Using Directional Antenna for Continuous Moving Object Tracking in WSN with Uncovered Holes

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Abstract—As a distinguished target monitoring system, wireless sensor networks have spawned great advances. Most existing work concentrates on improving the accuracy and energy saving in a fully covered area by making full use of omnidirectional antenna. In reality, however, due to the death of nodes caused by harsh environment or energy depletion, the target may enter into a hole that is not covered by sensors. On the other hand, representative researches on boundary detection do not take target tracking into consideration. To address this issue, we introduce the idea of applying directional antenna to accomplish mobile target tracking in WSN with uncovered holes. We propose a collaborative signaling protocol to achieve the goal of continuous target tracking with low-energy-consumption. Simulation results have shown that the proposed approach can realize the real-time detection of moving object when it runs into and out of the hole, and at the same time, consume much less energy than the omnidirectional antenna based methods.

I. INTRODUCTION

As a promising direction to enrich the interactions between physical world and human beings, wireless sensor networks (WSN) have emerged and simulate great changes in the collection and handling of information. One of the most important applications of wireless sensor networks is continuous moving target tracking, such as for wild animal habit monitoring and forest fire tracing. Different from the centralized monitoring system, the advantages of applying WSN in those applications are distinguished, since it catches with the physical world in real-time and thus can satisfy the quality of service, e.g., the demand of high accuracy of path detection.

Normally all nodes in the wireless sensor network are randomly deployed with some density to achieve full coverage. However, nodes may suffer from the harsh environment that may lead to the death of nodes. Due to the unexpected changes in the entire monitoring area, several holes (the subareas that are not covered by the sensing nodes) will appear as time elapses. Under the assumption that nodes are deployed unattended in the remote field, how to keep tracking moving objects in the environment where the sensor network functions well even holes exist is a challenging problem.

First, we never know when a hole may suddenly appear. The unequal death of nodes may be caused by the different energy depletion or the outside factors, e.g., fire or rain. How to predict whether the tracking target is moving into the hole and when it should come out is the first problem that will be investigated in this paper. Second, as the objects are moving, the path could be totally random. If it passed the hole, how to awake the relevant nodes that can catch up with the trace in real-time, but at the same time, keep low energy consumption is another objective that will be addressed here.

Most existing work of target tracking concentrates on improving the accuracy and energy saving in a fully covered area by making full use of omnidirectional antenna [1], [2]. On the other hand, representative researches on boundary detection do not take target tracking into consideration [3]–[5]. The major contributions of this work are as follows.

- We introduce the idea of applying directional antenna to mobile target tracking in wireless sensor networks, which breaks the omnidirectional antenna’s presumption in this field.
- We propose a collaborative based prediction algorithm to not only achieve continuous tracking, but also minimize the energy consumption by automatically switching the mode from active sensing to idle status for those boundary nodes that are not needed any more. In addition, a signaling protocol is applied in order to make real-time and accurate path prediction.
- Extensive simulation results have shown that this proposed protocol can realize the real-time detection of moving target when it runs into and out of the hole, and at the same time, reduce energy consumption compared to the traditional representative methods.

To the best of our knowledge, we are the first to propose to use direction antenna to achieve continuous moving target under the condition when the hole exits. This rest of the article is organized as follows. Section II surveys the related work. Section III presents the system models and problem statement. Section IV introduces the real-time tracking protocol. Section V discusses the performance evaluation. Finally, Section VI concludes the paper and points out the future work.

II. RELATED WORK

Target tracking algorithms in WSN: Moving target tracking is one of the most important applications in wireless sensor networks. Most of them aim at prolonging the network lifetime or meeting the demands of accuracy prediction in static sensor networks [1], [2], [6]. FindingHumo [7] relies on the complex construction to reduction of energy consumption. [8] tracks targets based on the combination of a Kalman Filter and
maximum likelihood estimator. Bubble [6] takes accuracy as the major issue but the realtime property is not considered. Some special conditions, like the unreliable node sequence are discussed in [9], and [10] investigates the scenario in mobile sensor networks. Although those approaches try to either achieve energy efficiency or improve tracking accuracy, few of them take both requirements into consideration at the same time.

**Directional antenna:** The directional antenna has several advantages over the omnidirectional antenna, especially in the energy consumption and the reduction of collisions for multiple sensor nodes’ communication.

As an earlier research on MAC protocol with directional antenna, [11] designed MAC protocols for static wireless networks to reduce power consumption at the sensor nodes. Expect for the fundamental problems of MAC layer study, other issues such as the prediction of delay performance [12], the deafness/hidden-terminal/exposed terminal problems [13], and neighbor discovery with a little amount of energy consumption [14], are investigated in recent research.

With respect to routing protocol, [15] proposes algorithms for maximizing the lifetime, and [16] proposes dynamic source routing. In addition, ORRP [17] and MORRP [18] are lightweight-but-scalable routing protocols utilizing directional communications to relax information requirements.

As a pilot study of coverage with directional antenna in wireless sensor network, [19] proposes a set of optimal patterns to achieve full coverage and global connectivity under two different antenna models. Advanced researches include: the coverage and energy consumption control in mobile heterogeneous wireless sensor networks [20], optimal sensor deployment on 3D surfaces, aiming to achieve the highest overall sensing quality [21], and connectivity problem that is extremely challenging in the duty-cycled WSNs [22].

Till now, most researches using directional antenna in WSN are on the study of coverage, MAC layer and routing layer. The study of using directional antenna for continuous moving object tracking in WSN with uncovered holes remains to be considered.

**Hole detection and boundary discovery algorithms:** As defined in [23], a boundary separates two regions of interest in a phenomenon, which can be visualized as an edge if there is a sharp change in the field value between the two regions or alternatively, as a contour with a field value \( f = \tau \) separating two regions with field values \( f > \tau \) and \( f < \tau \). Under this condition, holes can be defined as the area not covered by the sensing area of any nodes as \( \tau = 0 \). This is different than the definition in BubbleTrace [6] where a hole refers to a target that is covered by less than three sensors. In this paper, we adopt the first definition.

With regards to boundary discovery, several problems are discussed in the literature, i.e., field estimation, localized estimation and adaptive estimation. Field estimation is to sample the entire field and query for the points on boundary. [24] generates contour maps at the sink by gathering information from the whole network. Localized estimation is to identify which sensors lie on the boundary. [5], [25] examine the problem of tracking dynamic boundaries occurring in natural phenomena using a network of range sensors. [26] proposes and analyzes an algorithm to monitor an environmental boundary with mobile agents to optimally approximate the boundary with a polygon. Different from others, [4] aims at localized fault-tolerant event boundary detection. Adaptive estimation is to sparsely sample the field at random manner and determine where to sample next. [27] presents an efficient algorithm to actively select queries for identifying the boundaries.

According to our survey, no representative papers have investigated the mobile target tracking under the hole detection. What’s more, most of the algorithms focus on the improvement of the boundary detection’s accuracy and reduction of calculation time. Besides, how to take use of directional antenna to save energy is not considered in those scenarios.

### III. System Models and Problem Statement

#### A. Network Model

The wireless sensor network can be represented by a graph \( G(V, E) \), where \( V \) is the set of sensor nodes and \( E \) stands for the set of communication edges. Two nodes can communicate with each other only if their Euclidean distance is less than the maximum transmission distance given by the system settings. We assume that \( R_T = 3R_S \) (\( R_T \) denotes the transmission range and \( R_S \) denotes the sensing distance). This assumption is based on [28] in which the transmission range is proved to be at least twice of the sensing range to achieve a complete coverage of a convex area according to the investigation of the relationship between coverage and connectivity.

Sensor nodes can turn on/off the communication function according to the system demand. We also assume that each sensor node is able to realize its location by GPS or related localization algorithms. Note here, how to achieve this is out of the scope of this work.

#### B. Energy Model

In this work, we only consider the energy depletion for sensing and communication procedure and ignore others since they dominate the system energy consumption. As in previous work [29], the sensing energy is the product of voltage, electric current and time used to sense the environment, so the total sensing energy consumption is described in Eq. (1). The energy consumption for a communication process is represented in Eq. (2) [30]. The notations are shown in Table I.
### TABLE I. ENERGY MODEL RELATED ATTRIBUTES

<table>
<thead>
<tr>
<th>Notation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{sensing}}$</td>
<td>energy consumption for sensing</td>
</tr>
<tr>
<td>$V_s$</td>
<td>voltage</td>
</tr>
<tr>
<td>$I_s$</td>
<td>electric current</td>
</tr>
<tr>
<td>$t_{\text{sen}}$</td>
<td>time spent in sensing</td>
</tr>
<tr>
<td>$E_{\text{comm}}$</td>
<td>energy consumption for communication</td>
</tr>
<tr>
<td>$E_{\text{tx}}$</td>
<td>energy consumed in transmitting $k$ bits data</td>
</tr>
<tr>
<td>$E_{\text{rx}}$</td>
<td>energy consumed in receiving $k$ bits data</td>
</tr>
<tr>
<td>$E_{\text{elec}}$</td>
<td>transmitters electric circuit consumed energy</td>
</tr>
<tr>
<td>$k_s$</td>
<td>the number of bits sent</td>
</tr>
<tr>
<td>$k_r$</td>
<td>the number of bits received</td>
</tr>
<tr>
<td>$\varepsilon_{\text{amp}}$</td>
<td>power amplifier consumed energy</td>
</tr>
<tr>
<td>$r$</td>
<td>communication range</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>path loss</td>
</tr>
</tbody>
</table>

#### IV. REAL-TIME MOBILE TARGET DETECTION PROTOCOL

When a hole exists, how to design a protocol to guarantee a real-time and low-energy consumption detection of the mobile target when it runs into and out of the hole is the problem to be addressed in this section. Three subproblems: 1) detection of the hole, 2) boundary node discovery, and 3) convergence of the protocol, are considered here. We assume that the design is based on a lossless channel.

#### A. Detection of the hole

Suppose the nodes keep sensing with the interval of $\Delta t$ until the target moves out of their sensing coverage area. At the moment when the node cannot catch the moving target, we can prove that the target must be in the neighbors’ sensing area. So once the target is moving out of the sight of current sensing nodes, these nodes will immediately send a start-sensing packet to all its neighbors, and wait for the replies. If no sensed-ACK is received, the senders are considered to be on the boundary and the target has entered the hole; otherwise, the target does not enter the hole and the sensing procedure continues as in normal condition.

At initial stage, the nodes who firstly detect the existence of the hole will broadcast a hole-detection query signal to the nodes in all directions, and then initiate the boundary detection process (see the next section). Once the node can tell that it is on the boundary, it will then continue to send out hole-detection signal to the next nodes on some directions using direction antenna and start sensing process till the target-catch-up signal feedbacked/propogated to it. Then it is realized that the target has moving out of the hole and has been successfully detected by some sensing nodes on the boundary, the whole hole-detection process can thus stop.

Except for the initial stage, in order to save energy, we design to take use of the direction antenna to transmit the signal to the neighboring nodes on the boundary. The problem is how to calculate the angle so that all nodes on the boundary can be covered. As illustrated in Fig.2, the receiver will choose a 180$^\circ$ degree in total from the sum of the angle of clockwise and counter-clockwise directions (each covering 90$^\circ$), based on the vector calculated from the position of sender to the receiver. Note here, we use a relative large angle so make sure that all boundary nodes can be covered for the signalling transition. In fact, in order to save the energy, the angle can be smaller and more adaptive to the scenario if the algorithm can predict the speed and the shape of the hole in more precise manners. This will be one of our future work.

#### B. Boundary node discovery

Although one node may receive several hole-detection signals from different nodes from one direction, for simplicity, upon the receipt of the first signal, this node will send out boundary-discovery query packet right away to the nodes in all directions at initial stage or some directions for the following steps, and then wait for the ACKs from those who received this packet. Other detection signals will be ignored since the first one already contains the proximity of the curve.

Suppose the underneath protocol is CSMA-based MAC layer protocol, so it will not guarantee that all ACKs can

\[
\sum_{i=1}^{N} E_{\text{sensing}}(t_{s}) = \sum_{i=1}^{N} (V_s * I_s * t_{s}) = V_s * I_s * \sum_{i=1}^{N} t_{s} 
\]

(1)

\[
\begin{align*}
E_{\text{comm}} &= E_{\text{tx}} + E_{\text{rx}} \\
E_{\text{tx}} &= E_{\text{elec}} * k_s + \varepsilon_{\text{amp}} * k_s * r^\lambda \\
E_{\text{rx}} &= E_{\text{elec}} * k_r 
\end{align*}
\]

(2)

If the transmission range is fixed, $E_{\text{elec}}$ and $r^\lambda$ are constant, so we can set $r^\lambda = M * E_{\text{elec}}$, where $M$ is a constant. Thus, the total communication energy consumption is the sum of all the energy consumed in processes of transmission and reception, as follows:

\[
\sum_{i=1}^{N} E_{\text{comm}}(i) = \sum_{i=1}^{N} (E_{\text{tx}}(i) + E_{\text{rx}}(i)) = E_{\text{elec}} * \left( \sum_{i=1}^{N} k_s(i) + \sum_{i=1}^{N} k_r(i) + \sum_{i=1}^{N} (\varepsilon_{\text{amp}}(i) * k_s(i) * M) \right) 
\]

(3)

Note here, for directional antenna, the amplifier energy consumption is proportional to the angle [31].

#### C. Problem Statement

The scenario addressed in this work can be depicted in Fig. 1. Suppose a moving object is walking/running across the hole in a field with a predictable average speed, and each sensor node knows its position and its one-hop neighbors’ information. The problem is: how the nodes can cooperate with one another to discover the hole accurately and detect the mobile target in time before it enters the hole and after it runs out of the hole.

There are two objectives for solving this problem, they are: 1) to minimize the energy consumption in the communication and sensing processes; and 2) to guarantee the accuracy in real-time detection.
reach the sender without collision. To solve this problem, we introduce a threshold to help proceed the boundary discovery process. That is: if \( \frac{\#ACK}{\#neighbors} \leq \text{Threshold} \), this node will be identified as a boundary node. For any identified boundary node, it (1) starts hole-detection signal to some direction as discussed before; and (2) starts sensing target procedure. Otherwise, this node is not on the boundary, and it will stop involving in the hole detection process. Note here, \( \#neighbors \) refers to the number of live neighbors (on the direction) that can be obtained using regular neighboring discovering process, and \( \text{Threshold} \) is an empirical value that may be affected by the property of physical/MAC layer protocols.

Still, for those nodes who need to tell if they are boundary nodes will also take use of directional antenna to send out the boundary-discovery packet instead of flooding to all directions, as illustrated in Fig.3. Here, we will use the hole-detection signal to calculate the 180° angle along the vector, to cover the area that faces to the hole.

C. Convergence of the protocol

The hole-detection signal may transit along the two directions of the hole. So if a sensor node receives a hole-detection signal later again, it should check if it is from a different direction than previous ones. Since the time for one hop neighboring transition is relatively much shorter than the signal transition from another direction, we can easily design the timer to handle the neighboring case. Thus, we can draw a conclusion if the signal is received from another direction in the first time, the signalling protocol actually converges and no more signals need to be sent out.

Suppose the target may keep moving till out of the hole or stay for a while inside the hole and then move out. To handle both cases, in the protocol, we simply use the Stop signal to indicate the target-catch-up on the reversed path propagated back to the initial hole detection nodes. All sensing nodes that received this signal will stop sensing process immediately. Although the state about the neighboring boundary nodes should be maintained, the cost is very small since the number of those nodes is very limited.

V. PERFORMANCE EVALUATION

A. Experimental settings

In this section, we evaluate the performance of the proposed protocol using simulation performed in NS3. We use the following parameters throughout the simulation: the sensed field is a rectangle with length 1000m and width 1000m, the sensors are randomly deployed and fixed, the default number of sensors is 450, the sensor’s transmission range \( R_T \) and sensing range \( R_S \) are 150m and 50m respectively, and the sensing interval is 0.1s.

Four experiment settings are designed, where each contains an uncovered hole as follows: those nodes that are within the areas in the following coordinates are presumed to be dead:

- hole_area_1 \((x, y)\) = \(\{ (x, y) | x \in [575, 800], y \in [135, 285]\}\),
- hole_area_2 \((x, y)\) = \(\{ (x, y) | x \in [575, 800], y \in [135, 285]\}\),
- hole_area_3 \((x, y)\) = \(\{ (x, y) | x \in [650, 750], y \in [500, 700]\}\),
- hole_area_4 \((x, y)\) = \(\{ (x, y) | x \in [0, 200], y \in [800, 1000]\}\).

Corresponding to each setting, one path is carried out as shown in Fig. 4-7. The design principles are based on different moving areas, turning around angles, running speed.
is detected by some boundary nodes. Still, we compared the be measured by the delay of the time between the moment C. Real-time analysis

different uncovered scenarios.

Third, the total sensing time (Fig. 10) of the proposed approach 1:6, because of the small angle in the directional transmission. and the one using omnidirectional antenna can be as much as

of bits sent and received (Fig. 8) in the approach using omnidirectional antenna is 1.6 to 3.3 times as much as that

energy consumption, compared to the approach using omnidirectional antenna.

Though we have tackled the fundamental problem of using directional antenna to make continuous tracking possible in WSN under holes, several issues remains to be considered. For example, how to design an effective algorithm to precisely predict the boundary nodes and how to handle the unreliable and lossy channel are among the ones in our future work.

B. Energy analysis

According to the energy consumption models depicted in Eq. 1 and Eq. 3, the minimization of energy consumption can be obtained by the following three equations. Accordingly, Fig. 8 - 10 present the three corresponding results under the comparison of directional and omnidirectional antenna.

\[
\begin{align*}
&\min\left(\sum_{i=1}^{N} k_s(i) + \sum_{i=1}^{N} k_r(i)\right) \\
&\min\left(\sum_{i=1}^{N} \text{angle}(i) \cdot k_s(i)\right) \\
&\min\left(\sum_{i=1}^{N} t_{s_i}\right)
\end{align*}
\]

We have the following observations. First, the total number of bits sent and received (Fig. 8) in the approach using omnidirectional antenna is 1.6 to 3.3 times as much as that of the proposed approach. Second, the ratio of the minimal objective factor 2 (Fig. 9) between the the proposed approach and the one using omnidirectional antenna can be as much as 1:6, because of the small angle in the directional transmission. Third, the total sensing time (Fig. 10) of the proposed approach is less than that of the one using omnidirectional antenna, especially in path4, which is the result of on-demand sensing in the proposed approach.

In summary, the proposed protocol outperforms the one using omnidirectional antenna for all different paths under different uncovered scenarios.

C. Real-time analysis

The performance evaluation of real-time target tracking can be measured by the delay of the time between the moment when the target is moving out of the hole and the moment it is detected by some boundary nodes. Still, we compared the proposed approach and the one using omnidirectional antenna. Fig.11 illustrates the results. As we can see, our method can not only converge, but also catch up the moving target in shorter delay than the one using omnidirectional antenna.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents continuous moving target tracking in WSN with uncovered holes. On one hand, we introduce the idea of using directional antenna, which breaks the omnidirectional antenna’s presumption in this field. On the other hand, we propose a collaborative based prediction algorithm and a signal protocol in order to realize a real-time and low-energy-consumption target tracking. Our simulations demonstrate the performance guarantee for real-time detection and reduction in energy consumption, compared to the approach using omnidirectional antenna.

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