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Survey on Data Aggregation Techniques for Wireless Sensor Networks

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Abstract: Wireless sensor networks (WSNs) consist of sensor nodes. These networks have huge application in habitat monitoring, disaster management, security and military, etc. Wireless sensor nodes are very small in size and have limited processing capability and very low battery power. This restriction of low battery power makes the sensor network prone to failure. Data aggregation is a very crucial technique in WSNs. Data aggregation helps in reducing the energy consumption by eliminating redundancy. This work focuses on summarizing various approaches used for the purpose of data aggregation and its various energy-efficient uses in WSN.

Keywords: Wireless Sensor Networks, Data Aggregation, Co-relation, Scale free aggregation.

I. INTRODUCTION

Data aggregation is the process of collecting and aggregating the useful data.Data aggregation is considered as one of the fundamental processing procedures for saving the energy. In WSN, data aggregation is an effective way to save the limited resources. The main goal of data aggregation algorithm is to gather and aggregate data in an energy efficient manner so that network lifetime is enhanced. Wireless sensor networks have limited computational power, limited memory and battery power, hence increased complexity for application developers which results in applications that are closely coupled with network protocols. In this paper, a data aggregation framework for wireless sensor networks is presented along with a survey on various energy-efficient algorithms for data aggregation. The framework works as a middleware for aggregating data measured by the number of nodes within a network.

(i) Data Aggregation: An Overview

The data aggregation is a technique used to solve the implosion and overlap problems in data centric routing. Data coming from multiple sensor nodes is aggregated as if they are about the same attribute of the phenomenon when they reach the same routing node on the way back to the sink. Data aggregation is a widely used technique in wireless sensor networks. The security issues, data confidentiality and integrity, in data aggregation become vital when the sensor network is deployed in a hostile environment. Data aggregation is a process of aggregating the sensor data using aggregation approaches.

(ii) The Need for Data Aggregation

Sensor nodes are deployed in remote environments to a multi-hop WSN over a wide range of area. Very rarely do the users have global information on the sensor nodes' distribution. That is why when users request state-based sensor readings of the attributes like temperature and humidity in an arbitrary area, networks may suffer the unpredictable heavy traffic. This problem needs data aggregation to comply with user requirements and manage overlapped aggregation trees of multiple users efficiently. Many practical applications like environmental monitoring, military applications, scientific research etc., are exploring the use of WSNs. Such applications require transferring a huge amount of relevance, sensed data from one point of the network to another. Since WSNs are mostly equipped with low power batteries, battery life is a major constraint in any real-time application. This necessitates the use of energy efficient data dissemination protocols for aggregation of the sensed data. Nodes of a WSN in close proximity usually hold similar data due to a property called spatial correlation.

Energy is therefore wasted when the same data value from multiple sources is individually routed to the sink. It is desirable to process as much data locally as possible so as to reduce the number of bits transmitted in the air, particularly over a long distance. It is a known fact that, transmitting 1 KB of data a distance of 100 m [13] costs the same amount of energy as executing 300 million instructions on a general purpose processor with a modest computing device rate of 100 million instructions per second (MIPS). In an ideal data aggregation scheme, each sensor should be spending the same amount of energy in each data gathering round.

A data aggregation scheme is energy efficient if it maximizes the functionality of the network. If we assume that all sensors are equally important, we should minimize the energy consumption of each sensor. As soon as a query is sent by the BS to a sensor, the first step followed is to handle the query. This is followed by data collection from sources and aggregation of that data.

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II. TYPES OF DATA AGGREGATION

Network Data aggregation is of two types:

- Address-centric (AC) and
- Data-centric (DC).

a) Address-centric (AC)

In AC routing protocol [2], query is routed to a specific address or a given sensor based on the address specified in the query. Each source independently Address Centric Routing sends data along the shortest path to sink ("end-to-end routing"). Data is then sent from this specific location to the BS. The source with the address specified in the query, sends its data directly to the BS.

b) Data-centric (DC)

However, in DC routing [2], based on the condition specified in the query, all sensors satisfying that condition, need to respond and therefore, the query is broadcast to all the nodes (within range) in the network. In Figure 2.4, we observe that packets are combined from neighboring nodes satisfying a given condition are combined at the cylindrical node, before being sent to the BS. This is defined as in-network processing of data. The cylindrical nodes perform data aggregation before sending the final data packet to BS. By employing data aggregation, redundant data are removed before being sent to the BS thus contributing to substantial savings in the energy and the bandwidth. The sources send data to the sink, but routing nodes en-route can look at the content of the data and perform aggregation on multiple input packets.

III. DATA AGGREGATION TECHNIQUES

Based on the nature of the network, data aggregation can be done via data aggregation tree (DAT for flat networks) or by a clustering strategy for hierarchical networks. In flat network architecture, all nodes are equal and connections are set up between nodes that are within each other's radio range, although constrained by connectivity conditions and available resources. In a hierarchical network, all nodes typically function both as switches/routers, with one node in each cluster being designated as the cluster head (CH). The number of tiers within a hierarchical network can vary according to the number of sensor nodes. Traffic between nodes of different clusters must always be routed through their respective CHs or via gateway nodes that are responsible for maintaining connectivity among neighboring CHs. Although the hierarchical network architecture is energy efficient for collecting and aggregating data from the entire WSN or all nodes within a larger target region, using knowledge of their relative locations, flat network architecture is suitable for transferring data between source-destination pairs separated by a large number of hops.

Data-diffusion is suitable for flat networks. A very common architecture used for data aggregation in flat networks is DAT. It begins with the route discovery phase when a designated node is selected as the root of the DAT and nodes in turn join the existing nodes of the DAT (also called parents) to construct the tree. A single network flow is assumed where a single data sink attempts to gather information from a number of data sources in the WSN. Data is collected from sources in proximity, aggregated at the parent nodes till it reaches the final aggregation point, i.e., the root node. With a DAT, a lower marginal energy cost is required in connecting additional sources to the sink along the shortest distance from the source to the DAT. Key Points in data aggregation are as follows:

- Nodes sense attributes over the entire network and route to nearby nodes.
- Node can receive different versions of same message from several neighboring nodes.
- Communication is usually performed in the aggregate.
- Neighboring nodes report similar data.
- Combine data coming from different sources and routes to remove redundancy.

There exists some research to study the correlation in WSN. In [3], [4], [5], the theoretical aspects of the correlation are explored in depth. Basically, these studies aim to find the optimum rate to compress redundant information in the sensor observations. More recently, in [6], the relation between spatiotemporal bandwidth, distortion, and power for large WSNs has been investigated.

a) Spatio-temporal correlation

In [7], Vuran et al. have proposed a theoretical framework to model the spatial and temporal correlations in WSN. Important key elements have been investigated to exploit the correlation in the WSN for the development of efficient communication protocols. In this paper, the authors show that the spatio-temporal correlation among the sensor observations is another significant and unique characteristic of the WSN which can be exploited to drastically enhance the overall network performance. Authors characterize the correlation in the WSN as follows:

- **Spatial correlation.** Typical WSN applications require spatially dense sensor deployment in order to achieve satisfactory coverage. As a result, multiple sensors record information about a single event in the sensor field. Due to high density in the network topology, spatially proximal sensor observations are highly correlated with the degree of correlation increasing with decreasing internode separation.
- **Temporal correlation**. Some of the WSN applications such as event tracking may require sensor nodes to periodically perform observation and transmission of the sensed event features. The nature of the energy-radiating physical phenomenon constitutes the temporal correlation between each consecutive observation of a sensor node. The degree of correlation between consecutive sensor measurements may vary according to the temporal variation characteristics of the phenomenon. In addition to the collaborative nature of the WSN, the existence of above mentioned spatial and temporalcorrelations bring significant potential advantages for the development of efficient communication protocols well-suited for the WSN paradigm.

The main goal of the proposed framework in [7] is to enable the realization of efficient communication protocols that can exploit spatial and temporal correlations of the WSN paradigm. Based on the proposed framework, authors have discussed possible approaches to exploit these advantageous intrinsic features of WSN for efficient medium access and reliable event transport.

b) Scale Free Aggregation in Sensor Networks

Extensive research has been done on in-network aggregation for WSNs over the last few years [5,8,9]. In [10], Enachescu et al. have shown that a very simple opportunistic aggregation scheme can be achieved with near optimum performance under widely varying scales of correlation. It is called Opportunistic aggregation scheme because data from a sensor to the central agent is always sent over a shortest path. In this model, authors formalize a notion of correlation that can vary according to a parameter k. Then they relate the expected collision time of "nearby" walks on the grid to the optimum cost of scale-free aggregation. They also propose a very simple randomized algorithm for routing information on a grid of sensors that satisfies the appropriate collision time condition. Thus, they prove that this simple scheme is a constant factor approximation (in expectation) to the optimum aggregation tree simultaneously for all correlation parameters k. The key contribution in randomized analysis is to bound the average expected collision time of non-homogeneous random walks on the grid, i.e. the next hop probability depends on the current position

An ideal setting of sensor nodes has been considered, i.e., sensors arranged on an N X N grid. The central agent or the base station is assumed to be located at the origin (0, 0). The transmitting power of the sensors has been assumed to be limited such that each sensor node can communicate only with its four neighbors on either side of the grid. Spatial correlation has been modeled by assuming that each sensor can record the information in a K x K square. K is referred to as the correlation parameter that can depend on the intensity of the information being sensed. For example, a volcanic eruption might be recorded by many more sensors and would correspond to a much higher K than a campfire. The proposed opportunistic aggregation algorithms are expected to work well simultaneously for a wide range of correlation parameter.

c) Impact of Network Density on Data Aggregation in WSNs

In-line data aggregation is essential for WSNs where the energy resources are limited. In [11,17], Intanagonwiwat et al. have proposed a so-called greedy aggregation scheme. This is a novel approach that adjusts aggregation points to increase the amount of path sharing, reducing energy consumption. The greedy aggregation differs from opportunistic aggregation in path establishment and maintenance. To construct a greedy incremental tree, a shortest path is established for only the first source to the sink whereas each of the other sources is incrementally connected at the closest point on the existing tree.

In this greedy approach, each exploratory sample also contains an energy cost for delivering this sample from the source to the current node. In addition, each source of the existing tree (i.e., a source on an established path) also generates an on-tree incremental cost message which corresponds to each new exploratory sample received. The incremental cost message contains the incremental energy cost required for delivering the corresponding exploratory sample of the existing tree. This incremental cost message is only sent and updated along the aggregation tree toward the sink. To find the closest point on the tree, the incremental energy-cost field can be updated only by closer nodes (i.e., nodes which have received the corresponding exploratory sample at lower cost). In this greedy approach, the most preferred neighbor to reinforce is a neighbor, which has delivered the exploratory sample or its corresponding incremental cost message at the lowest energy cost.

The results presented in [11] suggest that greedy aggregation can achieve up to 45% energy savings over opportunistic aggregation in high-density networks without adversely impacting latency or robustness.

d) An Ultra-Low Power And Distributed Access Protocol For Broadband Wireless Sensor Networks

In [12], Zhong et al. have presented an ultra-low power MAC scheme. Energy saving is achieved by turning off the radio whenever it is not receiving or transmitting. This scheme does not try to reduce the data redundancy. Instead, it takes the advantage of the redundancy built in the network in that, it allows the destination to recover the lost data packets based on the data it receives from the neighborhood of the original sender. The authors propose that due to the high spatial correlation between neighboring sensors' data and high temporal correlation of every sensor node, it is possible for the receiver to recover the original information from the vast data available. Therefore, acknowledgements can be totally eliminated. A simple error detection code can be used at the transport level to allow the destination to detect the error. The results presented in the paper show that by removing the acknowledgements at link level, a saving of at least 304 bits (per data packet) can be achieved. Although this scheme works well to reduce the number of bits transmitted considerably, it does not check the flow of redundant packets in the network.

e) On the Interdependence of Routing and Data Compression in MultiHop Sensor Networks

In [5], Scaglione et al. have considered a problem of broadcast communication in a multi-hop WSN, in which samples of a random field are collected at each node of the network, and the goal is for all nodes to obtain an estimate of the entire field within a prescribed distortion value. The proposed scheme involves compression of the data generated by different nodes as this information travels over multiple hops. This helps in eliminating correlations in the representation of the sampled field. The main contributions of this paper to construct a large class of physically-motivated stochastic models for sensor data, for which we are able to prove that the joint rate/distortion function of all the data generated by the whole network grows slower than the bounds. Joint routing and source coding has been introduced to reduce the amount of traffic generated in dense WSNs with spatially correlated records.

f) Spatio-Temporal Sampling Rates and Energy Efficiency in Wireless Sensor Networks

While the proposed scheme works well to reduce the number of transmitting bits, the number of transmitting packets remains unchanged, which can be minimized by regulating the network access based on the spatial correlation. The relation between spatial and temporal sampling rate on the overall network delay and energy consumption has been studied in [13].

Bandyopadhyay et al. [13] have proposed a transmission-scheduling scheme that completely eliminates collisions at the MAC layer. This helps in avoiding energy wastage due to retransmission of data due to collisions. This paper addresses an important issue in the design of such networks: determining the spatio-temporal sampling rate of the network under conditions of minimum energy usage. A new collision-free protocol for gathering sensor data is used to obtain analytical results that characterize the tradeoffs among sensor density, energy usage, throughput, delay, temporal sampling rates and spatial sampling rates in wireless sensor networks. The authors also show that the lower bound on the delay incurred in gathering data is $O(k^2n)$ in a clustered network of n sensors with at most hops between any sensor and its cluster head (CH). Simulation results on the tradeoff between the achievable spatial sampling rates and the achievable temporal sampling rates when IEEE 802.11 distributed coordination function (DCF) is used as the media access scheme are provided and compared with the analytical results obtained in this paper. The proposed transmission-scheduling scheme exploits spatial reuse in the wireless media. However, the spatial and temporal correlation between sensor observations has not been investigated.

g) Spatial and Temporal Multi-Aggregation for State-Based Sensor Data in Wireless Sensor Networks

In [14], spatial and temporal multiple aggregation (STMA) scheme has been proposed to minimize energy consumption and traffic load when a single or multiple users gather state-based sensor data from various sub-areas through multi-hop paths. Spatial aggregation has been exploited in this scheme. An aggregation tree is created with an optimal intermediary between a target area and a sink. Temporal aggregation uses the interval so that users obtain an appropriate amount of data they need without suffering the excess traffic. The performance of STMA has been evaluated in terms of energy consumption and area-to-sink delay.

In this paper, we address the problem of aggregation to alleviate the traffic load when multiple sinks request diverse specifications. We propose spatial and temporal multiaggregation (STMA), where multiple remote sinks ask for sensors in a specific area to send the aggregated data through the multi-hop path at their desired intervals. Two different aggregation schemes, spatial aggregation and temporal aggregation, are combined and used in STMA. In spatial aggregation, data of sensor nodes in the specified area called target area (TA), are aggregated along an aggregation tree (A-tree) having an A-tree root (AR) as the top node. AR send the aggregated result to sink that ask for data from TA. In temporal aggregation, a sensor aggregates its own raw data during the time the sink specifies and it generates the aggregated result. It prevents sensor nodes from generating data too frequently and makes them comply with intervals that the users request. STMA finds an optimal AR among the sensor nodes in TA. For multiple sinks, the aggregation result of sensor nodes in the area shared with other sinks' TAs is reused and redundant links are removed from the trees. It is called multi-aggregation in this paper and alleviates traffic load.

h) HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad-hoc Sensor Networks

An energy-efficient hierarchical data aggregation protocol, HEED has been proposed by Younis et al. in [15]. The authors have assumed that multiple power levels are available at sensor nodes. A cluster head (CH) is selected on the basis of the node residual energy. Another factor that is counted while selecting the CH is the node proximity to its neighbors. This parameter has been referred to as the node degree. Communication cost is estimated on the basis of average minimum reachability power (AMRP), which is defined as the average of the minimum power levels required by all nodes within the cluster range to reach the CH. CHs are probabilistically selected based on the AMRP and residual energy. From the set of tentative CHs, a node with lowest AMRP is chosen as the CH. After which every node changes its probability PCH of becoming the CH to min (2 (PCH), 1) in the next iteration. The iterations are continued until every node is assigned to a CH. One drawback of HEED is that it does not address inter cluster communication.

i) Using Polynomial Regression for Data Representation in Wireless Sensor Networks

Banerjee et al. [1] have proposed a Tree based polynomial REGression algorithm, (TREG) that addresses the problem of energy-efficient data aggregation in WSNs. Multiple attribute-based binary trees called query trees are created first. There are two types of nodes in the network: Nodes that are part of query tree and nodes that are not part of query tree. Nodes that are part of query tree are called tree nodes and nodes that are not connected to tree nodes are called sensing nodes. After the trees are created, sensing nodes send the recorded data values to the nearest tree nodes. Each tree node, then runs a regression function to find a polynomial in the space coordinates (x, y) such the sensed values fit in the polynomial. Instead of sending the raw data, tree nodes send the coefficients of the polynomial function to a higher level. A new regression polynomial is found at each higher level using the coefficients sent by the children nodes and values reported by sensing nodes. The approximation function, thus gets improved at each level and this procedure stops at the root. At the end of regression the sink has an approximation function f (x, y) for the attribute value as a function of space coordinates. This scheme scales well with the growing network density. Since each tree node transfer only the coefficients of polynomial in the data packet, data packet size remains the same for all tree nodes. This helps in significant energy savings. This thesis is based on the TREG algorithm, which has been discussed in detail in the next chapter.

j) READA: Redundancy Elimination for Accurate Data Aggregation in Wireless Sensor Networks

In this paper, a novel data aggregation algorithm called Redundancy Elimination for Accurate Data Aggregation (READA) has been proposed [22]. By exploiting the range of spatial correlations of data in the network, READA applies a grouping and compression mechanism to remove duplicate data in the aggregated set of data to be sent to the base station without largely losing the accuracy of the final aggregated data.

One peculiarity of READA is that it uses a predictive model derived from cached values to confirm whether any outlier is actually an event which has occurred. From the various simulations conducted, it was observed that in READA the accuracy of the data has been highly preserved taking into consideration the energy dissipated for aggregating the data.

k) An Energy Efficient Clustering Scheme for Data Aggregation in Wireless Sensor Networks

In author proposes a comprehensive energy consumption model for multi-tier clustered sensor networks [17, 18, 23], in which all the energy consumptions not only in the phase of data transmissions but also in the phase of cluster head rotations are taken into account. This model included the energy consumption of protocols DD, LEACH to be its special cases.

By using this new model, they are able to obtain the solutions of optimal tier number and the resulted optimal clustering scheme on how to group all the sensors into tiers by the suggested numerical method.

This algorithm is theoretically analyzed in terms of time complexity. Simulation results show that, the theoretically calculated energy consumption by the new model matches very well with the simulation results, and the energy consumption is indeed minimized at the optimal number of tiers in the multi-tier clustered wireless sensor networks.

l) An Energy Efficient Spatial Correlation Based Data Gathering Algorithm For Wireless Sensor Networks

In this paper a dual prediction algorithm is implemented along with the clustering algorithm and its performance in a clustered architecture is analyzed [20,21,24]. The clusters are formed based on the spatial correlation in the network. The main objective of this algorithm is to reduce the communication between source and sink node. The algorithm works in two phases. In the first phase the sink node collects the data from all the sensor nodes. The sink node computes the magnitude similarity and trend similarity of the sensed data from the nodes. Then the nodes are partitioned into disjoint groups or clusters using the clustering algorithm. In the second phase the sensor node transmits the data according to the schedule generated by the sink node.

During data transmission a NLMS based prediction algorithm is performed synchronously at the source and the sink. The prediction algorithm predicts the value of the sensor node based on the previous values.

If the predicted value is less than the predetermined threshold value, then the sensor node will not communicate the sensed value. If the predicted value is more than the threshold, then the sensor node communicates the current data to the sink node. The sink node instead of the predicted value it updates the received value and then continues the prediction with the received value. Simulation results show that the proposed algorithm reduces the average energy consumption of the network.

m) Energy Efficient and Balanced Cluster-Based Data Aggregation Algorithm for Wireless Sensor Networks

In this paper problem of unbalanced energy dissipation in cluster based WSNs is investigated [25]. This paper addresses this problem in cluster-based and homogeneous WSNs in which cluster heads transmit data to base station by one-hop communication. In this paper author proposes an energy efficient and balanced cluster-based data aggregation algorithm (EEBCDA).

The operation of EEBCDA is also divided into rounds and every round consists of a set-up phase and a steady-state phase, especially, there is a network-division phase before the first round.

The network is divided into rectangular regions firstly, called swim lanes, then, each swim lane is further partitioned into smaller rectangular regions, called grids. The node with the maximal residual energy of each grid is selected as CH.

The grids further away from BS are bigger and have more nodes to participate in CHs rotation. It divides the network into rectangular grids with unequal size and makes cluster heads rotate among the nodes in each grid respectively, the grid whose cluster head consumes more energy has more sensor nodes to take part in cluster head rotation and share energy load, by this way, it is able to balance energy dissipation. Besides, it adopts some measures to save energy.

The results of the simulation show that EEBCDA can remarkably enhance energy efficiency, balance energy dissipation and prolong the network lifetime.

Algorithm	Routing Protocol	Latency	Energy Efficiency	Accuracy
Spatio-temporal correlation	Cluster based	Yes	High	High
Scale Free Aggregation	Cluster based	No	High	High
Impact of Network Density on Data Aggregation	Tree based	No	Medium	Medium
An Ultra-Low Power And Distributed Access Protocol	Cluster based	Yes	High	High
Interdependence of Routing and Data Compression	Multihop based	No	High	Medium
Spatio-Temporal Sampling Rates	Cluster based	Yes	Medium	Medium
Spatial and Temporal Multi-Aggregation	Multihop based	No	Medium	Medium
A Hybrid, Energy-Efficient, Distributed Clustering	Hybrid	No	High	Low
polynomial regression for data representation	Tree based	Yes	High	Medium
Redundancy Elimination for Accurate Data Aggregation	Cluster based	No	Low	High
An Energy Efficient Clustering Scheme for Data Aggregation	Cluster based	No	High	Medium
An Energy Efficient Spatial Correlation Based Data Gathering	Cluster based	No	High	Medium
Energy Efficient and Balanced Cluster-Based Data Aggregation	Cluster based	No	High	High

Table I: Comparitive Study Of Data Aggregation Algorithm

IV. CONCLUSION

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. We have described the main features, the advantages and disadvantages of each data aggregation algorithm shown in table I.

REFERENCES

[1] T. Banerjee, K. Choudhury and D. P. Agrawal, “Using Polynomial Regression for Data Representation in Wireless Sensor Networks,” in Special Issue of Wiley International Journal of Communication Systems on Energy-Efficient Network Protocols and Algorithms for Wireless Sensor Networks, 2006.

[2] K. Sohrabi, J. Gao, V. Ailawadhi and G. J. Pottie, “Protocols organization of a wireless sensor network,” in Proceedings of IEEE Personal Communications, 7(5), 16–27 (October 2000)

[3] M. Gastpar and M. Vetterli, “Source-channel communication in sensor networks,” in Proceedings of 2nd Int. Workshop on Information Processing in Sensor Networks (IPSN’03), vol. 219, pp. 162–177, 2003.

[4] S. S. Pradhan, J. Kusuma, and K. Ramchandran, “Distributed compression in a dense microsensor network,” IEEE Signal Process. Mag., vol. 19, no. 2, pp. 51–60, Mar. 2002.

[5] A. Scaglione and S. D. Servetto, “On the interdependence of routing data compression in multi-hop sensor networks,” in Proc. ACM MobiCom, Atlanta, GA, Sep. 2002, pp. 140–147.

[6] M. Gastpar and M. Vetterli, “Power, spatio-temporal bandwidth, and distortion in large sensor networks,” IEEE J. Sel. Areas Commun., vol. 23, no. 4, pp. 745–754, Apr. 2005.

[7] M. C. Vuran, O. B. Akan, I. F. Akyildiz, "Spatio-Temporal Correlation: Theory and Applications Wireless Sensor Networks,"

[8] Computer Networks Journal (Elsevier Science), vol. 45, no. 3, pp. 245 -259, June 2004

[9] B. Krishnamachari, D. Estrin and S . B. Wicker, “The Impact of Data Aggregation in Wireless Sensor Networks,” ICDCS Workshop on Distributed Event-based Systems (DEBS), 2002

[10] C. Intanagonwiwat, R. Govindan, D. Estrin, J. S. Heidemann, and F. Silva, “Directed diffusion for wireless sensor networking”, IEEE/ACM Transactions on Networking, vol. 11, no. 1, p. 2-16, 2003

[11] M. Enachescu, A. Goel, R. Govindan and R. Motwani, “Scale Free Aggregation in Sensor Networks,” Preprint submitted to Elsevier Science 24 January 2006.

[12] C. Intanagonwiwat, D. Estrin, R. Govindan and J. Heidemann, “Impact of Network Density on Data Aggregation in Wireless Sensor Networks,“ University of Southern California, Information Sciences Institute

[13] L. Zhong, R. Shah, C. Guo, and J. Rabaey, “An ultra-lowpower and distributed access protocol for broadband wireless sensor networks,” presented at the Networld + Interop: IEEE Broa dband Wireless Summit, Las Vegas, NV, May 2001.

[14] S. Bandyopadhyay and E. J. Coyle, “Spatio-temporal sampling rates and energy efficiency in wireless sensor networks,” in Proc. IEEE INFOCOM, Mar. 2004, vol. 3, pp. 1728–1739

[15] H. S. Kim and W. H. Kwon, “Spatial and Temporal Multi-Aggregation for State-Based Sensor Data in Wireless Sensor Networks,” Telecommunication Systems, Springer Netherlands Volume 26, Numbers 2-4 / June, 2004 161-179

[16] O. Younis and S. Fahmy, “HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc se nsor networks,” in Proceedings of IEEE Transactions on Mobile Computing, vol .3 , no. 4, Dec 2004, pp. 366-79.

[17] N. Jain, S. Gupta, and P. Sinha, “Clustering Protocols in Wireless Sensor Networks: A Survey,” Int. J. Appl. Inf. Syst., vol. 5, no. 2, pp. 41–50, 2013.

[18] S. Gupta, N. Jain, and P. Sinha, “Node Degree based Clustering for WSN.,” Int. J. Comput. Appl., vol. 40, no. 16, pp. 49–55, 2012.

[19] N. Rathore, P. Gour, and B. Meena, “Improved Clustering Protocol for Delay Minimization,” Int. J. Comput. Networking, Wirel. Mob. Commun., vol. 3, no. 5, pp. 41–48, 2013.

[20] S. Gupta, N. Jain, and P. Sinha, “A density control energy balanced clustering technique for randomly deployed wireless sensor network,” … Networks (WOCN), 2012 Ninth …, pp. 1–5, 2012.

[21] S. Gupta, N. Jain, and P. Sinha, “Energy Efficient Clustering Protocol for Minimizing Cluster Size and Inter Cluster Communication in Heterogeneous Wireless Sensor Network,” Int. J. Adv. Res. Comput. Commun. Eng., vol. 2, no. 8, pp. 3295–3305, 2013.

[22] K. Khedo, R. Doomun and S. Aucharuz, “READA: Re- dundancy Elimination for Accurate Data Aggregation in Wireless Sensor Networks,” Wireless Sensor Network, Vol. 2, No. 4, 2010, pp. 302-308.

[23] Meng, Jin-Tao, Jian-Rui Yuan, Sheng-Zhong Feng, and Yan-Jie Wei. "An Energy Efficient Clustering Scheme for Data Aggregation in Wireless Sensor Networks." Journal of Computer Science and Technology 28, no. 3 (2013): 564-573.

[24] Tharini, C., Vanaja Ranjan, P.: An Energy Efficient Spatial Correlation Based Data Gathering Algorithm for Wireless Sensor Networks. International Journal of Distributed and Parallel Systems 2(3), 16–24 (2011)

[25] Yuea, Jun, Weiming Zhang, Weidong Xiao, Daquan Tang, and Jiuyang Tang. "Energy efficient and balanced cluster-based data aggregation algorithm for wireless sensor networks." Procedia Engineering 29 (2012): 2009-2015.