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Review

Classical and swarm intelligence based routing protocols for wireless sensor networks: A survey and comparison

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ABSTRACT

High efficient routing is an important issue for the design of wireless sensor network (WSN) protocols to meet the severe hardware and resource constraints. This paper presents a comprehensive survey and comparison of routing protocols in WSNs. The first part of the paper surveys state-of-the-art routing protocols in WSNs from classical routing protocols to swarm intelligence based protocols. The routing protocols are categorized based on their computational complexity, network structure, energy efficiency and path establishment. The second part of the paper presents a comparison of a representative number of classical and swarm based protocols. Comparing routing protocols in WSNs is currently a very challenging task for protocol designers. Often, much time is required to re-create and re-simulate algorithms from descriptions in published papers to perform the comparison. Compounding the difficulty is that some simulation parameters and performance metrics may not be mentioned. We see a need in the research community to have standard simulation and performance metrics for comparing different protocols. To this end, the final part of the paper re-simulates different protocols using a Matlab based simulator: routing modeling application simulation environment (RMASE), and gives simulation results for standard simulation and performance metrics which we hope will serve as a benchmark for future comparisons for the research community.

Contents

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1. Introduction

A sensor network is an infrastructure composed of sensing (measuring), computing, and communication elements that gives a user or administrator the ability to instrument, observe, and react to events and phenomena in a specific environment (Akkaya and Younis, 2005; Sohraby et al., 2007; Akyildiz et al., 2002). Wireless sensor networks (WSNs) are collections of compact-size, relatively inexpensive computational nodes that measure local environmental conditions, or other parameters and forward such information to a central point for appropriate processing. WSN nodes can sense the environment, communicate with neighboring nodes, and in many cases perform basic computations on the data being collected. The environment can be the physical world, a biological system, or an information technology (IT) framework. Through advanced mesh networking protocols, these sensor nodes form a wide area of connectivity which extends the reach of cyberspace out into the physical world. The sensing circuitry measures ambient conditions related to the environment surrounding the sensor, which transforms them into an electric signal. Processing such a signal reveals some properties about objects located and/or events happening in the vicinity of the sensor. The sensor sends such collected data, usually via radio transmitter, to a command center (sink) either directly or through a data concentration center (a gateway). The decrease in the size and cost of sensors, resulting from such technological advances, has fueled interest in the possible use of a large set of disposable unattended sensors. Such interest has motivated intensive research in the past few years addressing the potential of collaboration among sensors in data gathering and processing and the coordination and management of the sensing activity and data flow to the sink. A natural architecture for such collaborative distributed sensors is a network with wireless links that can be formed among the sensors in an ad hoc manner.

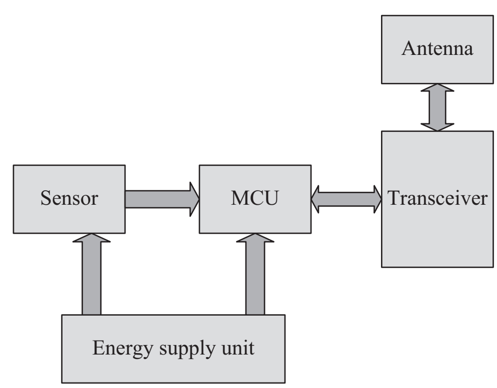
The backbone of WSNs lies in the ability to deploy large number of tiny nodes that assemble and configure themselves for a specific purpose. WSN is used in many applications such as radiation and nuclear-threat detection systems, weapon sensors for ships, toxins and to trace the source of the contamination in public-assembly locations, structural faults (e.g., fatigue-induced cracks) in ships, volcanic eruption, earthquake detection, aircraft, and buildings, biomedical applications, habitat sensing, and seismic monitoring. More recently, interest has focused on networked biological and chemical sensors for national security applications, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, process control, inventory management, distributed robotics, weather sensing, environment monitoring, national border monitoring, building and structure monitoring (Sohrabi et al., 2000). The most common application of sensor network technology is to monitor remote environments for low frequency data trends. For example, a chemical plant could be easily monitored for leaks by hundreds of sensors that automatically form a wireless interconnection network and immediately report the detection of any chemical leaks. Unlike the traditional wired systems, deployment cost is set to a minimum (Chong and Kumar, 2003). In addition to reducing the installation costs, wireless sensor networks also have the ability to adapt dynamically to changing environments. These can respond to changes in network topologies. A wireless sensor network node consists of four major parts such as

1. Sensor unit.
2. Processing unit.
3. Energy source unit.
4. Transceiver.

Depending on the area and purpose of use, additional components might be required such as localization unit, energy harvesters, position changers and monitors as shown in Fig. 1.

In many WSN applications, the deployment of sensor nodes is performed in an ad-hoc manner without proper planning or studies. Once deployed, the sensor nodes must be able to autonomously organize themselves into a wireless communication network. As sensor nodes are battery powered and expected to operate and execute their duties without attendance for a long duration of time during the application, it is difficult and even impossible to change or recharge batteries for the sensor nodes (Akyildiz et al., 2002; Chong and Kumar, 2003).

Despite the different objectives of sensor networks applications, the main function of wireless sensor nodes is to sense and collect information (data) from a target area, process, and transmit the information via a radio transmitter back to a command center where the underlying application resides (sink) (Akkaya and Younis, 2005; Sohraby et al., 2007). In order to achieve this task efficiently, an efficient routing protocol is needed to set up paths of



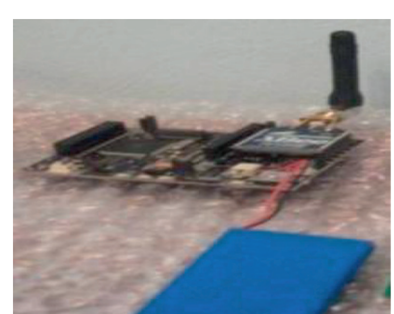


Fig. 1. WSN node architecture and a real Waspmote example.

communication between the sensor nodes (sources), and the command center (sink). The path selection must be such that the lifetime of the network is maximized. Due to the characteristics of the environment in which the sensor node is to operate, coupled with severe resource constraints in on-board energy, transmission power, processing capability, and storage limitations, this prompts for careful resource management and new routing protocols so as to counteract the differences and challenges.

Social insect communities have many desirable properties from the WSN perspective as surveyed in (Çelik et al., 2010; Saleem et al., 2010). These communities are formed from simple, autonomous, and cooperative organisms that are interdependent for their survival. Despite a lack of centralized planning or any obvious organizational structure, social insect communities are able to effectively coordinate themselves to achieve global objectives. The behaviors which accomplish these tasks are emergent from much simpler behaviors or rules that the individuals are following. The coordination of behaviors is also adaptive, flexible and robust, and necessary in an unpredictable world which is capable of solving real world problems. No individual is critical to any operation, and task progress can easily be recovered from any setback. The complexity of the solutions generated by such simple individual behaviors indicates that the whole is truly greater than the sum of the parts (Hölldobler and Wilson, 1990). The characteristics described above are desirable in the context of sensor networks. Such systems may be composed of simple nodes working together to deliver messages, while resilient against changes in its environment. The environment of sensor network might include anything from its own topology to physical layer effects on the communications links, to traffic patterns across the network. A noted difference between biological and engineered networks is that the former have an evolutionary incentive to cooperate, while engineered networks may require alternative solutions to force nodes to cooperate (Buttyan and Hubaux, 2000; MacKenzie and Wicker, 2001). The ability of social insects to self organize relies on four principles: positive feedback, negative feedback, randomness, and multiple interactions. A fifth principle, stigmergy, arises as a product of the previous four (Roth and Wicker, 2003). In general, such self organization is known as swarm intelligence. Swarm intelligence (Dorigo and Caro, 1998) is a relatively novel field that was originally defined as ''any attempt to design algorithms or distributed problem-solving devices inspired by the collective behavior of social insects and other animal societies''. However, it now generally refers to the study of the collective behavior of multi-component systems that coordinate using decentralized controls and self-organization. From an engineering point of view, swarm intelligence emphasizes the bottom-up design of autonomous distributed systems that can show adaptive, robust, and scalable behaviors. Research on this field of swarm intelligence is based on working principles of ant colonies as adopted in (Bonabeau et al., 1999; Dorigo and Caro, 1998), slime mold (Li et al., 2011), Particle swarm optimization (Liu et al., 2012) and honey bees (Saleem and Farooq, 2007b).

The process by which data and queries are forwarded efficiently between the source and the sink is an important aspect and basic feature of wireless sensor networks. The decrease in size and cost of sensor nodes due to technological advancement has encouraged researchers in the past years to engage in an intensive research on addressing the potential of collaboration among sensors in data gathering, processing, coordination, and management of the sensed data flow to the sink (Akkaya and Younis, 2005). A simple approach to accomplish this task is for each sensor node to exchange data directly with the sink (a single-hop-based approach), or allowing intermediate nodes to participate in forwarding data packets between the source and the destination (multi-hop) (Sohraby et al., 2007). Determining which set of intermediate node is to be selected to form a data forwarding path between the source and the destination is the principal task of the routing algorithm. The differences in the way data are forwarded from the nodes to the sink, leads to classifying the routing protocols.

However, many approaches have been taken by different researchers in the field of sensor networks to classify and group each of the routing protocols based on some metrics. But there has been no survey paper based on our knowledge that covers up-to-date routing protocols. Even the ones among them that treated relatively high number of protocols, tends to focus only on the conventional routing protocols (classical) or biologically inspired routing protocols (swarm intelligence). This paper presents a comprehensive up-to-date survey and comparison of routing protocols in WSNs. The first part of the paper surveys state-of-the-art routing protocols in WSNs from classical routing protocols to swarm intelligence based protocols. The routing protocols are categorized based on their computational complexity, network structure, energy efficiency and path establishment. The second part of the paper presents a comparison of a representative number of classical and swarm based protocols. Comparing routing protocols in WSNs is currently a very challenging task for protocol designers. Often, much time is required to re-create and re-simulate algorithms from descriptions in published papers to perform the comparison. Compounding the difficulty is that some simulation parameters and performance metrics may not be mentioned. We see a need in the research community to have standard simulation and performance metrics for comparing different protocols. To this end, the final part of the paper re-simulates different protocols using a Matlab based simulator; routing modeling application simulator environment (RMASE), and gives simulation results for standard simulation and performance metrics which we hope will serve as a benchmark for future comparisons in the research community. To the best of our knowledge, this is the first survey paper that combines both classical routing and swarm based routing protocols, and proposes a standard of comparison among routing protocols designers.

The rest of the paper is organized as follows. Section 2 reviews previous survey articles on WSN routing, Section 3 describes the design factors of WSNs and how they affect routing in WSNs. Section 4 discusses the taxonomy of routing protocols in WSNs. Section 5 deals with classical routing protocols. In Section 6, swarm intelligence routing protocols are discussed. Section 7 presents analytical comparison of classical and swarm intelligence routing protocols, while Section 8 deals with their experimental comparison. In Section 9, we present a general discussion of the reviewed routing protocols in WSN. And finally, Section 10 concludes the paper with proposed future direction.

2. Previous surveys of WSN routing

Routing is a very important function in the design of WSN. There have been some survey papers on routing. Akyildiz et al. (2002) surveyed protocols on wireless sensor networks, while dealing with few of the classical routing protocols and their methods of information forwarding. Their work was based on a short period of review (1999–2000). Karaki and Kamal (2004) surveyed different routing techniques in WSNs. The authors surveyed quite a number of routing protocols, but they were limited to classical routing, and were back as old as 2004 protocols. In a similar survey, Akkaya and Younis (2005) survey was still based on classical routing protocols, and not much different from that of Karaki and Kamal (2004), even as it was more recent, did not capture in their work protocols that were designed as of 2004. In the same year, Yang and Mohammed (2005)

Table 1
Summary of previous survey on routing protocols in WSN.

S/no.	Year of survey	Authors	Survey characteristic
1	2002	Akyildiz et al.	Classical routing
2	2004	Karaki and Kamal	Classical routing
3	2005	Akkaya and Younis	Classical routing
4	2005	Yang and Mohammed	Classical routing
5	2010	Singh et al.	Classical routing
6	2010	Saleem et al.	Swarm intelligence routing
7	2010	Çelik et al.	Swarm intelligence routing
8	2009	Villalba et al.	Classical routing
9	2010	Baranidharam and Shanthi	Classical routing

work was also based on classical routing, and their survey was also based on selected protocols.

Recently, Singh et al. (2010) surveyed articles, only surveyed few among the classical protocols without much comparison among the few surveyed by them. Saleem et al. (2010) was the first survey on swarm intelligence based routing protocols. The authors did quite a good survey, while also considering their area of applications and simulation environments. They concentrated on swarm based protocols and left behind some of the promising protocols among the swarm based that were present as at the time of their work. Following the trends, Çelik et al. (2010) the most recent among the swarm based protocol survey, concentrated on just few protocols in swarm based even as their work was based on swarm based protocol survey. They also did not compare the protocols based on their performance, area of application and environment of simulations. Villalba et al. (2009), also a most recent article, in their work, comparison was based on two selected protocols, and also on classical routing protocols. Baranidharan and Shanti (2010) survey work was based on energy efficient protocols and on classical routing. Though, they call it a survey on energy efficient protocols for wireless sensor network, their work did not cover all the energy efficient classical based routing protocols. At this end, we summarize the previous work related to ours in Table 1. The table highlights the contribution of each author along with the year of survey and the survey characteristics.

3. WSNs design and routing factors

A large number of research have been carried out to overcome the constraints of WSNs and also to solve the design and application issues. The characteristics of sensor networks and application requirements have direct impact on the network design issues in terms of network performance and capabilities (Akyildiz et al., 2002). Due to the large number of sensor nodes and the dynamics of their operating environment, these then pose unique challenges on the architectural design of sensor networks. New platforms are needed to overcome all the challenges and cover the following issues; power consumption, fault tolerance, scalability, productive cost, quality of service, data aggregation and fusion, node mobility, connectivity, security, congestion, latency, etc. Routing design is closely related to the network system architecture mode and the design of routing protocols in WSNs is influenced by many challenging factors to be addressed which are outlined and discussed below.

1. Limited energy capacity: the process of setting up routes in a network is greatly affected by energy considerations. Since sensor nodes are battery powered, they have limited energy capacity. Energy poses a great challenge in many applications of sensor networks. Since radio transmission degrades with distance much faster than transmission in free space, it then implies that communication distance and energy consumption must be well managed. In the case of directed and multi-hop routing, directed routing would perform well enough if all sensor nodes are close to the sink, whereas multi-hop routing consumes less power than directed routing due to the fact that, sensors are usually randomly scattered in the area of deployment, though it may introduce significant overheads for topology management and MAC protocols. For applications in the battle field where it is virtually impossible to access the sensors and recharge their batteries (Akyildiz et al., 2002; Chong and Kumar, 2003), routing protocols design for sensor networks should be as energy efficient as possible to extend their lifetime, and hence, prolong the network lifetime without performance degradation.
2. Node deployment: sensor nodes deployment in WSNs is application dependent and affects the performance of the routing protocol. If nodes are randomly deployed, they need to create an infrastructure in an ad-hoc manner and organize themselves to establish paths to route the events using route discovery so as to allow connectivity and energy efficient network operation.
3. Sensor location: sensor location at the early stage of route discovery is a great challenge in the design of routing protocols. As most of the already proposed protocols assumes that the sensor nodes either are equipped with global positioning system (GPS) receivers or other forms of sensing the destination or sink as in Chong and Kumar (2003) and Zhang et al. (2004b), to learn about their locations, another challenge which has to be managed is the location of the sensors.
4. Dynamic network: sensor networks consist of three main components; sensor nodes, event, and sink. Since sensor node and sink are always assumed to be fixed or mobile, though, nodes are fixed in most of the applications, this have to support the mobility of sinks or gateways in the network. Hence, the stability of the routing data is an important design issue in addition to energy consumptions and bandwidth utilization (Akyildiz et al., 2002; Chong and Kumar, 2003; Singh et al., 2010).
5. Hardware resource constraints: sensor nodes also have limited storage and processing capacities, and hence, low computational capabilities. The hardware constraints present many challenges in the network and software protocol design for sensor networks, which have to be considered alongside with the limited energy.
6. Data aggregation and gathering: data gathering or reporting is concerned with any physical event of the sensor network. This could be event driven, query driven, or automated time driven, or both combined. Data gathering methods are highly important with respect to sensor network routing, as after receiving signal or data, the node has to transfer or route the data or information to the sink (Yang and Mohammed, 2005). Also, since sensor nodes may generate significant redundant data, similar packets from multiple nodes can be aggregated so that the number of transmissions is reduced, which will help in energy minimization.
7. Latency: latency or end-to-end delay in WSNs is an expression of how much it takes for a data packet to get from one node to the sink or vice versa. This is the measure of either one-way (the time it takes for the source to send a packet to the sink), or round-trip (the one-way latency from source to sink and from sink back to the source). Data aggregation and multi-hop relays can affect latency (Zaman and Abdullah, 2010; Karaki and Kamal, 2004).

Table 2
Taxonomy of routing protocol classification in wireless sensor networks.

	Classical based routing protocols	Swarm intelligence based routing protocols
Data-centric	SPIN (5.1.3) F&G (5.1.1), DD (5.1.2), EAR (5.1.5), RR (5.1.6) CADR (5.1.7), COUGAR (5.1.9), EAD (5.1.10) GBR (5.1.4), ACQUIRE (5.1.8)	CRP (6.1.2) PEADD (6.1.1)
Location based	GEAR (5.2.2), TBF (5.2.5), EAGRP (5.2.6) GAF (5.2.1), MECN (5.2.3), SMECN (5.2.4)	SC (6.2.1)
Hierarchical	LEACH (5.3.1), SOP (5.3.3) TEEN (5.3.4) PEGASIS (5.3.2), APTEEN (5.3.5), HEED (5.3.6) EAR-CSN (5.3.7), BCEE (5.3.8)	SDG (6.3.1), EBAB (6.3.2), ACO-C (6.3.3), ACALEACH (6.3.4) MACS (6.3.5) AntChain (6.3.6), PZSWiD (6.3.7), ACMRA (6.3.8), ACMT (6.3.9) ACLR (6.3.10), MSRP (6.3.11), JARA (6.3.12), ACOLBR (6.3.13), ACO-RC (6.3.14)
Network flow and QoS aware	MLDG (5.4.1) AODV (5.4.8) SAR (5.4.2), MLER (5.4.3), SPEED (5.4.4), EAQSR (5.4.5), MCBR (5.4.6)	EEABR (6.4.1), AR & IAR (6.4.5), iACO (6.4.7), MO-IAR (6.4.9) Ant-aggregation (6.4.10), ASAR (6.4.11), BABR (6.4.12) ACO-EAMRA (6.4.13), EAQR (6.4.14), IACR (6.4.15) E-D ANTS (6.4.4), Beesensor (6.4.6), ACO-QoSR (6.4.8), QDV (6.4.16) FF (6.4.2), FP (6.4.3), ANTSENSNET (6.4.17)

8. Scalability: since sensor applications may have many sensor nodes, it implies that, since the number of sensor nodes deployed in the sensing area may be in the order of hundreds or thousands, it then means that routing algorithms must be scalable enough to handle and respond to the events. Abstraction and simplicity mechanism is a demanding factor, since a large amount of data is expected to be decreased to manageable size (Çelik et al., 2010).
9. Fault tolerance: the failure of a particular sensor node due to power, physical damage, or environmental interference in a network, should not in any way affect the overall network performance or task handling. In case of the failures, routing protocols should be able to generate new routes to the data collection point or sink (Krishnamachari et al., 2002).

Due to the factors mentioned above, researchers have designed and developed various routing protocols specifically for WSNs due to the differences between routing in WSNs and other wireless networks. Routing in sensor networks involves a lot of challenges due to differences in some properties between them and contemporary communication and wireless ad hoc networks (Akkaya and Younis, 2005). First of all, it is not possible to build a global addressing scheme for the deployment of large number of sensor nodes. Therefore, classical IP-based protocols cannot be applied to sensor networks. Second, in contrary to typical communication networks, almost all applications of sensor networks require the flow of sensed data from multiple regions (sources) to a particular sink. Third, generated data traffic has significant redundancy in it since multiple sensors may generate the same data within the vicinity of a phenomenon. Such redundancy needs to be exploited by the routing protocols to improve energy and bandwidth utilization. Fourth, sensor nodes are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage and thus require careful resource management. Due to such differences, many new algorithms have been proposed for the problem of routing data in sensor networks. These routing mechanisms have considered the characteristics of sensor nodes along with the application and architecture requirements. Almost all of the routing protocols can be classified as data-centric, hierarchical or location based although there are a few distinct ones based on network flow or quality of service (QoS) awareness (Lin and Gerla, 1997). Some protocols also fit into other categories. We will summarize the routing protocols categories and their differences according to some metrics as shown in Table 2.

4. Taxonomy of routing protocols in WSNs

Determining which set of intermediate nodes are to be selected to form a data forwarding path between the source and the destination is the principal task of the routing algorithm. The computational complexity and the differences in the way data are forwarded from the nodes to the sink, leads to classifying the routing protocols as either classical or swarm intelligence based, and or data-centric, hierarchical, location based, network flow and quality of service (QoS) awareness (Akkaya and Younis, 2005). Shown in Table 2 is the taxonomy of the routing protocol classification in wireless sensor networks. The numbers in parentheses indicate the section numbers for easy and quick referencing. Routing protocols could also be classified based on path establishment. Using the path establishment classification, routing path can be established in one of the three ways: proactive, reactive or hybrid.

1. *Swarm intelligence based routing protocols*: these are protocols that depend on the collective behavior of biological species (e.g., ants) to provide a natural model for distributive problem solving without any extra central control or coordination. The basic concepts of the protocols are self-organization, which include positive feedback, negative feedback, fluctuation amplification, and multiple interactions. Consider the ant colony as an example to illustrate these concepts. The action of disposing pheromone is a positive feedback mechanism to recruit more ants such that more pheromones are disposed on the shorter path. However, the evaporation of pheromone is a negative feedback to reduce the pheromone level. In this way, the shortest paths to the food source can be found accordingly. Moreover, stigmergy is defined as the indirect communication used by ants in nature to coordinate their joint problem solving activities. Ants achieve stigmergic communication by laying a chemical substance called pheromone (Dorigo, 2001) that induces changes in the environment which can be sensed by other ants.
2. *Classical routing protocols*: classical routing protocols are those protocols which were primarily designed for Mobile ad hoc Network (MANET), but have now been used for WSN. Though suited for WSN applications it still has a lot of challenges like scalability and robustness. Classical routing methods are employed by a sensor node or a base station independently.
3. *Proactive routing protocols*: proactive protocols compute all the routes before they are actually needed, and the routes are

stored in a table format called a routing table in each node. Each node stores information on routes to every other node in the network. The settling time for a network using this kind of algorithm is extremely high, and the number of messages exchanged in order to maintain route information does grow at an alarming rate, hence, limiting the scalability of the algorithm.
4. *Reactive routing protocols*: reactive protocols compute routes only when they are needed. In this class, each node store routes only to its immediate neighbors, and determine multi-hop routes as required. In reactive protocols, routing table maintenance overhead is drastically reduced in lieu of the time required to send a message, as the path has to be determined each time a packet has to be transmitted across multiple hops to the sink.
5. *Hybrid routing protocols*: hybrid protocols use the combination of reactive and proactive strength, and use a proactive system within a given radius, while using reactive system in determination of routes to nodes outside the radius. The radius is always a function of some metric like the number of hops.
6. *Energy efficiency*: it is a measure of the ratio of total packet delivered at the sink node (base station) to the *total energy consumed* by the network's sensor nodes (Kbits/J). In most cases, sensor nodes are equipped with small and non-rechargeable batteries, usually of few ampere-hours. Therefore, the efficient battery energy utilization of a sensor node is a critical aspect to support the extended operational lifetime of the individual nodes and of the whole network. A WSN routing protocol is expected to: (i) minimize the total number of transmissions involved in route discovery and data delivery, and (ii) distribute the forwarding of the data packets across multiple paths, so that all nodes can deplete their batteries at a comparable rate. This will result in the overall increase of the network lifetime. In the comparison section of this paper, we assigned very strong, strong, moderate, and weak energy utilization efficiency to respective routing protocols depending on the total packets successfully delivered at the destination with respect to the energy consumed during the experiments. Especially for the algorithms that were purposely design for QoS tend to consumed high energy as compared to the successful packet delivered at the sink node. Such algorithms are mostly weak in energy utilization efficiency, while some are moderate depending on the packets delivered in relation to the energy consumption. And algorithms that prioritize routes on the basis of energy metric (energy aware) with less packet delivery will fall under the categories of moderate, while those with average packet delivery are strong, and others with high packet delivery and same time energy-aware, are very strong energy efficient algorithms.

But in general, routing in WSNs can be divided into four main categories as Data-centric, Location-based, Hierarchical, or Network flow and QoS-aware protocols.

In this section, we looked at state of the art routing protocols for wireless sensor networks, from the classical routing to the swarm intelligence based. The white, light gray and dark gray colors as shown in Table 2 indicate another classification based on path selection as proactive, reactive and hybrid respectively.

5. Classical based routing protocols

5.1. Classical based data-centric routing protocols

Broadcast and unicast are two operations that sensor nodes use to communicate with each other. In data centric routing, the sink sends queries to certain regions and waits for data from the sensors located in that area. Data centric utilizes data aggregation in relaying of data, which when data are measured or arrive from a neighbor, the sensor needs to decide whether or not they are important enough to forward them (Dulman, 2005). The coding techniques used need to minimize the number of forwarded bits. The new data may also be combined with other received data, in order to minimize the number of bits to forward. SPIN (Heinzelman et al., 1999; Kulik et al., 2002), which happen to be the first data-centric protocol, utilizes negotiation between nodes in the sensor networks so as to eliminate information that are redundant, and as such save energy.

5.1.1. Flooding and gossiping (F&G)

These are protocols which do not utilize routing algorithm and topology maintenance for data transmission in sensor networks (Heinzelman et al., 1999; Kulik et al., 2002; Hedetniemi et al., 1988). In flooding, sensor nodes flood or broadcast data to its entire neighbor any time it receive data from other neighbors. Gossiping is an improved version of flooding, in which the receiving nodes broadcast data to only selected neighbors. Flooding finds its drawback in data overlapping when two or more nodes sensing the same region sends similar data to the same neighbor. Implosion is caused by duplicated messages sent to the same node, and increases a large amount of energy consumption without preference to the energy constraints as illustrated in Fig. 2(a) and (b). Gossiping avoids the problem of implosion by selecting nodes randomly to send the data rather than broadcasting. It may cause delay in the propagation of data through the node.

In Fig. 2(a), the implosion problem, Node A starts by flooding its data to all of its neighbors, while D gets two same copies of data eventually which is not necessary. While in (b), the overlap problem where two sensors cover an overlapping geographic region and C gets same copy of data from these sensors.

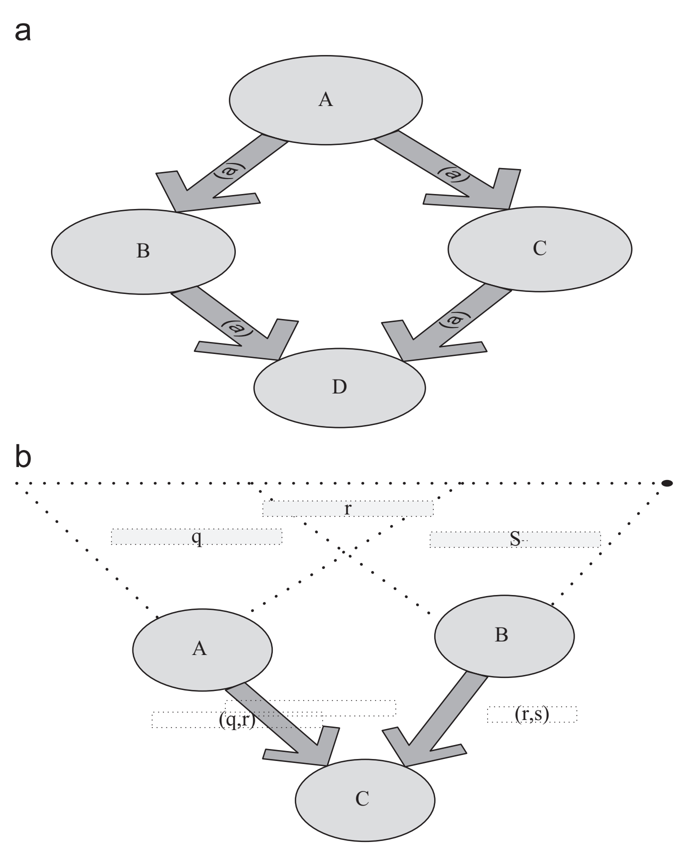


Fig. 2. (a) Implosion problem and (b) The overlap problem.

5.1.2. Directed Diffusion (DD)

In DD (Intanagonwiwat et al., 2000, 2003), events are diffused through sensor nodes by using a naming scheme for it. Attribute value pairs for the event is adopted while querying the sensors in an on demand basis. It is a popular data aggregation paradigm for WSNs. It is a data-centric and application aware paradigm in the sense that all data generated by the sensor nodes is named by attribute-value pairs. Creation of query is achieved by defining an interest using a list of attribute value pairs such as name of objects, duration of the event, and geographical location etc, the Directed Diffusion algorithm uses three steps in sensing data transmission. For each active task, an interested node normally the sink node periodically floods the network with an interest message as shown in Fig. 3(a). The interests are broadcasted by using some flooding algorithm to the entire network or to some selected direction. When an intermediate node receives an interest, the intermediate nodes relaying interests create and save the information of the previous hop as their routing information called gradients as shown in Fig. 3(b). A gradient is utilized as a routing state toward the sink node when sensing data is relayed. The gradient direction is set to the neighboring node from which the interest is received. Through this process, interests are propagated to the sensing nodes and sensing data starts flowing toward the originators of interests by using multiple gradient paths. The originators select and reinforce one or a small number of these paths that are better for sensing data transfer as shown in Fig. 3(c). When a sensor node detects a target, it searches its interest cache for a matching entry. When it finds one, it computes the highest requested event rate among all its outgoing gradients. At this time, it becomes a source and sends the data to all neighbors to which it has gradients Directed Diffusion differs from SPIN due to its on demand data querying scheme. DD cannot be applied to some applications of sensor networks due to its query-driven data delivery model, since those requiring continuous data delivery to the sink will not perform efficiently.

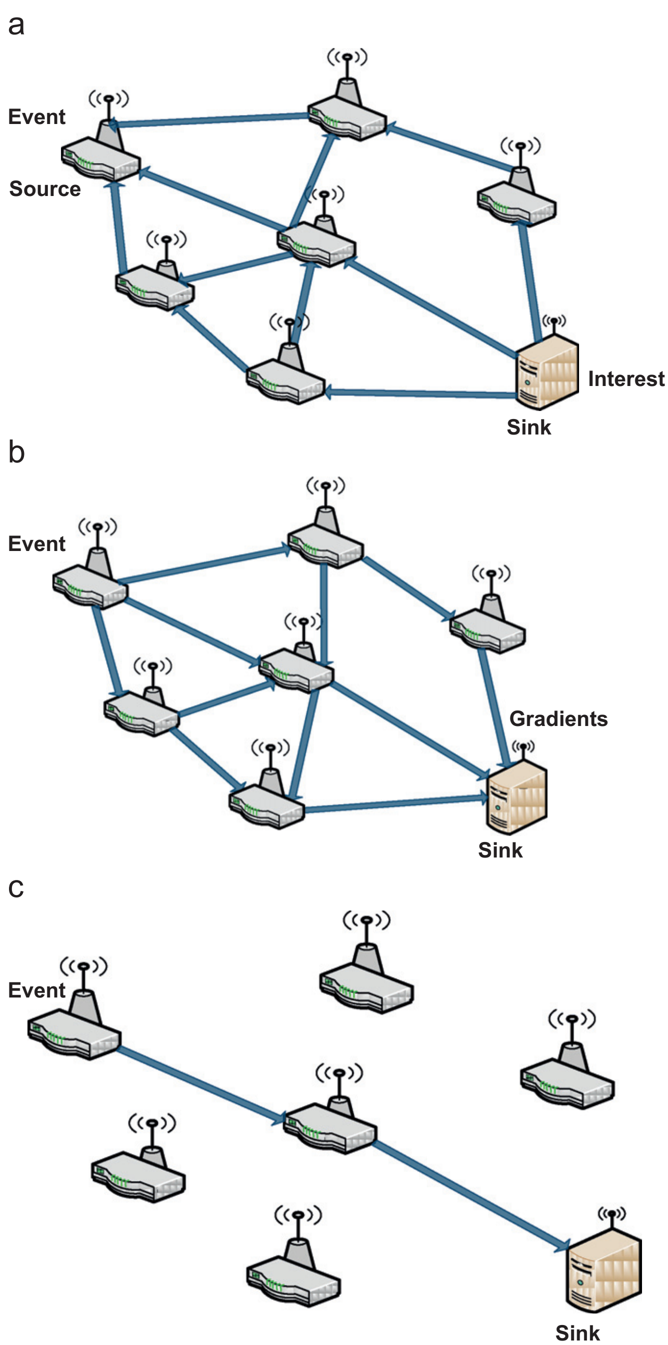


Fig. 3. Directed Diffusion routing scheme. (a) Propagate interest, (b) setup initial gradients and (c) send data.

5.1.3. Sensor protocol for information via negotiation (SPIN)

SPIN (Heinzelman et al., 1999; Kulik et al., 2002) is the first data-centric routing protocol. In SPIN, data are named using meta-data. The protocol meta-data negotiation helps in elimination of overlapping, redundant information and resource blindness as drawbacks of flooding and as such saves a lot of energy. In SPIN, three messages are defined to aid in data dissemination: ADV message for advertisement of data, REQ message for data request, and DATA message that carry the actual information. SPIN applications are resource-aware and resource-adaptive. Figure 4 demonstrates the exchange of information in SPIN protocol. The advertisement method of SPIN does not guarantee the delivery of data as nodes that are interested in the data may be far away from the source node, and nodes in between the source and the sink may not be interested. In that case, such data will not get to the sink. Hence this is not a good protocol for security measures e.g., intrusion detection and car tracking.

5.1.4. Gradient based routing (GBR)

This is an improved version of Directed Diffusion. Its main idea is to maintain the number of hops when the interest is diffused through the network (Akkaya and Younis, 2005). This then implies that each node participating in the sensing can discover minimum number of hops to the destination known as height of the node. The difference in height between the node and its neighbor is termed gradient on the link. In GBR, data is aggregated and traffic spread over the entire network so as to balance the traffic uniformly over the network. In the protocol a query (about an event) is forwarded based on the information gradient in the sensor nodes. A node forwarding the query to its neighbors includes its information level about the queried event. If a node is able to resolve the query, it uses the reverse path to reply. The spreading technique helps in balancing the load on sensor nodes and as such increases network lifetime. The protocol outperforms DD in (Schurgers and Srivastava, 2001) through simulation.

5.1.5. Energy-aware routing (EAR)

The EAR protocol (Shah and Rabaey, 2002) considers the utilization of sub-optimal paths occasionally so as to increase the lifetime of sensor network. The point of argument is the fact that using the minimum energy path all the time depletes the energy of nodes on that path. Hence, it encourages the use of multiple paths with a certain probability. The approach assumes

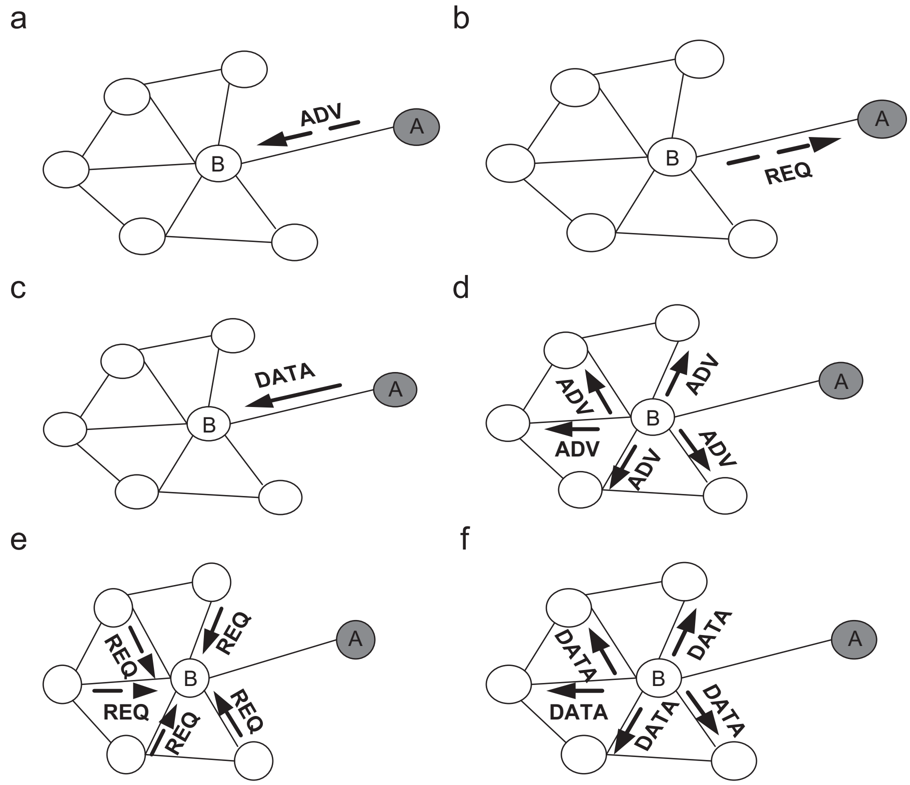


Fig. 4. SPIN protocol. (a) Node A starts by advertising its data to node B. (b) Node B responds by sending a request to node A. (c) Data received at node B. (d) After received data, node B then sends out advertisements to its neighbors. (e) Request is sent back to node B. (f) Data sent to neighbors.

the possibility of addressing each sensor node through a class-based addressing scheme that includes the location and types of the nodes. The protocol has three phases (Shah and Rabaey, 2002):

1. *Setup phase*: localized flooding occurs to find the routes and create the routing tables. As such, the total energy cost is calculated in each node. For instance, if the request is sent from node N_i to node N_j,N_i calculates the cost of the path as follows:

$$C_{Nj,Ni} = Cost(N_i) + Metric(N_j, N_i) \quad (1)$$

Energy of nodes is used for decision making on the path of propagation. Paths having a high cost are discarded. Node assigns a probability to each of its neighbors in routing table corresponding to the formed paths

$$P_{Nj,Ni} = \frac{1/C_{Nj,Ni}}{\sum_{k \in FTj} 1/C_{Nj,Ni}}; \quad (2)$$

N_j then calculates the average cost for reaching the destination using the neighbors in the forwarding table as

$$Cost(N_j) = \sum_{i \in FTj} P_{N_j,N_i} C_{N_j,N_i}. \quad (3)$$

2. *Data communication phase*: each node forwards the packet by randomly choosing a node from its forwarding table using the probabilities.
3. *Route maintenance phase*: localized flooding is performed so as to keep all the paths alive. EAR has similarity with Directed Diffusion as potential paths from sources to destination are discovered, but when compared to DD, it gave an improvement of 21.5% energy saving of nodes, and 44% increase in network lifetime.

5.1.6. Rumor routing (RR)

RR (Akkaya and Younis, 2005; Braginsky and Estrin, 2002; Patra et al., 2010) is another improved version of Directed Diffusion. The main aim of the algorithm is to fill the region between query flooding and event flooding. It is useful if the number of queries compared to the number of events is between the two intersection points. That is to say that, it floods events if the number is small and number of query is large, and hence deals with event flooding and query flooding. It does that so as to route queries to the nodes that have sensed a particular event rather than flooding the entire network in other to access particular information about an occurring event. In the algorithm, each node maintains a list of its neighbors, as well as an events table, with forwarding information to all the events it knows. The neighbor list can be actively created and maintained by actively broadcasting a request, or passively, through listening for other node broadcasts. The algorithm was tested on static topology, where each node simply broadcast its id at the beginning of the routing process.

When a node witnesses an event, it adds it to its event table, with a distance of zero to the event. It also probabilistically generates an agent. The agent is a long-lived packet, which travels the network, propagating information about local events to distant nodes. It contains an events table, similar to the nodes, which it synchronizes with every node it visits. The agent travels the network for some number of hops (*La*), and then dies. Any node may generate a query, which should be routed to a particular event. If the node has a route to the event, it will transmit the query. If it does not, it will forward the query in a random direction. This continues until the query TTL (*Lq*) expires, or until the query reaches a node that has observed the target event. If the node that originated the query determines that the query did not reach a destination, it then tries retransmitting, giving up, or flooding the query. The protocol ensures that only one path is utilized between source and sink as against DD, where data can be routed through multiple paths at low rates. It performs better when number of data is small.

5.1.7. Constrained anisotropic diffusion routing (CADR)

This is another version of Directed Diffusion, in which Information-driven Sensor Querying (IDSQ) and Constrained Anisotropic Diffusion (CAD) routing constitute the protocol (Chu et al., 2002). The techniques' main goal is to query sensors and route events in a network so as to maximize information gain, while also minimizing the bandwidth and latency of the network. The protocol implores the activation of sensors closer to a particular event and adjusts dynamically data routes. It differs from DD in its consideration of information gain in addition to communication cost. IDSQ is a complementary optimization procedure for CADR. The protocol is more energy efficient than DD, since in DD, queries are diffused in an isotropic manner, reaching the nearest neighbor before the others.

5.1.8. ACtive Query forwarding In sensor nEtworks (ACQUIRE)

ACQUIRE, is a novel mechanism for data extraction in an energy constraint sensor network (Sadagopan et al., 2003). It was proposed so as to deal with one-shot, complex queries for data where response could be provided by several sensor nodes. The protocol provides efficient querying by modifying the value of d parameter, where d is the look-ahead parameter meaning each sensor can request information from sensors d hops away from it. In a case where d tends to the network size, the algorithm behaves as flooding, else, a larger number of hops are required if d is small (Sadagopan et al., 2003). The protocol decides on the next node to forward query based on random selection or maximum potential of query satisfaction. ACQUIRE is similar to Rumor and CADR in terms of query forwarding.

5.1.9. COUGAR

The COUGAR approach to In-Network Query Processing in Sensor Networks (Yao and Gehrke, 2002) is a data-centric protocol which tasks sensor networks through declarative queries. A query optimizer generates an efficient query plan for in-network query processing so as to save energy. The protocol utilizes sensor data base system whereby sensor nodes select a leading node to perform aggregation and transmit the data to the destination (sink). The sink is responsible for generating query layout, which gives the necessary information about the data flow and in-network computation for the incoming query and send it to the relevant sensor nodes. The layout also gives the procedure in the selection of a query leader as shown in Fig. 5. Though COUGAR provides a network layer independent of querying the sensors, its main drawback is the extra query layer on each sensor node which in turn brings extra overhead to the sensor nodes, and as such increases energy consumption and storage.

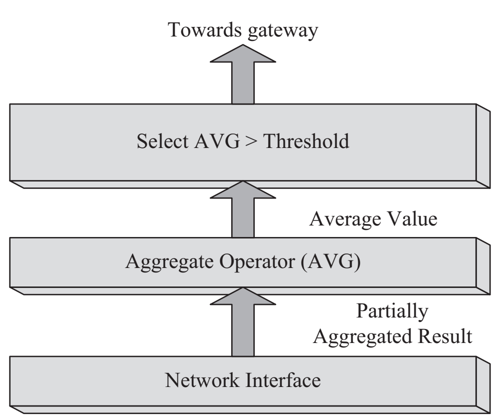


Fig. 5. Query plan at a leader node.

5.1.10. Energy-aware data-centric routing (EAD)

EAD (Singh et al., 2010; Boukerche et al., 2003) is a distributed routing protocol with the aim of building a virtual backbone consisting of active sensors for in-network data processing and traffic relaying. It tends to build a broadcast tree that approximates an optimal spanning tree with a minimum amount of leaves, hence reducing the size the backbone formed by the active sensors. The protocol introduces two concepts; neighboring broadcast scheduling and distributed competition among neighbors. While its concept fits quite well in the data-centric network, as the non-leaf nodes are also responsible for data aggregation, it does not address mobility in the sensor network. The problem is that, data-transmit phase is substantially longer than the initialization. In a highly mobile environment, this means in practice that before a round is completed, the tree may already be dissolved.

5.2. Location-based protocols

In routing, some of the protocols for sensor networks require location information for the nodes; the nodes are addressed by means of their locations. The information of their respective location is needed so as to aid in the calculation of distance between two nodes, and be able to diffuse a query to a particular region, hence eliminating the number of transmission (Roychowdhury and Patra, 2010). This in turn helps in the estimation of the energy consumption.

5.2.1. Geographic adaptive fidelity (GAF)

GAF (Xu et al., 2001) was mainly designed for mobile ad-hoc networks, but is also applicable to sensor networks. The protocol ensures low consumption of network energy by disabling nodes that are not active in the routing process without necessarily affecting the routing performance. Each node has a GPS sensor on it indicating its location so as to associate itself with a point on the virtual grid (Akkaya and Younis, 2005). In GAF, nodes change states from sleeping to active in order to balance its load. The three states that exist in GAF are Discovery for location of the neighbors on the grid, active indicating the participation of the nodes in routing, and Sleep when the radio is switched off. GAF can also be considered as Hierarchical routing, where clusters are based on geographic locations. In each of the grid area, there exists a leading node to transmit data to other nodes. GAF differs from that of hierarchical protocol since the leader does not do any aggregation or fusion.

5.2.2. Geographic and energy-aware routing (GEAR)

GEAR (Yu et al., 2001) is an energy-efficient routing algorithm for routing queries to target regions in a sensor network. In GEAR, each sensor node is equipped with a GPS sensor for location identification (Bulusu et al., 2000). The protocol utilizes energy aware heuristics which is based on geographic information for the selection of nodes to route data to the sink, and uses geographically recursive forwarding algorithm for data dissemination within the target area. The main idea is to restrict the number of interests in Directed Diffusion by only considering a certain region rather than sending the interests to the whole network. By doing this, GEAR can conserve more energy than Directed Diffusion. In GEAR, each node keeps an estimated cost and a learning cost of reaching the destination through its neighbors. The estimated cost is a combination of residual energy and distance to destination. The learned cost is a refinement of the estimated cost that accounts for routing around holes in the network. A hole occurs when a node does not have any closer neighbor to the target region than itself. If there are no holes, the estimated cost is equal to the learned cost. The learned cost is propagated one hop back every time a packet reaches the destination so that route setup for the next packet will be adjusted. There are two phases in the algorithm:

- *Forwarding packets toward the target region*: upon receiving a packet, a node checks its neighbors to see if there is one neighbor that is closer to the target region than itself. If there is more than one, the nearest neighbor to the target region is selected as the next hop. If they are all further than the node itself, this means there is a hole. In this case, one of the neighbors is picked to forward the packet based on the learning cost function. This choice can then be updated according to the convergence of the learned cost during the delivery of packets
- *Forwarding the packets within the region*: if the packet has reached the region, it can be diffused in that region by either recursive geographic forwarding or restricted flooding. Restricted flooding is good when the sensors are not densely deployed. In high-density networks, recursive geographic forwarding is more energy-efficient than restricted flooding. In that case, the region is divided into four sub regions and four copies of the packet are created. This splitting and forwarding process continues until regions with only one node are left. GEAR does not only reduce energy usage, but also outperforms GPSR (Karp and Kung, 2000) in terms of packet delivery.

5.2.3. Minimum energy communication network (MECN)

MECN (Li and Halpern, 2001) is a protocol design for achieving minimum energy in a randomly deployed ad hoc network using a GPS. The protocol is best used for sensor networks which are not mobile. In order to efficiently utilize the protocol, a minimum power topology for stationary nodes including a master node is used. Its main idea is to source for a sub-network, that will have fewer number of nodes and require minimum power for transmission between set of nodes in a sensor network. In this way, global minimum power paths are found without considering all the nodes in the network. This is performed using a localized search for each node considering its relay region. MECN is self-reconfiguring and thus can dynamically adapt to node failure or the deployment of new sensors. This is achieved using a localized search for each node considering its relay region. It is based on the position of sensors on the plane and consists of two main phases; the enclosure graph construction and cost distribution. MECN can dynamically adapt to node's failure or new nodes deployment as it can be self-configured. MECN assumes that at every point in time, every node can transmit to any node in the network, which is not always possible.

5.2.4. Small minimum energy communication network (SMECN)

SMECN (Li and Halpern, 2001) is an improved version of MECN. In SMECN, possible obstacles between any pair of nodes are considered against MECN which assumes that every node can transmit to every node in a network which is practically not realistic. The network of SMECN is a fully connected network as that of MECN. The sub-network produced by SMECN for minimum energy relaying is smaller in terms of number of edges. Simulation results show that SMECN uses less energy, and lower links maintenance cost as compared to MECN. Though, the introduction of sub-network with smaller edges will yield more overhead in the algorithm.

5.2.5. Trajectory-based forwarding (TBF)

TBF (Nat and Niculescu, 2003) is a routing algorithm whose main idea is the use of a dense network in the presence of a coordinate system for the sensor nodes to be able to position themselves so as to estimate distance to their neighbors. The source of an event specifies the trajectory in a packet, but does not give the path on a hop-by-hop basis (Singh et al., 2010). Based on the location information of the neighbors, a sensor node forwarding data makes a greedy decision to determine the closest trajectory fixed by the source node. In TBF, multipath is also possible, and route maintenance is unaffected by sensor mobility.

5.2.6. An energy-aware WSN geographic routing protocol (EAGRP)

EAGRP (Elrahim et al., 2010) is an energy aware forwarding protocol for multi-hop WSNs. The algorithm deals with two parameters, location and energy level of each node. Each node knows the location and energy level of its neighbor in order to forward packets. The approach basically calculates the average distance of all the neighbors of transmitting node and checks their energy level while selecting the neighbor who is alive based on the energy level i.e. having energy above the set threshold, and having the maximum energy plus whose distance is equal or less than the calculated average among its entire neighbors. The simulation result as compared to DSR and AODV, perform better in terms of packet delivery ratio, delay, energy consumption and throughput.

5.3. Hierarchical protocols

A hierarchical protocol is an approach to the balance between scalability and performance. In hierarchical routing, energy consumption of sensor nodes is drastically minimized when the sensor nodes are involved in multi-hop communication in an area of cluster and performing data aggregation and fusion so as to reduce the number of transmitted information to the sink. The clusters formation is based on the energy reserve of sensor nodes and its proximity to the cluster head (Akkaya and Younis, 2005; Lin and Gerla, 1997). In hierarchical routing, data moves from a lower clustered layer to higher region, hopping from one node to another which covers larger distances, hence moving the data faster to the sink faster. Clustering provides inherent optimization capability at the cluster heads. A view of the architecture of hierarchical network, is as shown in Fig. 6.

5.3.1. Low-energy adaptive clustering hierarchy (LEACH)

LEACH (Heinzelman et al., 2000, 2002) became the most popular and the first energy-efficient hierarchical algorithm proposed for power consumption reduction in sensor networks. LEACH rotates the clustering task among the participating nodes based on duration. Each cluster head communicates directly to the sink. The algorithm is also based on data aggregation or fusion

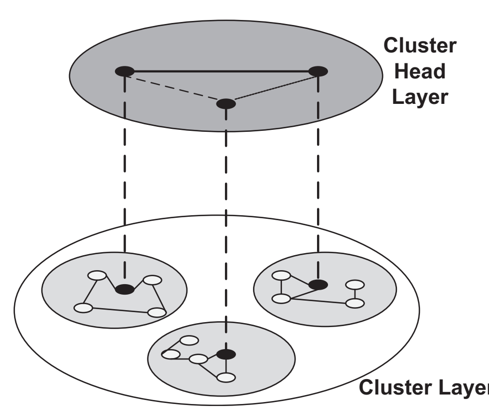


Fig. 6. Hierarchical network architecture.

techniques as the original data is combined and aggregated into smaller size of data that carry only required information to all individual nodes. Cluster heads change randomly over time so as to balance the energy dissipation of nodes. The protocol is completely distributed and requires no global knowledge of the network. As it uses formation of cluster heads, or dynamic clustering, it brings extra overheads, hence diminishing the gain in energy saving. It is also not friendly in a large network deployment.

5.3.2. Power-efficient gathering in sensor information systems (PEGASIS)

PEGASIS (Lindsey and Raghavendra, 2002) is an improved version of LEACH. It avoids the formation of multiple clusters. Each node can transmit and receive data from a neighbor and only one node is selected from a chain at a time to communicate with the sink. Data is combined and moved from node to node, aggregated and sent to the sink. Unlike LEACH, it avoids the formation of cluster and uses only a node in a chain to transmit to the sink rather than using multiple nodes. However, the protocol introduces excessive delay for distant nodes on the chain. In addition, the single leader exhausts its energy as it involves regular transmission. In (Lindsey et al., 2001) comes an improved version of the PEGASIS, known as Hierarchical-PEGASIS. Its aim is to find a solution to the delay incurred during the transmission of packets to the sink, and as such proposed a solution to the data gathering problem by putting energy x delay metrics. It involves CDMA in its approach to deal with the problem of signal interference among the sensor nodes, and also allow only spatially separated nodes to transmit at the same time.

5.3.3. Self-organizing protocol (SOP)

The SOP (Subramanian and Katz, 2000) involves basically the self organization of the router nodes and creation of routing tables based on four phases; Discovery phase, where node in the neighborhood are discovered; organizing phase, where groups are formed and merged by forming a hierarchy of which nodes are addressed based on their position in the hierarchy; self-reorganizing phase, dealing with the situation when partition of nodes fails, and group reorganization takes place; and maintenance phase where updating of routing tables and energy levels of nodes is made. SOP adopts local Markov Loops algorithm which performs a random walk on spanning trees of a graph in dealing with fault tolerance, and use for broadcasting. The algorithm is cost effective in routing table maintenance, and consumes less energy in broadcasting messages than SPIN protocol, due to broadcast trees used in the algorithm. Due to the organization phase of the algorithm which is not on-demand, it introduces extra overhead.

5.3.4. Threshold sensitive energy efficient sensor network protocol (TEEN)

TEEN (Akkaya and Younis, 2005; Lou, 2005; Manjeshwar and Agrawal, 2002) is a hierarchical protocol whose main aim is to respond to sudden changes in the sensed attributes such as temperature. The protocol combines the hierarchical technique in line with a data-centric approach. It then involves the formation of clusters along with cluster leaders which broadcast two thresholds to the nodes; the hard and soft thresholds. Hard threshold have the minimum values of an attribute for sensor node to trigger to power on its transmitter so as to transmit to the cluster head. It is normally not suited in applications where continuous data is needed, since it is threshold dependant.

5.3.5. Adaptive threshold sensitive energy efficient sensor network protocol (APTEEN)

APTEEN (Manjeshwar and Agrawal, 2002) is an improved version of TEEN, whose main function is not limited to the formation of clusters, but also aim at both capturing periodic data and reacting to time dependant events. In APTEEN, cluster leaders perform aggregation as well as conserve energy. Three queries are supported in the protocol; historical for analysis of past information values, persistent for monitoring of events for some time duration, and one-time for snapshot view of the sensor network. Simulation results show that it outperforms LEACH, having the problem of overhead and complexity in clusters formation in multiple levels, and implementation of the threshold based functions.

5.3.6. Hybrid energy-efficient distributed clustering (HEED)

HEED (Younis and Fahmy, 2004) is an extension of LEACH which uses node density and residual energy as a metric for cluster selection so as to balance the network energy. The HEED execution process takes three phases; 1. The initialization phase where cluster heads are selected based on their residual energy and intra-cluster communication cost. 2. Repetition phase where the probability of selection of the cluster head is repeated due to some parameters if at the first stage it was not selected. 3. Finalization phase where the selection of cluster head is finalized. However, the cluster selections consider some parameters, which may impose some drawback on the network, though it is suitable for prolonging network lifetime.

5.3.7. Energy-aware routing for cluster-based sensor networks (EAR-CSN)

The algorithm (Younis et al., 2002) was proposed based on three tier architecture, grouping of sensor nodes known as clusters, cluster heads formation which are less energy constraint and tends to know other nodes location and maintenance of the states of the sensors while also setting up multi-hop routes for data collection. It uses TDMA based MAC in communicating with the gateway or cluster heads. In the algorithm, sensor nodes in the cluster could be in any of the sensing only, relaying only, sensing relaying or inactive states. A cost function is defined between any pairs of nodes in terms of delay optimization, energy consumption, throughput, and other performance parameters. The algorithm suffers in transmission range, and as the algorithm uses many cluster heads, it introduces more overheads and hence consumes much energy.

5.3.8. A balanced-clustering energy-efficient hierarchical routing protocol (BCEE)

BCEE (Cui and Liu, 2009) aims at equalizing the consumption of energy in sensor network nodes and to prolong the network lifetime by adopting mixed hierarchical and ant based routing method. The protocol operates in two phases similar to other hierarchical protocols where routing is done in two phases. In phase one, cluster heads are selected adopting K-means algorithm where the actual location of nodes is unknown, but uses the idea of receive signal strength indicator (RSSI) for cluster formation. And in the second phase called the steady state, utilizes the techniques of ant colony optimization to establish an optimal multi-hop route from cluster heads to the sink using rational and hop-selecting technique. The protocol was compared with LEACH in simulation and performs better in terms of energy consumption of nodes. BCEE has some drawbacks in terms of network overhead as cluster formation also requires more energy in the network, and delay of data transmission to the sink node.

5.4. Network flow and QoS-aware protocols

Some of the routing protocols which do not belong to data-centric, hierarchical or location based tends to fit into network flow and QoS-aware approach. In some protocols, routing setup is modeled and treated as a network flow problem, while in QoS-aware protocols, end-to-end delay is the major metric considered when setting up paths or routing in the sensor network.

5.4.1. Maximum lifetime data gathering (MLDG)

Maximum lifetime data aggregation (MLDA) (Kalpakis et al., 2002) is a polynomial algorithm in which the system lifetime is defined as the number of periodic data readings from the sensor till the first sensor ceased to exist. The data routing technique, specifies for each period how data can be obtained and routed to the sink. As the network lifetime depends on the duration for which the schedule remains valid, the aim is to maximize network lifetime of the schedule. The protocol considers data aggregation while setting up the maximum network lifetime route. In some special cases where data aggregation is not achievable as in streams from video sensors, maximum lifetime data routing (MLDR) comes into play and is modeled as a network flow problem with energy constraints on sensors. Both MLDA and MLDR as compared to Hierarchical-PEGASIS, outperforms the protocol in terms of the network lifetime. Hierarchical-PEGASIS is better than MLDA in terms of delay for data packets. Cluster-based MLDA (CMLDA) (Dasgupta et al., 2003) which is an improvement on MLDA and MLDR was developed so as to solve the problem of large networks and hence reduce the delay problem of MLDA.

5.4.2. Sequential assignment routing (SAR)

SAR (Sohrabi et al., 2000) is the first routing protocol that involves the principle of QoS in its routing decision. It is a table-driven multipath algorithm whose aim is to achieve network fault tolerance while saving as much energy for the network. In SAR, failure recovery is achieved by enforcing routing table consistency between downstream and upstream nodes on each path. It creates trees rooted at one-hop neighbors of the sink by taking the QoS metric, energy resource on each path and priority level of each packet into consideration (Akkaya and Younis, 2005). Through creating trees, SAR builds multiple paths from sink to sources. It suffers from the overhead of maintaining the table and states at each sensor nodes.

5.4.3. Maximum lifetime energy routing (MLER)

MLER (Chang and Tassiulas, 2000) is proposed as a solution to the problem of routing in sensor networks. The protocol is based on a network flow. The main idea is to maximize the network lifetime by defining a link cost as a function of the residual energy of a node, and using the link while requiring transmission energy. By maximizing the lifetime of the network, the protocol leads to establishing traffic distribution, which is a possible solution to the routing problem in sensor networks. When compared to the MTE algorithm, only the energy consumed when a packet is transmitted as the link cost performs better since relative residual energy that reflects the forecasted energy consumption rate was adopted.

5.4.4. A stateless protocol for real-time communication in sensor networks (SPEED)

SPEED (He et al., 2003) is a QoS routing protocol for sensor networks. The protocol involves three types of communication techniques: real-time unicast, real-time area-multicast and real-time area-anycast. It requires each node to maintain information about its neighbors and uses geographic forwarding in order to locate the paths. The protocol is aimed to be a stateless and localized algorithm with minimal control overhead. The protocol provides end-to-end soft real-time communication by maintaining a desired delivery speed across the sensor network through a novel combination of feedback control and non-deterministic geographic forwarding. SPEED is a highly efficient and scalable protocol for sensor networks where the resources of each node are scarce. As compared to DSR (Johnson et al., 1996) and AODV (Perkins and Royer, in press), the protocol performance is better in terms of end-to-end delay and energy consumption of nodes.

5.4.5. Energy-aware QoS routing protocol (EAQSR)

Energy aware QoS routing (Akkaya and Younis, 2003, 2005) is a table driven multi-path routing protocol with embedded QoS in its routing decision. Its aim is to find an optimal path to the gateway in terms of energy consumption and error rate while meeting the end-to-end delay requirements. Both the paths that meet the requirements for real-time traffic, as well as well as maximizing the throughput for non-real time traffic were considered. Due to the fact that critical applications such as battlefield surveillance have to receive for instance acoustic data regularly in order not to miss targets. The bandwidth ratio which is evenly distributed over the network nodes makes the protocol not flexible for adjustment of bandwidth sharing for different links. The author did not mention the simulation environment used and the results obtained were not compared to any standard algorithm to compare performance.

5.4.6. Message-initiated constraint-based routing (MCBR)

MCBR (Zhang and Fromherz, 2004), is a message-initiated constraint based routing protocol for wireless ad-hoc sensor network. The authors proposed MCBR which is a general message specification mechanism to explicitly encode the routing destinations, constraints and objectives in messages, so that generic-purpose instead of objective-specific or destination-specific routing strategies can be applied. In their work, they tried to separate routing specifications and routing strategies, hence making it possible for Meta routing exploration, and allowing quality-of-service (QoS) requirements at the application layer for individual messages. Two types of Meta routing were proposed for the MCBR; the search based and constrained-flooding. In MCBR, each node in the network has a list of attributes whose types are predefined.

An MCBR protocol specification for a message m is; (U_m^o, C_m^d, C_m^r, O_m) where U_m^o is the source of the message, C_m^d is the set of destination, C_m^r is the set of route constraints and O_m is the objective. The goal of the routing is to deliver the message from U_m^o to one (unicast) or all of the destination nodes (multicast) while satisfying C_m^d via intermediate nodes p: $U_m^i,\ldots,U_m^{n-1}$ such that C_m^r is satisfied at U_m^i and $\min_p \sum_i O_m(U_m^i)$. The algorithm was implemented in NesC on TinyOS-1.x, and simulations were performed in the TOSSIM/TinyViz simulation environment. No comparisons were made with any existing routing protocols.

5.4.7. Smart routing with learning-based QoS-aware meta-strategies

Smart routing with learning-based QoS-aware Meta-strategies is a framework of MCBR (Zhang et al., 2004a). The protocol consists of QoS specifications and sets of QoS-aware meta-strategies. The meta-strategies are; real-time search, constrained flooding and adaptive spanning tree. Its main focus is on learning based meta-strategies of which it does not create and maintain explicit routes. Instead, packets are discovered and routes improved during the search for destination. The authors assume that, if a routing specification is given for a message, including the destination and QoS requirements, it is then easy to define the cost function on each node, called *Q*-value indicating the minimum cost-to-go from the present node to the destination. For a distributed sensor network, the cost is initially unknown, and an initial estimation is made according to the type of message. Furthermore, a node also stores its neighbors' Q-values, NQ-values, which are estimated initially according to the neighbors' attributes and updated when packets are received from neighbors. The learning-based meta-routing strategies typically consist of an initialization phase, a forwarding phase, and a confirmation phase. Learning happens in all phases. For each packet sent out from a node, the current Q-value of the node for the type of message is attached. All the nodes are set to be in promiscuous listening mode. Whenever a node overhears a packet of type m, whether it is the designated receiver or not, it updates the corresponding NQ-value and re-estimates its own Q-value using the equation

$$Q_m = (1-\alpha)Q_m + \alpha(O_m + \min_n NQ_m(n)) \quad (4)$$

where α is a learning rate, O_m is the current value of the local objective function, and n is a neighbor of this node.

Using the Q-value, real-time search passes the packet to the "best" neighbor according to the estimates. Constrained flooding is used to decide if and when to re-broadcast the packet according to the cost estimates, and adaptive spanning tree forwards the packet to its parent, with parents possibly changing over time pointing to a neighbor with the best Q-value. This approach has a number of attractive properties: (1) explicit use of destination and QoS specifications for finding optimal routes; (2) automatic adaptation with different routes when network conditions change; (3) no need for extra maintenance packets; and (4) no infinite looping if a path to the destination exists. The protocols were simulated in Prowler Rmase, compared with AODV, and found to perform well in term of success rate and low energy consumptions.

5.4.8. *Ad-hoc on-demand distance vector (AODV) routing protocol*

Ad-hoc on-demand distance vector (AODV) (Charles et al., 1999) is a popular classical routing protocol for mobile ad-hoc networks. AODV discovers routes only when required. When a node has some data to send to a destination and it does not have the valid routing table entry, it generates a Route Request (RREQ) packet and broadcasts it to all its neighbors. When an intermediate node receives this RREQ, it searches its local routing table for a valid route to the requested destination. If the search is successful, it generates an RREP packet, which is sent as a unicast message back to the source node using the reverse links. If the node has no valid route to the destination, it sets up a reverse link to the node from which RREQ message was received and further broadcasts the RREQ packet. When the destination node receives an RREQ packet, it generates an RREP which is unicast back to the source node. On reception of an RREP packet, each intermediate node updates its routing table to set up a forward pointer and relays the RREP message to the next hop using the reverse pointer. The process continues till RREP is received by the source node. AODV in its original form uses periodic HELLO messages to check the validity of links with its neighbors. If a link involved in an active route fails, a route error (RERR) message is generated which is unicast back to the node where the message was initiated, and it flushes the corresponding routing table entries for the intermediate nodes. The source node is likely to get more than one RREP packet and it selects the one with the least number of hops. The version of AODV implemented in this paper for evaluation process is an energy optimized version of AODV for wireless sensor networks that is distributed with RMASE. This does not use HELLO packets to detect link failures rather it uses feedback from the link layer to achieve the same objective. Furthermore, intermediate nodes do not generate reply (RREP) even if they have a valid route which avoids the overhead of multiple replies. This version of AODV also employs cross layer techniques to avoid paths which have high packet loss.

6. Swarm intelligence based routing protocols

Swarm based routing protocol (Dorigo, 2001) is a promising research on ants' behavior of which many ants are blind and communication between them is based on adoption of chemicals like substance known as pheromones, produced by the ants and deposited on the paths while walking in search for food. By sensing pheromone trails, foragers can take the path to food discovered by other ants. This behavior whereby an ant is influenced by a chemical trail left by other ants was the inspiring source of ant colony optimization, as illustrated in the double bridge experiment which is an important experiment in the field of ant algorithms. An ant nest is connected to a food source via two paths of different length. At start time all ants are in the nest and they are left free to move. The experiment is in such a way that the only way for the ants to get to the food is by using one of the two bridge branches. At start, the ants move randomly and they choose between the shorter and the longer branch with equal probability. While traversing the paths, ants deposit on the ground a pheromone trail; when choosing their paths, ants choose with higher probability those directions marked by a stronger pheromone concentration. A pheromone table at each node guide through the path selection. The pheromone table keeps the information gathered by the forward ant. Each node maintains a table keeping the amount of pheromone on each neighbor path. The node has a distinct pheromone scent, and the table is in the form of a matrix with destination nodes listed along the side and neighbor nodes listed across the top. Rows correspond to destinations and columns to neighbors. An entry in the pheromone table is referenced by $T_{n,d}$ where n is the neighbor index and d denotes the destination index. The values in the pheromone table are used to calculate the selecting probabilities of each neighbor. When a packet arrives at C from previous hop S, i.e. the source, the source pheromone decay, and pheromone is added to link $\overrightarrow{SC}$. Route is more likely to take through C, since it is the shorter path to the destination i.e. $\overrightarrow{SCED}$. The pheromone table of node C is shown in Fig. 7 with nodes E and S as its neighbor, A, B, E, D and S are the possible destinations.

As those ants choosing the shorter branch will also be the first to find the food and to go back to the nest, the pheromone trail on the shorter branch will grow faster, increasing this way the probability that it will be used by forthcoming ants. This autocatalytic (positive feedback) process is at the heart of the auto-organizing behavior that very quickly leads all the ants to choose the shortest branch. The probability of selection is given as

$$P_k(r,s) = \begin{cases} \frac{[\tau(r,s)^{\alpha}]\cdot[\eta(r,s)^{\alpha}]^{\beta}}{\sum_{u \in J_{k}(r)} [\tau(r,s)^{\alpha}]\cdot[\eta(r,s)^{\alpha}]^{\beta}}, & s \in j_k(r) \\ 0, & \text{else} \end{cases}, \quad (5)$$

where $J_k(r)$ is the set of nodes that remain to be visited, β the parameter that determines the relative pheromone versus distance savings, η the savings of combining two nodes on one tour as opposed to serving them on two different tours, τ the pheromone level on edge, (r,s,u) the node identifier, P_k the probability with which ant k chooses to move from node to node, τo the pheromone increment level on edge, ρ evaporation coefficient of local research and α the evaporation coefficient of global research. Swarm based routing are classified into three categories: ant based, bee based, and slime based.

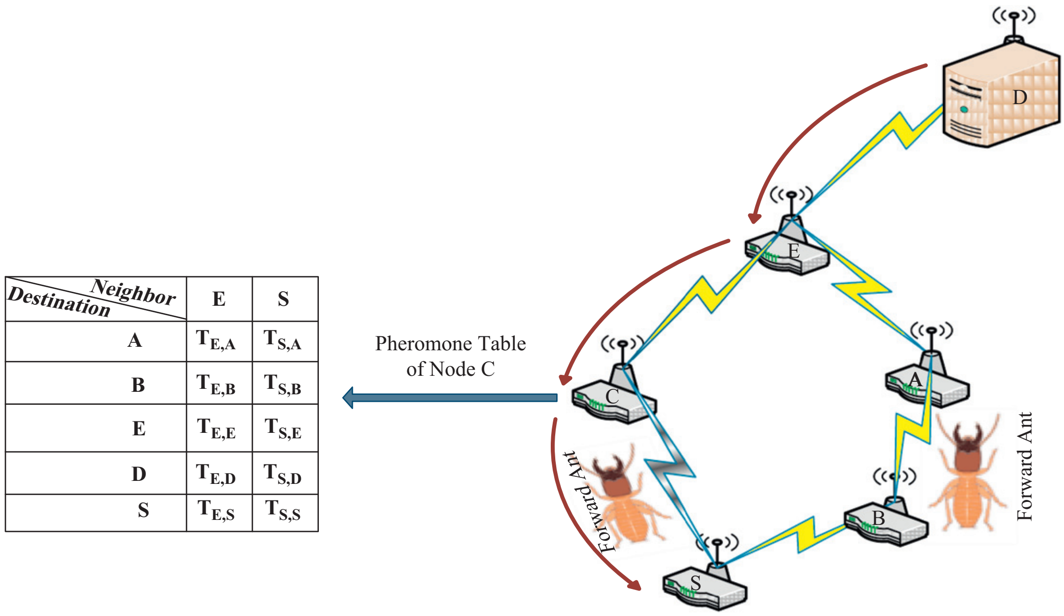


Fig. 7. Description of pheromone table of node C.

6.1. *Swarm based data-centric routing protocols*

6.1.1. *Pheromone based energy aware Directed Diffusion (PEADD)*

PEADD (Zhu, 2007) is a variant of DD (Intanagonwiwat et al., 2003) in swarm intelligence based and based on ant colony optimization heuristic. The protocol is aimed at maximizing the lifetime of the sensor networks by involving nodes with higher energy in the information gathering process. The algorithms' ants increase the pheromone on a path proportionally to the remaining energy levels of the nodes. Paths with larger residual energy are increased, while others are reduced i.e. the amount of pheromone decay with transmitting data because the pheromone is linked to the remaining energy. The pheromone level is updated based on the amount of transmitting data. The algorithm use the same route selection and updating as that of the general ant based routing as described above. The simulation results reported in the paper show that for an increasing number of dead nodes, the network lifetime achieved by the protocol is significantly higher compared to that achieved by Directed Diffusion.

6.1.2. *Comprehensive routing protocol (CRP)*

Guo et al. (2010) proposed a comprehensive routing protocol (CRP) based on ant colony algorithm. The algorithm is an improved version of energy aware routing (EAR). But in its routing decision, it uses probability of selection of which it considers the network lifetime and data packet arrival rate. The protocol argues that always using the path which is considered as the best and optimal path from the point of view might not be the best as it will lead to depletion of the path nodes energy, and instead proposes the use of sub-optimal paths occasionally. The protocol has three phases: routing table setup, data communication, and route maintenance. In the routing table setup, from the destination node, searching packet is locally flooded until it reaches the source node to find all the routes from source to destination and make sure the probability of each one is being chosen according to the square of transmission distance along the path, the strength of pheromone on each path, the remaining energy of the nodes, and the frequency a node acting as a router. All this are gotten from the probabilistic routing tables during the route discovery and update phases. In the data communication, the source node sends the data packet to any of the neighbors in the forwarding table, with the probability of the neighbor being chosen equal to the probability in the forwarding table. Each of the intermediate nodes forwards the data packet to a randomly chosen neighbor in its forwarding table, also with the probability of the neighbor being chosen equal to the probability in the forwarding table. This is continued till the data packet reaches the destination node. During the data transmission, when a node is chosen as the next forwarding one, the pheromone strength on the branch between it and the previous node will be updated according to (6) and (7)

$$I_{ij} = I_{ij} + \Delta I_{ij} \tag{6}$$

where I_{ij} is the strength of pheromone on the branch between nodes *i* and *j*. and ΔI_{ij} is the updated quantity, and is calculated as follows:

$$\Delta I_{ij} = \left(1 - D_{jd}^2 / \sum_{k \in N_i} D_{kd}^2) xT \right) \tag{7}$$

where D_{jd} is the distance between node *j* and the destination *d* and *T* a constant. The route maintenance is responsible for reflection of the actual condition of the network. Localized flooding is performed infrequently from destination to source to keep all the paths alive and update the routing tables in accordance with the current conditions. The algorithm was compared with EAR in NS-2, and shows promising solution but lacks QoS metrics.

6.2. *Swarm based location-based protocols*

6.2.1. *Sensor driven and cost-aware ant routing (SC)*

In SC (Zhang et al., 2004b), it is assumed that ants have sensors so that they can smell where there is food at the beginning of the routing process so as to increase in sensing the best direction that the ant will go initially. In addition to the sensing ability, each node stores the probability distribution and the estimates of the cost of destination from each of its neighbors. It suffers from misleading data when there is obstacle which might cause errors in sensing. Assuming that the cost estimate is Q_n for neighbor n, the cost from the current node to the destination is 0 if it is the destination, otherwise, $C = min_{n \in N}(c_n + Q_n)$, where c_n is the local cost function.

The initial probability is calculated according to the expression:

$$P_n \leftarrow \frac{e^{(C-Q_n)^{\beta}}}{\sum_{n \in N} e^{(C-Q_n)^{\beta}}} \quad (8)$$

6.3. Swarm based hierarchical protocols

6.3.1. Self-organizing data gathering scheme (SDG)

SDG protocol (Kiri et al., 2007) aims to achieve scalability and reliability in sensor networks. In the protocol, a node uses another sink in case of sink failure. The protocol queries the fact that with a single sink, a sensor network cannot tolerate energy depletion as once a node around the sink runs out of energy, the sink remains isolated and the sensor network becomes useless as packets can no longer be routed to the sink. In the protocol, in order to minimize the routing overhead, agents are only generated by sink nodes in the form of backward ants, which are broadcasted by sink nodes on proactive basis. Sensor nodes communicate data and event information to their sink through the usual ACO techniques of stochastic forwarding. Node clustering in the algorithm is inspired from eggs and larvae grouping behaviors observed in ant colonies. Ants repeatedly pick up and drop eggs according to their degree of similarity. Nodes at the borders of their cluster can dynamically change cluster membership according to a probabilistic mechanism that favors clusters with higher cluster pheromone. The protocol was evaluated in NS-2 with reliability metric. The algorithm consumes a significant amount of energy due to its proactive nature and hello packets exchange, and was also not compared with any existing protocol.

6.3.2. Energy balanced ant based routing protocol (EBAB)

Wang et al. (2009a) proposed an energy balanced ant based routing protocol (EBAB) which is an adaptive dynamic routing algorithm based on ant colony optimization. In order to achieve their aims by energy consumption balance in the network to prolong network life time, the algorithm is divided into two parts, intra-cluster and intercluster. In the intra-cluster, the algorithm is further divided into rounds, and clusters created at the beginning of the routing process. The intra-cluster comprises the completion for cluster heads where clusters head are competed for based on the areas of which each nodes belongs due to the strength to the base station. After the cluster heads selection, cluster is set up, and Cluster head send message in a range to tell the other nodes. The node sends ‘‘ACK’’ message to join the cluster. If the node receives more than one message, it will choose the optimal cluster head according to the distance and energy. When the cluster head energy falls below a certain value, it broadcast information about collecting rest energy and distance of cluster member, and then calculate the fitness of all the nodes, the node who has the biggest fitness will become the successor of cluster head. In the data transmission phase, at the beginning of every round, all the nodes turn on the receiver. Then the cluster head will broadcast a message about TDMA time slot information. Each cluster member will know the time slot of themselves, and then the cluster number will keep the transceiver off until its time slot. In its time slot, cluster members transmit the sensing data to the cluster head. The Intra-cluster section used the improved ACO algorithm. When compared with LEACH, it performs better in terms of survived number of nodes and the amount of packets received at the sink at the end of the simulation.

6.3.3. Adaptive clustering for energy efficient WSN based on ACO (ACO-C)

Ziyadi et al. (2009) proposed ACO-C which is an adaptive clustering for energy efficient wireless sensor networks based on ACO. The algorithm proposed a new energy aware clustering protocol by using appropriate cost functions implemented at the base station. It minimizes and distributes the cost of long distance transmission and data aggregation among all sensor nodes evenly. The routing problem was adapted as a clustering problem in which the objective is to select K out of N nodes as cluster heads, which was achieved through agent consideration called software ants. The algorithm simulated in the Matlab platform was evaluated and compared with LEACH. LEACH-C and PSO-C were found to perform better in terms of data delivery and network life time.

6.3.4. Ant colony clustering algorithm (ACALEACH)

Wang et al. (2009b) proposed an Ant Colony Clustering Algorithm which is an ant colony based improved version of LEACH. The algorithm not only considers the node residual energy, but also the distance between the cluster heads was considered in selection of cluster heads. It applies the ACA into inter-cluster routing mechanism to reduce the energy consumption of cluster heads and finally prolong the lifetime of sensor networks. The algorithm as compared with its counterpart LEACH in the Matlab environment outperforms it in terms of average energy consumptions and survival nodes at the end of the simulation. The protocol did not consider throughput and delay in its routing process, and hence may also be weak in energy efficiency due to overheads.

6.3.5. Multipath routing based on ant colony system (MACS)

Xiu-li et al. (2008) proposed multipath routing based on ant colony system in wireless sensor networks which endues the ant with new characteristic and searching method. The protocol tries to solve the problem of basic ACS being trapped in the solution of global optimum, and also deal with the constringency problem as soon as possible. The protocol was simulated in NS-2, and found to perform better than DD and ACS in terms of average transmission delay.

6.3.6. Data gathering communication (AntChain)

AntChain (Liu, 2004) is aimed at energy efficiency, data integrity, and node's life time parameters. It achieves a near optimal chain by using ant colony optimization method running in the base station. The sensor nodes in the network form a bi-directional chain structure which is self adaptive to any minor changes. Unlike other sensor routing protocols where sensor nodes have to communicate with each other to set up a transmission route, its sensor nodes only receive useful information through base station broadcast. The discarding of the routing operation preserves a significant amount of energy in the sensor network. In AntChain, sensor nodes do not have to be aware of the prior network knowledge. In the scheme, the sink initially sends a setup enable signal to all the nodes informing them of the starting of the network. The nodes by getting the message from the sink reply by sending their ID and locations or by just simply sending a short message to indicate that they are still alive. The main drawback of the protocol is the fact of being centralized, and hence missing the robustness of fully distributed algorithms. The assumption of each node being able to directly communicate with the sink is usually un-realistic in practical use.

6.3.7. Probabilistic, zonal and swarm-inspired system for wildfire detection (PZSWiD)

PZSWiD (Ramachandran et al., 2008) aims at covering the speed of information propagation, the accuracy of the information being propagated and the reliability of the network as a whole over a long period of time. The protocol follows a data centric approach whereby the system executes a swarm inspired routing and aggregation algorithm. The algorithm uses a probabilistic model for representing information in a data centric sensor network. In PZSWiD, nodes perform two functions: 1. they respond to different queries generated by a sink node, and 2. they transport detected events e.g., outbreak of fire to the sink. It works with both event and query based applications. The sensor nodes can also generate periodic reports or emergency reports which depend on the urgency or criticality of sensed data and then transport to the sink in a proactive manner. The protocol is complex and the description of its parameters is rather vague. It assigns probability P_{sd} of satisfying a query sent from sink s to each node d in the network. The probability is assigned on the basis of: 1. how closely the locally sensed data matches with the queried data, 2. the amount of pheromone. The algorithm was simulated in NS-2 with variation of different zone radii, while analyzing its average energy dissipated and the average delay. It has not been compared with any existing protocol for performance measurements.

6.3.8. Ant colony based multipath routing algorithm (ACMRA)

ACMRA (Yang et al., 2008) discovers disjoint multipath between the source nodes and sink node. In multipath routing, multiple paths between source and destination are established. The algorithm generates two types of ants: search ant (SANT) and reinforcement ant (RANT). SANT is used to collect information about paths and the intermediate nodes local information as they travel along the path. RANT is used to update the pheromone table along the reverse path, and bring information of path to source node, such as residual energy of node, path length and energy consumption of the current path. It is an on demand multipath protocol and adopts a two-phase routing process involving the constructing routing and data transmission phases. In the constructing routing phase, cluster head in the event region generates SANTs according to the number of neighbor nodes, and chooses the next node to move to according to probability of selection. While in the data transmission phase, the network lifetime relates to hop count, energy consumption and the minimum energy at a path. The algorithm was compared with primary and replication mode of multipath routing and found to perform better in terms of energy consumption and standard deviation of node energy. The environment of simulation of the protocol is not stated, and the network nodes not properly distributed, while also not considering quality of service metrics in its design.

6.3.9. Ant colony multicast trees (ACMT)

De-min et al. (2008) proposed ACMT based on ant colony multicast trees of wireless sensor network routing. The algorithm tries to prolong the network lifetime by minimizing the communication process to energy consumption. In the algorithm, ants found trees, of which the tree that the ant found includes all the destination nodes. There is no single current node for every ant. Every node on the tree that has been found is likely to be the current node. Every step made by each ant has no other meaning of any path than to enable the current tree to grow further. The only principle observed by the new algorithm is the positive feedback mechanism of basic ant colony algorithm. The protocol compared with the YANG model and Flooding performs better in simulation. Also, as the network grows faster, the death rate of nodes becomes higher.

6.3.10. Ant colony optimization based location aware routing (ACLR)

ACLR (Wang et al., 2008) is a communication protocol which main logic is the selection of next hop by ants to a subset of the set of node's neighbors instead of its whole neighbors which guarantees that the data packets are delivered towards the destination while avoiding loops. The protocol proposed a formula for estimating transition probability with which ants select their next hop nodes. For the determination of pheromone deposited by ants, a model was used and a novel scheme to evaporate the pheromone on various paths according to the residual energy and location information of nodes was proposed so as to increase diversity of the best solution by the ants. The protocol was compared with BAR, SC, FF, and IAR for performance.

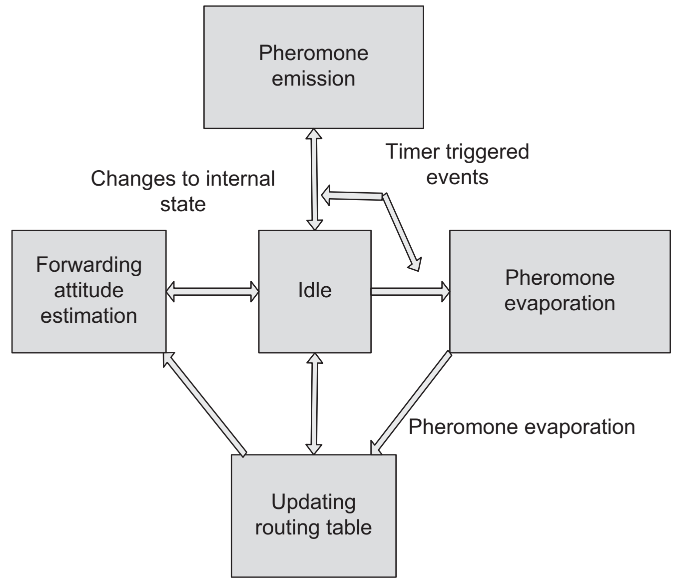


Fig. 8. Signaling process phases of multi-sink swarm based routing.

6.3.11. Multi-sink swarm-based routing protocol (MSRP)

MSRP (Paone et al., 2009) is a routing protocol for sensor networks which is self organized, fault tolerant and environmental adaptable. The protocol is inspired by slime mold organisms. The organism finds their advantage in the ability to organize themselves in clusters using pheromone generation and evaporation. The protocol organizes data traffic towards the sink by adopting the gradient concept while showing autonomy and fault tolerance. The algorithm uses OMNET++ in the evaluation of its performances, signaling overhead, and adaptation to changes in environment. Figure 8 shows the signaling process phases of the algorithm.

6.3.12. Jumping ant routing algorithm (JARA)

JARA (Chen et al., 2007) combines the advantages of reactive and proactive routing to speed up the route discovery time and reduce the route discovery overhead in the sensor network. It combines ant routing algorithm for mobile ad-hoc networks (ARAMA), and the zone routing protocol (ZRP), while also employing jumping mode to reduce the proactive overhead. The algorithm has two parts. The first part deals with the process by which nodes uses proactive routing protocol to maintain the topology of number of hops. The second part involves how each node applies ant routing to discover paths outside its zone. This means that every node maintains a zone, and each ant can jump a zone. The algorithm shortens the route discovery time and reduces route discovery overhead especially in dense topologies as compared to ARAMA in its simulation results.

6.3.13. An ant colony optimization-based load balancing routing algorithm (ACOLBR)

Bi et al. (2010) proposed an ant colony optimization-based load balancing routing algorithm for wireless multimedia sensor networks to help in solving constraints of WSNs, the protocol first built intra-cluster routing by a minimum spanning tree algorithm with cluster head as the root. Then the inter-cluster routing is built by ACO to get an optimal path from cluster heads to the sink. It also uses the message's positive feedback to take the node's residual energy, transmission delay and the propagation distance as the heuristic factor which ensure the QoS of the network transmission. The algorithm as compared with M-IAR and AGRA perform better in terms of end-to-end delay and energy efficiency.

6.4. Network flow and QoS-aware protocols

6.4.1. Energy efficient ant based routing (EEABR)

EEABR (Camilo et al., 2006) is based on ant colony optimization (ACO) metaheuristic. In the protocol, each node in the network launches a forward ant at a regular interval with the aim of finding a route to the destination (sink). In the protocol, each ant only carries the address of the last visited nodes which means intermediate nodes carries the records of received and forwarded ants in the tables. The table content of each node contains the previous node, forward node, ant identification, and timeout value. Each time a node receive a forward ant, it looks up its table to search for any possible loop. If no loop exists, the node saves into its table the information of the ant and restarts a timer and forwards it to the next hop. When the forward ant reaches its destination, it is converted to backward ant with the mission to update the pheromone trail of the path traversed by the forward ant. The amount of pheromone trail to be deposited by the backward ant is calculated using;

$$\Delta\tau = \frac{1}{C-[(EMin_k-Fd_k)/(EAvg_k-Fd_k)]} \quad (9)$$

And the equation used to update the routing tables at each node is

$$\tau(r,s) = (1-\rho)*\tau(r,s) + \left[\frac{\Delta\tau}{\phi.Bd_k}\right] \quad (10)$$

where ρ represents pheromone evaporation factor, C the initial energy level of the nodes, Bd_k the number of visited nodes by the backward ant k, $EMin_k$ is the minimum value of the vector E_k, $EAvg_k$ the average of the vector values, ϕ is a coefficient of which ϕ and Bd_k, are two parameters that will force the ant to lose part of the pheromone strength during its way to the source node. The idea behind the behavior is to build better pheromone distributions in order for nodes near the sink to have more pheromone levels and hence forces remote nodes to find better paths. Such behavior is important when the sink node is able to move, since pheromone adaptation will be much quicker (Kalpakis et al., 2002). When compared to basic ant based routing (BABR) and improved ant based routing (IABR), it performs better in terms of energy efficiency, average energy of nodes and the energy of node with minimum energy. The disadvantages are that it lacks quality of service and increases excessive delay in packet delivery.

6.4.2. Flooded forward ant routing (FF)

FF (Zhang et al., 2004b) argues the fact that ants even augmented with sensors, can be misguided due to the obstacles or moving destinations. The protocol is based on flooding of ants from source to the sink. In the case where the specific destination is not known at the beginning by the ants, or cost cannot be estimated (e.g., address-based destination), the protocol SC reduces to basic ant routing, and the problem of wandering around the network to find the destination exist. This is the case where FF exploits the network with the broadcast channel of wireless sensor networks. That is, the protocol simply uses the broadcast method of sensor networks so as to route packets to the destination. The idea is to flood forward ants to the destination. If the search is successful, forward ants will create backward ants to traverse back to the source. Multiple paths are updated by one flooding phase. Probabilities are updated in the same way as in the basic ant routing. The flooding can be stopped if the probability distribution is good enough for the data ants to the destination. The rate for releasing the flooding ants when a shorter path is traversed is reduced. Two strategies are used to control the forward flooding. First, a neighbor node will broadcast a forward ant to join the forward search only if it is closer to the destination than the node that broadcasted at an earlier time. Link probabilities are used for the estimation, i.e. a forward ant is to broadcast only if $P_n < 1/|N|$, where n is the neighbor the ant is coming from and N is the set of neighbors. If initially there is no hint, i.e. $P_n = 1/|N|$ for all n, each node will broadcast once. Secondly, delayed transmission is used in that a random delay is added to each transmission, and if a node hears the same ant from other nodes, it will stop broadcasting.

6.4.3. Flooded piggyback ant routing (FP)

FP (Zhang et al., 2004b) brings a new ant species to forward ants; namely data ants whose function is to carry the forward list. The control of the flooded forward ants is the same as in FF. The protocol succeeded in combining forward ants and data ants using constrained flooding to route data and to discover optimal paths at the same time so as to minimize energy consumption of the network with the data ants carrying the forward list. In the case of control of the flooded forward ant, the data do not only pass the data to the destination, but also remember the paths which can be used by the backward ants to reinforce the probability on the links. The probability distribution constrains the flooding towards the destination for the future data ants. As compared to FF, SC, and basic ant routing in routing modeling application simulation environment (RMASE), it was found to outperforms others with high success rate, but incurred relatively high energy consumption.

6.4.4. Energy-delay ant-based routing (E-D ANTS)

E-D ANTS (Wen et al., 2008) is designed to minimize the time delay in fixed packet transfer for the purpose of energy constrained sensor networks. In the protocol, Energy x Delay model based on ant algorithms was proposed called E and D ants. The protocol aimed at lifetime maximization, and real time data transmission service of sensor networks. The protocol is reactive based on the iterative generation and unicast transmission of multiple forward ants to discover minimum energy and delay paths, which is similar to AntNet. In the protocol, each ant stores in its stack the residual energy level and the hop delay experienced while hopping from node to node. In the simulation environment of OPNET where it is being simulated, E and D ANTS converges faster than AntChain and AntNet which it was compared with. The algorithm being flat in nature would be difficult to scale through large topologies, unless it introduces hierarchical techniques.

6.4.5. Ant colony based reinforcement learning algorithm (AR and IAR)

Adaptive and improved adaptive AR and IAR (Ghasemaghaei et al., 2007) uses probability distribution like other ant based routing in decision making on the paths to take in its routing decision. Its main difference is the reinforcement learning algorithm implored by the backward ants in order to get a better and more efficient route than the one taken by the forward ant. In the improved version, IAR, a modified heuristic correction factor $A_{i,d}$ is used which is the cost from the neighbor node i to the destination node d so as to find a better probability of choosing a better path for hopping. The algorithm as compared with Basic ant routing, SC, FF, and FP performs better in low energy consumption of nodes, high energy efficiency, less latency, and high success rate.

6.4.6. A bee-inspired power aware routing (beesensor)

Beesensor (Saleem and Farooq, 2007a,b) is an algorithm based on the foraging principles of honey bees with an on-demand route discovery (AODV). The algorithm works with three type of agents; packers, scouts and foragers. Packers locate appropriate foragers for the data packets at the source node. Scouts are responsible for discovering the path to a new destination using the broadcasting principle. Foragers are the main workers of beesensor which follow a point-to-point mode of transmission and carry the data packets to a sink node. When a source node detects an event and does not have a route to the sink node, it launches a forward scout and caches the event. A forward scout is propagated using the broadcasting principle to all neighbors of a node. Each forward scout has a unique id with the detected event in its payload. Intermediate nodes at a distance of two hops or less always broadcast the forward scout while rest of the nodes stochastically decide whether to broadcast it further or not. The forward scouts do not create a source header in which complete sequence of the traversed nodes up to the sink node is saved. Hence their size is fixed and is independent of the length of the followed path. The approach is based on the interactions of scouts and source routing in which small forwarding tables are built during the return of a scout. Its analysis was done and compared with EEABR, FP, and AODV in RMASE simulator. It is an on demand based protocol and may not be fit for security applications or applications where information needs to be updated at regular intervals of time.

6.4.7. A bio-inspired power efficient routing scheme (iACO)

iACO (Mahadevan and Chiang, 2010) is based on metaphor of ant food foraging behavior, and partly based on the efficient max–min algorithm and quite suitable for flexible structure of wireless sensor networks. In the proposed algorithm, each packet is regarded as individual ant communicating with each other via pheromone values stored in each sensor node routing table. The algorithm constitutes of mainly three steps: generation of local solution based on the paths; pheromone update; and decision making in its update of pheromone table. A mutation parameter is added to the pheromone update rules, where the concept of threshold is also involved so as to increase the convergence speed of the algorithm. The mutation parameter is partly based on best–worse ant algorithm (BWACA) as well as max–min ant system. The algorithm was not compared with other existing algorithms for performance evaluation. The throughput decreases as the network grows and hence has poor QoS.

6.4.8. ACO-based quality-of-service routing (ACO-QoSR)

ACO-QoSR (Cai et al., 2006) is a reactive protocol whose main aim is to find a solution to delay requirements as well as limited energy and computational limitation of sensor networks. The address problem consists of finding routes from sensor nodes to sink in a way that the total end-to-end delay is less than a boundary value D, while the energy residual ratio, $ERR=E_{residual}/E_{initial}$, is above a certain threshold value. In the protocol, an ant broadcast is unicast to the next hop nodes using selection probability as in (Cai et al., 2006). In ACO-QoSR, when a source/sensor node has data to send, it checks its routing table for an appropriate path. If such a path does not exist in the routing table, a probe phase to find a new route is initiated. It has m forward ants for each path probe. It also uses the max–min ant system for smoothing and boundary mechanism. The unicast ant for finding the delay constrained routes is somehow questionable. Since the algorithm also keeps the routing information on the header of forward ants, more energy will be consumed, and delays in packet delivery will be encountered especially in a large network.

6.4.9. Ant colony based many-to-one sensory data routing (MO-IAR)

Many-to-one improved adaptive routing (MO-IAR) (Ghasemaghaei et al., 2008) works in two phases. During the first phase forward and backward ants are employed to find the shortest route within multi-hop sensor networks, while in the second phase data ants route the actual sensory data through the shortest path. The protocol is able to route the upstream data flow through the shortest path by avoiding congestion, and hence can handle both event-based and periodic many-to-one sensory data flow. The first phase which is concerned with finding the best route using ant colony optimization assumes that each sensor node knows its location and the location of the priori which can be achieved using GPS technology. One of the sensor nodes is initially deployed and each sensor node locally broadcasts a HELLO message to its neighbors to form the neighbor table. In the second phase as soon as the shortest path to the sink is found, the protocol employs the data ants to route the actual data captured by N number of source nodes destined for the sink. The performance of the protocol as compared with SC, FF, and FP in simulation, outweigh the three protocols in terms of low average latency and fewer number of collisions. The use of source routing and the inclusion of other state information in the header of forward ants can cause excessive use of energy and also delay in packet delivery to the sink.

6.4.10. Ant-aggregation

Ant-aggregation (Misra and Mandal, 2006) argues the fact that a multi hop communication model coupled with in-network aggregation can significantly reduce energy consumption and in turn enhance network lifetime. The protocol therefore addresses the problem of optimal aggregation in a multicast tree, which is an NP-hard problem. The algorithm is based on ACO to build minimum cost aggregation trees of which forward ants look for the shortest path to the destination or for a close by aggregation point. At every node, a forward ant is unicast to the next hop with a certain probability defined in the protocol. In the protocol, the ants either try to find the shortest route to the sink or find the closest aggregation point of the route searched by previous ants or terminates. The algorithm converges to local best aggregation tree. As compared with opportunistic aggregation and greedy algorithms, it performs better in terms of energy reduction consumed in the network.

6.4.11. An ant based service-aware routing algorithm (ASAR)

ASAR (Sun et al., 2008) chooses suitable paths to meet diverse QoS requirements from different kind of services and is mostly suited for multimedia sensor networks. The work aimed at targeting of two different operating network modes having different QoS requirements: 1. the query-driven which includes both D-services based on data query, and S-service which is stream query. S-service is intolerant to errors, but more tolerant to delays like a user querying about parking information. 2. The event-driven mode includes only R-service that puts strict requirements in both delay and reliability for event detection and notification as in surveillance of elderly people. In the protocol pheromone update, pheromone values assume discrete values between 0, and τ^{h}_{max}, which accelerates convergence and reduces the number of needed pheromone updates. The algorithm compared with DD and Dijkstra's algorithm in NS-2, performs better in latency, energy consumption, bandwidth, and packet loss rate metrics.

6.4.12. Basic ant based routing (BABR) for WSN

The basic ant routing algorithm and its main characteristics (White et al., 1998; Dorigo and Caro, 1998) can be summarized as follows:

1. At regular intervals along with the data traffic, a forward ant is launched from source node to sink node.
2. Each agent (forward ant) tries to locate the destination with equal probability by using neighboring nodes with minimum cost joining its source and sink.
3. Each agent moves step-by-step towards its destination node. At each intermediate node a greedy stochastic policy is applied to choose the next node to move to. The policy makes use of (i) local agent-generated and maintained information, (ii) local problem-dependent heuristic information, and (iii) agent-private information.
4. During the movement, the agents collect information about the time length, the congestion status and the node identifiers of the followed path.
5. Once destination is reached, a backward ant is created which takes the same path as the forward ant, but in an opposite direction.
6. During this backward travel, local models of the network status and the local routing table of each visited node are modified by the agents as a function of the path they followed and of its goodness.
7. Once they have returned to their source node, the agents die.

The link probability distribution is maintained by;

$$\sum_{i \in N_k} P_{ji} = 1; \quad j = 1,\ldots,N. \tag{11}$$

The traffic local model M_k is updated with the values carried in $S_{s\to d}$. The trip time $T_{k\to d'}$ employed by $F_{s\to d}$ to travel from k to d' is used to update $\mu_d, \sigma^2_{d'}$ list trip$_k$ (μ_i, σ_i^2) of estimate arithmetic mean values μ_i and associated variances σ_i^2 for trip times from node k to all nodes i $(i \neq k)$ according to the expressions:

$$\mu d' \leftarrow \mu d' + \eta(Tk\to d' - \mu d')$$
$$\sigma^2_{d'} \leftarrow \sigma^2_{d'} + \eta((Tk\to d' - \mu d')^2 - \sigma^2_{d'}) \tag{12}$$

The trip time $T_{k\to d'}$, η is the weight of each trip time observed, the effective number of samples will be approximately $5(1/\eta)$,

The routing table for k is updated in the following way:

The value $P_{fd'}$ (the probability for selecting the neighbor node f, when the node destination is d') is incremented by means of the expression:

$$Pfd' \leftarrow Pfd' + r(1 - Pfd'). \tag{13}$$

where, r is a reinforcement factor indicating the goodness of the followed path.

The $P_{nd'}$ probabilities associated to the other nodes decreases respectively:

$$P_{nd'} \leftarrow P'_{nd} - rP_{nd'}.n \in N_k, \quad n \neq f. \tag{14}$$

The factor of reinforcement r is calculated considering three fundamental aspects: (i) the paths should receive an increment in their probability of selection, proportional to their goodness, (ii) the goodness is a traffic condition dependent measure that can be estimated by M_k, and (iii) they should not continue all the traffic fluctuations in order to avoid uncontrolled oscillations. It is very important to establish a commitment between stability and adaptability. Between several tested alternatives, expression (14) was chosen to calculate r:

$$r = c_1\left(\frac{W_{best}}{T}\right) + c_2\left(\frac{I_{sup-I_{\inf}}}{(I_{sup-I_{\inf}}) + (T - I_{I_{\inf}})}\right) \tag{15}$$

where W_{best} represents the best trip of an ant to node d', in the last observation window $W_{d'}$,

6.4.13. Ant colony-based energy-aware multipath routing algorithm (ACO-EAMRA)

Xia and Wu (2009) proposed ant colony-based energy-aware multipath routing algorithm. The algorithm considers the available power of nodes and the energy consumption of each path as the reliance of routing selection. Parameters q and q_o were proposed to improve the state transition rule and the possibility of ants to find a new path to avoid local optimization. The algorithm was compared with DD and performs better in term of energy saving ability. It does not put QoS into consideration in its routing process.

6.4.14. Energy efficient ACO based QoS routing (EAQR)

Jietai et al. (2009) proposed energy efficient ACO based QoS routing (EAQR), which is based on improved ant colony optimization algorithm. The protocol gives preference to provision of QoS and balancing of energy consumption over the entire network. With its introduction of minimum path energy, path hop count, and by means of advancing pheromone trail model of the ant colony system, it innovatively provides two heuristic ways based on the length and the comfort of the path to meet the different performance requirements of real time and common traffics. Hence, it provides service differentiation between real time and best effort traffic by introducing the new dual pheromone heuristic model in ant colony system.

6.4.15. An adaptive QoS and energy aware routing algorithm (IACR)

Peng et al. (2008) proposed an adaptive QoS and energy aware routing algorithm which is an improved version of ant colony routing (IACR). The protocol considers QoS along side with balancing the nodes energy utilization so as to prolong the network lifetime. The algorithm is composed of two parts, the routing discovery as in the basic ant routing, and routing maintenance where the routing table is maintained and timely response to topology changes. Due to the concern of available bandwidth, the algorithm is more meaningful for real time high bandwidth traffic requirement like voice and video transmission. Simulation result in Omnet++ as compared with DD, show its best performance though delay in packet forwarding to the sink.

6.4.16. Quality of service based distance vector routing protocol (QDV)

Dhurandher et al. (2008) proposed a quality of service based distance vector routing protocol using ant colony optimization for wireless sensor networks (QDV). The protocol considers quality of service and reputation of the network in its routing decision. It pointed out that the high value of reputation of a node signifies that the node is trusted and is more reliable for data communication purposes, and as node shows signs of misbehavior, its reputation decreases which in turn affects its quality of security, thereby disabling the malicious nodes from gaining access to the network. In the algorithm, every sensor node has information about the neighboring nodes in the network, the network has independent nodes and communication between them is distance dependent. In the network, any node can be malicious, so isolating it, facilitating efficient, and secure transfer is the protocol area of consideration. Simulation results show that its performance is better than SNEP, though due to selection of the most secure node, it causes excessive delay in packet delivery and hence consumes network energy.

6.4.17. Ant-based routing for wireless multimedia sensor networks (AntSensNet)

Cobo et al. (2010) proposed an ant-based routing for wireless multimedia sensor networks using multiple QoS metrics known as AntSensNet. The protocol uses an efficient multi-path video packet scheduling in order to achieve minimum video distortion transmission. AntSensNet combines hierarchical structure with ACO-based routing so as to certify the quality of service requirement of sensor networks. Beside its support for power efficient multi-path video packet scheduling scheme for minimum video distortion transmission, it comprises of both reactive and proactive components. It is reactive since routes are set up when needed, and proactive due to the fact that, while a data session is in progress, paths are probed, maintained, and improved proactively using a set of special agents. The algorithm is operated in three parts. The cluster network forms nodes into colonies, network route between clusters that meet the requirements of each application using ants, and forwarding of network traffic using the previously discovered route by the ants. In the clustering process, only the channel heads transmit information out of cluster which helps in preventing collision between sensor nodes in the cluster, hence promoting energy saving and latency. Simulation result on NS-2 shows that the proposed distortion reduction technique used to transport video packets results in better quality video than using TPGF, and ASAR.

7. Analytical comparison of classical and swarm intelligence routing protocols

7.1. Comparison of data-centric classical and swarm intelligence routing protocols

Tables 3–6 show the main characteristics of the different routing protocols in both classical and swarm intelligence based. The tables, show the analytical comparison of all the surveyed routing protocols according to their network structure; Data-centric, Location, Hierarchical, Network flow and QoS aware. Each of the routing protocols were described based on the network structure, energy efficiency, data aggregation, location awareness, route selection and either being query based or not, and also the simulation environment in which the original protocols were simulated.

7.2. Discussion on analytical comparison of data-centric routing protocols

Many protocols in this category belong to the classical routing protocols. CRP which is a variant of swarm intelligence has the highest energy utilization efficiency, though, it is not a query based protocol and as such has limitation when it comes to query based applications. Being a proactive protocol, it is most suited in periodic based applications. This means that, it will generate high overhead in dynamic or mobility scenario of sensor network. As seen from the table, GBR as a hybrid protocol show reasonable performance. The environment in which the authors conducted the experiment was not defined, hence it did not give room for comparison or even to verify the results in which they reported in their work. The most efficient among this category is the EAR, which is strong in energy utilization efficiency, and at the same time reactive and location aware. Due to its location awareness, it will generate fewer control packets in addition to the fact that it is an on demand (reactive) protocol.

7.3. Discussion on analytical comparison of location based routing protocols

In Table 4, the only protocol that belongs to swarm intelligence is SC. It is strong in energy utilization efficiency and the same time a hybrid protocol. This means that as a hybrid protocol, it combines the characteristic of both reactive and proactive,

Table 3
Comparison of data-centric routing protocols in WSNs.

Routing protocols	Classification	Energy efficiency	Data aggregation	Location awareness	Route selection	Query based	Simulation environment
SPIN (5.1.3)	Classical	Weak	Yes	No	Proactive	Yes	NS-2
F&G (5.1.1)	√	Moderate	Yes	No	Reactive	Yes	NS-2
DD (5.1.2)	√	Weak	Yes	No	Reactive	Yes	NS-2
EAR (5.1.5)	√	Strong	No	Yes	Reactive	Yes	OPNET
RR (5.1.6)	√	Weak	Yes	No	Reactive	Yes	LecsSim
CADR (5.1.7)	√	Weak	Yes	No	Reactive	Yes	Math. Model
COUGAR (5.1.9)	√	Weak	Yes	No	Reactive	Yes	Unknown
EAD (5.1.10)	√	Strong	Yes	No	Reactive	No	NS-2
GBR (5.1.4)	√	Moderate	Yes	No	Hybrid	Yes	Unknown
ACQUIRE (5.1.8)	√	Moderate	Yes	No	Hybrid	Yes	Math. Model
CRP (6.1.2)	Swarm	Very strong	No	No	Proactive	No	NS-2
PEADD (6.1.1)	√	Strong	Yes	No	Reactive	Yes	NS-2

Math.model = mathematical modeling, C-lang. = C-language, DES = discrete event simulator.

Table 4
Comparison of location based routing protocols in WSNs.

Routing protocols	Classification	Energy efficiency	Data aggregation	Location awareness	Route selection	Query based	Simulation environment
GEAR (5.2.2)	Classical	Moderate	No	Yes	Reactive	No	Testbed
TBF (5.2.5)	√	Moderate	Yes	No	Reactive	Yes	NS-2
EAGRP (5.2.6)	√	Strong	Yes	Yes	Reactive	No	OPNET
GAF (5.2.1)	√	Weak	No	Yes	Hybrid	No	NS-2
MECN (5.2.3)	√	Weak	No	Yes	Reactive	No	NS-2
SMECN (5.2.4)	√	Weak	No	Yes	Reactive	No	NS-2
SC (6.2.1)	Swarm	Strong	No	No	Hybrid	No	RMASE

Table 5
Comparison of hierarchical routing protocols in WSNs.

Routing protocols	Classification	Energy efficiency	Data aggregation	Location awareness	Route selection	Query based	Simulation environment
LEACH (5.3.1)	Classical	Strong	Yes	No	Proactive	No	Matlab
SOP (5.3.3)	√	Weak	No	No	Proactive	No	Unknown
TEEN (5.3.4)	√	Strong	Yes	No	Reactive	No	NS-2
PEGASIS (5.3.2)	√	Strong	Yes	No	Hybrid	No	Unknown
APTEEN (5.3.5)	√	Very strong	Yes	No	Hybrid	No	NS-2
HEED (5.3.6)	√	Strong	Yes	No	Hybrid	No	Unknown
EAR-CSN (5.3.7)	√	Strong	Yes	Yes	Hybrid	No	Math. model
BCEE (5.3.8)	√	Strong	Yes	No	Hybrid	No	Matlab
SDG (6.3.1)	Swarm	Very strong	Yes	No	Proactive	No	NS-2
EBAB (6.3.2)	√	Strong	Yes	No	Proactive	No	Unknown
ACO-C (6.3.3)	√	V. strong	Yes	No	Proactive	No	Matlab
ACALEACH (6.3.4)	√	Very strong	Yes	No	Proactive	No	Matlab
MACS (6.3.5)	√	Moderate	No	No	Proactive	No	NS-2
AntChain (6.3.6)	√	Strong	Yes	Yes	Reactive	Yes	NS-2
PZSWiD (6.3.7)	√	Very strong	Yes	No	Reactive	Yes	NS-2
ACMRA (6.3.8)	√	Moderate	No	No	Reactive	No	Unknown
ACMT (6.3.9)	√	Weak	No	No	Reactive	No	Unknown
ACLR (6.3.10)	√	Strong	No	Yes	Hybrid	No	OPNET
MSRP (6.3.11)	√	Strong	No	No	Hybrid	No	OMNET++
JARA (6.3.12)	√	Weak	No	No	Hybrid	No	Unknown
ACOLBR(6.3.13)	√	Moderate	Yes	No	Hybrid	No	NS-2
ACO-RC (6.3.14)	√	Very strong	No	No	Hybrid	No	Matlab

Table 6
Comparison of network flow and QoS-aware routing protocols in WSNs.

Routing protocols	Classification	Energy efficiency	Data aggregation	Location awareness	Route selection	Query based	Simulation environment
MLDG (5.4.1)	Classical	Strong	Yes	Yes	Proactive	No	Unknown
SAR (5.4.2)	√	Weak	Yes	No	Hybrid	Yes	Parsec
MLER (5.4.3)	√	Strong	No	No	Hybrid	No	C-lang
SPEED (5.4.4)	√	Weak	No	No	Hybrid	Yes	GloMoSim
EAQSR (5.4.5)	√	Strong	No	No	Hybrid	Yes	Math. Model
MCBR (5.4.6)	√	Strong	No	No	Hybrid	No	RMASE
AODV (5.4.8)	√	Weak	No	No	Reactive	Yes	Parsec
EEABR (6.4.1)	Swarm	Very strong	No	No	Proactive	No	NS-2
AR & IAR (6.4.5)	√	Strong	No	No	Proactive	No	Java
iACO (6.4.7)	√	Strong	No	No	Proactive	No	Castalia
MO-IAR (6.4.9)	√	Moderate	No	No	Proactive	No	Java
Ant-Aggregation (6.4.10)	√	Strong	Yes	No	Proactive	No	Matlab
ASAR (6.4.11)	√	Strong	No	No	Proactive	No	NS-2
BABR (6.4.12)	√	Weak	No	No	Proactive	No	RMASE
ACO-EAMRA (6.4.13)	√	Strong	No	No	Proactive	No	Unknown
EAQR (6.4.14)	√	Very strong	No	No	Proactive	No	NS-2
IACR (6.4.15)	√	Strong	Yes	No	Proactive	Yes	OMNET++
E-D ANTS (6.4.4)	√	Strong	No	No	Proactive	No	OPNET
Beesensor (6.4.6)	√	Very strong	No	No	Reactive	No	RMASE
ACO-QoSR (6.4.8)	√	Strong	No	No	Reactive	No	NS-2
QDV (6.4.16)	√	Moderate	No	No	Reactive	No	GloMoSim
FF (6.4.2)	√	Weak	No	No	Hybrid	No	RMASE
FP (6.4.3)	√	Weak	No	No	Hybrid	No	RMASE
AntSensNet (6.4.17)	√	Strong	Yes	No	Hybrid	No	NS-2

hence it is good in event based applications as well as periodic based applications to some level, but cannot be applied to query based applications. Moreover, the protocol experiment was conducted in a well known and suited environment for WSN routing. TBF is a query based protocol and good in query based applications and not also bad in energy utilization efficiency. Being also reactive, it will generate fewer control packets in dynamic and mobility scenario of WSN environment.

7.4. Discussion on analytical comparison of network flow and QoS-aware routing protocols

Many protocols in this group belong to swarm intelligence, and the classical protocols in this group are hybrid. Hybrid protocols have advantages in the sense that they combine both the characteristic of reactive and proactive in path establishment. The only proactive algorithm that belongs to classical in this group has no defined environment of the experiment. The authors reports promising results in energy utilization efficiency. Among this group, beesensor is more energy efficient and at the same time a reactive protocol. Being a reactive (on-demand) protocol, it has lot of advantages like low network overhead since fewer control packets will be generated during routing process. Its performance was conducted in a well known WSN environment. Some promising protocols like MLER, MO-IAR, Ant-Aggregation, perform their experiment in self designed simulation environment which will not give fair comparisons. EEABR is also very strong in energy efficiency, but it is proactive which means that it will have high overheads since many control packets are used in the path update even when the path is not needed at the time of route discovery. It is suited in areas where information is periodically needed (periodic based applications).

8. Experimental comparison of classical and swarm intelligence routing protocols

8.1. Experimental parameters

We used the routing modeling application simulation environment (RMASE) (Zhang, 2005) which is a framework implemented as an application in the probabilistic wireless network simulator (Prowler) (Sztipanovits, 2004). The simulator is written and runs under Matlab, thus providing a fast and easy way to prototype applications and having nice visualization capabilities for the experimental and comparison purpose.

Prowler is an event-driven simulator that can be set to operate in either deterministic or probabilistic mode. Prowler consists of radio model as well as a MAC-layer model.

The radio propagation model determines the strength of a transmitted signal at a particular point of the space for all transmitters in the system. Based on this information, the signal reception conditions for the receivers can be evaluated and collisions can be detected. The signal strength from the transmitter to a receiver is determined by a deterministic propagation function, and by random disturbances. The transmission model is given by:

$$P_{rec,ideal}(d) = P_{transmit}\frac{1}{1+d^{\gamma}} \quad (16)$$

$$P_{rec}(i,j) = P_{rec,ideal}(d_{i,j}).(1+\alpha(i,j)).(1+\beta(t)) \quad (17)$$

where $P_{rec,ideal}$ is the ideal reception signal strength, $P_{transmit}$, the transmission signal power, d, the distance between the transmitter and the receiver, γ, a decay parameter with typical values of $2 \leq \gamma \leq 4$, α and β, random variables with normal distributions $N(0,\sigma_{\alpha})$ and $N(0,\sigma_{\beta})$, respectively. A node i can receive a packet from node j if P_{rec} $(j,i) > \Delta > 0$ is the threshold. There exists a collision if two transmissions overlap in time and both could be received successfully. The default radio model in PROWLER has $\gamma = 2$, $\sigma_{\alpha} = 0.45$, $\sigma_{\beta} = 0.02$, $\Delta = 0.1$ and $P_{error} = 0.05$.

The transmission model for radio model with SINR in the PROWLER environment is given by:

$$P_{rec}(i,j) = P_{rec,ideal}(d_{i,j}).(1+\alpha(i,j)) \quad (18)$$

where, all the variables have the same values and meaning as in the case of normal radio model described above.

The transmission model for radio model with Raleigh fading in PROWLER is given by:

$$P_{rec}(i,j) = P_{rec,ideal}(d_{i,j}).R \quad (19)$$

where R is a random variable with exponential distribution, where the coherence time is 1sec.

The MAC layer simulates the Berkeley motes' CSMA protocol, including the random waiting and back-offs. When the application emits the Send Packet command, after a random waiting time interval, the MAC layer checks if the channel is idle, if not, it continues the idle checking until the channel is found idle. The time between idle checks is a random interval characterized by Back-off Time. When the channel is idle, the transmission begins, and after Transmission Time, the application receives the Packet Sent event. After the reception of a packet on the receiver's ends, the application receives a Packet Received or Collided Packet Received event depending on the success of the transmission.

Table 7
Simulation parameters.

Parameters	Values
Routing protocols	EEABR, SC, FF, FP, Beesensor, and BABR, AODV, MCBR.
*X*_dist, *Y*_dist	1, 1
Number of nodes	9
Source type, center type, radius, rate, Random rate	Static, random, 1, 4, 0
Destination type, center type, radius, rate, random rate	Static, random, 1, 0.5, 0
Maximum hops	Infinity
Data traffic	Constant bit rate (CBR)
Data rate	250 kbps
Simulation time	100 s
Nodes energy	30 J each
Ant ratio	2
AntStart, EEABRAntStart	240,000, 240,000
Window size, C1, Z	10, 0.7, 1
Reward scale	0.3
Data gain	1.2
Bees learning rate	1
Bees Resend, ForwardDelta, MaxDelay, FloodTemp	1, Inf, 4000, 5
Rrep_delay, Rreq_Timeout, Rreq_Delay, Aodv_Rtable_size, Aod_RQCache_size, Rrep_Retries	40,000, 40,000, 4000, 10, 10, 3

8.2. Performance metrics

From several results obtained from our simulation results using the simulation parameters shown in Table 7, we report the following performance metrics for clarity purpose.

1. *Latency*: the time delay of an event sent from the source node to the destination node. We reported it in seconds (s).
2. *Success rate*: it is a ratio of total number of events received at the destination to the total number of events generated by the nodes in the sensor network. We reported it in percentage (%).
3. *Energy consumption*: it is the *total energy consumed* by the nodes in the network during the period of the experiment (Joules).
4. *Energy efficiency*: it is a measure of the ratio of total packet delivered at the destination to the *total energy consumed* by the network's sensor nodes i.e.

$$\left(\frac{Succes\ rate * total\ packet\ sent\ to\ the\ sink}{Total\ energy\ consumed}\right)(\text{Kbits/J}).$$

5. *Throughput:* it is the average rate of successful packets delivered over the network. It is measured in data packets per second (Kbits/s).
6. *Standard Deviation:* this gives the average variation between energy levels of all nodes in the network (Joules).

8.3. Simulation results

In our evaluation, we compare the performance of six (6) swarm-based routing protocols in WSNs: EEABR (6.1), SC (6.2), FF (6.3), FP (6.4), beesensor (6.10), BABR (6.21), and Classical routing protocols; AODV, MCBR-AST, MCBR-RTSR, and MCBR-CFR using the metrics above. The results are shown in Tables 8–17.

Table 18 shows the comparison table summarized from the simulation results in Tables 8–17. The result is an average of 10 simulation sets of each of the protocols. As can be seen from the table, EEABR is the most highest in terms of energy efficiency, though SC consumes lesser energy, but its low performance in terms

Table 8
Simulation results for energy-efficient ant-based routing Protocol (EEABR).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.0312	3.5812	88.8890	2.0064	0.2411	36	15.9490
20	0.3227	3.6439	90.7890	3.7024	0.5105	76	18.6365
30	0.0317	3.7322	93.1030	5.2544	0.7910	116	20.5541
40	0.0320	3.6982	92.3080	6.9152	1.0531	156	20.8238
50	0.0317	3.6987	92.3470	8.5936	1.3186	196	21.0622
60	0.0315	3.6988	92.3730	10.1104	1.5923	236	21.5620
70	0.0319	3.699	92.3910	11.8064	1.8616	276	21.5984
80	0.0318	3.6991	92.4050	13.4848	2.1271	316	21.6540
90	0.0316	3.6993	92.4160	15.0016	2.4009	356	21.9311
100	0.0315	3.6994	92.4240	16.6624	2.6624	396	21.9656

Table 9
Simulation results for sensor-driven and cost-aware ant routing (SC).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.0380	1.2519	30.5560	1.1872	0.1180	36	9.2656
20	0.0327	2.1298	52.6320	2.7424	0.4389	76	14.5859
30	0.0319	2.3625	58.6210	4.2352	0.7493	116	16.0560
40	0.0317	2.5013	62.1790	5.7328	1.0613	156	16.9200
50	0.0315	2.6034	64.7960	7.3056	1.3880	196	17.3839
60	0.0314	2.6369	65.6780	8.8128	1.7016	236	17.5881
70	0.0314	2.6748	66.6670	10.3680	2.0250	276	17.7470
80	0.0314	2.7037	67.4050	11.9232	2.3484	316	17.8643
90	0.0314	2.7258	67.9780	13.4336	2.6626	356	18.0147
100	0.0313	2.7534	68.6870	14.9488	2.9782	396	18.1955

Table 10
Simulation results for flooded forward ant routing (FF).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.1030	1.0178	25.0000	3.4320	0.1464	36	2.6224
20	0.0683	2.3348	57.8950	6.4320	0.3816	76	6.8408
30	0.0612	2.7044	67.2410	8.4960	0.6488	116	9.1807
40	0.0564	2.8812	71.7950	10.2960	0.9218	156	10.8780
50	0.0551	3.0894	77.0410	11.8800	1.2015	196	12.7105
60	0.0562	3.1423	78.3900	14.1360	1.4750	236	13.0872
70	0.0548	3.2377	80.7970	15.6720	1.7633	276	14.2292
80	0.0547	3.2596	81.3290	17.6640	2.0453	316	14.5493
90	0.0546	3.3081	82.5840	19.2960	2.3283	356	15.2363
100	0.0542	3.3285	83.0810	20.8560	2.6133	396	15.7749

Table 11
Simulation results for flooded piggybacked ant routing (FP).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.0357	4.0124	100.0000	5.3024	0.1704	36	6.7894
20	0.0342	4.0059	100.0000	10.9696	0.3663	76	6.9282
30	0.0338	4.004	100.0000	16.6352	0.5617	116	6.9732
40	0.0340	4.003	100.0000	22.3040	0.7572	156	6.9943
50	0.0335	4.0023	100.0000	27.9632	0.9528	196	7.0092
60	0.0334	4.0019	100.0000	33.6240	1.1486	236	7.0188
70	0.0336	4.0017	100.0000	39.2800	1.3441	276	7.0265
80	0.0335	4.0014	100.0000	44.9504	1.5403	316	7.0300
90	0.0333	4.0012	100.0000	50.6192	1.7358	356	7.0329
100	0.0333	4.0012	100.0000	56.3024	1.9320	396	7.0334

of energy efficiency is due to the low turn-up in packet delivery. Beesensor has the highest lifetime predication. Applications that require almost 100% packet delivery, without minding the energy consumption will prefer to work with FP which in most cases delivers almost all the packets generated in the network. Only a few of the classical routing protocols perform well in terms of energy efficiency, as it can be seen from the table. MCBR-CFR and AODV perform below expectation, while MCBR-AST and MCBR-RTSR performs quite well while also being QoS aware.

9. General discussion on the reviewed routing protocols in WSN

From the high number of papers we have reviewed on routing in WSN, it is clearly seen so far that significant efforts have been made in addressing the techniques to design effective, and efficient routing protocols for WSNs. In this section we discuss the results presented in Tables 3–6, and 18 and 19. We also discuss some methods related to the way these protocols have

Table 12
Simulation results for beesensor routing.

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.0930	3.5723	88.8900	0.8128	0.1753	36	39.3706
20	0.0587	3.7450	93.0000	1.4688	0.3758	76	48.1209
30	0.0755	3.6819	93.1030	3.0016	0.5535	116	35.9806
40	0.0927	3.7219	92.9490	5.3984	0.7154	156	26.8599
50	0.1103	3.7172	93.3670	8.2272	0.8611	196	22.2432
60	0.1091	3.7483	93.6440	10.0832	1.0401	236	21.9176
70	0.1247	3.5221	88.4060	12.8320	1.1856	276	19.0150
80	0.1256	3.5969	89.8730	15.3440	1.3613	316	18.5088
90	0.1264	3.6415	91.0110	17.5040	1.5267	356	18.5100
100	0.1229	3.6379	90.9090	18.9696	1.7042	396	18.9777

Table 13
Simulation results for basic ant-based routing (BABR).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.1533	0.5645	13.8890	2.6880	0.1386	36	1.8601
20	0.1201	1.6413	40.7890	6.2640	0.4636	76	4.9489
30	0.0897	2.3538	58.6210	8.4480	0.8130	116	8.0493
40	0.0822	2.6766	66.6670	10.7040	1.1664	156	9.7160
50	0.0787	2.8229	70.4080	12.7200	1.5383	196	10.8490
60	0.0760	2.9379	73.3050	14.8320	1.9328	236	11.6640
70	0.0739	3.0195	75.3620	16.9440	2.3129	276	12.2757
80	0.0724	3.0308	75.6330	18.7920	2.6882	316	12.7182
90	0.0716	3.0937	77.2470	20.7600	3.0646	356	13.2466
100	0.0704	3.1652	79.0400	22.6560	3.4390	396	13.8153

Table 14
Simulation results for ad-hoc on-demand distance vector (AODV) routing.

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.0352	1.6941	41.6700	2.7205	0.5033	36	11.7627
20	0.0324	1.8032	44.7400	5.3749	1.0558	76	13.1500
30	0.0325	1.7547	41.3800	8.3765	1.6799	116	12.8932
40	0.0327	1.7501	43.5900	11.3333	2.2951	156	12.7942
50	0.0331	1.6750	41.3300	14.4245	2.9375	196	12.6867
60	0.0331	1.5971	39.8300	17.3813	3.5525	236	12.7148
70	0.0331	1.5976	39.8600	20.3717	4.1746	276	11.9774
80	0.0331	1.5471	38.6100	23.8213	4.8918	316	11.9220
90	0.0331	1.5123	37.6400	26.9909	5.5507	356	12.0040
100	0.3281	1.5265	38.0100	29.4661	6.0657	396	12.2174

Table 15
Simulation results for adaptive spanning tree (MCBR-AST).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy efficiency
10	0.0307	3.6958	91.6700	2.4720	0.3547	36	12.9451
20	0.0308	3.6984	92.1100	4.6800	0.7370	76	15.1026
30	0.3102	3.7682	93.9700	6.6720	1.1319	116	16.1870
40	0.0309	3.8018	94.8700	8.5680	1.5257	156	16.9235
50	0.0308	3.8218	95.4100	10.4640	1.9196	196	17.4885
60	0.3082	3.7843	94.4900	12.2880	2.2988	236	17.9850
70	0.0307	3.8011	94.9300	14.1840	2.6928	276	17.2025
80	0.0308	3.8009	94.9400	16.0560	3.0820	316	17.6880
90	0.0308	3.8233	95.5100	17.9760	3.4810	356	18.0240
100	0.0308	3.8007	94.9500	19.8000	3.8604	396	18.1818

been presented and evaluated, and we then build on these results to provide some indications and steps about designing efficient routing protocols for WSNs.

The results from our analytical elaborations are reported in Tables 3–6. The performances of the protocols from our experimental study are summarized in Table 18. The proposed model for routing protocol comparison is reported in Table 19. In general terms, from the survey and the report presented in Table 3 through Table 6, there exist some major shortcomings common to the large majority of the considered works: (i) algorithms are not evaluated over a large set of operational scenarios, (ii) the simulation environment is not satisfactorily described, (iii) most of the protocols are not compared with other state-of-the-art protocols for routing in WSNs. Therefore, most of the reported protocols seem to have promising properties and good performance, but in the other, the way they are actually presented and evaluated seems to lack

Table 16
Simulation results for real-time search routing (MCBR-RTSR).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy Efficiency
10	0.0305	3.8590	94.4400	2.3760	0.3407	36	13.4682
20	0.0306	3.7747	93.4200	4.3200	0.7264	76	16.3611
30	0.0306	3.8183	94.8300	6.3360	1.1259	116	17.0454
40	0.0306	3.8392	95.5100	8.4280	1.5219	156	17.2046
50	0.0306	3.8106	94.9000	10.4160	1.9099	196	17.5691
60	0.0306	3.8430	95.7600	12.4320	2.3097	236	17.7767
70	0.0307	3.8074	94.9300	14.5440	2.6976	276	16.7767
80	0.0307	3.7939	94.6200	16.6320	3.0931	316	17.0754
90	0.0307	3.8059	94.9400	18.7440	3.4878	356	17.2855
100	0.0307	3.8255	95.4600	20.7840	3.8929	396	17.3210

Table 17
Simulation results for constrained flooding routing (MCBR-CFR).

Simulation time	Latency	Throughput	Success rate	Energy consumption	Standard deviation	Number of packets	Energy Efficiency
10	0.2186	3.6816	91.6700	7.2960	0.0695	36	4.3860
20	0.2187	3.8577	96.0500	15.4800	0.0862	76	4.5659
30	0.2185	3.8374	95.6900	23.1600	0.1147	116	4.6632
40	0.2177	3.8322	95.5100	30.7920	0.1616	156	4.7090
50	0.2169	3.7993	94.9000	38.2560	0.2130	196	4.7835
60	0.2149	3.8018	94.9200	45.8160	0.2659	236	4.8236
70	0.2151	3.8131	95.2900	53.6160	0.3145	276	4.5509
80	0.2152	3.8143	95.2500	61.4160	0.3640	316	4.6242
90	0.2156	3.8236	95.5100	69.3600	0.4031	356	4.6713
100	0.2142	3.8102	95.2000	76.9680	0.4487	396	4.6773

Table 18
Comparison of the routing protocols based on different metrics.

Routing protocols	Latency (S)	Success rate (%)	Energy consumption (J)	Energy efficiency	Standard deviation	Lifetime
EEABR	0.0315	92.4240	16.6624	21.9656	2.6624	265.4862
SC	0.0313	68.6870	14.9488	18.1955	2.9782	265.3608
FF	0.0542	83.0810	20.8560	15.7749	2.6133	265.0694
FP	0.0333	100.0000	56.3024	7.0334	1.9320	261.8122
Beesensor	0.1229	90.9090	18.9696	18.9777	1.7042	266.1881
BABR	0.0704	79.0400	22.6560	13.8153	3.4390	264.0437
AODV	0.3281	38.0100	29.4661	12.2174	6.0657	260.6603
MCBR-AST	0.0308	94.9500	19.8000	18.1818	3.8604	263.9396
MCBR-RTSR	0.0307	95.4600	20.7840	17.3210	3.8929	263.7978
MCBR-CFR	0.2142	95.2000	76.9680	4.6773	0.4487	260.9993

Table 19
Proposed models for routing protocol comparison in wireless sensor networks.

Protocol characteristics		**Routing protocols**									
		EEABR	SC	FF	FP	Beesensor	BABR	AODV	MCBR-AST	MCBR-RTSR	MCBR-CFR
Analytical	Network structure	Qos aware	Location	Qos aware	Qos aware	Qos aware	Qos aware	Qos aware	Qos aware	Qos aware	Qos aware
	Energy efficiency	Ver Strong	Strong	Weak	Weak	Very strong	Weak	Weak	Strong	Moderate	Weak
	Data aggregation	No	No	No	No	No	No	No	Yes	No	No
	Location awareness	No	No	No	No	No	No	No	No	No	No
	Route selection	Proactive	Hybrid	Hybrid	Hybrid	Reactive	Proactive	Reactive	Proactive	Proactive	Proactive
	Query based	No	No	No	No	No	No	Yes	No	No	No
	Simulation environment	NS-2	Rmase	Rmase	Rmase	Rmase	Rmase	Parsec	Rmase	Rmase	Rmase
Performance	Latency (s)	0.032	0.031	0.054	0.033	0.123	0.070	0.033	0.031	0.031	0.214
	Throughput	3.699	2.753	3.329	4.001	3.638	3.165	1.527	3.800	3.826	3.810
	Success rate (%)	92.424	68.680	83.081	100.000	90.909	79.040	38.010	94.950	95.460	95.200
	Energy Consumption (J)	16.662	14.95	20.856	56.302	18.969	22.656	29.466	19.800	20.784	76.968
	Energy efficiency	21.966	18.20	15.775	7.033	18.978	13.815	15.935	18.182	17.321	4.677
	Standard dev.	2.662	2.978	2.613	1.932	1.704	3.439	1.855	3.860	3.893	0.449

true scientific soundness. The most evident deficiencies from the methodological point of view of most of the routing protocols are:

1. Many protocols end up in self analysis and comparison, whereby no comparison is made with any standard state of the art routing algorithm in WSNs.
2. Simulation environment or tools used for simulation and experimental setup of some promising protocols were not defined which hinders repeatability.
3. Algorithms are not evaluated over a large network, and hence, most of the protocols are good on scanty networks were there exists fewer nodes.

4. Some protocols which are promising and very good at energy efficiency, lack quality of service awareness and as such, experience excessive delay in packet delivery which may not be so good in some applications such as; security applications and environmental monitoring.
5. Statistical significance of the reported data and the performed experiments looks quite weak. In the case of performance comparison with other algorithms, no statistical hypothesis tests are carried out to assess the significance of the relative difference in performance, because it is only few of the authors that actually.
6. Finally, it is clearly seen from the survey that only one of the simulation environments among the surveyed has some WSNs protocols already patched into it. While some are not even available for others to test their algorithm, and are only available for commercial purpose. We encourage protocols designers to patch their algorithms in whichever environments their experiment was performed to aid in comparison with the new algorithms.

However, from our reports, since energy utilization efficiency and reliability are the major factors for the evaluation of an efficient routing protocol for WSN, Table 19 present the combination of the performance metrics and analytical characteristic of the protocols. As can be seen in the table, FP has the highest success rate leading to high reliability (Throughput) of value 4.001, but with low energy efficiency due to high energy consumption. EEABR has the highest energy utilization efficiency (21.966 Kbits/J) as against FP (7.033 Kbits/J). But in the real application of target tracking scenario (event based), Beesensor will be preferable since it is an on-demand (reactive) routing protocol, moreover, it was the next in performance in term of energy utilization efficiency. This choice of Beesensor is due to its high data delivery rate per energy consumption and the same time, it will generate fewer overheads in a dynamic network. Besides, it network lifetime is longer as compared to other since the average variation between the energy levels of all the nodes in its network (standard deviation) is lower. The only problem it will encounter is that it will have a slightly higher delay in packets or event delivery as can be seen in Table 19. Its end-to-end delay (latency) is 0.123 s as against 0.032 of EEABR. But AODV will also do well when it comes to an application that has to do with querying each node for information (query based). Even with its relatively high energy consumption, it has a very low standard deviation and low latency, hence will be better when it comes to deliver events of high importance and at a faster rate as compared to Beesensor. Finally, it then means that, AODV for query based applications, EEABR for periodic based application due to its high energy efficient and proactive routing scheme, while Beesensor will be suited in event based applications due to its high throughput and on-demand (reactive) routing scheme.

10. Conclusions and future direction

From the review protocols it is clearly seen so far that, significant efforts have been made in addressing the techniques to design effective, and efficient routing protocols for WSNs.

The results from our Analytical comparison are reported in Tables 3–6, while that of the experimental comparison is shown in Table 18. There exist some drawbacks in the presentation of most of the routing protocols for comparison purpose for most of the routing in WSNs, apart from the problems mentioned above, it is clearly seen that many surveyed algorithm ends up in either mathematical modeling or simulation. Also, a lot of them do not compare their protocols with any of the standard ones. Simulation based studies should be complemented with mathematical models, which will then allow for studying a very large system, and also favors fair comparison among protocols. In other words, the actual steps in research should take into account mathematical modeling, simulation, and real world testing or implementation, since it is a general belief that simulation makes assumptions while hardware verifies the assumptions. Towards this end, we present Table 19 as a proposed standard table for routing protocols comparison.

However, the performance of the protocols is promising in terms of energy efficiency. Further research would be needed to address issues such as QoS posed by video and imaging sensors and real-time applications. Energy-aware QoS routing in sensor networks will ensure guaranteed bandwidth or delay through the duration of connection as well as providing the use of most energy efficient path. QoS routing in sensor networks have several applications including real time target tracking in battle environments, emergent event triggering in monitoring applications etc. Currently, there is very little research that looks at handling QoS requirements in a very energy constrained environment like sensor networks. Also, routing protocols should node mobility. Most of the current protocols assume that the sensor nodes and the sink are stationary. However, there might be situations such as battle environments where the sink and possibly the sensors need to be mobile. In such cases, the frequent update of the position of the command node and the sensor nodes and the propagation of that information through the network may excessively drain the energy of nodes. New routing algorithms are needed in order to handle the overhead of mobility and topology changes in such energy constrained environment.

We hope that this will encourage protocol designers to take into account the various protocol characteristics when designing an efficient protocol; QoS awareness, energy efficiency, mathematical models, simulation environment and settings, and finally real time implementation. This will then enable and facilitate more research on the set goals as well as allow researchers to perform fair comparison.

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