Adaptive routing for wireless sensor networks: a survey

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Course: 60-510, Winter 2007

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With the advancement of wireless communication, software engineering and Micro-Electro-Mechanical Systems (MEMS) technology, the sensor nodes are much more capable now and have found their application in many areas of life. In view of this, the design of efficient routing protocols is very critical. The routing protocols need to be adaptive to cater the wide variety of applications of wireless sensor networks. In general, adaptive routing is essential for wireless sensor networks to be fault tolerant, secure, and have increased life-time and real-time capabilities. This survey provides an in-depth view of past and on-going research on adaptive routing protocols in wireless sensor networks from 1999 to 2007. In this survey, we present our investigation of various routing objectives for adaptation and approaches used by various routing algorithms to achieve adaptation. Routing objective of routing protocols often change due to changes application requirement and network dynamics during the life-time of the wireless sensor network. In this survey, adaptive routing algorithms are classified broadly into two categories. The adaptive routing protocols in the first category emphasize energy aware routing objectives while the ones in the second category emphasize on non energy routing objectives. It is found that there is much less referral of work of one research group by the other research group in adaptive routing research in wireless sensor networks.

General Terms: Routing, Sensor networks
Additional Key Words and Phrases: Adaptive routing, Wireless sensor networks, Energy aware routing, Routing objectives

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Contents

1. INTRODUCTION

This survey reviews past and current research on adaptive routing protocols for Wireless Sensor Networks (WSNs). It contains 65 references in the bibliography section that consists of 2 Masters theses, 3 PhD theses, 1 technical report, 3 books, 41 conference papers, and 15 journal papers. IEEE explorer, ACM online search, Springer-Verlag online search, Scopus, Google scholar, Citeseer, Science Direct online search, University of Windsor's Laddy library online search, ProQuest online thesis search, and Collectionscanada online thesis search engines were used to search the references for this survey. Out of these 65 references, 32 references are annotated and are right on topic. Out of these 32 references, 19 references are on adaptive routing protocols that have energy awareness as their main routing objective, 11 references are on adaptive routing protocols that have non energy goals as their main routing objectives, and 2 references give equal emphasis to both of above mentioned routing objective categories. These 32 annotated references range from 2002 to 2007. It is observed that out of the 32 annotated references, only 2 papers are referred to by the papers from other research groups, otherwise, most of the referrals of papers are by the later papers from the same research group.

In this survey, in section 2, a general discussion on adaptive routing is presented along with the references for background information on the topic. Section 3 contains the main survey on adaptive routing protocols in WSNs. This section is divided into 2 subsections that are further divided into 3 subsections each on the basis of routing objectives. The summery of research in each subsection is given at the end of each subsection followed by a final summery in Table VII at the end of this survey. Section 4 contains the concluding comments on this survey followed the bibliography. The annotations are given at the end of this survey.

2. GENERAL DISCUSSION

WSNs have tremendous potential applications in the military, environment, health, home, space exploration, chemical processing, disaster relief, and other commercial areas. WSNs are made of sensor nodes that have sensing, computation, and wireless communications capabilities. The sensor nodes are often deployed randomly, therefore the sensor network protocols and algorithms should have self-organizing capabilities to act cooperatively to form a multi-hop WSN. The sensor nodes collect data about the environment and transmit only the required data or forward the data from neighboring sensor nodes to the base station or a sink node using a routing protocol. In WSNs, the routing protocols depend on application requirements and the network architecture, hence they need to adapt to any changes to the application requirements and network dynamics during run-time of WSNs. Routing adaptability also includes the capability of providing fault tolerance, real-time support, energy balance, security and handling variations in the traffic flow in WSNs. The next paragraph discusses the references to understand issues related with WSN in general and routing protocol research in particular.

In Jones et al. [2001], the authors present a summery of contemporary research work on energy efficient and low power design of entire network protocol stack of wireless networks in general. In Kohno et al. [2001], the authors state that adaptiveness is essential for sensor systems to be fault tolerant and have real-time capabilities. In their paper, the authors describe the components and a position-based addressing scheme for a sensor network in which the number and location of sensor nodes change dynamically. In Akyildiz et al. [2002], the authors provide an introductory survey on all aspects of WSNs. This paper is later referred to by a large number of papers written on WSNs. Bandyopadhyay et al. [2003] is a book that covers comprehensively the advances in location management and routing in both single-hop and multi-hop mobile wireless networks. A comprehensive description of WSNs from a systems perspective is given in the book Bulusu et al. [2003]. HAC et al. [2003] is a book that presents networked embedded systems, smart sensors, and WSNs, with an emphasis on architecture, applications, networks and distributed systems support for WSNs. In Culler et al. [2004], the authors give an overview of Sensor Networks.

In Al-karaki et al. [2004], the authors give a classification and comparison of routing protocols in WSNs in Table 3 on page 26 of their paper. In Hollick et al. [2004], the authors present a survey of consistency of behavior and performance of the routing services in sensor networks. In Jiang et al. [2004], the authors compare and contrast contemporary routing protocols for sensor networks. The authors also analyze the requirements and similarities of Mobile Ad hoc Networks (MANETs) and sensor networks. In Akkaya et al. [2005], the authors have given a contemporary survey of routing protocols in WSNs. A classification of routing protocols in sensor networks is given in Table I on page 346 of their paper. The three main categories explored in the paper are data-centric, hierarchical and location-based routing protocols. In Dai et al. [2005], the authors present classification, analysis and comparison of routing protocols existing till that point of time. In Puccinelli et al. [2005], the authors present a survey of application, challenges and hardware requirements of WSNs. In Jiang et al. [2006], the authors present an overview and classification of contemporary routing protocols in WSNs. The authors categorize the routing protocol in data-centric, hierarchical, location-based, and network flow and QoS-aware categories. The authors also provide an overview of the existing hardware and software research platforms for WSNs. In Renyi et al. [2007], the authors present a survey of routing protocols for sensor networks. In their paper, the authors provide a comparative study of routing protocols and classify them as indicator-based and indicator-free routing protocols. The next section presents a survey of adaptive routing protocol in WSNs.

3. SURVEY OF RESEARCH

Adaptive routing algorithms generally have more than one routing objective and adapt to one or the other routing objective on the basis of changing application requirements or network scenario. Hence, putting them into any one routing objective category is quite difficult. Therefore, in this survey, the routing algorithms are broadly categorized on the basis of the routing objectives that are particularly emphasized in the adaptive routing algorithm. With this criterion, the routing protocols are classified broadly into two categories. First, the adaptive routing algorithms that place emphasis on energy aware routing objective, and second, the ones that place emphasis on non energy routing objective. In the subsection 3.1, the adaptive routing protocols belonging to the first category are presented while in subsection 3.2, the ones that belong to second category are presented.

3.1 Energy awareness as the main routing objective

The energy aware routing objectives are further divided into three categories. The first category puts emphasis on routing protocols that adapt to minimizing energy consumption along with minimizing delay in message delivery. The second category puts emphasis on routing protocols that adapt to minimizing energy consumption along with other routing objectives. The third category puts emphasis on routing protocols that adapt to energy balance along with other routing objectives.

3.1.1 *Minimizing energy consumption along with minimizing delay.*

This subsection presents the adaptive routing protocols that minimize energy consumption to increase life-time of WSNs and at the same time, they support fast or real-time message delivery.

Gao [2002] presents an adaptive routing algorithm that facilitates data processing in an energy efficient manner and also provides a trade-off between messaging overhead and delay. The author states that the proposed algorithm gives one or multiple winners by a context-dependent distributed election procedure.

In Zhang and Fromherz [2004b], the authors appear to be the first to apply a real-time search and reinforcement learning technique for adaptive routing in WSNs. The authors state that previous research on application of real-time or agent-centered search methods of AI and reinforce learning is the basis of their work in the paper. The authors also state that to adapt routing in sensor networks, the energy and latency are traded by setting the forward propagation policy, and success rate and energy are traded by the retransmission policy. In the paper, the authors present the algorithmic framework and complexity analysis of search-based routing strategies. The authors also present the description of proposed piggybacked heuristics, heuristic estimation, promiscuous learning, indirect confirmation, and forward propagation mechanism. The authors state that "for a given static and symmetric network and admissible initial estimate Q[0,m] for message m, and assuming that the destination is not empty and there is a path from the source to the destination, then both the message complexity and time complexity of the search-based routing are O(nd), where n is the number of nodes in the network and d is the diameter of the network". The authors also state that "If the initial estimates are admissible, then the search-based strategy guarantees delivery for a symmetric network if a path exists and it also guarantees convergence to an optimal route if the change rate of the network is slower than the convergence rate". The authors state that "the search-based strategy guarantees delivery in O(nd) time if the initial over-estimate is bounded by O(d)". The authors also state that the comparison of the proposed routing framework with other routing strategies will be discussed in another paper. The authors also state that the search-based routing strategies have been implemented on Berkeley motes, but the details of the implementation are outside the scope of their paper.

Sun et al. [2005] address the problem of adaptive routing in a data querying sensor network that minimizes both delivery delay and total energy consumption of data delivery as well as making the energy consumption even among the nodes. The authors state that the work presented in their paper is based on previous research on energy aware routing, data querying routing and geographic routing. The authors present, what they claim to be novel idea, a Dynamic Energy Aware Routing (DEAR) algorithm for data querying sensor networks. The authors state that in DEAR, the sink node uses restricted flooding to spread routing instruction that contains hop count and minimum residual energy information. The authors also state that in DEAR, the next hop is decided by both the hop count to sink node and residual energy of the data path. The authors state that as the data is transmitted from destination to sink node, the data path will be adjusted dynamically according to the residual energy of each node along it. The authors claim, on the basis of their results, that DEAR can prolong the lifetime of networks as compared to Directed Diffusion (DD), Minimum Transmission Energy routing (MTE), and Energy Aware Routing (EAR). The authors state that it is hard for DEAR to gain less average delay than DD when the network runs for a long time because of the fact that to consume power evenly, DEAR may not always choose the paths that deliver data quickly. However, the authors state that DEAR provides less average delay than MTE and EAR.

In Wong et al. [2005], the authors propose, what they claim to be novel idea, an Adaptive Wakeup Schedule Function (AWSF) that adapts to network topography to support fast routing in sensor networks. The authors state that most of data-centric wakeup schemes put radio modules to idle mode for data snooping, while AWSF assumes complete radio turn-off in the sleep mode that provides a real energy saving. The authors state that AWSF guarantees asynchronous neighbor discovery and it automatically adapts from a cyclic schedule to a non-cyclic one depending upon the network topography. The authors implement the proposed routing algorithm in real Crossbow Mica2 motes and claim, on the basis of their results, that AWSF guarantees hard delay bounds, and provides better average delays and smaller delay variances without increasing the duty cycles of sensor nodes as compared to CYCLIC and RANDOM wakeup designs.

In Gundappachikkenahalli and Ali [2006], the authors appear to be the first to address the problem of routing the data based on data priorities and Quality of Service (QoS) requirements with the constraint of bringing down the latencies while remaining energy efficient in the context of WSNs. Previous research on QOS was targeted for primitive sensor networks. In the paper, the authors propose, what they claim to be a solution, that works for highly sophisticated sensor nodes that can transmit video/images and critical information. The authors use an energy aware AODV routing protocol and an Ants' based routing protocol as basis of their work in their paper. The authors propose a new adaptive routing protocol framework, called AdProc that supports a short rapid route for data with high priority and strict QoS requirements, and an energy efficient route for lower priority data. The authors state that the shortest route to the destination is computed using an energy aware AODV routing protocol and an energy efficient route is computed using an Ants' based routing protocol. The authors state that the proposed routing algorithm provides 70% improvement over the AODV protocol in terms of overall latency, hence providing a good Quality of Service. The authors claim, on the basis of their results, that the proposed routing algorithm helps to distribute energy consumption that prolong the network life and reduce network holes.

Peng et al. [2007] present an adaptive routing algorithm for WSNs with the objective that it should support applications with real-time constraints and at the same time, it should ensure balanced energy consumption. The authors state that the routing algorithm proposed in their paper is similar to the MM-SPEED algorithm. The authors also state that the MM-SPEED algorithm differentiates the different real-time levels, but it doesn't dynamically adjust routing paths according to nodes' energy states, while the algorithm presented in their paper supports both of above mentioned considerations. In the paper, the authors propose, what they claim to be new idea, an adaptive real-time routing scheme (ARP). The authors state that ARP dynamically changes packets' requirement to transmission speed and adjusts their real-time priority during the end-to-end transmission period. In ARP, sensors get the links' state information by exchanging information with one-hop and two-hop neighbors. The authors state that when nodes choose the next hop neighbor, they not only consider the real-time requirement, but also synthetically consider the energy index. The authors state that the real-time transmission level is adjusted dynamically using RT and TTL fields of the packet. The RT (real-time) field is used to indicate if the packets have real-time transmission requirement. The TTL (time to live) field is used to indicate how much time remains for the data to arrive at the sink. In their paper, the authors present the description, rules, algorithms, and mathematical formulation for ARP and its various modules. The authors state that when network overload increases, ARP has better performance than SPEED and MMSPEED, because it differentiates the different real-time data and takes different transmission methods for them. The authors also state that among the three schemes, the control cost of ARP and MMSPEED are higher than SPEED, because both ARP and MMSPEED use more information to track link changes. The authors claim, on the basis of their results, that ARP dynamically adjusts route and real-time level of data packets, and that the energy consumption of nodes is relatively even. The authors state that their research is just the preliminary work and it will serve as a guide for future research.

In Shah et al. [2007], the authors present a Routing by Adaptive Targeting (RAT) protocol that allows dynamic sensor-to-actor coordination in response to emergencies, and improves the response time and energy conservation in Wireless Sensor/Actor Networks. The authors state that RAT uses the mobility of actor nodes to form dynamic responsibility clusters that ensure an event specific response time to emergencies. The authors state that a subscription message from actors showing their interest and range of action is used to trigger the information dissemination. Once the subscription of an actor is performed by the sensor nodes, a push policy continues to push the event data until the validity of subscription. The subscription is renewed in case it expires or an actor moves. The authors also state that with the proper choice of actor action range and A-A coordination, the higher delivery rate, better response time, and better energy consumption can be achieved through the proposed protocol.

Simao [2007] addresses the routing problem in sensor networks with the constraint that an event should be reported to a sink node with as little delay as possible and at the same time, the power consumption by individual nodes should be as low as possible and balanced. This paper presents a heuristics model of Adaptive Self-Organization for Surveillance and Routing (ASOS) in sensor network that addresses the aforementioned routing requirements. The author states that the proposed routing protocol is a variation of Gradient-Based Routing (GBR). The author states that in the proposed routing protocol, the nodes exchange DIST and WHO messages to handle network reconfigurations efficiently, instead of diffusing interest messages as in case of GBR. The author claims to present a new surveillance protocol that explores correlation between source location and event types, and a new routing protocol that adapts continuously to energy available at selected routes and to changes in topology. The author states that the proposed routing protocol uses minimum hop count as a distance metric and doesn't require global link cost information to be collected at nodes. In the paper, the author presents the model design of ASOS that includes the rules for routing and surveillance protocol. The author claims that the ASOS increases network longevity compared to gradient-based routing in sensor networks. The author states that the proposed protocols scale well with network size, and perform well in dynamic regimes and correlated events. The author also mentions that the proposed model has a drawback that the sensing resolution/precision must be made to match the communication range of sensors. However, the author states that this may not be a serious issue for many applications with small communication range of sensor.

Ye et al. [2007] addresses the problem of routing in WSNs that establishes a trade-off between data aggregation, delay, and energy consumption. The authors appear to be the first to use the Ant Colony Optimization Algorithm (ACO) to address such routing challenges in WSNs. The authors state that their work is based on previous research on the Directed Diffusion (DD) routing algorithm, ACO, and the concept of Mobile Agent-Based Distributed Sensor Networks (MADSNs). The authors present an Ant Colony Algorithm based Routing (ACAR) scheme for WSNs. The authors state that the proposed routing algorithm performs optimization of the data aggregation route by Ant-Like Mobile Agent (AMA) using the three heuristic factors concerning energy, distance and aggregation gain. The authors state that each AMA is a small signaling packet transporting state information and builds a path from its source nodes to its destination by sharing their knowledge among neighbors. The authors state that the AMA chooses a node as the data transfer/routing candidate if the node has higher residual energy and lower gain of data aggregation. The authors state that the proposed algorithm is a distributed routing algorithm. In their paper, the authors present a description, mathematical formulation, and analysis of the proposed routing algorithm. The authors claim, on the basis of their results, that the ACAR algorithm has better energy efficiency than DD for larger network size. However, the authors state that at the initial stages of simulation (1 to 7 seconds), the energy consumption in ACAR is less than DD, but in later stages of simulation (10 to 20 seconds), ACAR consumes more energy than DD. The authors claim that the ACAR algorithm has better energy efficiency than the LEACH algorithm at the initial stages of simulation, but in later stages of simulation (10 to 20 seconds), the energy consumption is faster in the ACAR algorithm than the PEGASIS algorithm. The authors claim, on the basis of their results, that ACAR performs 1.5 times better than PEGASIS, and 7 times better than LEACH in terms of energy efficiency.

Table I summarizes the contribution of research discussed in this subsection.

Table I. Summery of adaptive routing research discussed in subsection 3.1.1

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Comment
Zhang and Fromherz 2004b	Guaranteed delivery with minimum delay and minimum energy consumption.	Reinforcement learning, Real-time search, Trade-off energy and latency, Trade-off success rate and energy.	Search-based adaptive routing strategies.	Static and symmetric wireless sensor network.
Sun et al. 2005	Minimizing delivering delay and total energy consumption of data delivery, Making energy consumption even.	Using restricted flooding to spread routing instruction that contains hop count and minimum residual energy information.	Dynamic Energy Aware Routing (DEAR) algorithm.	Data querying sensor networks
Gundappachikke-nahalli et al. 2006	Minimizing the latencies while remaining energy efficient.	Considering data priorities and QoS requirements.	Adaptive routing Protocol framework (AdProc).	Data centric decision making.
Peng et al. 2007	Minimum energy consumption, Energy balance, Real time.	Choosing next hop neighbor based on real-time requirement and energy index. Uses RT and TTL fields of the packet.	An adaptive real-time routing scheme (ARP).	Distributed decision making.
Simao 2007	Minimum number of hops, Maximizing energy levels on the route, Energy balance, Minimum delay, Adaptive to topology changes	Data aggregation, correlated events, consideration to message importance.	Adaptive Self-Organization for Surveillance and Routing (ASOS).	Data centric decision making.

Ye et al. 2007	Minimum energy consumption, Minimum delay.	Using Multi Agents, Data aggregation using ANT colony algorithm.	Ant Colony Algorithm based Routing (ACAR).	Distributed decision making.

3.1.2 *Minimizing energy consumption along with other routing objectives.*

This subsection reviews adaptive routing protocols that minimize energy consumption in WSNs and at the same time, they support other routing objectives such as minimizing routing overhead and minimizing number of hops etc.

In his Masters thesis Zhu [2002], the author appears to be the first to identify the problem of adaptive routing in WSNs. In the Thesis, the author begins by stating that no routing protocol exists that is energy efficient, self-adaptive and error tolerant at the same time. The author states that the routing protocols proposed in his thesis meet all these requirements. The author states that previous research on table-driven (proactive) routing protocols and source-initiated on-demand (reactive) routing protocols have made significant progress for routing in ad hoc networks. However, these routing approaches lack adaptation, energy efficiency and error tolerance needed in WSNs. In his thesis, the author claims to present a new peer to peer (P2P) routing notion based on the theory of cellular automata. The author states that he presents two new routing adaptation models that are Spin glass and Multi-Fractal. The author claims that the proposed models use the ideas from Physics and Chemistry for the first time for distributed adaptation. In the thesis, the author presents the description, analysis, and simulation details of his proposed Spin glass and Multi-Fractal routing adaptation models. The author evaluates the Spin glass routing model for Temperature Effect, Cell Failure Probability, and Adaptation to disturbance, Disturbance Locations, Energy Map, and Damping Effect. The author evaluates the Multi-fractal routing Model for Linear inhibition curves, Tree with quadratic curves, and Adaptation to Topological Disturbance. The author states that both of the proposed routing models have communication complexity O(8N), where N is number of nodes in the network. The author claims, on the basis on his results, that the proposed routing protocol not only saves significant amount of communication and computation cost but also adapt to the highly volatile environment of ad hoc WSNs. In the future work, the author says that several modifications need to be made in cellular automata model to adjust to practical application. Author also states that he plans to apply the proposed routing models to hierarchical structured WSNs.

Tateson and Marshall [2003] address the problem of finding a dynamic way to maintain an efficient routing structure with minimal overhead. With this objective, the authors present an adaptive routing mechanism that enables sensor nodes to minimize route cost by varying their transmission range, and by experimenting with the neighbors from which they forward data. The authors state that their work is an extension of the routing hierarchy used by the Smartdust project of University of California at Berkeley. In the routing hierarchy used by the Smartdust project, the network sink or sinks initiate a cascade of local broadcasts that allow shortest paths to be established. The authors state that in the proposed adaptive routing protocol, the node levels are dynamically updated according to locally exchanged information as part of data transfer, so that changes in network configuration propagate quickly with minimal protocol overhead. In their paper, the authors describe proposed adaptive routing mechanism. The authors state that they carry out the simulation using 9 sensor nodes around a network sink. The authors state that the results are limited in scope and represent a system that has been modeled fairly simplistically. The authors state that in the proposed routing mechanism, taking the sum of link costs as route cost delivers fewer packets than using the costliest node as the route cost. The authors also state that in the proposed routing algorithm, to maximize the quantity of data collected, there is a trade-off between the energy cost of a route and the cost of the route in terms of loss of integrity of the network. The authors claim that the proposed routing mechanism generates minimal communication overhead and requires very limited memory as compared to shortest path first routing.

Cerpa et al. [2004] describes the ASCENT algorithm, in which each node assesses its connectivity and adapts its participation in the multi-hop network topology based on the measured operating region to establish a routing forwarding backbone. The authors claim that with the proposed algorithm, the energy saving is increased linearly as a function of the density and the convergence time. The authors also state that proposed algorithm performs well in case of node failures while still providing adequate connectivity.

Alqamzi et al. [2005] investigates how adaptive distributed compression can be efficiently integrated with the practical cluster-based sensor architecture in general and the low-energy adaptive clustering hierarchy (LEACH) protocol in particular. The authors claim that using an adaptive scheme based on rate compatible punctured convolutional codes, an additional energy reduction of 20% to 41% is achievable compared to conventional compression without modifying the routing protocol or complicating the system architecture.

In Luo et al. [2005] and Luo et al. [2006], the authors state that although in-network data fusion reduces communication cost, the data fusion process can itself introduce significant energy consumption in WSNs with vectorial data. In these papers, the authors present, what they claim to be a novel idea, the Adaptive Fusion Steiner Tree (AFST) routing algorithm for gathering correlated data in sensor networks that optimizes communication cost as well as fusion cost in terms of energy efficiency. The authors claim, on the basis of their analytical and experimental results, that AFST achieves better performance than fusion driven routing algorithms such as SLT, MFST, and SPT. The authors also claim that AFST achieves near optimal solutions under various network conditions

Santhanam et al. [2005] propose an Adaptive Multi-path Routing Algorithm (AMRA) for sensor networks that minimizes the energy consumption and provides better load balancing by dispersing traffic over the network. In their paper, the authors formulate a Hamiltonian costate representation for queue length of every sensor node in the network as a function of the cost incurred and the benefit obtained by a sensor node for forwarding packets. The authors state that this Hamiltonian is then subjected to Pontryagin's cost minimization for efficiently diffusing the packets among the next-hop neighbors. The authors compute the traffic diffusion by solving the steady state queue length equation in the frequency domain. The authors use an NS-2 based simulation program for performance analysis of the proposed algorithm. The authors claim that AMRA performs better in terms of increasing the lifetime of the network as compared to the AODV routing protocol. It is observed that the authors compare the performance of AMRA with the AODV protocol that is primarily meant for ad-hoc network not for sensor networks.

In Yi et al. [2005], the authors present Energy Aware Routing based on Adaptive Clustering Mechanism (EAR-ACM) to increase the lifetime of WSNs. The authors state that EAR-ACM is based on the Energy Aware Routing [EAR] algorithm. The authors also state that EAR-ACM uses a data aggregation technique and adaptive clustering mechanism to reducing the cumulative size of packets in WSNs. The authors claim, on the basis of their results, that EAR-ACM reduces the cumulative amount of data packets and significantly reduces energy usage among the nodes as compared to previous clustering based routing algorithm for WSNs.

There is one paper titled "Fuzzy based energy-efficient adaptive routing algorithm for wireless sensor networks" which appears to be relevant to the subject being discussed in this subsection. It has been published in 2005. Only Google scholar finds this paper, but this paper is not downloadable.

In et al. [2005] presents a Data Rate Adaptive Route Optimization (DRARO) scheme that provides a method for adjusting the route optimization level on the basis of the amount of data traffic, to minimize overall energy consumption. The previous research on routing algorithms such as Directed Diffusion (DD), TTDD, SEAD, ONMST, and HLETDR has made significant progress to support mobility in WSNs. These algorithms have various problems such as path management overhead increases as the number of sources increases or the stimuli frequently change their position. The authors claim that the proposed routing algorithm not only reduces the path management overhead due to mobility but it is not affected by the number, distributed area, speed, and duration of stimuli as well. In their paper, the authors present two new schemes, namely, Agent-Based Incremental Path Extension (ABIPE) and Directional Route Optimization (DRO) as part of proposed DRARO strategy. The authors state that near optimal paths can be constructed by DRO with significantly low overhead compared to that of flooding. The authors also state that as the source data rate increases, a higher level of route optimization is required to minimize overall energy consumption. In the paper, the authors state that the overhead and energy consumption increases linearly with the increase in the number and the speed of the sinks. The authors also state that throughput, energy consumption, and overhead are independent of the movements of the stimuli. The authors state that the throughput, and overhead are independent of the number of the stimuli also, but the energy consumption increases with the number of the stimuli because of the data traffic increase. The authors claim that DRARO can efficiently provide highly optimized paths for active sources, and ceaseless data forwarding paths for every sensor node.

In Zhou et al. [2006b], the authors address the problem of adaptive monitoring and routing in WSNs with the constraint that the routing scheme should conserve the energy of nodes with important data and should be robust to the failure of sensor nodes and transmission medium. The authors state that the routing algorithm proposed in their paper couples application requirements with energy conditions in the network and is designed for a flood early warning system as part of FloodNet project at University of Southampton. The details of Floodnet project is given in Zhou, and Roure [2007]. This paper is an extension of an earlier paper Zhou et al. [2006a] by same author. The authors state that previous research on power-aware localized routing, GEAR, LEACH, PEGASIS, and the Energy Aware Routing (EAR) protocol have made significant progress in extending network lifetime by evenly distributing the energy load among all the nodes in the network. However, the authors state that none of this earlier research work looks at the effect of the diversity in the reporting rates of nodes on the protocol design.

In Zhou et al. [2006b], the authors propose, what they claim to be a new idea, the FloodNet Adaptive Routing (FAR) that takes into account the distinct behaviors of individual nodes and uses priority as well as a set of rules in determining the routing path. The authors state that in FAR, the decision that a sensor node should be used to forward data messages is based on the distance, the residual battery power, the link cost, and the data importance of the node. Hence, FAR allows data messages to be routed across nodes with ample energy and light reporting tasks while conserving energy for those nodes which have a low level of energy and heavy reporting tasks. The authors state that FAR is a network layer protocol that assumes a collision-free, multiple retry MAC layer. In the paper, the authors present the description, design methodology, algorithm, and performance analysis of the proposed routing algorithm. The authors use two self developed simulators for the performance analysis of the proposed algorithms. Simulation results are summarized in Table I, II, III, and IV on page 90, and 91 of the paper. The authors claim, on the basis of their simulation results, that FAR can extend the network lifetime and the node operational time over EAR in the FloodNet topology and the performance increase of FAR over EAR grows as the network density becomes higher. The authors also claim that FAR outperforms Minimum Energy Consumption Forwarding (MECF) in the FloodNet topology by producing a longer network lifetime (NL) and a node operational time (NOT). The authors claim that FAR is robust to topological changes due to transient node and link failure due to the fact that in FAR, the optimal path is computed on demand.

Table II summarizes the contribution of research discussed in this subsection.

Table II. Summery of adaptive routing research discussed in subsection 3.1.2

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Comment
Zhu et al. 2002	Energy efficient, self-adaptive and error tolerant at the same time.	Spin glass and Multi-Fractal routing adaptation models.	Two new routing adaptation models.	Masters Thesis, ideas based on the theory of cellular automata.
Tateson and Marshall 2003	Minimize route cost in terms of energy consumption and loss of integrity of the network, Minimum overhead.	Varying the transmission range, Experimenting with the neighbors.	An adaptive routing mechanism that enables sensor nodes to minimize route cost.	
In et al. 2006	Minimizing energy consumption, Minimum path management overhead, Not affected by the number, distributed area, speed, and duration of stimuli.	Adjusting the route optimization level on the basis of amount of data traffic. Agent-Based Incremental Path Extension.	Agent-Based Incremental Path Extension (ABIPE) and Directional Route Optimization (DRO) as part of DRARO strategy.	
Zhou et al. 2006b	Minimize energy depletion of imp. Nodes, Adaptive to Application requirement.	Reporting rate.	FloodNet Adaptive Routing (FAR).	Centralized decision making, FloodNet topology.

3.1.3 *Energy balance along with other routing objectives.*

If all sensor nodes use only energy efficient paths, then after a period of time, the sensors nodes in the energy efficient paths become inactive as a result of energy depletion due to overuse. This causes an energy imbalance in the WSNs. The adaptive routing algorithms, presented in this subsection, try to balance the energy among sensor nodes along with the other routing objectives.

In Heinzelman et al. [1999], the authors present adaptive Sensor Protocols for Information via Negotiation (SPIN) that disseminate information among sensors in WSN. The authors state that in the proposed protocols, the meta-data negotiations are used to eliminate the transmission of redundant data throughout the network. The authors also state that in SPIN, the nodes take their routing decisions on the basis of application-specific knowledge of the data and the knowledge of the resources available to them. It facilitates the sensors to distribute data as per the available energy in the sensor network. The authors claim that the SPIN can deliver 60% more data for a given amount of energy than conventional approaches. The authors also claim that SPlN performs close to theoretical optimum in terms of dissemination rate and energy usage.

In her Ph.D. thesis Jain [2004], defended at University of Cincinnati, the author presents an adaptive distributed routing protocol for minimizing energy consumption in a sensor network. The author states that previous research on MDSR protocol, Backup Routing on AODV, and modified directed diffusion protocol with multiple path routing have made significant progress towards multiple path routing schemes that supports fault tolerance and load balancing in ad hoc and sensor networks. However, the author states that these multiple path schemes are based on probabilistic models and might not perform work successfully to achieve an equal load distribution with heavy and uneven traffic. The author claims that the proposed protocol is based on a deterministic model that guarantees uniform traffic spreading because it accurately assigns load to all possible available paths on the basis of current energy level of the nodes.

In her thesis, the author claims that an adaptive energy aware routing infrastructure, which enables in-network processing of spatio-temporal queries in sensor networks, is presented for the first time. In the thesis, the author also proposes the multiple path routing protocol MidHopRoute that spreads the routing load between the source and destination nodes over a large number of sensor nodes to minimize disparity in the energy levels of the sensor nodes. In this thesis, the author presents a detailed discussion, mathematical analysis, and simulation results of the proposed adaptive routing infrastructure. The author uses an NS2 network simulator for simulation of the proposed algorithms. The author claims that the proposed protocol is able to avoid congestion in the network that enhances the overall network lifetime in presence of heavy traffic due to random multiple queries in the network. The author also claims that the proposed protocol provides low response time for time critical queries as well as a longer lifetime of the network at the cost of response time for non-critical queries. In this thesis, in future work, the author states that multiple path protocol may be extended to include link quality of paths as a parameter to grade paths so that resilience to path failure may also be achieved while routing data.

Lin et al. [2004] address the problem of adaptive routing with the constraint that it should increase the network life time and support immobility management in clustered WSNs. The authors state that their proposed algorithm is an improvement of the Pure Shortest-Path Routing (PSPR) protocol. The authors state that in the PSPR protocol, the massed power consumption of routing along the same paths speedily decreases the energy of the active nodes, while the protocol proposed in their paper is designed to avoid such decisions in order to extend the lifetime of the WSNs. The authors introduce, what they claim to be a novel idea, the idea of Power-aware Chessboard-based Adaptive Routing (PCAR) that combines the vector-oriented propagation, power-consideration decision, and multi-path routing protocols to guide the data to its destination. The authors state that the properties of the cluster are combined in the PCAR to form cluster-plates in a chessboard-based clustered sensor network. In the paper, the authors present the PCAR algorithm and its simulated Implementation using self-developed Java simulation programs. The authors state that due to the strategy of the dynamic routing path, the levels of power consumption of nodes in PCAR schemes are lower and more balanced than those of nodes in PSPR schemes. The authors claim that the overall lifetimes of the network are largely improved with PCAR scheme as compared to the traditional PSPR, RMPR, MPOR and POMPR schemes.

The report by Close and Mishra [2005] presents a routing technique that dynamically adapts to the changes in individual nodes' power levels to increase the lifetime of the remote sensor networks. The authors state that the previous research in the area of path routing to conserve energy and lengthen network lifetime requires a centralized scheme with great fore-knowledge about the network including its node dispersal and frequency at which a particular node will generate a message and send it to the base-node. In the paper, the authors present an adaptive decentralized routing scheme that will allow dynamic paths. The authors state that the algorithm proposed in their report assume to have one base node and no knowledge of the present state of the network after its deployment. In the report, the authors claim to present the new idea of P2P Assisted Voice Communication for Power aware packet routing. The authors state that the central idea of this method is that routing paths through-out the network can change as power reserves in individual nodes diminish. In the report, the authors present the simulation results with respect to location of base node for power adaptive topology and compared them with the least hop topology. The authors state that proposed power-adaptive routing topology produces increased life span as compared to least-hop routing topology irrespective of the network size and the placement of the base node. The authors claim that proposed topology requires very little computational overhead as well as it does not need any additional transmissions or hardware. The authors claim that the lifespan of the networks can be improved by up to 60% by using their power-adaptive topology as compared to least hop topology.

In Golampour et al. [2005], the authors present a power efficient data routing technique for a two-tiered WSN that has fixed location Application Nodes (AN) and Base station. The Authors state that the proposed routing approach controls the data flow routing path adaptively in order to use the remaining power of the network as efficiently as possible. The adaptive routing algorithm presented in Sun et al. [2005], which is already discussed in subsection 3.1.1, also has the energy balance feature.

In Chen et al. [2006], the authors present optimal Packet Length Adaptation (PLA) that adjusts packet length adaptively as per the network instant statistics in order to maximize the throughput and energy utilization in noisy wireless channels. The authors state that as the noise introduces more energy consumption, it is equivalently regarded as lengthening of transmission distances. The authors integrate the PLA with the Energy-Proportional Routing (EPR) algorithm to provide energy balance in WSNs.

In Wang and Wang [2006], the authors address the problem of adaptive routing that selects the optimum route with the objective of maximizing network life time by making the correct trade-offs between multiple routing objectives. In their paper, the authors use reinforcement learning technique that addresses above mentioned routing requirements. The authors begin by stating that most of previous research on routing focuses on reducing routing cost by optimizing one goal such as routing path length, load balance, re-transmission rate, etc, in real scenarios. The authors appear to be the first to propose a routing scheme that considers multiple routing optimization goals together. The authors state that the paper is based on previous research on machine-learning-based routing for WSNs. The authors claim to present a novel routing scheme, AdaR that is based on the Least Squares Policy Iteration (LSPI) based reinforcement learning technique, which makes it possible to learn a best strategy with a small number of tries and is insensitive to the initial parameter setting. The authors state that AdaR adaptively learns an optimal routing strategy depending on multiple optimization goals. The authors claim that quality of the optimal routing strategies in terms of cumulative reward and success rate of routing is almost the same in both AdaR and the Q-learning based routing implementation. However, the authors state that AdaR shows a significant performance gain in terms of convergence speed over a Q-learning based routing implementation.

In Xu et al. [2006], the authors appear to be the first to apply spatial diversity for Energy-aware and Link-adaptive routing for Ultra Wide Band (UWB) sensor networks. The authors state that, unlike the proposed algorithm in their paper, the previous research on routing protocol for WSNs focuses on energy conservation and does not take into account other network performance metrics such as throughput and end- to-end delay. The authors state that the paper extends the work of a previous paper Xu et al. [2005] by same authors, by considering a time varying channel environment and a more realistic mobility model. In the paper, the authors propose energy-aware and link-adaptive next hop routing metrics, such as such as Maximum Forward Progress (MFP) or Maximum Information Progress (MIP), based on the availability of sensor node's location, link quality and next hop battery capacity information. In the paper, the authors utilize the ranging capability of UWB and employ adaptive modulation to take advantage of favorable link conditions. In the paper, the authors present the description of system model, routing metrics, and routing schemes. The authors state that the energy-aware routing metrics (MFPenergy and MIPenergy) have equal or better average throughput than the corresponding metrics that do not use battery capacity information in the routing decision (MFP and MIP). The authors also state that the routing schemes MFP metric with Adaptive Modulation (MFP-AM) and MIP metric with Adaptive Modulation (MIP-AM) perform better in terms of average throughput before any node dies out than the non-link-adaptive scheme MFP metric with fixed modulation (MFP-FM). The authors claim that MIP metrics increase average throughput by 30-50% (100-300% in a time varying channel environment) before network performance deteriorates compared to MFP metrics while exhibiting smaller delay. The authors state that it is due to the ability of the MIP metrics to adapt to the link quality in the routing decision. The authors state that mobility improves throughput performance and prolongs network lifetime for all of the metrics compared to the static node scenario due to the added spatial diversity and equalized energy consumption.

In Zhang and Huang [2006a], the authors paper presents an adaptive spanning tree routing mechanism using real-time reinforcement learning strategies for WSNs. The authors state that earlier they have proposed four major routing strategies for WSNs. These routing strategies are Message-initiated Constraint-Based Routing (MCBR), real-time search, constrained flooding, adaptive spanning tree. The authors state that the work done in the paper is an extension of previous work by the same authors on adaptive spanning tree proposed in Zhang and Huang [2006b]. The authors state that basic ideas and protocol of adaptive trees have been presented Zhang and Huang [2006b]. The authors also state that the new contributions of the paper include defining new routing metrics for energy-aware load balancing to increase lifetime, and for congestion-aware routing to reduce latency and increase reliability. In the paper, the authors state that Adaptive trees is different from real-time search and constrained flooding routing strategies in the sense that it requires a known sink at its initialization. The authors also state that implicit confirmation and retransmission are used, rather than sending periodical maintenance packets from the sink node as in many tree-based routing protocols. The authors state that the Adaptive Tree Protocol is between structure-based and structure-less. In the paper, the authors present an extended study of the adaptive tree protocol, as well as performance analysis and comparisons with other peer routing protocols. The authors state that simulation test for performance analysis is done on RMASE that is an application built on PROWLER sensor network simulator. The authors state that the parameters in the protocol such as learning rates for Q-values, update rates for NQ-values, parent reset threshold, and the maximum number of retransmissions for failed confirmations, can be tuned to make the routing best for a particular application. In the paper, the authors claim that adaptive tree protocol is robust for un-predictable link failures and mobile sinks, and can be applied to achieve load balancing and to control network congestion effectively in real time. In the paper, in future work, the authors state that lots of research still needs to be done on the selection of parameter values and understanding the relationship between different parameters.

In Chen et al. [2007], the authors begin by stating that it is inefficient to choose different routing algorithms manually for different applications. In their paper, the authors present an auto-adaptive routing mechanism that facilitates the use of the two or more routing methods in a WSN. The authors state that previous research on the Geographical and Energy Aware Routing (GEAR), Graph Embedding Routing (GEM), and the Directed diffusion (DD) routing algorithm have made significant progress in the routing in WSNs. However, the authors state that once any of these routing methods are deployed, it does not change as per the application requirements in a particular sensor network. The authors also state that the proposed routing method based on a node's geography position is similar to the Ant Colony Optimization Algorithm In the paper, the authors proposed two routing methods that are for sensor node's localization and for object's localization respectively. The authors state that node positions are obtained through the node localization algorithms, and then energy aware Geography Position based Routing method (RGP) is used for the object's information acquisition. The authors state that proposed RGP routing method selects either minimum distance path or the path with larger average energy based on the a and ß parameters in the algorithm. In the paper, the authors present the description, flow chart and mathematical formulation of proposed routing algorithms. The authors provide the simulation results for the proposed routing method based on Node's Geography Position. The authors state that in the proposed routing mechanism, the average energy consumption is smaller than DD routing algorithm. The authors claim that the proposed routing algorithm has a high performance as it can choose a shorter path routing or energy balanced routing as per the application requirement by adjusting its parameters.

In Dong and Quan [2007], the authors appear to be the first to apply a topology matrix for controlling the power for routing adaptation in WSNs. The authors state that previous research on LEACH and PEGASIS, and MECH have made significant progress in the hierarchical routing in WSN. However, in these algorithms, either the energy state of nodes is ignored or the overuse of leader nodes or cluster heads causes fast depletion of their energy. In their paper, the authors present a new hierarchical Topology-Based Power-Adaptive Routing (TBPAR) algorithm. The authors state that TBPAR uses the information of a topology matrix to build more reasonable routing paths. The authors also state that the nodes adapt their transmitting power according to their energy status to balance energy consumption among themselves. In the paper, the authors present the methodology of calculation of topology-matrix and description of proposed routing protocol. The comparative results for maximum and minimum life-times of sensor nodes for three routing protocols are summarized in Table 3 on page 2794 of this paper. The authors state that the proposed TBPAR has the biggest mean life-time and smallest deviation as compared to LEACH and PAGASIS. The authors claim, on the basis of their results, that the proposed algorithm increases the life-time of whole network and reduces the difference in life-time between each node. The authors also claim that TBPAR provides high energy efficiency and high stability to the network.

In Ok et al. [2007], the authors appear to be the first to propose a routing algorithm for WSNs that has support for energy balance and is capable to responding properly to events that have uncertainty in their position and generation rates. The authors state that previous research on direct communication approaches, hierarchical routing methods, and self-organized routing algorithms have made significant progress in routing research in WSNs. However, the authors state that the previous routing approaches have little or no support for energy balance and robustness against diverse event generation patterns, while the routing algorithm proposed in their paper provides support for these requirements. In the paper, the authors present a new routing algorithm, called Distributed Energy Adaptive Routing (DEAR). The authors state that in the proposed algorithm, sensors do not care if the receiving node sends data to the base station or passes data to one of its neighboring nodes. Through this local decision making process, a sensor network can achieve energy balance and prolong the lifetime of the sensor network. The authors state that the proposed algorithm uses a new heuristic metric, called Energy Cost (EC) that represents transmission energy cost relative to available energy and it is used to establish energy sufficiency as well as efficiency to pursue energy balance for the sensor network. In the paper, the authors present the description of the DEAR algorithm, energy consumption model, and event generation functions. The authors present the simulation results using a self developed simulation program in the C programming language. The authors use the LP solver, called LINDO, for solving the mathematical model. The authors state that the DEAR algorithm with 20m neighboring distance of the square sensor network has better performance in terms of lifetime of sensor nodes than Direct Communication (DC), Minimum Transmission Energy (MTE), and Self-Organized Routing (SOR) algorithms until 50(%) of nodes die. The authors also state that in the DEAR algorithm with 100m neighboring distance, the majority of sensors are alive up to 200 rounds and deplete simultaneously, thus indicating good energy balance throughout the network. The authors claim, on the basis of their results, that the proposed algorithm is simple and supports scalability.

The adaptive routing algorithm presented in Peng et al. [2007], which has already been discussed in subsection 3.1.1, also has an energy balance feature. Wang et al. [2007] is available in the Chinese language, hence the description presented here for this paper are based its rough English translation. In the paper, the authors address the problem of adaptive data fusion routing in WSNs in which the mobile agent (MA) collects correlated data with energy validity. The authors state that the work presented in the paper is based on the previous research on Full Fusion Genetic Algorithm (FFGA), Multi-objective mobile agent, routing correlated data with fusion cost, and adaptive data fusion for energy efficient routing for WSNs. In the paper, the authors introduce, what they claim to be a novel idea, a genetic algorithm based adaptive data fusion routing algorithm, called Adaptive Fusion Genetic Algorithm (AFGA). The authors state that in the proposed routing algorithm, the MA moves to every sensor node that performs data fusion. The authors also state that to provide energy efficient route, the MA is adaptively adjusted according to data transmission cost, data fusion cost and energy gain. In the paper, the authors present the mathematical formulation, and algorithmic description of the proposed routing algorithm. The authors also present a performance analysis based on MATLAB based simulator. The authors claim, on the basis of their results, that the energy efficiency of adaptive fusion routing algorithm has better performance than full fusion routing algorithm and Local Closest First (LCF) heuristics algorithm.

Table III summarizes the contribution of research discussed in this subsection.

Table III. Summery of adaptive routing research discussed in subsection 3.1.3

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Comment
Jain 2004	Maximizing energy levels on the route, Minimize disparity in	In-network processing of spatio-temporal queries,	An adaptive energy aware routing infra. and a multiple path	Ph.D. Thesis, Distributed decision making.

	the energy levels, avoiding congestion.	deterministic model.	routing protocol (MidHopRoute).	
Lin et al. 2004	Power adaptive, increasing the network life time and supporting immobility management.	Combining vector-oriented propagation, power-consideration decision, and multi-path routing protocols.	Power-aware Chessboard-based Adaptive Routing (PCAR).	Clustered wireless sensor networks.
Close and Mishra 2005	Adapts to the changes in individual node's power levels to increase the life time of network.	P2P Assisted Voice Communication.	Power aware packet routing.	Technical Report, Remote Sensor Networks.
Sun et al. 2005	Minimizing delivering delay and total energy consumption of data delivery, Making energy consumption even.	Using restricted flooding to spread routing instruction that contains hop count and minimum residual energy information.	Dynamic Energy Aware Routing (DEAR) algorithm.	Data querying sensor networks
Wang and Wang 2006	Maximizing network life time.	Reinforcement learning, Consideration of various optimization goals together.	An Adaptive Routing scheme (AdaR).	
Xu et al. 2006	Maximizing energy levels on the route, Link adaptive.	Spatial diversity, Geographical awareness through feedback	Energy-aware and link-adaptive routing metrics.	Ultra Wide Band (UWB) sensor networks.
Zhang and Huang 2006a	Energy balance, Control network congestion, Adaptive to Network condition, Adaptive to Application req.	Reinforcement learning, Real-time search, Parametric tuning.	A Learning-based Adaptive Routing Tree.	
Chen et al. 2007	Choosing shortest path routing or energy balanced routing as per the application requirement.	Tuning using parameters in the algorithm.	Node localization algorithm and Geography Position based Routing method (RGP).	
Dong and Quan 2007	Energy balance	applying topology matrix for controlling the power	Hierarchical Topology-Based Power-Adaptive Routing (TBPAR) algorithm.	
Ok et al. 2007	Energy balance and responsiveness to the events.	Using Energy Cost (EC) heuristics	Distributed Energy Adaptive Routing (DEAR).	Distributed decision making.
Peng et al. 2007	Minimum energy consumption, Energy balance, Real time.	Choosing next hop neighbor based on real-time requirement and energy index. Uses RT and TTL fields of the packet.	An adaptive real-time routing scheme (ARP).	Distributed decision making.

Wang et al. 2007	Maximizing network life time.	Uses Genetic Algorithm, Multi Agents is adaptively adjusted according to data transmission cost, data fusion cost and energy gain.	Adaptive Fusion Genetic Algorithm (AFGA).	Data centric decision making.

3.2 Non-energy goal as the main routing objective

Non energy routing objectives are further divided into three categories. The first category puts emphasis on adaptive routing protocols that provides fault tolerance along with other routing objectives. The second category puts emphasis on adaptive routing protocols that are capable of selecting appropriate routing service from a given set of available routing services, and at the same time, consider other routing objectives as well. The third category puts emphasis on routing protocols that have routing objectives, which do not fall under any of earlier mentioned categories.

3.2.1 *Fault tolerance along with other routing objectives.*

In this subsection, those adaptive routing protocols are presented that have a fault tolerance feature. The adaptive routing algorithm presented in the Masters thesis Zhu [2002], which has already been discussed in subsection 3.1.2, also has fault tolerance feature.

In Brooks et al. [2003], the authors appear to be the first to address the problem of distributed adaptation of data routing using emergent behavior for WSNs. The authors state that previous research on the Link State (LS) routing algorithm, Destination Sequenced Distance-Vector routing algorithm (DSDV), Dynamic Source Routing (DSR) protocol, Ad hoc On Demand Distance Vector (AODV) routing protocol, and the Greedy Perimeter Stateless Routing (GPSR) algorithm have made significant progress on distributed routing problem. However, these previous approaches either lack adaptation in routing or have very limited support for it. In their paper, the authors focus on the adaptation feature of distributed routing algorithms and claim to use emergent behavior for routing adaptation for the first time. The authors present four new adaptation methods that are Spin glass, Multi-Fractal, Coulombic and Pheromone. In fact, one of the authors of this paper has already proposed Spin glass, and Multi-Fractal adaptation methods earlier in the Masters thesis Zhu [2002]. The authors claim that they use the ideas from Physics, Biology and Chemistry for the first time for distributed adaptation. In the paper, the authors present mathematical formulation and performance evaluation based on simulation of all four proposed adaptation methods. The authors state that Multi-Fractal model works well for overhead sensitive applications that require quick deployment, while the Spin glass model works well for applications requiring low data paths. The authors say that Pheromone is suitable where error resilience and low overhead is the requirement while the Coulombic model works well where data sources are evenly distributed throughout the network. The authors claim that routing adaptation based on emergent behavior could perform global adaptation using only locally available information. In the paper, in future work, the authors say to workout a unifying abstraction that contains proposed four adaptation methods as subsets.

In the Masters thesis, Gregoire et al. [2007], the author claims to be the first to propose an adaptive mechanism for fault tolerant message re-routing that is useful for WSNs in the harsh environment. The author states that previous research on Directed Diffusion (DD), Dynamic Source Routing (DSR), Distance Vector Routing (DVR), and Optimized Link State Routing

(OLSR) protocols have made significant progress in the routing research in WSN. However, the author states that these routing algorithms do not always have a fault tolerant plan. In the thesis, the author proposes a series of routing algorithms that run on top of and in conjunction with existing routing protocols by adding fault tolerance in the form of retransmitting and rerouting messages at the routing layer. The research work done in the thesis is an extension of an earlier published paper, [Gregoire et al. 2007], by the same author. The author states that the proposed fault tolerant mechanism uses an algorithm that watches radio activity to detect the occurrence of a fault and then takes actions at the point of failure by re-routing the data through a different node without starting over on an alternative path from the source. Figure 7 on page 13 of the thesis gives an example of fault tolerant re-routing. The author states that the proposed routing mechanism works in an entirely distributed fashion, in which each node makes its decision solely based on information it gathers by passively monitoring radio traffic around it and no feedback or direct communication with other nodes is involved. The author also incorporates different learning methodologies, support for correlated events, and message combining mechanism in the proposed routing algorithms.

In the Masters thesis, Gregoire [2007], the author presents a description and algorithms for the proposed routing mechanism that includes two algorithms for the next best neighbor selection schemes. The author states that limited testing is performed on the real hardware with 12 mica motes as sensor nodes and thorough testing is done using 50 nodes on a TOSSIM simulator and TinyViz that comes with TinyOS. The author claims that by using the parameters, such as the number of retries, the proposed routing mechanism can be tuned to provide a high message success rate while still being energy-efficient in both benign and hostile environments. The author also claims, on the basis of results on node depth, that fault tolerant routing mechanism is able to expand the size of the networks far beyond what it could be without fault tolerant routing. The author claims that by combining similar messages into one message and scaling the number of retries accordingly, the correlated events are dealt properly both in terms of energy usage and message success rate. The author also states that as the sleep period of the nodes increases, the energy is reduced and the success rate holds relatively constant until a point is reached where there is not enough node wake-up time to transmit all the data and the success rate rapidly drops off. The author states that comprehensive test of the proposed routing mechanism needs to be done using hardware in future.

Table IV summarizes the contribution of research discussed in this subsection.

Table IV. Summery of adaptive routing research discussed in subsection 3.2.1

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Comment
Zhu et al. 2002	Energy efficient, self-adaptive and error tolerant at the same time.	Spin glass and Multi-Fractal routing adaptation models.	Two new routing adaptation models.	Masters Thesis, ideas based on the theory of cellular automata.
Brooks et al. 2003	Error resilience, Low overhead, Support for evenly distributed data sources and low data paths, Quick application deployment.	Spin glass, Multi-Fractal, Coulombic and Pheromone routing adaptation models.	Four new routing adaptation models.	Based on ideas from Physics, Biology and Chemistry.

Gregoire 2007	Fault tolerant message re-routing.	Watching radio activities to detect faults, re-routing data through different nodes at the point of failure.	Adaptive mechanism for fault tolerant message re-routing.	Masters Thesis, WSN in harsh environment, Distributed decision making.

3.2.2 *Routing service selection along with other routing objectives*.

The majority of WSN routing protocols have built-in routing objectives and strategies, therefore it is not possible to change the routing objective and strategies once the protocol is implemented on the sensor nodes. In contrast to this inflexibility, the routing protocols discussed in this subsection are capable of selecting an appropriate routing service from a given set of available routing services when needed.

In Figueiredo et al. [2005], the authors appear to be the first to apply policies-based approach for adaptive routing in autonomous WSNs. The Authors begin by stating that previous research on Adaptive and hybrid approaches for routing in WSNs consists of viable solutions to deal with variable scenarios but, they generally provide rigid solutions for some specific cases. The authors state that their work shows how policies can effectively be used in the routing for autonomous WSNs. In their paper, the authors introduce the policy based approach for routing that allows the autonomous selection of the best routing strategy in view of network conditions and application requirements. The paper presents the conception and implementation of routing policies through a generic model. The authors present case studies of adaptive routing using policies and the associated results in the paper. The authors state that Simulation results show the consistent benefits and resource savings offered by the use of policies for adaptive routing in WSNs. The author claim that for a highly variable WSN environment, the policy-based adaptive hybrid approaches perform better than a single routing algorithm. In the paper, in future work, the authors say to implement policy-based routing rules on real sensor nodes as well as to devise and implement policy-based routing rules to modify the routing QoS metric.

In the Ph.D. thesis, HE [2005], defended at University of Southern California, the author addresses the problem of choosing appropriate routing service in ad-hoc and sensor networks based on application requirements and changes in the network properties. The author states that previous research on Diffusion filters, Mate, and Impala have made significant progress in improving the service flexibility in sensor networks. However, the author states that in the above mentioned routing mechanisms, the changing granularity can be large in terms of code size and energy overhead. In this thesis, the author presents a new routing paradigm that facilitates the routing service change with fine granularities with small energy overhead in sensor networks. The author also states that proposed routing protocol for sensor network is heavily influenced by Directed Diffusion routing protocol.

In the thesis, the author proposes a general approach called active ad-hoc network routing for mobile ad-hoc networks that uses a helper module to improve existing routing algorithms without changing their inner mechanisms. The author states that DSR is used as a target service for proof of concept of proposed routing approach and the resulting service is called Active Dynamic Source Routing (ADSR). The author also presents, what he claims to be novel idea, a new routing paradigm called X Visiting-pattern Routing (XVR) that facilitate multiple routing services with different visiting-patterns to run simultaneously in a sensor network. The author states that XVR provides a unified and comprehensive environment to study the effects of various visiting-patterns on routing and application performance. The author also states that in

XVR, packet handlers are separated from their corresponding visiting-pattern components and this separation enables independent visiting-pattern changes. In the thesis, the author presents an Automatic Visiting-pattern Routing (AVR) protocol for sensor networks that automatically chooses and changes visiting-patterns on top of the XVR with changing application and network dynamics.

In the thesis, the author simulates AVR routing algorithm in NS-2 network simulator with simulated sensor network composed of 100 nodes in a 1500m x 1500m field that does not contain partitions. The author provides the description of how to use XVR to study existing and new routing algorithms, and how to build automatic routing services on top of XVR. The author also presents a case study to show how to conduct automatic routing changes between two known routing services, push and pull, with XVR, and evaluates the performance gains. In this thesis, the author also presents the description and algorithm of active ad-hoc network routing services for mobile ad-hoc networks. The author claims, on the basis of simulation results of ADSR, that the routing performance is improved up to 47%, the TCP performance is improved up to 70%, and the energy consumption per transmitted data is saved up to 25%. The author also claims that the XVR version of one-phase pull Directed Diffusion obtains scalable energy consumption while improving delivery ratio by 70% as compared with conventional one-phase pull Directed Diffusion. The author states that in terms of future work of XVR, the associations between different visiting-patterns, application, and network performance are important to realize automatic mapping.

Yuan-yuan et al. [2005] present an adaptive directed diffusion routing in WSNs based on application (ADDRA). In the paper, the authors begin by stating that the performance of traditional Directed diffusion routing protocol can degrade drastically if it is not matched with the sensor applications. In this work, the authors present an improvement in Directed diffusion routing protocol by taking application scenario into consideration while taking routing decisions. In the paper, the authors claim to present a new general message machine that is used for adaptive selection of possible routing approaches for WSNs. The authors state that the general message machine is applicable where the application scenario does not change quite often. In the paper, the authors propose ADDRA routing protocol that works as per the application environment by switching adaptively from normal model to push model to match current application scenarios.

In the paper, the authors present the description and model of ADDRA protocol. The authors evaluate the performance of proposed protocol on a simulated environment with various simulated application scenarios. The authors use NS2 simulator with a network size of 250 nodes with transmission range of 20 meters. The authors also compare the performance of ADDRA protocol with other versions of directed diffusion algorithm. The authors claim that the ADDRA has better performance in varying application environment and network dynamics than the other versions of directed diffusion algorithm such as One-Pull Phase directed diffusion routing algorithm (OPP), and push directed diffusion routing algorithm. In the paper, in future work, the authors plan to develop an extended message machine to include QoS requirements of applications.

The adaptive routing algorithm presented in Chen et al. [2007], which has already been discussed in subsection 3.1.3, also has the routing service selection feature.

Table V summarizes the contribution of research discussed in this subsection.

Table V. Summery of adaptive routing research discussed in subsection 3.2.2

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Comment
Figueiredo et al. 2005	Selection of the best routing strategy as per network conditions and application requirements.	Policies-based approach.	Policy-based approach for routing adaptation.	Autonomous wireless sensor networks.
He et al. 2005	Selection of the appropriate routing service as per network conditions and application requirements.	Using X Visiting-pattern Routing that facilitate multiple routing services to run simultaneously.	X Visiting-pattern Routing paradigm (XVR), and Automatic Visiting-pattern Routing (AVR) protocol.	Ph.D. Thesis
Yuan-yuan et al. 2005	Adaptive to Application requirement, Adaptive to topology changes.	General message machine for adaptive selection of possible routing approaches.	Adaptive Directed Diffusion Routing Algorithm (ADDRA).	A Variant of directed diffusion routing.
Chen et al. 2007	Choosing shortest path routing or energy balanced routing as per the application requirement.	Tuning using parameters in the algorithm.	Node localization algorithm and Geography Position based Routing method (RGP).	

3.2.3 *Other routing objectives.*

The adaptive routing protocols discussed in this subsection do not fall under any of earlier mentioned routing objective categories.

In Okino and Corr [2002a], the authors appear to be the first to identify the problem to adaptive routing in the sensor networks in general, and Statistically Accurate Sensor Network (SANS) in particular. The authors state that the paper is an extension of an earlier paper Okino and Corr [2002b] by the same authors. In the paper, the authors present new performance results and analysis of adaptive Best Effort multi-Hop Geographical Routing (BEHGR) protocol that is proposed in Okino and Corr [2002b].

In their paper, the authors use BEHGR protocol as the basis of work, where BEHGR statistically attempts to dynamically route packets to a central location in a "best effort" manner for SANS. The authors state that to adapt routing, some percentage of the collected and transmitted data from each of the nodes in SANS reach home in order to provide an accurate picture of the measured and collected data of the network. The authors state that in SANS, no routing tables are required, no route discovery procedure is explicitly executed end-to-end, and nodes either acts as a client to forward packets or as servers in order to receive packets. In the paper, the authors present extended analysis of BEHGR protocol as a sequel of earlier analysis of same protocol, proof of theorems, and analysis and comparison of currentness of BEHGR protocol for line, star and grid topologies. In the paper, the authors define the performance metric for measuring network throughput and delay in SANS. The authors evaluate the performance of BEHGR protocol on a real test-bed, in which the sensor modules are distributed in a k X k grid arrangement. The authors claim that the star topology appear to provide the better overall currentness for BEHGR protocol. The authors state that currentness decreases rapidly as the grid size increases due to queuing losses.

In his Ph.D. thesis, Ke [2006], defended at Boston University, he appears to be the first to address the problem of adaptive routing for extremely large wireless sensor networks (WSNET).

The author states that WSNETs may be deployed incrementally by potentially different owners, with no single addressing system guarantees. The author also states that in WSNETs, the underlying routing mechanism must be selective enough to propagate data only to relevant parts of the network, and adaptive enough to offer services that can conciliate different addressing needs and meets different application level communication requirements. The author states that previous research on clustering based routing algorithms and cluster heads election algorithms have made significant progress in routing in WSNs. However, the author states that the past research have been done for the sensors that are programmed and deployed for a single task, with all communication paradigms set for one purpose.

In the thesis, the author presents, what he claims to be novel idea, an attribute based single unified routing infrastructure for sensor networks that is flexible in its naming/addressing and packet forwarding schemes. The author states that previous clustering algorithms attempt formation of clusters that satisfy certain invariant properties, communication metrics or topological properties. The author states that in contrast to previous clustering algorithms, the proposed algorithm forms clusters that reflect application level communication needs by tying attributes, which are relevant to inquiries posed to the sensor network, to the overlaid cluster structure. The author states that in the proposed routing infrastructure, multiple hierarchies can be supported simultaneously that enables multiple applications to select the set of sensors that best meet their own addressing needs.

In the thesis, the author presents the specification of attribute hierarchies, data structures for routing, pseudo code and algorithms for cluster formation and maintenance, and routing rule sets for tree traversal mode and mesh traversal mode of the hierarchies. The author claims, on the basis of his results, that attribute based hierarchical schemes offer increased communication gains as opposed to flooding mechanisms for disseminating new inquiries. The author also claims that the performance of tree based traversal modes surpasses mesh traversal modes in transmission costs for address resolution in the worst scenario case, but underperforms when considering the speed of the resolution process and the path length formed. In the future work, the author states that optimality analysis of the tradeoff between the number of levels in the hierarchy and the gains obtained is still need to be done. The author also states that different traversal modes and their performance expectations can also be investigated as it contribute to the increased performance of applications being executed over deployed sensor networks.

In Leibnitz et al. [2006], the authors appear to be the first to address the problem of routing in mobile ad-hoc/sensor networks with the constraint that nodes have no explicit knowledge of the network topology, except for their coordinates and the neighboring nodes within an RF transmission range. The authors state that the routing scheme proposed in their paper is an extension of biologically inspired Adaptive Response by Attractor Selection (ARAS) algorithm. In the paper, the authors present, what they claim to be new idea, an entirely distributed self-adaptive multi-path routing mechanism called Mobile Ad-hoc Routing with Attractor Selection (MARAS), where each node operates autonomously and gathers information about the network topology only by exchanging messages with its neighbors. The authors also state that proposed mechanism determines the probabilities for choosing the next hop of a packet on its path to the destination. The authors state that the suitable paths with small number of hops or high path length-to-distance ratio are rewarded, whereas long paths or those which do not lead to the destination are penalized. The authors state that the proposed routing method can easily compensate for sudden changes in the topology of the network. The authors also state that the routing scheme proposed in the paper is designed primarily for Ad-hoc networks, the implementation of the proposed routing scheme can be performed in a straightforward manner with numerical methods, which makes it applicable for networks with nodes that have only limited computational capabilities like sensor networks.

In the paper, the authors present the analytical description, mathematical formulation, and algorithm of proposed MARAS algorithm and elaborate on how to apply it to self-adaptively determine the next hop in routing. The authors states that the greedy selection routing scheme always outperforms MARAS for higher node density, whereas for small node density, for average packet delivery rate as a function of the node density, MARAS achieves better performance than the greedy approach especially when the radius is small. The authors claim that as the selection of next hop is done independently by each node in the proposed routing algorithm, it scales well with the number of nodes.

Macedo et al. [2006] presents an adaptive rule-based routing protocol for continuous data dissemination WSNs that interacts with the application for route determination. The Authors refer to previous research on Directed Diffusion (DD) protocol, Energy-Aware Distributed routing (EAD), TinyOS Beaconing protocol, and SPAN, as the basis of their work. The authors state that earlier no protocol was designed for continuous data dissemination network that uses application information for efficient route determination. The authors state that the proposed protocol extends backbone concept of SPAN routing protocol to WSNs. In the paper, the authors present a Proactive Routing with Coordination (PROC) protocol that interacts with the application to determine efficient routes. In the paper, the authors present algorithm, analysis, and model of PROC protocol. In the paper, the authors estimate that the upper bounds is O(v) for memory utilization and O(2v) for number of routing messages required to build the backbone, where v is the number of neighbors. The authors claim that PROC increases network lifetime around 7% to 12%, and has a higher throughput than both EAD and a simplified version of TinyOS Beaconing when number of nodes in the network changes from 20 to 200. The authors state that "PROC presents a graceful performance degradation when the number of nodes in the network increases".

In Mascolo and Musolesi [2006], the authors present an adaptive routing protocol that forwards data towards the right direction at any point in time in mobile sensor networks by exploiting the movement and resource prediction techniques over context of the sensor node. The authors state that the previous research on epidemically inspired approaches and probabilistic delivery approaches has made significant progress for mobile sensor data gathering. However, the authors state that these approaches have quite a high overhead in terms of communication and, therefore, energy consumption is quite high. The authors claim that proposed approach has less communication overhead as compared to previous approaches for mobile sensor data gathering. The Authors state that the work presented in the paper is an extension of their previous work on Context-aware Adaptive Routing (CAR) protocol for mobile ad hoc networks.

In the paper, the authors present, what they claim to be novel idea, the idea of Sensor Context-Aware Routing (SCAR) routing approach that uses Kalman filter forecasting techniques over context of the sensor node to predict its neighbors that are the best carrier for the data messages. The authors state that SCAR has maintained the prediction based approach used in CAR but all the aspects related to the communication and the replication are redesigned. In the paper, the authors present the algorithm for SCAR routing, the analytical model for forecasting techniques for probabilistic routing, and the analysis of buffer management procedures and replication process. The authors state that they are yet to evaluate the proposed algorithm. The authors claim, on the basis of their theoretical analysis, that SCAR provide a better trade-off between the delivery ratio and the energy consumption as compared to traditional epidemically inspired approaches or probabilistic delivery approaches for mobile sensor data gathering.

Mahjoub and El-Rewini [2007] addresses the problem of routing in WSNs with the constraint that it should be adaptive to the environment, the network state or the orders of an external authority. The additional constraints are that the routing scheme should be able to change the objective to avoid hazards that the communication might encounter on the route as well as the routing decision should be solely dependent on localized knowledge. The authors state that the work presented in their paper is based on the previous research on Geographical and energy aware routing, improved distance vector routing (nLRTS) and Message-initiated constraint-based routing Zhang and Fromherz [2004a].

In the paper, the authors introduce a new architecture that distributes routing plans from a Central Control Authority (CCA) to the sensors. The authors state that CCA assumes knowledge of the field's boundaries and breaks it into regions, where each region is assigned a powerful sensor node called Region Control Node (RCN) that coordinates with the sensor nodes in its region. The authors state that using this architecture, routes adapt to changes in the environment based on the learned estimated cost values to the destination of each neighbor. The authors also state that in the proposed architecture, a real time search algorithm is used as a decision making method for routing a message to the next hop. The authors state that in the proposed architecture, greedy geographic routing is used by default, but in the face of a hazardous environment, the messages have to switch objectives and minimize the hazard instead of distance. Once the messages reach to relaying nodes in safer areas, the routing switches back to the default geographic routing to minimize the traveled distance. Fig.1 gives an example of routing adapting

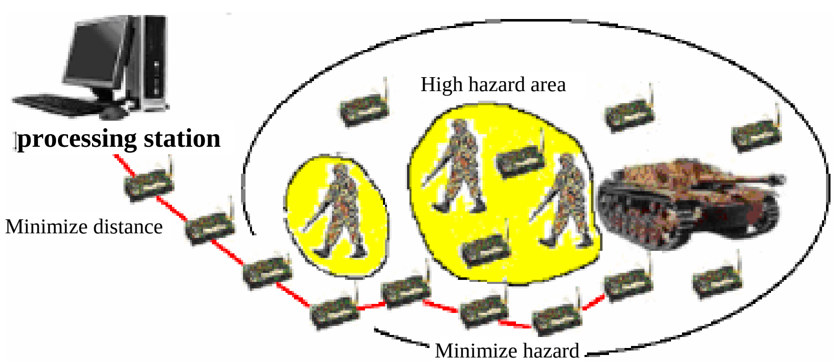

Fig.1. An example of routing adapting to the environment [Mahjoub et al. 2007, 72]

to the environment to avoid hazard on the way to relaying nodes. In the paper, the authors provide the description of the proposed routing framework, format of control messages, algorithm for next hop neighbor selection, and protocol control flow chart. It would appear that in the paper, the authors provide some preliminary simulation scenarios of the proposed routing framework, but the details of simulation and performance analysis is not given in the paper. In the paper, In future work, the authors state that methods such as fuzzy logic and Bayesian inference that are suitable for localized learning and conflicting objectives need to be explored.

Table VI summarizes the contribution of research discussed in this subsection.

Table VI. Summery of adaptive routing research discussed in subsection 3.2.3

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Comment
Okino and Corr 2002a	Maximizing overall currentness of nodes.	Samples of data transmission reach Base station.	Best Effort multi-Hop Geographical Routing (BEHGR) protocol.	Centralized decision making, Statistically Accurate Sensor Networks (SANS).
Ke 2006	Able to conciliate different addressing needs and meets different application level communication requirements.	By tying query specific attribute to the overlaid cluster structure.	An attribute based adaptive single unified routing infrastructure.	Ph.D. Thesis, Extremely large wireless sensor networks (WSNET).
Leibnitz et al. 2006	Routing with the constraint that nodes have no explicit knowledge of the network topology.	Using biologically inspired Adaptive Response by Attractor Selection algorithm.	Mobile Ad-hoc Routing with Attractor Selection (MARAS).	Probabilistic approach.
Macedo et al. 2006	Continuous data dissemination.	Interaction with the application to determine efficient routes.	Proactive Routing with Coordination (PROC) protocol.	
Mascolo and Musolesi 2006	Context-awareness.	Kalman filter forecasting techniques over context of the sensor node.	Sensor Context-Aware Routing (SCAR) routing.	Delay tolerant mobile sensor networks.
Mahjoub and El-Rewini 2007	Minimizing hazard on the route, adaptive to environment, the network state or the orders of an external authority.	Real time search algorithm, Switching between minimum hazard and minimum distance routing.	Adaptive Constraint-Based Multi-Objective Routing framework.	Distributed decision making.

4. CONCLUDING COMMENTS

This survey provides a comprehensive view of past and recent research on adaptive routing protocols in WSNs. The adaptive routing protocols are broadly classified into two categories on the basis of their routing objectives. In the first category, the routing protocols have energy awareness as the prime routing objective while in the second category, the routing protocols have non energy aware routing objectives such as fault tolerance and adaptive selection of routing services. The main contribution of various researchers in the area of adaptive routing is highlighted in this survey. The parameters or the approaches used for routing adaptation are also highlighted for all of the adaptive routing protocols considered in this survey.

A comprehensive summery of research on adaptive routing protocols is given in Table VII at the end of this survey. It is observed that out of 32 annotated references, only 2 papers are referred by the papers from other research groups, otherwise, most of the referrals of papers are by the later papers from same research group. The papers mentioned in the ‘refer to’ or ‘referred by’ column of Table VII, are mostly referred by either same research group or are general survey papers that are referred in general to introduce the topic. Incidentally, the two important adaptive routing algorithms in WSNs have the same popular acronym, called DEAR. In the adaptive routing algorithm proposed in Ok et al. [2007], DEAR refers to Distributed Energy Adaptive

Routing, while in case of Sun et al. [2005], it is Dynamic Energy Aware Routing algorithm. It appears that the reason for the non referral for each others work is largely due to the fact that most of the papers are published quite recently i.e. in 2005, 2006 and 2007. Another reason seems to be the fact that routing algorithms in WSNs are highly specific to application and network conditions. Therefore, various research groups do their routing research that generally suits their kind of scenario. Hence, they have their own method of routing adaptation, which may not be relevant to others as it is. It is also observed that, in general, there is a lack of mathematical framework for routing adaptation, therefore it would be good area to explore for future research.

ACKNOWLEDGMENTS

I gratefully acknowledge the invaluable guidance and support I received from Dr. R. A. Frost. From the course 60-510, I have learnt a lot on how to undertake a literature review and how to compose a survey. I also sincerely thank Dr. K. E. Tepe and Dr. A. K. Aggarwal for their constant encouragement and invaluable suggestions and help on my research topic.

Table VII. Summery of research on adaptive routing in Wireless Sensor Networks

Reference	Routing objective	Adaptation approach / Tuning parameter	Major contribution	Refers to	Referred by	Comment
Okino and Corr 2002a	Maximizing overall currentness of nodes.	Samples of data transmission reach Base station.	Best Effort multi-Hop Geographical Routing (BEHGR) protocol.	Okino and Corr 2002b	-	Centralized decision making, Statistically Accurate Sensor Networks (SANS).
Zhu et al. 2002	Energy efficient, self-adaptive and error tolerant at the same time.	Spin glass and Multi-Fractal routing adaptation models.	Two new routing adaptation models.	-	Brooks et al. 2003	Masters Thesis, Based on theory of cellular automata.
Brooks et al. 2003	Error resilience, Low overhead, Support for evenly distributed data sources and low data paths, Quick application deployment.	Spin glass, Multi-Fractal, Coulombic and Pheromone routing adaptation models.	Four new routing adaptation models.	Zhu et al. 2002	-	Based on ideas from Physics, Biology and Chemistry.
Tateson and Marshall 2003	Minimize route cost in terms of energy consumption and loss of integrity of the network, Minimise routing overhead.	Varying the transmission range, Experimenting with the neighbors.	An adaptive routing mechanism that enables sensor nodes to minimize route cost.	-	-	-
Jain 2004	Maximizing energy levels on the route, Minimize disparity in the energy levels, avoiding congestion.	In-network processing of spatio-temporal queries, deterministic model.	An adaptive energy aware routing infrastructure and a multiple path routing protocol (MidHopRoute).	-	-	Ph.D. Thesis, Distributed decision making.
Lin et al. 2004	Power adaptive, increasing the network life time and supporting immobility management.	Combining vector-oriented propagation, power-consideration decision, and multi-path routing protocols.	Power-aware Chessboard-based Adaptive Routing (PCAR).	-	-	Clustered wireless sensor networks.
Zhang and Fromherz 2004b	Guaranteed delivery with minimum delay and minimum energy consumption.	Reinforcement learning, Real-time search, Trade-off energy and latency, Trade-off success rate and energy.	Search-based adaptive routing strategies.	Zhang and Fromherz 2004a	Cerpa et al. 2004, Zhang and Huang 2006a, Zhang and Huang 2006b	Static and symmetric wireless sensor network.

Close and Mishra 2005	Adapts to the changes in individual node's power levels to increase the life time of network.	P2P Assisted Voice Communication.	Power aware packet routing.	-	-	Technical Report, Remote Sensor Networks, Distributed decision making.
Figueiredo et al. 2005	Selection of the best routing strategy as per network conditions and application requirements.	Policies-based approach.	Policy-based approach for routing adaptation.	Akyildiz et al. 2002, Al-Karaki et al. 2004	-	Autonomous wireless sensor networks.
He et al. 2005	Selection of the appropriate routing service as per network conditions and application requirements.	Using X Visiting-pattern Routing that facilitate multiple routing services to run simultaneously.	X Visiting-pattern Routing paradigm (XVR), and Automatic Visiting-pattern Routing (AVR) protocol.	Akyildiz et al. 2002, Heinzelman et al. 1999	-	Ph.D. Thesis
Sun et al. 2005	Minimizing delivering delay and total energy consumption of data delivery, Making energy consumption even.	Using restricted flooding to spread routing instruction that contains hop count and minimum residual energy info.	Dynamic Energy Aware Routing (DEAR) algorithm.	-	-	Data querying sensor networks
Yuan-yuan et al. 2005	Adaptive to Application requirement, Adaptive to topology changes.	General message machine for adaptive selection of possible routing approaches.	Adaptive Directed Diffusion Routing Algorithm (ADDRA).	-	-	A Variant of directed diffusion routing.
Gundappachikkenahalli and Ali 2006	Minimizing the latencies while remaining energy efficient.	Considering data priorities and QoS requirements.	Adaptive routing Protocol framework (AdProc).	-	-	Data centric decision making.
In et al. 2006	Minimizing energy consumption, Minimum path management overhead, Not affected by the number, distributed area, speed, and duration of stimuli.	Adjusting the route optimization level on the basis of amount of data traffic. Agent-Based Incremental Path Extension.	Agent-Based Incremental Path Extension (ABIPE) and Directional Route Optimization (DRO) as part of DRARO strategy.	-	-	-
Ke 2006	Able to conciliate different addressing needs and meets different application level communication requirements.	By tying query specific attribute to the overlaid cluster structure.	An attribute based adaptive single unified routing infrastructure.	-	-	Ph.D. Thesis, Extremely large wireless sensor networks (WSNET).

Leibnitz et al. 2006	Routing with the constraint that nodes have no explicit knowledge of the network topology.	Using biologically inspired Adaptive Response by Attractor Selection algorithm.	Mobile Ad-hoc Routing with Attractor Selection (MARAS).	-	-	Probabilistic approach.
Macedo et al. 2006	Continuous data dissemination.	Interaction with the application to determine efficient routes.	Proactive Routing with Coordination (PROC) protocol.	-	-	-
Mascolo and Musolesi 2006	Context-awareness.	Kalman filter forecasting techniques over context of the sensor node.	Sensor Context-Aware Routing (SCAR).	-	-	Delay tolerant mobile sensor networks.
Wang and Wang 2006	Maximizing network life time.	Reinforcement learning, Consideration of various optimization goals together.	An Adaptive Routing scheme (AdaR).	Culler et al. 2004	-	-
Xu et al. 2006	Maximizing energy levels on the route, Link adaptive.	Spatial diversity, Geographical awareness through feedback	Energy-aware and link-adaptive routing metrics.	Xu et al. 2005	-	Ultra Wide Band (UWB) sensor networks.
Zhang and Huang 2006a	Energy balance, Control network congestion, Adaptive to Network condition, Adaptive to Application req.	Reinforcement learning, Real-time search, Parametric tuning.	A Learning-based Adaptive Routing Tree.	Zhang and Fromherz 2004a, Zhang and Fromherz 2004b, Zhang and Huang 2006b	Zhou et al. 2007	-
Zhou et al. 2006b	Minimize energy depletion of imp. Nodes, Adaptive to Application requirement.	Reporting rate.	FloodNet Adaptive Routing (FAR) algorithm.	Zhou et al. 2006a	Zhou et al. 2007	Centralized decision making, FloodNet topology.
Chen et al. 2007	Choosing shortest path routing or energy balanced routing as per the application requirement.	Tuning using parameters in the algorithm.	Node localization algorithm and Geography Position based Routing (RGP)	Akkaya et al. 2005	-	-
Dong and Quan 2007	Energy balance	applying topology matrix for controlling the power	Hierarchical Topology-Based Power-Adaptive Routing (TBPAR).	-	-	-
Gregoire 2007	Fault tolerant message re-routing.	Watching radio activities to detect faults, re-routing data through different nodes at the point of failure.	Adaptive mechanism for fault tolerant message re-routing.	Gregoire et al. 2007	-	Masters Thesis, WSN in harsh environment, Distributed decision making.

Mahjoub and El-Rewini 2007	Minimizing hazard on the route, adaptive to environment, the network state or the orders of an external authority.	Real time search algorithm, Switching between minimum hazard and minimum distance routing.	Adaptive Constraint-Based Multi-Objective Routing framework.	Zhang and Fromherz 2004a	-	Distributed decision making.
Ok et al. 2007	Energy balance and responsiveness to the events.	Using Energy Cost (EC) heuristics	Distributed Energy Adaptive Routing (DEAR).	Akyildiz et al. 2002	-	Distributed decision making.
Peng et al. 2007	Minimum energy consumption, Energy balance, Real time.	Choosing next hop neighbor based on real-time requirement and energy index. Uses RT and TTL fields of the packet.	An adaptive real-time routing scheme (ARP).	Akyildiz et al. 2002	-	Distributed decision making.
Simao 2007	Minimum number of hops, Maximizing energy levels on the route, Energy balance, Minimum delay, Adaptive to topology changes.	Data aggregation, correlated events, consideration to message importance.	Adaptive Self-Organization for Surveillance and Routing (ASOS).	Akyildiz et al. 2002, Akkaya et al. 2005, Heinzelman et al. 1999	-	Data centric decision making.
Wang et al. 2007	Maximizing network life time.	Uses Genetic Algorithm, Multi Agents is adaptively adjusted according to data transmission cost, data fusion cost and energy gain.	Adaptive Fusion Genetic Algorithm (AFGA).	Luo et al. 2005, Luo et al. 2006	-	Data centric decision making.
Ye et al. 2007	Minimum energy consumption, Minimum delay.	Using Multi Agents, Data aggregation using ANT colony algorithm.	Ant Colony Algorithm based Routing (ACAR).	Akyildiz et al. 2002	-	Distributed decision making.

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A. ANNOTATED BIBLIOGRAPHY

A.1 [Brooks et al. 2003]

Ref. BROOKS, R., PIRRETTI, M., ZHU, M., AND IYENGAR, S.S. 2003. Adaptive routing using emergent protocols in wireless ad hoc sensor networks. *Proceedings of SPIE - The International Society for Optical Engineering, 5205,* 197-208.

In this paper, the authors appear to be the first to address the problem of distributed adaptation of data routing using emergent behavior for WSNs.

The authors state that previous research on Link State (LS) routing algorithm, Destination Sequenced Distance-Vector routing algorithm (DSDV), Dynamic Source Routing (DSR) protocol, Ad hoc On Demand Distance Vector (AODV) routing protocol, and Greedy Perimeter Stateless Routing (GPSR) algorithm have made significant progress on distributed routing problem. However, past research either lack adaptation in routing or have very limited support for it. In this paper, the authors focus on adaptation feature of distributed routing algorithm and claim to use emergent behavior for routing adaptation for the first time.

The authors present four new adaptation methods that are Spin glass, Multi-Fractal, Coulombic and Pheromone. The authors claim that they use the ideas from Physics, Biology and Chemistry for the first time for distributed adaptation.

In this paper, the authors present mathematical formulation and performance evaluation based on simulation for all four proposed adaptation methods. The authors also present comparison of these proposed adaptation methods for various applications scenarios.

The authors state that Multi-Fractal model works well for overhead sensitive applications that require quick deployment, while Spin glass model works well for applications requiring low data paths. The authors say that Pheromone is suitable where error resilience and low overhead is the requirement while Coulombic model works well where data sources are evenly distributed throughout the network.

The authors claim that routing adaptation based on emergent behavior could perform global adaptation using only locally available information. In this paper, in future work, authors say to workout a unifying abstraction that contains proposed four adaptation methods as subsets.

This paper refers to Zhu et al. [2002].

A.2 [Chen et al. 2007]

Ref. CHEN, W., MEIL, T., LI, Y., LIANG, H., LIU, Y., AND MENG, M. Q.-H. 2007. An Auto-adaptive Routing algorithm for Wireless Sensor Networks, *International Conference on Information Acquisition, ICIA '07,* 574-578.

The authors begin by stating that it is inefficient to choose different routing algorithms manually for different applications. In this paper, the authors present an auto-adaptive routing mechanism that facilitates the use of the two or more routing methods in a WSN.

Previous research on Geographical and Energy Aware Routing (GEAR), Graph Embedding Routing (GEM), and Directed diffusion (DD) routing algorithm have made significant progress in the routing in WSNs. The authors state that once any of these routing methods are deployed, it does not change as per the application requirement in a particular sensor network. The authors also state that the proposed routing method based on node's geography position is similar to the Ant Colony Optimization Algorithm

In this paper, the authors proposed two routing methods that are for sensor node's localization and for object's localization respectively. The authors state that node positions are obtained through the node localization algorithms, and then energy aware Geography Position based Routing method (RGP) is used for the object's information acquisition. The authors state that proposed RGP routing method selects either minimum distance path or the path with larger average energy based on the a and ß parameters in the algorithm.

In this paper, the authors present the description, flow chart and mathematical formulation of proposed routing algorithms. The authors provide the simulation results for the proposed routing method based on Node's Geography Position.

The authors state that in the proposed routing mechanism, the average energy consumption is smaller than DD routing algorithm.

The authors claim that the proposed routing algorithm has a high performance as it can choose a shorter path routing or energy balanced routing as per the application requirement by adjusting of its parameters.

This paper refers to Akkaya et al. [2005]

A.3 [Close et al. 2005]

Ref. CLOSE, R., AND MISHRA, P. 2005. Power-Adaptive Routing Topology for Remote Sensor Networks, *CISE Technical Report 05-006, Department of Computer and Information Science and Engineering*, University of Florida.

This report presents a routing technique that dynamically adapts to the changes in individual node’s power levels to increase the life time of the remote sensor networks.

Previous research in the area of path routing to conserve energy and lengthen network lifetime require a centralized scheme with great fore-knowledge about the network including its node dispersal and frequency at which a particular node will generate a message and send it to the base-node. In this paper, the authors present an adaptive decentralized routing scheme that will allow dynamic paths. The authors state that the proposed algorithm assume to have one base node and no knowledge of the present state of the network after its deployment.

In this report, the authors claim to present the new idea of P2P Assisted Voice Communication for Power aware packet routing. The authors state that the central idea of this method is that routing paths through-out the network can change as power reserves in individual nodes diminish.

In this report, the authors present the simulation results with respect to location of base node for power adaptive topology and compared them with the least hop topology.

The authors state that proposed power-adaptive routing topology produces increased life span as compared to least-hop routing topology irrespective of the network size and the placement of the base node. The authors claim that proposed topology requires very little computational overhead as well as it does not need any additional transmissions or additional hardware.

The authors claim that the lifespan of the networks can be improved up to 60% by using their power-adaptive topology as compared to least hop topology.

A.4 [Dong et al. 2007]

Ref. DONG, Y., AND QUAN, Q. 2007. Topology-Based and Power-Adaptive Routing Algorithm for Wireless Sensor Network, *International Conference on Wireless Communications, Networking and Mobile Computing, WiCom 2007*, 2791-2794.

The authors appear to be the first to apply topology matrix for controlling the power for routing adaptation in WSNs.

The authors state that previous research on LEACH and PEGASIS, and MECH have made significant progress in the hierarchical routing in WSN. However, in these algorithms, either the energy state of nodes is ignored or the overuse of leader nodes or cluster heads causes fast depletion their energy.

In this paper, the authors present a new hierarchical Topology-Based Power-Adaptive Routing (TBPAR) algorithm. The authors state that TBPAR uses the information of topology matrix to build more reasonable routing paths. The authors also state that the nodes adapt their transmitting power according to their energy status to balance energy consumption among themselves.

In this paper, the authors present the methodology of calculation of topology-matrix and description of proposed routing protocol. The authors also present simulation results using self developed simulation program for a system with 100 nodes distributed in an area of 100m X 100m.

The authors claim that the proposed algorithm increases the life-time of whole network and reduces the difference in life-time between each node. The authors also claim that the proposed TBPAR has the biggest mean life-time and smallest deviation as compared to LEACH and PAGASIS. The authors claim, on the basis of their experiments, that TBPAR provides high energy efficiency and high stability to the network.

A.5 [Figueiredo et al. 2005]

Ref. FIGUEIREDO, C.M.S., SANTOS, A.L.D., LOUREIRO, A.A.F., AND NOGUEIRA, J.M.S. 2005. Policy-Based Adaptive Routing in Autonomous WSNs. *DSOM 2005, Lecture notes in computer science, 3775,* 206–219.

The authors appear to be the first to apply policies-based approach for adaptive routing in autonomous WSNs.

The Authors begin by stating that previous research on Adaptive and hybrid approaches for routing in WSNs consist of viable solutions to deal with variable scenarios but, they generally provide rigid solutions for some specific cases. The authors state that their work shows how policies can effectively be used in the routing for autonomous WSNs.

In this paper, the authors introduce the policy based approach for routing that allows the autonomous selection of the best routing strategy in view of network conditions and application requirements.

This paper presents the conception and implementation of routing policies through a generic model. The authors say that they used NS-2 network simulator to implement policies for routing adaptation. The authors present case studies of adaptive routing using policies and the associated results in this paper.

The authors state that Simulation results show the consistent benefits and resource savings offered by the use of policies for adaptive routing in WSNs.

The author claim that for a highly variable WSN environment, the policy-based adaptive hybrid approaches perform better than a single routing algorithm. In this paper, in future work, the authors say to implement policy-based routing rules on real sensor nodes as well as to devise and implement policy-based routing rules to modify the routing QoS metric.

This paper refers to Akyildiz et al. [2002], and Al-Karaki et al. [2004].

A.6 [Gregoire 2007]

Ref. GREGOIRE, M. 2007. Adaptive algorithms for fault tolerant re-routing in wireless sensor networks, Masters Thesis, University of Massachusetts Amherst.

In this thesis, the author claims to be the first to propose adaptive mechanism for fault tolerant message re-routing that is useful for WSNs in the harsh environment.

The author states that previous research on Directed Diffusion (DD), Dynamic Source Routing (DSR), Distance Vector Routing (DVR), and Optimized Link State Routing (OLSR) protocols have made significant progress in the routing research in WSN. However, the author states that these routing algorithms do not always have a fault tolerant plan. In this thesis, the author proposes a series of routing algorithms that run on top of and in conjunction with existing routing protocols by adding fault tolerance in the form of retransmitting and rerouting messages at the routing layer. The research work done in thesis is an extension of earlier published paper, Gregoire et al. [2007], by the same author.

The author states that the proposed fault tolerant mechanism uses an algorithm that watches radio activity to detect the occurrence of fault and then takes actions at the point of failure by re-routing the data through a different node without starting over on an alternative path from the source. The author states that the proposed routing mechanism works in an entirely distributed fashion in which, each node makes its decision solely based on information it gathers by passively monitoring radio traffic around it and no feedback or direct communication with other nodes is involved. The author also incorporates different learning methodologies, support for correlated events, and message combining mechanism in the proposed routing algorithms.

In this thesis, the author presents description and algorithms of the proposed routing mechanism that includes two algorithms for next best neighbor selection schemes. The author states that limited testing is performed on the real hardware with 12 mica motes as sensor nodes and thorough testing is done using 50 nodes on TOSSIM simulator and TinyViz that comes with TinyOS.

The author claims that by using the parameters, such as the number of retries, the proposed routing mechanism can be tuned to provide a high message success rate while still being energy-efficient in both benign and hostile environments. The author also claims, on the basis of results on node depth, that fault tolerant routing mechanism is able to expand the size of the networks far beyond what it could be without fault tolerant routing. The author claims that by combining similar messages into one message and scaling the number of retries accordingly, the correlated events are dealt properly both in terms of energy usage and message success rate. The author also states that as the sleep period of the nodes increases, the energy is reduced and the success rate holds relatively constant until a point is reached where there is not enough node wake-up time to transmit all the data and the success rate rapidly drops off. The author states that comprehensive test of proposed routing mechanism need to be done using hardware in future.

This thesis refers to Gregoire et al. [2007].

A.7 [Gundappachikkenahalli et al. 2006]

Ref. GUNDAPPACHIKKENAHALLI, K., AND ALI, H.H. 2006. AdProc: An adaptive routing framework to provide QOS in wireless sensor networks. *Proceedings of the IASTED International Conference on Parallel and Distributed Computing and Networks, as part of the 24th IASTED International Multi-Conference on APPLIED INFORMATICS 2006*, 76-83.

In this paper, the authors appear to be the first to address the problem of routing the data based on data priorities and Quality of Service (QoS) requirements with the constraint of bringing down the latencies while remaining energy efficient in the context of WSNs.

Previous research on QOS was targeted for primitive sensor networks. In this paper, the authors claim to propose the solution that works for highly sophisticated sensor nodes that can transmit video/images and critical information. The authors use energy aware AODV routing protocol and Ants based routing protocol as basis of their work in this paper.

The authors propose a new adaptive routing protocol framework, called AdProc that supports a short rapid route for data with high priority and strict QoS requirements, and an energy efficient route for lower priority data. The authors state that shortest route to the destination is computed using an energy aware AODV routing protocol and energy efficient route is computed using Ants based routing protocol.

In this paper, the authors present the AdProc algorithm and its simulated Implementation using NS2 network simulator.

The authors state that the proposed routing algorithm provides 70% improvement over AODV protocol in terms of overall latency, hence providing a good Quality of Service. The authors claim, on the basis of their results, that the proposed routing algorithm helps to distribute energy consumption that prolong the network life and reduce network holes.

A.8 [He et al. 2005]

Ref. HE, Y. 2005. Adaptive routing services in ad-hoc and sensor networks, Ph.D. Thesis, University of Southern California.

In this thesis, the author addresses the problem of choosing appropriate routing service in ad-hoc and sensor networks based on application requirements and changes in the network properties.

The author states that previous research on Diffusion filters, Mate, and Impala have made significant progress in improving the service flexibility in sensor networks. However, the author states that in above mentioned routing mechanisms, the changing granularity can be large in terms of code size and energy overhead. In this thesis, the author presents a new routing paradigm that facilitates the routing service change with fine granularities with small energy overhead in sensor networks. The author also states that proposed routing protocol for sensor network is heavily influenced by Directed Diffusion routing protocol.

In this thesis, the author proposes a general approach called active ad-hoc network routing for mobile ad-hoc networks that uses a helper module to improve existing routing algorithms without changing their inner mechanisms. The author states that DSR is used as a target service for proof of concept of proposed routing approach and the resulting service is called Active Dynamic Source Routing (ADSR). The author also presents, what he claims to be novel idea, a new routing paradigm called X Visiting-pattern Routing (XVR) that facilitate multiple routing services with different visiting-patterns to run simultaneously in a sensor network. The author states that XVR provides a unified and comprehensive environment to study the effects of various visiting-patterns on routing and application performance. The author also states that in XVR, packet handlers are separated from their corresponding visiting-pattern components and this separation enables independent visiting-pattern changes. In this thesis, the author presents an Automatic Visiting-pattern Routing (AVR) protocol for sensor networks that automatically chooses and changes visiting-patterns on top of the XVR with changing application and network dynamics.

In this thesis, the author simulates AVR routing algorithm in NS-2 network simulator with simulated sensor network composed of 100 nodes in a 1500m x 1500m field that does not contain partitions. The author provides the description of how to use XVR to study existing and new routing algorithms, and how to build automatic routing services on top of XVR. The author also presents a case study to show how to conduct automatic routing changes between two known routing services, push and pull, with XVR, and evaluates the performance gains. In this thesis, the author also presents the description and algorithm of active ad-hoc network routing services for mobile ad-hoc networks.

The author claims, on the basis of simulation results of ADSR, that the routing performance is improved up to 47%, the TCP performance is improved up to 70%, and the energy consumption per transmitted data is saved up to 25%. The author also claims that the XVR version of one-phase pull Directed Diffusion obtains scalable energy consumption while improving delivery ratio by 70% as compared with conventional one-phase pull Directed Diffusion. The author states that in terms of future work of XVR, the associations between different visiting-patterns, application, and network performance are important to realize automatic mapping.

This thesis refers to Akyildiz et al. [2002], and Heinzelman et al. [1999].

A.9 [In et al. 2006]

Ref. IN, J., KIM, J.-W., HWANG, K.-I., LEE, J., AND EOM, D.-S. 2006. Data Rate Adaptive Route Optimization for Sink Mobility Support in Wireless Sensor Networks. *ICDCIT 2006, Lecture notes in computer science, 4317,* 73–80.

This paper presents the Data Rate Adaptive Route Optimization (DRARO) scheme that provides a method for adjusting the route optimization level on the basis of amount of data traffic, to minimize overall energy consumption.

The previous research on routing algorithm such as Directed Diffusion (DD), TTDD, SEAD, ONMST, and HLETDR has made significant progress to support mobility in WSNs. These algorithms have various problems such as path management overhead increases as the number of sources increases or the stimuli frequently change their position. The authors claim that the proposed routing algorithm not only reduces the path management overhead due to mobility but it is not affected by the number, distributed area, speed, and duration of stimuli as well.

In this paper, the authors present two new schemes, namely, Agent-Based Incremental Path Extension (ABIPE) and Directional Route Optimization (DRO) as part of proposed DRARO strategy.

In this paper, the authors present the simulated Implementation of proposed DRARO using NS2 network simulator. The authors use 2000 sensor nodes in their simulation that are randomly distributed on a 5 square km field.

The authors state that near optimal paths can be constructed by DRO with significantly low overhead compared to that of flooding. The authors also state that as the source data rate increases, higher level of route optimization is required to minimize overall energy consumption. In this paper, the authors state that the overhead and energy consumption increases linearly with the increase in the number and the speed of the sink. The authors also state that throughput, energy consumption, and overhead are independent of the movements of the stimuli. The author state that the throughput, and overhead are independent of the number of the stimuli also, but the energy consumption increases with the number of the stimuli because of the data traffic increase.

The authors claim that DRARO can efficiently provide highly optimized paths for active sources, and ceaseless data forwarding paths for every sensor node.

A.10 [Jain 2004]

Ref. JAIN, N. 2004. Energy Aware and Adaptive Routing Protocols in Wireless Sensor Networks. Ph.D. Thesis, University of Cincinnati.

In this thesis, the author presents an adaptive distributed routing protocol for minimizing energy consumption in a sensor network.

Previous research on MDSR protocol, Backup Routing on AODV, and modified directed diffusion protocol with multiple path routing have made significant progress towards multiple path routing schemes that supports fault tolerance and load balancing in ad hoc and sensor networks. However, the author states that these multiple path schemes are based on probabilistic model and might not perform work successfully to achieve an equal load distribution with heavy and uneven traffic. The author claim that the proposed protocol is based on deterministic model that guarantees uniform traffic spreading because it accurately assigns load to all possible available paths on the basis of current energy level of the nodes.

In this thesis, the author claims that an adaptive energy aware routing infrastructure, which enables in-network processing of spatio-temporal queries in sensor networks, is presented for the first time. In this thesis, the author also propose the multiple path routing protocol MidHopRoute that spreads the routing load between the source and destination nodes over a large number of sensor nodes to minimize disparity in the energy levels of the sensor nodes.

In this thesis, the author presents a detailed discussion, mathematical analysis, and simulation results of the proposed adaptive routing infrastructure. The author uses NS2 network simulator for simulation of proposed algorithms.

In this thesis, the author evaluates the performance of the proposed MidHopRoute algorithm in terms of load distribution achieved, network lifetime, and control overheads.

The author claims that the proposed protocol is able to avoid congestion in the network that enhances the overall network lifetime in presence of heavy traffic due to random multiple queries in the network. The author also claims that the proposed protocol provides low response time for time critical queries as well as a longer lifetime of the network at the cost of response time for non-critical queries.

In this paper, in future work, the author states that multiple path protocol may be extended to include link quality of paths as a parameter to grade paths so that resilience to path failure may also be achieved while routing data.

A.11 [Ke 2006]

Ref. KE, W. 2006. Adaptive attribute-based routing in clustered wireless sensor networks, Ph.D. Thesis, Boston University.

In this thesis, the author appears to be the first to address the problem of adaptive routing for extremely large wireless sensor networks (WSNET). The author state that WSNETs may be deployed incrementally by potentially different owners, with no single addressing system guarantees. The author also states that in WSNETs, the underlying routing mechanism must be selective enough to propagate data only to relevant parts of the network, and adaptive enough to offer services that can conciliate different addressing needs and meets different application level communication requirements.

The author states that previous research on clustering based routing algorithms and cluster heads election algorithms have made significant progress in routing in WSNs. However, the author states that the past research have been done for the sensors that are programmed and deployed for a single task, with all communication paradigms set for one purpose.

In this thesis, the author presents, what he claims to be novel idea, an attribute based single unified routing infrastructure for sensor networks that is flexible in its naming/addressing and packet forwarding schemes. The author states that previous clustering algorithms attempt formation of clusters that satisfy certain invariant properties, communication metrics or topological properties. The author states that in contrast to previous clustering algorithms, the proposed algorithm forms clusters that reflect application level communication needs by tying attributes, which are relevant to inquiries posed to the sensor network, to the overlaid cluster structure. The author states that in the proposed routing infrastructure, multiple hierarchies can be supported simultaneously that enables multiple applications to select the set of sensors that best meet their own addressing needs.

In this thesis, the author presents the specification of attribute hierarchies, data structures for routing, pseudo code and algorithms for cluster formation and maintenance, and routing rule sets for tree traversal mode and mesh traversal mode of the hierarchies.

The author claims, on the basis of his results, that attribute based hierarchical schemes offer increased communication gains as opposed to flooding mechanisms for disseminating new inquiries. The author also claims that the performance of tree based traversal modes surpasses mesh traversal modes in transmission costs for address resolution in the worst scenario case, but underperforms when considering the speed of the resolution process and the path length formed.

In the future work, the author states that optimality analysis of the tradeoff between the number of levels in the hierarchy and the gains obtained is still need to be done. The author also state that different traversal modes and their performance expectations can also be investigated as it contribute to the increased performance of applications being executed over deployed sensor networks.

A.12 [Leibnitz et al. 2006]

Ref. LEIBNITZ, K., WAKAMIYA, N., AND MURATA, M. 2006. Self-adaptive ad-hoc/sensor network routing with attractor-selection, *IEEE Global Telecommunications Conference, GLOBECOM '06, Article no. 4151620,* 1-5.

In this paper, the authors appear to be the first to address the problem of routing in mobile ad-hoc/sensor networks with the constraint that nodes have no explicit knowledge of the network topology, except for their coordinates and the neighboring nodes within an RF transmission range.

The authors state that the routing scheme proposed in this paper is an extension of biologically inspired Adaptive Response by Attractor Selection (ARAS) algorithm.

In this paper, the authors present, what they claim to be new idea, an entirely distributed self-adaptive multi-path routing mechanism called Mobile Ad-hoc Routing with Attractor Selection (MARAS), where each node operates autonomously and gathers information about the network topology only by exchanging messages with its neighbors. The authors also state that proposed mechanism determines the probabilities for choosing the next hop of a packet on its path to the destination. The authors state that the suitable paths with small number of hops or high path length-to-distance ratio are rewarded, whereas long paths or those which do not lead to the destination are penalized. The authors state that the proposed routing method can easily compensate for sudden changes in the topology of the network.

In this paper, the authors present the analytical description, mathematical formulation, and algorithm of proposed MARAS algorithm and elaborate on how to apply it to self-adaptively determine the next hop in routing. The authors present the simulation results in a simulate environment that consists of 100 nodes randomly distributed in a unit area size of $[0, 1]\times[0, 1]$.

The authors states that the greedy selection routing scheme always outperforms MARAS for higher node density, whereas for small node density, for average packet delivery rate as a function of the node density, MARAS achieves better performance than the greedy approach especially when the radius is small.

The authors claim that as the selection of next hop is done independently by each node in the proposed routing algorithm, it scales well with the number of nodes.

A.13 [Lin et al. 2004]

Ref. LIN, T.H., CHEN, Y.S., AND LEE, S.L. 2004. PCAR: a power-aware chessboard-based adaptive routing protocol for wireless sensor networks. *Proceedings of IEEE 6th Circuits and Systems symposiumon Emerging technologies: Frontiers of mobile and wireless communications, 1,* 145-148.

In this paper, the authors address the problem of adaptive routing with the constraint that it should increase the network life time and support immobility management in clustered WSNs.

The authors state that the proposed algorithm in this paper is an improvement of Pure Shortest-Path Routing (PSPR) protocol. The authors state that in PSPR protocol, the massed power consumption of routing along the same paths speedily decreases the energy of the active nodes, while the protocol proposed in this paper is designed to avoid such decisions in order to extend the lifetime of the WSNs.

The authors introduce, what they claim to be novel idea, the idea of Power-aware Chessboard-based Adaptive Routing (PCAR) that combines the vector-oriented propagation, power-consideration decision, and multi-path routing protocols to guide the data to its destination. The authors state that the properties of cluster are combined in the PCAR to form cluster-plates in a chessboard-based clustered sensor network.

In this paper, the authors present the PCAR algorithm and its simulated Implementation using self-developed Java simulation programs.

The authors state that due to the strategy of the dynamic routing path, the levels of power consumption of nodes in PCAR schemes are lower and more balanced than those of nodes in PSPR schemes. The authors claim that the overall lifetimes of the network are largely improved with PCAR scheme as compared to the traditional PSPR, RMPR, MPOR and POMPR schemes.

A.14 [Macedo et al. 2006]

Ref. MACEDO, D.F., CORREIA, L.H.A., SANTOS, A.L.D., LOUREIRO, A.A.F., AND NOGUEIRA, J.M.S. 2006. A rule-based adaptive routing protocol for continuous data dissemination in WSNs. *Journal of Parallel and Distributed Computing, 66, 4,* 542-555.

This paper presents an adaptive rule-based routing protocol for continuous data dissemination WSNs that interacts with the application for route determination.

The Authors refer to previous research on Directed Diffusion (DD) protocol, Energy-Aware Distributed routing (EAD), TinyOS Beaconing protocol, and SPAN, as the basis of their work. The authors state that earlier no protocol was designed for continuous data dissemination network that uses application information for efficient route determination. The authors state that the proposed protocol extends backbone concept of SPAN routing protocol to WSNs.

In this paper, the Authors proposed a new Proactive Routing with Coordination (PROC) protocol that interacts with the application to determine efficient routes.

In this paper, the authors present algorithm, analysis, and model of PROC protocol. The authors also present simulated implementation of PROC protocol and compared its performance with EAD and a simplified version of TinyOS Beaconing.

In this paper, the authors estimate that the upper bounds is O(v) for memory utilization and O(2v) for number of routing messages required to build the backbone, where v is the number of neighbors. The authors claim that PROC increases network lifetime around 7% to 12%, and has a higher throughput than both EAD and a simplified version of TinyOS Beaconing when the number of nodes in the network changes from 20 to 200. The authors state that "PROC presents a graceful performance degradation when the number of nodes in the network increases".

A.15 [Mahjoub et al. 2007]

Ref. MAHJOUB, D., AND EL-REWINI, H. 2007. Adaptive Constraint-Based Multi-Objective Routing for Wireless Sensor Networks, *IEEE International Conference on Pervasive Services*, 72-75.

This paper addresses the problem of routing in WSNs with the constraint that it should be adaptive to the environment, the network state or the orders of an external authority. The additional constraints are that the routing scheme should be able to change the objective to avoid hazards that the communication might encounter on the route as well as the routing decision should be solely dependent on localized knowledge.

The authors state that the work presented in this paper is based on the previous research on Geographical and energy aware routing, improved distance vector routing (nLRTS) and Message-initiated constraint-based routing Zhang and Fromherz [2004a].

In this paper, the authors introduce a new architecture that distributes routing plans from a Central Control Authority (CCA) to the sensors. The authors state that CCA assumes knowledge of the field's boundaries and breaks it into regions, where each region is assigned a powerful sensor node called Region Control Node (RCN) that coordinates with the sensor nodes in its region. The authors state that using this architecture, routes adapt to changes in the environment based on the learned estimated cost values to the destination of each neighbor. The authors also state that in the proposed architecture, a real time search algorithm is used as a decision making method for routing a message to the next hop. The authors state that in the proposed architecture, greedy geographic routing is used by default, but in the face of hazardous environment, the messages have to switch objective and minimize the hazard instead of distance. Once the messages reach to relaying nodes in safer areas, the routing switches back to the default geographic routing to minimize the traveled distance.

In this paper, the authors provide the description of the proposed routing framework, format of control messages, algorithm for next hop neighbor selection, and protocol control flow chart. It would appear that in this paper, the authors provide some preliminary simulation scenarios of the proposed routing framework, but the details of simulation and performance analysis is not given in this paper.

In this paper, In future work, the authors state that other methods like fuzzy logic and Bayesian inference, which are suitable to localized learning and conflicting objectives, need to be explored.

This paper refers to Zhang and Fromherz 2004a.

A.16 [Mascolo et al. 2006]

Ref. MASCOLO, C., AND MUSOLESI, M. 2006. SCAR: Context-aware adaptive routing in delay tolerant mobile sensor networks. *Proceedings of the 2006 International Wireless Communications and Mobile Computing Conference, IWCMC 2006,* 533-538.

In this paper, the authors present an adaptive routing protocol that forwards data towards the right direction at any point in time in mobile sensor networks by exploiting the movement and resource prediction techniques over context of the sensor node.

Previous research on epidemically inspired approaches and probabilistic delivery approaches has made significant progress for mobile sensor data gathering. However, the authors state that these approaches have quite a high overhead in terms of communication and, therefore, energy consumption is quite high. The authors claim that proposed approach has less communication overhead as compared to previous approaches for mobile sensor data gathering. The Authors state that the work presented in this paper is an extension of their previous work on Context-aware Adaptive Routing (CAR) protocol for mobile ad hoc networks.

In this paper, the authors present, what they claim to be novel idea, the idea of Sensor Context-Aware Routing (SCAR) routing approach that uses Kalman filter forecasting techniques over context of the sensor node to predict its neighbors that are the best carrier for the data messages. The author state that SCAR has maintained the prediction based approach used in CAR but all the aspects related to the communication and the replication are redesigned.

In this paper, the authors present the algorithm for SCAR routing, the analytical model for forecasting techniques for probabilistic routing, and the analysis of buffer management procedures and replication process. The authors state that they are yet to evaluate the proposed algorithm.

The authors claim that SCAR provide a better trade-off between the delivery ratio and the energy consumption as compared to traditional epidemically inspired approaches or probabilistic delivery approaches for mobile sensor data gathering.

A.17 [Ok et al. 2007]

Ref. OK, C., MITRA, P., LEE, S., AND KUMARA, S. 2007. Distributed Energy-Adaptive Routing for Wireless Sensor Networks, *IEEE International Conference on Automation Science and Engineering, CASE 2007,* 905-910.

In this paper, the authors appear to be the first to propose a routing algorithm for WSNs (WSNs) that has support for energy balance and is capable to respond properly to events that have uncertainty in their position and generation rates.

The authors state that previous research on direct communication approaches, hierarchical routing methods, self-organized routing algorithms have made significant progress in routing research in WSNs. However, the authors state that the previous routing approaches have little or no support for energy balance and robustness against diverse event generation patterns, while the routing algorithm proposed in this paper provide support for these requirements.

In this paper, the authors present a new routing algorithm, called Distributed Energy Adaptive Routing (DEAR). The authors state that in the proposed algorithm, sensors do not care if the receiving node sends data to the base station or passes data to one of its neighboring nodes. Through this local decision making process, a sensor network can achieve energy balance and prolong the lifetime of the sensor network. The authors state that the proposed algorithm uses a new heuristic metric, called Energy Cost (EC) that represents transmission energy cost relative to available energy and it is used to establish energy sufficiency as well as efficiency to pursue energy balance for the sensor network.

In this paper, the authors present the description of DEAR algorithm, energy consumption model, and event generation functions. The authors present the simulation results using self developed simulation program in C programming language. The authors use the LP solver, called LINDO, for solving the mathematical model.

The authors state that DEAR algorithm with 20m neighboring distance of the square sensor network has better performance in terms of life time of sensor nodes than Direct Communication (DC), Minimum Transmission Energy (MTE), and Self-Organized Routing (SOR) algorithms until 50(%) of nodes die. The authors also state that in the DEAR algorithm with 100m neighboring distance, the majority of sensors are alive up to 200 rounds and deplete simultaneously, thus indicating good energy balance throughout the network. The authors claim, on the basis of their results, that the proposed algorithm is simple and supports scalability.

This paper refers to Akyildiz et al. [2002].

A.18 [Okino and Corr 2002a]

Ref. OKINO, C.M., AND CORR, M.G. 2002. Best effort adaptive routing in statistically accurate sensor network. *Proceedings of the 2002 International Joint Conference on Neural Networks, IJCNN '02, 1,* 345 – 350.

The authors appear to be the first to identify the problem to adaptive routing in the sensor networks in general, and Statistically Accurate Sensor Network (SANS) in particular.

The authors state that this paper is an extension of an earlier paper Okino and Corr [2002b] by the same authors. In this paper, the authors present new performance results and analysis of adaptive Best Effort multi-Hop Geographical Routing (BEHGR) protocol that is proposed in Okino and Corr [2002b].

In this paper, the authors use BEHGR protocol as the basis of work, where BEHGR statistically attempts to dynamically route packets to a central location in a "best effort" manner for SANS. The authors state that to adapt routing, some percentage of the collected and transmitted data from each of the nodes in SANS reach home in order to provide an accurate picture of the measured and collected data of the network. The authors state that in SANS, no routing tables are required, no route discovery procedure is explicitly executed end-to-end, and nodes either acts as a client to forward packets or as servers in order to receive packets.

In this paper, the authors present extended analysis of BEHGR protocol as a sequel of earlier analysis of same protocol, proof of theorems, and analysis and comparison of currentness of BEHGR protocol for line, star and grid topologies. In this paper, the authors define the performance metric for measuring network throughput and delay in SANS. The authors evaluate the performance of BEHGR protocol on a real test-bed, in which the sensor modules are distributed in a k X k grid arrangement.

The authors claim that the star topology appear to provide the better overall currentness for BEHGR protocol. The authors state that currentness decreases rapidly as the grid size increases due to queuing losses.

This paper refers to Okino and Corr [2002b].

A.19 [Peng et al. 2007]

Ref. PENG, H., XI, Z., YING, L., XUN, C., AND CHUANSHAN, G. 2007. An Adaptive Real-Time Routing Scheme for Wireless Sensor Networks, *Proceedings of 21st International Conference on Advanced Information Networking and Applications Workshops, AINAW'07, Article no. 4224223*, 918-922.

In this paper, the authors present an adaptive routing algorithm for WSNs with the objective that it should support applications with real-time constraints and at the same time, it should ensure balanced energy consumption.

The authors state that the routing algorithm proposed in this paper is similar to MM-SPEED algorithm. The authors also state that MM-SPEED algorithm differentiates the different real-time levels, but it doesn’t dynamically adjust routing paths according to nodes’ energy states, while the algorithm presented in this paper support both of above mentioned considerations.

In this paper, the authors propose, what they claim to be new idea, an adaptive real-time routing scheme (ARP). The authors state that ARP dynamically changes packets’ requirement to transmission speed and adjusts their real-time priority during the end-to-end transmission period. In ARP, sensors get the links’ state information by exchanging information with one-hop and two-hop neighbors. The authors state that when nodes choose the next hop neighbor, they not only consider the real-time requirement, but also synthetically consider the energy index. The authors state that the real-time transmission level is adjusted dynamically using RT and TTL fields of the packet. RT (real-time) field is used to indicate if the packets have real-time transmission requirement. TTL (time to live) field is used to indicate how much time remains there for the data to arrive at the sink.

In this paper, the authors present the description, rules, algorithms, and mathematical formulation for ARP and its various modules. The authors take 100 sensor nodes in a network area of 200m x 200m for their simulation. The authors use OMNET++ simulator for the simulation study of proposed algorithm.

The authors state that when network overload increases, the ARP has better performance than SPEED and MMSPEED, because it differentiates the different real-time data and takes different transmission methods for them. The authors also state that among the three schemes, the control cost of ARP and MMSPEED are higher than SPEED, because that both ARP and MMSPEED spend more information to track link changes.

The authors claim, on the basis of their results, that ARP dynamically adjusts route and real-time level of data packets and the energy consumption of nodes is relatively even. The authors state that their research is just the preliminary work and it would serve as a guide for the future research.

This paper refers to Akyildiz et al. [2002].

A.20 [Simao 2007]

Ref. SIMAO, J. 2007. ASOS: An Adaptive Self-organizing Protocol for Surveillance and Routing in Sensor Networks. *Book Chapter of Engineering Self-Organizing Systems, 4th International workshop, ESOA 2006, Lecture Notes in Computer Science, 4335,* 115-131.

In this paper, the author addresses the routing problem in sensor networks with the constraint that an event should be reported to a sink node with as little delay as possible and at the same time, the power consumption by individual nodes should be as low as possible and balanced. This paper presents a heuristics model of Adaptive Self-Organization for Surveillance and Routing (ASOS) in sensor networks that addresses above mentioned routing requirements.

In this paper, the author states that the proposed routing protocol is a variation of Gradient-Based Routing (GBR). The author states that in the proposed routing protocol, the nodes exchange DIST and WHO messages to handle network reconfigurations efficiently, instead of diffusing interest messages as in case of GBR.

In this paper, the author claims to presents a new surveillance protocol that explores correlation between source location and event types, and a new routing protocol that adapts continuously to energy available at selected routes and to changes in topology. The author states that proposed routing protocol uses minimum hop count as distance metric and doesn't require global link cost information to be collected at nodes.

In this paper, the author presents the model design of ASOS that includes the rules for routing and surveillance protocol. The author evaluates the model using a self-developed visual simulator for a sensor network. The author also compares the proposed approach with other approaches for self-organization of sensor networks.

The author claims that the ASOS increases network longevity compared to gradient-based routing in sensor network. The author states that proposed protocols scale well with network size, and perform well in dynamic regimes and correlated events. The author also mentions that the proposed model has a drawback that the sensing resolution/precision is made to match the communication range of sensors. However, the author states that this may not be a serious issue for many applications with small communication range of sensor.

This paper refers to Akyildiz et al. [2002], Akkaya et al. [2005], and Heinzelman et al. [1999].

A.21 [Sun et al. 2005]

Ref. SUN, L.M., YAN, T.X., BI, Y.Z., AND ZHU, H.S. 2005. A Self-adaptive Energy-Aware Data Gathering Mechanism for Wireless Sensor Network. *ICIC 2005, Part II, Lecture notes in computer science, 3645,* 588-597.

In this paper, the authors address the problem of adaptive routing in data querying sensor network that minimizes both delivering delay and total energy consumption of data delivery as well as makes the energy consumption even among the nodes.

The authors state that the work presented in this paper is based on previous research on energy aware routing, data querying routing and geographic routing.

In this paper, the authors present, what they claim to be novel idea, a Dynamic Energy Aware Routing (DEAR) algorithm for data querying sensor networks. The authors state that in DEAR, the sink node uses restricted flooding to spread routing instruction that contains hop count and minimum residual energy information. The authors also state that in DEAR, the next hop is decided by both the hop count to sink node and residual energy of the data path. The authors state that as the data is transmitted from destination to sink node, the data path will be adjusted dynamically according to the residual energy of each node along it.

In this paper, the authors present the description, and performance analysis of proposed routing protocol. For simulation, the authors take up to 200 nodes in a 100m x 100m network.

The authors claim, on the basis of their results, that DEAR can prolong the lifetime of networks as compared to Directed Diffusion (DD), Minimum Transmission Energy routing (MTE), and Energy Aware Routing (EAR). The authors state that it is hard for DEAR to gain less average delay than DD when the network runs for a long time because of the fact that to consume power evenly, the DEAR may not always choose the paths that deliver data quickly. However, the authors state that DEAR provides less average delay than MTE and EAR.

A.22 [Tateson et al. 2003]

Ref. TATESON, J.E., AND MARSHALL, I.W. 2003. An Adaptive Routing Mechanism For Ad Hoc Wireless Sensor Networks. *London Communications Symposium 2003, Organizing Committee Chair: Dr. Mitchell, J.*

In this paper, the authors address the problem of finding a dynamic way to maintain an efficient routing structure with minimal overhead. With this objective, the authors present an adaptive routing mechanism that enables sensor nodes to minimize route cost by varying their transmission range, and by experimenting with the neighbors from which they forward data.

The authors state that their work is an extension of the routing hierarchy used by the Smartdust project of University of California at Berkeley. In routing hierarchy used by the Smartdust project, the network sink or sinks initiate a cascade of local broadcasts that allow shortest paths to be established.

The authors state that in the proposed adaptive routing protocol, the node levels are dynamically updated according to locally exchanged information as part of data transfer, so that changes in network configuration propagate quickly with minimal protocol overhead.

In this paper, the authors presented the description of proposed adaptive routing mechanism. The authors state that they carry out the simulation using 9 sensor nodes around a network sink. In this paper the authors compare the performance of three link cost functions, namely maxexp, sum r squared, and maxbatt.

The authors state that the results are limited in scope and represent a system that has been modeled fairly simplistically. The authors state that in proposed routing mechanism, taking the sum of link costs as route cost delivers fewer packets than using the costliest node as the route cost. The authors also state that in the proposed routing algorithm, to maximize the quantity of data collected, there is a trade-off between the energy cost of a route and the cost of the route in terms of loss of integrity of the network. The authors claim that the proposed routing mechanism generates minimal communication overhead and require very limited memory as compared to shortest path first routing.

A.23 [Wang et al. 2006]

Ref. WANG, P. AND WANG, T. 2006. Adaptive Routing for Sensor Networks using Reinforcement Learning. *The Sixth IEEE International Conference on Computer and Information Technology, CIT '06,* 219-219.

In this paper, the authors address the problem of adaptive routing that selects the optimum route with the objective of maximizing network life time by making the correct trade-offs between multiple routing objectives. In this paper, the authors use reinforcement learning technique that addresses above mentioned routing requirements.

The authors begin by stating that most of previous research on routing focuses on reducing routing cost by optimizing one goal such as routing path length, load balance, re-transmission rate, etc, in real scenarios. The authors appear to be the first to propose a routing scheme that considers multiple routing optimization goals together. The authors state that this paper is based on previous research on machine-learning-based routing for WSNs.

The authors claim to present a novel routing scheme, AdaR that is based on Least Squares Policy Iteration (LSPI) based reinforcement learning technique, which makes it possible to learn a best strategy with small number of tries and is insensitive against initial parameter setting. The authors state that AdaR adaptively learns an optimal routing strategy depending on multiple optimization goals.

In this paper, the authors present description of AdaR routing scheme. The authors evaluate the performance of AdaR on a simulated network, which consists of 400 sensors that are deployed on a perturbed grid over a square with length 80 units.

The authors claim that quality of the optimal routing strategies in terms of cumulative reward and success rate of routing is almost same in both AdaR and the Q-learning based routing implementation. However, the authors state that AdaR shows a significant performance gain in terms of convergence speed over a Q-learning based routing implementation.

This paper refers to Culler et al. [2004].

A.24 [Wang et al. 2007]

Ref. WANG, T.-J., YANG, Z., AND HU, H.-F. 2007. Adaptive data fusion routing algorithm based on genetic algorithm for wireless sensor networks, *Dianzi Yu Xinxi Xuebao/Journal of Electronics and Information Technology 29, 9,* 2244-2247

In this paper, the authors address the problem to adaptive data fusion routing in WSNs in which the mobile agent (MA) collects correlated data with energy validity.

The authors state that the work presented in this paper is based on the previous research on Full Fusion Genetic Algorithm (FFGA), Multi-objective mobile agent, routing correlated data with fusion cost, and adaptive data fusion for energy efficient routing for WSNs.

In this paper, the authors introduce, what they claim to be a novel idea, a genetic algorithm based adaptive data fusion routing algorithm, called Adaptive Fusion Genetic Algorithm (AFGA). The authors state that in the proposed routing algorithm, the MA moves to every sensor node that performs data fusion. The authors also state that to provide energy efficient route, the MA is adaptively adjusted according to data transmission cost, data fusion cost and energy gain.

In this paper, the authors present the mathematical formulation, and algorithmic description of proposed routing algorithm. The authors also present the performance analysis based on MATLAB based simulator. In the simulation study, the authors use a 50m X 50m simulation area with the number of sensor nodes as variable parameter.

The authors claim, on the basis of their results, that the energy efficiency of adaptive fusion routing algorithm has better performance than full fusion routing algorithm and Local Closest First (LCF) heuristics algorithm.

This paper refers to Luo et al. [2005], and Luo et al. [2006].

A.25 [Xu et al. 2006]

Ref. XU, J., PERIC, B., AND VOJCIC, B. 2006. Performance of energy-aware and link-adaptive routing metrics for ultra wideband sensor networks. *Mobile Networks and Applications, 11, 4,* 509-519.

The authors appear to be the first to apply spatial diversity for Energy-aware and Link-adaptive routing for Ultra Wide Band (UWB) sensor networks.

The authors state that, unlike the proposed algorithm in this paper, the previous research on routing protocol for WSNs focuses on energy conservation and does not take into account other network performance metrics such as throughput and end- to-end delay. The authors state that this paper extends the work of a previous paper Xu et al. [2005], by same authors, by considering a time varying channel environment and a more realistic mobility model.

In this paper, the authors propose energy-aware and link-adaptive next hop routing metrics, such as such as Maximum Forward Progress (MFP) or Maximum Information Progress (MIP), based on the availability of sensor node's location, link quality and next hop battery capacity information. In this paper, the authors utilize the ranging capability of UWB and employ adaptive modulation to take advantage of favorable link conditions.

In this paper, the authors present the description of system model, routing metrics, and routing schemes. The authors present the performance analysis of proposed routing metrics on random and grid network topologies with 100 nodes located in a square region of 500 × 500 meters.

The authors state that the energy-aware routing metrics (MFPenergy and MIPenergy) have equal or better average throughput than the corresponding metrics that do not use battery capacity information in the routing decision (MFP and MIP). The authors also state that routing schemes MFP metric with Adaptive Modulation (MFP-AM) and MIP metric with Adaptive Modulation (MIP-AM) perform better in terms of average throughput before any node dies out than the non-link-adaptive scheme MFP metric with fixed modulation (MFP-FM).

The authors claim that MIP metrics increase average throughput by 30-50% (100-300% in a time varying channel environment) before network performance deteriorates compared to MFP metrics while exhibiting smaller delay. The authors state that it is due to the ability of the MIP metrics to adapt to the link quality in the routing decision. The authors state that mobility improves throughput performance and prolongs network lifetime for all of the metrics compared to the static node scenario due to the added spatial diversity and equalized energy consumption.

This paper refers to Xu et al. [2005].

A.26 [Ye et al. 2007]

Ref. YE, N., SHAO, J., WANG, R., AND WANG, Z. 2007. Colony Algorithm for Wireless Sensor Networks Adaptive Data Aggregation Routing Schema, *Bio-Inspired Computational Intelligence and Applications, Lecture Notes in Computer Science, 4688*, 248-257.

In this paper, the authors address the problem of routing in WSNs that establishes a trade-off between data aggregation, delay, and energy consumption. The authors appear to be the first to use Ant Colony Optimization Algorithm (ACO) to address such routing challenges in WSNs.

The authors state that their work is based on previous research on Directed Diffusion (DD) routing algorithm, ACO, and the concept of Mobile Agent-Based Distributed Sensor Networks (MADSNs).

In this paper, the authors present Ant Colony Algorithm based Routing (ACAR) scheme for WSN. The authors state that the proposed routing algorithm performs optimization of data aggregation route by Ant-Like Mobile Agent (AMA) using the three heuristic factors about energy, distant and aggregation gain. The authors state that each AMA is a small signaling packet transporting state information and builds a path from its source nodes to its destination by sharing their knowledge among neighbors. The authors state that the AMA chooses a node as data transfer/routing candidate if the node has higher residual energy and lower gain of data aggregation. The authors state that the proposed algorithm is a distributed routing algorithm.

In this paper, the authors present description, mathematical formulation, and analysis of the proposed routing algorithm. For the simulation study of the proposed algorithm, the authors use the network simulator for WSNs developed by Naval Research Laboratory (NRL) that is an extended simulation environment based on NS2.

The authors claim, on the basis of their results, that the ACAR algorithm has better energy efficiency than DD for larger network size. However, the authors state that at the initial stages of simulation (1 to 7 seconds), the energy consumption in ACAR is less than DD, but in later stages of simulation (10 to 20 seconds), the ACAR consumes more energy than DD. The authors claim that the ACAR algorithm has better energy efficiency than LEACH algorithm at the initial stages of simulation, but in later stages of simulation (10 to 20 seconds), the energy consumption is faster in ACAR algorithm than PEGASIS algorithm. The authors claim, on the basis of their results, that ACAR performs 1.5 times better than PEGASIS, and 7 times better than LEACH in terms of energy efficiency.

This paper refers to Akyildiz et al. [2002].

A.27 [Yuan-yuan et al. 2005]

Ref. YUAN-YUAN, Z., BO, X., AND ZI-MING, Z. 2005. Adaptive directed diffusion routing in wireless sensor networks based on application. *Canadian Conference on Electrical and Computer Engineering 2005*, 2147 – 2150.

This paper presents an adaptive directed diffusion routing in WSNs based on application (ADDRA).

In this paper, the author begin by stating that the performance of traditional Directed diffusion routing protocol can degrade drastically if it is not matched with the sensor applications. In this work, the authors present an improvement in Directed diffusion routing protocol by taking application scenario into consideration while taking routing decisions.

In this paper, the authors claim to present a new general message machine that is used for adaptive selection of possible routing approaches for WSNs. The authors state that the general message machine is applicable where the application scenario does not change quite often. In this paper, the authors propose ADDRA routing protocol that works as per the application environment by switching adaptively from normal model to push model to match current application scenarios.

In this paper, the authors present the description and model of ADDRA protocol. The authors evaluate the performance of proposed protocol on a simulated environment with various simulated application scenarios. The authors use NS2 simulator with a network size of 250 nodes with transmission range of 20 meters. The authors also compare the performance of ADDRA protocol with other versions of directed diffusion algorithm.

The authors claim that the ADDRA has better performance in varying application environment and network dynamics than the other versions of directed diffusion algorithm such as One-Pull Phase directed diffusion routing algorithm (OPP), and push directed diffusion routing algorithm. In this paper, in future work, the authors plan to develop an extended message machine to include QoS requirements of applications.

A.28 [Zhang et al. 2004b]

Ref. ZHANG, Y., AND FROMHERZ, M. 2004. Search-based adaptive routing strategies for sensor networks. *AAAI04 workshop on Sensor Networks.*

The authors appear to be the first to apply real-time search and reinforcement learning technique for adaptive routing in WSNs.

The authors state that previous research on application of real-time or agent-centered search methods of AI and reinforce learning is the basis of their work in this paper.

In this paper, the authors state that to adapt routing in sensor networks, the energy and latency are traded by setting the forward propagation policy, and success rate and energy are traded by the retransmission policy.

In this paper, the authors present the algorithmic framework and complexity analysis of search-based routing strategies. The authors also present the description of proposed piggybacked heuristics, heuristic estimation, promiscuous learning, indirect confirmation, and forward propagation mechanism. In this paper, the authors evaluate the performance of proposed routing strategies in PROWLER sensor network simulator.

The authors state that “for a given static and symmetric network and admissible initial estimate Q[0,m] for message m, and assuming that the destination is not empty and there is a path from the source to the destination, then both the message complexity and time complexity of the search-based routing are O(nd), where n is the number of nodes in the network and d is the diameter of the network”. The authors also state that “If the initial estimates are admissible, then the search-based strategy guarantees delivery for a symmetric network if a path exists and it also guarantees convergence to an optimal route if the change rate of the network is slower than the convergence rate”. The authors state that “the search-based strategy guarantees delivery in O(nd) if the initial over-estimate is bounded by O(d)”.

In this paper, the authors state that the comparison of proposed routing framework with other routing strategies will be discussed in another paper. The authors also state that the search-based routing strategies have been implemented on Berkeley motes, but the details of the implementation are outside the scope of this paper.

This paper refers to Zhang and Fromherz [2004a].
This paper is referred by Cerpa et al. [2004], Zhang and Huang [2006a], and Zhang and Huang [2006b].

A.29 [Zhang et al. 2006a]

Ref. ZHANG, Y., AND HUANG, Q. 2006. A Learning-based Adaptive Routing Tree for Wireless Sensor Networks. *JOURNAL OF COMMUNICATIONS, 1, 2,* 12-21.

This paper presents an adaptive spanning tree routing mechanism using real-time reinforcement learning strategies for WSNs.

The authors state that earlier they have proposed four major routing strategies for WSNs. These routing strategies are Message-initiated Constraint-Based Routing (MCBR), real-time search, constrained flooding, adaptive spanning tree. The authors state that the work done in this paper is an extension of previous work by the same authors on adaptive spanning tree proposed in Zhang and Huang [2006b].

The authors state that basic ideas and protocol of adaptive trees have been presented Zhang and Huang [2006b]. The authors also state that the new contributions of this paper include defining new routing metrics for energy-aware load balancing to increase lifetime, and for congestion-aware routing to reduce latency and increase reliability. In this paper, the authors state that Adaptive trees is different from real-time search and constrained flooding routing strategies in the sense that it requires a known sink at its initialization. The authors also state that implicit confirmation and retransmission are used, rather than sending periodical maintenance packets from the sink node as in many tree-based routing protocols. The authors state that the Adaptive Tree Protocol is between structure-based and structure-less.

In this paper, the authors present an extended study of the adaptive tree protocol, as well as performance analysis and comparisons with other peer routing protocols. The author state that simulation test for performance analysis is done on RMASE that is an application built on PROWLER sensor network simulator.

The authors state that the parameters in the protocol such as learning rates for Q-values, update rates for NQ-values, parent reset threshold, and the maximum number of retransmissions for failed confirmations, can be tuned to make the routing best for a particular application.

In this paper, the authors claim that adaptive tree protocol is robust for un-predictable link failures and mobile sinks, and can be applied to achieve load balancing and to control network congestion effectively in real time. In this paper, in future work, the authors state that lots of research still needs to be done on the selection of parameter values and understanding the relationship between different parameters.

This paper refers to Zhang and Fromherz [2004a], Zhang and Fromherz [2004b], and Zhang and Huang [2006b].

A.30 [Zhang et al. 2006b]

Ref. ZHANG, Y., AND HUANG, Q. 2006. Adaptive tree: A learning-based meta-routing strategy for sensor networks. *3rd IEEE Consumer Communications and Networking Conference, CCNC 2006, art. no. 1593000*, 122-126.

In this paper, the authors present an adaptive spanning tree routing mechanism that is a type of real-time reinforcement learning-based meta-routing strategy for the constraint-based routing.

The authors refer to Message-initiated Constraint-Based Routing (MCBR), presented in an earlier paper Zhang and Fromherz [2004a] by the same authors, and indicate that they use the framework of MCBR as the basis of their work.

In this paper, the authors propose learning-based meta-strategies for MCBR. The authors state that in the proposed routing mechanism, given a routing specification of a message, a cost function can be estimated for each node, called Q-value that indicate the minimum cost-to-go from this node to the destination. The authors state that a node also stores its neighbors' Q-values, called NQ-values that are estimated initially according to the neighbors' attributes and updated when packets are received from neighbors. The authors state that proposed routing mechanism adapt to different routes automatically when network conditions change.

In this paper, the authors present the description of routing specification and reinforcement learning kernel. The authors also present the description, pseudo code and performance analysis of adaptive tree protocol. For performance analysis, the authors use Matlab based WSN simulation environment for Berkeley Motes, called Rmase.

The authors claim, on the basis of their results, that without additional control packets for tree maintenance, the adaptive spanning trees can maintain the best connectivity to the base station as compared to Backbone tree and Grid Routing algorithms, in spite of node failures or mobility of the base station. In the future work, the authors state that the selection of parameter values and the relationship between different parameters need to be explored.

This paper refers to Zhang and Fromherz [2004a], Zhang and Fromherz [2004b].
This paper is referred by Zhang and Huang [2006b], and Zhang and Huang [2007].

A.31 [Zhou et al. 2006b]

Ref. ZHOU, J., ROURE, D.D., AND VIVEKANANDAN, S. 2006. Adaptive Sampling and Routing in a Floodplain Monitoring Sensor Network. *IEEE International Conference on Wireless and Mobile Computing, Networking and Communications, WiMob'06*, 85-93.

In this paper, the authors address the problem of adaptive monitoring and routing in WSNs with the constraint that routing scheme should conserve the energy of nodes with important data and should be robust to the failure of sensor nodes and transmission medium. The authors state that the routing algorithm proposed in this paper couples application requirements with energy conditions in the network and is designed for a flood early warning system as part of FloodNet project at University of Southampton.

This paper is an extension of an earlier paper Zhou et al. [2006a] by same author. The authors state that previous research on power-aware localized routing, GEAR, LEACH, PEGASIS, and the Energy Aware Routing (EAR) protocol have made significant progress in extending network lifetime by evenly distributing the energy load among all the nodes in the network. However, the authors state that none of these research work looks at the effect of the diversity in the reporting rates of nodes on the protocol design.

In this paper, the authors propose, what they claim to be a new idea, the FloodNet Adaptive Routing (FAR) that takes into account the distinct behaviors of individual nodes and uses priority as well as a set of rules in determining the routing path. The authors state that in FAR, the decision that a sensor node should be used to forward data messages is based on the distance, the residual battery power, the link cost, and the data importance of the node. Hence, FAR allows data messages to be routed across nodes with ample energy and light reporting tasks while conserving energy for those nodes which have a low level of energy and heavy reporting tasks. The authors state that FAR is a network layer protocol that assumes a collision-free, multiple retry MAC layer.

In this paper, the authors present the description, design methodology, algorithm, and performance analysis of the proposed routing algorithm. The authors use two self developed simulators for the performance analysis of the proposed algorithms.

The authors claim, on the basis of their simulation results, that FAR can extend the network lifetime and the node operational time over EAR in the FloodNet topology and the performance increase of FAR over EAR grows as the network density becomes higher. The authors also claim that FAR outperforms Minimum Energy Consumption Forwarding (MECF) in the FloodNet topology by producing a longer network lifetime (NL) and a node operational time (NOT). The authors claim that FAR is robust to topological changes due to transient node and link failure due to the fact that in FAR, the optimal path is computed on demand.

This paper refers to Zhou et al. [2006a].
This paper is referred by Zhou et al. [2007].

A.32 [Zhu et al. 2002]

Ref. ZHU, M. 2002. Decentralized and Adaptive Sensor Data Routing. Masters thesis, Louisiana State University.

The author appears to be the first to identify the problem of adaptive routing in WSNs. In this Thesis, the author begins by stating that no routing protocol exist that is energy efficient, self-adaptive and error tolerant at the same time. The author states that the routing protocols proposed in this thesis meet all these requirements.

The author states that previous research on table-driven (proactive) routing protocols and source-initiated on-demand (reactive) routing protocols have made significant progress for routing in ad hoc network routing. However, these routing approaches lack adaptation, energy efficiency and error tolerance needed in WSNs.

The author states that in this thesis, he presents a new peer to peer (P2P) routing notion based on the theory of cellular automata. The author states that he presents two new routing adaptation models that are Spin glass and Multi-Fractal. The author claims that the proposed models use the ideas from Physics and Chemistry for the first time for distributed adaptation.

In this thesis, the author presents the description, analysis, and simulation detail of proposed Spin glass and Multi-Fractal routing adaptation model. The author implements two Dynamic Link Libraries in C++ using cellular automata Cantor modeling tool. The author implemented corresponding graphic display procedures in Tcl/tk.

The author evaluates Spin glass routing model for Temperature Effect, Cell Failure Probability, and Adaptation to disturbance, Disturbance Locations, Energy Map, and Damping Effect. The author evaluates Multi-fractal routing Model for Linear inhibition curve, Tree with quadratic curve, and Adaptation to Topological Disturbance. The author states that both of the proposed routing models have communication complexity O(8N).

The author claims, on the basis on their results, that the proposed routing protocol not only save significant amount of communication and computation cost but also adapt to the highly volatile environment of ad hoc WSNs. In the future work, the author says that several modifications need to be made in cellular automata model to adjust to practical application.

This paper is referred by Brooks et al. [2003].