Node Scheduling for Localization in Heterogeneous Software-Defined Wireless Sensor Networks

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Abstract. In this paper, a node scheduling scheme for localization in heterogeneous software-defined wireless sensor networks (SD-WSNs) is proposed. An expression to evaluate the connectivity degree of the localized agent is derived, which is used to judge if the agent is connected with an expected number of anchors. The node scheduling scheme is designed on the basis of the software-defined networking (SDN) paradigm, and the state of each anchor is determined by the SDN controller through a flow table via sensor OpenFlow. In the proposed scheme, a timer for each anchor is calculated based on the Cramer-Rao lower bound (CRLB) value and the residual energy. Simulations show that the proposed node scheduling scheme can reduce the number of active nodes while ensuring an expected number of anchors for localization. It can also be shown that the scheme can reduce the energy consumption with only a slight decrease in positioning accuracy.

Keywords: Node scheduling · Localization
Heterogeneous wireless sensor network · Software-defined networking

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1 Introduction

With the development of sensor technology, wireless sensor networks (WSNs) have attracted intensive interest for their variety of promising applications over a decade [1]. Most applications in WSNs are based on the specific locations of sensors, such as environmental monitoring, social networking, asset tracking and indoor navigation [2]. Therefore, sensor positioning in WSNs has been a research topic of particular interest over the past few years.

Considering the resource-constrained characteristic of WSNs, existing researches have made great efforts to reduce energy consumption in the sensor localization algorithms. In [3], a distributed scheduling algorithm based on information evolution is proposed for the cooperative localization. Through neighbor selection and collision control, this scheduling algorithm decreases the complexity and overhead of localization. By decomposing the power allocation problem into infrastructure and cooperation phases, the authors in [4] establish an optimization framework for robust power allocation in cooperative wireless network localization. An effective transmit and receive censoring method is proposed in [5]. This method blocks selected broadcasts and discards less useful incoming information from neighboring nodes, thus, it can reduce the traffic in the localization algorithm.

Recently, an architecture called the software-defined WSN (SD-WSN) has become appealing for application-specific wireless communications [6]. The fundamental idea of software-defined networking (SDN) is introduced into the SD-WSN, which separates the data and control planes. Such a separation makes the SD-WSN programmable and thus the network structure becomes dynamic. The SDN controller in the abstract control plane can centralize the whole network intelligence and dictate the whole network behavior. Therefore, the SDN paradigm can impose a centralized operation for the network management. The physical data plane simply executes flow-based packet forwarding. In order to accommodate to the SD-WSNs, a sensor Open Flow (SOF) is proposed as a southbound interface in [7]. It is worth noting that the SDN technique in SD-WSNs provides a chance to design more flexible node scheduling strategies for the localization algorithms.

In addition, to meet the diverse need of network applications, the heterogeneous WSNs (HWSNs) have become popular recently, in which the nodes possess different software and hardware. The heterogeneity of HWSNs partitions the network tasks, ensuring a more efficient implementation of the overall network function, which can increase the network lifetime, reliability and validity [8]. To adapt to the development of HWSNs, this paper will study the localization algorithms in a more general network that consisting of different kind of nodes. To reduce the energy consumption in HWSN localization, a node scheduling strategy is designed with the support of the SDN technique, in which the state (sleep or active) of anchors at each time slot is determined by the SDN controller. The main contributions in this paper can be summarized as follows.

- An expression to evaluate the connectivity degree of the localized agent is derived in the HWSNs, and is used to judge if the agent is connected with a desired number of anchors.
- To improve the positioning accuracy as well as prolong the network lifetime, a timer for each anchor is calculated based on the Cramer-Rao lower bound (CRLB) value and the residual energy.
- A node scheduling scheme is designed on the basis of the SDN paradigm, and the state of each anchor is determined by the controller through a flow table via SOF.

The remainder of this paper is organized as follows. In Sect. 2, the system model and problem formulation are introduced. The specific node scheduling scheme is elaborated in Sect. 3. In Sect. 4, simulation results and analysis are presented. Finally, Sect. 5 concludes this paper.

2 System Model and Problem Formulation

2.1 System Model

Consider an HWSN with N_b anchors and N_a agents. The anchors in the heterogeneous network can be categorized into K different types. Note that the heterogeneity of anchors is reflected by their communication ranges in the research of localization algorithms. The agents are software-defined that can communicate with any kind of anchor. The positions of anchors are exactly known. The agents are mobile devices with unknown positions and attempt to acquire their locations through the range measurements with anchors. Denote the sets of anchors and agents by $\mathcal{N}_b = \{1, 2, \ldots, N_b\}$ and $\mathcal{N}_a = \{N_b + 1, N_b + 2, \ldots, N_b + N_a\}$, respectively. The position of node i in the network is indicated by the vector $\mathbf{x}_i = (x_i, y_i)^{\mathrm{T}} \in \mathbb{R}^2$ in a two-dimensional (2D) localization system. The distance between nodes i and j is denoted by d_{ij}. Assume that the communication of a type $k \quad (1 \leq k \leq K)$ 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 $\|(\mathbf{x}_k, c_k)\| = \pi c_k^2$.

2.2 Metric Evaluation for Expected Anchor Number

Now, the probability of an agent that is connected with a user-defined number of anchors is derived. By using this probability as a metric, an expected anchor number is ensured during the localization.

The mobile area (MA) of agent a $(a \in \mathcal{N}_a)$ at time slot n is defined as all possible positions of $\mathbf{x}_a^{(n)}$, which is modeled as a disc of radii R_a centered at point $\mathbf{x}_a^{(n-1)}$,

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

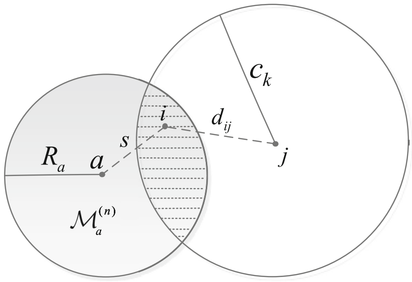


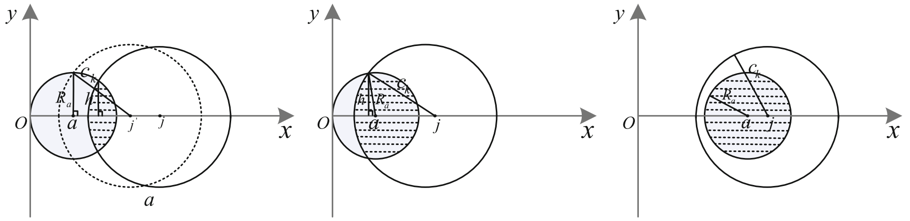
Fig. 1. A point inside the MA of agent a is connected with a type k anchor.

where $\Theta = [\cos\theta, \sin\theta]^{\mathrm{T}}$, and θ is a random variable uniformly distributed in $[0, 2\pi]$. The MA is the set of $\mathbf{x}_a^{(n)}$, which is denoted by $\mathcal{M}_a^{(n)}$ and shown as the gray area in Fig. 1.

Consider a point inside the MA which is at a distance of s from $\mathbf{x}_a^{(n-1)}$. The possible values of s are $0 \le s \le R_a$. Let S denote the variables of s, and the probability density function (PDF) for S is given as $f_S(s) = 2s/R_a^2$. In Fig. 1, a point i in the MA is at a distance of s from agent a, and the anchor j is a type k node having a communication range of c_k. Denote the probability that a node in the MA of agent a can be connected with anchor j by $p_{aj}^{(n)}(s)$. The value of $p_{aj}^{(n)}(s)$ is equal to the ratio of the intersection area (i.e., the shaded area in Fig. 1) to the possible mobile area. To calculate the area of the shaded region, the model is placed into an $x-y$ coordinate plane as shown in Fig. 2. Assume that $c_k > R_a$, the distance between the anchor's position (x_j, y_j) and agent a is d_{aj}. The area is calculated by using the integral of the difference of circle equations enclosing it. Note that, in some cases (Fig. 2b), the area is acquired by subtracting the complementary region from the whole mobile area, and the border value separating these cases is shown in Fig. 2a which is denoted by $d_{aj'}$. Then, the estimate of $p_{aj}^{(n)}(s)$ is given by Eq. (2) for different values of d_{aj} in three cases. For the cases of $c_k \le R_a$, the calculation of $p_{aj}^{(n)}(s)$ follows the similar way. However, in the third case $0 < d_{aj} \le R_a - c_k$, the intersection area corresponding to Fig. 2c becomes πR_a^2 and thus $p_{aj}^{(n)}(s) = \frac{R_a^2}{c_k^2}$.

$$p_{aj}^{(n)}(s) = \begin{cases} 0, & d_{ij} > c_k + R_a; \\ \frac{2\int_0^h (R_a + \sqrt{R_a^2 - y^2} - x_j + \sqrt{c_k^2 - (y - y_j)^2}) dy}{\pi R_a^2}, & \sqrt{c_k^2 - R_a^2} < d_{aj} \le c_k + R_a; \\ 1 - \frac{2\int_0^h (x_j - \sqrt{c_k^2 - (y-y_j)^2} - R_a + \sqrt{R_a^2 - y^2}) dy}{\pi R_a^2}, & c_k - R_a < d_{aj} \le \sqrt{c_k^2 - R_a^2}; \\ 1, & 0 < d_{aj} \le c_k - R_a. \end{cases} \tag{2}$$

Take the expected value of $p_{aj}^{(n)}(s)$ as the probability that a point inside the MA of agent a can be connected with anchor j at time slot n, which is written as



(a) $\sqrt{c_k^2 - R_a^2} < d_{aj} \le c_k + R_a$ (b) $c_k - R_a < d_{aj} \le \sqrt{c_k^2 - R_a^2}$ (c) $0 < d_{aj} \le c_k - R_a$

Fig. 2. The calculation of the intersection area in an $x - y$ coordinate plane.

$$p_{aj}^{(n)} = \mathbb{E}[p_{aj}^{(n)}(s)] = \int_{s=0}^{s=R_a} p_{aj}^{(n)}(s) f_S(s) ds. \tag{3}$$

To ensure an expected number of anchors for each agent during the localization, a probabilistic method is used to set a threshold indicating the degree that an agent is connected with a user-defined number of anchors. Let $B_M^{(n)}(a)$ denote the event that a point in the MA of agent a is connected with M anchors at time slot n, in which the number of type k anchor is m_k, and $\sum_{1 \le k \le K} m_k = M$. Denote all the possible combinations of M anchors with various numbers of each type by $\mathcal{C}^{(n)} = \{\mathcal{C}_1^{(n)}, \mathcal{C}_2^{(n)}, \cdots, \mathcal{C}_Q^{(n)}\}$. The probability of event $B_M^{(n)}(a)$ can be calculated as (omitting the time slot index)

$$P(B_M(a)) = \sum_{1 \le q \le Q} p(\mathcal{C}_q) \prod_{1 \le k \le K, \forall j \in \{k\}} p_{aj}^{m_{qk}}, \tag{4}$$

where $\sum_{1 \le q \le Q} p(\mathcal{C}_q^{(n)}) = 1$, m_{qk} is the number of connected type k anchor in the qth combination. In particular, $p(\mathcal{C}_q)$ can be calculated through the enumeration. To interpret Eq. (4), if $P(B_M^{(n)}(a)) = 0.80$, then, agent a at time slot n has 80% possibility of connecting with M anchors of different types. The following definition provides the degree metric for the level in which the agent is connected with an expected number of anchors.

Definition 1. *The degree metric* $\xi_a^{(n)}$ *for agent* a *at time slot* n *is defined as the integration of* $P(B_M^{(n)}(a))$ *over the whole MA, i.e.,* $\xi_a^{(n)} = \int\int_{\mathcal{M}_a^{(n)}} P(B_M^{(n)}(a)) d\mathcal{M}$. *This degree describes the overall probability that agent a is connected with* M *anchors considering all its possible positions at time slot* n.

With this definition, the node scheduling scheme under the premise of satisfying a user-defined degree threshold ξ_{th} is designed. For example, if we set $M = 4$ and $\xi_{th} = 0.85$, it means that the scheme ensures an at least 85% possibility that the localized agent is connected with 4 anchors when scheduling the anchors.

3 SDN-Based Node Scheduling Scheme

To design the node scheduling scheme, the following three aspects are taken into account when selecting the anchors: (1) the benefit that anchor can bring to the localization accuracy; (2) the residual energy of the anchor; (3) the number of anchors for each agent. A timer considering these three factors is set for each anchor. Upon the timer expires, the state of the anchor at every time slot is determined by the SDN controller through a flow table via SOF.

3.1 Timer of Anchor

To select the anchors which are more beneficial to the localization accuracy, the CRLB is used as a measure for the positioning performance. The CRLB is defined as a theoretical lower bound on the variance of the estimator (i.e., position of agent), and can be calculated by taking the inverse of the Fisher information matrix (FIM) [9]. The FIM is defined as

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

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

For a given network configuration, the CRLB value for the localized agent is unique. Denote the configuration of all anchors and the localized agent a by $\mathcal{T}_a$. When one of the anchors (say anchor j) is taken away from the localization scenario, the CRLB of agent a will increase. Let $\mathcal{T}_a \backslash j$ denote the configuration that anchor j is taken away from the network. A weight factor indicating the quantified value that anchor j contributes to localizing agent a is defined as

$$\omega_{aj} = \frac{1}{\mathrm{tr}\{\mathbf{F}^{-1}_{\mathcal{T}_a \backslash j}\} - \mathrm{tr}\{\mathbf{F}^{-1}_{\mathcal{T}_a}\}}, \tag{6}$$

where, $\mathbf{F}$ is the FIM and $\mathrm{tr}\{\cdot\}$ is the trace of a square matrix.

To prolong the network lifetime, the energy consumption of each node should be kept as balanced as possible, thus, the anchors are selected based on the condition of its remaining energy. Then, considering the anchor's residual energy as well as its contribution to the localization result, the timer of each anchor j is given by

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

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 to avoid the same value of residual energy from different anchors; and t_0 is a coefficient to limit the scheduling time.

The timer of each anchor allows anchors for competition to be active. The anchors having smaller weights and more residual energy will have more chances of being scheduled to be active. Once the timeout occurs, the anchor will send a message to the controller to ask for its next state.

3.2 Node Scheduling on the Basis of the SDN Paradigm

A node scheduling scheme is proposed to select a subset of active anchors at each time slot at the same time ensuring an expected number of anchors for localization. The SDN controller in the control plane is responsible for the selection process.

Table 1. Match using CAV in SDN flows (x_coordinate = 13.8, y_coordinate = 15.6)

CAV:

cav_offset	cav_cast	cav_op	cav_value

oxm_type = CAV	cav_offset = 40	cav_cast = int32	cav_op = "="	cav_value = 13.8

oxm_type = CAV	cav_offset = 42	cav_cast = int32	cav_op = "="	cav_value = 15.6

To cater for the special addressing schemes in SD-WSNs, two classes of address in SOF is proposed in [7], 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 OpenFlow. In this paper, the flow tables are refined by creating Class-2 flows which defines the Match in the CAV format as illustrated in Table 1. An example of the Match for a flow entry in CAV format using the node's position is shown in Table 1, where the x_coordinate and y_coordinate of a node is assumed to be an int32 stored at offset 40 and 42 of each packet, respectively.

Now, the work mechanism for the SDN-based node scheduling scheme is illustrated for localizing agent a. Before the scheduling round, agent a broadcasts a HELLO message to its neighbors, and anchors which receive this message are set to be active. Each active anchor sends a message with the information of its position, type, initial energy, residual energy and the range measurement with the agent to the controller. The controller stores this information in an information table. Then, the position of agent a is estimated and recorded as the initial position. The timer of each anchor is calculated by the controller and disseminated to the node.

At the beginning of each time slot, the mobile agent a sends a message to activate its neighbors which are within its communication range. The neighbors then send the information to the controller. If the position has been stored before, the controller only updates the residual energy and range measurement; otherwise, a new table containing all the information is constructed. Then, the SDN controller calculates the degree level of agent a as defined in Definition 1. The degree is compared with the predefined degree threshold ξ_{th}. As long as the timer of an anchor expires, it sends a packet to the controller with its new remaining energy. If the agent's current degree is lower than ξ_{th}, this anchor is set to keep active; otherwise, it is scheduled to go to sleep. At the same time, the SDN controller updates the table for this anchor and renews its information. The procedure of the proposed node scheduling scheme is depicted in Algorithm 1.

Algorithm 1. Node Scheduling for Heterogenous SD-WSNs

1: **Initialization:**
2: Time slot n=0;
3: The localized agent sends a HELLO message to its neighboring anchors;
4: Each activated neighboring anchor sends its information (position, type, initial energy, residual energy and the range measurement) via SOF to the SDN controller;
5: The SDN controller constructs an information table for the anchors.
6: **While** $n < N$ (N is the maximum time slot) **do**
7: Once the timer of an anchor expires, it sends a message to the SDN controller;
8: The SDN controller checks whether the address of the anchor is stored in the information table, if stored, updates the information of the anchor; otherwise, constructs a new table for the new anchor;
9: The SDN controller checks whether the current connectivity degree of the agent satisfies the desired requirement, if satisfies, schedules the anchor to sleep; otherwise, sets the anchor to be active;
10: $n = n + 1$.
11: **End while**

4 Simulation Results

In this section, the performance of the proposed node scheduling scheme is evaluated through simulation results. Consider a rectangular sensor field of $120\,\text{m} \times 120\,\text{m}$, in which 200 anchors are distributed in a uniform distribution. These anchors are categorized into three types and the communication ranges are $c_1 = 10$ m, $c_2 = 15$ m and $c_3 = 18$ m, respectively. The ratio of these three types nodes is 2:1:1. There are 20 mobile agents moving in the field, with the destination and moving distance at each time slot set between $[0, 2\pi]$ and [1 m, 1.5 m], respectively. Assume that the power consumption at anchors during transmission, reception and sleep modes is 60 mW, 12 mW and 0.03 mW, respectively. The initial energy of each node is assumed to be 30 J.

Figure 3 shows the total remaining energy of nodes in the network. When no scheduling is performed, all the nodes keep active during the tracking process, then the total energy is expended at about the 4/5 stage of the simulation. A great reduction in energy consumption is achieved when the anchors are scheduled to be active or sleep with the proposed node scheduling scheme. According to the scheme, only when the anchor receives the HELLO message from the agent or the command from the SDN controller, will it be active, otherwise it will go to the "sleep" mode. In addition, more energy will be saved when we

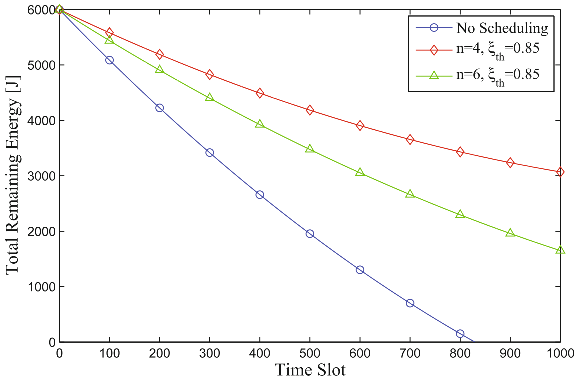


Fig. 3. The total remaining energy in nodes.

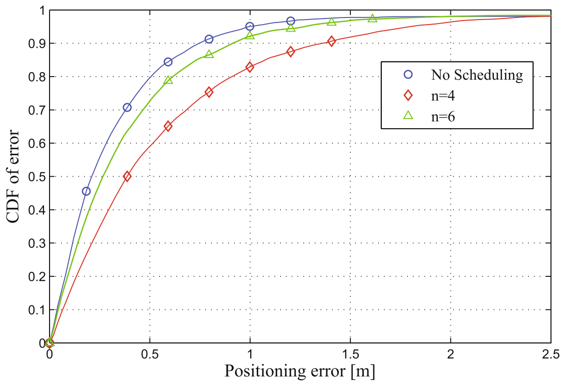


Fig. 4. Comparison of positioning accuracy.

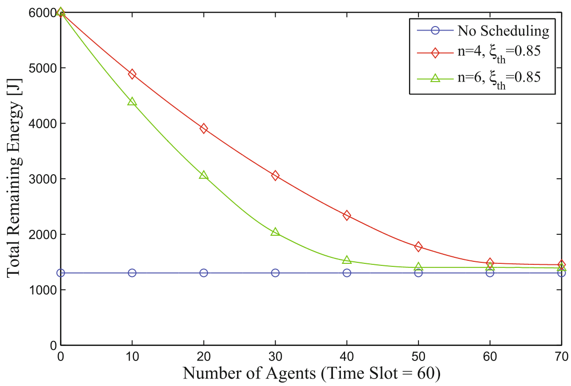


Fig. 5. Total remaining energy for different numbers of agents.

arrange 4 anchors for localizing each agent compared with 6 ones, leading to longer network lifetime.

The cumulative distribution function (CDF) of positioning errors is shown in Fig. 4. When there is no scheduling and all the anchors keep active, average 9 anchors are connected to each agent, which achieves the best performance in terms of localization accuracy among the three cases. The ratio of errors smaller than 0.5 m is reduced to 60% when the required number of anchors is set as 4, while 80% of the errors are controlled in this regime when no scheduling is performed. The distinction between the two schemes with and without scheduling decreases when the number is increased to 6.

Actually, the advantage of the proposed scheme is related to the number of agents. If the number of localized agents in the network is small, only a few anchors are required to be active. However, if the number is large, a high proportion of anchors will be scheduled to be active. In an extreme case, all anchors are activated if there are an awful lot of agents in the network, which is equivalent to the "no scheduling" case. Consider the cases that there are different numbers of agents moving in the network, the comparison of total remaining energy at time slot 600 is shown in Fig. 5. It can be seen that, as the number of agents grows, the remaining energy gets smaller under the proposed scheduling scheme since more anchors are activated. When the number gets large enough, almost all the anchors keep active during the whole localization process, thus, the advantage of the proposed scheduling scheme becomes invalid in terms of network-energy conservation.

5 Conclusion

In this paper, an efficient node scheduling scheme was proposed for the localization in heterogeneous SD-WSNs. The expression to evaluate the connectivity degree of the localized agent has been derived to judge if the agent is connected with an expected number of anchors. The state determination of each anchor has been manipulated by the SDN controller based on the SDN paradigm. Simulation results has shown that the proposed node scheduling scheme ensures an expected number of anchors for the localization. It could also be shown that the scheme prolongs the network lifetime while only slightly decreases the positioning accuracy.

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