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A Review on Data Aggregation Protocols in Wireless Networks

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Abstract— **Wireless sensor networks are composed of many cheap sensor nodes with limited sensing, computation, and communication capabilities. These networks have a variety of applications in both military and civilian usage, including battlefield surveillance, target tracking, environmental and health care monitoring, wildfire detection, and traffic regulation. Because of the need to low deployment cost of wireless sensor networks, sensor nodes have simple hardware and this leads severe resource constraints. Bearing in mind the limited resources of sensor nodes, it is critical to minimize the amount of data transmission to improve the average sensor lifetime and the overall bandwidth utilization. The process of summarizing and combining sensor data, which is used to reduce the amount of data transmission in the network, is referred to as data aggregation. Adopting an appropriate data aggregation is significantly important for improving the data accuracy, latency, fault-tolerance, and security. This paper reviews the data aggregation protocols in wireless sensor networks based on the existing research. The study can provide future research directions in this area.**

Keywords— Wireless Sensor Network, Data Aggregation

I. Introduction

Recent progress in micro-electro-mechanical systems (MEMS) and low power and highly integrated digital electronics have led to the advent of micro-sensors [1–5]. Such sensors are generally capable of data processing and communication. Ambient conditions of the surrounding environment of the sensor are identified by the sensing circuitry and are converted into an electric signal. Processing such a signal reveals some information about objects located and/or events happening near-by the sensor. The sensor sends the signal via a radio transmitter, to a command center (sink) either directly or through a gateway. Decreasing the size and cost of sensors has attracted a lot of interest. Such interest has motivated extensive research in the recent years exploring the potential of collaboration among sensors in data collection and processing and the coordination and management of the sensing activity and data flow to the sink. The typical architecture for such interconnected distributed sensors is a wireless network.

Wireless sensor networks are composed of a large number of inexpensive, low-powered sensing devices with limited memory, computational, and communication resources [6, 7]. These networks have a variety of applications in both military and civilian usage, including battlefield surveillance, target tracking, environmental and health care monitoring, wildfire detection, and traffic regulation [8, 9]. Because of the low deployment cost requirement of wireless sensor networks, sensor nodes have simple hardware and severe resource constraints [10]. As such, it is a challenging and critical task to provide efficient solutions to data gathering problem. Among these constraints, ‘‘battery power” is the most limiting factor in designing wireless sensor network protocols. Therefore, for the purpose of minimizing the power consumption of wireless sensor networks, several mechanisms are adopted such as radio scheduling, control packet elimination, topology control, and most importantly data aggregation [7]. The goal of data aggregation protocols is to combine and summarize data packets of several sensor nodes so that amount of data transmission is reduced.

An example representing data aggregation scheme is shown in Fig. 1 in which a bunch of sensor nodes gather information from a target region. When the base station asks the network for the information through a query, instead of sending each sensor node’s data to base station, one of the sensor nodes, called data aggregator, collects the information from its neighboring nodes, aggregates them (for example, computes the average), and sends the aggregated data to the base station over a multihop path. As understood by this example, data aggregation reduces the number of data transmissions thereby improving the bandwidth and energy usage in the network. Data aggregation problem still has the potential to provide many interesting research opportunities because of the many challenges facing the problem such as improving the accuracy, latency, fault-tolerance, and security. Hence, this review can be a starting point for conducting future research in this field.

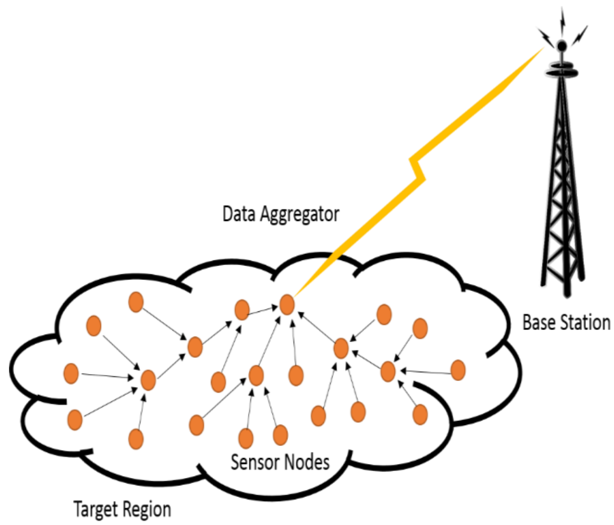

Fig. 1. The schematic representation of data aggregation in a wireless sensor network [10]

This paper, has been organized as follows: in section I a background of data aggregation in wireless sensor networks will be discussed. Further, in section II as related work some data aggregation protocols will be discussed. Further, in section II, most important works in data aggregation in wireless sensor networks by defining their main characteristics will be discussed. Finally in section III, a conclusion and future work will be discussed.

II. Related Work

1. Tree-based data aggregation protocols

The simplest scheme for distributed data aggregation is tree-based data aggregation protocol in which are some data aggregator nodes are specified in the network and the data paths of sensor nodes are chosen such that they include these data aggregator nodes. These protocols have been extensively studied in the literature [11–20]. In this section, some of the important work in tree-based data aggregation are presented.

The construction of an energy efficient data aggregation tree is the major task in a tree-based data aggregation protocol. Figure 2 demonstrates a typical example of such aggregation. One promising data-centric routing protocol is a greedy incremental tree (GIT) [11] which allows path sharing improvement in directed-diffusion-based data aggregation [12]. In [13] the performance of GIT is evaluated and compared with the performance of two other sub-optimal data-centric routing procedures namely Center at Nearest Source (CNS) and Shortest Path Tree (SPT) [11]. It is found that GIT outperforms the other two protocols in terms of average number of transmissions. In [14] EADAT is introduced as an efficient energy-aware distributed heuristic to generate the aggregation tree. This algorithm is based on residual power and utilizes neighboring broadcast scheduling and distributed competition among neighbors. There are also several data aggregation protocols which use the information theory as routing metric. An example of such protocols is the approach proposed in [15] where the routing is based on the joint entropies of the pockets. However, it should be noted that global knowledge of the information entropy of each sensor node as well as the joint entropy of each node pair is required for this approach which makes it not practical.

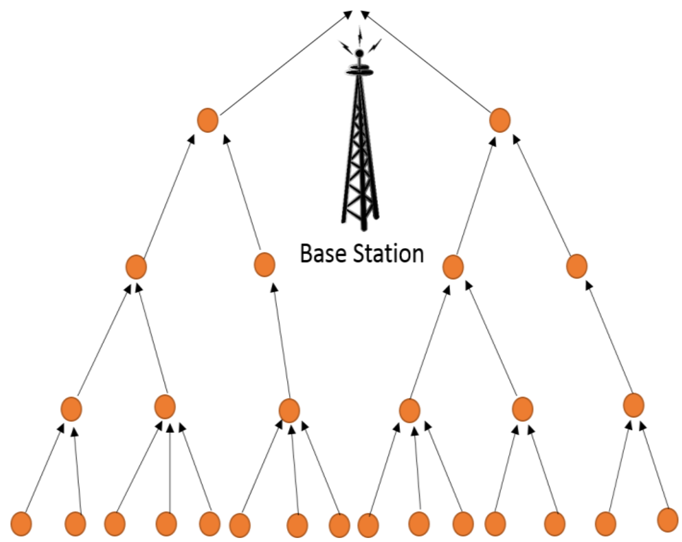

Fig. 2. The schematic representation of tree-based data aggregation [20]

A generic data-centric aggregation framework called Tiny AGgregation (TAG) is developed by Madden eta al. in [16] service for ad hoc networks of TinyOS motes. There are two great advantages about this framework. First, it has a simple and declarative interface for data collection and aggregation which is inspired by selection and aggregation facilities in database query languages. Second, it possess a smart distribution and execution system for aggregation queries in the sensor network making it time and power-efficient. Moreover, it is sensitive to the resource constraints and lossy communication properties of wireless sensor networks. TAG consists of two phases: a distribution phase, in which aggregate queries are supplied into the network, and a collection phase, where the aggregate values are routed up from children to parents. In the distribution phase, the bases station broadcasts a signal requiring a routing tree organized between the sensor nodes through which the bases station can send its inquires. A level or distance from the root of the sending node is associated with each signal. As this signal is received by a node not belonging to the associated level, is assigns the sender as its parent and adds a level to the current level of the signal, setting its own level. This procedure continues until all the sensor nodes in the wireless network are included in the tree and are assigned with a parent. The tree structures is kept updated by repeating the signaling periodically. After formation of the tree, the base station queries the network via the aggregation tree. Sensor nodes reply to the base station queries through their parent nodes. The queries are carried out using an SQL like language and they specify the quantity of interest, aggregation function and the operational sensor nodes.

A reactive data centric paradigm is introduced in [12] which is called Directed Diffusion. In such a network all the sensor nodes are application aware and all the communication is data-centric. This allows diffusion to save the energy by selecting empirically good paths and by caching and processing data in-network. The data aggregation in such a network is performed in three phases: interest dissemination, gradient setup, and path reinforcement and forwarding. During interest dissemination, the base station sends an interest message specifying the required data and the operational mode. As a sensor node receives the message, it resends the message to the surrounding nodes. In the next phase (gradient setup), the sensors prepare the interest gradients, which describe the next hop required to send the query back to the bases station. This gradient may be different for different types of the data. Finally, in the path reinforcement and forwarding phase, data aggregation is performed by adopting a single path for each data type to route packets toward the sink. A representative example of directed diffusion protocol is presented in Fig. 3. This can result into expensive operational costs in case of a network with a dynamic topology. The performance can be enhanced by a hierarchical aggregation technique [17]. In this scheme, interest messages are used to build up a hierarchical structure. After that, exploratory data and reinforcement message are used in Directed Diffusion to carry information needed. Based on the newly defined attribute property in each node, real data can be aggregated from the sources to the sink and thus unnecessary traffic is significantly reduced. Another similar protocol for enhancing the directed diffusion is proposed in [18].

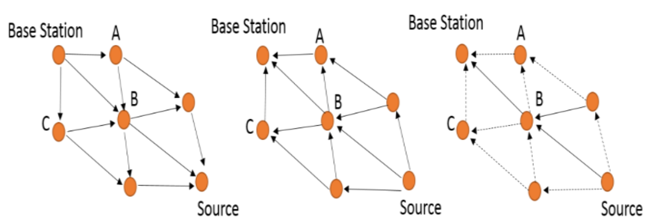

Fig. 3. Schematic representation of directed diffusion [22]

which reaches to the sensor nodes of A and B and subsequently gets forwarded to the node C, the node C creates the interest gradient consisted of two vectors indicating that the data matching the interest must be returned to A and/or B.

In [19], PEGASIS (Power-Efficient GAthering in Sensor Information Systems) is presented as a near-optimal chain-based protocol that minimizes the energy. In PEGASIS, the sensor nodes communicate only with close neighbor nodes and take turns transmitting to the base station, which results into reducing the amount of energy spent per round. The main idea of PEGASIS is to form a chain among the sensor nodes in such a way that each node will receive from and transmit to a close neighbor node.

Collected data pass from node to node, get fused, and, eventually, a designated node transmits to the base station. The transmission to from the nodes to the base station is performed turn and consequently the average energy spent by each node per round is reduced. The greedy approach can be used to build a simple chain, which performs quite well with the radio communication energy parameters. However, there are two major drawbacks associated with PEGASIS. First, each sensor needs to have a complete view of the network topology in order for the chain to be formed properly. Second, the energy expenditure of sensor nodes can be significantly high if the separation distances between the nodes in a chain are large.

This can be addressed by the energy-aware distributed heuristic to generate the aggregation tree, referred to as EADAT [14] which only relies on local knowledge of the network topology, and is based on residual power. The base station propagates a control message, initiating the formation of the tree. Each control message is associated with five fields namely ID, parent, power, status, and hop count. The message routes from node to node till each node has sent the message once. As such an aggregation tree will be formed rooted at the base station. There is a higher probability for a sensor node with higher residual power to become a non-leaf tree node and the sensor nodes possessing high energy levels will perform data forwarding. This results into drastic energy saving and the network lifetime increase compared to the case when no data aggregation is adopted.

There are several other approach adopted for efficient construction of data aggregation trees in wireless sensor networks. A distributed MAC protocol designed for Delay-Bounded Applications in sensor networks (DB-MAC) is proposed is [20]. DB-MAC aims at minimizing the latency for delay bounded applications. The protocol is based on RTS/CTS/DATA/ACK handshaking, but is improved by means of two mechanisms to reduce latency and save energy. In particular DB-MAC implements an access with priority and path aggregation. The performance is shown to be near optimal as far as latency and energy consumption is concerned.

III. CLUSTER-BASED DATA AGGREGATION

Another group of data aggregation protocols are cluster-based data aggregation protocols in which the sensor nodes are subdivided into clusters. A cluster head is assigned to each cluster which collects and aggregate the data locally and send the aggregated data to the base station. Cluster heads are able to communicate with the sink directly through long range radio transmission however this is very inefficient and energy-consuming bearing in mind the limited resources of the sensor nodes. For this reason, a tree structure is formed between the cluster heads to transmit the data by multihopping between each other resulting into saving the energy consumption drastically. A schematic representation of cluster-based data aggregation is depicted in Fig. 4. Several cluster-based data aggregation schemes have been developed recently [23-29]. In the following, we review some of the important works.

Low-energy adaptive clustering hierarchy (LEACH) has been proposed in [23] as a protocol architecture for microsensor networks that combines the ideas of energy-efficient cluster-based routing and media access together with application-specific data aggregation to achieve good performance in terms of system lifetime, latency, and application-perceived quality. Leach exploits distributed cluster formation technique which enables self-organization of large numbers of nodes, algorithms for adapting clusters and rotating cluster head positions for even distribution of the energy load among all the nodes, and techniques enabling distributed signal processing to save communication resources. LEACH adopts randomized rotation of the high-energy cluster head position among the sensors to avoid draining the battery of any one sensor in the network. In this way, the energy load of being a cluster head has an even distribution among the nodes. The LEACH operated in two phases: cluster structure formation and cluster head aggregation and broadcast.

In the first phase, the election of cluster heads in LEACH is performed in rounds and is based on a distributed probabilistic approach. In each round, the following threshold $T(n)$ is calculated in the sensor nodes:

$$T(n) = \begin{cases} \dfrac{P}{1 - P(R \bmod (1/P))} & \text{if } n \in G, \\ 0 & \text{otherwise.} \end{cases}$$

where P is the desired percentage of cluster heads, R is the round number, and G is the set of nodes that have not been cluster heads during the last $1/P$ rounds. For a sensor node n to become a cluster head, it is required that a random number associated with the sensor node becomes lower than the threshold $T(n)$. Cluster heads send out the signals to the sensor nodes and the sensor nodes join to the cluster based on the receiving signal strength. In order to manage the local transmissions optimally, each cluster head schedules its cluster based on TDMA according to the number cluster nodes.

In the second phase, the data are transmitted to the cluster heads from the sensor nodes according to the established schedule. This allows the sensor nodes to turn off their radio until their turn in the schedule which results into saving the energy. The aggregated data are subsequently transmitted to the base station from the cluster heads through single links. This can be viewed as a disadvantage for LEACH since the single links can be very expensive. Moreover, LEACH is negatively affected by dynamic network topologies. But on the other hand, it can improve system lifetime by an order of magnitude compared with general-purpose multihop approaches.

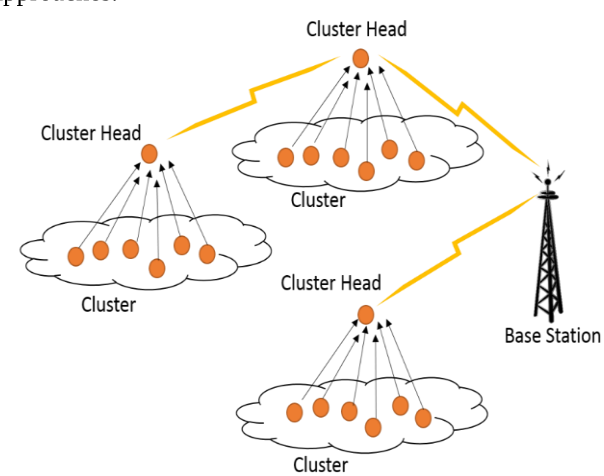

Fig. 4. A schematic representation of cluster-based data aggregation [30]

In [24] a Hybrid Energy-Efficient Distributed clustering called HEED is proposed, that periodically chooses cluster heads based on a hybrid of the node residual energy and a secondary parameter, such as node proximity to its neighbors or node degree. HEED terminates in O(1) iterations, subject to low message overhead, and achieves relatively uniform cluster head distribution across the network.

HEED utilizes Average Minimum Reachability Power (AMRP) to estimate the communication cost in the clusters. AMRP is defined as the average of the minimum power level required by all sensor nodes within the cluster to reach the cluster head. The cluster heads election criteria is based on evaluation of the following probability in each sensor node:

$$P_{(CH)} = C \times \frac{E_{residual}}{E_{\max}}$$

where C and $E_{residual}$ and $E_{\max}$ are the initial percentage of cluster heads, the current residual, and initial energy of the sensor node, respectively. All the sensor nodes send a cluster head message and then the sensor node with the lowest AMRP within the set of received cluster head messages is selected as the cluster head. This procedure continues repeatedly until each node is assigned as the cluster head. Similar to the LEACH, communication of base stations and cluster heads in HEED is performed directly. It has been found that HEED is effective in prolonging the network lifetime and supporting scalable data aggregation. HEED can asymptotically guarantee connectivity of clustered networks, with appropriate bounds on node density and intra-cluster and inter-cluster transmission ranges.

The Cougar approach to tasking sensor networks through declarative queries is proposed in [25] which is suitable for applications where sensor nodes continuously generate correlated data. Given a user query, a query optimizer generates an efficient query plan for in-network query processing, which can vastly reduce resource usage and thus extend the lifetime of a sensor network. Moreover, as the queries are asked in a declarative language, the user is shielded from the physical characteristics of the network. Cougar uses a gateway node for communication of cluster heads and the base station. The cluster head selection procedure in Cougar is based on more than one metric, which allows sensor nodes to be more than one hop away from their cluster heads. This requires routing algorithms to exchange packets within clusters. The Ad Hoc On Demand Distance Vector (AODV) protocol is adopted for this purpose. The correctness of the aggregated data is improved in Cougar through synchronization mechanism in which the cluster heads do not send the aggregated data to the gateway node until the data is received from all the sensor nodes.

A hybrid approach called Clustered Diffusion with Dynamic Data Aggregation (CLUDDA) is proposed in [26] to improve the network efficiency by combining Directed Diffusion with clustering during the initial phase of the interest message broadcasting. CLUDDA includes entire query definitions within interest messages sent by the base station, allowing nodes to process data collected from sensors and subsequently aggregate the data even in completely unfamiliar environments. Interest messages define the queries describing the operations to be performed on the data components. Using the existing knowledge of the queries reduces the processing overhead. By adopting the clustering algorithm, the transmission of interest messages is carried out only by the cluster heads. The regular sensor nodes are not involved in data transmission unless they are capable of servicing a request, which leads to energy conservation. The aggregation in CLUDDA can be performed with any cluster head with the knowledge of the query. Cluster heads also have the addresses of all the neighboring nodes from which the data messages had originated. These addresses are used to propagate interest messages directly to certain specific nodes rather than broadcasting them to all the clusters.

There are several other cluster-based data aggregation algorithms. In [28] a network formation algorithm is designed through a cross-layered approach. Addressing the excessive contention carries out the designing of the link formation procedures at the MAC layer. The network of interconnected clusters is then produced using the interactions at the MAC layer. It is shown that the cross-layer optimization results in prompt network formation and reduced overhead by making the overall protocol to contention-aware. A simple, location-based clustering scheme is presented in [29]. In this scheme, given a sensor field and a cluster size, nodes close to each other form clusters. The formed clusters remain static for the lifetime of the network. The data from each of the nodes is routed along a shortest path tree (SPT) to a cluster head node, within each cluster. The cluster head then transmits the aggregated data from its cluster to the sink via a multi-hop path with no intermediate aggregation.

IV. CONCLUSION

This paper provides a detailed review of data aggregation protocols in wireless sensor networks covering the main issues in each protocol. Such study can lead to future research directions for improving the data accuracy, latency, fault-tolerance, and security adopting improved aggregation techniques.

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