OPERATIONAL DESIGN AND MODELLING OF FIRE EVENT TRACKING SYSTEM IN WIRELESS SENSOR NETWORKS

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ABSTRACT

In recent years, WSNs have been widely used for monitoring of environmental changes as they are capable of combining their sensing of a phenomenon with their computational functions and operate with limited resources to accomplish an intended task. Sensors can cooperatively monitor the surrounding environment and provide data that help in realizing the time evolution of the phenomenon and anticipating its effects. Consequently, such information would facilitate performing control actions that meet the predetermined goals. As distributed computing enables the exchange of real time data statistics obtained from various sources that need to be combined together to infer real abnormal conditions for management decisions. As tracking of an event depends on the event type, high-accuracy localization of an event such as fire is a serious challenge, where most of traditional detection systems depend on visualization (cameras) in making their control decision. Moreover, those systems concern the continuous detection of fire and do not provide reliable and feasible mechanism for tracking fire spread. This paper presents the design and modelling of a fire event tracking system that consists of indoor distributed sensor nodes and a powerful intelligent processing unit (controller) to detect fire events and compute information to provide desired safety decisions. Whenever the temperature in a premise increases, the system deploys cooperative centralized control functions to collect and process data statistics related to the fire. It exchanges direction, velocity, and/or position to take proper decision such as evacuating people from fire areas to a safe exit.

Keywords: wireless sensor networks (WSNs); event detection; event tracking; environmental monitoring systems; cooperative distributed sensing environment.

1. INTRODUCTION

The high potentials of Wireless Sensor Networks (WSNs) led to wide development of applications for sensing and monitoring of the physical environmental changes. WSNs are capable of gathering data for intended purposes usefully and efficiently. Premises are provided with sensor nodes, that are self-organize and capable of forming multi-hop network, and grid computing devices distributed within the site of interest [1]. Such network can execute a distributed sensing of environmental changes such as fire, gas leak, explosion etc. Event detection, control, and management are where distributed sensor nodes collect information about a specific phenomenon and send it for real-time processing at a powerful host(s) which combines the collected data to detect an event and to make appropriate decisions related to the event development [2]. It requires that the location of sensing nodes should be known in advance. Therefore, sensors should be capable of determining their location and exchange their position information with their neighbours and the base station (sink) that connects them with the rest of Internet. Location information can be used for different purposes such as tracking a certain event or saving energy where redundant or out of job sensor nodes can be powered down (go in sleeping mode) [3].

In event detection and monitoring, the base station (called controller in this paper) usually injects specific queries (instructions) into the network to perform a particular monitoring mission. Thus, by having such queries, each single sensor node can only detect the event of interest; while analysing and studying the trajectories of the events are done by the controller as it usually obtains a global view of the current ongoing events based on the information provided by sensor nodes.

Directed Diffusion is a robust and scalable communication standard that enables the utilization of database management in WSN where sensor nodes are application-aware. Database management helps in expressing the sensing tasks that would be performed by the sensor nodes according to the instructions for acquiring data from the surrounding environment and also in processing the data for providing useful information. Most of sensing distributed management systems developed for environmental sensing utilise Directed Diffusion model as it supports query-specific sources [4-7].

2. RELATED WORK

Event detection and tracking have received considerable attention among researchers interested in this domain. Many research works have addressed the detection and tracking of a target using WSN. H. Yang and B. Sikdar [8] have developed a distributed predictive protocol that precisely tracks mobile objects using WSN. Their protocol is considered scalable and robust as it uses a cluster-based architecture. Whenever there is an object to track, the protocol runs a distributed algorithm to select the sensor nodes that are appropriate for tracking. Thus, only determined nodes are activated; while the rest of nodes are in sleeping mode; hence, this would save energy for future task. The protocol also uses a prediction algorithm to notify cluster heads (CHs) when the targeted object is approaching. CHs in turn would activate the suitable nodes before the object arrives. Such method is also used by Chong *et al.* [9] to track several moving objects with the help of cooperated clusters in the network. In event detection and tracking systems that are based on prediction [10, 11], the next location of the target is anticipated according the path and speed with which the target moves. Several measurements are considered in tracking a target such as the received signal strength [12], time difference of target arrival [13, 14]. Other systems use binary sensor nodes to provide 1-bit readings about the phenomenon they detect [15]. F. Mourad *et al.* [16] combined likelihood estimation and Kalman filtering to improve the accuracy of tracking based on distance measurement. A maximum likelihood estimator is used to estimate the near future location of the target and measurement conversion. Then, the converted measurement and its associated noise statistics are utilized in Kalman filter to update on the current status of the target. Liu Mei *et al.* [17] proposed an ant colony algorithm for detecting and tracking a target using a mix of mobile and stationary sensor nodes. The locations of the mobile nodes are assigned by the algorithm to ensure continuous coverage of the monitoring area. M. Wiilchli *et al.* [18] proposed a system localization and tracking of a detected event where sensor nodes nearby the target are clustered to track the event. CHs are accountable for gathering and processing of sensed data. Their work had been extended for classifying the detected events [19]. Hybrid of static and dynamic clustering method used by Chang *et al.* [20] to develop an algorithm for detecting and the tracking of events such as gas, fire etc. Static clusters are formed during the deployment stage, while dynamic clusters are formed whenever such event is detected. Dynamic clustering is triggered based on the data acquired by sensor nodes located nearby the border of the extended event. This way reduces the unnecessary communications between the nodes.

The aforementioned methods are based on Directed Diffusion paradigm; hence, they are well capable of supporting event detection but do not provide specific reliable mechanism for tracking an event based on its properties such as position, direction, and velocity. They lack of tracking recovery technique when the target is missed; tracking accuracy is not sufficient; unable to deal with an event that has dynamic changes in shape, size, direction, and varying speed; unable to identify multiple targets and their tracking.

It is believed that, for efficient detection and tracking of evolvable environmental phenomena, it requires that the resourceful base station guides the nodes in the network to acquire data when the event is nearby them. Our aim in this paper is to propose a system for detecting and tracking continuous events such as fire (in an indoor environment such as inside home, bookstore, shopping centre, or factory) by collecting and analysing the related data during their progression in time and space according to their properties.

3. EVENT MODELLING

As any single sensor node is capable of detecting an event, there should be a mechanism to represent or describe the occurrences of the event in place. It is important to mention that sensor nodes are deployed for phenomena detection only; the analysis of the event's trajectory is usually done in a powerful base station (BS). Based on data aggregated at the BS, a global observation of the current events is concluded. An event can be detected directly or indirectly if several sensor nodes that are closed to each other in a given space report different readings (with respect to a predefined threshold) over a short period of time. Upon the event detection, knowledge about its spatial properties would be available to optimize the action required according to the information offered in regard to where the event is directed and how fast it is moving.

In WSN, data-event can represent an event according a set of raw sampled data of the phenomenon reported by a group of surrounding sensor nodes. It is a representation of a real-event in place such as fire, gas leak, or explosion in an industrial site or a building, etc. Thus, we are interested in the analysis of the raw homogeneous data acquired from different sensor nodes for building the data-event. The data-event is valuable to the BS rather than the individual sensor nodes involved in reporting data about the event. When an event takes place, BS would have data corresponding to that specific event. As the work proposed in this paper considers fire event, the event modelling is done based on physical properties of fire event. Therefore, the corresponding data-event can be defined as FROM Fire denotes the data source, select Position denotes the data of concern, which is the location of the fire in this case; and the temperature property of the fire, which is measured through the readings that are certain to a predefine threshold which is denoted by FIRE: (temperature > 400 °C). In order to acquire such information, the BS builds the data-event according to the information collected by nodes located in the area where the event occurs. Hence, the acquired data are processed by the BS to perform a quick and efficient reaction.

Temperature reading is done by individual sensor nodes reporting about any glowing surface on an object at a temperature around 400 °C (a Celsius degree at which glowing surface on an object can cause fire flame). Nevertheless, fire may cover wider area that involves many sensor nodes. In such case, building data-event requires computing an aggregation of the reading received from the nodes close to the event. For instance, temperature readings above a specified threshold reported by a node might be triggered by a regular safety maintenance work (such as welding process for joining materials) nearby that node. But, if the average of all temperature readings of nodes in certain place is higher than the predetermined threshold, it can be concluded that a serious fire accident has happened. Thus, in the proposed system, the fire event is:

- **Detected** by gathering and computing temperature data sensed by several nodes close to the fire event.
- **Tracked** by establishing a correct approximation of the location, direction, and spreading speed of the fire.

4. PROPOSED FIRE EVENT TRACKING SYSTEM

In this section, the proposed fire event tracking system is described theoretically and operationally.

4.1 Procedures and functions

The proposed fire event tracking system consists of procedures for detecting and tracking the fire event based on temperature value sensed by sensor nodes located in the fire area.

4.1.1 Event detection

The aim of the detection procedure is to monitor a given area, called detection domain (see Figure-1), to check whether a fire event occurs in the domain or not. The detection of the fire happens when the condition of comparing temperature readings from sensor nodes to the predefined threshold are found to be true. Capturing of the fire event depends on the temperature readings rate and the fire zone parameters. The temperature readings rate is the frequency of the readings updates received from (reported by) sensor nodes. It is an important parameter as some fire events may progress fast during a short period of time. Accordingly sensor nodes should monitor the location and updates with an appropriate reporting rate. The event zone (blue area in Figure-1) includes a specific number of sensor nodes that are involved in detecting the fire event. The fire is detected once the readings from sensor nodes within the event area (which are close to each other) show high temperature values. However, readings received form sensor nodes located far from each other do not imply that a serious fire event has occurred. Figure-1 shows the detection domain which is the rectangle area where sensors are deployed uniformly and the fire event zone, depicted in blue, signifies the size of the area under fire.

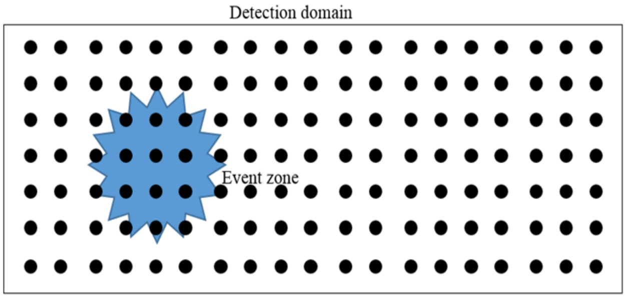
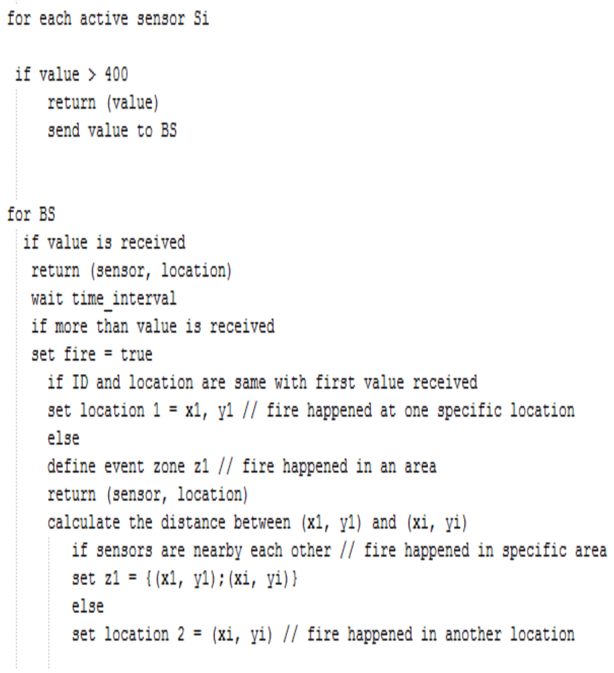


Figure-1. Detection domain and fire event zone where neighbouring sensor nodes report higher temperature values'

The detection procedure is performed continuously (or periodically but for short time where adjacent sensor nodes are activated alternately for an effective detection) until a fire incident is detected. This procedure consists of two functions: fire event definition function and fire detection function.

Fire event definition function: This function defines the fire event as a data-event, which includes the temperature property that is bound to a specific condition. A comparative relational operator (>) is used to manipulate TRUE/FALS cases. The function also defines the size of the area under fire. Temp identifies the collection and characteristic that translates the fire into the *data-event*. The fire event is characterized by high temperature in the fire area. Then, after obtaining Temp value, it is bound to a predetermined threshold (>) to procedure the condition phrase of the *data-event.*

Fire detection function: This function identifies the detection parameters such as the location of the fire zone. zone defines the domain where the detection of the fire should be executed. It can be defined by the geographical coordinates of sensor nodes located in the detection domain. time interval defines the sampling rate of sensing the temperature and evaluating the relational expression based on the scenario in place (whether it is in factory, shopping mall, library etc). The sampling rate is usually one second in case of fire. Figure-2 below shows the general procedure for fire detection.

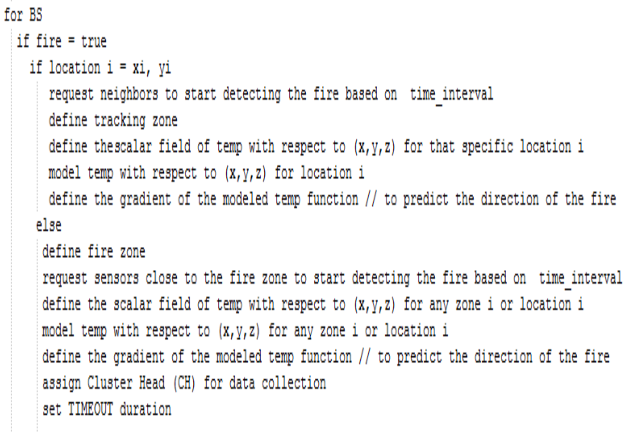


```
for each active sensor Si

 if value > 400
     return (value)
     send value to BS


for BS
  if value is received
   return (sensor, location)
   wait time_interval
   if more than value is received
   set fire = true
     if ID and location are same with first value received
     set location 1 = x1, y1 // fire happened at one specific location
     else
     define event zone z1 // fire happened in an area
     return (sensor, location)
     calculate the distance between (x1, y1) and (xi, yi)
        if sensors are nearby each other // fire happened in specific area
        set z1 = {(x1, y1);(xi, yi)}
        else
        set location 2 = (xi, yi) // fire happened in another location
```

Figure-2. Pseudo code of fire detection procedure.

4.1.2 Event tracking

When a fire incident happens, the condition (i.e. avgTemp > 400) of the data-event becomes true and the tracking of the fire starts. Tracking procedure aims at monitoring the fire while it progresses in time and space for further control. Tracking of the fire is triggered by the detection of the fire. That is, event tracking process obtains data about the fire development, but not the detection process which only acts as a trigger for tracking the fire. Fire tracking process produces data regarding position, direction, and speed of the fire spread periodically depending on the sensor nodes nearby the fire zone. Tracking process is responsible for constantly monitoring the fire during its spatial progress over the time. The fire may move and enlarge according to the atmosphere conditions of the premise. With the purpose of tracking the fire, the controller performing the tracking job request the sensors nodes close to the fire zone to start detecting the fire on regular basis and accordingly report to the controller in order to have a clear image on the spatial evolution of the fire being tracked. Fire tracking procedure is presented in Figure-3 below:



```
for BS
  if fire = true
    if location i = xi, yi
       request neighbors to start detecting the fire based on  time_interval
       define tracking zone
       define thescalar field of temp with respect to (x,y,z) for that specific location i
       model temp with respect to (x,y,z) for location i
       define the gradient of the modeled temp function // to predict the direction of the fire
     else
      define fire zone
      request sensors close to the fire zone to start detecting the fire based on  time_interval
      define the scalar field of temp with respect to (x,y,z) for any zone i or location i
      model temp with respect to (x,y,z) for any zone i or location i
      define the gradient of the modeled temp function // to predict the direction of the fire
      assign Cluster Head (CH) for data collection
      set TIMEOUT duration
```

Figure-3. Pseudo code of fire tracking procedure.

Tracking zone indicates the potential area (expressed in number of alerted nodes), through which, the tracked fire possibly spreads and that must be detected. It is usually wider than the actual fire area. TIMEOUT indicates the expiration time of the tracking, where sensor nodes change to sleeping mode. At the controller, some of the information related to the fire such as position and spreading speed are selected and reported in a specific time interval to higher level where a proper action is taken.

4.2 Theoretical description

In this section, we describe theoretically how the proposed system works when the fire occurs. Suppose that there are several temperature sensor nodes in a three dimensional premise, where the height *z* is a function of *x* and *y*, *z* = *f*(*x*, *y*), that gives the surface in three dimensional space. Let the temperature *T* in the atmosphere of the premise represents a function of where are the sensor nodes in the premise. Let's say it is a function of the *x, y,* and *z* coordinates, *T* = *f*(*x, y, z*).

Assume that a heat force (fire event) appears somewhere in the premise as shown in Figure-1. By getting further and further away from that fire source, it is going to get colder and colder.

Assume that the temperature function or the model of temperature is:

$$T(x,y,z) = 60\,e^{-r^2} \tag{1}$$

Note that *r* is a function of *x, y,* and *z*; it means that it exponentially decays as getting further and further away from that fire source. It is kind of radially further and further away from that source. The radius away from the fire source is $\boldsymbol{r^2}$, which is just$\boldsymbol{x^2+y^2+z^2}$
This is Pythagorean Theorem in three dimensions.

$$\mathrm{T(x,y,z)} = 60\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)} \tag{2}$$

$\boldsymbol{e}^{-(\boldsymbol{x^2+y^2+z^2})}$ expression means that the square of the distance as getting away from the source of the fire.

That is, at any point in the three dimensional space of the premise, a value can be associated (taking a thermometer and measuring any point in space in the premise gives a temperature). But, it cannot provide temperature and direction together. We can only get a temperature, and this what the temperature sensor nodes do.

If we view the gradient of the function $\boldsymbol{(x,y,z) = 60\,e^{-(x^2+y^2+z^2)}}$, the gradient could tell in which direction is the largest increase in temperature, and how large is the increase in the temperature. Therefore, the gradient of the function $\boldsymbol{T(x,y,z) = 60\,e^{-(x^2+y^2+z^2)}}$ is equal to:

$$\boldsymbol{\nabla T = \frac{\partial T}{\partial x}\hat{\imath} + \frac{\partial T}{\partial y}\hat{\jmath} + \frac{\partial T}{\partial z}\hat{k}} \tag{3}$$

$$\begin{aligned}\nabla \mathrm{T} = {} & (-2\mathrm{x}.\,60.\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)})\hat{\imath} + \left(-2\mathrm{y}.\,60.\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)}\right)\hat{\jmath} + \\ & (-2\mathrm{z}.\,60.\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)})\hat{k}\end{aligned} \tag{4}$$

$$\begin{aligned}\nabla \mathrm{T} = {} & (-120\mathrm{x}.\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)})\hat{\imath} + (-120\mathrm{y}.\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)})\hat{\jmath} + \\ & (-120\mathrm{z}.\,\mathrm{e}^{-(\mathrm{x}^2+\mathrm{y}^2+\mathrm{z}^2)})\hat{k}\end{aligned} \tag{5}$$

Consequently, if the gradient at any point in the space is of interest, then, its *x, y,* and *z* should be substituted in (5).

Figure-4 below shows the gradient of the function above. Here, a sensor node (or cluster head) reports the readings of temperature at its location and the controller (base station) would compute the gradients at that location point and then graph them as a vectors. Thus, the length of vectors is just the magnitudes of the *x, y,* and *z* components and adds them together. And then the direction is given by the relative weighting of *I, J,* and *K* components. As getting closer and closer to the fire source, the rate, at which the temperature enlarges, increases. In other words, as getting closer, the vectors get bigger and bigger. These are the information needed in order to make proper safety decisions.

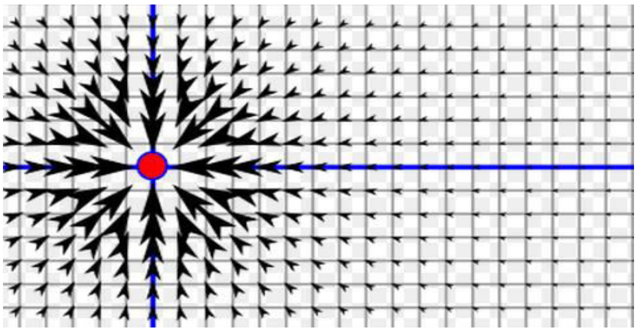


Figure-4. The gradient at the point of fire location.

4.3 System operation

In the proposed fire event tracking system, the controller and sensor nodes cooperate together to execute the detection and tracking procedures in order to obtain data related to the fire event while it develops in both time and space. The fire event is modelled as data source, from which data critical to fire location and tracking is acquired. The concept of relational view of data would be considered in implementing the procedures of fire detection and tracking performed in a distributed fashion in a WSN that consists of sensor nodes and controller networked for this purpose. Sensor nodes can be deployed uniformly provided that they cover the area under monitoring properly, taking into account their transmission range. For example, considering the packet transmission overhead, data traffic management, and sensing activation, data collection is done hierarchically by sensor nodes while aggregating data and executing the average is done by the controller.

Every sensor node in the area of monitoring (detection domain) is programmed with the detection procedure mentioned earlier. Then, according to time_interval period, each sensor node periodically obtains the information needed to detect the fire, and it cooperates with its neighbouring nodes that are located in the area of size event Zone, and also with its controller so as to calculate the relational clause that describes the fire event and examine whether the relational clause is true or not.

Once the fire incident happens, several nodes in (or nearby) the fire area should have detected it. Thus, the controller would recognize that such several detections in a certain area are related to a single fire incident. In order to utilize the network resources efficiently, the controller would execute a distributed algorithm for selecting leader for routing data during the tracking stage where sensor nodes sense and transmit data consistently. The leader is responsible for collecting information about the fire and report directly to the controller. Such information includes the IDs of sensor nodes detecting the fire and the readings they provide. This information also defines the scope (degree) of the fire according to the fire expanding area and the number of nodes in that area. The location of the fire is also determined during detection stage. Figure-5 shows a situation in which a fire incident is detected by 23 sensor nodes located in the area (presented by the blue cloud) that is covered by the fire. Yellow sensor nodes are the ones located at the margin of the fire zone. The readings from those nodes would help confirming the direction of the fire spread.

The red node in the center of the event zone, and all its one-hop neighbours have detected the fire, confirming the exact location of the fire.

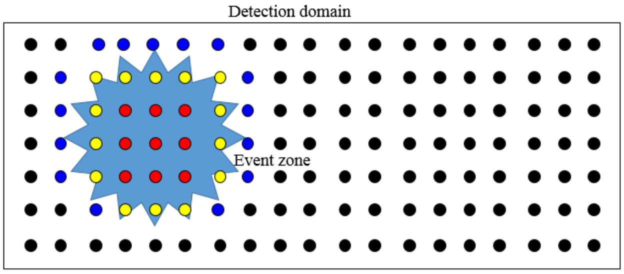


Figure-5. Detection domain and the fire event zone.

The collected data from sensor nodes is combined to detect the fire and compute information to provide the expected desired decision. The application of distributed system in the controller should take action whenever complexity increase (change in temperature). For example, to ease the merging people from fire place to a safe exit. The controller can compute the direction, velocity, and/or position information and find the best way people should take out of the premise.

The controller deploys cooperative centralized control functions such as collecting and transferring of data traffic statistics to local intelligent agents (cluster heads). Upon detecting the fire, the controller would assign a Cluster Head (CH) (the green node in Figure-6) for data collection in order to trace the fire evolution. The assignment of the leader is done based on the node resources (such as transmission power and energy) and location with respected to the fire event zone. According to the routing protocol in use, the sensor nodes could send their readings directly to the CH (as shown in Figure-7) or hop-by-hop. Also, the CH would report directly to the controller or hop-by-hop.

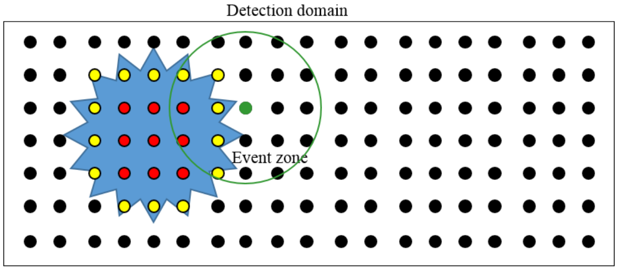


Figure-6. Cluster Head (CH) assignment according to resources and location.

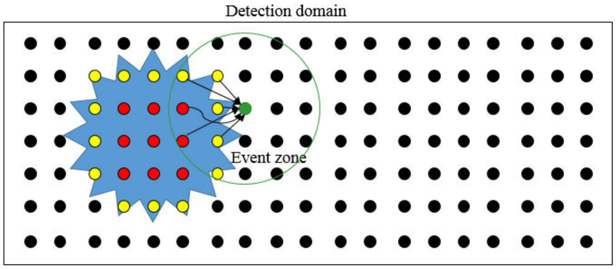


Figure-7. Sensor nodes send their readings directly to their CH.

Once the data is aggregated at the controller, the temperature readings would help estimating the location of the event. After detecting the fire and its location is known, the stage of tracking the fire begins where the controller needs to collect more information about the fire event. It would instruct the sensor nodes that are located one-hop away from the border nodes (blue sensor nodes in Figure-5) for continuous temperature sensing. Then, as a reaction to the progress of the fire, the controller would compute the potential direction of the fire as described earlier. Figure-8 and 9 show the output of the calculation based on the information provided by sensors, which show the directions of the fire spreading and the potential evolution.

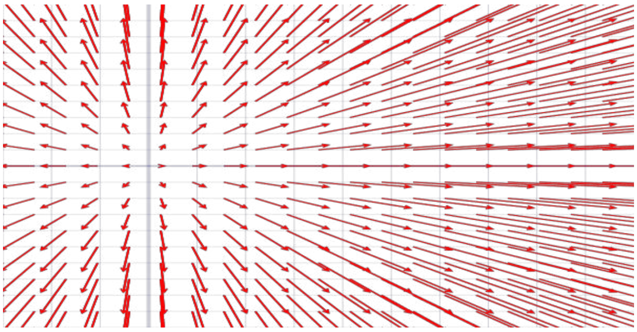


Figure-8. The direction of the fire spread based on the readings received from sensor nodes.

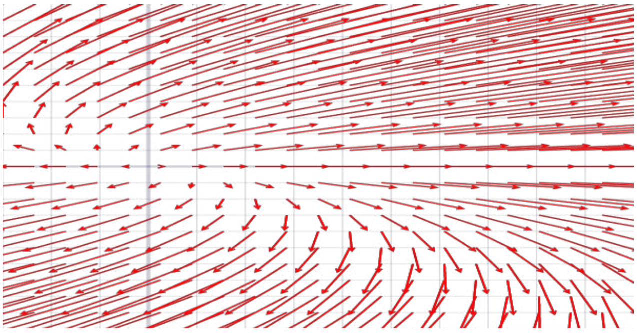


Figure-9. The potential evolution of the fire.

As the event expands over time, sensor nodes (including CHs) may die due to energy depletion or destroyed by the fire. Thus, as a consequence of the fire progress and that the data shows that the fire moves towards other places, the controller may instruct more new sensor nodes that are not initially close or nearby the event zone to start detecting and collecting more data that would help in projecting the evolution of the fire in near future. The instructed sensor nodes located outside the event zone would start sensing or reacting accordingly whether they are CHs or merely sensing nodes. Continued detection activities instructed by the controller expire (stop) after certain period of time (based on the TIMEOUT duration). This is essential procedure as it is necessary to stop nodes from sensing when the fire moves far from them; hence saving resources for another incident that might happen. Conversely, the controller would recall (refresh) the timeout periods if the fire remains in their area. Also the controller may replace the CHs in order to ensure efficient data acquisition and management operations.

5. CONCLUSION AND FUTURE WORK

As distributed computing enables sensors to exchange position and velocity information, real time data traffic statistics from various sources can be combined together to infer real abnormal conditions for management decisions. Existing event detecting and tracking systems are based on Directed Diffusion concept. Even though they provide techniques for event detection but do not have reliable schemes for tracking the event according to its properties such as position, direction, and velocity. This paper proposes a system for detecting and tracking continuous events such as fire by collecting and analysing the related data during events progression in time and space based on their properties. We believe that intelligence should be added to the network in order to enforce proper instructions that yield useful information for appropriate decision to control the fire event. As a powerful resources machine, the base station can compute the received readings from the sensor nodes to estimate the current status of the fire and figure out its intensity and scale, and then takes the right safety decision accordingly. In this paper, we have presented the operational design and modelling of the proposed system. In the future work, we are going to investigate the efficiency of the proposed system in simulated wireless sensor networks using the ns-2 network simulator.

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