CollECT: Collaborative Event deteCtion and Tracking in Wireless Heterogeneous Sensor Networks*

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Abstract

Event detection and tracking are attractive research issues in the wireless sensor network (WSN). The paper proposes a fully distributed protocol, CollECT, to event detection and tracking in a Wireless Heterogeneous Sensor Network (WHSN), composed of many kinds of sensors. In CollECT, three major procedures, vicinity triangulation, event determination, and border sensor selection are used to construct the logical triangle in the vicinity of a sensor, to determine the event, and to select the border sensor to identify the event boundary, respectively. The procedures perform repeatedly to both detect and track events. Simulation results demonstrate that CollECT is promising for event detection and tracking due to satisfactory event accuracy and reasonable fitness of border sensors.

1. Introduction

In a wireless sensor network (WSN), event detection and tracking are significant for several applications [4, 9]. Typically, a sensor needs to continuously sense the attribute of the event of interest. An attribute is regarded as a user specified predicate on sensor data, which satisfies some properties (e.g., temperature greater than fifty) [8]. The majority of existing works primarily utilize sensors, equipped with the same sensing units to track the single event formed by only one attribute [2, 6, 9]. However, event detection and tracking are unlikely to be achieved if the event is formed by multiple attributes, any one of which is unable to be detected by the same kind of sensors (i.e., sensors with the same sensing units). Thus, sensors with various kinds of sensing units are necessary for such application. A network comprising different kinds of sensors in the paper is called the *wireless heterogeneous sensor network* (WHSN).

The formidable challenge of event detection and tracking in a WHSN is the constraint on sensor's sensing capability. In general, with the characteristics of low power, low cost, and short communication range, a sensor has the potentiality to collaborate with other sensors to fulfil various tasks. Motivated by the collaboration in sensors, the paper develops an efficient and distributed protocol, CollECT, to event detection and tracking in the WHSN. CollECT consists of the *vicinity triangulation*, *event determination*, and *border sensor selection* procedures. The vicinity triangulation procedure enables the same kind of sensors to construct the respective attribute region. The attribute region is primarily represented by multiple triangles, named *logical triangles* to accurately identify the event region. During the event determination procedure, a sensor locally determines the existence of the event according to its sensor data and received messages from the different kinds of sensors within its logical triangles. Like most existing protocols [3, 7], the border sensor selection procedure aims to select sensors, called *border sensors* to stand for event boundary. The above procedures perform repeatedly to quickly and promptly track the event since the event spreads out from a small region with time elapsed.

To our best knowledge, the paper is the first investigation to concentrate on event detection and tracking in a WHSN. Overall, CollECT involves the following significant advantages: (1) CollECT is a fully distributed scheme. (2) CollECT effectively takes advantage of the collaborations of both the same and the different kinds of sensors. (3) CollECT does not require complicated computation. (4) CollECT enables sensors to promptly detect and track the event. (5) CollECT is cost-effective because of no need of sensor redeployment.

The rest of the paper is organized as follows. Section 2 formulates the network model. Section 3 then details the

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proposed CollECT protocol. Meanwhile, the simulation results are shown in Section 4. Finally, Section 5 presents conclusions and future research directions.

2. Network Model

A WHSN considered comprises many kinds of sensors, parts of which have different sensing units. That is, one kind of sensors can only detect the individual attribute. Let K be the number of kinds of sensors, and $N_s^{(k)}$ be the number of the kth kind of sensors. We are given N_E events, e_i, $i = 1, 2, ..., N_E$. A sensor, termed $s_i^{(k)}$ is able to detect attribute a_k, where $1 \leq k \leq K$ and $1 \leq i \leq N_s^{(k)}$. Assume all sensors are stationary and time-synchronized. Each sensor is aware of its physical location via either the installed GPS receiver or other GPS-less localization scheme [1, 5]. All kinds of sensors are randomly deployed in the network. Each sensor has the same communication capability. We also consider a connected network, within which each sensor has at least one neighbor. The event, formed by multiple attributes is assumed to spread out from a small region with time elapsed. The spread of the event is assumed to be slower than packet dissemination.

Here, we respectively define the *attribute region* and the *event region* as below.

Definition 1 *The attribute region, R_{a_i}, is defined as a contiguous area, wherein attribute a_i is detected.* □

Definition 2 *The event region, R_{e_i}, is defined as an overlapping area between multiple attribute regions, wherein all attributes form event e_i.* □

In CollECT, we use the following roles of sensors to identify the status of a sensor.

- Ordinary: A sensor is set to be ordinary when it does not sense any attribute of the event.
- Alert: A sensor is set to be alert if it perceives any kind of attributes of the event.
- Urgent: A sensor is set to be urgent if the event exists in its sensing range.

Figure 1 shows a network including two attributes regions, which forms an event region. The circle sensors are able to perceive attribute a_1, while square sensors can detect attribute a_2. All white, gray, and dark sensors respectively represent the ordinary, alert, and urgent sensors.

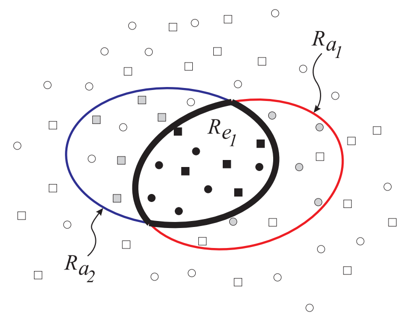

Figure 1. Attribute and event regions.

3. Collaborative Event DeteCtion and Tracking Protocol (CollECT)

The inspiration of CollECT comes from the collaboration in sensors. In principle, CollECT enables the same kind of sensors to construct the individual attribute region, each of which is composed of multiple triangles. The triangle is formed by connecting three same kind of sensors. From the logical viewpoint, such triangle is termed *logical triangle* because the sensors at any two of the vertices of a logical triangle may not be within the communication range of each other. The sensor at any vertex of a logical triangle is regarded as *logical neighbor* of the sensor at any other vertex. In the section, we respectively elaborate the major procedures, vicinity triangulation, event determination, and border sensor selection, for event detection and tracking.

3.1. Vicinity Triangulation

The main goal of vicinity triangulation is to identify the individual attribute region, which is represented by multiple logical triangles. In CollECT, each sensor is assumed to be aware of the attributes related to each event. Once detecting the attribute, an ordinary sensor, $s_i^{(k)}$, becomes an alert sensor, and then sends an ATR packet to its neighbors. The ATR packet is mainly used for a sensor to announce its sensing situation to all of the other same kind of sensors in the vicinity. The ATR packet involves the id and the location of $s_i^{(k)}$, the attribute what $s_i^{(k)}$ detects, and timestamp when $s_i^{(k)}$ detects the attribute. Upon receiving an ATR packet from $s_i^{(k)}$, a sensor with regardless of its kind and role needs to keep the above information carried in the ATR packet owing to the collaboration of sensors. Additionally, the sensor with the same kind of $s_i^{(k)}$ regards $s_i^{(k)}$ its logical neighbor because it is likely to be near the attribute region.

For ease of explanation, let the sensor, receiving an ATR packet be $s_j^{(k)}$ or $s_j^{(l)}$ if its sensing unit is identical to or different from $s_i^{(k)}$'s sensing unit, respectively. Obviously,

$s_j^{(k)}$ has to construct the logical triangle due to the identical sensing capability of $s_i^{(k)}$. Sensor $s_j^{(k)}$ also inhibits from forwarding the ATR packet for the reduction of unnecessary communication overheads. However, $s_j^{(l)}$ needs not to construct the logical triangle since it is unable to detect attribute a_k. Thus, $s_j^{(l)}$ only forwards the ATR packet because it is unable to collaborate with $s_i^{(k)}$ for determination of attribute a_k's region.

Obviously, more logical triangles generate with the spread of the event. The union of all logical triangles of the same kind of alert sensors is approximately regarded as the corresponding attribute region. Recall that the same kind of sensors constructs the individual logical triangle, so a sensor may receive numerous ATR packets with different attributes. A sensor receiving two ATR packets with the same attribute (e.g., a_1) will collaborate with the originators of the two ATR packets to form a logical triangle. The originator here means the sensor which issues rather than forwards the ATR packet. Subsequently, the sensor, once receiving another ATR packet with attribute a_i, uses the following *Vicinity Triangulation* test to efficiently select some corresponding logical neighbors to construct its logical triangles.

Vicinity Triangulation (VT) Test: For a sensor, if the originator of a new received ATR packet is within the sensor's logical triangle, or the sensor is within the triangle formed by the sensor's logical neighbors and the originator of the new received ATR packet, the triangle will be divided into three non-overlap triangles. □

In principle, the VT test focuses on minimizing the overlapping area of multiple logical triangles to avoid a large amount of computation overhead. That is, a sensor does not require regarding all of the originators of the received ATR packets its logical neighbors. For a sensor, reduction of the number of logical neighbors significantly speeds up event determination due to the distributed manner in CollECT.

In CollECT, an alert sensor regards that an event occurs within its logical triangle if receiving the ATR packet, whose originator is within its corresponding logical triangle, and the originator is another kind of alert sensors able to detect the attribute of the event. Obviously, small size of the logical triangle significantly benefits the accuracy in event determination. Thus, the VT test also scales down the size of the triangle.

Figure 2 shows the result of three cases after performing the VT test. Let w, x, and y be the same kind of sensors. Assume that w receives the ATR packets from alert sensors x and y prior to other same kind of alert sensors. Obviously, w, x, and y form a logical triangle, $\triangle wxy$. Here, we focus on w to illustrate the VT test. In Figure 2(a), if z is within $\triangle wxy$, upon the receipt of the third ATR packet from z, w selects x and z as the logical neighbors in terms of $\triangle wxz$, and regards y and z the logical neighbors corresponding to the logical triangle $\triangle wyz$. Additionally, the logical triangles of x are $\triangle wxz$ and $\triangle xyz$, while the logical triangles of y are $\triangle wyz$ and $\triangle xyz$. According to the VT test, in Figure 2(b), the logical triangles for w are $\triangle wxy$, $\triangle wyz$, and $\triangle wzx$, for x are $\triangle wxy$ and $\triangle wxz$, for y are $\triangle wxy$ and $\triangle wyz$, as well as for z are $\triangle wxz$ and $\triangle wyz$.

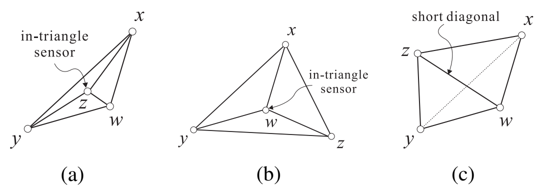

Figure 2. Result of three cases of the VT test.

If z is not within $\triangle wxy$, w is unable to use the VT test to determine its logical triangles when receiving the ATR packet from z. In CollECT, we devise a technique, called *Short Diagonal Wins*, to enable w to determine its logical neighbors based on its location and the locations of the originators of the ATR packets received. As shown in Figure 2(c), CollECT intends to divide the quadrangle, whose vertices are w, x, y, and z into two non-overlapping triangles, and prefers the two triangles sharing the shorter diagonal of the quadrangle. As a result, the logical triangles generated are $\triangle wyz$ and $\triangle wxz$ because the length of $\overline{wz}$ is shorter than that of $\overline{xy}$.

3.2. Event Determination

In CollECT, event determination is locally performed at each alert sensor. An alert sensor is aware of the timestamp when its logical neighbor detects the attribute, depending on the ATR packets from the logical neighbor. Such timestamp is mainly used for event determination. Basically, CollECT aims to select only one alert sensor to determine the existence of the event. For a logical triangle, because the alert sensor, which issues the ATR packet with the largest value of timestamp is likely to be near the event boundary at the certain time, such alert sensor is designated for event determination to timely adapt to the variation in event. Motivated by the collaboration of various kinds of sensors, CollECT adopts the following *Alert-In-Triangulation* test for an alert sensor to determine the existence of the event.

Alert-In-Triangulation (AIT) Test: An alert sensor regards the event occurs within its logical triangle if it receives the ATR packets from all kinds of the alert sensors, each of which has detected any one of the other attributes of the event. □

Once the AIT test is passed, an alert sensor becomes an urgent sensor, and then transmits an EVT packet to inform other sensors the existence of the event. The EVT packet involves the event id, sender's id, and logical neighbor entries, each of which represents all of the alert logical neighbors of the individual logical triangle of the sender.

Figure 3 shows an example of event determination for the sensor able to detect attribute a_1. Let $K = 2$. For ease of explanation, we here focus on the sensors able to detect attribute a_1 . In Figure 3(a), the dark, gray, dark/gray, and white sensors respectively indicate the urgent, alert, border, ordinary sensors. $s_1^{(1)}$, $s_2^{(1)}$, $s_3^{(1)}$, $s_4^{(1)}$, $s_6^{(1)}$, $s_7^{(1)}$, and $s_8^{(1)}$ are alert sensors due to the detection of attribute a_1. Additionally, the vicinity triangulation in terms of attribute a_1 is also constructed. The logical triangle of $s_3^{(1)}$ is $\triangle s_1^{(1)} s_3^{(1)} s_4^{(1)}$, and the logical triangles corresponding to $s_7^{(1)}$ are $\triangle s_3^{(1)} s_4^{(1)} s_7^{(1)}$ and $\triangle s_4^{(1)} s_7^{(1)} s_8^{(1)}$.

Without loss of generality, $s_3^{(1)}$ and $s_7^{(1)}$ are assumed to detect attribute a_1 later than the other two logical neighbors of their respective logical triangles. Thus, $s_3^{(1)}$ and $s_7^{(1)}$ are responsible for event determination. In Figure 3(a), $s_1^{(2)}$ is also an alert sensor of attribute a_2. Once receiving the ATR packet from $s_1^{(2)}$, $s_3^{(1)}$ considers that the event exists within $\triangle s_1^{(1)} s_3^{(1)} s_4^{(1)}$ because $s_1^{(2)}$ is located within its triangle. Meanwhile, $s_3^{(1)}$ becomes an urgent sensor, and then transmits an EVT packet. Similarly, $s_7^{(1)}$ also becomes an urgent sensor, and then sends an EVT packet due to the receipt of the ATR packet from alert sensor $s_2^{(2)}$.

Once receiving an EVT packet, a sensor mainly depends on its sensing capability for role transition and EVT packet forwarding. For a sensor with the same sensing capability of the originator of the EVT packet, the sensor requires becoming an urgent sensor if it appears in any one of logical triangle entries of the EVT packet. Moreover, the sensor inhibits from forwarding the EVT packet for the avoidance of heavy packets flooding in the network. Otherwise, the sensor not in the logical triangle entries needs not to rebroadcast the EVT packet because it is outside the logical triangle of the originator of the EVT packet. Namely, such sensor is not in the event region. Once a sensor unable to detect any attribute of the event receives an EVT packet, it has to forward the EVT packet owing to unawareness of the existence of the attribute in its sensing range.

Recall that $s_3^{(1)}$ and $s_7^{(1)}$ transmit EVT packets to inform other sensors the existence of the event. Obviously, in Figure 3(b), $s_1^{(1)}$ and $s_4^{(1)}$ will become urgent sensors since they are the logical neighbors of $s_3^{(1)}$. Similarly, $s_8^{(1)}$ also becomes an urgent sensor when receiving the EVT packet from $s_7^{(1)}$. However, although detecting attribute a_1, $s_2^{(1)}$ and $s_6^{(1)}$ will not become urgent sensors due to outside the logical triangles of $s_3^{(1)}$. Additionally, $s_{10}^{(1)}$ remains an ordinary sensor for lack of the same sensing capability of $s_7^{(1)}$, but requires forwarding the EVT packet received.

3.3. Border Sensor Selection

In general, the knowledge of the event boundary is more useful than that of the sensors in the event region. Thus, CollECT intends to select several sensors to efficiently identify the event boundary. Basically, in CollECT, either the alert or the ordinary sensor able to detect the attribute of the event may be selected as a border sensor.

As mentioned before, a sensor, receiving an EVT packet has to make a decision of EVT packet forwarding. Meanwhile, the sensor performs the border sensor selection procedure to identify itself as a border sensor, depending on its role. For an alert sensor, if any one of logical neighbors of its corresponding logical triangle is an urgent sensor, the alert sensor regards itself a border sensor. Alternatively, an ordinary sensor regards itself a border sensor in case all of the logical neighbors of its corresponding logical triangle are urgent sensors. In CollECT, a sensor not only maintains the information of its role for the event, but also uses a *border flag* for the representation of a border. The values of 0 and 1 indicate that the sensor is a non-border sensor and a border sensor, respectively.

As shown in Figure 3(c), suppose $\triangle s_1^{(1)} s_2^{(1)} s_3^{(1)}$ is the logical triangle of $s_2^{(1)}$. $s_2^{(1)}$ requires becoming a border sensor because either $s_1^{(1)}$ or $s_3^{(1)}$ is an urgent sensor. Similarly, $s_6^{(1)}$ becomes a border sensor as well. Besides, the ordinary sensor $s_{10}^{(1)}$ will become a border one owing to its two urgent logical neighbors (namely, $s_7^{(1)}$ and $s_8^{(1)}$).

3.4. Event Tracking

In principle, the attribute and the event regions vary with time elapsed. The prior ordinary sensor is likely to detect the attribute, and then becomes an alert sensor. The vicinity triangulation procedure is timely invoked for an alert sensor to construct the new logical triangle(s) adapt to the variation in the attribute region. The VT test is also carried out once a sensor receives multiple ATR packets. Then, based on the event determination procedure, such alert sensor or the prior alert sensor may further become an urgent sensor if the AIT test is passed. Additionally, the border sensor also probably becomes a non-border one when it is not in the event region. Obviously, an ordinary or alert border sensor has to change its role so as to adapt efficiently to the variance with the event. As a result, the proposed procedures require performing repeatedly to promptly detect and track events.

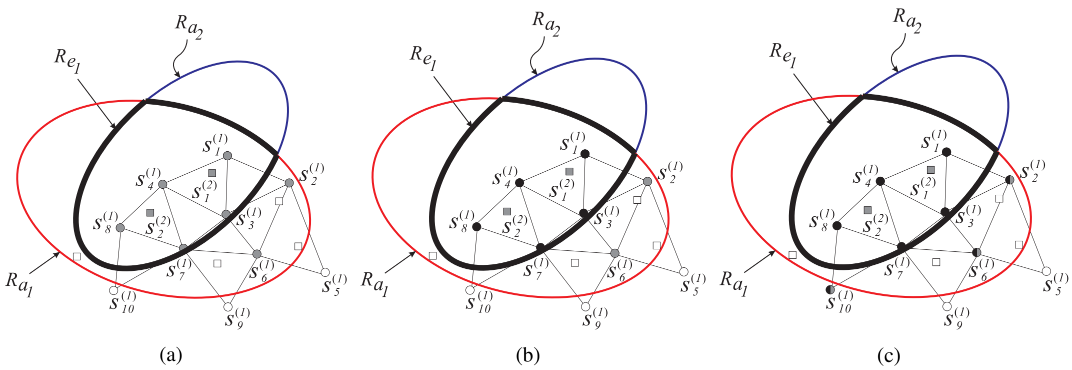

Figure 3. Example of event determination.

4. Performance Evaluations

In the section, we conduct numerous simulations to evaluate the performance of CollECT in accuracy and fitness, respectively representing the effectiveness of the urgent and the border sensors.

4.1. Simulation Setup

In the simulation, two different kinds of sensors are randomly scattered with a uniform distribution in a square area with the size of $600m \times 600m$. Our simulations differ from the numbers of sensors with 400, 450, 500, 550, and 600. The numbers of two kinds of sensors are identical. All sensors have the same communication range (r_c) and the same sensing range (r_s), where $r_c = r_s$. The sensing ranges in the simulation range from $30m$ to $50m$ with a step of $5m$. The event is composed of two attributes a_1 and a_2. R_{a_1} and R_{a_2} respectively spread out from $(200, 200)$ and $(300, 300)$ at a speed of $5m/s$. All simulation results are averaged over 10 runs.

4.2. Simulation Results

Accuracy in the paper is defined as the ratio of the number of urgent sensors obtained by CollECT to the number of sensors, whose sensing ranges cover the event region. Institutively, the higher the value of accuracy, the better urgent sensors determined by CollECT. Fitness focuses on the metric, μ_b, which denotes the mean Euclidean distance between each border sensor and the actual event boundary. Obviously, the result with fewer μ_b implies that the border sensors selected by CollECT are exactly close to the event boundary.

Figure 4, where $N_s^{(1)} = N_s^{(2)} = 200$ and $r_s = 30m$, shows an example result of spatial sensor distribution. The circle and square sensors are respectively for the detections of attributes a_1 and a_2. The black, gray, and white sensors respectively indicate the urgent, border, and ordinary sensors. The red and blue sensors indicate the alert sensors corresponding to a_1 and a_2, respectively. 16 sensors, whose sensing ranges cover the event correctly become urgent sensors (i.e., event accuracy is 100%). Note that two sensors (i.e., $s_1^{(1)}$ and $s_2^{(1)}$) also become the urgent ones although they are a bit distant from the event boundary. The sensors both detect attribute a_1 and there exacts an alert $s_1^{(2)}$ in their logical triangles, so they are consequently regarded as the urgent sensors according to the AIT test. We reason that the faulty is likely to be generated in the network with low sensor density.

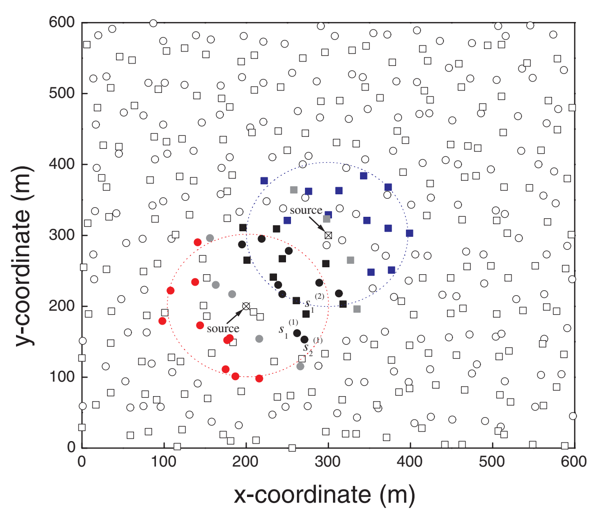

Figure 4. Example result of spatial sensor distribution.

Figure 5 shows the simulation result of event accuracy and border sensor fitness. The number of sensors is 400, and the sensing range, r_s, is $30m$. As shown in Figure 5(a), accuracy keeps rising with the increase of r_s. The increase of r_s causes the number of alert sensors with regardless of their kinds increases. An alert sensor's logical triangle most probably has the inside alert sensor able to detect the attribute of the event. As a result, CollECT performs well in event detection, especially for large sensing range. Institutively, more sensors deployed lead to more alert sensors. However, the number of sensors unable to detect the attribute of the event also increases. Thus, the curve in Figure 5(b) does not significantly rise or fall when the number of sensors increases. The value of accuracy is limited between 88% and 93%. Thus, we conclude that the event accuracy is independent of N_s.

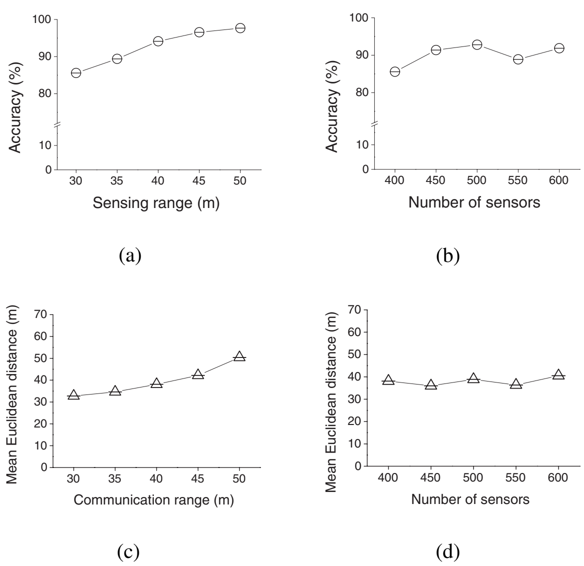

Figure 5. Simulation results of event accuracy and border sensor fitness.

Ideally, the border sensor is most likely to be at the place with distance r_c from the realistic event boundary. With the aid of the proposed vicinity triangulation, CollECT is able to minimize the size of the logical triangle. Additionally, by using the AIT test, there exist the urgent sensors in the vicinity of the event boundary. Thus, the border sensor and the urgent sensor closest to the realistic event boundary is approximately one-hop apart (i.e., r_c). Obviously, in Figure 5(c), the value of μ_b approximately equals the corresponding r_c of the sensor. In Figure 5(d), the value of μ_b is limited between $34.5m$ and $40.5m$ for different numbers of sensors because $r_c = 40m$. The variation in μ_b is apparently not significant for different numbers of sensors.

5. Conclusions

Basically, the paper is the first investigation to event detection and tracking in WHSNs. Motivated by sensor collaboration, we propose a fully distributed protocol, CollECT, including the vicinity triangulation, the event determination, and the border sensor selection procedures to not only construct the vicinity triangulation for event determination, but also select several reasonable border sensors for identification of event boundary. Our on-going work is to enhance CollECT to increase event accuracy, and to deal with the phenomenon wherein the event may disappear with time elapsed. Future studies can also explore the solutions to deployment, routing, and active/asleep scheduling in WHSNs.

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