IJMTST | Volume: 2 | Issue: 06 | June 2016 | ISSN: 2455-3778

Communication Cost Reduction by Data Aggregation: A Survey

Nithin Kumar[1] | Nagarathna[2]

[1]M.Tech Scholar, Department of CS&E, P.E.S College of Engineering, Mandya, Karnataka, India
[2]Associate Professor, Department of CS&E, P.E.S College of Engineering, Mandya, Karnataka, India

ABSTRACT

Wireless Sensor Networks have gained wide popularity in the recent years for its high-ranking applications such as remote environment monitoring, target tracking, safety-critical monitoring etc. However Wireless Sensor Networks face many constraints like low computational power, small storage, and limited energy resources. One of the important issues in wireless sensor network is to increase the network lifetime to keep the network operational as long as possible. In this survey paper, we provide a comprehensive review of the existing literature on techniques and protocols for data aggregation to reduce communication cost and increase network lifetime in wireless sensor networks.

KEYWORDS: *Data Aggregation, Wireless Sensor Network, Communication cost, Energy Efficiency.*

I. INTRODUCTION

A wireless sensor network (WSN) is a group of sensors nodes (transducers) that are deployed across a geographical area for regulating and monitoring that area for physical phenomena's like sound, temperature, particular events and so on. Typically a sensor is a small device that consists of three main components such as, *sensing subsystem* which is responsible for data acquisition from the environment in which sensor is deployed to work, *processing subsystem* which is responsible for local data processing and storage within that sensor node,*wireless communication system* is responsible for data transmission.

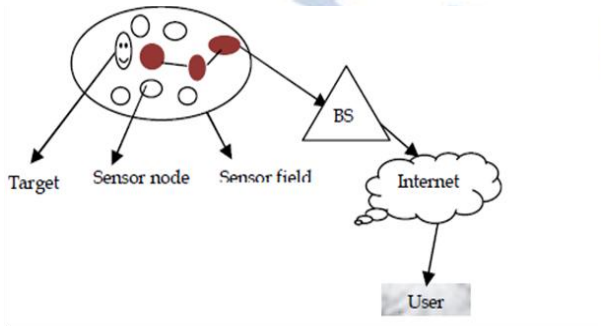

Fig 1:- Sensor Network Architecture

On the other hand, a wireless sensor network should possess long lifetime so that it can fulfill the requirement of deploying it, so it may take several days or months or even it may take years together to fulfill the requirement of deploying it. Therefore energy conservation is a key constraint in the design issue of system's based on wireless sensor networks.

Experimental measures have shown that generally communication cost is very high in terms of energy consumption compared to data processing [1], is that the communication cost for transmitting a bit of information is exactly the same energy required for processing thousands of instructions in a sensor node [2]. Therefore the lifetime of a wireless sensor network (WSN) can be extended by applying some sort of techniques on two subsystems that reduces the energy consumption that are, *network subsystem* in which energy consumption was taken into account on the operation's performed on a sensor node by using some networking protocols, *sensing subsystem* in which energy consumption was taken into account by reducing the amount and frequency of high energy expensive samples. The lifetime of WSN can be extended by applying different techniques [3], for example energy management protocols are applied on nodes during data transmission to

reduce energy consumption, similarly some nodes consume more energy even in idle state so for that sort of energy consumptions, power management schemes are used for switching off node components that are not needed for particular processing.

In this survey paper we majorly focus on reducing communication cost by data aggregation and data management, these techniques allows us to trade-off communication for computational complexity in any application area and in fact when compared to communication cost, the local computation consumes less power.

Data aggregation and data management are the most important part of network research in which available resource efficiency, timely delivery of computational results, accuracy of obtained results are conflicting goals, and all these mainly depends on the application so its application specific. Basically, in data aggregation techniques consists of different methods to route all packets in order to combine the data coming from different sources but combined data will be forwarded into same destination.

The main aim of this survey paper is to provide an overview of data aggregation by defining the main concepts and most important and recent work in field of reducing communication cost in wireless sensor networks (WSNs), and on other hand to recognize and propose directions for future research in this area. The survey paper is organized as follows. In Section II we explain general approaches that are available for reducing energy consumption in WSNs. In Section III we describe data aggregation paradigm to classify existing algorithms. In Section IV we introduce some network protocols with data aggregation and classify existing solutions. In Section V finally we summarize the different data aggregation approaches discussed throughout the survey paper and provide the directions and motivations of future research work in this area.

II. General Approaches to Energy Conservation

Before representing a high-level classification of energy conservation proposals, we should know about network and node-level architecture.

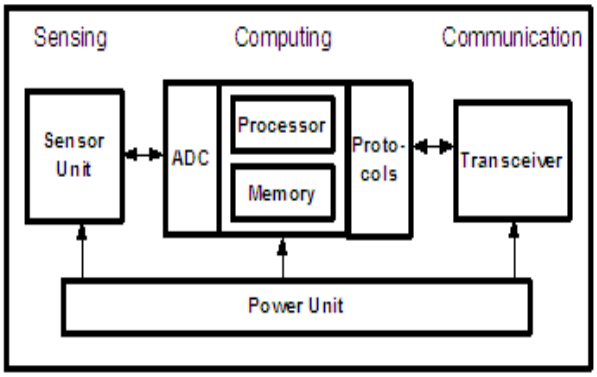

Fig 2: Represents the Architecture of typical Wireless Sensor Node.

Basically it is composed of four main components such as, *sensing subsystem* includes one or more sensors for data acquisition, *processing subsystem* includes a microcontroller and small amount of memory for local data processing, *radio subsystem* for wireless data transmission, *power supply unit* which will be based on specific application and it may include location search system and mobilizer to change their location and so on.

The radio subsystem consumes more energy than the processing subsystem. It has been shown that transmitting a bit consumes more power than executing thousands of instruction [2]. The radio energy consumption is of same order in receiving, transmitting, and even in idle states, so whenever energy drops, therefore the radio should be put into sleep or turned off whenever possible. The sensing subsystem may consume more energy depending on applications, it's an application specific constraint so it should be taken care.

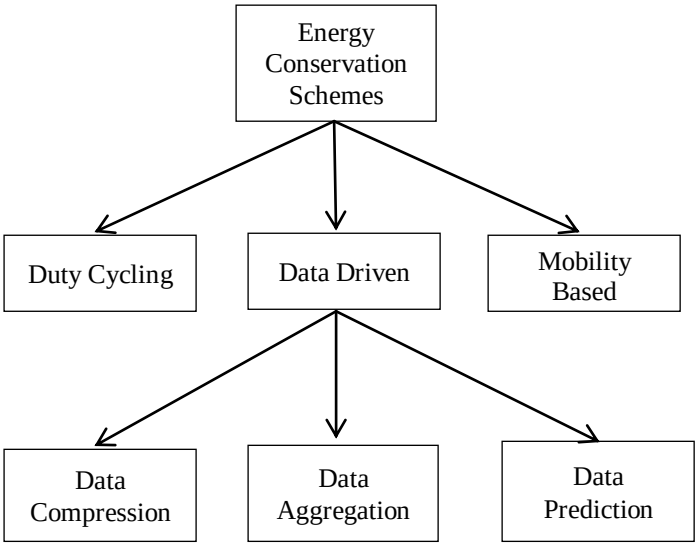

Fig 3: Hierarchy of Energy Conservation Schemes

A. Duty cycling is an approach of energy conservation in which, a sensor is switched to low power sleep mode, whenever communication is not required that is, if there is no data to send/receive. Sensor should be resumed as soon as new data becomes available. In this survey paper we won't concentrate on these sort of techniques, so interested readers can refer the papers [4], [5], [6], [7], [8].

B. Mobility based schemes in which mobile nodes can be divided into two categories such as, *part of network infrastructure* and *part of environment*. Whenever the mobility nodes are part of infrastructure their mobility can be fully controlled and customized. When nodes are part of environment they are not controllable. Finally mobile nodes may follow a mobility pattern that is neither predictable nor completely random. In this survey paper we strictly concentrating on data aggregation to reduce communication cost, so mobility is not discussed here, interested readers can refer the papers [9], [3], [10], [11].

C. Data driven approaches can be classified into two subclasses such as, *data reduction*, which aims to reduce the unneeded samples, and *energy efficient data acquisition* is an approach that mainly concentrates on energy spent by sensing subsystem. *Data compression* is a part of data reduction in data driven approaches in which the compression can be applied to reduce the amount of data sent from source node. *Data prediction* is a approach of developing an abstraction of sensed data, i.e. a model that defines the data that may evolve, and the model can predict the data sensed by sensor nodes.

In this survey paper we mainly concentrate on data aggregation approach of data driven so that interested readers about data compression and prediction can refer the following papers for more details about that [12], [13], [14], [15]. Basically data aggregation is an technique of aggregating data (computing average) at intermediate node between the source node and sink, so that the amount of data is reduced while transmission, in this way communication cost can be reduced by using data aggregation.

III. Data Aggregation Paradigm

Basic scenario of WSNs is the data collected from different sensor nodes, which will be made available in sink node, at sink node, collected data is analyzed and processed by particular application. The data produced by different sensors can be totally processed while being transmitting towards the sink, e.g., by combining together all sensor readings related to the same event or any physical quantity, or by locally processing raw data before the transmission. Data aggregation techniques consists of, how data is collected at the sensor nodes, and how data packets are routed in the network, and have more impact on energy conservation and efficiency (e.g., by reducing transmissions or amount of data to be transmitted).Data aggregation can be complex task, since the aggregation algorithms should be distributed in the network and requires co-ordination among sensor nodes for better performance.

Data aggregation is an technique of aggregating data (computing average) at intermediate node between the source node and sink, so that the amount of data is reduced while transmission, in this way communication cost can be reduced, which in turn increase's network lifetime.

There are two common approaches of data aggregation:

- *Data aggregation with size reduction* is a process of fusing and compressing data obtained from different sources to reduce the amount of information to be transmitted in the network. As an example, assume that a node receives two packets from two different source nodes containing some readings. Instead of forwarding the two packets, the sensor may compute the average of the two readings and transmitted as a single packet.
- *Data aggregation without size reduction* is a process of combining data coming from different sources into the same data packet without processing: assume that two packets carrying different physical quantities, for e.g., sound and vibration, these two values cannot be processed together but they can be sent as a single data packet, thereby reducing communication cost and overhead.

The first approach is good one for reducing the amount of data that may be transmitted over the network, but it will reduce the accuracy, because

after applying the aggregation operation, it is not possible to reconstruct the original data successfully. The second approach, in which the accuracy of original information is maintained, but these sort of approaches usually depends on many factors including the application type, the data rate, the network properties, and so on.

In data aggregation techniques, there must be some sort of synchronization between nodes. In some cases, the bet strategy is that at a given node is not always to transmit the data as soon as it is available. Node must wait for information from neighbor node, this may lead to better data aggregation and increase in performance. Timing strategy must be required, especially in some monitoring applications where sensor node should report their data within some particular timeslot.

Based on timing strategies involved in data aggregation, it is been classified as follows:

- *Periodic simple aggregation* in which, a node must wait until predefined timeslot to aggregate all data values that it received, and then sends a summarized value of all received data within that time as a single packet.
- *Periodic per-hop aggregation* it is similar to periodic simple aggregation, but the only difference is that the aggregated value is transmitted as soon as node hears from its child nodes. This approach requires each root node to know about its child nodes.
- *Periodic per-hop adjusted aggregation* in which the time lot to send aggregated data can be adjusted based on the position of node in the tree.

The most important functionality that data aggregation techniques must provide is the ability to aggregate the data obtained from different nodes. Based on aggregation function, the data aggregation approaches can be classified as shown.

- *Lossy and lossless* in which aggregation functions is applied on amount of data information that is to be transmitted in the network. The first approach is good one for reducing the amount of data that may be transmitted over the network, but it will reduce the accuracy, because after applying the aggregation function, it is not possible to reconstruct the original data successfully. The second approach, in which the accuracy of original information is maintained, that is all of its original readings can be perfectly reconstructed from their aggregated value at receiver end.
- *Duplicate sensitive and duplicate insensitive* in data aggregation process an intermediate node may receive multiple data packets of the same information. In such case, the same data is considered multiple times during data aggregation. If the aggregation function is duplicate sensitive, the final aggregated result depends on the number of times the same value has been taken during aggregation. Otherwise, the aggregation function is duplicate insensitive.

IV. Networking Protocols for DATA Aggregation

The concepts that are discussed so far deals with transmission of data packets to facilitate data aggregation process of information. Basically, the idea is to enhance existing routing algorithms to improve the performance of data aggregation to reduce communication cost. In this survey paper we mainly focus on four classes of routing protocols such as *tree-based, cluster-based and multi-path.* In these approaches, the tree based approach is a classical approach, which consists of routing algorithm based on tree rooted at the sink node. In some cases, the tree-based structures are grouped into particular cluster based on the type of data gathered in it, to improve efficiency of data aggregation. In this survey we focus on multi-path routing, which overcomes the drawbacks of tree-based routing. Finally, some recent researcheshave been done to improve the mixture of *tree-based* and *multi-path* routing are called as *hybrid* approach to improve efficiency and adaptive nature of existing routing algorithm.

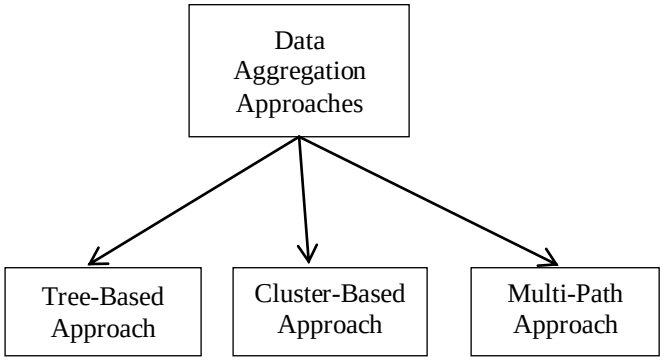

Fig 4: Different Data Aggregation Approaches

A. Tree-Based Approaches

Classic routing techniques [16], [17] are usually based on hierarchical organization of nodes in network. In tree-based approaches, the data is flowing from source node to sink node, between them selected intermediate nodes perform aggregation function on obtained data and then transmits the aggregated data in preferred direction. In tree-based approaches, a node may be selected based on some criteria's such as its position within the tree [18], its resources [19], and processing cost of aggregation [20]. In tree-based approaches, a spanning tree is constructed rooted towards the sink node, these constructed structures is exploited upon generation of queries by the sink node. This can be done by performing data aggregation along the *aggregation tree* by proceeding level by level from its leaf node to its root node. These kind of tree-based approaches have some failures, because WSNs are not always free from failures. When a data packet is lost due to some failures in tree at that level E.g., node failure, may lead to loss of data coming from related sub tree, so tree-based approaches are suitable in designing optimized aggregation function to perform energy management. Finally, a new approach that is based on tree-based routing is the construction of *connecting dominating sets* [21] which consists of selected number of nodes, they form a network in which any node can collect data from any point in network. These connecting dominating sets construction is recommended for energy balancing.

1. TAG [22]

The Tiny Aggregation (TAG) is a data centric approach, it is particularly designed for monitoring systems which produces similar information periodically. TAG approach can be classified as *periodic per-hop adjusted aggregation* approach. TAG algorithm can be implemented in two phases *distribution phase* where queries are distributed to sensors, and *collection phase* where aggregated sensor values are obtained. TAG is a tree-based approach which is rooted at sink node, the sink node broadcasts a message to nodes for the construction of tree structure, upon receiving that message every node then re-broadcasts the received message with ID (identifier) and its associated level to sink node.

The sink node sends query by specifying the attributes (attrs) and how attributes must be aggregated (agg(expr)) and the sensor nodes that should be involved in data retrieval is mentioned using WHERE, GROUPBY, HAVING clauses, and EPOCH field specifies the period of time (sec) each sensor should wait before sending its data values. During the *collection phase* in which each parent node has to wait for data to be collected from all child nodes, Upon receiving all data from child nodes it aggregated in intermediate node and transmitted to sink node.

2. DIRECTED DIFFUSION [23]

Direct diffusion is a reactive data centric approach, which is specifically designed for applications those requires specific information by flooding the network with frequent queries. There are three main phases associated with direct diffusion *interest message, gradient setup,* and *path reinforcement and forwarding*. Basically, certain sink nodes propagates interest message about the information that they are interested in collecting it from particular sensors (interest message). Each node upon receiving interest message, they re-broadcasts it to neighbor nodes. After that sensor nodes setup interest gradients that has to be used propagate results back to sink node (gradient setup). After gradient setup is complete, there will be only single path for every source node is reinforced and that path will be used to forward packets to that path will be used to forward packets towards the sink node (path reinforcement and forwarding).

3. EDGE (efficient data gathering protocol)

EDGE (efficient data gathering protocol) is a data gathering protocol, EDGE is a tree-based approach rooted towards a sink node. In EDGE protocol, deletion and addition of nodes requires the tree reconstruction. EDGE is a multi-point-to-point approach, in which every sensor node tries to send data to the sink node. In EDGE protocol, every node is added to tree structure by making *request* and *replies*. Firstly the base station broadcasts child requests (CRQ) to all nodes, then all non-members nodes replies to the request obtained from base station (CRP). Based on several metrics associated with non-member node, best among them will be selected and replied to accept child (CAC). Then the child will be joined to tree structure. EDGE protocol is best suited for applications, where new route found and reconstruction of tree is required.

4. PEGASIS[24]

Power efficient data gathering in sensor information system (PEGASIS) is more robust routing protocol in which sensor nodes are

organized in a chain. Nodes in a chain take turns to act as a chain leader, where chain leader is one and only node that is allowed to transmit data directly to the sink. In this way, it is possible to reduce communication cost in the network. PEGASIS proved to be more reliable and efficient, it is also known as chain based data aggregation algorithm. The chain construction process requires knowledge of all nodes in a network, the chain building process start with node nearer to sink, then the closest neighbor to this node is selected and so on.

Chain leader selection takes place according to following rule: let i be elected leader in round i, there are N nodes in network {1, 2….N} among them node will be selected in TDMA schedule. For this type of scheme a direct communication channel from each sensor in a network to the sink is required. In PEGASIS, each node receives data from its neighbors and aggregates with its own data and aggregated packet of some length it transmitted to next neighbor until it reaches to chain leader. At the chain leader, it includes its own data into received packet and then aggregated single packet of data is directly transmitted into the sink.

5. PEDAP

Power-efficient data gathering and aggregation protocol (PEDAP), these are data aggregation scheme based on construction of minimum spanning tree. PEGASIS and PEDAP two data aggregation algorithm with same procedure but PEDAP is the power-aware version of PEGASIS. Firstly, a node is selected as base-station after that, the tree starts to build in network of nodes with minimum weighted edge. The node that wants to transmit its values will attach to the constructed tree and transmits its data through the indicated edge. This process is repeated until all nodes get attached to tree and transmits there data through the indicated edge. The constraint that is associated with PEDAP is the sensors should be in fixed location. The sensors will sense data periodically from their associated environment and aggregate the data and transmits the aggregated values to selected base-station in round basis. This protocol can save much energy and show improved efficiency than PEGASIS.

B. Cluster-Based Approaches

Cluster-based approaches [25] [26] [27] [28] are similar to tree-based approaches, it is a hierarchical organization of network in which nodes are classified into particular cluster on types of data gathered in them. Some special nodes are selected has *cluster heads*(CH) based on some criteria's will perform aggregation function on obtained data from all nodes of particular cluster and transmits aggregated data into the sink node.

1. LEACH[25]

Low-energy adaptive clustering hierarchy (LEACH) is a cluster topology data aggregation algorithm. The important goal of this algorithm is to reduce the communication cost of data transmission from normal nodes by having cluster heads for every particular cluster, where cluster heads act as aggregator points. There are two main phase associated with LEACH protocol *setup phase* is to form clusters and *steady phase* is to transmit data to sink node. Firstly nodes will organize to form clusters, within each cluster a special node is elected as cluster head where data is aggregated which is collected from other nodes in particular cluster. The cluster head selection is based on distributed probabilistic approach for current round of data transmission.

Actual data transmission takes place in second phase in which all nodes in a cluster send their sensed data from associated environment to cluster head. The TDMA protocol is used to avoid collision among nodes in cluster during data transmission. After receiving all data from source nodes, the cluster head performs aggregation on obtained data and transmits it to sink using single direct transmission.

LEACH provides the following communication cost reduction key areas:

- No overhead in selection of cluster heads.
- TDMA protocol is used during data transmission to avoid collision.
- Minimizing communication cost of each node is calculated to communicate with its clusters.

2. DEDA

Delay-minimized energy-efficient data aggregation, DEDA is a distributed and energy-efficient data gathering algorithm with minimum delay. As power-consumption and delay are two constraints in wireless sensor networks. In this approach based on data gathered in nodes they are classified into clusters with particular cluster (CH), and nodes are cluster members (CM), and there will be data link between CH and base-station (BS).

In this approach any two same sized clusters are joined together to form bigger clusters, and the

process is repeated until clusters cannot be joined with same sized cluster. Then these joined clusters form direct connection with base station. Finally the network consists of clusters of different sizes. The straight forward scheduling algorithm is applied and each node is assigned with particular time-slot to transmit data by its rank, every node of particular cluster have different ranks with corresponding different time-slots. By using DEDA schema minimum delay can be achieved with reduction in communication cost.

C. *Multi-Path Approach*

Multi-path approaches are used to overcome the robustness problem of aggregation trees [29], [30], [31]. In aggregation trees each node sends partial result to its single parent, but in these approaches sends data over multiple paths. The main strategy of multi-path approaches is that each node can send data through its multiple neighbors by using broadcast characteristics of wireless medium. An aggregation structure used in multi-path approach is *ring topology* where nodes are distinguished into several levels according to number of hops separating them from sink node. Data aggregation will be performed on data in multiple levels towards the sink node. Multi-path approach helps to transmit duplicates of same information.

1. SYNOPSIS DIFFUSION[8]

The authors of [8] present the synopsis diffusion protocol in which data aggregation is performed through a multi-path approach. Synopsis diffusion consists of two main phases such as, *distribution of queriesphase* and *data retrieval phase.* Whenever a nodes send query over a network leads to formation of ring topology in synopsis diffusion protocol. There are two different structures to be considered in synopsis diffusion. Firstly, a simple ring structure in which during query distribution phase the network nodes form a set of rings across a query node Q. another type of topology has improvements over simple ring topology, its robust and can cope with changes in network is called as *adaptive topology.* In synopsis diffusion using one of these two topologies, the data aggregation on obtained data from nodes will be performed in multiple levels towards the sink node to reduce communication cost.

V. CONCLUSION

In this survey paper we have presented a detailed review of data aggregation techniques for communication cost reduction in wireless sensor networks. One of the important design issues for wireless sensor network architectures is energy efficiency, to keep the network operational as long as possible to accomplish the requirement of deployment. Therefore, data aggregation techniques are an essential building block, as they aim at reducing the communication cost by decreasing number of transmissions required for data collection which, in turn reduces energy consumption.

REFERENCES

[1] V. Raghunathan, C. Schurghers, S. Park, M. Srivastava, “Energy-aware Wireless Microsensor Networks”, IEEE Signal Processing Magazine, March 2002, pp. 40-50.

[2] G. Pottie, W. Kaiser, “Wireless Integrated Network Sensors, Communication of ACM, Vol. 43, N. 5, pp. 51-58, May 2000.

[3] G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, “How to Prolong the Lifetime of Wireless Sensor Networks”, Chapter 6 in Mobile Ad Hoc and Pervasive Communications, (M. Denko and L. Yang, Editors), American Scientific Publishers, to appear, available at http://info.iet.unipi.it/~anastasi/papers/Yang.pdf

[4] M. C. Vuran, O. B. Akan, and I. F. Akyildiz, “Spatio-Temporal Correlation: Theory and Applications for Wireless Sensor Networks”, Computer Networks Journal, Vol. 45, No. 3, pp. 245-261, June 2004.

[5] J. Li, P. Mohapatra, “Analytical Modeling and Mitigation Techniques for the Energy Hole Problem in Sensor Networks”, Pervasive Mobile Computing, 3(3):233-254, June 2007.

[6] D. Ganesan, A. Cerpa, W. Ye, Y. Yu, J. Zhao, D. Estrin, “Networking Issues in Wireless Sensor Networks”, Journal of Parallel and Distributed Computing, Vol. 64 (2004) , pp. 799-814.

[7] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler and J. Anderson, “Wireless Sensor Networks for Habitat Monitoring”, Proc. ACM Workshop on Wireless Sensor Networks and Applications, pp. 88-97, Atlanta (USA), September 2002.

[8] A. Warrier, S.Park J. Mina and I. Rheea, “How much energy saving does topology control offer for wireless sensor networks? – A practical study”, Elsevier/ACM Computer Communications, Vol. 30 (14-15), Pp. 2867-2879, 15 October 2007.

[9] I. F. Akyildiz and I. H. Kasimoglu, “Wireless Sensor and Actor Networks: Research Challenges”, Ad Hoc Networks Journal, Vol. 2, No. 4, pp. 351-367, October 2004

[10] I. Papadimitriou and L. Georgiadis, “Energy-aware Routing to Maximize Lifetime in Wireless Sensor Networks with Mobile Sink”, Journal of

Communications Software and Systems, Vol. 2, No. 2, pp. 141-151, June 2006.

[11] Z. M. Wang, S. Basagni, E. Melachrinoudis, C. Petrioli, "Exploiting Sink Mobility for Maximizing Sensor Networks Lifetime", Proc. of the 38th Annual Hawaii International Conference on System Sciences (HICSS '05), Hawaii, 03-06 Jan. 2005.

[12] S. S. Pradhan, K. Ramchandran, "Distributed source coding using syndromes (DISCUS): design and construction",IEEE Transactions on Information Theory, Vol. 49 (3), Pp. 626-643, March 2003.

[13] C. Tang, C. S. Raghavendra, "Compression techniques for wireless sensor networks", Chapter 10 in book WirelessSensor Networks, Pp. 207 - 231, Kluwer Academic Publishers, 2004.

[14] M. Wu, C. W. Chen, "Multiple Bit Stream Image Transmission over Wireless Sensor Networks", Chapter 13 in book Sensor Network Operations, Pp. 677-687, IEEE & Wiley Interscience, 2006.

[15] Z. Xiong; A. D. Liveris, S. Cheng, "Distributed source coding for sensor networks", IEEE Signal Processing Magazine, Vol. 21 (5), Pp. 80-94, Sept. 2004.

[16] K. Akkaya and M. Younis, "A survey of routing protocols in wireless sensor networks," Elsevier Ad Hoc Network Journal, vol. 3, no. 3, pp. 325–349, May 2005.

[17] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: a survey," IEEE Wireless Communications, vol. 11, no. 6, pp. 6–28, Dec. 2004.

[18] I. Solis and K. Obraczka, "Isolines: energy-efficient mapping in sensor networks," in IEEE ISCC 2005, Cartagena, Spain, Jun. 2005.

[19] V. Erramilli, I. Matta, and A. Bestavros, "On the interaction between data aggregation and topology control in wireless sensor networks," in IEEE SECON 2004, Santa Clara, CA, US, Oct. 2004.

[20] H. Luo, J. Luo, Y. Liu, and S. Das, "Energy efficient routing with adaptive data fusion in sensor Networks." in Third ACM/SIGMOBILE Workshop on Foundations of Mobile Computing, Cologne, Germany, Aug. 2005.

[21] H. Gupta, V. Navda, S. R. Das, and V. Chowdhary, "Efficient Gathering of Correlated Data in Sensor Networks," in ACM MobiHoc 2005, Urbana-Champaign, IL, US, May 2005.

[22] S. Madden, M. J. Franklin, J. M. Hellerstein, and W. Hong, "TAG: a Tiny AGgregation Service for Ad-Hoc Sensor Networks," in OSDI 2002, Boston, MA, US, Dec. 2002.

[23] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, and F. Silva, "Directed diffusion for wireless sensor networking," IEEE/ACM Trans. Networking, vol. 11, no. 1, pp. 2–16, Feb. 2002.

[24] S. Lindsey, C. Raghavendra, and K. M. Sivalingam, "Data GatherinAlgorithms in Sensor Networks using Energy Metrics," IEEE Trans. Parallel Distrib. Syst., vol. 13, no. 9, pp. 924–935, Sep. 2002.

[25] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," IEEE Trans. Wireless Commun., vol. 1, no. 4, pp. 660–670, Oct. 2002.

[26] Y. Yao and J. Gehrke, "Query processing for sensor networks," in ACM CIDR 2003, Asilomar, CA, US, Jan. 2003.

[27] B. Zhou, L. H. Ngoh, B. S. Lee, and C. P. Fu, "A Hierarchical Scheme for Data Aggregation in Sensor Network," in IEEE ICON 2004, Singapore, Nov. 2004.

[28] A. Mahimkar and T. S. Rappaport, "SecureDAV: A secure data aggregation and verification protocol for sensor networks," in IEEE GLOBECOM 2004, Dallas, TX, US, Nov. 2004.

[29] S. Nath, P. B. Gibbons, Z. R. Anderson, and S. Seshan, "SynopsisDiffusion for Robust Aggregation in Sensor Networks," in ACM SenSys 2004, Baltimore, MD, US, Nov. 2004.

[30] A. Manjhi, S. Nath, and P. B. Gibbons, "Tributaries and Deltas:Efficient and Robust Aggregation in Sensor Network Stream," in ACM SIGMOD 2005, Baltimore, MD, US, Jun. 2005.

[31] S. Chen and Z. Zhang, "Localized algorithm for aggregate fairness in wireless sensor networks." in ACM/SIGMOBILE MobiCom 2006, Los Angeles, CA, US, Sep. 2006.