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Routing Protocols for Structural Health Monitoring of Bridges Using Wireless Sensor Networks

Muhsin Atto
School of Systems Engineering, University of Reading, Reading
United Kingdom
Tel: 0044-791-464-1891 E-mail: m.h.atto@pgr.reading.ac.uk

Chris Guy
School of Systems Engineering, University of Reading, Reading
United Kingdom
Tel: 0044-118-378-8757 E-mail: c.g.guy@reading.ac.uk

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Abstract

Monitoring older bridges using Wireless Sensor Networks (WSNs) has had a lot of attention in recent years. In much of this research tasks like sensor data processing, environment states and events decision making are done by a remote server. A Structural Health Monitoring (SHM) application using WSNs to provide the data collection necessary for rapid structural assessment after an event such as a natural disaster has been simulated in this paper. Efficient MAC and routing protocols must be designed for the proposed application to offer a guarantee for the reliability of the data delivered from source nodes to a sink. The number of delivered reports, delay and the lifetime of the network are considered in the proposed application. As a result, a new cross layer protocol based on MAC and routing protocols is designed and simulated for SHM application taking different scenarios into consideration and results are presented in this paper. Simulation results show that the proposed protocol increases performance of the target application, in varies scenarios.

Keywords: WSNs, Environment Monitoring, Routing Protocols, SHM, Quality of Services.

1 Introduction

A Wireless Sensor Network(WSN) is composed of tiny, battery powered devices called sensor nodes. Each sensor node has a capability of sensing the target environment and then sending the collected information from source nodes to a sink over multi hop networks. WSNs support different kinds of applications in distinct areas, such as military, healthcare, agriculture and environmental monitoring. Generally, there are 3 models of applications using WSNs: continuous, on-demand and event driven. In the continuous model, sensors send data periodically to the sink. In the on-demand model, sensors sense continuously, store the data and send only when requested. In the event driven model, the sensors send data only when certain events occur [1].

The design and implementation of WSNs face several challenges, mainly due to the limited resources and limited capabilities of sensor nodes, such as power and storage. To accomplish their task, sensor nodes need to communicate with each other and act as intermediate nodes to forward data on behalf of others so that this data can reach the sink, which is responsible for taking the required decision. Different applications using WSNs have different requirements so generic results can not be used [2].

The initial applications supported by WSNs were mostly in environmental monitoring, such as temperature monitoring for a specific area, house alarms and so on. The main objectives in such applications only involved simple data processing. Energy consumption needed to be considered for specific applications, so little attention was paid to the data delivered and reliability related issues as shown in [2], [3] and [4].

WSNs have been extended and their designs have been advanced to support more complex applications, such as security, military, fire detection and health care related issues. In these applications, the data delivered and reliability must be taken as important parameters in addition to energy efficiency. This is because data must be collected from the sources of events and be forwarded to the sink in real time with high reliability, otherwise the applications may not fulfil their purpose [5]. This means that it is crucial that efficient routing and MAC protocols be designed to meat these requirements.

Routing is an essential feature in any multi hop sensor network. In such networks, a node should have the capability to deal with data transmission as required between source nodes and a sink in different situations. These capabilities may lead to extra energy consumption. In addition, mobility in the proposed applications using WSNs also needs to be considered. Designing mobility modules for WSN applications is a hot topic at the moment and providing mobility for such applications has been challenging over the last few years [6]. Hence efficient MAC and routing protocols need to be designed to enhance the lifetime of the network. These protocols require efficient algorithms to deal with different situations.

Recent studies such as [1] and [5] have discussed most of the recently designed protocols with their advantages and disadvantages in terms of their suitability for different applications using WSNs. It has been shown that there is no protocol which is directly suitable to be used for such applications. This is because of the challenges involved in designing protocols to offer the performance required for such applications. However, TDMA based MAC protocols such as GinMAC [7] and cluster based routing protocols such as LEACH [8], TEEN [9] and APTEEN [10], have often been preferred because of the following capabilities:

- Energy can be conserved by distributing energy usage between nodes in the network.
- Delay can be decreased and energy can be conserved by aggregating and reducing redundant copies of data at the intermediate nodes in the network.

- Nodes in each cluster send their data to their cluster heads over a single hope communication using their allocated slots, so energy is conserved.
- Only cluster heads are involved for routing and forwarding data to a sink. This reduces the routing complexity in large WSNs.
- Only cluster heads need to aggregate data from their members thus saving energy.

Based on these capabilities, the lifetime of the entire network and the required performance of the proposed applications can be optimized [11]. A new cross layer protocol, based on MAC and routing protocols, was designed to improve the capability of WSNs used for the SHM application and results are presented in this paper.

The protocol proposed in this paper combines different aspects from different layers such as MAC and routing protocols in order to improve the reliability of the data delivered and extend the lifetime of the network. Details about the proposed protocol and the target SHM application, taking various scenarios into consideration, are discussed in this paper.

The rest of the paper is structured as follows. Related work for the proposed application using WSNs is debated in Section 2. Routing protocols and the proposed application are described in Section 3. The design of the cross layer protocol is described in Section 4. Simulation scenarios and results discussion are described in Section 5. A conclusion and proposals for future work are presented in Section 6

2 Related Work

The process of continuously monitoring the status of a structure to detect possible damage can be defined as Structural Health Monitoring (SHM) [12]. The importance of health monitoring of civil structures has gained considerable attention over the last two decades [13]. A variety of methods have then been proposed for SHM, which have improved over time with the evolution of technology. One of the conventional methods is visual inspection by humans for any signs of apparent damage. But this technique is limited because it relies on visible defects only [13], [14].

A WSN is composed of a large number of sensor nodes that have sensing, processing and wireless communication capabilities. Based on this, a WSN for SHM has two key advantages: (i) system set-up and maintenance cost is remarkably reduced, (ii) no cables are required for data transfer because the communication is wireless [15].

A lot of research has carried out regarding SHM related applications using WSNs. The author in [15] proposed an intelligent framework for SHM applications based on different techniques. In this framework video cameras are deployed around the bridges being monitored. The authors in [16] simulated a realistic scenario for SHM system, considering different bridge sizes and using different simulation parameters. However, as shown in [16], very simple routing protocols were used such as broadcast based routing protocols. The author in [17] described a novel method of providing highly reliable synchronization based method to increase performance for the proposed SHM application given in the same paper.

Although all aspects of the SHM related applications using WSNs have been described in these methods, none of them has illustrated the required routing protocols for such applications where large deployments are considered. In these applications, data is required to be delivered over multi hops communication [15]. Based on this, it is crucial that efficient routing protocols be designed in order to increase performance for this application. This includes extending the lifetime of the network and improving the reliability of the data delivered to a sink.

In addition, cluster based routing protocols such as LEACH [8], TEEN [9] and APTEEN [10] and TDMA based MAC protocols such as GinMAC [18] have been preferred for different applications using WSNs. This is due to the fact that nodes are selected as Cluster heads (CHs) based on the nodes' remaining energy and data is transmitted based on the data thresholds. This will extend the lifetime of the entire network and reduce the collision from other nodes in the network [11]. Furthermore, lifetime of the network must be measured based on the realistic scenarios.

However, as shown above, current methods and routing protocols do not take into account all of these important design aspects at the same time in order to provide the required performance for this application. To fulfil these requirements, a new cross layer protocol based on the GinMAC and APTEEN protocols is designed to increase performance for the SHM application. This means that the motivations for this paper are the following:

- Design routing protocols for the SHM related applications where energy saving, quality and delay for the delivered data need to be considered.
- Design the cross layer protocol to improve its applicability to the application given in this paper.
- Simulate the cross layer based protocol for the proposed application where different scenarios are involved.

3 Routing Protocols and a Proposed Application Using WSNs

3.1 A Proposed Structural Monitoring Application

The process of detection of damage for civil, aerospace and other engineering systems is referred to as Structural Health Monitoring (SHM). Structural health monitoring systems have the potential to improve the regular operation and maintenance of structures. Wireless networks have recently been used to avoid the high cost of traditional generic wired systems. The most important limitations of SHM wireless systems are time-synchronization accuracy, scalability and reliability [17]. A complete application using WSNs taking different routing protocols into consideration on different bridges was simulated and result are presented in this paper.

Structural monitoring systems typically comprise vibration sensors, strain gauges and other similar sensors that are deployed around the target bridges and a central data acquisition system. The data acquisition systems not only record the data but also facilitate data interpretation so that any required action can be given before damage occurs to the bridges being monitored [12], [17]. An example of the Structural monitoring environment is given in Figure 1.

Wireless sensor networks have been extensively investigated as a means of collecting data for the SHM applications. Researchers have proposed new protocols using WSNs in different ways to enhance the performance of their networks for SHM-related applications [14].

Figure 1: An example of Structural Monitoring Environment [17]

3.2 Routing Protocols for the Proposed Application

Energy-efficient routing protocols have been proposed in the literature to deal with the limited battery life of sensor nodes in order to increase the lifetime of the network. In general, routing protocols are classified, based on the network structure, into flat, hierarchical and location based protocols. In the hierarchical based routing protocols, nodes are divided into different clusters with different roles. All nodes of flat routing based protocols are assigned the same role. In the location-based protocols, the geographic information of nodes is used for relaying data [1]. Cluster based routing protocols have been preferred over other routing protocols because of the cluster based concepts. In these protocols some nodes take a role on behalf of others and hence energy can be saved and the life time of the network can be extended [8, 19].

The Low Energy Adaptive Clustering Hierarchy (LEACH) [8] is a cluster based routing protocol for WSN where energy can be conserved by distributing energy usage between nodes over time. This protocol can not be used for applications where data do not need to be transmitted all the time. Most of applications using WSN do not need high traffic flows, so based on this feature, the Hierarchy Threshold-sensitive Energy Efficient (TEEN) protocol [9] has been designed. TEEN lets nodes transmit their data only when this data is in a range of interest based on some thresholds, otherwise, data is discarded. Based on this, users may not be updated with data for a long time, because data is not satisfying the given thresholds. Adaptive Periodic Threshold-sensitive Energy Efficient (APTEEN) [10] has been proposed to solve the problems associated with both LEACH and TEEN using Counter Time *CT* and handling queries.

At the MAC layer, as it has been debated in [20], MAC protocols only care about energy saving and can not provide good scalability and the required routing for different applications, when the number of nodes is high. On the other hand, as illustrated in [10], routing protocols can not provide the required reliability without using efficient MAC protocols. This implies that combining MAC and routing protocols can provide much better performance than the individual layer, this is because there is an interaction between MAC and network layers which let nodes be active at the same time. as a result, the cross layer based protocol has been designed and simulated for the proposed application and results are presented in this paper.

4 A Cross Layer Based Protocol

This section outlines the design of the proposed cross layer based protocol. This protocol combines the GinMAC and APTEEN implementations given in [18] and [10], respectively. A new algorithm has been designed to dynamically select the reliable routes for transmitting data to a sink, considering multi hops communication, cluster based topologies and cross layer mechanisms. More details about the cross layer based protocol and its implementation in this section are outlined below.

In order to minimize energy consumption and increase performance such as reliability of data delivered, extensive research has been conducted in the literature related to WSNs when designing energy efficient protocols for each layer alone [21]. Regarding the MAC layer [20], the most common way to conserve energy consists of putting the transceiver and the processor of a sensor node into a low power, sleep state when it is not being used. As such, the energy wasted due to collisions, overhearing and idle listening is reduced. On the other hand, [10] addressed the problem at the network layer by proposing new routing solutions that take into account the sleep state of some nodes. This can be achieved by distributing energy usage between nodes over time which increases the lifetime of the entire network.

On the MAC layer, as it has been discussed in [20], MAC protocols in WSNs only deal with energy saving and cannot provide good scalability and the required routing for widely dispersed applications, when the number of nodes is high. On the other hand, as illustrated in [10], routing protocols cannot provide the required reliability without using efficient MAC protocols. As a result, combining MAC and routing protocols can provide a much better performance than the individual layers alone as this will combine different cross layer information from different layers before relaying data to a sink. This concludes that the best possible routes for transmitting data can be selected based on network conditions.

GinMAC is a suitable MAC protocol to be used in real-time applications as shown in [18], where reliability, energy saving and delay can be guaranteed, and where there is a small number of nodes. Challenges and requirements that need to be considered before designing MAC protocols for such applications are also described in the same paper. Based on these features, the GinMAC protocol has been modified and implemented for real time applications, where a low number of nodes is required. GinMAC cannot provide the required routing for mobile nodes in the proposed applications when the number of nodes is high. Consequently, APTEEN [10] has been modified and new features, such as mobility modules and new algorithms for transmitting data over multi hop WSNs have been designed.

In this paper, a new cross layer based protocol is designed to improve the capability of WSNs used for the Structural Health Monitoring application, in various scenarios. This is by combining features of both the GinMAC and APTEEN protocols given in [18] and [10]. In addition, new features such as cross layer based information from different layers are considered for transmitting data over multi hop communication between source nodes and a sink. This shows that nodes in the proposed cross layer based protocol join to different clusters using various attachments based on node's remaining energy, location and RSSI, compared to the APTEEN and GinMAC protocols where only the RSSI is considered.

The cross layer based protocol involves two stages. The first stage starts by using the APTEEN protocol as a network layer, which extends the lifetime of the network by distributing energy usage between nodes using clustering capabilities. Hence this protocol drains energy slowly and uniformly among nodes, leading to the death of all nodes at a similar time. In addition, data is transmitted based on combining cross layer information from different layers in order to select the best routes for delivering data from source nodes to a sink. Section 4.5 defines algorithms in the cross layer based protocol which combine cross layer information for data transmission based on the RSSI, nodes' remaining energy and location. This lets nodes discover different routes based on various link related metrics to find the best path for data to be transmitted over multi hop communication and thereby increasing the reliability of the data delivered from source nodes to a sink. Furthermore, lifetime of the network using the proposed protocol increases where the selection of the cluster heads is based on node's remaining energy compared to the APTEEN protocol where only a random number is considered.

The second stage of the cross layer based protocol involves using the GinMAC protocol as the MAC layer. This uses a retry limit of retransmissions over each wireless link according to its properties and the required packet delivery probability. Usually, the MAC layer retransmits a packet whose transmission was not successful up to m retries, where m is the same retry limit for all the wireless links. In each retry a sender waits for an acknowledgement from the next hop to make sure that a packet has been received. If there is no reply, then the same packet is retransmitted until either the packet is received or m retries are undertaken. In the same way, the next hop uses retry acknowledgements to let a sender know that a packet has been received in order to avoid redundant packets being sent. This algorithm increases the number of successfully delivered packets to a sink, thereby increasing the reliability of the data delivered using the cross layer protocol. More details about this algorithm is described in Section 4.4. The reliable transmission algorithm used by the GinMAC protocol in the cross layer based protocol is shown in Figure 4. Details about the modified GinMAC protocol in the protocol proposed in this paper is given in section 4.3.

This concludes that this protocol is similar to the APTEEN protocol given [10] in most aspects, but new features have been added through modifying and combining the GinMAC and APTEEN protocols. These modifications include considering different network conditions for delivering data over multi hop WSNs. This is to increase the performance of the proposed protocol for the application given in this paper. More details about the cross layer protocol and these modifications are outlined in the following sections.

4.1 An Overview of the Proposed Cross Layer Based Protocol

The cross layer based protocol is a self configured, multi hop clustering and cross layer based routing protocol which has been designed for WSNs. This protocol uses a cross layer related technique to distribute energy usage between nodes over time, which conserves energy and reduces collisions. The aim of designing this protocol is to increase performance of the proposed applications given in section 5 by considering the APTEEN and GinMAC protocols together to improved the capability of WSNs for such applications. The key idea behind the cross layer protocol is considering cross layer information based on network conditions for selecting reliable routes from source nodes to a sink.

Nodes are joined into a set of different groups when they turn on their radios. Each group is called a *Cluster* and nodes belonging to each cluster are monitored by a special node which is called a *Cluster Head (CH)*. CHs are assigned to have more power and energy than other nodes, to deal with TDMA creation, finding routes, data aggregation and data transmission as in the

APTEEN protocol. Nodes send their data to their cluster heads and then go to sleep to save energy and reduce collisions with data from other nodes in the network. Cluster heads receive and aggregate this data and send it back to higher cluster heads until this data reaches a sink. Since cluster heads are selected based on their node's remaining energy, then the chance of nodes dying quickly is low compared to the APTEEN protocol when cluster heads are selected based on a random number as shown in [10].

Data aggregation using the proposed cross layer based protocol needs to be designed according to the requirements of the proposed applications. Different types of transmissions are supported such as multimedia and normal transmissions. As a result, the cross layer based protocol can be used for multimedia related applications when multimedia transmission is required to deliver events from source nodes to a sink such as intruder related applications. This protocol lets nodes transmit their data only when the sensed data is in the range of interest, based on the given data thresholds. This will reduce the number of unnecessary transmissions and consequently allow the proposed protocol to be used for critical and non-critical related applications using WSNs.

After cluster heads are selected, they need to advertise themselves to the rest of the nodes in the network by sending ADVs including different information such as RSSI, remaining energy and location. Upon receiving ADVs messages nodes reply to different cluster heads by sending back join request messages (JOIN) based on information included in the ADVs received from different CHs.

Various link related metrics are considered when selecting cluster heads for relaying data compared to the APTEEN protocol when only the RSSI is considered. This means that the most reliable routes are selected in the cross layer protocol based on network conditions. In addition, the lifetime of the network is optimized when selecting CHs by considering nodes' remaining energy for nodes, compared to the APTEEN protocol when the selection of cluster heads is based on a random number.

After the CHs advertisement, TDMA schedules are created and broadcast so that the required time slots for members can be allocated. After cluster heads are selected and TDMA schedules for members are allocated, nodes can transmit their data to their cluster heads using their allocated slots. This data will then be aggregated and sent back to a sink over multi hop communication.

4.2 Details of the Cross Layer Based Protocol

The operations of the cross layer based protocol are divided into *rounds*, where each round starts with 4 different phases which are *set-up*, the creation of *TDMA schedules*, *routes discovery* and *data transmission* as shown in Figure 2. In the set-up phase, nodes organize themselves into different clusters at the different levels in the network, where each cluster needs to be monitored by a cluster head. This is followed by an advertisement phase when cluster heads need to advertise themselves to the nodes in the network. Non cluster heads ask to join different clusters, based on the different costs. In the TDMA schedules phase, different slots are allocated for non-cluster heads to deal with data communication.

In the route discovery phase, cluster heads must find different routes for relaying data from members to a sink via multi hop communication. For this to happen, a new algorithm must be implemented to select routes between CHs and a sink which takes different situations into consideration. In the data transmission phase, nodes start to send data to their selected cluster heads over a single-hop communication and then go to sleep to save energy. This data is then aggregated and sent back to a sink over multi hop communication as shown in Figure 2. More details about these operations are given below.

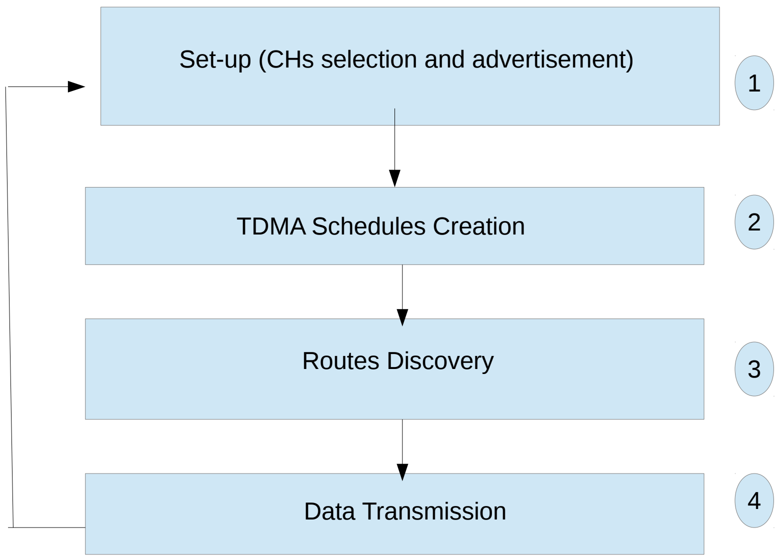

Figure 2: Protocol Operations

4.2.1 Cluster Heads Selection

The cross layer based protocol uses technique for selecting cluster heads which is used by the APTEEN protocol, which considers the nodes' remaining energy as shown below. When each node turns on its radio, it needs to decide whether or not to become a cluster head in the current round. This decision is based on the suggested percentage of the nodes that needs to be selected as cluster heads in the network and the number of rounds that this node has not yet been selected as a cluster head. The selection of the node *n* to become a cluster head in the current round depends on the probability of a random number between 0 and 1 which is denoted by (*rn*) and the pre-defined threshold value which is represented by *T(n)* as defined in the equation 1:

$$T(n) = \begin{cases} \frac{P}{1-P*(rmode\frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Where P is a percentage of cluster heads that needs to be selected, r is the current round and G is a set of nodes that have not been selected as cluster heads in the previous *1/P* rounds.

If *r* is less than T(n), then the node *n* is selected to be a cluster head in the current round *r*. One of the drawbacks of the algorithm used for selecting cluster heads given in [10] is that the sink does not consider the node's remaining energy when they become cluster heads. Hence nodes may be prone to die prematurely. To address this problem, [19] designed a new approach which considers remaining energy for nodes before they become cluster heads, using the following equation:

$$T(n)_{new} = \begin{cases} \frac{P}{1-P*(rmode\frac{1}{P})} * \frac{E\_cur}{E\_max} & \text{if } n \in G \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

Where E_cur, E_max are the current and an initial energy of the node *n*. This algorithm lets the sink select nodes with the maximum energy remaining to be cluster heads in each round, thereby extending the lifetime of the network. The selection of cluster heads in the proposed cross layer protocol is based on the method given in the equation 2.

4.2.2 A TDMA Schedule Allocation

After cluster heads have been selected, each CH needs to allocate different slots for their members using TDMA schedules, to let their members deal with data communication using their allocated slots. It has been assumed that a sink creates and sends queries to different parts of the network and then nodes reply as soon as they have data matching the query. So in some cases, nodes need to have different slots to deal with queries and data transmissions at the same time.

In addition, CHs need to have their own slots for finding routes and aggregating data. Based on these requirements, TDMA schedules for the proposed protocol are classified into five types of time slots: slots for data transmission, slots for answering queries, slots for finding routes, slots for aggregating data and slots to deal with multimedia related traffic. A sink should not ask nodes to answer a query at the same time as they are transmitting their own data [10]. Therefore, a TDMA schedule using the cross layer based protocol consists of the following fields:

1. **Member Slots:** Each cluster head creates a TDMA schedule for each member using *TX,QA* slots. Each member is active only during its allocated slots. A TX slot is used for transmitting data while a QA slot is used for answering queries.
2. **Aggregation Slots (AG):** Cluster heads use these slots to aggregate data from their members.
3. **Route Discovery Slots (RD):** Cluster heads use these slots to discover routes between nodes when transmitting aggregated data from their members to a sink.
4. **TX Slots:** Cluster heads use these slots to transmit their own data to a sink.

The allocated TDMA schedules allow members from different clusters to deal with data communication only in their allocated slots and then to go to sleep during the rest of the frame. This saves energy and avoids collisions from other nodes in the network. When mobility is considered, new algorithms need to be designed to update TDMA schedules according to different attachments. By combining all of these factors, a TDMA schedule for the cross layer protocol can be defined as shown in Figure 3.

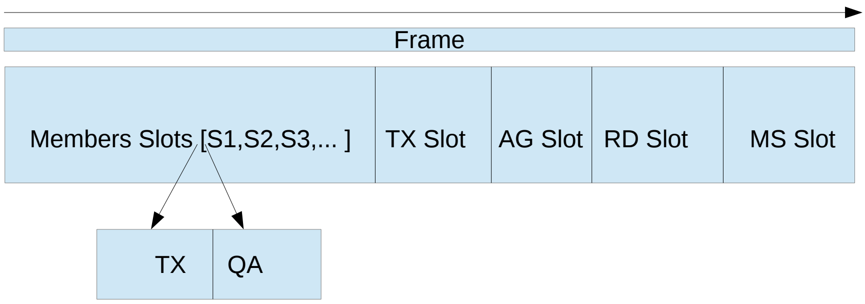

Figure 3: TDMA Schedule Structure

4.2.3 A Multi hop Clustering and Routes Selection

The algorithm required for selecting routes over multi hop communication between different nodes in the network described in the specifications given in [7] has been modified. This modification includes considering the cross layer information based on network conditions such as RSSI, nodes' remaining energy and location for selecting routes for data transmission. To achieve this, a new module to select routes considering multi hop communication and different cross layer based information has been designed. This module considers the node's remaining energy, location and RSSI as routing metrics for selecting reliable routes to forward data to a sink.

While the sink has global information about all nodes in the network, such as their remaining energy and location, in this implementation, the sink is additionally made responsible for dividing the network into different levels. Nodes close to the sink are selected as *higher level based nodes*, which communicate with a sink via a single hop communication, whereas nodes far away from the sink are selected as *low level based nodes* as in the APTEEN protocol.

Nodes on the low level in the network must select higher level based nodes (reliable CHs) based on the information received from different CHs using ADV messages to deal with data transmission. ADV messages for different cluster heads include node's remaining energy, distance (location) and RSSI for selecting reliable routes (CHs). Thus ADV and JOIN messages have to include additional fields to report this information. Since only cluster heads are involved in the route selection, energy consumption and collision can be minimized, simply by forcing the rest of the nodes to go to sleep.

Routes Selection Algorithms New algorithms such as those defined in algorithms 4.5, 4.1 and equation 3 have been designed to select reliable routes for data transmission after the selection of the cluster heads as shown in Figure 3. Nodes are classified into 3 different types in the proposed algorithms which are sink (SINK), CHs and Sensor Nodes (SN) as shown in the given algorithms. The proposed route selection algorithms provide valid routes between nodes such as cluster heads and a sink, CHs themselves and CHs and members. Nodes check first if there are valid routes before sending data. Where no routes are available, then nodes ask for urgent routes from their neighbours in order to send their data as soon as possible.

$$R(n, CH1, CH2) = \begin{cases} MAX\_RSSI(CH1, CH2) & \text{if CH1.RSSI} \neq \text{CH2.RSSI} \\ MAX\_RE(CH1, CH2) & \text{if CH1.RE} \neq \text{CH2.RE} \\ MIN\_DIST(CH1, CH2) & \text{otherwise.} \end{cases} \quad (3)$$

Where CH1 and CH2 are two current available cluster heads where node n must select the best one in terms of RSSI, remaining energy (RE) and location as shown in equation 3. This equation can easily be changed according to the requirements of the target applications.

4.2.4 Data Transmission

After cluster heads are selected and TDMA schedules for members are allocated, nodes can transmit their data to their cluster heads using their allocated slots. This data is then aggregated and sent back to a sink. The cross layer protocol deals with data communication based on scalar data and multimedia related transmissions, compared to the APTEEN protocol where only scalar data is transmitted, when delivering information about the detected events from source nodes to a sink as shown below:

- Nodes which belong to different clusters (non-cluster heads) sense the target environments and send their information back to their CHs via a single hop communication and then go to sleep.
- CHs then select a reliable route based on the algorithm given in 4.5 before data can be transmitted.
- CHs then aggregate this information and send it back to a sink over multi hop communication. Scalar or multimedia data is transmitted depending on the target applications.
- The sink then extracts this information and replies directly to source nodes which detect the events when needed.

Algorithm 4.1: NEXT HOP($N, CH1, CH2$)

---

comment: Finding next hop for node N

comment: RSSI:Receiver Strength Signal Indicator

comment: RE:Remaining Energy

comment: DIST:Distance from CHs to Sink

if CH1.RSSI≠CH2.RSSI
  then return (MAX_RSSI(CH1,CH2))
  else if CH1.RE≠CH2.RE
  then return (MAX_RE(CH1,CH2))
  else return (MIN(CH1,CH2))

Algorithm 4.2: MAX_RSSI($CH1, CH2$)

---

comment: RSSI:Receiver Strength Signal Indicator

if CH1.RSSI>CH2.RSSI
  then return (CH1)
  else return (CH2)

Algorithm 4.3: MAX_RE($CH1, CH2$)

---

comment: RE:Remaining Energy

if CH1.RE>CH2.RE
  then return (CH1)
  else return (CH2)

Algorithm 4.4: MIN_DIST($CH1, CH2$)

---

comment: LOC:Distance from CHs to Sink

if CH1.LOC<CH2.LOC
  then return (CH1)
  else return (CH2)

Algorithm 4.5: ROUTES DISCOVERY($N, CH[], CHS, grid, MaxHop$)

```
comment: Finding routes to deal with data communication for node N
comment: CH[]: is a set of CHs in the network in current round
comment: grid: size of the deployed network
comment: MaxHop: maximum hops
comment: SN: Sensor Node (Member)
if N is SINK
  then {
    for J ← 1 to CH[].SIZE
      do {
        F[J]←FALSE
        d[J]←0
        for I ← 1 to MaxHop and not F[J]
          do {
            d[J]←d[J]+grid/MaxHop
            if CH[I].distance≤d[J]
              then {
                CH[I].level←I
                F[J]←TRUE
                if CH[I].level≠MaxHop
                  { if CH[I].level == 1
                    CH[I].nextHop←SINK
                    P←new ADV(CH[I])
                    Broadcast P }
              }
            else
              then d[J]←d[J]+grid/MaxHop
          }
      }
  }
else if N is Cluster Head (CH)
  then { if ReceiveADV(CH1,CH2)
           then CH.NextHop←NEXT HOP(CH,CH1,CH2) }
else if N is SN (Member)
  then {SN.NextHop←NEXT HOP(N,CH1,CH2)
```

4.3 A Modified GinMAC for the Proposed Cross Layer Protocol

The GinMAC implementation given in [18] has been modified so that it can be combined with the APTEEN implementation given in [10] to design the cross layer protocol given in this section. The GinMAC protocol given in [18] has been modified so that it is no longer responsible for selecting routes between nodes in the network. This means that GinMAC follows information given by the APTEEN protocol as network layer in the proposed cross layer protocol. This shows that GinMAC is given a responsibility to confirm that data is delivered to the next hop over single hop communication using the algorithm given in Figure 4. Hence the APTEEN protocol is responsible for most of the operations that need to be undertaken in the cross layer protocol. These operations include selecting cluster heads, finding routes and then providing the connection between mobile and static nodes.

4.4 Reliable Transmission

Reliable data transmission between source nodes and a sink is one of the most important requirements for designing efficient protocols using WSNs. Different applications have different requirements in terms of reliability and consequently a lot of different protocols have been proposed to provide this. However, there are still problems with offering the required reliability for energy-ware and critical delivered data related applications using WSNs [22]. In addition, a further challenge is posed in terms of the reliability of the data delivered when mobile nodes are required.

In WSNs, critical applications, such as healthcare and forest fire related applications, information about events collected by the sensor nodes must be reliably delivered to the sink for successful monitoring of an environment. Therefore, given the nature of error prone wireless links, ensuring reliable transfer of data from resource constrained sensor nodes to the sink is one of the major challenges in WSNs [21]. A reliable transfer of data is achieved when the packet carrying event information arrives at the destination. In WSNs, reliability can be classified into different levels: Event reliability level and hop by hop or end to end reliability level.

Packet or event reliability is concerned with how much information is required to notify the sink of something happening in the target environment. Packet reliability requires all the packets carrying sensed data from all the sensor nodes in the network to be reliably transmitted to a sink. Packet reliability in terms of recovering the lost packets at the hop by hop or end to end level, can be achieved through the use of retransmissions and an acknowledgement [21].

This is simply the retransmission of the lost information which can either be performed on end to end or hop by hop basis. End to end retransmission requires the source node that generated the packet to retransmit the lost information. Hop by hop retransmission allows the intermediate nodes to perform retransmission of lost information by caching it in their local buffers [21]. The GinMAC implementation given in [18] has been modified to implement reliable transmission using *ACK* and *SENT* packets as shown in Figure 4.

In summary, the cross layer based protocol has the following features to improve the capability of WSNs for the proposed application considered in this paper :

- By sending queries over time to different parts of the network, users can gain a complete picture of the network, a feature which most of the recently cluster based routing protocols do not have.
- The cross layer based protocol can be used for critical and non-critical delivered data related applications by using different thresholds. This allows users to select thresholds according to the requirements of the proposed applications.
- The cross layer based protocol supports mobile nodes when different attachments are selected based on network conditions.
- Energy can be conserved by distributing energy usage between nodes in the network.
- Delay can be reduced and energy can be conserved by aggregating and reducing redundant copies of data at the intermediate nodes in the network.
- Nodes in each cluster send their data to their cluster heads over a single hop communication using their allocated slots, so the lifetime of the network is extended.
- As only cluster heads are involved with routing and forwarding data to a sink, the routing complexity in large WSNs is reduced.

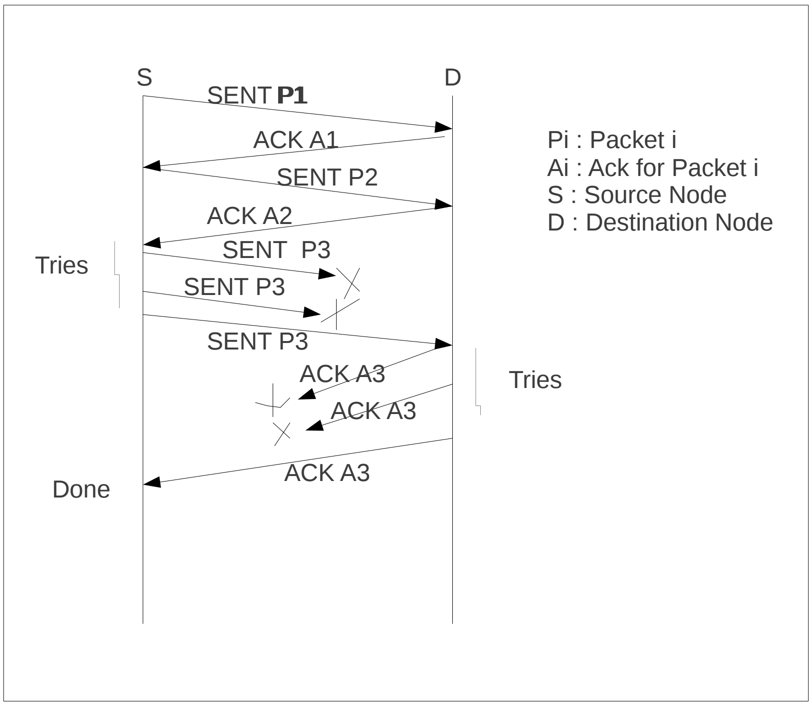

Figure 4: Reliable Transmission Using the Cross Layer Protocol

- As only cluster heads need to aggregate data from their members thus energy consumption is reduced.
- Data is transmitted to a sink over multi hop communication based on different information about network condition. This information includes a Receiver Signal Strength Indicator (RSSI), node's remaining energy and location. This means that reliable routes for delivering data from source nodes to a sink can be selected.
- The cross layer protocol combines information from different layers such as MAC, Radio (CC2420), physical (IEEE 802.15.4) and routing layers for selecting reliable routes for data transmission from source nodes to a sink. As a result, performance can be optimized.

5 Performance Evaluation

5.1 Simulation Scenarios and Parameters

A WSN using various numbers of nodes and sizes was simulated for four different bridges using WSN and the results are presented in this section. This simulation scenario was created to test some basic aspects of a WSN used for structural monitoring of a bridge. It has the following characteristics: the sensing nodes are placed in a grid throughout the simulation field within 50 meters from each other; the sink node is located in the middle of the field and all sensing node deliver their reports to the sink; every 5 minute (on average) a car appears in the simulation field (drives over the bridge).

Table 1: Simulation Parameters

Parameter	Value
Number of Nodes	20-120
Protocols	LEACH and CrossLayer
Physical Parameter	Vibration
Sensing Intervals	100s
Cars Intervals(in minutes)	5
Payload Packet Size	128 bytes
Transmission Power(LEACH)	0 dBm
Transmission Power(CrossLayer)	-10 dBm
Max Accumulated Load	120 bytes
Initial Energy	2 D batteries
Real Radio	CC2420
Slot Length (in ms)	80
Round Length (in sec)	50
Percentage of CHs	5 - 40
Multi hop	4

A car is guaranteed to trigger all sensing nodes along its path, thus creating a traffic flow towards the sink in the network. Nodes send their reports to the sink based on the given data thresholds and the accumulated loads on the monitored bridges from the car. Additionally, the sink node will distribute several packets to all sensing nodes at the beginning of the simulation and then will repeat this over a specific duration of time [23].

The aim of this simulation was to evaluate the performance of a WSN with different parameters, considering routing protocols, as well as the different sizes of the bridges being monitored, as shown in Tables 1 and 2. Simulation results for SHM related applications from other studies [16] missed the crucial routing functionality. In this study, the proposed application was simulated and results were presented using the cross layer based protocol and LEACH. The lifetime of the network, delay and reliability of the data delivered are crucial.

Table 2: Bridges with Different Sizes

Scenario	size of Bridge(in meters)
First Bridge (100M)	100 X 50
Second Bridge (200M)	200 X 50
Third Bridge (300M)	300 X 50
Fourth Bridge (400M)	400 X 50

The LEACH protocol was selected in this section as it is one of the cluster based routing protocols which aims to use less energy in running the WSNs. The target bridges were monitored by sensing the accumulated loads from the cars passing over the bridges. The objective was that high quality reports holding the required information should be delivered to the sink, whilst consuming a limited amount of energy. Further detail of the simulation scenarios, the target bridges and other specific parameters are given in Tables 1 and 2.

5.2 Analysis of the Results

Different scenarios for the proposed application using the cross layer based protocol and LEACH, where lifetime of the network, quality of the data delivered and delay are crucial, were simulated and results are discussed below.

5.2.1 Energy Saving and Network Lifetime:

Figure 5 shows the average lifetime of the network using the cross layer based protocol and LEACH for the proposed application across different scenarios. This figure shows that the cross layer based protocol extends the lifetime of the network compared with LEACH, in all of the simulated scenarios. The reasons for this are as follows: (i) CHs in the cross layer based protocol are selected based on the nodes' remaining energy. Consequently, the probability of nodes dying in their early stages is low, compared to LEACH, where CH selection is based on a randomly selected number between 0 and 1 as shown in [10].

(ii) CHs in the LEACH protocol use high transmission power (i.e., 0dB, as shown in Table 1) to deliver reports to the sink, in all scenarios, using a single hop communication. However, nodes in the cross layer based protocol use low transmission power (i.e., -10dB, as shown in Table 1). The higher transmission power consumes more energy [24].

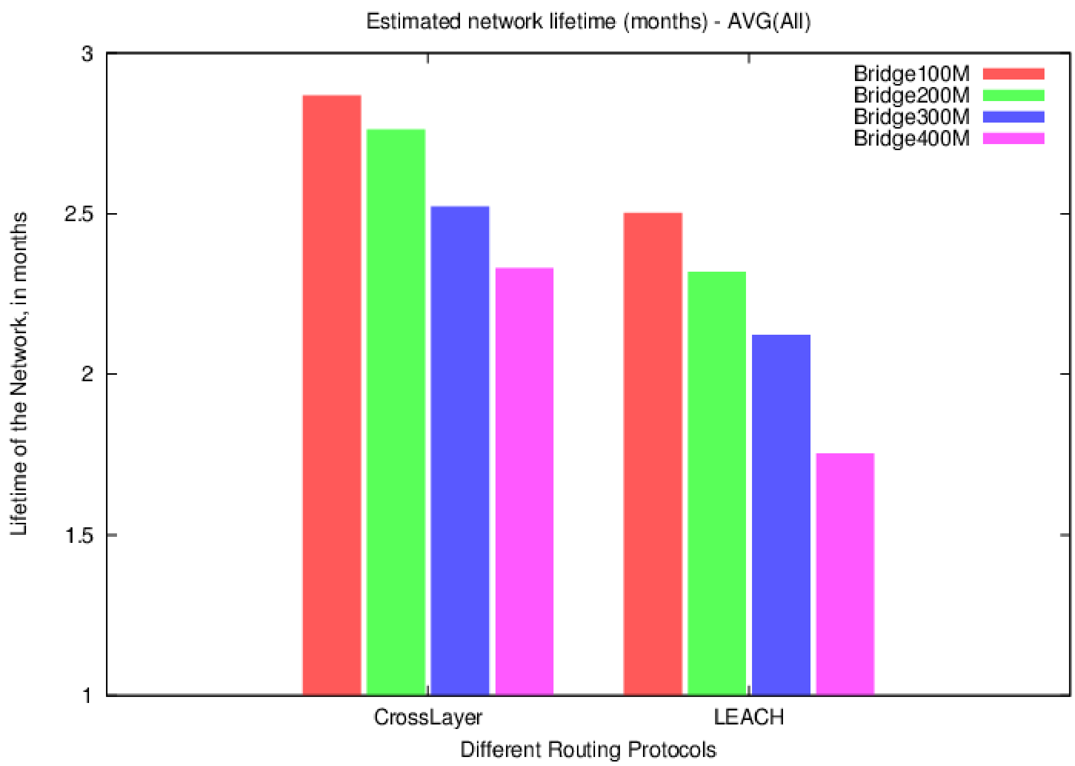

Figure 5: Network Lifetime using Different Protocols

In addition, nodes using the cross layer protocol send data based on different data thresholds and this conserves energy compared to the LEACH protocol where data is sent in all cases.

This means that the lifetime of the network using LEACH is decreased and this, therefore, makes LEACH an unsuitable protocol for large networks when saving energy is important.

Based on these results, it can be seen that a WSN for for the given scenarios using the cross layer protocol can survive for between 2 and 3 months, compared to LEACH where a WSN lasts between 1 and 2.5 months. This shows that the cross layer protocol could be used for this application where energy saving is the biggest issue.

5.2.2 Delivery of Report Packets:

Figure 6 shows the performance of the cross layer protocol and the LEACH protocols in terms of delivering the data to the sink across different scenarios. It can be seen that the number of reports delivered to the sink varied depending on the distance between the locations of the detected events and the sink.

As shown in the Figure 6, the cross layer based protocol performs better than LEACH in terms of delivering the report packets holding the required information from the source nodes to the sink. This is due to the fact that the cross layer based protocol uses multi hops utilizing the cross layer solution to select the most reliable routes based on network conditions, thereby increasing the number of successfully delivered packets.

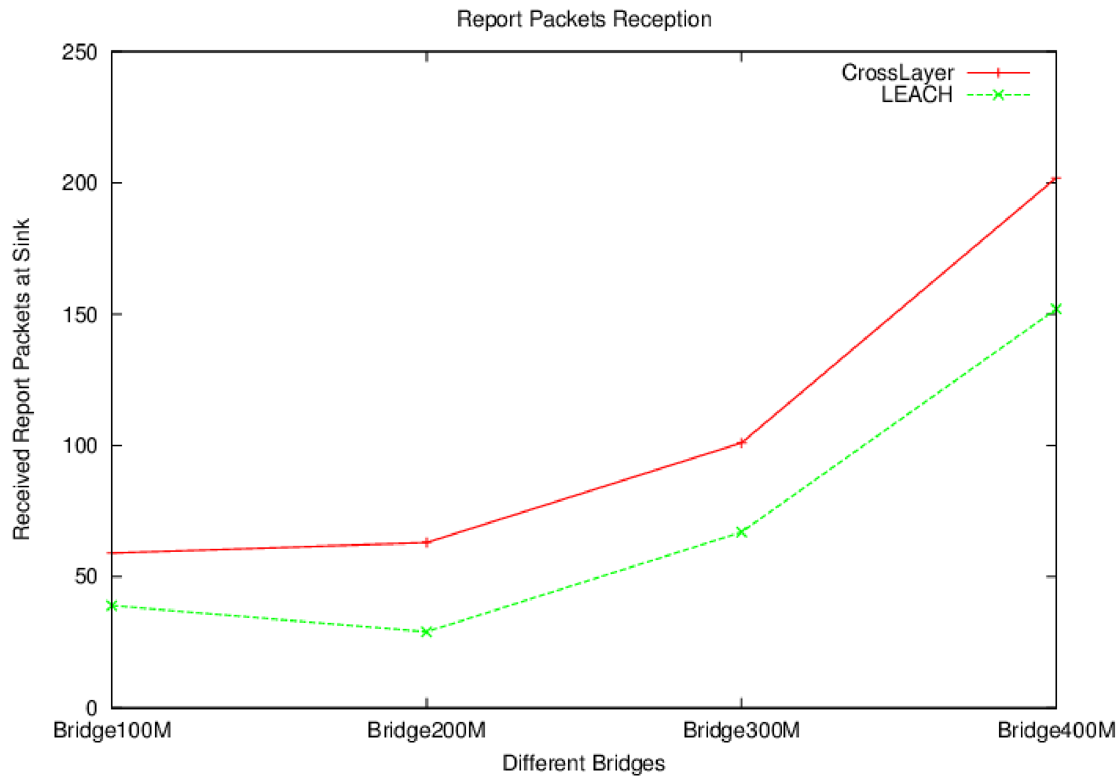

Figure 6: Report Packets Reception at Sink

On the other hand, the LEACH protocol does not use cross layer information to select reliable routes making LEACH an unreliable routing protocol for large WSNs. Nodes using the LEACH protocol cannot deliver a high number of reports to the sink, when the sink is not in the transmission range of such nodes and this results in a reduction in the number of delivered packets. This means that the cross layer protocol could be used for the proposed application when amount of data delivered is crucial.

5.2.3 Delay for the Delivered Data:

According to the results from Figure 7, all report packets from all simulated scenarios are delivered within the first minute. This shows that both the LEACH and cross layer based protocols can deliver data to a sink with minimum delay. This performance is due to the fact that: (i) only cluster heads are involved in routing and forwarding the data to the sink, which reduces the routing complexity in large WSNs and then decreases the delay in delivering data. (ii) the CHs nodes aggregate and thus reduce the redundant copies of data at the intermediate nodes in the network.

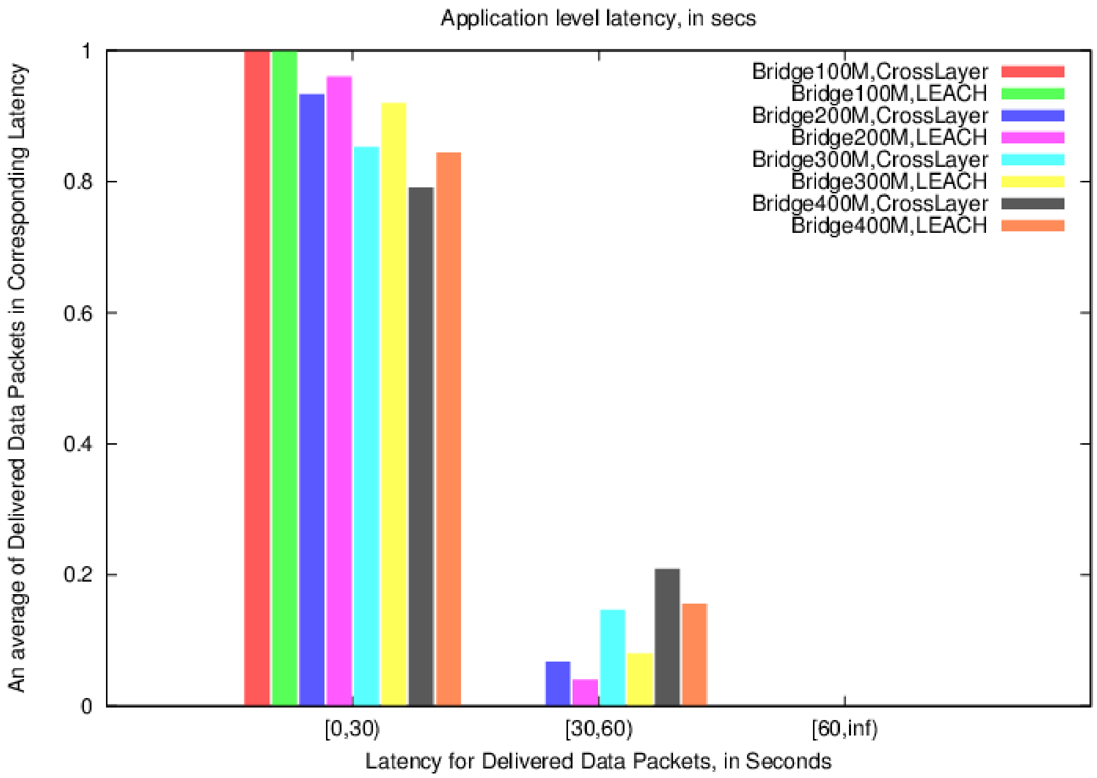

Figure 7: Latency of Delivered Data

As shown in Figure 7, most the data packets (more than 85%) from all simulated scenarios using both protocols are delivered within half a minute (30 seconds). The rest of the data packets (about 15%) are delivered within the first minute. Based on this, both protocols could be used for the proposed application if delay is the only significant.

6 Conclusion

A cross layer based protocol for structural health monitoring of bridges using WSNs where different scenarios with various sizes of bridges being monitored were simulated and results are presented in this paper. The cross layer based protocol was simulated compared to the LEACH protocol for the proposed application. Energy saving, delay and quality of the transmitted data were considered. Simulation results show that the cross layer based protocol can extend the lifetime of the network for the proposed application by distributing energy usage between nodes. The quality of the transmitted data can be optimized by considering the cross layer information based on the network conditions. Delay for the delivered data can be reduced by aggregating the redundant data before forwarding it to a sink. As a results, it has been shown that the cross layer based protocol performs better than the LEACH protocol for the target application where different scenarios are involved. The cross layer based protocol can be improved further so that the target environment can be monitored using real time images or videos so that the required actions using the visual information in real time can be easily undertaken.

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