A Distributed TDMA Scheduling Algorithm for Target Tracking in Ultrasonic Sensor Networks

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***Abstract*—Ultrasonic sensors are able to provide highly accurate measurements, however, they have to be carefully scheduled otherwise the inter-sensor interference (ISI) would greatly deteriorate the performance. It is also preferred that the scheduling scheme can be performed in a distributed and energy-efficient way so that it can be conveniently implemented for large-scale network. In this paper, for target tracking with multiple ultrasonic sensors, we convert the ISI avoidance problem to the problem of multiple access in a shared channel, and adopt the TDMA strategy which has the properties of collision-free and energy efficient. Then by graph theory, the scheduling problem is transformed into a coloring problem which aims at minimizing the number of used colors. Since the original problem has been proved to be NP-hard, we propose a distributed saturation degree based algorithm (DSDA) which can be implemented locally by each node with information collected from its neighbors. Furthermore, we verify that an interference-free schedule is guaranteed to be obtained by DSDA. We derive analytical results for the complexity of this algorithm. Specifically, for different sensor network topologies, we prove that the expected converging time and the expected message transmissions per node are both upper bounded by $\mathcal{O}(\delta)$, where δ is the maximum neighborhood size in the network. Extensive simulations demonstrate the effectiveness of our algorithm.**

***Index Terms*—Inter-Sensor Interference Avoidance, Coloring Problem, Distributed TDMA Scheduling, Target Tracking**

I. INTRODUCTION

Wireless sensor networks (WSNs) have been considered as a promising technique for different applications [1]–[3], where target localization/tracking is a fundamental requirement of the system. Many approaches have been proposed for target tracking within WSNs [4]–[7]. According to the target behavior, most of the previous works can be categorized into two classes, cooperative [4], [5] and non-cooperative [6], [8]. A cooperative target, as part of the network, can emit certain forms of physical signals that reveal its presence or report its own identification. In the non-cooperative scenario, however, the target will not provide any information of its own existence to the network cooperatively. Therefore, the sensor nodes have to emit the signal actively so that the target can be detected by the feedback signal. For example, [8] designs a tracking system for non-cooperative targets by utilizing the passive infrared sensors for target detection and active ultrasonic sensors for ranging.

In non-cooperative tracking systems where the echo-based sensors like ultrasonic sensors are used, the Inter-Sensor Interference (ISI) becomes severe especially when nearby active sensors work simultaneously in the same frequency band. Such interference results in erroneous sensor readings which may cause unacceptable tracking performance with a high probability. Therefore, it is necessary to schedule the activation of sensors at each time step to ensure that, in any ISI region, the number of sensors that are detecting the target should never be more than one at any specific time. In fact, if we take the ranging operation of a sensor node as the occupation of a shared channel, the ISI problem among active ultrasonic sensors in WSNs can be converted to the problem of multiple access in a shared channel. Hence we can deal with the ISI avoidance problem in a similar way as the media access control (MAC) problem.

A common MAC paradigm is CSMA (Carrier Sense Multiple Access), which is a simple, flexible and robust contention based access protocol, and especially fits for the networks with dynamic topology. However, it still suffers from the additional collisions which introduce serious energy waste, high overhead and throughput degradation on the already resource-constrained sensor nodes [9], [10]. Note that the distributed interfering sensor scheduling (DSS) algorithm proposed in [11] is based on CSMA, which requires the sensor nodes negotiate with each other frequently to decide the tasking node and results in high energy consumption.

Another classic access scheme is TDMA (Time Division Multiple Access) which divides the time into different slots that are assigned to different neighboring sensor nodes for access in a stationary way. The TDMA scheme often utilizes the topology information as a basis for access scheduling and requires clock synchronization among neighbors, thus may lack efficiency and scalability when the networks are subject to frequent topology changes. However, the TDMA scheme does not need frequent information exchange among sensors as long as the topology does not change, thus the additional energy consumption for ISI scheduling can be greatly reduced. Moreover, it is a totally collision-free protocol which helps to improve the channel utilization. Therefore, the TDMA scheme is highly preferred in the access scheduling design of many

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WSN applications [12]–[14], particularly when the topology of network are stationary most of time, which are the main scenario considered in this paper.

Consider that a number of sensor nodes with the same sensing range are deployed in a field of interest, where the target moves following an unknown trajectory. Since the sensor nodes have limited computational capacity and constrained resources, it is desirable to design a light-weighted and distributed activation scheme to avoid the ISI among nearby sensor nodes while achieving good tracking accuracy. In this paper, with the TDMA scheme, we focus on designing a static duty-cycled activation policy by exploring the local information of topology[1]. Taking the sensor nodes as vertices and the interference relations as edges (determined by the position and sensing range of sensor nodes), we transform the activation design issue into a coloring problem. The performance metric is to minimize the number of used colors, which corresponds to the number of time slots, so that the average sampling rate can be maximized. Our contributions of this paper can be summarized as follows:

- We consider the ISI avoidance problem for target tracking in ultrasonic sensor networks with stationary topology most of the time. The TDMA scheme is adopted and the issue is transformed into a coloring problem by graph theory.
- Since the coloring problem has been proved to be NP-hard, a distributed saturation degree based scheduling algorithm is proposed to solve the problem, which can be implemented in a distributed and parallel way, and therefore greatly increase the sampling rate to achieve better tracking performance.
- We verify that DSDA is guaranteed to generate an interference-free schedule. We provide an upper bound of the converging time for DSDA. For different sensor network topologies, we prove that the upper bound of the expected converging time can be greatly reduced to a linear function of the maximum neighborhood size in the network.
- We evaluate the performance of our algorithm by extensive simulations.

The remainder of the paper is organized as follows: Some related works on sensor scheduling are introduced in Section II. Section III demonstrates that the TDMA scheme is suitable to solve the ISI avoidance problem, and how the corresponding issue can be transformed into a coloring problem. Section IV presents the details of DSDA including the theoretical analysis for the performance of the algorithm. Section V evaluates the algorithm with extensive simulations. Finally, conclusions and future works are given in Section VI.

II. RELATED WORKS

Sensor scheduling has been a hot research topic for the past two decades. Different formulations and approaches have been proposed. Some previous works have addressed the sensor scheduling problem for different tracking systems in WSNs, most of which mainly focus on the tradeoff between tracking performance and energy consumption.

In [16], several feasible measures of information utility are introduced for considering the problem of distributed tracking with wireless sensor networks. In [17], the problem is formulated as a partially observable Markov decision process. A Monte Carlo method is developed, which combines the particle filters for belief-state estimation and a sampling based Q-value approximation for lookahead. In [18], the problem of stochastically selecting sensors is investigated which aims to minimize the expected tracking error covariance.

Priority list sensor scheduling is proposed in [19] , where the main idea is to prioritize the sensor nodes according to local sensor schedules based on the predicted estimation error. Adaptive sensor activation is introduced in [20], which dynamically adjusts the activation range of sensor, and a closed-loop control algorithm is propsoed according to the feedback of tracking quality. In [21], an adaptive multi-sensor scheduling scheme is proposed for collaborative target tracking in WSNs. The main idea is to calculate the sampling interval according to a specification of the tracking accuracy, and then select the cluster of tasking sensors based on their joint detection probability. In [22], the weighted sum of error covariance and the sensor usage cost are used as the performance measure. The authors also propose several suboptimal sensor scheduling algorithms for single target tracking with different sensor battery energy cases. In [23], a scheduling scheme is proposed to improve the scalability and energy-efficiency by limiting the number of active nodes participating in localization, while maintaining sufficient coverage to ensure acceptable location error.

Note that the interference caused by ultrasonic sensing has not been taken into account in the works above, and the methods cannot be applied directly to deal with the ISI problem for active sensors. The work of [6] considers a similar ISI avoidance problem to ours. However, only two centralized sensor scheduling schemes are investigated, which cannot be easily applied to large-scale networks in a distributed way.

III. PROBLEM FORMULATION

We formalize the sensor scheduling problem for ISI avoidance in the context of target tracking. Suppose a network of active ultrasonic sensor nodes has been deployed at a set of locations with the task of tracking the non-cooperative target. In order to avoid the ISI, in any ISI region, only one sensor node is tasked to actuate its ultrasonic sensors for range measurement at each time. And the time difference between two successive measurement epoches should be larger than T_d, where T_d is the die-out time of the ultrasonic wave in a ranging operation. The activated node then sends its data to the base station where the Extended Kalman Filter (EKF) is applied to estimate the state of the target.

In order to design a light-weighted and distributed sensor scheduling scheme, we adopt the TDMA strategy due to its properties of collision-free and energy-efficient. In the TDMA slot assignment, the real time is divided into non-overlapping periodic cycles called *time frames* which can be

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[1] The primary concept is presented in [15].

TABLE I
NOTATIONS

Symbol	Definition
$\|\cdot\|$	$\|\cdot\|$ represents the cardinality of a set.
T_d	die-out time of the ultrasonic wave in a ranging operation.
r_d	detection range of the ultrasonic sensors.
G	interference graph of the network.
V	set of the sensor nodes.
E	set of the edges that represents the interference relations.
x_v	position of sensor node v, $v \in V$.
$N(v)$	neighborhood set of sensor node v, $v \in V$.
$d(v)$	neighborhood size of sensor node v, i.e., $d(v) = \|N(v)\|$.
F	set of the assigned colors for the graph.
$f(v)$	function that records the assigned color of sensor node v, thus $f : V \to F$.
$sd(v)$	saturation degree of sensor node v, $v \in V$.
$SDI_v(u)$	saturation degree indicator of sensor node u calculated by sensor node v, detailed information can be found in Section **??**.
$UN(v)$	uncolored neighborhood set of sensor node v, $v \in V$.
$LC(v)$	list that stores the information of colored neighbors of sensor node v, $v \in V$.
$LUC(v)$	list that stores the information of uncolored neighbors of sensor node v, $v \in V$.
C_v	the maximum color number assigned to sensor node v and its neighbors.

further divided into non-overlapping equal *time slots*. The time slots are assigned to nodes for data transmission. Similarly, by setting the time slot length as T_d and letting each sensor node sense the target at its allocated time slot, a periodic interference-free sensor scheduling scheme can be obtained from such collision-free TDMA slot assignment. Therefore, the key problem becomes how to conduct an efficient TDMA slot assignment.

Graph coloring problem has been regarded as a convenient tool for the channel assignment problem in time, frequency and code domains [24]. Given a simple graph $G = (V, E)$, where V is the set of vertices, and E is the set of edges. For each vertex v, define its neighborhood $N(v) = \{u : \{u, v\} \in E\}$ and vertex degree $d(v) = |N(v)|$. Then the vertex coloring problem is to find a color assignment for the vertices of G: $V(G) \xrightarrow{f} F$, where f is the assignment function and F is a set of colors, usually represented by some small subset of positive integers, so that any two adjacent vertices will be given different colors.

From the view of graph theory, we consider the nodes as vertices and the interference relations as edges. An edge will exist between nodes u and v if and only if the Euclidean distance between them does not exceed $2r_d$, where r_d is the detection range of the ultrasonic sensor. After each node gets its color which represents a determined TDMA time slot within a time frame, it will activate itself to detect the target at such slot during each time frame for interference-free sensing. Table I gives a summary of notations used in this paper.

It is shown in [8] that the tracking performance can benefit from higher sampling frequency. Therefore, in order to improve the tracking performance, it is desirable to minimize the number of used colors so that the minimum time frame, i.e., the highest sampling rate, can be achieved.

Thus, the problem considered in this paper is to find the optimal coloring solution for the following problem

$$\min \qquad |F|$$

$$s.t. \qquad f(u) \neq f(v), \text{ if } ||x_v - x_u|| \leq 2r_d$$

where $u, v \in V$. However, according to [25], [26], finding an optimal solution for this problem is NP-hard. Therefore, it is critical to propose a heuristic however effective algorithm which can provide a satisfactory performance. Moreover, it is highly preferred if the algorithm can be implemented in a distributed way. Considering time efficiency and energy cost, we will use three metrics to evaluate the heuristic algorithm:

- **Number of Used Color**: the number of colors required to properly color the entire graph by the given algorithm.
- **Running Time**: the amount of time taken by the given algorithm to color all the nodes in the graph.
- **Message Complexity**: the number of messages transmitted by all the nodes during the coloring process.

IV. DISTRIBUTED SATURATION DEGREE BASED ALGORITHM

Motivated by a centralized heuristic coloring algorithm DSATUR in [27], we propose the distributed saturation degree based algorithm (DSDA) which solves the ISI avoidance problem in a completely distributed manner. Note that the algorithm in [27] is a centralized algorithm which requires that each node must know the global information of the network.

Before presenting the main algorithm, we would like to first introduce some useful definitions and preliminaries. Define *Saturation Degree* of vertex v, denoted by $sd(v)$, as the number of different colors assigned to the neighbors of v. In order to utilize *Saturation Degree Heuristic* in a distributed way, we introduce *Saturation Degree Indicator*(*SDI*) for each node to calculate the priorities of the nodes within its neighborhood for coloring locally:

$$SDI_v(u) = (\Delta(v) + 1) \cdot sd(u) + d(u) + rand(u)$$

where

$$\Delta(v) = \max_{w \in N(v) \bigcup \{v\}} d(w)$$

$$u \in S(v) = UN(v) \bigcup \{v\}$$

and $UN(v)$ denotes the uncolored neighborhood of v, $rand(u) \in (0, 1)$ is a random value generate by node u for tie breaking. Note that $\Delta(v)$ is a constant for node v if the graph structure does not change. Additionally, we have the following proposition and definition:

Proposition 1: The SDI satisfies:

- $\forall\ u, w \in S(v),\ SDI_v(u) \neq SDI_v(w)$
- $SDI_v(v) > SDI_v(w) \iff SDI_w(v) > SDI_w(w)$

Definition 1: Node v is an *Extremum Node* if the following condition is satisfied:

$$SDI_v(v) = \max_{u \in S(v)} SDI_v(u)$$

A. Algorithm Specification

1) Assumptions: For simplifying the statements, several assumptions are adopted as follows

- Each node has an unique node ID, and all nodes in the network are synchronized.

- At the initial state, each node know the IDs and degrees of its neighbors, thus $\Delta(v)$ is known for each node v.
- The range of the radio signal is equal to the ISI range.
- Each one-hop message can be successfully delivered.

Note that the first assumption means all the nodes within the network are distinguishable, and own the same time clock which is the foundation of TDMA mechanism. The second assumption means the network has been initialized already, which is for simplifying the whole process so that we can focus on the coloring process. The third assumption is to ensure that the network topology is identical with the interference graph. The last assumption guarantees the quality of communication which is practical and not difficult to implement.

2) DSDA: The idea is to let each node decide its own slot according to the information collected from its neighboring nodes. For clarification, we define two types of data which represent the neighborhood information of each node.

Specifically, $LC(v)$ represents the list of colored neighbors of node v, as well as their colors. $LUC(v)$ contains the information of uncolored neighbors of v, including the saturation degrees, degrees and random values. Thus, we can get $sd(v)$ from $LC(v)$, and $SDI_v(u)$ from $LUC(v)$. In addition, there is a positive real value named age attached to each item in LUC, which represents the "vitality" of the item.

DSDA runs in rounds and each round is divided into two sequential subrounds: $subrnd1$ and $subrnd2$. The algorithm, running individually on each node regardless of the progress of the whole network and during each round the detailed procedure is summarized below.

- During $subrnd1$, by using a constant $maxAge$ which is set as an upper bound for the item age in LUC, each uncolored node u firstly updates the age of each item in $LUC(u)$ and deletes the expired items which is caused by node death or topology change. After that, u calculates $SDI_u(v)$ for itself and its uncolored neighbors to find out whether it is an *Extremum Node*. If u is an *Extremum Node* which implies that it can be colored in this round, it picks its color to be the minimum of the colors that have not been taken by its neighbors before this round and the information can be obtained from $LC(u)$. Then u enters the *colored* state and broadcasts a $release$ message containing its selected color.
- During $subrnd2$, on receiving the $release$ message, each uncolored neighbor of u, i.e., v, will update its neighborhood information and broadcast an $update$ message containing the updated $sd(v)$, $d(v)$, and $rand(v)$ to v's neighbors, so that they can update the item of v in LUC and refreshes the age of this item to zero. On the other hand, if an uncolored node w does not receive any $release$ message in the most recent $maxAge$ rounds, it will broadcast an $update$ message with the unchanged $sd(w)$, $d(w)$, and a newly generated $rand(w)$ to prevent being deleted by its neighbors.

The pseudo code of proposed algorithm executed on each node is described in Algorithm 1.

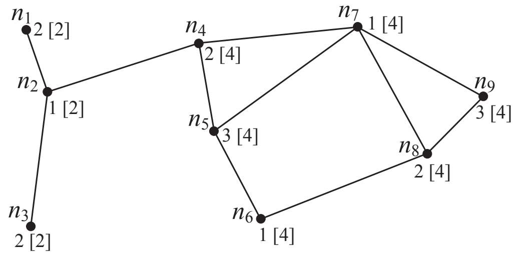
Algorithm 1 Distributed Saturation Degree Based Algorithm

```
let $u$ be an arbitrary node in the network

During subrnd1
if $u.color = 0$ (uncolored) then
    for each item $v$ in $LUC(u)$ do
        $age_v = age_v + 1$;
        if $age_v > maxAge$ then
            delete item $v$ from $LUC(u)$;
        else
            calculate $SDI_u(v)$;
        end if
    end for
    if $u$ is Extremum Node then
        $u.color$ = minimum unused color within its neighbors;
        broadcast release;
    end if
end if

During subrnd2
if $u.color = 0$ (uncolored) then
    if receive release from $v$ in subrnd1 then
        transfer the item of $v$ from $LUC(u)$ to $LC(u)$;
        calculate the updated $sd(u)$;
        generate a new $rand(u)$;
        broadcast update;
    else
        if not receive any release message in recent $maxAge$ rounds then
            generate a new $rand(u)$;
            broadcast update;
        end if
    end if
    if receive update from $v$ then
        update the item of $v$ in $LUC(u)$;
        $age_v = 0$;
    end if
end if
```

3) Local Time Framing: After selecting a time slot, each node needs to decide the time frame size during which it can use the slot for periodic sensing. Once a node finds that all its neighbors including itself have picked the time slots, it will change into *framing* state to decide its local time frame. Consider a node v, and let C_v denote the maximum color number of any node in $N(v) \bigcup \{v\}$. Then, the time frame for v is set to be 2^a where a is the positive number satisfying $2^{a-1} < C_v \leq 2^a$.

Since each node can determine its own time frame size based on the local information, DSDA is able to handle the local topology changes gracefully without involving any global changes. Fig. 1 shows an example of a TDMA schedule by DSDA.

Remark 1: Time synchronization and network adaptability are two practical concerns when implementing the slot assignments. In regard to time synchronization, in DSDA, only one-hop neighboring nodes are required to be accurately synchronized, which facilitates the implementation. Note that the existing synchronization algorithm has been able to achieve $1\mu s$ one-hop error [28] while the common slot length T_d is usually larger than $25ms$ [11]. For network adaptability, when a small amount of nodes die, the DSDA schedule can remain unchanged as the assignment is still collision-free. On the other hand, when several new nodes join in, we can assign them the colors which have not been taken by their neighbors



The number beside a node indicates the color assigned by DSDA and the number in the bracket is its frame size after local time framing. Then the slot schedule of all nodes is shown as follows.

1	2	3	4	1	···
n_2	n_1	n_5	n_1	n_2	···
n_6	n_3	n_9	n_3	n_6	···
n_7	n_4	n_2		n_7	···
	n_8				···

Fig. 1. Schedule Derived Using DSDA

without revising the schedule of existing nodes. Thus the cost for maintaining DSDA for small-scale topology changes is quite low. Moreover, we can restart DSDA periodically for handling the large-scale topology changes.

B. Performance Analysis

We first show that an interference-free schedule is guaranteed to be obtained by DSDA, then derive the analytical upper bound of time complexity as well as that of message complexity for DSDA. For three sensor network topologies, the upper bounds of the expected converging time and the expected message transmissions per node will be given.

1) Existence of Interference-free Schedule:

***Theorem** 1:* After the completion of DSDA, each two adjacent nodes will be assigned different colors.

Proof: This can be easily proved by the following three facts: (1) a node will not select a color until it becomes an *Extremum Node*; (2) At any round, since all nodes have different random values, the *Extremum Nodes* with locally highest priority can never be adjacent; (3) *Extremum Node* always selects the minimum color that is not taken by its neighbors. ■

***Theorem** 2:* After the local time framing is finished, each two adjacent nodes never use the same time slot.

Proof: We prove the theorem by contradiction. Consider two adjacent nodes i and j with the assigned color s_i and s_j respectively, $s_i \neq s_j$. After the local time framing, i's time frame is set to be 2^a and j's is 2^b, i.e., i uses only slots $k \cdot 2^a + s_i$ and j uses $l \cdot 2^b + s_j$, for all $k, l = 0, 1, 2, \cdots$. If it happens that j uses one of the slots that is chosen by i, then for some k, l, we have $k \cdot 2^a + s_i = l \cdot 2^b + s_j$. Without loss of generality, we assume that $a \leq b$. Then, we can get $s_i \equiv s_j (mod 2^a)$. Note that $1 \leq s_i, s_j \leq C_i \leq 2^a$, s_i and s_j must be the same, which is a contradiction. ■

With the above two theorems, we are ready to show that the TDMA time slot schedule derived by DSDA is interference-free.

***Theorem** 3:* DSDA never uses more than $\delta + 1$ colors.

Proof: Consider an uncolored node v in the round when it picks a color. In the worst case, all its neighbors are colored with different colors. If color $d(v) + 1$ has been used by its neighbor, it can select a color of value smaller than $d(v) + 1$, otherwise, it gets a color of value $d(v) + 1$, which are both no more than $\delta + 1$. ■

2) Complexity Analysis:

***Theorem** 4:* For DSDA, the number of rounds that a node required to be colored and the number of message transmissions per node are both bounded by $\mathcal{O}(|V|)$.

Proof: For the time complexity, if no node is dead during the execution of color assign, then in each round, at least one node picks its color, i.e., the upper bound for the number of rounds that a node takes to acquire a slot is $|V|$. On the other hand, if node's death occurs during the color assignment, after up to $maxAge$ rounds, the information about death nodes will be deleted, thus, in every $maxAge$ round, at least one node is deleted or picks its color, then the upper bound on the number of rounds is $maxAge \cdot |V|$.

For the message complexity, in one round, a node can send $\mathcal{O}(1)$ messages. Since there are no more than $\mathcal{O}(|V|)$ rounds, each node can send $\mathcal{O}(|V|)$ messages at most. ■

In practice, the number of rounds and the average number of message transmissions per node can be far less than that provided by Theorem 4. According to the distributed nature of our algorithm, we conjecture that DSDA has an *expected* time and message complexity of $\mathcal{O}(\delta)$, where δ is the maximum neighborhood size in the network, which is usually much smaller than $|V|$. The following part provides the proof of our conjecture for three cases: *uniform tree*, *ring* and *complete graph*.

***Definition** 2:* An *uniform tree* is a tree in which the degree of any node is either 1 or δ, $\delta > 1$. The node with degree of 1 is called *leaf node*.

***Theorem** 5:* For an uniform tree G with maximum neighborhood size δ, the expected number of rounds for non-leaf node to be colored is less than $\delta + 1$, and for leaf node it is less than $\delta + 2$.

Proof: Refer to Appendix. ■

***Theorem** 6:* The expected number of rounds for any node to be colored is less than 3 in a ring, and is $\frac{n+1}{2}$ in a complete graph K_n.

Proof: Consider an arbitrary node v in a ring. After the first round, the probability that v has been colored is $\frac{1}{3}$. If it remains uncolored, at least one node u is colored, then we cut off the ring at u to form an uniform tree with two identical leaf nodes u. After that, according to Theorem 5, the expected additional rounds for v to be colored is less than 3 as $\delta = 2$. Therefore, the total number of rounds for v to be colored is less than $\frac{1}{3} \cdot 1 + \frac{2}{3} \cdot (3 + 1) = 3$. The first part is proved.

For a complete graph K_n, since there is exactly one node being colored in each round, the possible round numbers for v to be colored are 1, 2, $\ldots$, n. On the other hand, as all nodes are the same in a complete graph, the probabilities for the n cases are equal to $\frac{1}{n}$. Therefore, the expected number of rounds for any node to be colored in K_n is $\frac{n+1}{2}$. ■

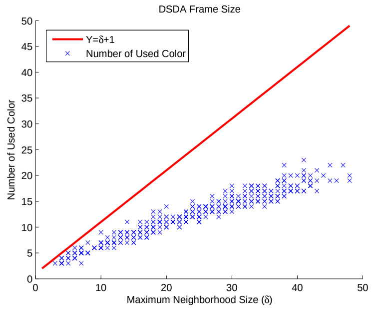


Fig. 5. Number of Used Color for DSDA

From Theorem 4, it's not difficult to prove that DSDA has an expected message complexity of $\mathcal{O}(\delta)$ for such three cases.

V. SIMULATION RESULTS

The proposed algorithm is evaluated by simulation in terms of the following two aspects: (1) the analytical results for coloring process are verified; and (2) the tracking performance of the generated TDMA schedule by DSDA is compared with the existing DSS algorithm [11].

A. *Validation of Analysis*

Nodes are placed randomly within a $15m \times 15m$ square with a communication range of $4m$. The neighborhood size of the network δ is changed between 3 and 50 by varying the number of nodes from 16 to 150. All the presented results are based on 20 independent simulation runs for high confidence.

Time Complexity and Message Complexity: Fig. 2 shows the number of rounds for all nodes deciding their slots, and Fig. 3 shows the average number of message transmissions per node. Specifically, the data points represent the numerical results of DSDA for different networks and the solid line indicates the average value of these data points. We can see that both the running time and the exchanged messages of DSDA support our conjecture as they grow linearly with δ.

For ring and uniform tree, the expected number of rounds for a node and for the whole network to be colored are presented in Fig. 4. The average number of rounds for a given node is bounded by $\delta + 1$ as proved in Fig. 4(a), which is consistent with Theorem 5 and 6. The expected round number by which the whole network can finish coloring is shown in Fig. 4(b), which supports the analysis. It should also be noted that, for DSDA, the expected round number will not increase along with the whole node number but only the δ. Such a property makes our algorithm applicable to large scale networks in practice.

Number of Used Color: By conducting experiments over different maximum neighborhood size, we summarize the number of used colors and plot them in Fig. 5. It can be observed that the number of color needed is far below the bound in Theorem 3, i.e, $\delta{+}1$, which proves that our algorithm provides a highly efficient schedule in practice.

Scalability: We examine the scalability of DSDA by ranging the number of nodes from 100 to 1000 and keep the same node density. The numerical results are given in Table II. It can be noticed that with the increase of network size, the running time (in terms of number of rounds), the message transmission number per node will remain relatively constant, which proves the scalability of DSDA. In addition, the number of used color generated by DSDA is quite close to that of DSATUR [27], the centralized near-optimal coloring algorithm, which means DSDA is able to approach the near-optimal performance.

TABLE II
SCALABILITY OF DSDA

Node Number	Color Number (DSDA)	Color Number (DSATUR)	Round Number	Msg Number	δ
100	14.03	13.85	41.29	29.78	28.37
200	15.34	14.98	51.45	31.98	31.2
300	16.25	15.81	57.48	33.13	32.96
400	16.46	16.17	58.11	33.7	33.56
500	16.99	16.72	60.32	34.27	34.84
600	17.01	16.64	61.97	34.53	34.78
700	17.47	17.22	63	34.63	35.52
800	17.48	17.21	63.29	34.84	36.04
900	17.77	17.36	65.88	35.01	36.34
1000	17.73	17.46	65.22	35.06	36.4

B. *Comparison of Tacking Performance*

Unless specified, we will use the default settings described in [11] for fairness. We first compare the two algorithms for tracking accuracy with different sensor numbers, ranging from 3 to 24. As depicted in Fig. 6(a), it can be seen that: (1) by increasing the number of deployed sensor nodes, the tracking error of both algorithms can be reduced, and will approach to a similar stationary performance limitation; and (2) the DSDA even outperforms the DSS when the sensor number is less than 9, which indicates that the sampling rate of provided by DSDA can be faster than that of DSS when the local sensor number is small. Then we examine the energy cost for these two algorithms. By recording the total number of radio operations for each node, we can calculate the total energy by the data reported in [29]. Fig. 6(b) shows that the energy cost for DSDA remains constant as it only requires to negotiate at the setup phase. However, for the DSS, the energy cost increases linearly with the simulation time since it requires nodes to keep negotiating at each time step.

VI. CONCLUSION

In this paper, we focus on the issue of avoiding ISI among active ultrasonic sensors by a distributed TDMA scheduling mechanism. We first transfer the issue to a coloring problem by introducing the saturation degree heuristic in graph theory. We then propose a simple however effective algorithm, DSDA, which can be implemented in a totally distributed way with local information of each node. We verify that an interference-free schedule is guaranteed to be obtained by DSDA, and we derive an upper bound of the algorithm complexity for DSDA. For different sensor network topologies, we prove that the expected time complexity as well as the expected message

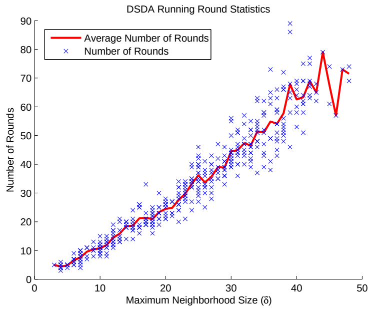


Fig. 2. DSDA Time Complexity

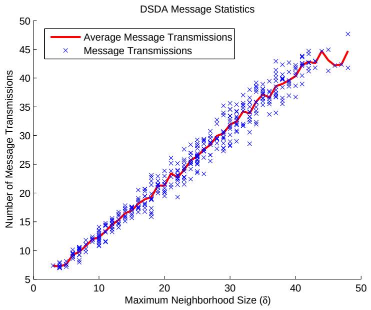


Fig. 3. DSDA Message Complexity

Fig. 4. DSDA Time Complexity for Uniform Tree and Ring

Fig. 6. Tracking Performance Comparison between DSS and DSDA

complexity can be bounded by a linear function determined by the maximum neighborhood size other than the network size. Extensive simulation results demonstrate that the DSDA is able to achieve a comparable tracking performance as the DSS algorithm while greatly reducing the energy cost. In the future, we will investigate the hybrid scheduling mechanism for combining the strengths of both TDMA and CSMA with the the help of the estimation of target states.

APPENDIX

Proof of Theorem 5

We firstly give some preliminary definitions and lemmas. Consider an uncolored node v in uniform tree G. In order to simplify the graph after i rounds coloring, we construct a *pruned tree* T_v^i with node number n_v^i. Specifically, we have $T_v^0 = G$ and $n_v^0 = |V|$. After i rounds coloring, for each node u in T_v^{i-1}, if there is at least one colored node on the path between u and v, delete u. Thus T_v^i is a subtree of T_v^{i-1}.

***Lemma** 1:* T_v^i can represent G in the view of v and T_v^i is uniform tree as well. Moreover, $n_v^i < n_v^{i-1}$.

Proof: From the executions of our algorithm, it's easy to know that the deleted nodes in T_v^{i-1} do not influence the coloring progress of the nodes in T_v^i. Therefore, in the view of v, T_v^i and T_v^{i-1} are the same, i.e., T_v^i can represent G.

According to the construction process of T_v^i, the colored nodes in T_v^i have degree of 1 and other nodes' degrees remain the same as that in T_v^{i-1}. As G is an uniform tree, we can prove that T_v^i is an uniform tree recursively. On the other hand, during the ith round coloring, there is at least one new colored node in T_v^{i-1}, i.e., at least one node will be deleted. We can conclude that $n_v^i < n_v^{i-1}$. Especially, after v being colored, T_v^i only has node v and $n_v^i = 1$. ■

Consider v as the root node of tree T_v^i, then the tree has $d(v)$ branches when v hasn't been colored. Denote each branch as $B_u(T_v^i)$, where u is the neighboring node of v in that branch.

***Definition** 3:* The *branch length* $l_u(T_v^i)$ for $B_u(T_v^i)$ is defined as the shortest distance (hop count) between v and any colored node in $B_u(T_v^i)$. If there is no colored node in $B_u(T_v^i)$, $l_u(T_v^i) = \infty$. The *depth* of T_v^i, denoted by $l(T_v^i)$, is defined as the shortest *branch length* in T_v^i.

***Lemma** 2:* $l(T_v^i) \leq l(T_v^{i-1})$

Proof: Consider branch B_u, we have $l_u(T_v^i) \leq l_u(T_v^{i-1})$, also as $l(T_v^i) = \min\limits_{u \in N(v)} l_u(T_v^i)$, we can conclude that $l(T_v^i) \leq l(T_v^{i-1})$. Especially, if v is colored, $l(T_v^i) = 0$. ■

Then Theorem 5 is proved as follows:

Proof: Consider an arbitrary non-leaf node v, and denote $E(T_v^i)$ as the expected number of rounds for v to be colored in T_v^i, and $Pr(T_v^i \to T_v^{i+1})$ as the probability that the pruned tree changes from T_v^i to T_v^{i+1} during the $(i+1)$th round. Since T_v^{i+1} may not be necessarily unique, we have $\sum\limits_{T_v^{i+1}} Pr(T_v^i \to T_v^{i+1}) = 1$ and $E(T_v^i) = \sum\limits_{T_v^{i+1}} Pr(T_v^i \to T_v^{i+1}) E(T_v^{i+1}) + 1$. For any T_v^i with $l(T_v^i) < 3$, we can prove the theorem by enumeration. Therefore, we have:

$$E(T_v^i) < \delta + 1, \quad \text{if } l(T_v^i) < 3 \tag{1}$$

$$E(T_v^i) = 0, \quad \text{if } l(T_v^i) = 0 \tag{2}$$

Otherwise, for any T_v^i with $l(T_v^i) \geq 3$ (note that G, i.e., T_v^0 belongs to this situation), there are three possible cases after the next round coloring:

Case 1: $l(T_v^{i+1}) = 0$, which means v is colored. Since v only needs to compete with at most δ neighbors by using $rand(v)$, the probability for v to win is at least $\frac{1}{\delta+1}$, i.e.,

$$\sum_{l(T_v^{k+1})=0} Pr(T_v^k \to T_v^{k+1}) \geq \frac{1}{\delta + 1} \tag{3}$$

Case 2: $0 < l(T_v^{i+1}) < 3$. it can be proved by (1).

Case 3: $l(T_v^{i+1}) \geq 3$. Consider n_v^{i+1} of T_v^{i+1} with $l(T_v^{i+1}) \geq 3$, note that $n_v^{i+1} < n_v^i$ and n_v^{i+1} is bounded by two finite values, i.e., $n_v^{i+1} \in [\min\limits_{l(T_v^i) \geq 3} n_v^i \ , \ n_v^0]$. Thus, there must exist $k \in \mathbb{N}$, which satisfies that $\forall T_v^k$, $l(T_v^k) < 3$. Additionally, according to Lemma 2 and (1), we have:

$$l(T_v^k) < 3 \text{ and } E(T_v^i) < \delta + 1, \quad \text{if } i \geq k \tag{4}$$

Thus for any T_v^{k-1}, we have

$$\begin{aligned}
E(T_v^{k-1}) &= \sum_{T_v^k} Pr(T_v^{k-1} \to T_v^k) E(T_v^k) + 1 \\
&= \sum_{l(T_v^k)=0} Pr(T_v^{k-1} \to T_v^k) E(T_v^k) \\
&\quad + \sum_{l(T_v^k)>0} Pr(T_v^{k-1} \to T_v^k) E(T_v^k) + 1 \\
&\overset{(2)}{=} \sum_{l(T_v^k)>0} Pr(T_v^{k-1} \to T_v^k) E(T_v^k) + 1 \\
&\overset{(4)}{<} (\delta + 1) \sum_{l(T_v^k)>0} Pr(T_v^{k-1} \to T_v^k) + 1 \\
&= (\delta + 1)[1 - \sum_{l(T_v^k)=0} Pr(T_v^{k-1} \to T_v^k)] + 1 \\
&\overset{(3)}{\leq} (\delta + 1)(1 - \frac{1}{\delta + 1}) + 1 = \delta + 1
\end{aligned} \tag{5}$$

With (1) and (5), we have $E(T_v^i) < \delta + 1$, if $i \geq k - 1$. Similarly, we can prove that $E(T_v^{k-2}) < \delta + 1$, $E(T_v^{k-3}) < \delta + 1$, …, $E(T_v^0) = E(G) < \delta + 1$, recursively. Thus the expected number of rounds for a non-leaf node to be colored in G is less than $\delta + 1$. While for a leaf node, the round number would be one more than its neighbor. Therefore the bound is $\delta + 2$ for leaf nodes, and the proof is completed. ■

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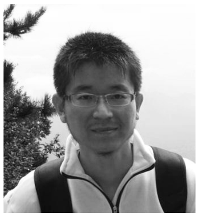

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