Diverse Data Aggregation Techniques in Wireless Sensor Networks: A Survey

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Abstract— **Wireless sensor network consists of a large number of sensor nodes with sensing and communication capabilities which co-operatively sense data and send the sensed data to the sink. One of the major constraints of sensor nodes is the power consumption requirement. Sensor nodes are portable devices that carry limited, generally irreplaceable power sources. As sensor nodes are battery driven, an efficient utilization of power is essential to reduce data traffic inside sensor networks thus reduce amount of data that need to send to the sink thereby enhancing the network lifetime. The major goal of data aggregation techniques is to gather and aggregate the data in an energy efficient manner to prolong the network lifetime. This paper provides some important aspects of data aggregation techniques used in Wireless sensor networks with certain performance measures like data accuracy, latency, bandwidth utilization and lifetime and concludes with possible future research directions.**

Keywords- Data Traffic, Data Aggregation, Network Lifetime, Bandwidth Utilization

I. INTRODUCTION

Sensor networks are event-based systems that differ from traditional communication networks in several ways: sensor networks have severe energy constraints, redundant low-rate data, and many-to-one flows. The end-to-end routing schemes that have been proposed in the literature for mobile ad-hoc networks are not appropriate under these settings. Data-centric technologies are needed that perform in-network aggregation of data to yield energy-efficient dissemination.

Sensor networks are quintessentially event-based systems. A sensor network consists of one or more “sinks” which subscribe to specific data streams by expressing interests or queries. The sensors in the network act as “sources” which detect environmental events and push relevant data to the appropriate subscriber sinks. Because of the requirement of unattended operation in remote or even potentially hostile locations, sensor networks are extremely energy-limited. However since various sensor nodes often detect common phenomena, there is likely to be some redundancy in the data the various sources communicate to a particular sink. In-network filtering and processing techniques can help conserve the scarce energy resources. Initially, in-network aggregation techniques involved different ways to destination(s). In other words, these protocols were simply routing algorithms that differed from more traditional ad hoc routing protocols in the metric they used to select the routing paths. More recently, many additional studies have been published, addressing not only the routing problem but also mechanisms to represent and combine data more efficiently. In-network data aggregation is a complex problem that involves many layers of the protocol stack and different aspects of protocol design, and a characterization and classification of concepts and algorithms is still lacking in the literature.

In applications of wireless sensor networks (WSNs), the aggregations of sensed data, such as sum, average, and predicate count are very important for the users to get summarization information about the monitored area. Instead of collecting all sensor data [1], [2], [3] and computing aggregation results at the base station (BS), in network aggregation allows sensor readings to be aggregated by intermediate nodes, which efficiently reduces the communication overhead. Many in-network aggregation schemes have been proposed [4], [5], [6], [7]. However, since WSNs are often deployed in an open and unattended environment, an adversary could undetectably take control of one or more sensor nodes and subvert correct in-network aggregations by manipulating the partial aggregation results or reporting arbitrary readings through compromised.

II. EASE OF USE

A. Data aggregation

The process of aggregating the data from multiple sensors to eliminate redundant transmission and provide fused information to the base station. Data aggregation usually involves the fusion of data from multiple sensors at intermediate nodes and transmission of the aggregated data to the base station.

B. Data Accuracy

It depends on the specific application for which the sensor network is designed. For instance, in a target localization problem, the estimate of target location at the sink determines the data accuracy.

C. Latency

The delay involved in data transmission, routing and data aggregation. It can be measured as the time delay between the data packets received at the sink and the data generated at the source nodes.

D. Energy Efficiency

In an ideal data aggregation scheme, each sensor should have expended the same amount of energy in each data gathering round.

E. Network Lifetime

The number of data aggregation rounds till α% of sensors die where α is specified based on the application specific scenario.

III. ROUTING MODELS

The focus of attention on a single network flow that is assumed to consist of a single data sink attempting to gather information from a number of data sources. We start with simple models of routing schemes which use data aggregation (which we term data-centric), and schemes which do not (which we term address-centric). In both cases we assume there are some common elements - the sink first sends out a query/interest for data, the sensor nodes which have the appropriate data then respond with the data. They differ in the manner the data is sent from:

Address-centric Protocol (AC): Each source independently sends data along the shortest path to sink based on the route that the queries took ("end-to-end routing").

Data-centric Protocol (DC): The sources send data to the sink, but routing nodes enroute look at the content of the data and perform some form of aggregation/ consolidation function on the data originating at multiple sources.

IV. ENERGY CONSUMPTION MODELS

In this, some analytical bounds on the energy costs and savings that can be obtained with data aggregation, based on the distances between the sources and the sink, and the inter-distances among the sources. The greatest gains due to data aggregation are obtained when the sources are all close together and far away from the sink.A more up to date approach regarding the energy consumption of the WSN nodes is presented.

Sensor Module. The energy consumption of sensor module is due to a few numbers of operations. This includes signal sampling, AD (Analogue to Digital) signal conversion and signal modulation. Also the energy consumption of this module is related to the sense operation of the node (periodic, sleep/wake, etc.). For example in periodic mode the energy consumption is modeled as

$$\mathbf{E}_{sensor} = \mathbf{E}_{on-off} + \mathbf{E}_{off-on} + \mathbf{E}_{sensor-run}$$

In this relation the $\mathbf{E}_{on-off}$ is the one time energy consumption of closing sensor operation, E_{off-on} is the one time energy consumption of opening sensor operation and $E_{sensor-run}$ is the energy consumption of sensing operation that is equal to the working voltage multiplied by the current of sensors and the time interval of sensing operation.

Processing Module. The main activities of this module are the sensor controlling, the protocol communication and data processing. In most cases this module supports three operation states (sleep, idle, run). The Processor energy consumption, denoted as $\mathbf{E}_{cpu}$ is the sum of the state energy consumption $\mathbf{E}_{cpu\text{-}state}$ and the state-transition energy consumption $\mathbf{E}_{cpu\text{-}change}$ where i=1,2,..m is the processor operation state and m is the number of the processor state, j=1,2,..n, is the is the type of state transition and n is the number of the state-transition.

$$\mathbf{E}_{cpu} = \mathbf{E}_{cpu-state} + \mathbf{E}_{cpu-change} = \mathbf{P}_{cpu-state(i)} * \mathbf{T}_{cpu-state(i)} + \mathbf{N}_{cpu-change(j)} * \mathbf{e}_{cpu-change(j)}$$

On this relation, $P_{cpu\text{-}state(i)}$ is the power of state *i* that can be found from the reference manual, $\mathbf{T}_{cpu\text{-}state(i)}$ is the time interval in state *i* which is a statistical variable. $\mathbf{N}_{cpu\text{-}change(j)}$ is the frequency of state transition *j* and $\mathbf{e}_{cpu\text{-}change(j)}$ is the energy consumption of one-time state transition *j*.

Power Supply Module. The power module of the nodes is related to the manufacturer and the model of each node. For example, a wireless sensor node LOTUS and node IRIS developed by MEMSIC, are both supplied by two AA batteries, while the current draw on receive mode is 16mA and on transmit for Tx value -17dBm, -3dBm, +3dBm consumes 10mA, 13mA and 17mA respectively. On the other hand, the known node MICA2, which is also supplied by two AA batteries, on transmit with maximum power it consumes 27mA and has an average receive of 10mA. Also on the sleep mode it consumes less than 0.001 mA.

V. ENERGY EFFICIENT ROUTE SELECTION POLICIES

Energy efficiency is a critical issue in WSNs. The existing energy-efficient routing protocols often use residual energy, transmission power, or link distance as metrics to select an optimal path. In this section, the focus is on energy efficiency in WSNs and the route selection policies with novel metrics in order to increase path survivability of WSNs. The novel metrics result in stable network connectivity and less additional route discovery operations.

The devices used in a WSN are resource constrained, they have a low processing speed, a low storage capacity and a limited communication bandwidth. The main design goal of WSNs is not only to transmit data from a source to a destination, but also to increase the lifetime of the network. This can be achieved by employing energy efficient routing protocols. The performance of a routing protocol depends on the architecture and design of the network, and this is a very important feature of WSNs. However, the operation of the protocol can affect the energy spent for the transmission of the data. The main objective of current research in WSNs is to design energy-efficient nodes and protocols that could support various aspects of network operations.

There are some terms related to the energy efficiency on WSNs that are used to evaluate the performance of the routing protocols and here are the most important ones

Energy per Packet. This term is referred to the amount of the energy that is spent while sending a packet from a source to a destination.

Energy and Reliability. It refers to the way that a tradeoff between different application requirements is achieved.

In some applications, emergency events may justify an increased energy cost to speed up the reporting of such events or to increase the redundancy of the transmission by using several paths.

Average Energy Dissipated. This metric is related to the network lifetime and shows the average dissipation of energy per node over time in the network as it performs various functions such as transmitting, receiving, sensing and aggregation of data.

Low Energy Consumption. A low energy protocol has to consume less energy than traditional protocols. This means that a protocol that takes into consideration the remaining energy level of the nodes and selects routes that maximize the network's lifetime is considered as low energy protocol.

Total Number of Nodes Alive. This metric is also related to the network lifetime. It gives an idea of the area coverage of the network over time.

Packet Size. The size of a packet determines the time that a transmission will last. Therefore, it is effective in energy consumption. The packet size has to be reduced by combining several packets into one large packet or by compression.

Distance. The distance between the transmitter and receiver can affect the power that is required to send and receive packets. The routing protocols can select the shortest paths between nodes and reduce energy consumption.

VI. NETWORK ARCHITECTURE

The architecture of the sensor network plays a vital role in the performance of different data aggregation protocols. In this section, we survey several data aggregation protocols which have specifically been designed for different network architectures.

Flat networks

In flat networks, each sensor node plays the same role and is equipped with approximately the same battery power. In such networks, data aggregation is accomplished by data centric routing where the sink usually transmits a query message to the sensors, e.g, via flooding and sensors which have data matching the query send response messages back to the sink. The choice of a particular communication protocol depends on the specific application at hand. In the rest of this subsection, we describe these protocols and highlight their advantages and limitations.

Hierarchical networks

A flat network can result in excessive communication and computation burden at the sink node resulting in a faster depletion of its battery power. The death of the sink node breaks down the functionality of the network. Hence, in view of scalability and energy efficiency, several hierarchical data aggregation approaches have been proposed. Hierarchical data aggregation involves data fusion at special nodes, which reduces the number of messages transmitted to the sink. This improves the energy efficiency of the network. In the rest of this subsection, the different hierarchical data aggregation protocols are described and highlight their main advantages and limitations.

TAXONOMY:

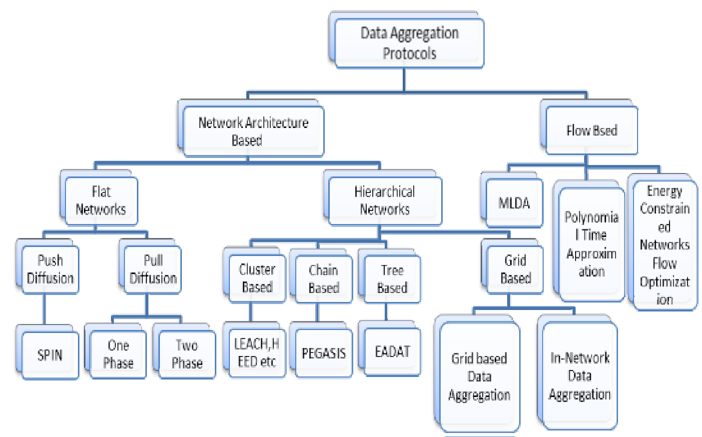

Fig 1. Taxonomy of different data aggregation Techniques

Push diffusion

In the push diffusion scheme, the sources are active participants and initiate the diffusion while the sinks respond to the sources. The sources flood the data when they detect an event while the sinks subscribe to the sources through enforcements.

SPIN:

The *sensor protocol for information via negotiation* (SPIN) [4] can be classified as a push based diffusion protocol. The two main features of SPIN are negotiation and resource adaptation. Simulation results show that SPIN performs almost identical to flooding in terms of the amount of data acquired over time. However, SPIN incurs a factor of 3.5 less energy consumption compared to flooding and is able to distribute 60% more data per unit energy compared to flooding. One of the main advantages of SPIN is that topological changes are localized since each node only requires the knowledge of its single hop neighbors. The main disadvantage of SPIN is its inability to guarantee data delivery.

Two phase pull diffusion

Intanagonwiwat et al. [5] have developed an energy efficient data aggregation protocol called directed diffusion. Directed diffusion is a representative approach of two phase pull diffusion. It is a data centric routing scheme which is based on the data acquired at the sensors. The sink initially broadcasts an interest message in the network. The gradient specifies the data rate and the direction in which to send the data. Intermediate nodes are capable of caching and transforming the data. Each node maintains a data cache which keeps track of recently seen data items. After receiving low data rate events, the sink reinforces one particular neighbor in order to attract higher quality data. Thus, directed diffusion is achieved by using data driven local rules.

One phase pull diffusion

Two phase pull diffusion results in large overhead if there are many sources and sinks. Krishnamachari et al. [7] have proposed a one phase pull diffusion scheme which skips the flooding process of directed diffusion. In one phase pull diffusion, sinks send interest messages that propagate through the network establishing gradients. However, the sources do not transmit exploratory data. The sources transmit data only to the lowest latency gradient pertinent to each sink. Hence, the reverse route (from the source to the sink) has the least latency.

In [7], simulations have been performed comparing push diffusion with one phase pull diffusion. The simulation results show that one phase pull outperforms push diffusion when the source event rate is very high. However, when the sink interest rate is high push diffusion performs better.

Data Aggregation in Cluster-Based Networks

In energy-constrained sensor networks of large size, it is inefficient for sensors to transmit the data directly to the sink. In such scenarios, sensors can transmit data to a local aggregator or cluster head which aggregates data from all the sensors in its cluster and transmits the concise digest to the sink. This results in significant energy savings for the energy constrained sensors. The cluster heads can communicate with the sink directly via long range transmissions or multi-hoping through other cluster heads. Recently, several cluster based network organization and data aggregation protocols have been proposed. The Pros and Cons of these protocols are listed in the table 1.

Tree-Based Data Aggregation

In this, sensor nodes are organized into a tree where data aggregation is performed at intermediate nodes along the tree and a concise representation of the data is transmitted to the root node. One of the main aspects of tree-based networks is the construction of an energy efficient data aggregation tree.

As Espan protocol considers distance as main parameter and remaining energy as second, the network coverage is not

CLUSTERING			
OBJECTIVES	**PROTOCOL NAME**	**PROS**	**CONS**
Network Longevity	LEACH	Cluster crowns were revolved periodically to balance the Energy depletion.	Scope is only one hop communication from each crown to the sink within a small square area.
	HEED	Well-thought-out the multi-hop transmission model. Remaining energy and node degree were used to select cluster heads to curtail exchange cost in a rectangular network.	The issue of harmonizing energy depletion is not taken into account.
	TEEN	Proposed a cluster-based reactive reporting model, wherein a hard threshold and a soft threshold were set for the reporting strategy.	The sink will never know whether those never reported nodes are dead or still alive but not reporting due to these thresholds.
Network scalability and energy hole consideration	Li and Mohapatra [15]	Analyzed the energy hole problem in a circular network, and pointed out that the hierarchical deployment and data compression have positive effects on mitigating the hole.	Not suitable for a rectangular region.
	In [12] - Olariu and Stojmenovic	Investigated theoretical aspects of the uneven energy depletion phenomenon under a concentric coronas model, and proved the possibility for avoiding energy hole problem with different parameters.	Not addressed the Large scale wireless sensor networks.
	UCR	Proposed an unequal cluster-based routing protocol to mitigate the ''hot spot'' problem. It groups the nodes into clusters and a greedy geographic and energy-aware routing protocol is designed for the inter-cluster communication.	It is not feasible for many applications with massive sensing data environments
	Wu et al. [13]	Optimum balanced energy depletion is achieved in geometric progression from the outer coronas to the inner ones except the outermost one.	In circular multi-hop sensor network with nonuniform node distribution and constant data reporting, the unbalanced energy depletion is the major concern
Even energy achievement	Gupta and Younis [22]	Proposed to balance the load among cluster crowns	Works well if the cluster crowns have no power constraint. it is tedious to provide in most unattended WSNs
	UCS[23]	Proposed an unequal clustering method for the network with heterogeneous clusters and it can be expanded to homogeneous sensor networks.	It was validated only for a circular network with two-hop inter-cluster communication.
	Zhang et	An energy-efficient multi-	Applicable only for

	al. [24]	hop polling method is used to avoid collision in data collection.	intra-cluster communication in two-layered heterogeneous sensor networks.
	Kumar et al. [25]	Based on weighted election probabilities of each node, energy depletion was abridged	It was validated only for a circular network with homogeneous sensor networks.
Clustering-based data aggregation	DRINA	Proved that in-network aggregation operations can eliminate severance to mend bandwidth utilization.	Validated only with small scale WSNs.
	B. Przydatek, D. Song, and A. Perrig	Formulated a problem devoted to perform optimal distributed firmness so as to minimize aggregation costs to a sink.	Applicable only to the static environment.
	SAPC	Sstatic cluster-based aggregation protocol where the head nodes play the role of aggregators and results of other heads will not be aggregated again by relay nodes.	Rapid energy depletion in cluster crowns was not addressed.

Table 1. Pros and Cons of various Cluster based protocols

high; because in some cases the nodes with low remaining energy are selected as parent. After local aggregation and data transmission, the remaining energy of these nodes is finished quickly. This causes the node failure and network cannot coverage region completely.

Chain-Based Data Aggregation

The key idea behind chain-based data aggregation is that each sensor transmits only to its closest neighbor. Lindsey *et al.* [14] presented a chain-based data-aggregation protocol called Power-Efficient Data Gathering Protocol for Sensor Information Systems (PEGASIS).

In PEGASIS, nodes are organized into a linear chain for data aggregation. The nodes can form a chain by employing a greedy algorithm or the sink can determine the chain in a centralized manner. Greedy chain formation assumes that all nodes have global knowledge of the network. The farthest node from the sink initiates chain formation and, at each step, the closest neighbor of a node is selected as its successor in the chain. In each data-gathering round, a node receives data from one of its neighbors, fuses the data with its own, and transmits the fused data to its other neighbor along the chain. Eventually, the leader node which is similar to cluster head transmits the aggregated data to the sink.

Grid-Based Data Aggregation

Vaidhyanathan *et al.* [18] have proposed two data-aggregation schemes which are based on dividing the region monitored by a sensor network into several grids. They are: grid-based data aggregation and In-network data aggregation. In grid-based data aggregation, a set of sensors is assigned as data aggregators in fixed regions of the sensor network. The sensors in a particular grid transmit the data directly to the data aggregator of that grid. Hence, the sensors within a grid do not communicate with each other.

In-network:

In-network aggregation is a well known technique to achieve energy efficiency when propagating data from information sources (sensor nodes) to multiple sinks. The main idea behind in-network aggregation is that, rather than sending individual data items from sensors to sinks, multiple data items are aggregated as they are forwarded by the sensor network.

Data aggregation is application dependent, i.e., depending on the target application, the appropriate data aggregation operator (or *aggregator*) will be employed. From the information sink's point of view, the benefits of in-network aggregation are that in general it yields more manageable data streams avoiding overwhelming sources with massive amounts of information, and performs some filtering and preprocessing on the data, making the task of further processing the data less time and resource consuming. Because of its well-known power efficiency properties, in-network aggregation has been the focus of several recent research efforts on sensor networks. As a result, a number of data aggregation algorithms and data base systems targeting different sensor network scenarios have been proposed [2, 8, 9, 10, 11, 12, 13, and 14].

VII. STRUCTURE FREE DATA AGGREGATION

In structure free data aggregation we do not maintain any structure. This method is very useful in event based application where event region changes very frequently. In structure free environment we don't have to reconstruct the structure at the time of node failure or the changing of event region.

There are two main challenges in performing structure free data aggregation. First, as there is no pre constructed structure, routing decisions for the efficient aggregation of packets need to be made on-the-fly. Second, as nodes do not explicitly know their upstream nodes, they cannot explicitly wait on data from any particular node before forwarding their own data.

The benefit of this approach is that we don't have to maintain the structure all the time whereas in structured environment we have to reconstruct the structure at the time of when some nodes fail due to energy failure. The first work about the structure free data aggregation can be found in [19]. First, the authors observe that packets need to be aggregated early on their route to the sink for efficiency. Based on this observation, they propose and model a MAC layer protocol for spatial convergence called Data-Aware Anycast (DAA). Second, they observe that, if some nodes wait for other nodes to send data, it can lead to efficient aggregation. They study the impact of Randomized Waiting (RW) for improved data aggregation. In DAA a source node sends the RTS packet to all of its neighbors with RTS it also attach the type of data it has sensed. After receiving the RTS only those neighbor nodes send CTS packet that have same type of data. After receiving the CTS from more than one neighbor, source node selects only one of them according to instantaneous channel condition. DAA is based on MAC layer any casting where we have the situation to select only one next hope among many. DAA improves the performance of data aggregation in comparison to structured approaches. If we use DAA with the RW it further improves the performance.

VIII. SECURITY ISSUES IN DATA AGGREGATION

In the data aggregation of WSN, two security requirements, confidentiality and integrity, should be fulfilled. Specifically, the fundamental security issue is data confidentiality, which protects the sensitive transmitted data from passive attacks, such as eavesdropping. Data confidentiality is especially vital in a hostile environment, where the wireless channel is vulnerable to eavesdropping.

Though there are plenty of methods provided by cryptography, the complicated encryption and decryption operations, such as modular multiplications of large numbers in public key based cryptosystems, can use up the sensor's power quickly [22]. The other security issue is data integrity, which prevents the compromised source nodes or aggregator nodes from significantly altering the final aggregation value [23].

IX. CONCLUSIONS

We have presented a comprehensive survey of data aggregation algorithms in wireless sensor networks. All of them focus on optimizing important performance measures such as network lifetime, data latency, data accuracy and energy consumption. Efficient organization, routing and data aggregation tree construction are the three main focus areas of data aggregation algorithms. The modeling tells us that whether the sources are clustered near each other or located randomly, significant energy gains are possible with data aggregation. These gains are greatest when the number of sources is large, and when the sources are located relatively close to each other and far from the sink. The modeling, though, also seems to suggest that aggregation latency could be non-negligible and should be taken into consideration during the design process.

Data-centric architectures such as directed diffusion should support a Type of Service (TOS) facility that would permit applications to effect desired tradeoffs between latency and energy. An efficient verification scheme is proposed to protect the authenticity of the temporal variation patterns in the aggregation results.

Compared with the existing secure aggregation schemes, our scheme only need to check a small portion of aggregation results in a time window and, thus, greatly reduces the verification cost. We define representative points and propose corresponding algorithms for representative point selection. By exploiting the spatial correlation among the sensor readings in close proximity, a series of security mechanisms are also proposed to protect the sampling procedure.

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