Survey on Swarm Intelligence based Routing Protocols for Wireless Sensor Networks

An Extensive Study

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***Abstract*—Swarm Intelligence techniques have been widely used in the science and engineer domains such as Mobile Ad Hoc Networks (MANETs) and Wireless Sensor Networks (WSNs). It is a relatively novel and promising field, focusing on the adaptation of collective behaviors of various natural creatures like ants, fish, birds, and honey bees, and a large number of routing protocols for WSNs have been developed according to the inspiration from the foraging behaviors of these species. In this paper, we first discuss the general principle of swarm intelligence and survey the research efforts on these SI based protocols according to various promising meta-heuristics. In the second part of the paper, we present the properties of termite colony optimization and fission-fusion social structure based spider monkey optimization based clustering in WSNs. Last, we conclude the paper with a comparative analysis, pointing out the fundamental issues and potential future directions.**

***Keywords*—Ant Colony Optimization, Particle Swarm Optimization, Routing Protocols, Wireless Sensor Networks**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) include a large collection of active sensor nodes working in a main area and organized into cooperative network [1]. Each node has properties of one or more sensors, memory storage, a rechargeable/non-rechargeable battery, and processing capability. Routing in sensor networks is an active research topic with many promising techniques, some of which are reviewed in [1-4]. A routing protocol enables nodes (like routers) in a network to specify a choice of route between the source node and destination node based on a routing algorithm. Some of these routing methods are not appropriate for Wireless Sensor Networks because of resource constraints and environmental interference. Hereafter, integrating with novel techniques and establishing a new research field are future trends.

Swarm Intelligence is a meta-heuristic methodology used to solve numerical optimization problems by simulating swarm behaviors found in nature. These techniques demonstrate the desirable properties of interpretability, scalability, effectiveness, and robustness. Previous research [5, 6] has shown that Swarm Intelligence based algorithms have potential to achieve optimal solutions in real world problems. The most popular swarm intelligence frameworks include Ant Colony Optimization (ACO) [5], Particle Swarm Optimization (PSO) [6], Bacterial Foraging Optimization (BFO) [7], Artificial Bee Colony (ABC) [8] and other swarm optimizations [9].

In order to understand whether a behavior is swarm intelligence behavior or not, two necessary properties need to be considered carefully, namely, Self-Organization and Division of Labor [8]:

1) *Self-organization:* is an essential feature which results in global level response. It consists of four characteristics: positive feedback, negative feedback, fluctuations, and multiple interactions. The system interacts among its local level components without a central authority, nor through planning, which means all swarms act at the same time and no swarm is a central coordinator.
2) *Division of labor:* represents the roles of its labors. In a group, there are various circumscribed tasks, which are executed simultaneously by particular individuals.

There is certain similarity between bioinspired systems and routing in networks, especially in WSNs and MANETs. The swarms or insects can be visualized as distributed adaptive systems of smart control packets. Each packet consumes a little computational and energy resources to explore the network. They efficiently cooperate with each other by exchanging information about the discovered paths and their estimated quality [1].

This paper presents an up-to-date survey and comparison of swarm intelligence based routing protocols in WSNs. Comparing routing protocols in WSNs is very challenging for protocol designers. It requires more efforts on re-implement and re-simulate algorithms from published manuscripts. In some cases, simulation parameters and performance metrics may not be fully presented in the paper. Hence, generalized performance metrics are needed for comparing different protocols. The first part of the paper discusses the general principle of swarm intelligence and survey the research efforts on these swarm based protocols according to various promising meta-heuristics. The routing protocols are categorized in a comprehensive classification systems based on the optimization strategies they adapted. The second part of the paper presents the properties of termite colony optimization, and spider monkey optimization based clustering algorithm. We aim to identify a new swarm intelligence based algorithm to solve routing problems in WSNs with sufficient mathematical modeling and real time application.

The rest of the paper is organized as follows: Section II reviews previous surveys on WSN and MANET routing. Section III defines the design challenges and taxonomy of routing protocols in terms of swarm intelligence. Section IV discusses existing swarm intelligence routing protocols with its weakness and strengths. Section V provides further discussion and potential future directions on other swarm based optimization algorithms. Finally, we conclude this paper in Section VI.

TABLE I
PREVIOUS SURVEY ON ROUTING PROTOCOLS

No.	Year	Domains	Authors	Ref.
1	2011	WSNs	Saleem et al.	[1]
2	2012	WSNs	Zungeru et al.	[2]
3	2013	WSNs and MANETs	Ali et al.	[3]
4	2015	WSNs	Saleh et al.	[4]

II. Related Work

In this section, we summarize previous Swarm Intelligence based routing algorithms. Saleem et al. [1] was the first detailed survey on swarm intelligence based routing protocols in WSNs. The survey is fascinating and comprehensive, where a number of design challenges and protocol taxonomies were considered. In addition, each presented work is classified based on the area of application and simulation environment. A list of must-have features were also identified for consideration during implementing real-world applications. Zungeru et al. [2] also surveyed swarm based routing protocols, comparing them with classical routing protocols. The authors categorized the protocols into four types based on the corresponding applications: data-centric, location, hierarchical, and network flow and quality of service aware. Ali et al. [3] published a recent survey on swarm based protocols. The algorithms are specially analyzed under MANETs and WSNs while their appropriateness is observed, and where the results indicate the bio inspired algorithms outperform the conventional approaches. The work by Saleh et al. [4] is the most recent one on surveying swarm intelligence based routing protocols. It provides a summary of the most important attributes of the previously analyzed schemes which specifically fall into the ACO algorithm category. Although, many swarm approaches have been classified and grouped based on certain metrics, to the best of our knowledge, there has been no survey paper that covers the most recent state-of-the-art routing protocols and up-to-date swarm intelligence technologies. In Table I, we summarize the previous surveys related to ours by highlighting the year, authors and survey domains.

A. Design Challenges

As mentioned in the Related Work, Saleem et al. [1] generated a list of must-have features for WSN routing protocols such as energy efficiency, security, scalability, sensor localization, self-organization, fault tolerance, and hardware and memory requirements. These characteristics and requirements have direct impact on network design issues in terms of outcome performance and capabilities [10]. However, new swarm based platforms are desired to cover the following issues: availability of multipath, scalable performance, self-organizing behaviors, locality of interaction, and failure detection and backup. The challenging factors are outlined and discussed in Table II.

TABLE II
SUMMARY OF SWARM INTELLIGENCE BASED PROTOCOL DESIGN CHALLENGES

No.	Factors	Description	Ref.
1	Multiple path	Multipath can extend the network lifetime and is used only as a backup when primary path fails. However, multipath routing algorithm update is fast and more reliable.	[10]
2	Scalable performance	Coverage and range is a typical issue in WSNs, thousands or millions sensor nodes are expected to be deployed in a wide area with long transmission path.	[1]
3	Self-organizing behaviors	Swarm based protocol must be resilient to unpredictable variations (static and dynamic) and sustain the long-term availability of essential network services.	[11]
4	Locality of interaction	Within a sensor network area, small group of sensors must coordinate to track targets; in other word, sensors have strong locality in their interactions when coordinate under uncertainty.	[27]
5	Failure detection and backup	Most time sensor nodes are equipped with non-rechargeable batteries. The communication between sensor nodes can be affected by signal strength, obstacles, weather conditions, antenna angle and so on.	[28]

B. Taxonomy

The routing protocols have been grouped into certain categories. In [1], the authors provide a comprehensive classification consists of energy aware, loop free, fault tolerant, data communication, performance guarantee, routing mechanism, transmission model, topology model, addressing model, controlling model, and traffic model. We believe routing protocols could also be classified based on routing algorithms properties or cluster formation (such as swarm intelligence based optimization algorithms). In Table III, the new taxonomy of the routing protocols classification in WSNs is shown. The classification properties mentioned in Table III can help protocol designers better review and assess an existing swarm intelligence based routing protocol model.

TABLE III
TAXONOMY OF SWARM BASED ROUTING PROTOCOL CLASSIFICATION

Routing Protocols	Routing Algorithm	Foraging Strategy	Routing in Nature	Terminate Criteria
CRP [15] IAMQER [16] ANT-BFS [17]	Ant Colony Optimization	Pheromone	Proactive	Variation in solution quality or distance between candidate or maximum number of cycle
TPSO-CR [18]	Particle Swarm Optimization	Velocity	Proactive	Maximum number of iteration
BFA-LEACH-C [19]	Bacterial Foraging Optimization	Swim and tumble	Reactive	Maximum function evaluations or maximum number of iteration
BEESENSOR-C [20]	Artificial Bee Colony	Waggle dance	Proactive	Maximum number of cycle or time limit

III. REVIEW OF SWARM INTELLIGENCE BASED ROUTING PROTOCOLS

In this section, we review selected swarm intelligence based routing protocols (Table III) for Wireless Sensor Networks. We highlight their properties in regard to the optimization mechanisms of Section III. In the following subsections, we first discuss ant colony based protocols, then particle swarm based, bacterial foraging based and artificial bee colony based, respectively.

A. *Ant Colony Optimization (ACO) based Protocols*

Ant Colony Optimization is one of the bio inspired mechanisms that optimizes routing paths. ACO is dynamic and reliable, which can provide data aggregation and gather routing structure, avoid network congestion, reduce energy consumption and support multi path data transmission to obtain reliable communications in Wireless Sensor Networks. ACO aims to maintain the maximum network lifetime, during data transmission by an efficient manner [21].

In network routing, Ant Colony Optimization based techniques deliver better performance due to real time computation and less control overhead [24]. ACO algorithms have several weakness such as performance extremely depends on previous cycle. It still seems to be appropriate to use ACO based routing protocols [15-17] in dynamic networks to prevent link failures (a number of artificial ants are generated at each period and search for the shortest path between source and destination).

Comprehensive routing protocol (CRP) was first presented by Guo et al. [15] in 2010 and mainly built by ACO. The algorithm is an updated version of energy aware routing (EAR), which was introduced by Shah and Rabaey [22] as a classical routing protocol. CRP consists of three phases: routing table setup, data communication, and route maintenance. By comparison with EAR on NS2 (Network Simulator 2) this protocol achieved better performance with respect to the network lifetime and packet loss rate. However, this approach lacks the consideration of Quality of Service (QoS) metrics as well as the ability to deal with link failures.

Wang et al. [16] established an ant colony based energy saving route supporting multi-constrained QoS technique (IAMQER). The proposed IAMQER algorithm increases network packet delivery ratio and reduces average energy consumption. This protocol was compared with the shortest route algorithm along with NQoS AODV (Ad-Hoc on Demand Distance Vector). The results indicate this technique can improve network throughput significantly under two constraints of average end-to-end delay and packet loss ratio. In addition, the authors defined a path evaluation function in order to evaluate the performance of routes. However, IAMQER technique focuses on the original ant colony optimization procedure which may need longer processing time.

In the past decade, ant colony technique have been applied to solve combinatorial optimization problems such as NP-complete cases. Moreover, it enhances the performance in terms of network lifetime and load balancing in Wireless Sensor Networks with various solutions in finding the shortest path. Khoshkangini et al. [17] proposed a hybrid approach, Ant Colony Optimization combined with Breadth First Search (ANT-BFS) to find the optimal (shortest) path in order to improve data transmission while consuming less energy. The drawback of the BFS technique is that it requires extra memory space and computational time if cluster head is far away from the sink, though, BFS may reach the best solution under certain circumstances. Therefore, ANT-BFS may not be suitable for extreme cases or large coverage area.

B. *Particle Swarm Optimization (PSO) based Protocols*

Particle Swarm Optimization a subfield of Swarm/Computational Intelligence which is a population based stochastic optimization technique. PSO applies the concept of social behaviors of bird flocking or fish schooling to real world problems. This approach maintains local solutions as well as global solutions and produces the best fitness of an objective function [18].

Elhabyan et al. [18] proposed a Particle Swarm Optimization inspired protocol to improve packet delivery rate, increase network coverage and reduce energy consumption. This Two-tier Particle Swarm Optimization for Clustering and Routing protocol in WSN is also known as TPSO-CR. It consists of two phases for each divided network operating time (round):

1) *Set-up phase:* neighbor discovery, control data broadcasting, network configuration, and configuration broadcasting.
2) *Steady-state phase:* Time Division Multiple Access (TDMA) scheduling, data transmission, data forwarding, and energy saving (sleep state).

The authors presented two Linear Programming formulations to optimize the performance. The outcomes showed that TPSO-CR is prominent among Low Energy Adaptive Clustering Hierarchy (LEACH) based, original

Particle Swarm Optimization (PSO) based and Genetic Algorithm (GA) based protocols with extensive simulations on 50 homogeneous and heterogeneous WSN models.

C. Bacterial Foraging Optimization (BFO) based Protocols

Bacterial Foraging Optimization is one of the bioinspired algorithms that have been applied to the routing strategy for Wireless Sensor Networks based on the foraging behavior of Escherichia coli bacteria. BFO is a newly introduced evolutionary optimization algorithm and has been used in many research fields like color images quantization, face recognition, engineering related problems and MANETs. This approach obtains better results than other bioinspired and conventional approaches. It is computationally efficient in solving complex numerical problems [26].

Pitchaimanickam and Radhakrishnan [19] presented a hybrid Bacterial Foraging Algorithm (BFA) using Particle Swarm Optimization (PSO) to form the k optimal clusters, which identify the cluster head that has the energy above the average energy of the k-optimal clusters. In Section IV (B), we mentioned that PSO based algorithm can achieve local best and global best positions in two updates: Synchronous and Asynchronous. In this paper, the authors obtain the new positions after evaluating both local and global best positions in the search area, which is suitable for synchronous update. Synchronous updates have the disadvantage includes offspring non-immediately feedback and are not beneficial in loosely connected nodes.

D. Artificial Bee Colony (ABC) based Protocols

Based on the foraging behavior of honey bee swarms, Artificial Bee Colony algorithm was designed to optimize multivariable and multimodal continuous functions [27]. ABC technique can be applied in the fields of mechanical and civil engineering, image processing, software and control engineering, and wireless sensor networks. The drawbacks of the original ABC algorithm are low convergence speed and it can be easily trapped into local optimum. Therefore, hybrid and modified versions are expected to be proposed by researchers.

Cai et al. [20] proposed an event-driven and on-demand multipath routing protocol based on dynamic cluster and foraging behavior of artificial bees. This protocol is an improved version of BEESENOR [23] and aims to reduce routing overhead and improve scalability using the technique of the multi-hop. However, low reliability is a deal killer in multi-hop technique. According to social insect ability, if the path's reliability becomes very poor, the forager will stop recruiting new swarms [20]. Hence, [20] has addressed this issue in both their topology and hardware solutions considering both single event scenario and dynamic scenario.

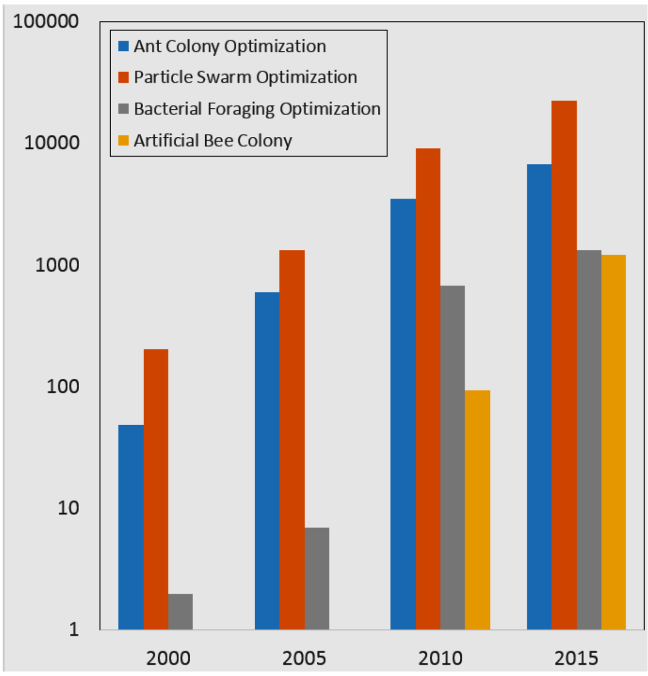

Fig. 1. Number of papers in Web of Science collection related to the subjects.

E. General Discussion on the Reviewed Work in WSN Routing

Due to the analogy between foraging behaviors and network routing, a relatively large number of swarm intelligence based routing protocols have been developed. In this section, we demonstrate the sharp increase in popularity that swarm intelligence based algorithms have encountered in engineering applications and other realms (Fig. 1). Next, we highlight strengths and weakness of the proposed algorithms. Last, we identify and propose new research directions in this

TABLE IV
COMPARISON OF SWARM INTELLIGENCE BASED ROUTING PROTOCOLS

Attributes	**CRP [15]**	**ANT-BFS [16]**	**IAMQER [17]**	**TPSO-CR [18]**	**BFA-LEACH-C [19]**	**BEESENSOR-C [20]**
Energy aware	Yes	Yes	Yes	Yes	Yes	Yes
Loop free	No	No	Yes	No	No	No
Fault Tolerant	No	Yes	Yes	Yes	Yes	Yes
Data communication	Single path	Multipath	Multipath	Single path	Multipath	Multipath
Performance guarantee	Best	QoS	QoS	QoS	Best	QoS
Routing mechanism	Hybrid	Proactive	Hybrid	Reactive	Hybrid	Reactive
Transmission model	Source	Next hop	Next hop	Next hop	Next hop	Next hop
Topology model	Flat	Hierarchical	Hierarchical	Flat	Hierarchical	Hierarchical
Addressing model	Data-centric	Data-centric	Data-centric	Address-centric	Data-centric	Address-centric
Controlling model	Distributed	Distributed	Centralized	Distributed	Centralized	Distributed
Traffic model	Event	Query	Query	Query	Event	Event

emerging domain. Each swarm intelligence based optimization algorithm has its strengths and weakness, especially in resource constrained sensor networks. To further explore the uniqueness and its suitability for designing routing protocols, it is necessary to understand the challenges in Table II, maximize its strengths and alleviate the weakness. In general, it is critical to develop an optimal solution that matches all criteria, especially in multimodal optimization problems. Table IV provides a summary of the proposed work based on important attributes that clearly derive the advantage and disadvantage for each routing protocol accordingly. Most of the existing protocols end up in no comparison with baseline approach or not implemented in real world environment. In other words, a good routing protocol should consider the components of mathematical modeling, sensing simulation, real world testing and implementation.

IV. FURTHER DISCUSSIOIN AND FUTURE DIRECTIONS

To the best of our knowledge, slight consideration and effort have been paid in utilizing the organization and behavioral principles of other swarms such as termites and spider monkeys to solve real world problem. The study of termite behavior has revealed remarkable achievements in the communication capabilities as compared to ants and bees. Termite Colony Optimization (TCO) is an inhabitants based optimization method which is inspired from autocatalytic behaviors of termites. Termite-Hill [25] is a good example that has been proposed to efficiently relay all the traffic destined for the sink and also to balance the network energy in static, dynamic and mobile sink scenarios at any location at any time.

Spider Monkey Optimization (SMO) is a recent addition to the family of swarm optimization algorithms by modeling the fission-fusion social structure behavior of spider monkeys. SMO is good in exploration and exploitation of local search space and it is a well-balanced methodology in most of the cases. Moreover, SMO is moderately straightforward, speedy as well as a population based search strategy and analogous to ABC approach in characteristics [9]. This algorithm has been proved to be efficient and reliable in most cases; it consists of six phases: local leader phase (LLP), global leader phase (GLP), local leader learning (LLL) phase, global leader learning (GLL) phase, local leader decision (LLD) phase, and global leader decision (GLD) phase. The authors in [9] believe a good search process should explore the new solutions, while maintaining satisfactory performance by exploiting existing solutions. Based on their assumption, the proposed method has been performed on 26 objective functions in order to analyze the sensitivity, efficiency, and scalability [9]. The results show that the SMO algorithm is competitive to PSO and ABC approaches and it is a strong and flexible candidate in the field of swarm intelligence based optimization algorithms.

Inspired by SMO, we aim to design a cluster-based routing algorithm (SMO-C) that studies social behaviors of spider monkeys for discovering the optimal route between the source and sink in Wireless Sensor Networks. Generally, SMO is initialized with a uniformly distributed population and in turn explores for optimal solution by means of updating new positions using self-experience, local leader experience and group member experience. If any local leader position is not updated within a predetermined threshold limit, then all members update their positions by random initialization. For global leader decision phase, if the situation reaches global limit, then the global leader divides the population into smaller groups. The number of groups is calculated based on the whole network area and size of a cluster,

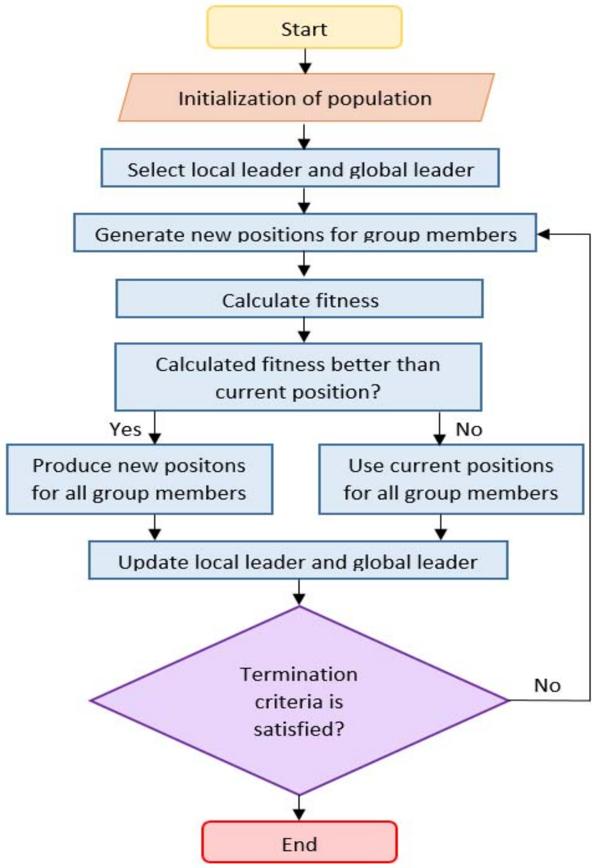

Fig. 2. Flow chart of SMO cluster formation

$$NG = SR / SM_k$$

where SR and SM_k are the entire sensor region and the size of a cluster which is k (spider monkeys), respectively. Fig. 2 shows the flow chart of SMO cluster formation. As a sample sensor network, it is divided into smaller groups called clusters with radius R, the coverage of any sensor node.

To the extent of our knowledge, SMO based routing protocol for WSN or MANET will give better result due to the following reasons,

- Self-organization behavior
- Adaptive to topological change
- Simple to design and interpret

- Availability in multipath model
- Link failure control

Improving SMO algorithm in terms of time and space complexity and developing SMO based energy aware routing protocol can be considered as future directions.

V. Conclusions

Wireless sensor network is a large collection of resources constraints sensor nodes. The development of robust, energy efficient, reliable routing protocols is challenging. In the first part of the paper, we have presented an extensive survey of recent swarm based routing protocols in WSNs. The second part of the paper, we present Table IV as a proposed standard table for SI based routing protocols comparison. Furthermore, we sketch out a spider monkey optimization based routing algorithm for discovering the optimal route path and preventing residual nodes. Finally we conclude our findings of this proposed approach along with the potential research directions, future simulation, and real world implementation.

We hope that this paper will encourage routing protocol designers to take into consideration the various swarm intelligence optimization algorithms and carry out studies on emerging QoS awareness, energy efficiency, mathematical modeling, simulation and real time implementation.

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