same processes described in Section 3.2 take place. The proactive hard hand-over takes place, if the predicted target location is inside the HR, where the old CH sends the target predicted location to its neighbour CHs through a Handover (HO) message. The new CH is the one that the target enters its HR and performs the same steps described in the soft handover. Other CHs keep monitoring for any recovery required. If the target changes its predicted direction and enters a cell unexpectedly, the unexpected CH will inform the predicted new CH about the situation and then follows the same steps described in Sections 3.1 and 3.2. Finally, behavioural data gleaned whilst observing or servicing a target is recorded as meta-data that can be transferred to subsequent nodes during proactive handovers to facilitate the configuration process.

4. Simulation Results

The C++ language has been used to build a simulation comprising 350 wireless sensor nodes that are randomly deployed across an area of 1km $\times$ 1km. We assume line of sight (LOS) communication between the nodes within the same coverage area. The radio and sensing ranges are set to 200m and 100m respectively. Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is used and the transmission speed is set to 1 Mb/s. We initialise the nodes battery capacity (E_{max}) to 500 units and assume each task requires 1 unit. Each node can execute 10 tasks each second and α=1, β=γ=δ=0.5. The simulator is run twenty times with different node deployments and is stopped after 10 minutes. The average results with 95% confidence are plotted. The BITA algorithm is evaluated against Distributed Computing Architecture (DCA) [8] in which the cluster performs high-level tasks. In the following figures, DCA is referred as n_g=1. The performance metric used for evaluation is:

$$P_m = \frac{\sum_{k=1}^{m} E_{s_k} / E_{\max}}{m} \tag{11}$$

As shown in Figure 2, due to node cooperation and based on equation (10), BITA can serve more targets than DCA and has a lower (P_m) than DCA. With increasing group membership size (n_g), more targets can be served and lower (P_m) is achieved because, based on equation (10), we can get more load balancing among the nodes.

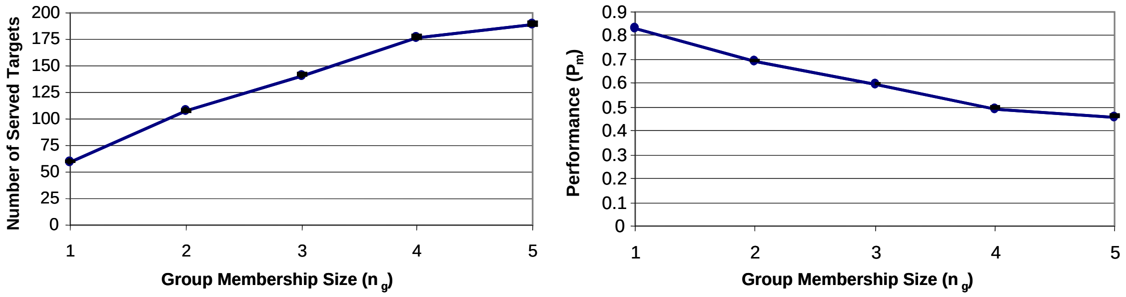

Figure 2 Served Targets and Performance Metric versus Node Group Membership Size (n_g)

In Figure 3, BITA ends with less Cooperative Execution time (CET) than DCA. CET increases with increasing number of tasks *N* and decreases with increasing n_g. In Figure 4, with decreasing δ in equation (6), the number of dying nodes decreases while the number of served targets increases. If we assume the tasks assignment and task results transmission is small enough compared to tasks sizes, the weight of nodes utility in equation (6) increases with deceasing δ more than the weight of node influences and this leads to better load balancing.

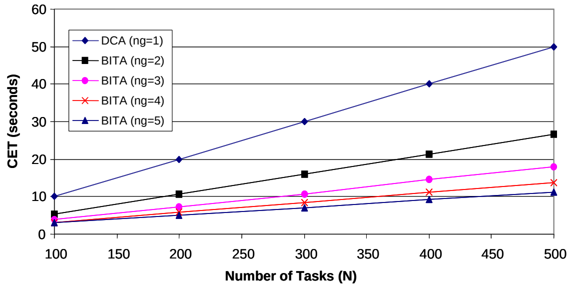

Figure 3 CET versus Number of Tasks (N)

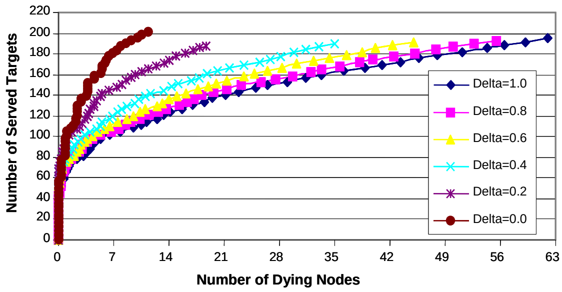

Figure 4 Dying Nodes versus Served Targets

3. Conclusion

This paper introduces an autonomic self-organized framework for target tracking in WSNs. The BITA algorithm, which divides applications into independent tasks, is introduced and evaluated. The aim is to reduce CET and increase the network lifetime by adopting load balancing. Simulation results show that compared with DCA, BITA can improve the network performance in terms of the number of served targets and CET.

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