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A Survey on Topology Maintenance in Wireless Sensor Networks

Hazique Aetesam[a], Itu Snigdh[a]

[a] *Department of Computer Science and Engineering, Birla Institute of Technology, Mesra, Ranchi-835215, India*

Abstract

The content presented in this article provides an insight into the current topology maintenance techniques in general and algorithms in particular. It makes the fine line between topology control, topology construction and topology maintenance all the more prominent. Additionally, it tries to find out how the meaning of topology control has evolved over a period of time since the inception of Wireless Sensor Networks (WSN). An attempt has been made to standardize the definition of topology control and topology maintenance.

Index Terms: Topology Control, Topology Construction, Topology Maintenance

1. Introduction

A sensor network is usually an infrastructure comprising sensing, computation and communication elements that gives the administrator the ability to instrument, observe and react to events and phenomena of physical and behavioural nature. The typical applications of WSN span several multidisciplinary areas including air traffic control, battlefield monitoring, defence systems, heat control, industrial and building automation, mobile robotics, process control, radiation and nuclear threat detection systems, traffic flow and surveillance, vehicle tracking, weather tracking, etc. (Sohraby, Minoli and Znati 2007). For such wide range of applications, a large number of sensors need to be deployed. However, the small size of sensors put a restriction over the amount of energy available in such devices. Hence, every hardware and software technology available in the design of WSN is inclined towards conservation of energy.

The various *Quality of Service* (QoS) metrics used in the design of Wireless Sensor Network include deployment, coverage, connectivity and lifetime of the network (Snigdh and Gupta 2014). A research on different areas of WSN shows that where 9.70%, 7.27% and 5.76% of researches have been done in the area of deployment, target tracking and routing and aggregation respectively at one extreme and 1.21%, 0.91% and

* Corresponding author.
E-mail address: hazique1234@gmail.com, itusnigdh@bitmesra.ac.in

0.61% of researches on detection and estimation, programming and software respectively at the other extreme (Sohraby, Minoli and Znati 2007). Using the same trend, only 1.21% of the researches have been done in the field of topology control which shrinks even further if we consider topology maintenance as a subset of topology control. In fact, this is the subject of discussion in this paper.

First of all, it is imperative to define the term topology. Topology means the arrangement of nodes present in a network. Here, the node is a WSN node, typically called a *mote*. The definition of topology control has evolved over a period of time. As can be noted from previous literature in WSN, topology control included only the construction of a reduced topology. However, during the process of communication, which is the most energy depleting process, the topology of the network cannot be maintained for a longer period of time. Hence, the optimal topology constructed initially can no longer maintain the connectivity of the network (Wightman and Labrador 2009). Thus, according to the new taxonomy, the job of topology control is taken over by *Topology Construction* and changing the topology time to time is termed as *Topology Maintenance*.

The rest of the paper is divided as follows. Section II provides a discussion on topology construction techniques. Section III squeezes out topology maintenance from topology control. Section IV concludes the paper.

2. Topology Construction

As defined in the previous section, *Topology Construction* is the technique of constructing a reduced topology right at the beginning. Extensive literature can be found related to topology construction. Fig. 1 shows the classification of topology construction techniques discussed in the literature. As shown in the figure, topology construction can be broadly classified into controlling transmission power, building hierarchical topology and applying the hybrid approach which is the amalgamation of the other two. Transmission power can be controlled using centralised algorithms, distributed algorithms and using heterogeneous devices. In the context of wireless ad-hoc and sensor networks, *Critical Transmission Range (CTR)* is defined as the

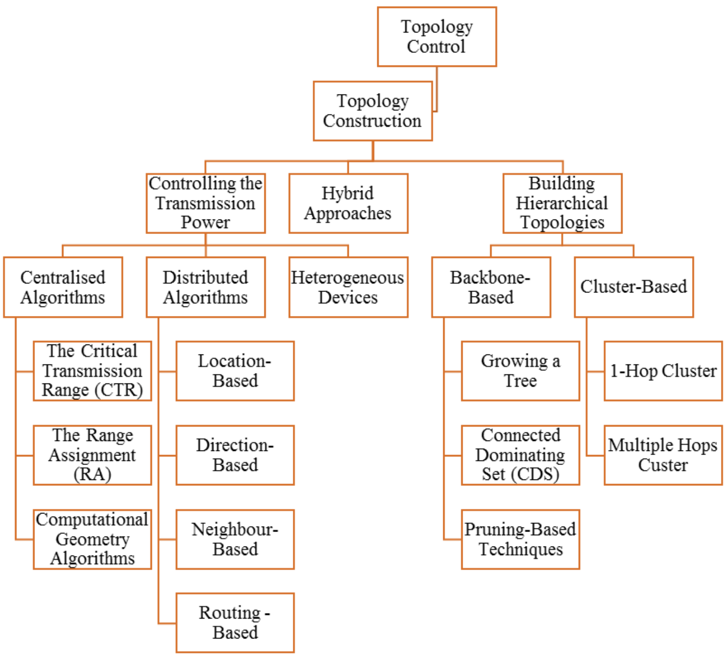

Fig.1.Classification of Topology Construction Algorithms *(Jiguo, et al. 2013)*

assignment of same minimum amount of energy so as to get a connected network. In (Qu, Feng and Zhang 2010), nearest neighbour nodes of the 2-D WSNs with Poisson Point Process is presented, which enables each node to find the 1st nearest neighbour node and adjust transmission range according to local requirement. In (Wan and Yi 2005), asymptotic distributions of two random variables ρ_n and ρ_n' are provided. ρ_n denotes the smallest transmission range at which active nodes form connected network and ρ_n' denotes the minimum transmission range at which active nodes from a connected network and each inactive node is adjacent to at least one active node. In the case of *Transmission Range Assignment (RA)* algorithms, topology construction is studied as the problem where the communication through each sensor node needs to be computed. The objective is to reduce the maximum transmission power of each node. In (Cardei, Perwaiz and Cardei 2006), energy-efficient range assignment for heterogeneous nodes assign minimum transmission range using approaches such as Integer Programming, distributed greedy protocol and minimum spanning tree based on clustering. It is to be noted that CTR can be classified under homogeneous category (since every node is having same transmission power) and RA can be classified under heterogeneous category (since every node is having different transmission range). Under the *Computational Geometry (CG) Algorithms*, we typically have *Voronoi Diagram (VD)* and *Delaunay Triangulation (DT)*. (Dai, et al. 2009) describes the construction of a clustered network based on VD and shortest path trees are dynamically generated after each round after seeing the network state after each round. (Wang, Lederer and Gao 2009) focuses upon the node localisation an uses only network connectivity to recover nodal positions.

The second broad classification of topology construction algorithm is *Distributed Topology Construction*. In this case, every node is individually participating in topology construction process, so a level of parallelism can be achieved. Hence, this category is faster than the centralised topology construction. In *location-based* and *direction-based* topology constructions, nodes acquire periodic information about nodes present in their proximity. *Geographic Adaptive Fidelity* (GAF) comes under location-based topology construction. Reference (Grover, Shikha and Sharma, Location Based Protocols in Wireless Sensor Networks- A Review 2014) gives an idea how nodes in GAF can be divided into several different cells in which only one node present in the cell needs to transfer data on behalf of the other node while the remaining nodes can go to the sleeping state; thereby conserving energy. It requires less control overhead with low memory requirement. Hence,

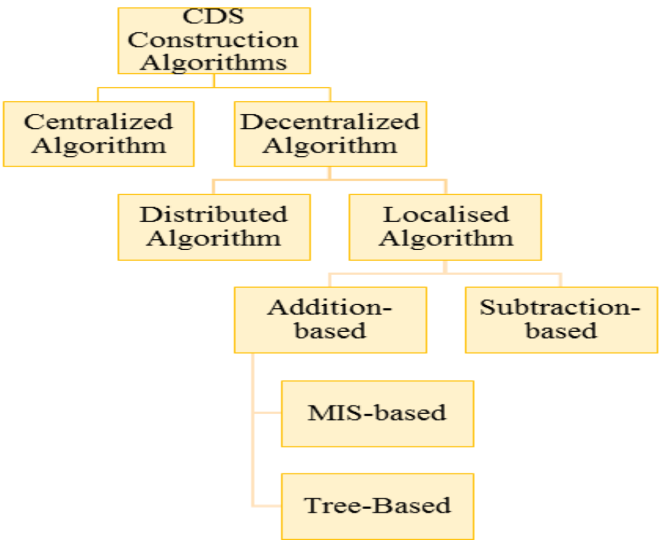

Fig.2.Classification of CDS Construction algorithms *(Jiguo, et al. 2013)*

connectivity to only neighbouring cells takes place; achieving restricted topology. (Grover, Shikha and Sharma, Optimised GAF in Wireless Sensor Network 2014) takes the discussion one level further and proposes an optimized GAF having three different phases; namely *discovery phase, active phase* and *sleeping phase*. Discovery Time in optimised GAF is more than in regular phase. During the sleeping phase, the next sleeping node after sleeping time in the sequence will awake. Also, here the discovery time is much more than regular GAF. (Osawa and Ishihara 2009) discusses another variation of GAF, called Hierarchical GAF with Honeycomb virtual Mesh (HGAF-h). Its main difference with regular GAF lies in the shape of cells which is hexagonal in nature. Also, HGAF-h does not make use of sub-cells. A collection of hexagonal cells are combined and one active node is selected from multiple cells combined clusters. For the direction based topology control, reference (Li, et al. 2005) gives an example of Cone-Based Distributed Topology Control which depends on the directional properties of the antenna to find out an optimum angle that covers at least one neighbour (angle $\alpha=5\pi/6$). In the *neighbour-based approach*, every node needs to have knowledge about its local neighbours. Each node acquires this information by sending initial broadcast messages. (Aziz, et al. 2013) provides an elaborate survey on distributed topology control by initially dividing it into those for 2-D and 3-D Region of Interest. 2-D category further divides it into those using *Power Adjustment Approach* (e.g. Minimum Energy Communication Network (MECN), Small MECN (SMECN), Communication Power (COMPOW)), *Power Mode Approach* (e.g. Geographic Adaptive Fidelity (GAF), Adaptive Self-Configuring Sensor Network Topologies (ASCENT)), *Clustering Approach* (e.g. Power Aware Connected Dominating Set (PACDS), Energy Efficient Distributed CDS (ECDS), Topology Management by Priority Ordering (TMPO)) and *Hybrid Approach* (e.g. SPAN, CLUSTERPOW, LEACH). Under the 3-D category, we have Sensor Topology Control Algorithm (STCA), Adaptive Yao Graph with Platonic Solid (APYG), Fixed Yao Graph (FiYG), Flexible Yao Graph (FlYG) and 3-D Spherical Delaunay Triangulation. In the heterogeneous devices, the heterogeneity of nodes can be defined on the basis of transmission power and mobility of nodes.

As far as hierarchical topology construction is concerned, the literature is flooded with such references that define it. In the case of *Backbone-Based* Topology Construction, topology can be constructed by *growing the tree*, *pruning the tree* and the most popular one, *Connected Dominating Set (CDS)*. Spanning Tree is one such method which grows the tree hierarchically. It is typically suited for applications requiring data aggregation at the parent nodes of the tree. (Khan, Pandurangan and Kumar 2009) considers a class of local distributed algorithms called *Nearest Neighbour Tree* (NNT) on lines of the construction of approximate Minimum Spanning Tree (MST). The algorithm includes exchanging three different types of messages among nodes: *request*, *available* and *connect*. (Kim and Lee 2009) proposes a *Wireless Spanning Tree Protocol (WSTP)* which consists of four different phases, namely: *Tree Configuration, calculating Proposed Path Cost*, *Faulty Node Detection* and *Partial Tree Reconfiguration*. The second category talks about the construction of CDS. CDS for a set of points S is defined as the set V such that every node in S-V is adjacent to at least one node in V and the sub-graph induced by V on S is connected. Reference (Jiguo, et al. 2013) define different CDS construction algorithms. Fig. 2 shows the classification of Connected Dominating Set construction techniques. In (Harutyunyan and Narayanan 2012), we get to know about two centralized CDS construction algorithms of *minimum 2-connected distance-k p-dominating sets*, one for a network modelled as unit-disk graph and another for arbitrary network topologies. (Wang, Li and Xu 2007) discusses a distributed topology construction for k-connected dominating set. Here, edges are truncated in terms of their weights in decreasing order. A Constant Factor Localised Algorithm for CDS is provided in (Islam, Akl and Meijer 2008). It includes the construction of convex hull and Maximal Independent Set (MIS), creating a CDS of size at most 38* |MCDS| (Minimum CDS). Reference (Zhang, Zhang and Yin 2011) provides an addition-based (k,r)-CDS for Robust Backbone in WSN. Pruning-based algorithms create a minimal set of nodes from the original set.

Cluster-based hierarchical topology construction causes division of the entire topology into distinct subsets with Cluster Head (CH) responsible for collecting local topology information and disseminating it across different CHs. It is often seen that cluster based algorithms discuss topology control along with routing leading to the minimisation of control traffic overhead that incurs when discussing the two separately. In 1-hop cluster, every node present in a cluster is one hop away from the CH; however, in multi-hop cluster, they can be several hops away, incurring more delay. CHs present in clusters are connected to one another either directly or using a gateway node. (Forghani, Rahmani and Khademzadeh 2008) provides a QoS-Based Clustering Topology Control Algorithm (QCTC) which decreases the average energy consumption in two ways: reduction in transmission power and by choosing only one among different possible paths between each sensor node and the base station. (Hong, Wang and Li 2016) elaborately discusses a clustering-tree topology control in WSN for heterogeneous WSN and accurately predicts the average energy consumption in terms of the difference between ideal and actual average residual energy using Central Limit Theorem.

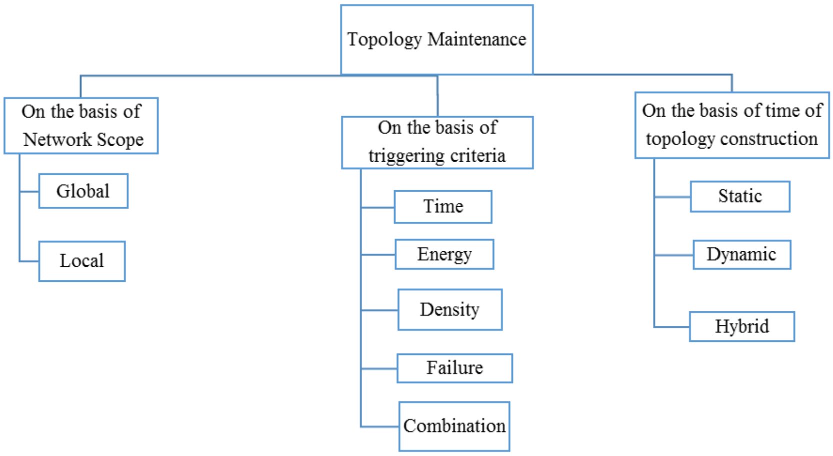

Fig.3.Classification of topology maintenance techniques

3. Topology Maintenance

We have discussed topology construction quite elaborately in the previous section. Now, it is time to drill into the topology maintenance techniques which form the main subject matter of this text. It is to be noted that the literature that define topology construction also define topology maintenance, as the two cannot be segregated. As stated earlier, when a topology is initially constructed, after certain period of time, it may no longer be optimal, and hence, needs to be changed. Before we actually change a topology, there are certain parameters that need to be taken into consideration. In the subparts to follow, we shall be discussing such criteria which affect the design of topology maintenance algorithms. The taxonomy for topology maintenance techniques is given in fig. 3.

3.1. Time of Topology Construction (Wightman and Labrador 2009)

On the basis of *time of topology construction*, we have *static*, *dynamic* and *hybrid* topology. In *static topology maintenance*, a number of topologies are constructed right at the time of initial topology construction which can be switched when the current one is no longer optimal. It is also called *topology rotation*. However, the experimental results show that since a network does not have any prior knowledge of the pattern of energy depletion, it does not yield good results. In dynamic topology maintenance algorithms, the topology is *reconstructed* on demand and is often integrated with routing. However, it is slower in operation as compared to static topology maintenance. Hybrid topology maintenance initially switches using static topology maintenance, which if does not ensure connectivity, resorts to dynamic topology maintenance.

3.2. Scope of the Network (Wightman and Labrador 2009)

Scope of the network in the context of topology maintenance can be divided into *global* and *local*. In global topology maintenance, topology of the entire network is changed when connectivity can no longer be ensured. However, the control messages exchanged in global topology maintenance causes energy depletion and topology reconstruction is done even when rest of the network is connected. On the other hand, topology can be maintained locally, i.e., topology reconstruction is restricted to only the section of network where communication is hampered while the topology of the other sections remain unaffected. Local topology maintenance is more energy efficient.

3.3. Triggering Criteria (Wightman and Labrador 2009)

Triggering criteria determine the reason behind invoking a topology maintenance algorithm. On that basis, it can be energy-triggered, time-triggered, failure-based, density-based, random-based or any combination of these. In the case of energy or time triggered topology maintenance, defining the time or energy threshold is an important optimisation decision. Density-based topology maintenance changes the topology when the density of the entire region of interest or certain chunk of it becomes less than a pre-defined threshold value.

A comparison of various topology maintenance algorithms is provided in table 1. The comparison is made on the basis of the following criteria; scope of the network, time of topology construction, triggering criteria, density of the network and simulation result of the topology under question.

Table 1. Existing Topology Maintenance Techniques in the Literature

	Scope	Triggering Criteria	Time of Topology Construction	Network Design and Assumptions	Simulation Results
LiY05 (Li, Wang, Baueregger, Xue, & Toh, 2005)	Local	Failure-based	Dynamic	Number of Nodes: 20-60 Area of RoI:1000×1000 Transmission Range (TR):50-500m No. of Simulations-200	• Low transmission range (TR) sufficient for Time to Live (TTL) = 3 than TTL = 4 • Gateway node has average degree of 5 • No. of gateway node is maximum (30-50) for TR=250-350
Wig09 (Wightman & Labrador, 2009)	Global	Energy-based Time-based	Static Dynamic Hybrid	Number Of Nodes: 50 (sparse), 100-400(dense) Area of RoI: 200m×200m Transmission Range: 37m	• Dynamic topology maintenance works better than static one in both A3 and CDS rule-K • Topology maintenance has no effect on sparse networks • A3 performs better in in static, dynamic and hybrid category for dense networks
Bas04 (Basagni, Carosi, & Petrioli, 2004)	Local	Energy-based	Dynamic	Number of Nodes: 100-300 Area of RoI: 200m×200m Transmission Range: 30m	• In a network with 300 nodes, Sensor Dynamic Media Access Control (S-DMAC) has 44% smaller backbone than Geographic Adaptive Fidelity (GAF) • Control packet reduction by 86.13% (100 nodes) and 94.13% (300 nodes)
LiL05 (Li, Halpern, Bahl, Wang, & Wattenhofer, 2005)	Local	Density-based Failure-based	Dynamic	Number of Nodes: 200 Area of RoI: 1500m×1500m Transmission Range: 500m	• Percentage of traffic sources dead at time 600 units is 45% Sensor Minimum Energy Communication Network (SMECN), 30% in Cone-Based Topology Construction (CBTC) and 79% in optimum CBTC (OPT-CBTC) • Amount of delivered times of packet are 1.66, 1.44 and 2.94 times in SMECN, CBTC and OPT-CBTC respectively than MaxPower

She05 (Shen, Chang, Zhang, & Cui, 2005)	Local	Failure-based	Dynamic	Number of Nodes: 30-210 Area of RoI: 500m×500m Transmission Range: 100m-400m	• When average node degree is plotted against number of nodes, Distributed Shortest Path Tree Maintenance (DSPTM) gives better result than Reactive Low-Overhead Scheme (RLS) • Number of responding nodes in 50% more in the case of DSPTM than RLS
Fyr06 (Fyre, Cheng, Du, & Bigrigg, 2006)	Local	Failure-based Random-based	Dynamic	Node Density: 0.1-8.0 (in increments of 0.1) Area of RoI: 625m^2 Node failure threshold: 25%	• For densities higher than 3, original NAPS without node failure (ORIGSAFE), original NAPS with node failure (ORIGNF), NFIR (modified NAPS in failed environment and increasing power in randomly selected node) and NFIM (modified NAPS in failed environment and choosing the node randomly selected node with maximum remaining power) have Maximum Component Accessibility (MCA)=1 • NAPS achieve better average MCA • NAPS achieve better factor increase in network lifetime
Zha09 (Zhang & Zhao, 2009)	Local	Failure-based	Dynamic	Node Density: 10-500 Initial Rx/Tx Energy: 78mW	• Energy consumption in the decreasing order is Flood Tree, Maximal Independent Set-CDS (MIS-CDS) Tree and Mesh Tree • During the maintenance process, the Flood Tree increases energy demand more as compared to MESH-CDS Tree and Mesh Tree • Mesh tree considers incremental deployment rather than concurrent deployment
Cho11 (Chou, Ssu, Jiau, & Wang, 2011)	Global, Local	Time-based	Dynamic	Number of nodes: 50,75,100 Area of RoI: 60m×30m Transmission Range: 15m Simulation Time: 900 seconds	• After 750 sec of simulation time, 80% of the nodes survived in the best case of Dead-End Free Topology Maintenance (DFTM) • Packet delivery ratio decreases after 450s which is the least in SPAN (clustering hierarchy protocol) • Average energy consumption is the least in the case of DFTM
Wan10 (Wang & Zhang, 2010)	Local	Time-based, Energy-based	Dynamic	Number of Nodes: 100-600 Area of RoI: 100m×100m Transmission Power levels: 0-6, P_{min}=0,P_{max}=6	• Network lifetime increases with the number of nodes • The algorithm avoids early dying of group leader • However, it pays less attention on node location and network hole.
Kri11 (Krishna & Doja, 2011)	Local	Failure-based	Dynamic	Number of Nodes: 150 Mobility Model: static Area of RoI: 800m×800m Transmission Range: 180m	• Particle Swarm Optimisation Topology Maintenance (PSO-TM) and Ant Colony Organisation (ACO-TM) achieve 20% and 18% power efficiency respectively than Neighbour-Based Topology Control (NBTC), location-based and Direction-Based Topology Control (DBTC) • Average success for congestion is 73% and 68% respectively in PSO-TM and ACO-TM • Average delay rate for link failure is 20% and 23% in PSO-TM and ACO-TM

Che121 (Cheng, Fei, & Fen, 2012)	Local	Failure-based	Dynamic	Number of nodes: 200 Area of RoI: 800m×800m Transmission Radius: 0~50m	• Comparison with Low Energy Adaptive Clustering Hierarchy (LEACH) shows more surviving nodes in the proposed algorithm • Overall survival is also longer
AlN14 (Al-Nabhan, Al-Rodhaan, & Al-Dhelaan, 2014)	Global, Local	Density-Based	Dynamic	Number ofNodes: 100-1000 Area of RoI: 40m×40m-100m×100m Transmission Raius:10m-50m	• CDS size increases with deployment area in Approach I, Centralised CDS, and distributed CDS • Increase in the replaced nodes for 5%, 25% and 50% shows increase in the CDS size respectively
Che14 (Cheng, Tang, & Tsai, 2014)	Local	Failure-based	Static	Number of Nodes: 250-450 Area of RoI: 10x Transmission Range: x	• VCP and Approximate Point-in-Triangulation Test+GFG (APIT+GFG) has no maintenance overhead. • Location-Free Greedy Face Greedy Routing (LF-GFG) requires little message overhead • The packet delivery rate does not reach 100% in APIT-GFG • LF-GFG requires less maintenance time

4. Conclusions

In the presently stated paper, we have started with categorising various topology construction algorithms based on three different classification criteria, namely; controlling the transmission power, building the hierarchical topology and hybrid topology construction. Then, we have taxonomised topology maintenance algorithms according to three different criteria, namely; scope of the network, triggering criteria and time of topology construction. Simulation results are obtained using such criteria. Time of topology construction is dynamic in most of the cases. Simulation results show that local and dynamic topology maintenance yield better results than global and static techniques.

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Authors’ Profiles

Hazique Aetesam has completed his B.Tech. in Information Technology from Hamdard University, New Delhi, India in 2013. He is currently pursuing his M.Tech. in Computer Science and Engineering from Birla Institute of Technology (BIT), Mesra, Ranchi, India. His area of research is Wireless Sensor Networks. His areas of interest include Software Engineering, Object Oriented Paradigm, Graph Theory and Database Management System.

Itu Snigdh received her Master’s Degree (Software Engineering) from Birla Institute of Technology (BIT), Mesra (Ranchi), India in 2002 and her Bachelor’s degree in electrical engineering from BIT Sindri, India in 1996. She joined the Department of Computer Science and Engineering at BIT Mesra in 2003 and is currently working as an Assistant Professor. She has completed her Ph.D. from the same Institute in the area of Wireless Sensor Networks, Department of Electronics and Communication Engineering. She has authored and co-authored a number of technical journal articles and conference papers. Her areas of interest include Software Engineering, Database Management Systems and Wireless Sensor Networks.