Fire Monitoring and Extinguishing Algorithm using Wireless Sensor and Actor Networks

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ABSTRACT

Buildings may be subjected to natural hazards such as earthquakes, winds and fires during their long-term use. Fire is a very common hazard and could be monitored and prevented using Wireless sensor and actor networks (WSANs). WSANs refer to a group of sensors and actors linked by wireless medium to perform distributed sensing and actuation tasks. In such a network, sensors gather information about the physical world, while actors take decisions and then perform appropriate actions upon the environment, which allows remote, automated interaction with the environment. In this paper , a routing algorithm for fire monitoring and extinguishing(FMEA) is proposed that makes use of the threshold sensing for monitoring and extinguishing fire. Initially when fire is detected sensors raise alarms so that lives could be saved with no waste in time .Once the temperature exceeds a certain threshold then extinguishing takes place. The sensing environment consists of many Monitoring Nodes that sense fire and report the data to the Cluster Head. The Cluster Head directs the Actors to extinguish the fire before sending the data to the Base Station.

Keywords

Wireless Sensor and Actor Networks ,fire monitoring ,threshold , Clusters, Cluster Head ,Base Station sensors, actors .

1. INTRODUCTION

Fire fighting is life threatening event and even though some systems exist to provide information about the fire, the most important that are required during fire fighting are proximity of the fire fighters to the danger, health status of the fire fighters , better radio communication, and proper information of the building floor plans. They also face sudden dangers like ignition of the room, explosions occurring due to sudden oxygen entry in oxygen starved fire locations, hidden fires in walls and release of toxic gases[4].Wireless Sensor and Actor Networks(WSAN) could be of great importance in such applications where sensors are used to detect fires and actors are used to extinguish the fire.

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In this context, the meaning of the term *actor* differs from the more conventional notion of *actuator*. An actuator is a device to convert an electrical control signal to a physical action, and constitutes the mechanism by which an agent acts upon the physical environment. From the perspective considered in this paper, however, an actor, besides being able to act on the environment by means of one or several actuators, is also a network entity that performs networking-related functionalities, i.e., receive, transmit, process, and relay data. For example, a robot may interact with the physical environment by means of several motors and servo-mechanisms (actuators). However, from a networking perspective, the robot constitutes a single entity, which is referred to as actor. Hence, the term actor embraces heterogeneous devices including robots, unmanned aerial vehicles (UAVs), and networked actuators such as water sprinklers, pan/tilt cameras, robotic arms, etc. Applications of wireless sensor and actor networks may include team of mobile robots that perceive the environment from multiple disparate viewpoints based on the data gathered by a sensor network, a smart parking system that redirects drivers to available parking spots, or a distributed heating, ventilating, and air conditioning (HVAC) system based on wireless sensors.

Peculiarities of Wireless Sensor and Actor Networks: However, due to the presence of actors, WSANs have some differences from wireless sensor networks (WSNs) as outlined below: While sensor nodes are small, inexpensive devices with limited sensing, computation and wireless communication capabilities, actors are usually resource-rich devices equipped with better processing capabilities, stronger transmission powers and longer battery life.

- In WSANs, depending on the application there may be a need to rapidly respond to sensor input. Moreover, to provide right actions, sensor data must still be valid at the time of acting. Therefore, the issue of real-time communication is very important in WSANs since actions are performed on the environment after sensing occurs.
- The number of sensor nodes deployed in studying a phenomenon may be in the order of hundreds or thousands. However, such a dense deployment is not necessary for actor nodes due to the different coverage requirements and physical interaction methods of acting task. Hence, in WSANs the number of actors is much lower than the number of sensors.
- In order to provide effective sensing and acting, a distributed local coordination mechanism is necessary among sensors and actors.

WSN routing algorithms pay much attention to energy savings as it is impossible to replace or recharge batteries of sensor nodes. The operating states of a sensor node can be categorised as transmitting, receiving and idle or sleep states. A sensor node in transmitting state consumes the most energy while in receiving or idle states consumes a little less energy. The energy consumption for data transmission is directly proportional to the square of a wireless transmission distance. A WSN therefore uses routing protocols that are, capable of data aggregation , distribution of energy dissipation evenly and energy efficient in order to increase the network lifetime.

This paper makes use of the Local Clustering and Threshold Sensitive routing algorithm [6] for threshold sensing. But the data transmission is done using Schedule Channel Polling(SCP) since SCP is proved to be more energy efficient than TDMA for event based reporting like fire sensing[ ]. Mini-slot structure works fine in short range wireless transmission environment however it cannot work in a Wireless Long Distance Environment (WILD)[5].

The contributions of this paper are described as follows.

(1) A solution for data gathering from the environment based on a certain threshold like finding all places where temperature level is greater than say LowerRiskThreshold(LRT). This is done by Monitoring Nodes (MN) and if the temperature exceeds LRT then sensors raise alarms so that human lives are saved earlier. Also these alarms will help in false alarm detection manually.
(2) If the MNs sense temperature or smoke above a certain threshold(T) that is higher than LRT they report the data to the Cluster Head(CH) in a single hop.
(3) The Extinguishing Nodes (EN) are the actors and takes care of extinguishing the fire in case the CH orders it to extinguish fire in a certain direction based on the intensity of the fire.
(4) If many Monitoring Nodes (MNs) sense higher temperature then the Extinguishing Nodes(EN) are informed of a high intensity fire and appropriate extinguishing takes place.

2. RELATED WORK

In this section, related routing protocols, with a focus on clustering sensor nodes in WSNs are discussed.

In TEEN[2] , at every cluster change time, in addition the attributes ,the CH broadcasts to its members,

Hard Threshold (H_T): This is a threshold value for the sensed attribute. It is the absolute value of the attribute beyond which, the node sensing this value must switch on its transmitter and report to its CH.

Soft Threshold (S_T): This is a small change in the value of the sensed attribute which triggers the node to switch on its transmitter and transmit.

The H_T tries to reduce the number of transmission by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The S_T further reduces the number of transmissions by eliminating all the transmissions which have otherwise occurred when there is little or no change in the sensed attribute once the $H_{T.}$

But the main drawback of this algorithm is that if the thresholds are not reached, the nodes will not communicate, the user will not get any data from the network, and will not come to know even if the nodes die. Therefore this scheme is not suited for applications where it is necessary to get data on a regular basis. Another problem with this algorithm is that there should not be any collisions in the cluster. So a TDMA or CDMA schedule is necessary to solve this problem.

APTEEN[1] is a variation of TEEN, designed as a hybrid protocol that changes the periodicity or threshold values used to provide a periodic state view of the network. It uses combination of proactive and reactive network's features. The CH selection in APTEEN is based on the mechanism used in LEACH-C. The cluster exists for a period called the cluster period, and the BS regroups the clusters, at a time called the cluster change time. APTEEN uses modified TDMA, where each node in the cluster is assigned a transmission slot, to avoid collisions. For query responses, APTEEN uses node pairs. This implies adjacent nodes that sense similar data, but only one of them responds to a query; the other can go to sleep. These two nodes can take the role of handling queries alternately, which helps them saving resources.
Power-Efficient Gathering in Sensor Information Systems(PEGASIS) [7] is an extension of the LEACH protocol, which chains from sensor nodes so that each node transmits and receives from

a neighbour and only one node is selected from that chain to transmit to the Base Station(sink). The data is gathered and moves from node to node, aggregated and eventually sent to Base Station (BS). The chain construction is done in a greedy way. Unlike LEACH, PEGASIS avoids cluster formation and uses only one node in a chain to transmit to the BS instead using multiple nodes. A sensor transmits to its local neighbours in the data fusion phase instead of sending directly to its CH as in the case of LEACH.

In [3] the optimal planning of sensor's states in cluster-based sensor networks is discussed. Typically any sensor can be turned on, turned off, or promoted cluster head and a different power consumption level is associated with each of these states. An energy-optimal topology that maximizes network lifetime ensuring simultaneous full area coverage and sensor connectivity to cluster heads ,which are constrained to form a spanning tree is used as a routing topology.

In our previous work[8] , only actuators were used and also no alarms were involved to alert human at an earlier stage.

3. REFERENCE NETWORK MODEL

As mentioned in the introduction , this paper focuses on how to gather information from the environment based on a certain threshold , the locations where the temperature is higher than the threshold . Accordingly the following assumptions of the WSN are made.

- The network consists of many Monitoring Nodes(MN) that sense the environment and form static clusters; many actors or Extinguishing Nodes(EN) in every cluster and one MN that acts as a Cluster Head(CH) in every cluster.
- All Monitoring Nodes(MN) are homogeneous and have the same initial energy supply;
- All the MNs can directly communicate with the Cluster Head(CH) in their region;
- The CH can order the actors to start or stop extinguishing based on the intensity of the fire.
- The radio channel is symmetric, i.e., the energy consumption for transmitting a message from one node to another is the same as on the reverse direction; and
- Energy consumption for a data transmission only depends on

  (1) the size of the data packet
  (2) the distance between the sender and receiver

Figure 2 illustrates the architectural model of such a WSAN with MNs and Extinguisher Nodes (ENs).

The clusters dynamically change later depending on the available energy of the other nodes and CH are elected based on rotation. The network is assumed as a 50 x 50 m network of Sensor Nodes as in Figure 2.

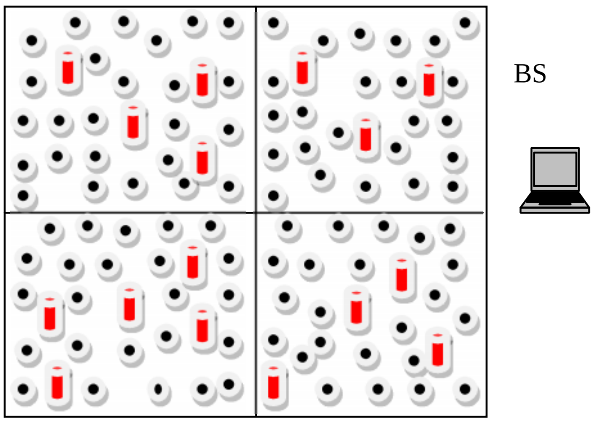
For energy analysis the first order radio model is adopted. Energy consumption in the circuitry for running the transmitter or receiver and in radio amplifier for wireless communication are $E_{ciruitry}$ = 50 nJ/bit and $E_{amplifier}$ = 100 pJ/bit/m2 respectively. The value of $E_{amplifier}$ is directly proportional to the square of transmission distance.

Therefore the energy for transmitting a packet where k is the size of the transmitted packets, and d is the distance between a transmitter and receiver is

$$E_{tansmit}(k,d) = E_{ciruitry} \times k + E_{amplifier} \times k \times d^{2} \quad (1)$$

The energy for receiving a packet is

$$E_{receive}(d) = E_{ciruitry} \times k \quad (2)$$



MN s - EN s

Figure 2. Architectural model of WSAN of 100 nodes showing Monitoring Nodes(CN) in clusters and actors or Extinguishing Nodes(EN) for every cluster.

An efficient routing algorithm aims at reducing the energy required for transmission and receiving and so this algorithm is aimed at energy efficiency as described in the section below.

4. Fire Monitoring and Extinguishing Algorithm(FMEA)

FMEA works in the following phases:

4.1. The Initial Cluster Set-up Phase:

The main activities of this phase are creation of clusters and selection of initial CH by the Base Station.

The network contains some Monitoring Nodes (MN) that form clusters in a region. The clusters are static and every cluster has several Extinguisher Nodes(EN) as shown in figure 2. The Cluster Heads for every cluster are created based on the decision taken by the Base Station (BS). Since all the nodes have the same energy initially, the BS decides Cluster Heads from the MNs in a cluster based on their locations . The CH thus selected by the BS will not be CH again until all other nodes with higher energy level is selected as CH since being a CH drains the battery of the node .Thus the clusters are static but Cluster heads are dynamic within each cluster.

4.2. Low Risk Threshold (LRT) Sensing:

Initially when temperature exceeds the LRT (that is lesser than HT) , the MNs raise alarms to alert human intervention. This phase helps to save human lives and also helps to avoid false alarms due to manual checking in buildings like hospitals or schools where lives need to be saved quickly even before extinguishing takes place.

4.3. Schedule Channel Polling (SCP):

Data Transmission is done by the MNs if the sensed value is greater than the Threshold as is in our previous work[6].The SCP protocol [9] is used for data gathering whenever the a fire is sensed. This protocol is proved to be more energy efficient than most of the slotted MAC protocols as seen in the performance evaluation of the algorithm.

The MNs contend for the channel in case the temperature crosses the Threshold and then the CH check if it has data to receive. If there is no MN that crosses the Threshold then, all MNs will observe a clear channel and go to sleep immediately. Figure 3 illustrates this process

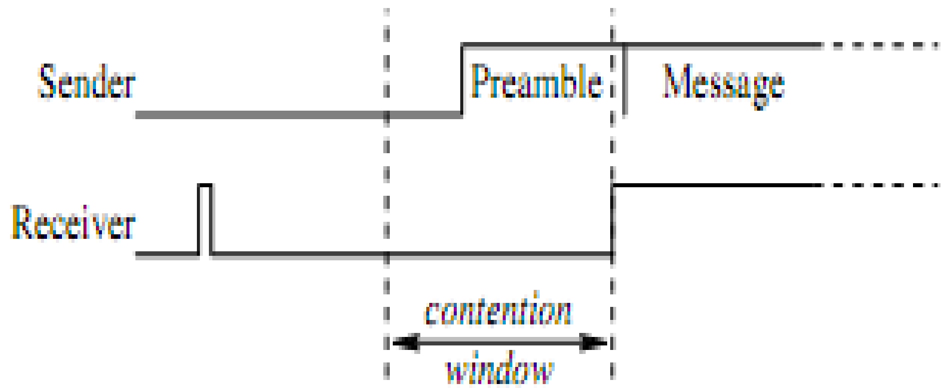


Figure 3: SCP-sender only contention resolution by means of stretched preamble.

Each slot starts with a contention window. At that moment , if a MN wants to send data, it chooses a random moment within this window. If the channel is clear, the MN switches on its radio and starts sending a preamble .The preamble acts as a busy tone and continues until the end of the contention window and thereby locks out any potential senders. Right after the contention window the CH wakes up and performs a carrier sense to see if there is a preamble followed by a message. Without any traffic, SCP-MAC thus only needs to perform one carrier sense per slot making it the most efficient protocol of its class.

Using SCP-MAC schedule as described above, each sensor transmits the sensed information to the CH if the sensed information is above the Hard Threshold(H_T).The sensed value is stored in an internal variable called *sensedvalue (SV).*The nodes will send again the value of SV only if it differs from SV by an amount equal to or greater than a Soft Threshold(S_T).

Whenever a node transmits the data, SV is set equal to the current value of the sensed attribute. Thus , the H_T tries to reduce the number of transmissions by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The S_T further reduces the number of transmissions by eliminating all the transmissions which might have otherwise occurred when there is little or no change in the sensed attribute once the hard threshold as in algorithm below.

Algorithm for threshold sensing.

```
If      ( (newsensordata  > HT)
        or  (( newsensordata  - SV )   > =  ST) )

then    let  SV = newsensordata;
        Send SV along with rem_energy_level  of  Sensor          Node to ClusterHead;
else
        send only rem_energy_level of SensorNode        to the Cluster Head.
```

During this phase, for each time slot, the sensor nodes will sense the environment and let its value be newsensordata and the energy available at each node be rem_energy_level.

After the clusters are formed, the ENs keep sensing the environment and if the temperature exceeds the Threshold(T), it sends data immediately to the CH. The CH receives the sensed data and sends the extinguishing instruction to the EN. If more than one MN sends data exceeding the Threshold(T), then the data is aggregated and sent to the EN nearest to the fire . The EN extinguishes the fire based on the data send and the direction of the MNs and the CH sends the aggregated data to the BS for the user.

4.4.Cluster Head change after a round of Fire detection and Extinguishing

The CH changes after every round of detecting temperature greater than the Threshold. The MNs that do not sense the fire send their remaining energy levels and the next CH is determined as given below.

Algorithm for Cluster Head Selection in every cluster after every round of Threshold sensing

1. For every cluster, select a Monitoring Node(MN) with maximum residual energy as Cluster Head
2. In case of ties , calculate the Euclidean distance between the EN of that cluster and the MNs of equal residual energy.
3. Select the MN with the least distance to the EN found in step 2 as the next CH.

In case more than one node has the same energy level, then the node that is closer to the EN is chosen as the CH. This ensures that the CH can communicate with the EN to extinguish the fire faster since the lower the distance between the nodes , faster the data transmission. The CH keeps their transmitters on during this phase to listen to the MNs.

Assuming that there are N nodes in a cluster, and the time for each frame is t_f and the channel bandwidth is $B_{w,}$ Each node will get $t_s = t_f/N$ seconds in which to transmit data. Assuming a 1 bit/sec/Hz signalling scheme, each node can transmit

$$B_w t_s = B_w t_f/N \text{ bits per frame} \quad (3)$$

$$\text{or } R_b = B_w/N \text{ bps.} \quad (4)$$

Once data from all the MNs have been received, in case of sensing a fire ,the CH performs data fusion and reduces the amount of raw data that have to be sent to the Base Station. The compressed data, along with the information required by the BS to properly identify and decode the cluster data , are routed back to the BS by CH-CH routing path created by the BS.

Radio interference is another issue in neighbouring clusters. Code Division Multiple Access (CDMA)codes are used to counteract this problem. Each cluster is assigned a spreading code that the nodes in the cluster use to distinguish from those nodes in neighbouring clusters. Once the data gathering process is complete, The CH uses the same spreading code assigned to the cluster to route data back to the BS.

After this phase the BS uses the data sent by the CH regarding the energy levels of the nodes to determine the next CH for the static clusters.

5. PERFORMANCE EVALUATION

The performance of FMEA was assessed by simulation using NS2. Performance is measured by quantitative metrics like average energy consumption and number of nodes alive. A random network of size 100 nodes where each node has an initial energy of 2J was considered. Further the number of data frames transmitted for each round is set at 50 and the data message size is fixed at 100 bytes of which 25 bytes represent the length of the packet header, 75 bytes for the sensed data. The simulation is done for the network where all nodes are assigned an initial energy of 2J. The 75 bytes used for sensed data are not always transmitted as this is relevant only to the nodes that cross the threshold. On an average if we assume that only 50% of the nodessend their data we found that k (the number of bits transmitted) is reduced by N/2 * 75*100 bits for every round of transmission. This significantly saves energy of the transmitting sensor nodes and the receiving CH as shown in Equation (1) and (2).

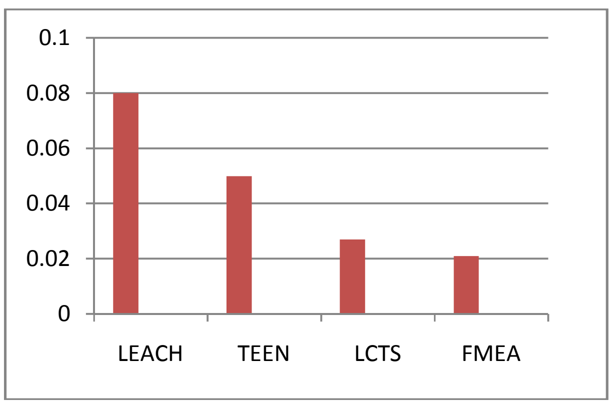


Figure 4(a) Average energy consumption during a round in a 50 x 50 m network.

Further, assuming that there are only 50% of the nodes in a network that transmit sensed data because of thresholds, the number of bits transmitted are reduced and thus energy can be saved as seen in equation (3) and (4).The transmission distance determines the energy consumption and so in FMEA the transmission distance is reduced because the data is transmitted to the actuator instead of the BS .

In FMEA 98 nodes were alive after 100 rounds, while only 75 nodes are alive in LEACH,72 were alive in TEEN and 95 in LCTS. Further during the time of Low Risk Threshold (LRT) sensing, many human lives can be saved because it is in the initial stage . Also since alarms raised help in human intervention, extinguishing takes place earlier and so the need for actuators may be reduced. This proves that FMEA is more energy efficient than its comparatives.
Since WSAN contain many actors that can extinguish the fire very quickly compared to actuators. This is more efficient in fire extinguishing and hence its performance is much better compared to DRATC [8].

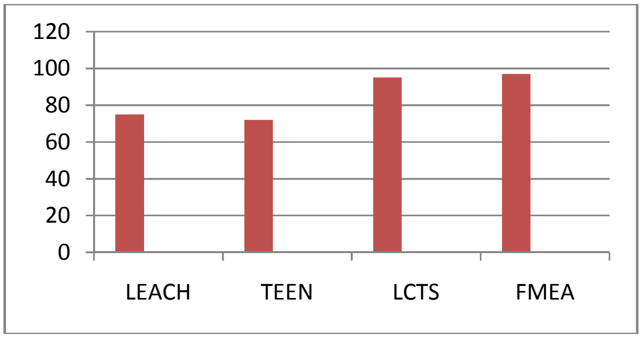


Figure 4(b) Number of nodes alive after 100 rounds in a network of 100 nodes

6. CONCLUSION

Fire extinguishers are important from a safety and regulatory compliance perspective and are often subject to vandalism, pressure loss, or obstruction from view. With a properly installed WSAN, fire extinguishers can be monitored on a real-time basis, contributing to lower costs and increased safety. Additionally, fire extinguisher monitoring solutions keep schools, government buildings, and private organizations' facilities compliant with local fire codes and ready to respond to emergencies.

This algorithm is proposed with an aim to provide a solution to time critical applications like fire extinguishing. SCP-MAC is used for data gathering since TDMA is not suitable for time critical applications. This protocol helps in reducing the energy of the transmitter and receiver and therefore increases the network lifetime.

Performance of the proposed FMEA routing algorithm is assessed by simulation and compared with other clustering protocols like LEACH, LCTS and TEEN. The simulation results show that FMEA outperforms its comparatives by using a decentralised approach using actors to take care of extinguishing in the clusters itself instead of data being sent to the BS for decision making. This reduces the transmission distance and helps in energy savings and also ascertains faster actions taken by CH to order the EN in case of fire. Further the nodes that do not meet the threshold are selected as cluster heads since they have more energy than the other nodes because they are not involved in sensing. Therefore FMEA provides an energy efficient routing scheme for effective fire monitoring and extinguishing.

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