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A Threshold-Chain-Based Protocol for Supporting Time-Critical Applications in Wireless Sensor Networks

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Abstract

Energy conservation and prolonging the network lifetime are recognized as key challenges in the design and implementation of wireless sensor networks. In this paper, we consider two types of applications in the wireless sensor network: Time-critical applications and non-time critical applications. We propose a Threshold Energy Efficient Chain based Protocol for supporting Time-Critical applications (TECP-TC) in wireless sensor networks to reduce transmission delay of time-critical data and energy consumption. TECP-TC aims at capturing periodic data collections and reacting to time-critical events in an energy efficient manner. In TECP-TC, time-critical data have higher priority and are immediately transmitted to the base station. TECP-TC is a threshold-sensitive protocol and organizes sensor nodes into a set of chains so that each sensor node receives non-time critical data from a previous neighbor and transmits to a next neighbor. TECP-TC improves the non-time critical data transmission mechanism from the chain heads to the base station via constructing a chain among the chain heads. Simulation results demonstrate that TECP-TC has better performance than other protocols in terms of network lifetime, energy savings and transmission delay of time-critical-data.

Keywords: *Wireless Sensor Network; Chain based Routing; Energy Efficient; Time-Critical Data; Threshold-sensitive*

1. Introduction

Rapid technological advances in micro-electro-mechanical systems and wireless communication have facilitated the development and application of wireless sensor networks in recent years [1]. Wireless sensor networks (WSN) are composed of hundreds or thousands of sensor nodes which are deployed in an environment to collect the information and then transmit report messages to a base station [1-9]. Since sensor networks have limited and non-rechargeable energy resources, energy conservation and maximization of network lifetime are important issues in the design and implementation of routing protocols in these networks [1-4, 10, 11]. Although energy conservation and maximization of network lifetime are principal challenges in wireless sensor networks, the requirement of low latency communication is getting more and more important in many applications [12].

Hierarchical routing protocols provide effective methods for reducing energy conservation and maximizing the lifetime of wireless sensor network [13, 14]. Using a hierarchical approach, sensor nodes can be managed locally by a header, a node elected to manage cluster or chain and be responsible for communication between the cluster or chain and the base station. Hierarchical routing protocols distribute the management responsibility from the base station to the headers [15]. The use of hierarchical structure in the routing of wireless sensor networks makes sensed data by the sensor nodes wait for the scheduled transmission time of a node to get transmitted. This delay in transmission is intolerable in case of time-critical data which needs to be sent quickly to the base station.

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There are a lot of hierarchical routing protocols in wireless sensor networks and a few of them have considered the quick transmission of time-critical data.

In this paper, we propose a Threshold Energy Efficient Chain based Protocol for supporting Time-Critical applications (TECP-TC) in wireless sensor networks to reduce transmission delay of time-critical applications and energy consumption. In our proposed protocol, the nodes react immediately to sudden changes in the value of a sensed attribute. For determining of time-critical data, TECP-TC utilizes a threshold parameter. If the sensed data value by a sensor node is equal to or greater than threshold value, the sensed data are considered as time-critical data and should be immediately transmitted to the base station. TECP-TC divides the wireless sensor network into a set of chains so that each sensor node receives non-time critical data from a previous neighbor and transmits to a next neighbor. Chain heads are elected based on the residual energy of the nodes and their distance from the header of upper level. TECP-TC improves the non-time critical data transmission mechanism from the chain heads to the base station via constructing a chain among the chain heads. We evaluate the performance of our proposed protocol via simulations and compare it to the performance of LEACH, PEGASIS and EECRP. The simulation results show that our proposed protocol can outperform in terms of network lifetime, energy consumption and transmission delay of time-critical data.

The reminder of this paper is organized as follows: Section 2 provides an overview of related work. Section 3 describes assumptions and radio energy dissipation model. Our proposed protocol is presented in Section 4. Section 5 presents transmission delay analysis of time-critical data. Performance evaluation is described in Section 6. Finally, in Section 7 conclusion of the paper is presented.

2. Related Work

In this section, some of the hierarchical routing protocols in wireless sensor networks are reviewed.

Heinzelman *et al.*, [16] proposed a clustering protocol called LEACH for periodical data-gathering applications. In LEACH, the nodes organize themselves into clusters, with one node acting as the cluster head. Non-cluster head nodes transmit their data to the cluster head and cluster head nodes aggregate the data and send aggregated data to the base station. LEACH does not guarantee good cluster head distribution and assumes uniform energy consumption for cluster heads.

LEACH-C [17] is an enhancement over the LEACH protocol. LEACH-C, uses a centralized clustering algorithm and the same steady-state phase as LEACH. During the set-up phase of LEACH-C, each node sends information about its current location and residual energy level to the base station. Once the cluster heads and clusters are found, the base station broadcasts a message that obtains the cluster head ID for each node.

PEGASIS [18] is a chain based power efficient protocol based on LEACH. Rather than forming multiple clusters, PEGASIS forms a chain from sensor nodes so that each node receives from and transmits to a neighbor. In PEGASIS, sensor nodes act as the chain head in turn. The chain head aggregates and transmits data to the base station. The sensed data are forwarded and fused node by node. Because of large number of hops in a single chain, PEGASIS induces a much longer data transmission delay.

TEEN [19] is a reactive protocol for time-critical applications. After clusters formation, the cluster head broadcasts hard and soft thresholds to the nodes. The hard threshold allows sensor nodes to transmit only when the sensed attribute is in the range of interest. Therefore, this reduces transmission to significant numbers and increases network lifetime. The soft threshold will further reduce the number of transmissions if there is little or no change in the value of sensed attribute. TEEN is not good for applications where periodic reports are needed.

Manjeshwar *et. al.*, [20] proposed Adaptive Threshold sensitive Energy Efficient sensor Network protocol which aims at capturing periodic data collections and reacting to time-critical events. The architecture of APTEEN is same as in TEEN, which uses the concept hierarchical clustering for energy efficient communication between source sensors and the base station. The main drawbacks of TEEN and APTEEN are the overhead and complexity associated with forming clusters at multiple levels.

Tang *et al.*, [21] proposed a Chain-Cluster based Mixed routing (CCM) algorithm for wireless sensor networks. CCM, organizes sensor nodes as a set of chains and a cluster with only chain heads. Data transmission in CCM proceeds in two stages: chain routing and then cluster routing. In the first stage, sensor nodes in each chain transmit data to their own chain head node in parallel, using an improved chain routing protocol. In the second stage, all chain head nodes are grouped as a cluster in a self-organized manner, where they transmit fused data to a voted cluster head using the cluster based routing.

ECCP [22] is a cluster-chain based routing protocol for balancing energy consumption in wireless sensor networks. It organizes sensor nodes into clusters and constructs a chain among the sensor nodes within each cluster. Clustering phase of ECCP is not performed in each round and sensor nodes use residual energy levels to select new cluster heads for the next round.

ECCPTC [23] is an extension of ECCP for time-critical applications. In ECCPTC, the nodes react immediately to sudden changes in the value of a sensed attribute. The main drawbacks of ECCP and ECCPTC are the higher overhead associated with forming clusters when a sensor node dies in the cluster. Also, ECCP and ECCPTC use a complex hybrid clustering approach for reducing energy consumption.

An Unequal Cluster-based Routing (UCR) protocol [24] was proposed by Chen et al. UCR groups the nodes into clusters of unequal sizes. Cluster heads closer to the base station have smaller cluster sizes than those farther from the base station. A greedy geographic and energy-efficient multi-hop routing protocol is designed for the inter-cluster communication.

Qing *et al.*, [25] proposed a distributed energy efficient clustering scheme for heterogeneous wireless sensor networks, which is called DEEC. In DEEC, cluster heads are selected based on their residual energy and average energy of the network. The nodes with high initial and residual energy will have more chances to be the cluster-heads than the nodes with low energy. DEEC uses the average energy of the network as the reference energy to control the energy expenditure of nodes by means of adaptive approach. DEEC does not need any global knowledge of energy at every election round.

Kumar *et al.*, [26] proposed an energy efficient heterogeneous clustered (EEHC) scheme for wireless sensor networks. EEHC is a desirable and robust protocol for wireless sensor networks. In order to improve the lifetime and performance of the network system, selection of cluster heads in EEHC is based on weighted probability.

Sheikhpour *et al.*, [27] proposed an Energy Efficient Chain-based Routing Protocol (EECRP) for wireless sensor networks to minimize energy consumption. EECRP organizes sensor nodes into a set of horizontal chains and a vertical chain. Sensor nodes transmit their data to their own chain head based on chain routing mechanism. EECRP also constructs a chain among chain heads for sending data packets from the chain heads to the base station.

3. Assumptions and Radio Energy Dissipation Model

We consider the following assumptions for the wireless sensor network.

- There is a base station located far from the sensing field.
- The base station is considered as a powerful node having enhanced communication and computation capabilities with no energy constraints.

- All sensor nodes have the same initial energy supply.
- Sensor nodes have CDMA functionalities.
- All sensor nodes are location aware, *i.e.*, equipped with GPS-capable antennae.
- The number of time-critical data messages is equal in all chains.
- Time-critical data have higher priority compared with non-time critical data.

3.1. Radio Energy Dissipation Model

The energy model that we used in our simulations is the same as in [16, 17]. Consider that the power attenuation is dependent on the distance between the transmitter and receiver. For short distances, the propagation loss is modeled as inversely proportional to d^2 while for long distances, the loss is modeled as inversely proportional to d^4. Thus, power must be controlled to invert this loss by setting the power amplifier to ensure a certain power at the receiver. Eq. (1) is used to calculate transmission energy, denoted as $E_{Tx}(k, d)$, required for a k bits message over a distance of d.

$$E_{Tx}(k,d) = \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2, & d < d_0 \\ kE_{elec} + k\varepsilon_{amp}d^4, & d \geq d_0 \end{cases} \tag{1}$$

To receive this message, the energy required is as Eq. (2).

$$E_{Rx}(k) = kE_{elec} \tag{2}$$

Where, the electronics energy, E_{elec}, depends on factors such as the digital coding, modulation, filtering, and spreading of the signal, whereas the amplifier energy, $\varepsilon_{fs}d^2$ or $\varepsilon_{amp}d^4$, depends on the distance to the receiver and the acceptable bit-error rate.

4. TECP-TC Protocol

An important requirement in some networks is that the sensor nodes react immediately to sudden and drastic changes in their environment so that the transfer of such data to the base station is not delayed.

In hierarchical protocols, the use of cluster and chain structure in routing of wireless sensor networks [16-18, 21-22, 24-28] makes sensed data by the sensor nodes wait for the scheduled transmission time of a node to get transmitted. This delay in transmission is intolerable in case of time-critical data which needs to be sent quickly to the base station. In order to avoid this situation, our aim in this paper is to have a network for reacting to time-critical events and also capturing periodic data collections in a very energy efficient manner. For this reason, we consider two types of applications in the wireless sensor network: Time-critical applications and non-time critical applications. Then, we propose a Threshold Energy Efficient Chain based Protocol for supporting Time-Critical applications (TECP-TC) to reduce transmission delay of time-critical applications and energy consumption. The proposed protocol is suited for time-critical applications such as intrusion detection, explosion detection and etc. When sending data to the base station, TECP-TC considers higher priority for time-critical data. In TECP-TC, sensor nodes are organized as a set of horizontal chains and a vertical chain. In each chain, a node is selected as the chain head. TECP-TC allows the sensor nodes to send their sensed data periodically and react immediately to sudden changes in the value of a sensed attribute. For determining of time-critical data, the proposed protocol utilizes a threshold parameter. When the sensed data value by a sensor node is equal to or greater than the threshold value, it is indicated that a sudden change has been occurred in the value of measured parameter. In this situation, the sensed data are considered as time-critical data and should be immediately transmitted to the base station. Non-time critical data are transmitted to the chain heads of horizontal chains based on chain routing mechanism. TECP-TC also adopts a chain based data transmission mechanism for sending non-time critical data packets from the chain heads to the base station.

Unlike PEGASIS, in TECP-TC, the workload of the network is distributed among different chains. Consequently, each chain will be of much smaller length than the single chain constructed in PEGASIS. TECP-TC has the advantages of chain based routing in terms of energy consumption and also reduces transmission delay of time-critical data.

At the beginning of the network operation, the base station sends the threshold value for all sensor nodes in the network. The operation of the TECP-TC protocol is divided into rounds. Each round begins with a set up phase followed by a data transmission phase. In TECP-TC, the network is divided into a set of strips as shown in Figure 1. Sensor nodes are placed in different levels. Base station is located in the highest level.

The height of each strip is *"h"* and there are *k=L/h* strips in the sensor network, where *L* is the length of wireless sensor network. In each strip, a greedy algorithm is used to form a chain among sensor nodes; then a chain head is selected in each chain.

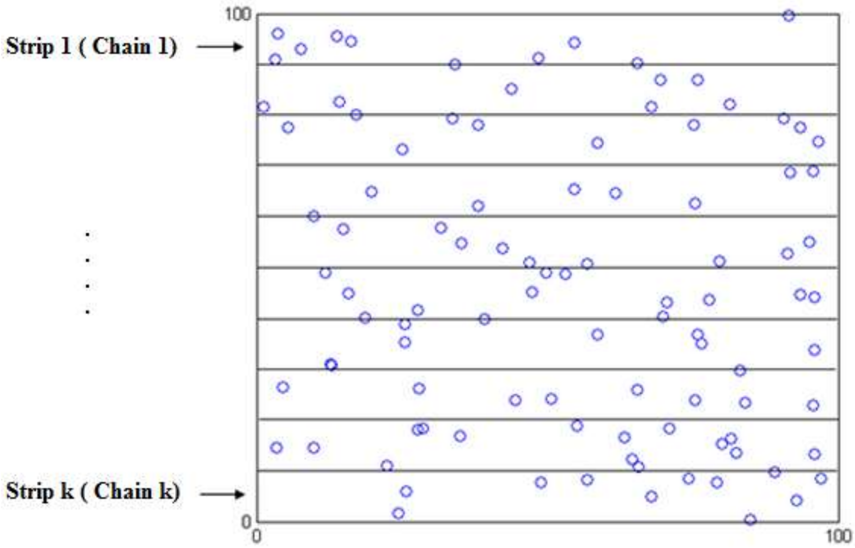

Figure 1. A Sensor Network with k Strips (Chains)

4.1. Setup Phase

In TECP-TC, sensor nodes are placed in different levels. The base station is located in the highest level. In setup phase, each node sends information about its current location (possibly determined using a GPS receiver) and energy level to the base station. Based on the received information, the base station select the chain head of each strip (level). In each strip (level), the chain head is selected based on the residual energy of its nodes and the distance of its nodes from the chain head of upper level. For selection of chain heads, base station calculates the weight of each node using Eq. (3) and selects the node with the highest weight in each strip as the chain head.

$$\text{weight}_i = \frac{RE_i}{dist^2_{to\ upper\ CH}} \tag{3}$$

Where RE_i is remaining energy of node *i* and $dist_{to\ upper\ CH}$ is the distance of node *i* from the chain head of upper level.

After the selection of chain heads, the greedy algorithm used in PEGASIS is utilized by the base station to create a chain among sensor nodes in each strip so that each sensor node receives data from a previous neighbor, aggregates its data with the one received from its previous neighbor and transmits aggregated data to a next neighbor. The chain created in each strip is called a horizontal chain. After the creation of horizontal chains, a chain among the chain heads is formed. The chain created in this stage, is called vertical chain and formed from the furthest to the nearest node from the base station. In TECP-TC, the selection of chain heads in horizontal chains is done in such a way that does not need to reselect the header of the vertical chain and chain head of strip 1 (level 1) acts as the header of chain heads so that all the chain heads send data to the header node through the chain; finally, the header node aggregates data and transmits them to the base station. When the chains are formed, the base station broadcasts a message that contains the chain and chain head ID for each node.

4.2. Data Transmission Phase

The data transmission phase is divided into several frames and sensor nodes transmit and receive data at each frame. Data transmission phase consists of time-critical data transmission and non-time critical data transmission. TECP-TC reacts immediately to the time-critical data and considers higher priority for transmitting these data. In each frame, initially, time-critical data are sent and then non- time-critical data are sent.

4.2.1. Time-critical Data Transmission

At the beginning of each frame, if the sensed data value by a sensor node is equal to or greater than the threshold value, the sensor node sets a bit in header of data packet to indicate it is time-critical data and immediately transmits the data directly to its chain head using CSMA MAC protocol. After that, each chain head that received time-critical data, respectively, according to its level transmit the time-critical data directly to the base station. For example, initially the chain head of chain 1 (level 1) transmits the time-critical data directly to the base station. Then, respectively, the chains heads in lower levels transmit the time-critical data directly to the base station. If time-critical data are received by a chain head that is waiting to access the channel to transmit time-critical data, the chain head will aggregate time-critical data and transmit aggregated data to the base station.

4.2.2. Non-time Critical Data Transmission

After the transmission of time-critical data, non-time critical data transmission is begun. Transmission of non-time critical data consists of two stages.

- Non-time critical data transmission among sensor nodes in the horizontal chains
- Non-time critical data transmission among chain heads in the vertical chain

Non-time critical data transmission among sensor nodes in the horizontal chains

For transmission of non-time critical data in each frame, chain based routing mechanism is utilized. At the beginning of non-time critical data transmission stage, the chain head node generates two tokens and transmits them to two end nodes of the chain. The two end nodes in each chain transmit data and tokens to their individual neighboring nodes in parallel. Each node aggregates its own data with its previous neighbor's data and transmits aggregated data and token to the next neighbor in the chain. The data are transmitted in an alternative way until all data are transmitted to the chain head node. If a node that has already transmitted its time-critical data to the chain head receives data from previous neighbor, the node only transmits received data and token to the next neighbor in the chain and does not perform data aggregation.

Once the chain heads receive data from previous neighbors in the latest frame of a round, data transmission among chain heads are begun.

Non-time critical data transmission among chain heads in the vertical chain

Similar to data transmission in horizontal chains, the chain head nodes in vertical chain transmit data to the header node using the chain based routing mechanism. At the beginning of the stage, the base station generates a token and then transmits it to the end chain head node in the vertical chain. The end node transmits data and token to the next neighbor. Each chain head receives data and token from previous neighbor, aggregates the data with its own data and transmits aggregated data and token to the next neighbor in the vertical chain. The data are transmitted until aggregated data are received by the header node in the vertical chain. Finally, the header node aggregates its own data with received data and transmits aggregated data to the base station.

Non-time critical data transmission in TECP-TC has been shown in Figure 2. As shown in Figure 2, nodes c6, c16, c26, c36, c46, c56, c65, c75, c85 and c95 are chain heads of horizontal chains and form a vertical chain to send their data to the base station. Node c6 is the header of the vertical chain because it is the chain head of level 1. The chain heads send their data to node c6 through the vertical chain and node c6 aggregates and transmits the data to the base station.

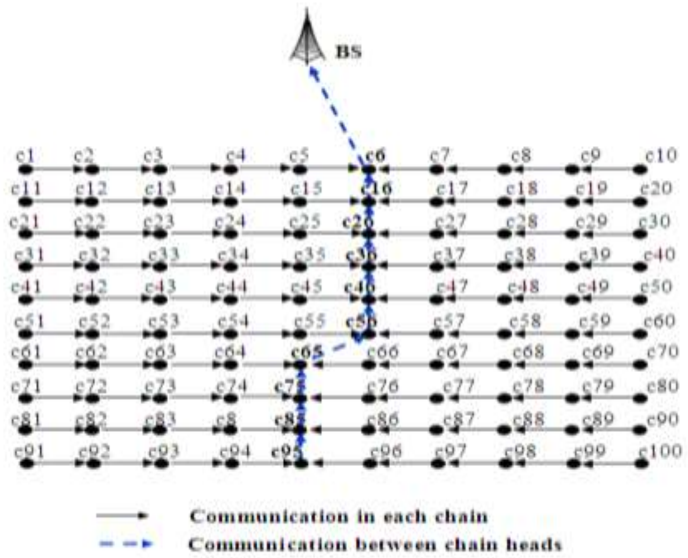

Figure 2. Non-time Critical Data Transmission in TECP-TC

Figure 3 shows the Pseudo code of TECP-TC.

The network is divided into a set of strips
Each node is located in strip x, $1 \leq x \leq k$
Strip (i) $\longleftarrow$ x
Base station sends a threshold value to the all sensor nodes
Phase 1: Set up phase
for i=1: N
  Chainheads(i) $\longleftarrow$ False
  Node i sends (location i , REi) to BS
  Weight $_i$ $\longleftarrow \frac{RE_i}{dist^2_{to\ heigher\ CH}}$ // BS computes Weight of all nodes
End

```
if   Weight i  > Weight of all nodes in each strip
   Chainheads(i) ⟵  True      // BS selects node i as chain head
end
if  Chainheads(i)=True
   if Strip(i)=1
      header(i) ⟵  True
   else
        header(i) ⟵  False
   end
   BS creates a chain among sensor nodes in each strip from farthest node to nearest
node from node i
end
BS sends chains and chain head ID to all nodes
```

Phase 2: Data transmission phase

```
for i=1:N
   TC(i) ⟵  False
   if sensed data value by node i ≥ threshold value
      TC(i)⟵ True
      Node i sends its data to the chain head and chain head transmits the received
data to BS
   end
end

for i=1: N
   if Chainheads(i)= True
      Node i in each chain generates 2 tokens and sends them to two end nodes in
the chain
   end
end

for i=1: N
   if Chainheads(i)= False
      if TC(i)= False
         Node i aggregates its data with the data of previous node
         Node i sends aggregated data and token to the next node in the chain
      else
         Node i sends received data of previous node and token to the next node in
the chain
      end
   end
end

for i=1: N
   if  Chainheads(i)=True
      if  Leader(i) = False
         Node i aggregates its data with the data of previous CH node in the chain of
CHs
         Node i sends aggregated data to the next CH node in the chain of CHs
(vertical chain)
      end
   end
end
```



```
for  i=1: N
   if Chainheads(i) =True
      if header(i) = True
         header i aggregates its data with the data of previous CH node in the chain of CHs (vertical chain)
         header i aggregates its data with the data of previous CH  and sends aggregated data to the BS
      end
   end
end
```

Figure 3. Pseudo Code of TECP-TC

5. Transmission Delay Analysis of Time-Critical Data

For intra-cluster communication in clustering scheme, a TDMA (Time Division Multiple Access) scheduling approach is utilized and for the inter-cluster communication, a CSMA (Carrier Sense Multiple Access) scheduling approach is utilized [2]. Most of the hierarchical routing protocols [16-18,21-22, 24-28] have been designed for transmitting of non-time critical data. The protocols consider same conditions for critical-data and non-critical data, therefore, they are not suitable for critical situations that data should be immediately reported to the base station.

Assume that there are N sensor nodes in the network and the delay of each transmission is regarded as 1 unit of time. The transmission delay of time-critical data is analyzed as follows:

In PEGASIS, the transmission delay of time-critical data is dependent on the network size. In this case, the delay is N units of time.

In LEACH, the delay for transmitting of time-critical data packets to the cluster heads is dependent on the size of the largest cluster (maximum number of nodes in the clusters). If all clusters have the same sizes, the maximum delay for transmitting of time-critical data packets in a round is calculated as Eq. (4).

$$T = \left(\frac{N}{K} - 1\right) + K + C \qquad (4)$$

Where N is the number of sensor nodes in the network and K is the number of clusters in the network.

Transmission delay analysis of time-critical data in EECRP is the same as that in LEACH.

In hierarchical protocols such as LEACH and EECRP, the maximum delay for transmitting of time-critical data packets or non-time critical data packets to the base station is T and the minimum delay for transmitting of the first time-critical data packet to the base station is dependent on the clusters sizes.

In our proposed protocol, time-critical data packets are immediately sent to the chain head using CSMA MAC protocol. The maximum delay for transmitting of time-critical data packets to the base station is dependent on the number of time-critical data packets and the minimum delay for transmitting of the first time-critical data packet to the base station is two units of time.

We assume that the number of time-critical data messages is equal in all chains. For time-critical data transmission in proposed protocol, in the first unit of time, the first time-critical data packet in each chain is sent to its chain head. In the second unit of time, the chain head of the first chain transmits the first time-critical data packet to the base station; at the same time, the second time-critical data packets in chains 2 to 10 are sent to their chain heads. The chain heads of chains 2 to 10 aggregate received time-critical data with previous time-critical data. In the third unit of time, the chain head of the second chain transmits the second time-critical data packet to the base station; at the same time, the time-critical data in chain 1 and chains 3 to 10 are sent to their chain heads. The chain heads of chains 3 to 10 aggregate received time-critical data with previous time-critical data. The number of iterations of this operation depends on the number of time-critical data. Suppose that there are 100 sensor nodes in the network and 40% of sensed data are time-critical data, so four sensed values in each chain are considered as time-critical data. In the fourth unit of time, the chain head of the third chain transmits third time-critical data packet to the base station; at the same time, the time-critical data packets in chain1, chain2 and chains 4 to 10 are sent to their chain heads. The chain heads of chain1 and chains 4 to 10 aggregate received time-critical data with previous time-critical data. In the fifth unit of time, the chain head of the fourth chain transmits the fourth time-critical data packet to the base station; at the same time, the last time-critical data packets in chain 1, chain 2, chain 3 and chains 5 to 10 are sent to their chain heads. The chain heads of chain 1, chain 2 and chains 5 to 10 aggregate received time-critical data with previous time-critical data. After that, at each unit of time, respectively, one of the chain heads in chains 5 to 10 and chains 1, 2 and 3 transmits aggregated time-critical data to the base station. Therefore, the transmission delay of time-critical data is calculated as Eq. (5)

$$Delay_{time-critical\ data} = k + m \tag{5}$$

Where k is the number of strips (chains) in the network and m is the number of time-critical data in each chain.

6. Performance Evaluation

For evaluation the performances of our proposed protocol, we performed the simulations by MATLAB and compared its performance with other protocols such as LEACH, PEGASIS and EECRP. This section describes simulation set up, performance metrics and simulation results.

6.1. Simulation Setup

We perform simulation studies in order to understand the performance benefits obtained with the proposed protocol. For this purpose, sensor nodes are randomly distributed in the area with the size of 100 m× 100m and a base station is located at position (50,175). The simulation network size is 100-250 numbers of nodes in increments of 50 nodes respectively.

For our simulation scenarios, the attribute to be sensed is the temperature. During each round of simulation runs, each node is assigned a random temperature between 0 and 100 degree Fahrenheit. The threshold value is set to 80 degree Fahrenheit. This means that if the environment temperature is equal or greater than 80 degrees Fahrenheit, a critical incident has occurred and should be immediately sent to base station. The transmission range of each sensor node is set to 20*m*. The initial energy level of each sensor node is 0.3*J*. The data packet size is 4000 bits and control packet size is 200 bits. The number of horizontal chains is set to 10. For the simulations in this paper, we adopted the same values given in [16] as $E_{elec=}$ 50 nJ/ bit, ε_{fs} =10 pJ/ bit/ m^2 and ε_{amp} = 0.0013 pJ/ bit/ m^4.

6.2. Performance Metrics

We use the following metrics to analyze and compare the performance of the protocols:

- Network lifetime: First Node Dies (FND), Half of the Nodes Alive (HNA), and Last Node Dies (LND) are used as performance metrics to evaluate the network lifetime. The metrics are a number of rounds that elapse before first node, half of the nodes and last node respectively, run out of energy [28, 29].

- Energy consumption: This metric indicates the total energy consumed by the nodes in receiving and sending the data packets.
- Average energy consumed per round: This metric shows the average energy consumed by the nodes in receiving and sending the data packets in each round.
- Transmission delay of time-critical data: It is the time interval from the moment when the time-critical data packets are generated to the moment when the base station receives these data packets.

6.3 Simulation Results

Network lifetime: Figure 4 shows the total number of nodes that remain alive over the simulation runs when the number of nodes in the network is 200. Figures 5, 6 and 7, respectively, show the performance comparison of the network lifetime in terms of FND, HNA and LND metrics with different sizes of the network. It is obvious from Figures 4, 5, 6 and 7 that TECP-TC has good performance in terms of network lifetime compared with LEACH and PEGASIS. This is mainly because the most of the nodes transmit to their nearest neighbors in the chain. TECP-TC also considers remaining energy of nodes and distance from header of upper level to elect chain heads.

Figure 4, 5, 6, 7, 8 and 9 show that EECRP has better performance than TECP-TC in terms of network lifetime and energy consumption. This is expected because EECRP is suited for non-critical conditions. To overcome the drawback of EECRP, we incorporated the time-critical data transmission to form TECP-TC. Therefore TECP-TC consumes more energy compared with EECRP to immediately transmit time-critical data to the base station and network lifetime in TECP-TC becomes smaller than that in EECRP.

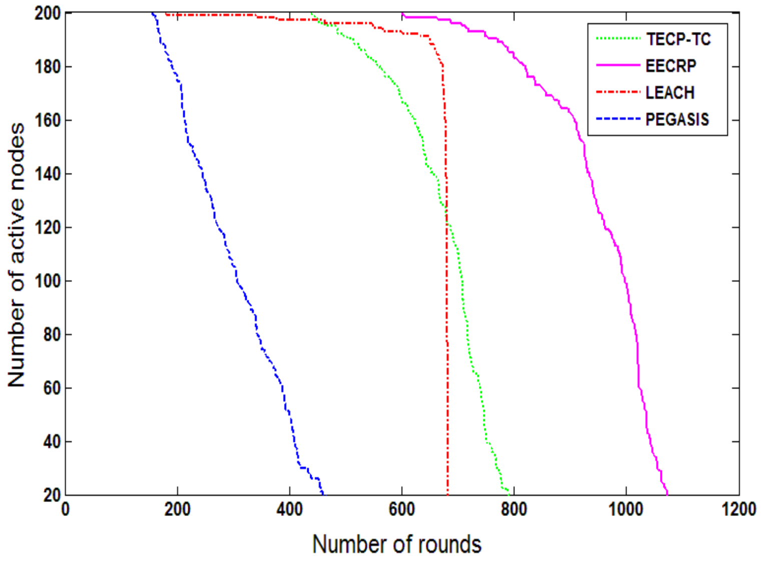

Figure 4. Number of Active Nodes Per Round with Network Size of 200

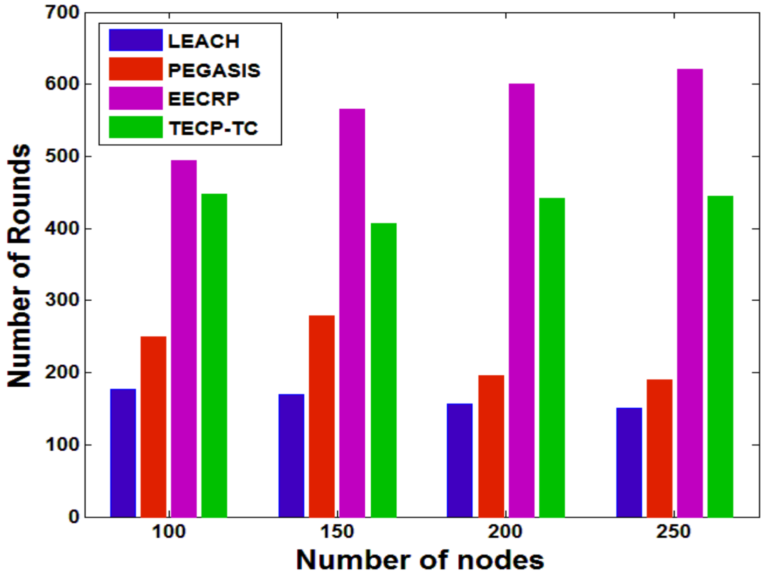

Figure 5. Performance Comparison of the Network Lifetime using FND Metric with Different Sizes of the Network

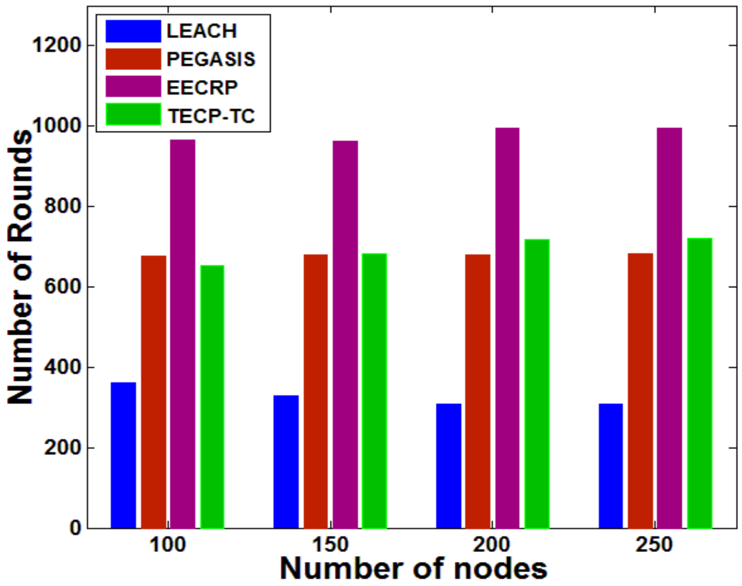

Figure 6. Performance Comparison of the Network Lifetime using HNA Metric with Different Sizes of the Network

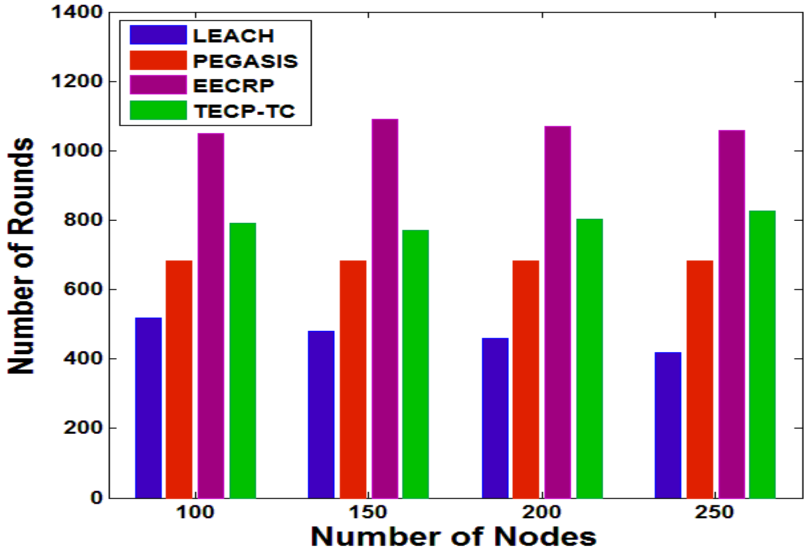

Figure 7. Performance Comparison of the Network Lifetime using LND Metric with Different Sizes of the Network

Energy consumption: Figure 8 shows the total energy consumed by all nodes during the simulation runs when the number of nodes in the network is 200. Figure 9 demonstrates the average energy consumed by the nodes in each round with different sizes of the network. It is clear from Figure 8 and 9 that TECP-TC consumes less energy compared to LEACH and PEGASIS. LEACH consumes more energy because sensor nodes transmit their data directly to cluster head and also cluster heads transmit the data directly towards the base station, while in TECP-TC, most of the sensor nodes transmit data to their nearest neighbors in the chain. Moreover, chain heads in TECP-TC don't transmit data directly to the distant base station. They do this through the vertical chain created among the chain heads. TECP-TC also has better performance than PEGASIS. This is due to the chains constructed in TECP-TC have smaller length than the single chain in PEGASIS. This reduces the amount of data to be aggregated and propagated along the chain and lead to savings in the energy consumption of the nodes.

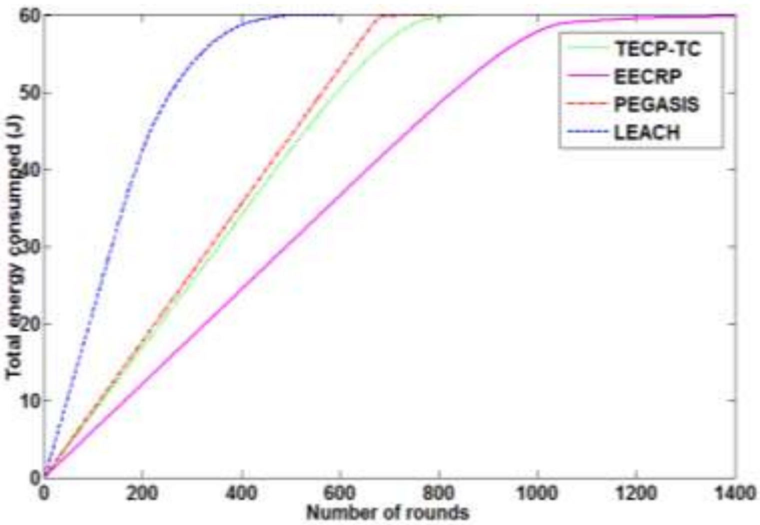

Figure 8. The Total Energy Consumption of the Network Over round with Network Size of 200

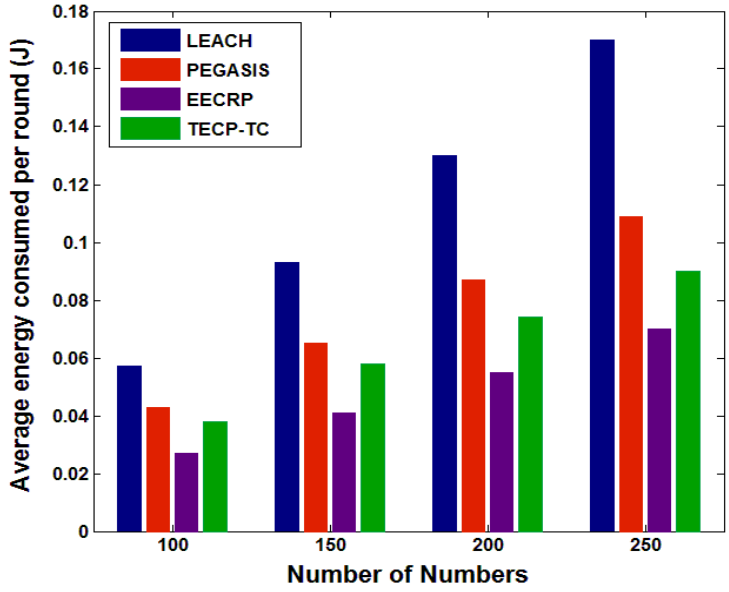

Figure 9. Average Energy Consumed per Round with Different Sizes of the Network

Transmission delay of time-critical data: We assume that 20% of sensed data by nodes in the network are time-critical data. In proposed protocol, the maximum delay for transmitting of all time-critical data packets to the base station is dependent on the number of time-critical data packets and the delay for transmitting of the first data packet to the base station is two units of time. Figure 10 shows the maximum transmission delay of all time-critical data in different routing protocols in each round. TECP-TC reduces transmission delay of time-critical data compared with LEACH, PEGASIS and EECRP. This is mainly because ECCPRT consider higher priority for time-critical data than non-time critical data so that time-critical data are immediately transmitted to the base station using CSMA MAC protocol.

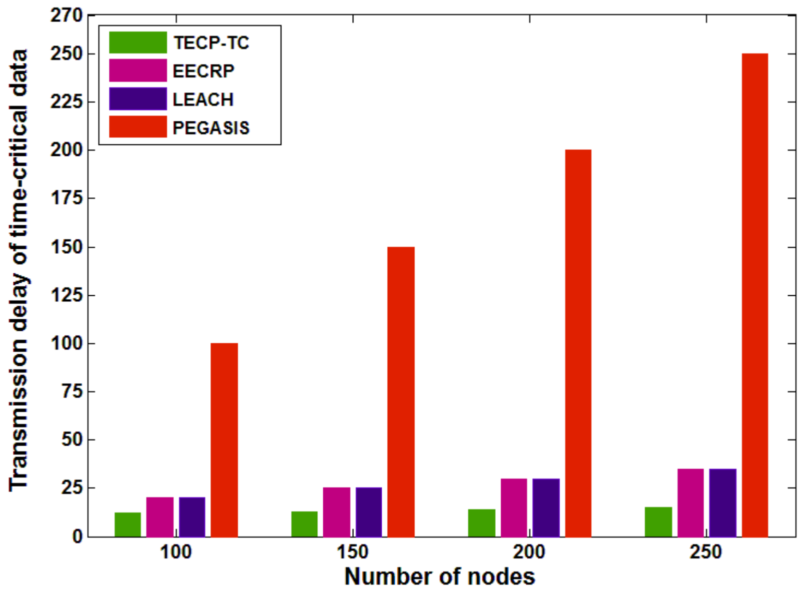

Figure 10. Maximum Transmission Delay of Time-Critical Data with Different Sizes of the Network in each Round

It is obvious from simulation results that proposed protocol in this paper is suited for reacting to time-critical events in a very energy efficient manner. Especially in large sensor networks, proposed protocol reacts immediately to sudden changes and reduces transmission delay of time-critical data compared with other protocols.

7. Conclusion

In this paper, we proposed TECP-TC, a Threshold Energy Efficient Chain based Protocol for supporting Time-Critical applications in wireless sensor networks. The main goal of TECP-TC is to utilize for time critical applications and minimize transmission delay of time-critical data and energy consumption. In our proposed protocol, the nodes transmit data periodically and react immediately to sudden changes in the value of a sensed attribute. In TECP-TC, sensor nodes are organized into a set of horizontal chains and a vertical chain. For determining of time-critical data, TECP-TC utilizes a threshold parameter. When the sensed data value by a sensor node is equal to or greater than threshold value, it indicates that a critical event has been occurred and should be immediately reported to the base station. At the transmission data phase, initially, time-critical data are transmitted to the base station. After that, non-time critical data transmission is begun. Each sensor node using the chain-based routing mechanism transmits non-time critical data to the chain head in the horizontal chain. Furthermore, TECP-TC utilizes a chain-based data transmission mechanism for transmitting non-time critical data packets from the chain heads to the base station. We evaluated the performance of TECP-TC via simulations and compare it to the performance of LEACH, PEGASIS and EECRP. The simulation results show that TECP-TC outperforms other protocols in terms of network lifetime, energy consumption and especially transmission delay of time-critical data and is suited for reacting to time-critical events in a very energy efficient manner.

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