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Investigative Analysis of Clustering Routing Protocols for Scalable Sensor Networks

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Abstract - **New advancements in the technology of wireless sensors have contributed to the development of special protocols which are unique to sensor networks where minimal energy consumption is vital and very important. As a result, the focus and effort of researchers is on designing better routing algorithms for a given application and network architecture of interest. Flat-based routing protocols have been found to be less advantageous to clustering routing protocols when their performance are compared in a large-scale wireless sensor network scenario. This is due to the fact that clustering operation reduces the amount of redundant messages that are transmitted all over the network when an event is detected. This paper is an investigation of cluster-based routing protocols for wireless sensor networks.**

Keywords* – *Clustering Routing Protocols; Wireless Sensor Network; Scalability; Flat-Based Routing

I. INTRODUCTION

Contemporary advancements in nanotechnology, micro-electro-mechanical systems (MEMS) technology, radio technology, digital electronics, digital signal processing and wireless communications have immensely contributed to the design of miniaturized and smart sensors. This technological progress made the concept of wireless sensor networking feasible and it created a lot of possibilities in using sensor nodes for monitoring remote events [2], [3], [4]. Wireless sensor network applications include tracking wildlife migration, monitoring infernos, reconnaissance and surveillance, weather observation and pervasive computing [1], [2], [3], [5]. Wireless sensor networks comprises of numerous nodes that cooperatively operate in order to attain a global task. The architecture of a sensor network comprises of a sink and sensor nodes. Communication is carried out among the nodes to relay valuable data to the sink. This communication can be affected by the time-criticality and accuracy of the desired data and other pertinent factors such as scarce energy resources and limited sensing, computing and communication capabilities [1], [3], [4].

Sensor nodes can be deployed in geographical areas where it can be extremely difficult to recharge the in-built batteries or even replace the nodes, hence it is the goal of every sensor network design to increase the longevity of the network. One of the most energy-consuming operations in sensor networking is the reception and transmission of data. An energy-efficient solution for this is to use low duty cycling by strategically turning on and off the radio of sensor nodes based on the demand to carry out a sensing task. Other means of conserving energy via minimizing redundant data transmission are data compression, data fusion, data aggregation and data filtering [2], [3], [4].

A number of routing algorithms have been recently designed for wireless sensor networks [5], [6]. However, designing energy-aware routing protocols is challenging as a result of the inherent energy constraints of the sensor nodes. Researchers are currently investigating and developing clustering routing protocols with the aim of solving the energy conservation problem [3], [7], [8], [9], [10], [11], [12]. It has been stated in the literature that though clustering may introduce overhead in terms of network configuration and maintenance, clustering routing protocols still perform better and they possess more desirable energy minimization capability when compared to flat network topologies [3], [4].

In this paper, a survey of cluster-based routing protocols is presented. The objective of this work is to promote better understanding of clustering routing algorithms and to remark on the possible areas of improvement which can be further investigated. The remainder of the paper is organized as follows: In Section 2, survey of selected clustering routing protocol is given. Section 3 summarizes the key features of the discussed protocols and section 4 concludes this paper.

II. CLUSTERING ROUTING PROTOCOLS

In this section, selected clustering routing protocols are investigated and examined.

A. Low-Energy Adaptive Clustering Hierarchy

The Low-Energy Adaptive Clustering Hierarchy (LEACH)

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is an adaptive and self-organizing protocol that minimizes energy consumption in wireless sensor networks [2], [7]. The underlying idea behind LEACH is the use of randomized rotation of cluster heads so that energy dissipation is shared evenly among all participating sensor nodes [2], [3], [4], [6].

Mechanism of Operation: The operation of LEACH can be categorized into two phases, namely; the set-up phase and the steady phase. In the set-up phase, a sensor node selects a random number in the range of 0 and 1. If this number is greater than a specified threshold, the sensor node will be elected as a cluster head.

After selecting the cluster heads, advertisements will be done by the newly-elected cluster heads to other nodes. Upon the reception of these advertisements, each node will determine the cluster to belong to based on the signal strength of the advertisements. This is because a strong signal strength means the cluster head is nearer to the node, hence minimum communication energy is required. Afterwards, the nodes notify the nearest cluster heads of their interest in becoming a cluster member. After cluster formation, the cluster heads allocate the time for sending data based on a Time Division Multiple Access (TDMA) approach. Subsequently, the nodes start sensing and sending data to cluster heads. Data aggregation is performed by the cluster heads before finally sending data to the sink. After successfully conveying the data to the sink, the network goes into reconfiguration and it selects new cluster heads. Finally, LEACH uses single-hop communication [3], [5], [6], [7].

Analysis of Performance: Energy consumption is minimized through the randomized rotation of the cluster head. Network lifetime is enhanced and transmission of redundant data is curtailed as a result of performing data aggregation. Inter-cluster and intra-cluster collisions are minimized by the use of negotiation and TDMA MAC scheme.

LEACH faces scalability problems when it is used in a dense network scenario because it uses single-hop communication which is ineffective and energy consuming for long distance communications. The use of dynamic clustering introduces extra overhead such as cluster head advertisements that can adversely diminish the energy conserved. Data collection is centralized and periodic hence periodic data transmissions can rapidly drain the limited amount of energy. Due to non-uniform distribution of cluster heads, it is possible that cluster heads will be unfairly concentrated in a network segment. Therefore, some nodes will suffer by not having cluster heads in their locality.

B. Threshold-Sensitive Energy-Efficient Sensor Network Protocol

TEEN (Threshold-Sensitive Energy-Efficient Sensor Network) and APTEEN (Adaptive Periodic Threshold-Sensitive Energy-Efficient Sensor Network) were proposed in [8] and [9] respectively for time-critical applications. TEEN is a protocol developed to respond to abrupt changes in the sensed attributes [3], [4], [5].

Mechanism of Operation: In the beginning, cluster formation is done by grouping nodes that are proximate to each other as clusters. Cluster heads of clusters nearer to the sink will be assigned higher priority while cluster heads of clusters farther from the sink will be assigned lower priority [1], [3], [5], [6], [8].

Cluster heads disseminate two thresholds to cluster members after cluster formation which are namely; hard and soft threshold. Hard threshold is the least possible value of the sensed attribute that will activate nodes to turn on their radio for transmitting data to their cluster heads. The nodes will commence the transmission of data if the following conditions are true: (1) The sensed attribute's present value is greater than the hard threshold (2) The sensed attribute's present value differs from the previous sensed value by an amount equal to or greater than the specified soft threshold. As a result, soft threshold helps in reducing transmissions when there are no significant changes in the sensed attributes [1], [3], [4], [5], [6], [8].

APTEEN, which is an extension of TEEN, aims at capturing periodic data collections and reacting to time-critical events. It changes the threshold values used in TEEN according to user demands and application type. Cluster formation is done by the base station and elected cluster heads distribute these parameters, (1) Attributes, (2) Thresholds, (3) Schedule and (4) Count Time. In APTEEN, the conditions for data transmission are just like TEEN. Data aggregation is performed by cluster heads to save energy [1], [3], [4], [5], [6], [9].

Analysis of Performance: The soft and hard threshold reduces the number of transmissions by preventing redundant data transmission which leads to energy conservation. APTEEN offers a wide range of flexibility by allowing users to set the count time interval and minimize energy consumption.

A limitation of TEEN is the inability to communicate if the thresholds are lost. TEEN is inapplicable for networks where periodic readings need to be delivered to the sink because the attributes' values might not reach the threshold at all. One of the drawbacks is that message can get lost if cluster heads are not in each other's transmission radius.

A common drawback of both TEEN and APTEEN are the complexity and overhead related to (1) cluster formation and (2) threshold management and query handling.

C. Geographic Adaptive Fidelity Protocol

Geographic Adaptive Fidelity (GAF) is a protocol originally developed for mobile ad hoc networks (MANETs) but found useful for sensor networks [3], [5], [10]. The fundamental idea behind GAF is that for each grid area, a node serves as a leader to convey data to other nodes but unlike other cluster routing protocols, these leader nodes do not perform data aggregation [4], [6], [10].

Mechanism of Operation: The protocol commences with forming a virtual grid over the deployed area. Afterwards, nodes use a Global Positioning System (GPS) to associate themselves with a location in the virtual grid. Nodes associated with the same location are equivalent nodes hence they form clusters [3], [4], [5], [10].

GAF consists of three states, namely; discovery, active and sleeping state. In the discovery state, nodes discover other neighboring nodes in the same grid by exchanging messages for a specified time period. Afterwards, routing is performed during the allotted active time and radios of active nodes are turned off for a specified sleeping period. Load balancing is ensured by allowing nodes to change from sleeping to active states. Mobility is supported by ensuring that each node in the grid calculate its leaving time and send this to its neighbors. One of the sleeping nodes wakes and becomes active before the leaving time of the active node expires. GAF is designed both for non-mobility (GAF-basic) and mobility (GAF-mobility adaptation) [3], [4], [5], [6], [10].

Analysis of Performance: This protocol preserves energy by discovering equivalent nodes and turning off idle nodes. As a result, GAF can considerably increase network longevity as the number of sensor nodes increases.

One of the drawbacks of this algorithm is the use of GPS technology which is energy-expensive and costly. The algorithm determines travel time in order to support mobility. This might be difficult or nearly impossible to estimate in sensor networks where nodes are deployed in areas with unfavorable environmental conditions.

D. Periodic, Event-driven and Query-based Routing Protocol

Periodic, event-driven and query-based (PEQ) protocol is designed for networks which are used as surveillance systems operating under critical conditions. The basic idea behind PEQ is the use of hop level of nodes to minimize redundant data transmission [3], [4], [11].

Mechanism of Operation: The protocol begins with configuring the entire network by finding the shortest distance from each sensor node to the sink. Initiation of this configuration process is done by the sink via broadcasting the hop value, time-stamp, and source address to nearest neighbors. Afterwards, nodes will store, increment and send the hop level to the next neighboring nodes. Each node compares its hop value with the one in the packet. If the hop value is greater, update is carried out and retransmission is done. This process goes on until the whole network is configured [3], [4], [11].

The sink broadcasts subscription message over the network just as in the configuration process. If a node detects an event matching the sink's interest, the node will send the event packet to its neighboring node. This event notification and data delivery process ends when the data reaches the sink. This protocol also implements an ACK-based repair mechanism [3], [4], [11].

Analysis of Performance: PEQ uses multi-hop communication which is simple and effective for long distance communication in a large network scenario. Low latency is ensured and energy consumption is minimized by using optimal path routing. Reliability is maintained by using an ACK-based repair mechanism. A major limitation is flooding and broadcasting of configuration and subscription messages. This leads to redundant transmission and reception of data and mismanagement of scarce energy resources.

E. Clustering Periodic, Event-driven and Query-based Routing Protocol

Clustering Periodic, Event-driven and Query-based (CPEQ) protocol is a cluster-based approach where sensor nodes with more energy are selected as cluster heads. Cluster heads form clusters and cluster members communicate with their respective cluster heads [3], [4], [11].

Mechanism of Operation: This protocol starts with network configuration just like in the PEQ protocol. The only difference here is the propagation of an additional field to specify the percentage of nodes that can become cluster heads. The process of cluster head selection is based on LEACH [3], [4], [11].

After selecting the cluster heads, the next stage is the cluster configuration stage where cluster heads form their clusters by broadcasting notifications. This process is the same as the configuration phase of PEQ. Whenever a node senses an event, they relay it to their respective cluster heads. This data routing scheme is also similar to the one used in PEQ. Additionally, CPEQ also employs an ACK-based path repair mechanism just like in the PEQ algorithm. [3], [4], [11].

Data aggregation is performed by the cluster heads on the incoming data to reduce redundancy. Subsequently, cluster heads will transmit the aggregated data to the sink via the shortest path. The event and data delivery process is similar to the one employed in PEQ [3], [4], [11].

Analysis of Performance: This algorithm possesses all the strengths of PEQ, namely; low energy consumption, support for low latency; support for reliability and simplicity. Another advantage of this algorithm is the aggregation of data which saves energy by reducing repetitive data transmission. However, a major limitation is the redundant transmission and reception of packets in the configuration process. In a highly-dense network scenario, high amount of energy will be wasted in the transmission of and listening to unwanted or unnecessary packets.

F. Energy Efficient Inter-cluster Communication based Routing Protocol

Energy Efficient Inter-cluster Communication based (ICE) algorithm is a protocol designed for periodic, event-driven and query-based networks. Message routing is accomplished via the help of cluster heads and nodes nearest to each other within two adjacent clusters. As a result, data transmission is carried out via short transmissions [3], [4], [12].

Mechanism of Operation: This protocol begins with the setup phase where the network is configured just like in the PEQ and CPEQ protocol. The cluster head selection is based on LEACH [3], [4], [12].

The cluster configuration process where cluster heads form clusters by broadcasting notifications to neighboring nodes is similar to that of the CPEQ algorithm. A unique property of this protocol is the discovery of free nodes which do not belong to any cluster. Free nodes send notification messages to adjacent nodes. These neighboring nodes forward their requests to their cluster heads [3], [4], [12].

This algorithm uses an improved version of the ACK-based path repair mechanism employed in PEQ and CPEQ. Whenever a cluster member has data to send to the sink, it selects one of its adjacent clusters to help relaying the data. The data will be transmitted to a node belonging to an adjacent cluster and that node will send the message to its cluster head. By following this sequence, the data is finally delivered to the sink [3], [4], [12].

Analysis of Performance: This protocol has the benefits of CPEQ and PEQ, namely; data aggregation, support for reliability, simplicity and support for low latency. Energy is conserved as a result of short-range transmissions using nearest neighbors. Load balancing, network longevity and fault tolerance is ensured through the use of multi-path routing. Notifications are prioritized and least-cost path is used to provide Quality of Service (QoS).

A limitation is the inability to form a logical line for clustering. This means no nearest neighbors will be discovered and data transmission will be negatively affected. Redundant transmission and reception of packets are highly likely to occur. Network management can be costly and difficult in a scenario where the network is mobile and growing.

III. SUMMARY OF FEATURES

In this section, a summary of the key features of the investigated clustering routing protocols is presented in the table below for easy comparison.

TABLE 1 COMPARISON OF FEATURES

	Mobility	Multi-Hop Routing	Data Aggregation	Multipath	Query-based	QoS	Energy Awareness	Sink Involved in Cluster Formation	Only CH are Relay Nodes	Optimal Route	Fault Tolerance
LEACH	NO	NO	YES	NO	NO	NO	YES	NO	YES	NO	NO
TEEN	NO	YES	YES	NO	NO	NO	YES	YES	YES	NO	NO
APTEEN	NO	YES	YES	NO	NO	NO	YES	YES	YES	NO	NO
GAF	YES	YES	NO	NO	NO	NO	YES	NO	NO	NO	NO
PEQ	NO	YES	YES	YES	YES	NO	YES	NO	NO	YES	YES
CPEQ	NO	YES	YES	YES	YES	NO	YES	NO	NO	YES	YES
ICE	NO	YES	YES	YES	YES	YES	YES	NO	NO	YES	YES

IV. CONCLUSION AND FUTURE WORK

Routing in sensor networks has attracted the attention of researchers and it has also posed interesting and important challenges. Clustering routing protocols organize sensor nodes in such a way that propagation of message to the sink is achieved with minimal energy. High energy nodes are often chose as cluster heads which are given the responsibility of data aggregation and transmitting data to the sink. This paper investigated selected clustering routing protocols and outlined their key features. The pioneering routing protocol LEACH is not applicable for scalable sensor networks because cluster heads communicate with the sink via single-hop transmission which is ineffective for large-scale sensor networks. Other routing algorithms address this challenging scalability issue by using multi-hop communication. In TEEN and APTEEN, only cluster heads are used as relay nodes during the multi-hop transmission of data to the sink. On the other hand, in PEQ, CPEQ and ICE, cluster nodes, cluster heads and free nodes are jointly employed for relaying data to sink. The mechanism used in PEQ, CPEQ and ICE where the responsibility of data delivery is shared by all sensor nodes in the sensor network ensures load balancing which in turn helps to conserve energy. Energy-efficient cluster formation, minimization of nodes' database operations, effective data aggregation and fusion techniques and provisioning for fault tolerance are key research issues in clustering routing protocols that need further investigation for scalable sensor networks.

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