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SDN-based Anchor Scheduling Scheme for Localization in Heterogeneous WSNs

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***Abstract*—In this letter, the anchor scheduling scheme for localization in heterogeneous wireless sensor networks (WSNs) is studied. In order to minimize the number of actively participating anchors to prolong the network lifetime, we propose a centralized anchor scheduling scheme on basis of the software-defined networking (SDN) paradigm. First an expression evaluating the connectivity degree of an agent is derived and used to judge if this agent has desired number of connected anchors for its localization. Then the state of each anchor is determined by the SDN controller through a flow table via sensor OpenFlow (SOF). Simulations show that the proposed anchor scheduling scheme reduces the number of active anchors and prolongs the network lifetime. It can also be shown that this scheme ensures the desired number of anchors for the localization, and can tradeoff the localization accuracy for energy by ensuring a better balance of energy consumption among minimum number of active anchors.**

***Index Terms*—Heterogeneous wireless sensor networks, localization, anchor scheduling scheme, software-defined networking.**

I. Introduction

Positioning in wireless sensor networks (WSNs) has attracted intensive research interest for its variety of promising applications [1], such as environmental monitoring, social networking, asset tracking and indoor navigation [2]. Recently, to meet the more diverse need of the network, the heterogeneous WSNs have become popular, which motivates the research activities in localization for these networks.

Due to the resource-limited nature of sensor networks, localization algorithms in WSNs have been suffering from serious energy conservation problems. Considering these constraints in WSN localization, the number of actively participating nodes should be kept to a minimum. Existing researches have made great efforts to design efficient scheduling schemes and optimize the power allocation for the localization algorithms [3-5]. In [4], a distributed scheduling algorithm based on information evolution is proposed for the localization. Through neighbor selection and collision control, this scheduling algorithm decreases the complexity and overhead of localization, thus conserving the energy in the network. Authors in [5] present a distributed iterative localization which uses minimal number of anchor nodes for sensor localization.

In existing distributed algorithms, the sensor nodes in the network exchange data with their neighboring nodes only; no centralized data processing or communication occurs, nor is there a centralized fusion center to compute the sensors' locations. Therefore, they are usually suboptimal and less energy-efficient compared with the centralized ones. The upsurge of the software defined networking (SDN) technique brings new chance to design optimal centralized algorithms for WSN localization by making a logically centralized software program control the behavior of the entire network [6]. In addition, for heterogeneous WSNs, there are more diversity and rigidity in the underlying infrastructures, resulting in their harder management compared with homogeneous ones. The SDN paradigm in networking can improve the network management for them, because it can control the networks from a global perspective. On the other hand, agents in the heterogeneous networks need to be software defined so that they can be redefined to communicate with the anchors of different types. Another advantage of the SDN paradigm is that, the controller in it is attached to the wall sockets and equipped with high-speed microprocessors and long-distance transceivers, hence, it can execute the localization algorithms more quickly and more efficiently.

In this letter, we study the anchor scheduling problem in localization for heterogeneous WSNs on basis of the SDN technique. The proposed scheme determines the state of anchors (sleeping/operating) in each time slot to reduce the energy consumption, as well as ensures an expected connectivity degree of each agent for localization. All the decisions are manipulated by the SDN controller and handled to each node by the flow tables. Simulations show that the proposed scheme ensures the desired number of anchors for localizing each agent and can make a tradeoff between the localization accuracy and energy consumption.

II. Problem Formulation

We consider a localization scenario in heterogeneous WSN on basis of the SDN paradigm, which is shown in Fig. 1. The network is composed of N_b anchor nodes and N_a agent nodes. Let $\mathcal{N}_b = \{1, 2, \ldots, N_b\}$ be the set of anchors and $\mathcal{N}_a = \{N_b + 1, N_b + 2, \ldots, N_b + N_a\}$ the set of agents, respectively. The sensor node positions are denoted by $\{\mathbf{x}_i = (x_i, y_i)^{\mathrm{T}} \in \mathbb{R}^2, i \in \mathcal{N}_b \cup \mathcal{N}_a\}$, and the distance between nodes i and j is denoted by d_{ij}. For anchors, they

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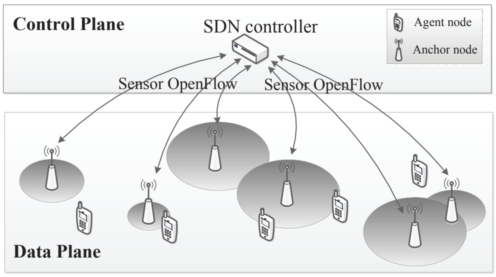

Fig. 1. SDN-based localization scenario in heterogeneous WSN.

can be categorized into K different types according to their communication ranges. Their positions are fixed and exactly known. Agents are mobile devices with unknown positions and are software-defined that can communicate with the anchor node of any type. We assume that the communication of a type k $(1 \leq k \leq K)$ node follows the binary disc model, in which one can perfectly be connected only within the disc of radius c_k centered at $\mathbf{x}_k$, where c_k is the communication range. The connected region is denoted by disc $\mathcal{A}(\mathbf{x}_k, c_k)$ and the area of communication disc is $\|(\mathbf{x}_k, c_k)\| = \pi c_k^2$.

In Fig. 1, the SDN-based network separates the control plane and the data plane, using the sensor OpenFlow (SOF) proposed in [7] as the southbound interface between these two planes. The SDN controller in the control plane centralizes all the network intelligence, dictating the whole network behavior. It determines the state of anchors and handles the decisions to each node through the flow tables. The sensor nodes in the data plane are controllable by the SDN controller. They receive control messages from the controller and then perform actions based on the flow tables on them.

III. Connectivity Degree

We assume the dynamic model of node i at time slot n is

$$\mathbf{x}_i^{(n)} = \mathbf{x}_i^{(n-1)} + R_m \cdot \Theta, \tag{1}$$

and $\Theta = [\cos\theta, \sin\theta]^{\mathrm{T}}$, θ is a random variable with uniform distribution in $[0, 2\pi]$. This is a simplified form of the Linear-Gauss model in [8], which follows a uniform stationary distribution. The possible area of $\mathbf{x}_i^{(n)}$ is a circle of radii R_m centered at point $\mathbf{x}_i^{(n-1)}$. We call this area the interest area and denote it by $\mathcal{A}_i^{(n)}$. Let S denote a random variable indicating the distance of the anchor in the interest area to the agent. The possible values s of S are $0 \leq s \leq R_m$, and the probability density function (PDF) for S is $f_S(s) = 2s/R_m^2$ [9].

Let $p_{ij}^{(n)}(s)$ be the probability that a point in $\mathcal{A}_i^{(n)}$ which is at a distance of s from $\mathbf{x}_i^{(n-1)}$, can be connected with anchor j. $p_{ij}^{(n)}(s)$ is equal to the ratio of the intersection area between $\mathcal{A}_i^{(n)}$ and the disc $\mathcal{A}(\mathbf{x}_j, c_j)$ to $\mathcal{A}_i^{(n)}$. As a result, the expected value of the probability (i.e., $E[p_{ij}^{(n)}(s)]$) that a point inside the interest area which is connected with anchor j is

$$p_{ij}^{(n)} = E[p_{ij}^{(n)}(s)] = \int_{s=0}^{s=R_m} p_{ij}^{(n)}(s) f_S(s) ds. \tag{2}$$

In a 2-D localization system, at least three range measurements with anchors are needed to estimate the position of agent according to the principle of triangulation [10]. Let $B_m^{(n)}(i)$ denote the event that a point in the interest area is connected with $m_i^{(n)}$ anchors, and $\mathbf{E}^{(n)} = \{E_1^{(n)}, E_2^{(n)}, \cdots, E_Q^{(n)}\}$ denote all the combinations of $B_m^{(n)}(i)$ anchors of different types. In the combination $E_q^{(n)}$ $(1 \leq q \leq Q)$, the number of type k anchor is $m_{qk}^{(n)}$, and $\sum_{1 \leq k \leq K} m_{qk}^{(n)} = m_i^{(n)}$. The probability of event $B_m^{(n)}(i)$ can be calculated as (omitting the time slot index)

$$P(B_m(i)) = \sum_{1 \leq q \leq Q} p(E_q) \prod_{1 \leq k \leq K, \forall j \in \{k\}} p_{ij}^{m_{qk}}, \tag{3}$$

where $\sum_{1 \leq q \leq Q} p(E_q) = 1$, and $p(E_q)$ can be calculated through the enumeration.

We obtain the connectivity degree of agent i at slot n by integrating (3) over the interest area, and define it as

$$\xi_i^{(n)} = \int\int_{\mathcal{A}_i^{(n)}} P(B_m^{(n)}(i)) d\mathcal{A}. \tag{4}$$

With this definition, we design our scheduling scheme under the premise of satisfying a specific connectivity degree threshold ξ_{th}. For example, if we set $m_i^{(n)} = 4$ and $\xi_{th} = 0.85$, it means the scheme ensures an at least 85% possibility that agent is connected with 4 anchors.

IV. Anchor Scheduling Scheme

A. Timer of Anchor

As the agent in the network is assumed to move continuously, the state of anchors may not change too frequently during several successive time slots. We design a timer for each anchor, the timer of each anchor is calculated according to its contribution to the localization of neighboring agents and its residual energy to balance the energy consumption for prolonging the network lifetime. When the timeout occurs, the anchor sends messages to the controller to ask for its state at the next time slot. The timer for the selection allows anchors for competition to be active. The anchors with shorter timer will have more chance of being selected for localization.

The Cramer-Rao lower bound (CRLB) can provide a measure for the localization accuracy [10], which is calculated by taking the inverse of the Fisher information matrix (FIM). The FIM is defined as

$$\mathbf{F_x} \overset{def}{=} E_{\mathbf{x}}[\frac{\partial}{\partial \mathbf{x}} \ln f(\hat{\theta}|\mathbf{x}) \cdot (\frac{\partial}{\partial \mathbf{x}} \ln f(\hat{\theta}|\mathbf{x}))^{\mathrm{T}}], \tag{5}$$

where $f(\hat{\theta}|\mathbf{x})$ is the joint PDF of measurements $\hat{\theta}$ conditioned on $\mathbf{x}$.

For a given configuration of anchors and agent in a specific scenario, the value of CRLB is unique. To weight the benefit that an anchor brings to the localization for the agent, we calculate the increase of the CRLB when that anchor is taken away from the scenario and take the reciprocal as the weight factor. This factor corresponding to anchor j and agent i is denoted by ω_{ij}, which is calculated as

$$\omega_{ij} = \frac{1}{\mathrm{tr}\{\mathbf{F}_{S_i \backslash j}^{-1}\} - \mathrm{tr}\{\mathbf{F}_{S_i}^{-1}\}}, \tag{6}$$

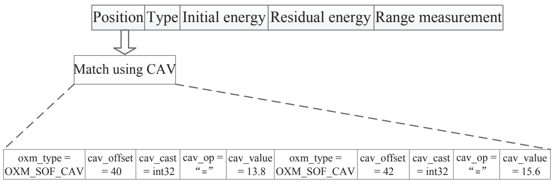

Fig. 2. Defining table of each anchor with Match using CAV in SDN flows.

where S_i denotes the configuration of all anchors and agent i, while $S_i \backslash j$ denotes the one that anchor j is taken away from the scenario. $\mathrm{tr}\{\cdot\}$ is the trace of a square matrix.

As mentioned before, to balance the energy consumption of each node and prolong the network lifetime, we should select the anchors based on the condition of its residual energy. A node with a lower remaining energy should have fewer opportunities to be awakened for localization. Then the timer of anchor j can be given by

$$t_s(j) = t_0[\alpha\omega_{ij} + \beta(\frac{|e_m - \tau e_j|}{e_m})], \tag{7}$$

where α and β are two coefficients such that $\alpha + \beta = 1$. e_j is the residual energy of anchor j; e_m is the maximum energy at the beginning; τ is a random variable between $[0.9, 1]$ to avoid the same value of residual energy from different anchors and t_0 is a coefficient to limit the scheduling time.

B. SDN based Anchor Scheduling

We assume the SDN controller in the control plane is responsible for the anchor scheduling process, and the state determination is manipulated through a flow table via SOF. Each anchor has an information table stored in the controller. The table consists of all the information for designing the timer of the corresponding anchor. To cater for the special addressing schemes in WSN, SOF defines two classes of address, i.e., Class-1, compact network-unique addresses and Class-2, concatenated attribute-value pairs (CAV). By exploiting the OpenFlow extensible match (OXM), the flow Matches in these two classes are defined compatible with the OpenFlow. In our scheme, for each sensor node, we refine the flow tables by creating the Class-2 flows which define the Match in the CAV format such as "x_coordinate =13.8 AND y_coordinate=15.6". An example of the stored table for the anchor whose position is $\mathbf{x} = [13.8, 15.6]^{\mathrm{T}}$ is shown in Fig. 2, where the x_coordinate and y_coordinate is assumed to be an int32 stored at offset 40 and 42 of each packet, respectively. The proposed SDN-based scheme selects a subset of active anchors at each time slot in a centralized way and ensures an expected connectivity degree for the localization of the agent. In this part, we illustrate the anchor scheduling scheme for localizing agent i. The scheme works in two phases: the initial phase and the scheduling phase.

Initial phase: Agent i broadcasts a HELLO message to activate its neighboring anchor nodes. Each active anchor sends the messages with its position, type, initial energy, residual energy and the range measurement with agent i to the SDN controller. The controller constructs the information tables for these anchor nodes, in addition, calculates and disseminates the timers to them. The position of agent i in this phase is estimated and recorded as its initial position.

Scheduling phase: At each time slot, the mobile agent i sends a message to the neighboring anchor nodes which are within its communication range. Then the neighbors send their information to the controller, if the position of the anchor has been stored before, the controller only updates its residual energy and range measurement, otherwise a new table will be constructed for this anchor. Once the timer of a certain anchor node expires, it sends a packet to the controller. The controller calculates the current connectivity degree for agent i, if the degree is lower than the predefined degree threshold ξ_{th}, this anchor will be kept to operate, otherwise it is set to sleep. At the same time, the controller updates the table of this anchor with its new residual energy. The next time slot follows the same process until the localization of agent i has finished.

V. Simulation Results

This section provides the performance evaluation of the proposed anchor scheduling scheme. A 120m $\times$ 120m rectangular sensor field with 200 randomly placed anchor nodes is considered. There are three types of anchors with the communication ranges as: $c_1 = 10$m, $c_2 = 15$m, $c_3 = 18$m, and the number of each type node is 100, 50, 50, respectively. 10 mobile agents move in the field with the dynamic model given in Section III. If the anchor is on the "operating" state and within the communication range of the agent, we assume this anchor is connected with the agent. An energy model similar to the one stated in [11] is used in our simulations. To be more realistic, we assume the anchors of different types have variable initial energy based on their usages, i.e., $E_1 = 30$J, $E_2 = 20$J, $E_3 = 40$J. The energy consumption in transmission, reception and sleeping modes is 60mW, 12mW and 0.03mW, respectively. An accumulator is set on each anchor for calculating the total consumed energy in the Matlab simulation. The results are obtained through Monte Carlo simulation by averaging over 200 repetitions of the localization process.

We will denote the proposed SDN-based anchor scheduling scheme by centralized anchor selection (C-AS). The performance of the scheme is compared with the conventional anchor selection method called reference selection using global distances (RS-GD) in [12]. This global algorithm requires that all the anchors in the network keep operating during the whole localization process, hence, they are able to share the knowledge of the distance estimates with other nodes.

Table I shows the average numbers of the anchors connected with agents with respect to the time slot. When no anchor scheduling is employed, RS-GD, average 8.9 anchors are connected with the agents in the early stages. The number sharply reduces to about 6.7 at time slot 400 for the anchors with initial energy of 20J have died out. Before time slot 800, all the anchors have consumed up their energy and the localization system stop working. In contrast, the desired

TABLE I
AVERAGE NUMBER OF ANCHORS CONNECTED WITH AGENTS

Time Slot	40	100	200	300	400	500	600	700	800	900	980
RS-GD	8.9	8.9	8.9	8.9	6.8	6.7	4.6	4.5	0	0	0
C-AS (n=4,ξ_{th}=0.85)	5.6	5.6	5.6	5.6	5.6	5.5	5.4	5.3	5.2	5.1	5.0
C-AS (n=6,ξ_{th}=0.85)	7.0	7.0	7.0	7.1	7.1	7.0	6.9	6.8	6.8	6.6	6.5

numbers of anchors are always ensured with our proposed anchor scheduling scheme, when we set the number as 4 and 6 with the connectivity degree threshold ξ_{th}=0.85, respectively. Since the anchors are scheduled on basis of their residual energy, the energy consumption of each node is balanced, thus there are still sufficient anchors alive for the localization even at the end of the simulation.

We now investigate the trade-off between the energy consumption and the localization accuracy with our proposed scheme. Fig. 3 shows the total remaining energy in anchors with respect to the time slot. The total energy is expended at about slot 760 in RS-GD, because all the anchors are kept active during the localization. In the proposed scheme, C-AS, only when the anchor receives the HELLO message from the neighboring agent or the command from the SDN controller, will it be set into the "operating'" state, otherwise it will keep "sleeping" thus conserving the energy. In Fig. 4, we compare the positioning performance in terms of the mean squares error (MSE). We can observe that the RS-GD achieves the best performance before time slot 320. The reason for this is that all the anchors are active for the localization and the agents have the most connected anchors among the three schemes. However, the errors increase as the number of active anchors decreases. When the number reduces to 4.6 (after time slot 600), the accuracy of RS-GD becomes the worst. In C-AS, the anchors are scheduled according to their timers, so they are utilized for the localization in balance. The desired numbers of connected anchors are ensured during the whole localization process in our simulations, which does not seriously affect the localization accuracy. In addition, we can see that more actively participating anchors (i.e., n=6) leads to less positioning errors while consumes more energy (shown in Fig. 3), so we can tradeoff the localization accuracy for energy by ensuring a better balance of energy consumption among the minimum number of anchors required to be employed by a specific application.

VI. CONCLUSION

This letter proposed an efficient anchor scheduling scheme in a centralized way based on the SDN paradigm. We derived an expression to evaluate the connectivity degree of an agent and used it to judge if this agent has desired number of connected anchors for its localization. The state (sleeping/operating) determination of each anchor was manipulated by the SDN controller through a flow table via SOF. The simulation results showed that the proposed anchor scheduling scheme reduces the number of active anchor nodes and increases the network lifetime. It can also be shown that the scheme can only slightly decrease the localization accuracy with a great reduction in the energy consumption.

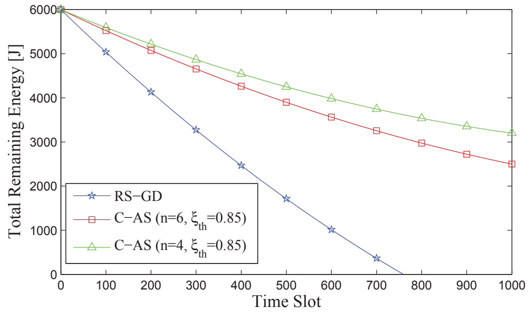

Fig. 3. Total remaining energy in anchors with respect to the time slot.

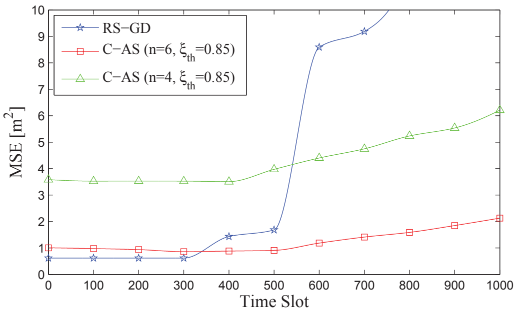

Fig. 4. Positioning performance comparison with different schemes.

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