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A Novel Comprehensive Taxonomy of Intelligent-Based Routing Protocols in Wireless Sensor Networks

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Abstract

Routing in ad-hoc networks, specifically intelligent-based ones, is a highly interested research topic in recent years. Most of them are simulation-based study. Large percentages have not even mentioned some of the fundamental parameters. This strictly reduces their validity and reliability. On the other hand, there is not a comprehensive framework to classify routing algorithms in wireless sensor networks yet. In this paper, we present a novel comprehensive taxonomy for routing algorithms along with a complete experimental evaluation framework. It makes the ability to put each routing algorithm in its place. It also provides a complete view of the algorithm behavior. At the end, a proper framework is introduced to express essential simulation parameters too. This can lead to improve the quality of scientific practices in the simulation studies.

Keywords: Taxonomy, Classify, Fundamental Parameters, Evaluation Frameworks

1. Introduction

Although wireless sensor networks (WSNs) have many common points with other networks, the unique attributes distinguish them. Wireless radio transmission power is proportional to the square of distance or even greater exponents in the presence of the hedges. So multi-hop routing consumes less energy than single-hop. On the other hand, sensor nodes are usually deployed with huge density and neighbor nodes are beside each other. So short radius communications and multi-hop packet transmissions are more suitable [1]. This data transmission results in saving energy and reducing transmission interference between nodes [2]. But this causes multi-hop transmission problems as well. If all nodes are near the sink, direct routing will be more suitable [3]. Often the nodes are randomly scattered over the field. So multi-hop communications would be unavoidable and WSNs are assumed as a subset of multi-hop wireless networks as Fig.1.

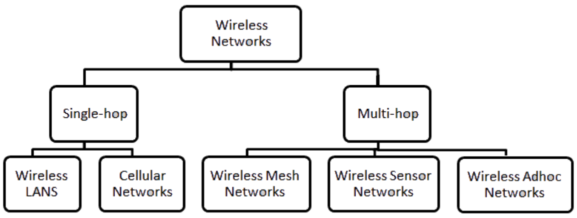

Fig.1. Wireless networks classification

Other networks routing protocols are not suitable for sensor networks, because they must cope with numerous problems such as resource constraints, efficiency, specific traffic patterns and etc. Due to the multiplicity of challenges posed in WSNs, design of an all-in-one routing that overcomes all the goals and requirements, is clearly impractical. All the existing designs and implementations focus on a specific application scenario and emphasis on different goals. This issue makes difficult to classify WSN routing algorithms. In this paper, we propose a novel, more comprehensive and fine-grained taxonomy for routing protocols in WSNs. This helps to identify and get a correct view of the routing algorithms. It makes easy to select proper algorithms for comparison too. We also prepare a complete framework to represent fundamental simulation parameters. This can lead to improve the quality of scientific practices in the simulation studies.

The remaining of the paper is organized as follows: Section 2 reviews the relevant literature. In Section 3, a comprehensive taxonomy is presented for WSN routing algorithms. In addition, a framework is provided for essential parameters of ad-hoc Networks. At the end of this section, several intelligent-based algorithms are classified and considered in the proposed frameworks. In the final section, the article ends with a conclusion.

2. Literature review

Routing in ad-hoc networks is a highly favorable research topic in recent years. In most cases, the evaluation of algorithms is based on simulation, not analytical. Simulation-based evaluation is common for three reasons: 1. this is the best way to code and implement a complex algorithmic logic in the network, which is closer to reality. 2. This is the easiest method in comparison with the evaluation based on mathematical proof in real networks. 3. It allows the designer to produce results of choice through simple programming tricks. The final reason is the most dominant and is examined seriously in recent studies. Article [4] reports a statistical study about proper scientific practices in the simulation studies. The researcher states that in more than 75 percent of the papers, 30% did not even mention the simulator name. The node density, simulation area and the radio range are three fundamental parameters in ad-hoc Networks which are not mentioned in 56% of the articles. In such cases, validity and reliability of the simulation-based studies are seriously doubted. We prepare a framework for this. Also a complete performance evaluation framework is needed to evaluate performance parameters over a wide operational perspective. Thus, metrics are proposed that provide a complete view of an algorithm's behavior in real world scenarios. This helps the protocol designer to achieve informed insight about the merits/demerits of a protocol [5]. These metrics are presented in Table 2 to examine the reviewed intelligent-based algorithms in this paper.

In addition, the researcher should properly identify and classify a routing protocol. Classification of the sensor networks based on different architectural properties is developed in the article [6]. It accurately represents typical sensor network architecture and its components. Such classifications are useful for designers to select the appropriate infrastructure. Mr. Akkaya and Younis in the article [2] have classified WSNs routing protocols into four categories: data-centric, hierarchical, localized and QoS-aware. Recently, [7] has proposed a classification that extends article [2] to six categories: Attribute-based, flat, hierarchical, geographical, multipath and QoS-aware. The paper [8] classifies based on some other criteria such as: Sink mobility, topology, network dynamic, sink numbers, single-hop or multi-hop, self-reconfigurable, heterogeneity. It is clear that there is no a single comprehensive taxonomy for WSNs routing protocols yet. Our proposed taxonomy is more comprehensive and fine-grained classification in comparison with [2], [7], [8] in the network layer. Our classification is based on [9]–[12] and expands them as well. This covers a relatively large set of features that is of interest for generic routing protocols, more specifically, for WSNs protocols.

3. Comprehensive taxonomy of routing protocols

In this section, a wide range of interested characteristics of a routing protocol is briefly described. These characteristics are divided into two groups: main features and additional. The main characteristics are inherent and inseparable attributes of a routing algorithm while additional features are the characteristics added to algorithms according to the application so that influences on the network performance metrics. The categories included in the taxonomy are individually discussed in the subsections. Then the characteristics and performance of some intelligent-based routing algorithms are considered in the designed frameworks and shown in the relevant tables. Finally, it is considered which the fundamental parameters are mentioned in the articles.

3.1. Main characteristics

Structure-based and Structure-less routing: Structure-based routings either creates a spanning tree (e.g. Backbone [13], Mint [14], Grid [15] and Adaptive Tree [16]) or generates one/more than one (e.g. AODV [17], DSR [18] and Multi-path Routing [19]). Structure-less routings generate a potential field instead of creating and maintaining a routing structure. The potential field is a map of nodes to cost-to-go values. The definition of cost-to-go depends on routing purpose. Flooding (e.g. Directed Routing [20], Gradient Broadcast [14], Gradient Routing [21], Constrained Flooding [16]) and real-time search (e.g. Q-Routing [22], GEAR [23], Ant Routing [24]) are of this class.

Single path and multipath routing: Routing protocols can support single or multiple routes from one or multiple sources to a particular destination. Single path protocols find one or more routes and always choose the best for data transmission. On the other hand, multipath routing protocols discover and support multiple paths as using them to transport the sensed data [12].

Reactive, proactive, and hybrid routing: In reactive/on-demand protocols, paths are searched and generated just in case. In proactive protocols, routing data for all known destinations is always up-to-date, regardless of whether or not the target is selected for data transmission. Some protocols use both techniques and hence are called hybrid, see [25] and [26] for more details [12]. A proactive approach is more suitable for continuous traffic but it may cause excessive energy consumption costs for applications in which data traffic is discrete. In these situations, reactive approaches might be more appropriate.

Source, next hop, and hybrid routing: In the next hop routing, a data packet only contains information about its final destination. The next hop is selected based on the information is stored in the local routing table at each node, see [17]. In the source routing, all the path information are stored in the packet datagram. Intermediate nodes just need the next hop information from the datagram in order to forward the packet, see [17]. Some use both techniques and called as hybrid protocols. Source routing restricts the protocol scalability and cause stability problems in highly dynamic networks, although it can be more effective because of the reduction processing requirements in each packet and loops avoidance [12].

Flat and hierarchical routing: A flat routing protocol considers the entire network as a collection of nodes with the same hierarchical level and finding a route between any arbitrary pair of nodes. However, the hierarchical protocols divide the network in two separate regions named zones/clusters [27]. For example, the article [28] shows that hierarchical routing protocol is the most effective suggestion in environment monitoring applications that has continuous data traffic to the sink. Lots of redundant data is usually generated in such applications. This routing approach can aggregate the packets into the sink path in order to reduce traffic and save energy.

Data-centric and address-centric routing: A data-centric protocol does not need universally unique node IDs, while an address centric protocol does. Data-centric protocol usually is not useful when assigning a unique ID to each node is impossible [29] or inappropriate for assumed the purpose/network size. Data-centric routing is one of the common operational ways in some networks [30]. Data packets are named using high level descriptors, in data-centric routing [12].

Distributed and centralized routing: In the centralized routing patterns, a single node called as base station/sink, explores and maintains of routing information. In distributed approaches, each node collects or generates routing information. This is more robust against network changes and is more appropriate for dynamic networks [12].

Best-effort and QoS-aware routing: Protocols that do not guarantee any quality of services (QoS) for the application are classified as best-effort. Protocols that can guarantee quality of routing services such as latency, jitter, available bandwidth, reliability and etc. are known as QoS-aware routing [12]. A network must provide QoS while maximize network resource usage. For this purpose, assessment of application requirements and extension of various mechanisms is needed in the network. The article [31] reviews QoS Support in WSNs.

Event-driven, query-based and hybrid routing: This classification is based on the nature of the application. In event-driven protocols, the data routing after event detection starts from the sensor node. In the case of query-based routing, particular query is sent to the sensor node [32]. Some protocols such as [33] are capable of supporting both applications [12].

Loop free routing: If the protocol guarantees that the data packet routes are loop free, it is called loop free routing. In addition to data packets, control packets can meet loops too. The data packet loops can have serious negative impact on network performance. This reduces throughput and/or increases packet latency and energy consumption. Control packet loops may be less critical but must be avoided due to the same reasons. Loop avoidance is a topic for all next hop routing protocols [12].

3.2. Additional characteristics

Fault-tolerance: Some sensor nodes may die due to physical damages in a hostile environment or because of their power depletion. The survived nodes may enter or leave the transmission radius of other nodes. On the other hand, the control packets may be lost due to interference or process/memory problems. The routing protocol that is robust against topology changes and packet loss caused by hardware failures is called fault-tolerance. In other words, the fault-tolerance is defined as the ability to maintain the sensor network operation in spite of some node failures. If many nodes are failed and malfunctioned, it ought to create a new arrangement of links and paths in order to collect data from base stations and adapt to these problems.

Scalability: The network should be scalable in the distribution and number of nodes. In other words, the sense/actuator network should be able to work with hundreds, even thousands of nodes. Certainly the number of nodes depends on the desired application and accuracy. On the other hand, it has to support different distribution densities of the nodes. The density differs from several nodes up to hundred. Also the scalability relates to the methods. Some methods may not be scalable, namely they just function in a limited number or density of nodes.

Energy-awareness: Cost-effective usage of energy is important in WSNs because replacing or filling nodes batteries may be impractical, expensive or dangerous after deployment. So the battery lifetime determines the node lifetime and practically the network lifetime. Routing protocols that prioritize paths base on the energy metrics, for e.g. remaining energy of sensor nodes on the path, are classified as energy-awareness. It is not considered in the applications that are responsible for obtaining very accurate information in a short time [12].

Data aggregation: Because sensor nodes may generate significant redundant data, similar packets from multiple nodes can be combined to reduce the number of transmissions. Data aggregation is a combination of various data sources, using functions such as average, minimum, maximum, and elimination [34]. Given that the calculations consume less energy than transmissions [3], significant energy savings can be obtained from data aggregation. This technique is used in a number of routing protocols to achieve more optimal energy efficiency and traffic. In some network architectures, all combination functions are assigned to particular and powerful nodes [35]. A review of WSNs data aggregation algorithms is presented in [36].

Security: Sense/actuator networks are more vulnerable because of some characteristics such as wireless communications, using single frequency for the entire network communications, dynamic topologies and etc. Due to such restrictions, it's necessary to investigate simple and efficient solutions based on sense/actuator network nature. Secure routing uses techniques to defend against attack. Many security challenges in WSNs are analyzed and key issues that must be resolved to achieve acceptable security are abstracted in [37]. Examples of routing attacks are presented in [38]. An overview of the security threats and defense mechanisms in WSNs is expressed in [39].

Flexibility: WSNs are naturally dynamic. There are three main elements in WSNs, namely sensor nodes, sinks, and monitored event. Network topology may be dynamic. New nodes may join the network and existing ones may move through the network or come out of it. The sensed phenomenon can also be both dynamic and static according to the application. The routing protocol is called as flexible if it can maintain the network operations against the topology changes and pack loss in result of nodes and/or events mobility.

Node/Link heterogeneity: Heterogeneous nodes have the same capacity in terms of arithmetic operations, memory, sensing, communications, and also power. A non-heterogeneous set of sensors causes many technical aspects related to the data routing [40]. For example, in hierarchical protocols, cluster heads are designed differently to other sensors. Various data sensing can be defined in different ratios for sensors. It is also possible to consider different QoS limitations and data delivery models for them.

Table 1 shows reviewed intelligent-based routing algorithms. In this table, “Yes +” indicates that the article discusses about that characteristic and its impact on the algorithm based on simulations while “Yes-” indicates that the article only mention of it. Sign “-” indicates that the article is not talking about it.

Performance metrics of Table 2 can be more, for example, QoS-aware routing algorithms measure metrics such as reliability, jitter, packet loss and etc. But as mentioned, the listed parameters are those performance metrics that give us a full view of the algorithm behavior only if they have been assessed on a larger operational perspective. In this table, “Yes +” indicates that the metric has been evaluated in several operational areas and “Yes” indicates just a single field.

As mentioned, with regard to various challenges in WSNs, routing protocols are designed based on application. Various factors affect algorithm behavior such as application scenarios, node deployment, coverage, traffic patterns and etc. So an accurate and complete framework that includes all the necessary ad-hoc network parameters is needed to express simulation parameters. This is categorized into four classes: radio channel, topology, and application and simulation models, see Table 3.

Table.1
Discussed protocol characteristics

Computational Intelligent Paradigm		Neural Networks		Fuzzy Logic		Evolutionary	Swarm Intelligence		Reinforcement Learning		Learning Automata	
		SIR [50]	SOM [49]	CHEF [48]	FEAR [47]	GAEEC [46]	EEABR [45]	BS [5]	CLIQUE [44]	FROMS [43]	LAC [42]	LABER [41]
Main Characteristics	Structure-based(SB)|Structure-less(SL)	SB	SB	SB	SB	SB	SL	SB	SL	SL	SB	SL
	Single path(S)|Multi path(M)	S	S	S	S	S	M	M	S	S	S	S
	Reactive(R)|Proactive(P)|Hybrid(H)	P	P	P	P	P	P	R	R	H	H	R
	Next hop(N)|Source(S)| Hybrid(H)	N	N	N	N	N	N	S	N	N	N	N
	Flat(F)|Hierarchal(H)	F	H	H	F	H	F	F	H	F	H	F
	Data centric(DC)|Address centric(AC)	AC	AC	AC	AC	AC	AC	AC	DC	DC	DC	DC
	Distributed(D)|Centralized(C)	D	C	D	D	C	D	D	D	D	D	D
	Optimal(O)|QoS(QS)	QS	O	O	O	O	O	O	O	O	O	O
	Query-based(Q)|Event driven(E)|Hybrid(H)	E	E	E	E	E	E	E	E	E	E	E
	Loop free	-	-	-	-	-	Yes	Yes	-	-	-	-
Additional Characteristics	Fault-Tolerance	Yes +	No	No	Yes +	No	Yes -	Yes -	Yes -	Yes +	No	No
	Scalability	No	No	No	Yes +	Yes +	Yes +	Yes +	Yes +	Yes +	No	No
	Energy-awareness	Yes +	Yes +	Yes +	Yes -	Yes +	Yes +	Yes +	Yes +	No	Yes +	Yes +
	Data aggregation	No	Yes -	Yes -	No	No	No	No	Yes -	No	No	No
	Data security	No	No	No	No	No	No	No	No	No	No	No
	Flexibility	No	No	No	Yes -	No	Yes +	Yes +	Yes -	Yes +	No	No
	Node/Link heterogeneity	No	Yes -	No	No	No	No	No	No	No	No	No

Table.2
Reported performance metrics in the reviewed protocols

Performance Metrics	Reported intelligent-based routing algorithm metrics										
	SIR	SOM	CHEF	FEAR	GAEEC	EEABR	BS	CLIQUE	FROMS	LAC	LABER
Delivery Ratio	No	No	No	No	No	No	Yes+	Yes+	No	No	No
Latency	Yes+	No	No	Yes+	No	No	Yes+	No	No	No	No
Energy Consumption	Yes+	No	Yes-	Yes+	Yes-	Yes+	Yes+	Yes+	Yes+	Yes-	Yes-
Energy Efficiency	No	No	No	No	No	Yes+	Yes+	No	No	No	No
Control Packets Overhead	No	No	No	Yes+	No	No	Yes+	Yes+	Yes+	No	Yes-
Network Lifetime	Yes+	Yes-	Yes-	No	Yes+	No	Yes+	Yes+	No	Yes-	Yes-

Table.3
Fundamental simulation parameters

Model	Parameters	Reported simulation parameters										
		SIR	SOM	CHEF	FEAR	GAEEC	EEABR	BS	CLIQUE	FROMS	LAC	LABER
Radio Channel	Propagation function	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	No	Yes
	Link (Fading model)	No	No	No	Yes	No	No	Yes	No	No	No	No
	Radio channel model	No	No	No	No	No	No	Yes	Yes	No	No	No
	Probability of not modeled errors	No	No	No	No	No	No	Yes	No	No	No	No
	MAC layer model	No	No	No	IEEE 802.14.5	TDMA	No	CSMA	CSMA	CSMA	No	No
	Radio range	No	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes
	Packet length	No	Yes	Yes	No	No	No	Yes	No	No	No	No
	Initial nodes power	No	Yes	No	No	No	Yes	Yes	Yes	No	Yes	No
Topology	Nodes number	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Deployment	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Area	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Application	Application	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
	source & destination properties	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Simulation	Simulator name	OLIMPO	MATLAB*	MATLAB*	Java*	Java*	NS2	PROWLER	OMNET++	OMNET++	J-Sim	NS2
	Number of iterations	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No
	Time intervals of calculations	No	No	No	No	No	No	Yes	No	No	No	No
	Simulation time	No	Yes	No	No	No	No	Yes	No	Yes	No	No

*. These are named self-made simulators. They have no enough validate in scientific societies.

4. Conclusion

A complete evaluation framework is needed to evaluate WSNs routing algorithms in simulation-based studies. In addition, a comprehensive taxonomy is necessary to identify and classify routing algorithms, especially intelligent-based ones. It improves researcher's insight and analysis. It helps to select proper algorithms for comparison too. In order to improve the validity of these studies, a detailed fundamental simulation parameters framework is introduced. It is hoped that this paper can elevate the quality of the future researches in WSN fields.

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