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Recent Advances in Energy-Efficient Routing Protocols for Wireless Sensor Networks: A Review

JINGJING YAN[1,2], MENGCHU ZHOU[3,4], (Fellow, IEEE), AND ZHIJUN DING[1], (Senior Member, IEEE)
[1]Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China
[2]Department of Computer Engineering, Taizhou Vocational and Technical College, Zhejiang 318000, China
[3]Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA
[4]Renewable Energy Research Group, King Abdulaziz University, Jeddah, Saudi Arabia

Corresponding author: M. Zhou (zhou@njit.edu)

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ABSTRACT Due to a battery constraint in wireless sensor networks (WSNs), prolonging their lifetime is important. Energy-efficient routing techniques for WSNs play a great role in doing so. In this paper, we articulate this problem and classify current routing protocols for WSNs into two categories according to their orientation toward either homogeneous or heterogeneous WSNs. They are further classified into static and mobile ones. We give an overview of these protocols in each category by summarizing their characteristics, limitations, and applications. Finally, some open issues in energy-efficient routing protocol design for WSNs are indicated.

INDEX TERMS Wireless sensor networks (WSNs), energy-efficient routing protocol, internet of things.

I. INTRODUCTION

Advances in micro-electro-mechanical systems, wireless communication and distributed information processing technologies have enabled the rapid development and deployment of wireless sensor networks (WSNs) [1]. Their applications vary from military uses to environmental monitoring [2]. However, their nodes are normally equipped with energy-constrained batteries to meet size and cost constraints. Therefore, it is imperative to design energy-efficient protocols for them in order to prolong their lifetime.

Energy consumption of a sensor node has a significant impact on the lifetime of WSNs. The energy of a WSN can be saved by applying different techniques, such as duty-cycle scheduling [3], energy-efficient MAC (Medium Access Control) [4], energy-efficient routing [5], node replacement [6], energy harvesting [7], energy replenishment [8], and energy balance [9]. As shown in Fig. 1 [10], the communication needed by a typical sensor node is the biggest power consumer. Its wireless communication module has four states, *send, receive, idle and sleep*. Transmitting signals, i.e., sending and receiving, take about two thirds of its total energy consumption, while the number of transmitting data packets of a node depends to a great extent on a routing strategy. In other words, an efficient routing protocol can help balance the energy consumption levels among WSN nodes. Giving the same hardware conditions, it can help prolong the lifetime of WSN, as well as improve the quality of data transmission. However, traditional routing protocols tend to focus on how to make the data packets reach fastest their destination nodes with the shortest transmission path. They may not be the best from the viewpoint of WSN lifetime

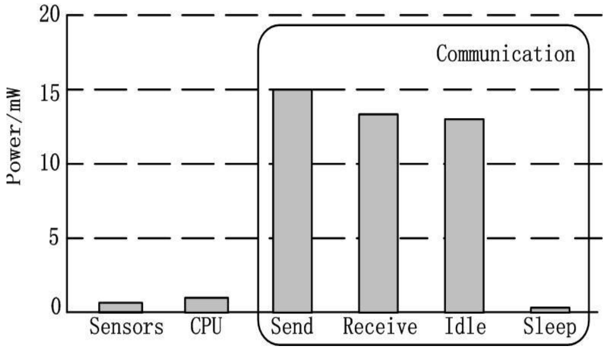

FIGURE 1. Energy consumption of a sensor node [10].

owing to energy-constrained sensor nodes. Furthermore, due to the energy consumption at the sleep and idle states are minimal in comparison with the others, researchers often consider the energy consumption of the sending and receiving states only.

Generally, the energy model is adopted from [11]. In this model, both free-space and multipath fading channel models are used, depending on the distance between a transmitter and receiver. When the distance is less than a threshold value d_0, the former is used; otherwise, the latter is used. Then to transmit an l-bit message for a distance d, the energy model is given as follows:

$$E_T(l, d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4 & d \geq d_0 \end{cases}$$

where E_{elec} represents the electronics energy, and $\varepsilon_{fs}d^2$ or $\varepsilon_{mp}d^4$, is the amplifier energy.

To receive an l-bit message, the energy is given as follows:

$$E_R(l) = lE_{elec}$$

Many routing protocols for WSNs have been proposed, and many surveys and introductory papers on routing protocols, e.g., [2], [12]–[14], are available in the literature. Their classification in [2] is extended in [14] which is comprehensive but not all the protocols described are energy-aware. Furthermore, each protocol involved in [14] also considers only one base station. The survey [2] divides WSN routing protocols into four classes known as *Network Structure*, *Communication Model*, *Topology Based* and *Reliable Routing Schemes*. The *Network Structure* class is subdivided into flat and hierarchical protocols. The *Communication Model* class has query, coherent and negotiation ones. *Topology Based* protocols are further classified into location and mobile agent ones. *Reliable Routing Schemes* refer to either multipath or QoS (Quality of Service) ones. The routing challenges and design issues in WSNs are given. The work [2] comprehensively introduces various routing protocols for WSNs. Yet it largely misses their performance results. The work [12] presents a survey with its focus on the scalability of routing protocols. It classifies them according to motivations such as control overhead reduction, energy consumption mitigation and energy balance. The work [13] gives an exhaustive overview of intelligent routing protocols. It first defines network lifetime in three aspects. Then, it categorizes the protocols based on such algorithms as reinforcement learning, ant colony optimization, fuzzy logic, genetic algorithm, and neural networks. It also highlights the performance analysis results and applications of each surveyed routing protocol.

However, in [2], [12], and [13], most routing protocols assume their sensors to be static. Consequently, sensors close to sinks tend to deplete their energy more quickly than the others and may cause "energy holes", also called "hot spots". Clearly, a routing protocol that cannot cope with mobility at all affect negatively the lifetime of WSNs—and a definition of network lifetime that does not explicitly account for mobility at all may likely yield false lifetime estimation. By introducing mobility in WSNs, mobile nodes can move to the sensors near sinks or isolated parts of the network and hence energy consumption in the nodes becomes even and connectivity is better maintained [15]–[17].

All the sensor nodes in homogeneous WSNs in [2], [12], and [13] are assumed to be of the same type, especially in their power supply, communication bandwidth, computation and storage capacity. Homogeneous WSNs may help researchers understand and analyze WSNs at the beginning, but with the expansion and in-depth research, they cannot meet the needs for practical applications. Their network model is too ideal and simple. In reality, heterogeneous WSNs are more common. In intelligent building monitoring applications, for example, there exist some nodes in monitoring air humidity and indoor temperature, and others in monitoring light intensity. These nodes have function heterogeneity. Moreover, their initial energy may be different due to different manufacturers or different batch production. Their computing power and link capacity may vary as well. Their sensing capability and transmission range may differ. Heterogeneous WSNs are those composed of different types of nodes to meet diverse application requirements [18]. Traditional routing protocols for homogeneous WSNs are not fit for heterogeneous ones. Hence, routing protocols for heterogeneous WSNs should be studied [19]–[21].

Table 1 provides a comparative summary of these prior surveys in terms of their shared and most recent cited references. From Table 1, we have:

i) The 2004 survey [14] presents a comprehensive survey of earlier routing protocols, but not all described are energy-efficient; [7] addresses various aspects of energy harvesting sensor systems; [12] exploits routing protocols designed for large-scale WSNs; [2] describes energy-efficient routing protocols; [15] classifies routing protocols based on different design criteria, and discusses the mobility including mobile sinks only, few mobile nodes act as mobile relays, all nodes mobile and few nodes are stationary; [1] gives an overview of WSNs from an industrial perspective; [12] discusses routing protocols based on intelligent algorithms; [16] considers only the routing protocols with mobile sinks; [20] focuses on hierarchical routing protocols for heterogeneous WSNs; and [21] categorizes various heterogeneous routing protocols for WSNs based upon various predefined parameters. Besides, routing characteristics of WSNs, such as energy-aware, cluster-based, mobility, scalability, homogeneity and heterogeneity are given in the above surveys. Note that, although an energy model plays an important role in the conservation of energy, it is not mentioned in the above surveys.

ii) This work aims to provide a new classification of WSN protocols and their discussions. The rationale behind our classification is to categorize routing protocols for homogeneous and heterogeneous WSNs together with static and mobile scenarios, with the common goal to increase energy efficiency while maintaining WSN functionality and performance. To the best of our knowledge, the work presented in this

TABLE 1. Comparisons between reference of survey and this work.

Survey pub. year	**Top two most commonly cited papers by these surveys**		**Protocols involved**							
	[14] 2004	**LEACH [22] 2000**	Energy awareness	Cluster -based	Mobility	Scalability	Homo-geneity	Hetero-geneity	Energy model	Other characteristic
[14] 2004	×	√	Not all	Not all	Not all	Not all	Not all	Not all	×	-
[7] 2011	×	√	√	Not all	-	-	-	×	×	Energy harvesting, not routing
[12] 2011	√	√	√	√	Not all	√	√	×	×	Large-scale
[2] 2013	√	√	√	Not all	√	Not all	√	×	×	-
[15] 2014	√	√	√	Not all	√	Not all	√	×	×	-
[1] 2014	×	√	Not all	Not all	×	Not all	√	Mentioned	×	Industrial
[13] 2014	√	Mentioned	√	Not all	Not all	Not all	√	×	×	Intelligent, applications
[16] 2014	√	√	√	Not all	√	Not all	√	×	×	Distributed
[20] 2014	×	Mentioned	√	√	×	Not all	×	√	×	-
[21] 2015	×	√	√	√	Not all	Not all	×	√	×	-
This work [2016]	√	√	√	Not all	Not all	Not all	Not all	Not all	√	Applications

paper is the first attempt at such a survey with the focus on the energy-efficient routing protocols in these distinct types of WSNs. Furthermore, this work aims to provide the state-of-the-art in the subject by including the recently developed techniques and proposals. In addition, this work gives application scopes of each protocol which were missing in the earlier surveys [2], [12], [14], [15], [17], [20].

iii) LEACH (Low Energy Adaptive Clustering Hierarchy) [22] is cited and studied by almost all the survey papers [1], [2], [7], [12]–[16], [20], [21]. This is because cluster-based routing is more energy-efficient, more scalable, and more secure as compared with traditional flat routing [14]. As the first cluster-based routing protocol, its basic idea is that all sensor nodes are grouped into several clusters. In each cluster, a lead node called cluster head (CH) whose duty is to gather data and transmit data to the base station (BS) is elected based on a predetermined probability. It works in two phases, namely, setup and steady phases. In the former, CH is elected by rotation and clusters are formed. In the latter, nodes sense and transmit data to the CH. Then the CH aggregates and sends data to the BS directly. Thus it is not suitable for large WSNs. The main limitation of this protocol is its random selection of CH, which may pick up a CH that has low energy and thus dies quickly. Therefore, many routing protocols proposed thereafter aim to make improvements on it. For example, HEED (Hybrid Energy-Efficient Distributed clustering approach) [23] takes residual energy and communication cost into consideration when selecting a CH. In contrast with LEACH, HEED uses multi-hop communications between CHs and the BS while LEACH uses single-hop communication. Moreover, HEED also provides guaranteed coverage of nodes in WSNs. However, it assumes that nodes can control their transmission power level. This is not always a realistic assumption.

The rest of the paper is organized as follows: Section II categorizes current routing protocols for WSNs into different classes according to whether WSNs are homogeneous or heterogeneous and static or mobile. Sections III and IV give a detailed analysis of currently representative routing protocols, with the objective to highlight the critical characteristics influencing routing protocol design and applications. A comparative summary of the current routing techniques is also provided. Finally, conclusions and open issues are discussed in Section V.

II. CLASSIFICATION OF ENERGY-EFFICIENT ROUTING PROTOCOLS IN WSNs

The network layer aims to realize the communication among sensors, and between sensors and observers, data routing and cooperative sensing. WSN routing protocols must be designed to meet the desired performance requirements in energy efficiency, scalability, robustness, and convergence.

Their main goal is to establish a reliable and energy-efficient path for WSN nodes, and achieve the longest lifetime for the entire WSN. Energy consumption in routing is caused by neighborhood discovery, communication and computation. We discuss the state-of-the-art representative routing protocols for WSNs. We summarize the methods for improving energy-efficient according to their motivation. The classification is shown in Fig. 2.

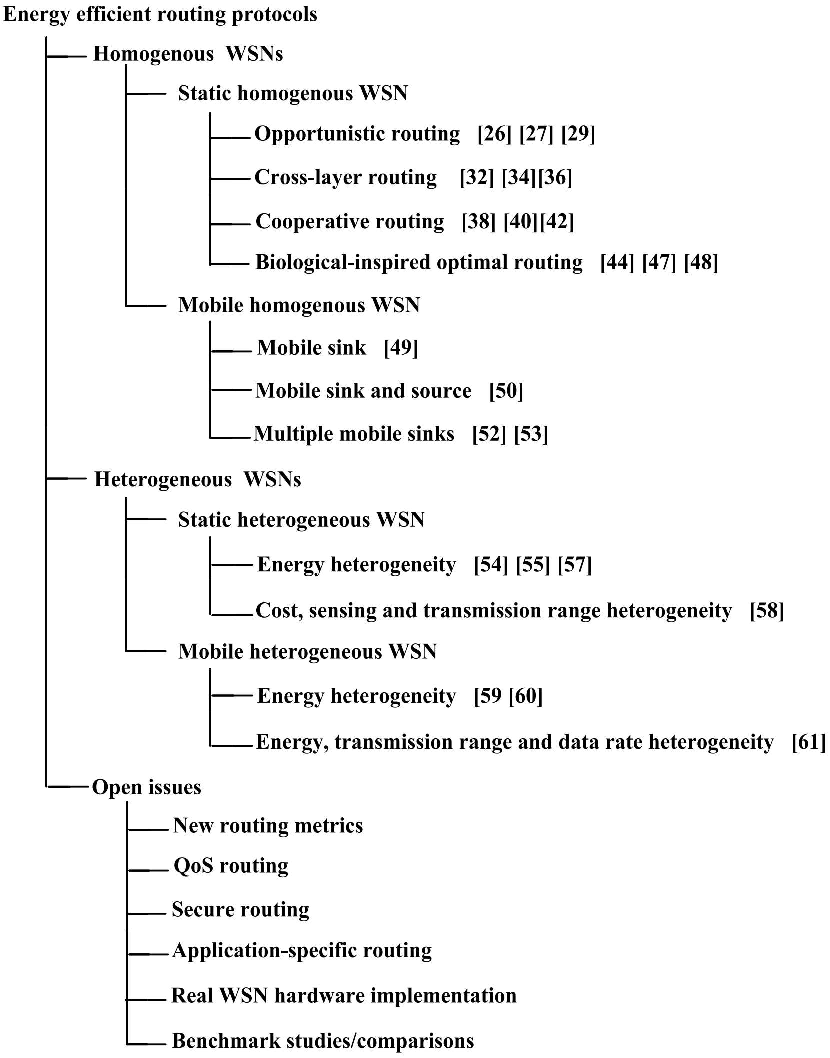

FIGURE 2. Classification and open issues of energy-efficient routing protocols.

Routing protocols for homogeneous WSN deal with identical nodes. Its energy-efficient routing protocols are proposed from different points of view. They can be subdivided into static and mobile ones. The former includes opportunistic, cross-layer, cooperative and biologically inspired optimal routing protocols depending on their protocol design and principles while the latter aims to deal with not only energy problems but also mobile scenarios. Mobile nodes can be sources and sinks.

Routing protocols for heterogeneous WSN aim to tackle heterogeneity as well as energy issues. According to [18], heterogeneity can triple the average delivery rate and provide a fivefold increase in network lifetime when properly deployed. The heterogeneity is reflected via energy, computation, network protocol and/or links.

Note that cluster-based routing is not classified as a class in Fig. 2 for the following two reasons. One is that such routing is widely used in both homogeneous and heterogeneous WSNs. The other is due to limited space. Thus, the characteristics of cluster-based routing are well described in static heterogeneous WSNs.

III. HOMOGENEOUS WSN

A. STATIC HOMOGENEOUS WSN

1) OPPORTUNISTIC ROUTING

Opportunistic routing [24] is proposed to solve unreliable link problems and reduce unnecessary retransmission. Thus it can improve not only transmission reliability, but also energy efficiency. It involves multiple forwarders to increase network communication throughput by taking advantage of the broadcast nature of wireless communication. An Extremely Opportunistic Routing (ExOR) protocol in [24] is the first such scheme. The MAC-independent Opportunistic Routing and Encoding protocol (MORE) [25] is its extension. MORE presents the first integration of opportunistic routing with intra-flow network coding to bypass the coordination issue previously resolved by an ExOR's highly structured scheduler. Although ExOR and MORE are the two early and famous opportunistic routing schemes, they do not take the energy consumption issue into consideration. Therefore, they are not further discussed in this paper.

EEOR: An Energy-Efficient Opportunistic Routing (EEOR) protocol is proposed in [26] with the aims to reduce energy cost in selecting and prioritizing a forwarder list under opportunistic routing and to increase the lifetime of a network. It is multipath routing. Its Expected Energy Cost (EEC) is studied as a primary metric instead of its Expected Transmission Count (ETX) in [24] and [25]. Then a forwarder list can be prioritized based on EEC. Since the smaller transmission power, the smaller energy consumed to transmit one packet of data received successfully by at least one node in a forwarder list, several algorithms are introduced to calculate the forwarder list and EEC. EEOR has two power models, nonadjustable and adjustable ones. Simulation results prove that EEOR is more efficient in terms of energy consumption, packet delivery, throughput, loss ratio and delay than ExOR. However, one component of EEC, namely the energy consumed for communication agreement, is not accurately computed. Furthermore, EEOR fits for unicast cases only.

E^2R: A simple but robust multipath routing protocol named energy efficient routing protocol (E^2R) is introduced in [27]. According to [27], in some opportunistic routing protocols, such as ExOR [24] and EEOR [26], pre-selecting a forwarding list beforehand can be unwise, especially for a very large network. E^2R introduces a forwarder self-selection scheme in a data delivery phase. Its key idea is to use a node's own route metric value to compare with that attached in its received data packets. If the former value is smaller than the latter's and the node does not overhear one of its neighbors with a better route metric during the node's back-off time interval, the node selects itself as a relay node. As a result, the less needed information of the node, the less decreased size of the data packet, which in turn consumes less energy during wireless transmission. Moreover, a greedy forwarding algorithm in a route metric discovery phase is proposed to further decrease the overhead of control messages. Simulation results show that E^2R achieves superior performance in terms of packet delivery ratio, control overhead, packet delivery delay and energy consumption over AODV (Ad-hoc On-demand Distance Vector) [28]. Note that E^2R can work in a mobile environment. It is thus well suitable for large scale WSNs.

K-S: Kaliszan and Stanczak [29] integrate opportunistic routing with network coding (we named this protocol as K-S for short) by considering the energy consumed to transmit one packet of data and receive it by another node. It prolongs network lifetime by avoiding duplicate transmissions without using a coordination mechanism as used by the prior protocols [26], [27]. Giving a fixed reception probability, a linear program is formulated and a low-complexity heuristic algorithm is designed to solve it. Simulation results indicate that K-S reduces energy up to 20% compared with MORE [25]. Because of the characteristic of network coding, this protocol can be applied to delay-tolerant applications. It is, however, not suited for the real-time application of WSNs.

Table 2 provides a comparative summary of the characteristics of opportunistic routing-based protocols discussed in this section.

2) CROSS-LAYER ROUTING

Because controllers at the network layers interact with each other, the parameters of each layer should be jointly decided to achieve the optimal network performance. Apart from a stringent layered protocol, cross-layer design that violates the principle of layered protocol and permits the interaction of non-adjacent layers has received much attention [30], [31]. It can realize flexible and intelligent management and control of WSNs so as to achieve high energy efficiency and extend the WSN lifetime.

JRPRA: It represents Joint Routing, Power control and Random access Algorithm (JRPRA) proposed by He *et al.* [32]. They have performed a joint optimal design of the physical, MAC and routing layers to maximize lifetime of a single-sink WSN with energy constraints. Given the link access probabilities, the problem can first be formulated as a convex optimization problem. A distributed algorithm, called Joint Routing and Power control Algorithm (JRPA), is then proposed. Its power control protocol and routing strategy protocol are regulated by a Lagrangian multiplier and work in physical and network layers, respectively. However, the link access probabilities are often not directly available in real networks. Thus, the problem is deteriorated into a non-convex problem. As a heuristic algorithm, JRPRA is then developed. Both JRPA and JRPRA try to minimize energy consumption

TABLE 2. **Comparison of the presented opportunistic routing-based protocols.**

Protocol	Forwarder list selection	Forwarder list generation by	Metrics	Coordination	Coding	Data communication	Application scope
EEOR [26]	Pre-selection	Source	EEC	ACK-based	No	Multipath	Unicast cases
E^2R [27]	Self-selection	Relay node	Compatible with all other metrics, e.g., ETX, hop count	Back-off time based	No	Multipath	Large scale WSN
K-S [29]	Pre-selection	Source	ETX	N/A	Yes	Singlepath/ Multipath	Delay-tolerant WSN

TABLE 3. Comparison of the presented cross-layer-based routing protocols.

Protocol	Assumptions	Cross-layer objection	Integrated technology	Relay selection	Congestion control	Application scope
JRPRA [32]	Lossless transmission	Physical, data link, and network layers	Correlated data gathering	Total rate of data flows	Yes	High- stability WSN
LMCRTA [34]	QoS requirement	Physical, data link, and network layers	Cooperative diversity	Channel state, and residual energy	No	High- quality-channel WSN
CLOD [36]	Fixed link capacity	Data link, network, and transport layers	Compressed sensing	Transmitted capacity	Yes	Lightly loaded WSN

of the nodes by adopting correlated data gathering technique that uses Slepian-Wolf coding [33]. JRPRA also increases the network lifetime by adjusting link capacity. Furthermore, it uses multipath routing in transmission according to the total rate of data flows over a link and selects the route by employing the Bellman-Ford shortest path algorithm. Simulation results show that JRPRA significantly improves the lifetime of WSN. Note that it maximizes the lifetime with the assumption of lossless transmission. Thus, it is suitable for the network of high stability since a network of low stability invalidates the assumption.

LMCRTA: A distributed algorithm called Lifetime Maximization Cooperative Routing with Truncated Automatic repeat request (LMCRTA) is presented in [34]. It combines together cooperative diversity at the physical layer, truncated automatic repeat request at the data link layer and distributed routing strategy at the network layer. It decreases the consumed energy and optimizes lifetime through the following ways: *i*) integrating cooperative diversity techniques [35] whose significance in saving energy and improving quality of a wireless channel is proved; *ii)* exploiting power allocation based on the average packet error rate and the average symbol error rate through two modulations, i.e., BPSK (Binary Phase-Shift Keying) and QPSK (Quadrature Phase-Shift Keying), and *iii)* choosing a cost-least routing path in terms of channel state and residual energy. It uses the residual energy information to balance the energy among all nodes to avoid any energy hole, thereby prolonging the WSN lifetime. Besides, it utilizes cyclic redundancy check appended behind the data information as the metric of judging the correctness of received signal instead of popularly used SNR (Signal Noise Ratio) threshold. Simulation results show that it is highly efficient in a high-quality channel network. However, it has some rooms for its improvement. For example, it is desired to evaluate the energy consumption associated with this switching process, although it enables sensor nodes in different states to avoid unnecessary energy waste. Since each node is equipped with one omnidirectional antenna, which sends signals in unnecessary transmission direction as well, extra energy consumption is caused, which may be avoided by using directional or smart antenna.

CLOD: The work [36] develops a robust and efficient Cross Layer Optimal Design (CLOD) that performs scheduling at the data link layer, routing at the network layer, and congestion control at the transport layer. It reduces energy mainly by congestion control. Node-level congestion at a transport layer is reduced through a compressed sensing technique that attributes to decreasing transmitted bits, while link-level congestion at the data link layer is reduced via proper resource allocation. Simulation results demonstrate that its computational complexity is greatly reduced and performs well under light load. Note that CLOD assumes that the link capacity is fixed.

Table 3 provides a comparative summary of the characteristics of cross-layer-based routing protocols discussed above.

3) COOPERATIVE ROUTING

Cooperative communication is able to mitigate channel fading, achieve high spectral efficiency and improve transmission capacity [37]. Strictly speaking, it is a part of cross-layer routing. It is developed from the traditional MIMO (Multiple-Input and Multiple-Output) techniques that can reduce the transmission power and extend the transmission coverage. Its basic idea is to allow multiple nodes to form a virtual MIMO system to share their antennas and resources, thereby gaining the advantage of space diversity in a multi-node scenario instead of equipping each node with multiple antennas.

RBCR: As an energy-efficient cooperative routing scheme with space diversity, Relay selection Based Cooperative Routing (RBCR) is established by considering the consumed energy as well as channel quality in [38]. It first models the problem based on the minimum cost path problem with relays [39] and formulates it as a multi-objective optimization problem. To solve it, RBCR uses a distributed algorithm based on two labeling algorithms aided by auxiliary matrixes that store labels with different metrics. It finds a single-node cooperative route by using channel state information of a node's two-hop neighborhood and consumed energy at each node. In such a route, each relay has one node only. In addition, nodes use a decode-and-forward strategy without cyclic redundancy check and transmit decoded information to a receiver node that combines its received signals to retrieve data. Simulation results show that energy efficiency is enhanced by not only utilizing the cooperative diversity available which can overcome rayleigh fading but also selecting the best paths in terms of channel state information and energy consumed. RBCR performs better under good-quality channels since non-cooperative transmission outperforms fixed relay cooperative transmission under poor-quality channels.

EBCR: An Energy-Balanced Cooperative Routing (EBCR) [40] along the underlying non-cooperative path is proposed to ensure high energy efficiency. Instead of requiring two-hop neighborhoods in RBCR, it introduces and uses only one hop neighborhoods. It determines the optimal relaying set and utilizes a multiple-relay strategy. The selected multiple neighboring nodes act as multiple transmitting and receiving antennas. The protocol provides higher throughput and similar delay performance compared with the traditional single-relay strategy and single receiving diversity routing methods [41]. However, EBCR is not taking the fading problem into consideration, thereby yielding relatively high bit error rate. It is suitable for applications in which network reliability is not essential, namely a network with low SNR.

mp-MILP: The minimum energy cooperative routing problem is formulated as a Multi-Parametric Mixed-Integer Linear Program (mp-MILP) to determine the optimal relay selection and power allocation while meeting an SNR constraint [42]. Unlike RBCR and EBCR, instead of multiple hops, the scope of cooperative relay depends on Euclidean distance among nodes to decide next nodes. Similar to EBCR, it involves multiple neighboring relays. Another feature in the systematic determination of the optimal relaying set is that the transmission power of each node is adjusted and cooperative nodes with the smallest possible total transmission power are selected. Since mp-MILP aims to minimize the total transmission power, the uneven energy consumption among nodes and much shorter network lifetime than EBCR's may result. Note that, to obtain a low complexity implementation, mp-MILP is solved off-line by using multi-parametric programming theory. A modulation scheme is used to solve the fading problem. Simulations show that mp-MILP achieves superior performance in terms of both power consumption and bit error rate. Such a framework is well suitable for networks requiring high reliability.

Table 4 provides a comparative summary of the characteristics of cooperative routing-based protocols discussed above.

4) BIOLOGICALLY INSPIRED OPTIMAL ROUTING

Biologically inspired principles have led to various technological innovations in different fields of research [43]. Their applications to routing sensor networks are represented by the following protocols.

BIOSARP: A Biologically Inspired self-Organized Secure Autonomous Routing Protocol (BIOSARP) [44] is proposed. It is based on ant colony optimization whose results heavily depend on how efficiently the pheromone is handled. It employs two types of ants: forward and backward ones. It makes improvement in terms of probability choice formula and pheromone factor renewing ways. It uses end-to-end delay, remaining battery power, and link quality as heuristic factors and applies them to the ant pheromone value/probability formula. Therefore, it provides not only minimum delay and high energy efficiency, but also low packet loss. In addition, its data communication is many-to-one. It is tested through NS-2 simulator and the results obtained for different mobility scenarios are compared with protocols like secure real-time load distribution routing [45] and improved energy efficient ant-based routing [46]. The results through real testbed experimentation are also obtained. They verify that BIOSARP not only outperforms the mentioned ones [45], [46] in terms of routing load and energy consumption, but also works well in real environment. It is suitable for event-driven applications.

BeeSensor: Different from BIOSARP, BeeSensor [47] is inspired by the honey-bee colony. It is composed of four types of agents: packers, scouts, foragers and swarms. Its main operators include scouting, foraging, swarming and routing loops and path maintenance. Its high energy efficiency is achieved by decreasing route-discovery overhead. It is more applicable for monitoring applications that require frequent data transfer since a bee's communication skill is better than an ant. Simulations show that BeeSensor achieves superior performance in terms of both power consumption and packet-delivery ratio than AODV [28].

Bee-Sensor-C: An enhanced version of BeeSensor called Bee-Sensor-C [48] where C stands for "cluster" further extends the network lifetime by reducing energy consumption through a dynamic clustering scheme and balancing energy through a multipath construction method. Besides, compared with BeeSensor, it adds a new agent called HiveHeader whose major role is to claim that it wants to be selected as a cluster head when it detects an event. Furthermore, a free-space energy model is used in Bee-Sensor-C when sending or receiving a one-bit message. Note that, the data communication of both BeeSensor and Bee-Sensor-C is through multi-paths. Through simulation, it is shown to not only increase the network lifetime but also enhance other performance metrics

TABLE 4. Comparison of the presented cooperative routing-based protocols.

Protocol	Cooperative strategy	Scope of cooperative Relay	Relaying node count	Relay selection	On-line computation	Optimal	Application Scope
RBCR [38]	Fixed	Two-hop	One	Channel state, energy consumption	Yes	No	Good channel quality WSN
EBCR [40]	Adaptive	One-hop	Multiple	Residual energy	Yes	Yes	Low-SNR WSN
mp-MILP [42]	Adaptive	Euclidean distance	Multiple	Transmission power	Off-line	Yes	High-reliability WSN

TABLE 5. Comparison of the presented biologically inspired optimization routing protocols.

Protocol	Inspiring insect	Members/agents	Data communication	Congestion control	Implementation	Application scope
BIOSARP [44]	Ant	Forward ants and backward ants	Many to one	Yes	Simulation, and real environment	Event-driven applications
BeeSensor [47]	Bee	Packers, scouts, foragers and swarms	Multipath	Yes	Simulation	WSN with periodic data transferring
Bee-Sensor-C [48]	Bee	Packers, scouts, foragers, swarms and HiveHeader	Multipath	Yes	Simulation	Large scale WSN

like packet delivery rate and scalability as compared with BeeSensor.

Table 5 provides a comparative summary of the characteristics of biologically inspired optimization routing protocols discussed in this section.

5) DISCUSSION

As mentioned above, traditional routing protocols assume static and homogeneous WSNs. Opportunistic, cross-layer, cooperative and biologically inspired optimal routings are used to achieve high energy efficiency and network performance. Opportunistic routing is proposed to deal with unreliable link problems and reduce unnecessary retransmission. The idea of cross-layer routing is straightforward. But its main drawback is its high computation complexity, which may be too heavy for most sensor devices. The main advantage of cooperative routing is that it is robust and can achieve high network throughput. It is clear that reducing the size of a forward list of opportunistic routing or the scope of cooperative relay can decrease communication overhead and energy consumption, so as to achieve the purpose of prolonging the network lifetime. Biologically inspired optimal routing is more suitable to large scale WSNs. However, it faces the difficulty to achieve global optimal results. Note that, protocols in this class do not assume any special energy models, except JRPRA [32] and Bee-Sensor-C [48]. JRPRA describes the energy model in sending and receiving states, but does not give more details to explain how to compute the energy consumption, while Bee-Sensor-C only describes the free-space energy model in sending or receiving one bit message.

B. MOBILE HOMOGENEOUS WSN

1) MOBILE SINK

Termite-Hill: Termite-hill [49] is proposed to balance the energy consumption among sensor nodes of WSNs to avoid the emergence of any energy holes. Its idea is to adopt one mobile sink that can move without constraints. It can avoid energy holes caused by the excessive energy consumption at those nodes near sinks in a static WSN. Termite-hill is an intelligent algorithm, inspired by the behaviors of termites. To evaluate its performance, it is simulated in static and mobile sink scenarios, and implemented on real WSN hardware. The results show that it can achieve higher throughput, success rate and energy efficiency as compared with AODV [28] in mobile sink scenario with varying speed. It can improve network lifetime lightly over a static sink approach.

2) MOBILE SINK AND SOURCE

TARS: It represents Trace-Announcing Routing Scheme. Unlike [49], Chi and Chang [50] focus on some applications that need the support of both mobile sinks and targets. Since both can move freely in the network, a virtual-grid-based routing scheme called Trace-Announcing Routing Scheme (TARS) is designed. It is an extension to the tracking-assisted routing scheme for WSNs [51]. Its key idea is to capture the mobile objects' moving path by broadcasting a Trace-Announcing packet rather than re-constructing a routing path. To this end, TARS maintains both routing and tracking information tables. Besides, a lightweight shortcutting scheme and time-scheduling radio method are proposed to optimize a routing path in terms of energy consumption.

3) MULTIPLE MOBILE SINKS

MobiCluster: As an energy-efficient distributed clustering protocol with a path predicable mobile sinks, MobiCluster is introduced in [52]. It is proposed to deal with the isolated ‘‘sensor islands’’ where mobile nodes cannot move through. Its cluster heads need only communicate with so-called ‘‘rendezvous nodes’’ which are located near a mobile sink's trajectory, and they take turns in communicating with the latter. Its operations have five phases: *i*) clustering, *ii*) rendezvous node selection, *iii*) cluster head attachment to rendezvous nodes, *iv*) data aggregation and forwarding to the rendezvous nodes, and *v*) communication between rendezvous nodes and mobile sinks. A clustering algorithm is introduced to optimally control the cluster size in terms of the distance between a cluster head and mobile sink. The larger distance, the bigger cluster size. By this way, energy consumption among static nodes can be balanced. An algorithm is also given to select rendezvous nodes, such that packet collision and energy consumption are reduced while data throughput is increased. To further prolong WSN lifetime, cluster heads or rendezvous nodes can be replaced on demand when their energy level is low. This protocol assumes that the trajectories of mobile sinks are fixed.

W-L: Wang *et al.* [53] propose an energy-efficient distance-aware routing algorithm with multiple mobile sinks (we name it as W-L). To reduce energy consumption, it uses the first radio energy model to adjust transmission power

TABLE 6. Comparison of the presented routing protocols for mobile homogeneous WSN.

Protocol	Mobile elements	Moving trajectory	Solution methods	Speed considered	Application scope
Termite-hill [49]	Sink	Random	Intelligent algorithm	Yes	WSN with one mobile sink
TARS [50]	Sinks and targets	Random	Virtual-grid-based routing scheme	Yes	Location aware WSN
MobiCluster [52]	Sinks	Fixed	Clustering based	No	WSN with fixed trajectories of mobile sinks
W-L [53]	Sinks	To a rectangle boundary	Distance aware	No	Distance aware WSN

according to distance. When transmission power decreases, the risk of interference decreases. A relay node with a shorter distance to mobile sinks and with enough energy is selected to use. Unlike other protocols, its mobile sinks can only gather data at certain positions called parking positions by moving along the boundary of a rectangle. Mobile sinks cannot collect data when they are moving. In contrast to the selection of the number and positions of rendezvous nodes in MobiCluster, W-L determines the number and parking positions of mobile sinks. The simulation results show that WSN lifetime increases with the number of mobile sinks. Note that the number of mobile sinks is always proportional to cost.

Table 6 provides a comparative summary of the characteristics of routing protocols for mobile homogeneous WSNs discussed in this section.

4) DISCUSSION

Routing techniques in this class can deal with not only a hot spot problem but also sparse and disconnected WSNs. The mobility makes the signal transmission distance shorter to save energy. It makes the energy consumption among nodes easily balanced. The major advantage of these protocols is flexibility and scalability.

However, a possible side effect brought by this mobility is an increase in packet loss rate due to topology changes and increased data latency. Besides, since the cost of mobile sinks is much higher as compared to static nodes, the adoption of all mobile sensors is unlikely. The performance of a WSN using multiple mobile sinks is superior to that using a single one if the cost is not a major issue. Otherwise, choosing an optimal number of mobile sinks becomes an important problem to be answered. The trajectory of mobile nodes has a great influence on a sensor network topology and thus on the routing performance. MobiCluster and W-L adopt a fixed trajectory, which is simple and convenient. But in this way, energy consumption of nodes near the sink is relatively large, which cannot fundamentally solve the problem of uneven energy consumption among nodes. Since their sinks move without constraints, Termite-hill and TARS can select a path in real time according to a network condition. They are more flexible, but their implementation is more complicated and may meet more uncertainty. In a large network with a limited moving speed of mobile nodes, the contradiction between the speed of mobile nodes and the requirements for data collection is critical. More work is required to design reliable and real-time routing protocols that can be effective in energy conservation while providing delay-guaranteed services. Note that, protocols in this class do not assume any special energy models, except W-L [53]. W-L uses the same energy model as that in [11].

IV. HETEROGENEOUS WSN

A. STATIC HETEROGENEOUS WSN

1) ENERGY HETEROGENEITY

ECDC: An Energy and Coverage-aware Distributed Clustering protocol (ECDC) [54] for area coverage and point coverage in heterogeneous WSNs and aims at prolonging the lifetime of WSNs. ECDC divides its sensor nodes into three types, i.e., cluster head, cluster member and plain node in terms of their energy. Its obvious advantage is that it elects a CH based on residual energy and coverage. Due to this, its cluster sizes are even. In addition, its lifetime is defined from the initial time to the time when more than 30% of nodes are not alive. Compared with LEACH [22] and HEED [23], simulation results show that it can gain less energy consumption and better coverage performance. It is applicable to WSNs whether nodes deployed uniformly or not.

EEMHR: An Energy-Efficient Multilevel Heterogeneous Routing (EEMHR) protocol [55] aims at saving energy by partitioning all nodes into k level normal nodes and k level advanced nodes where k represents the level of energy. The bigger k, the higher energy level. First, all nodes are divided into two categories as level-1 normal nodes and level-1 advanced nodes. Then the latter are further divided into two categories as level-2 normal nodes and level-2 advanced nodes and so on. At end, level k-1 nodes are composed of level k normal nodes and level k advanced nodes. Since the level k advanced nodes have the highest energy, they become cluster heads, and thus may cause an "energy hole". EEMHR uses weighted election probabilities to elect cluster heads to avoid such holes. It is evaluated on experiments that involve five different lifetime definitions with respect to the ratio of alive nodes, three different network sizes and two different initial energy level. Simulation results show that EEMHR is superior to other existing heterogeneous routing protocols, like multi-hop communication routing [56], in terms of lifetime, stability and the number of cluster heads per round.

LE-MHR: Tyagi et al. present a Lifetime Extended Multi-levels Heterogeneous Routing (LE-MHR) protocol [57] to enhance EEMHR. First, they indicate the latter's disadvantage by proving that an enhancement of initial energy of a network may not guarantee an enhancement of initial energy for higher level nodes in comparison with the lower level nodes, and the number of higher level nodes depend only on lower level nodes in EEMHR. Then, they select k levels of horizontal energy heterogeneity, where each level has a different amount of initial energy so as to enhance the overall initial energy of a network, rather than use k levels of vertical energy heterogeneity in EEMHR. Simulation results show that LE-MHR almost doubles the lifetime of a network with EEMHR.

2) COST, SENSING AND TRANSMISSION RANGE HETEROGENEITY

CSLRP: To address three major issues in the design of sensor networks: sensor deployment or sensing area coverage, sink location, and data routing, the work [58] characterizes the integrated Coverage, Sink Location and Routing Problem (CSLRP) in heterogeneous WSNs. All sensors are divided into K types, where K denotes the set of sensor types with different deployment cost. Each type also has a different sensing and transmission range. Two mixed-integer linear programs are designed. One is to consider the total routing energy consumption on the arcs. The other aims to minimize the total routing energy that consists of the sensor-to-sink assignment. The simulation results show that CSLRP is only applicable to a small-size network with its total node count not exceeding 49. To tackle such complexity issue, it is reduced to the classical p-median problem by giving the sensor location and then tabu search is adopted to solve it. Coverage threshold is also considered as additional QoS metric.

3) DISCUSSION

As discussed above, well-designed routing proposed for heterogeneous WSN can effectively prolong the network lifetime, improve network reliability and meet diverse application requirements. Most existing ones are based on a cluster topology, while they differ in their cluster head selection. Besides energy, the WSN heterogeneity is also manifested in computational capability, network protocols and links, which are related to energy. The future work has to deal with more diverse heterogeneity.

Table 7 provides a comparative summary of the characteristics of routing protocols for static heterogeneous WSN as discussed above with respect to different parameters. Note that, protocols in this class do not assume any special energy models, except EEMHR [55] and LE-MHR [57]. They use the same energy model as that in [11]. Moreover, cluster-based routing protocols, like those in [54], [55], and [57], all use single-hop intra-cluster routing methods and multiple-hop inter-cluster routing ones to achieve more energy.

B. MOBILE HETEROGENEOUS WSN

1) ENERGY HETEROGENEITY

HARP: A Hierarchical Adaptive and reliable Routing Protocol (HARP) [59] partitions the nodes into two types only, normal nodes and cluster nodes according to their residual energy capacities. Next, cluster head selection is performed based on the residual energy of nodes. Its main idea is to build a hierarchical tree in two layers: intra-cluster and inter-cluster. The former builds a hierarchical tree among normal nodes with their cluster head as a root while the latter among cluster heads with the sink as a root. Moreover, HARP introduces a local recovery mechanism and mobility management to rebuild trees when link failures occur. Simulation results show that HARP can achieve more efficient, reliable and scalable performances than LEACH.

RAHMoN: A Routing Algorithm for Heterogeneous Mobile Network (RAHMoN) [60] divides all sensors into static and mobile ones, while the energy of the former is less than the latter's. The latter can be cluster heads or sink nodes, with different mobility models. Its operations are composed of three phases: *i*) network configuration, *ii*) detection and election of cluster-heads and *iii*) delivery of data to a sink.

TABLE 7. Comparison of the presented routing protocols for static heterogeneous WSN.

Protocol	Heterogeneity	Node types	Lifetime definition	Cluster head selection	Uniformity of cluster sizes	Intra-clustering routing	Inter-clustering routing	Application scope
ECDC [54]	Energy	Cluster head, cluster member, and plain node	Till 30+% of nodes are not alive	Residual energy and coverage	Even	Single-hop	Multiple-hop	Whether nodes deployed uniformly or not
EEMHR [55]	Energy	level-k energy	FND, QND, HNA, QNA and LNA	Weighted election probabilities	Uneven	Single-hop	Multiple-hop	Vertical energy heterogeneity
LE-MHR [57]	Energy	Normal, and level-k energy	FND, QNA and LNA	Weighted election probabilities	Uneven	Single-hop	Multiple-hop	Horizontal energy heterogeneity
CSLRP [58]	Cost, sensing and transmission range	K types: grouped by a deployment cost	WSN is disconnected	N/A	N/A	N/A	N/A	Nodes with varying cost, sensing and transmission

FND-First Node Dies, QND-Quarter Nodes Dies, HNA-Half Nodes Alive, QNA-Quarter Nodes Alive and LNA-Last Node Alive

TABLE 8. Comparison of the presented routing protocols for mobile heterogeneous WSN.

Protocol	Heterogeneity	Node types	Mobile elements	Cluster head selection	Data transmission	Application scope
HARP [59]	Energy	Cluster head and normal nodes	Sinks	Residual energy	Multi-hop	Reliable WSN
RAHMoN [60]	Energy	Mobile and static nodes	Cluster heads and sinks	Mobility level, energy and distance to the sink	Multi-hop	Hydropower plant
HSN [61]	Energy, transmission range and data rate	L-nodes, H-nodes, and sink	Sink	Predetermined	Single-hop	Large scale WSN

It assumes that all sensors can be elected as a cluster head. The selection of a cluster head depends on mobility level, energy and distance to the sink. The results indicate that it is efficient with respect to overhead messages and transmitted data packets.

2) ENERGY, TRANSMISSION RANGE AND DATA RATE HETEROGENEITY

HSN: A clustered Heterogeneous Sensor Network called HSN [61] is proposed with a mobile sink. The nodes in the network are divided into three categories according to their energy: H-nodes (high energy level), L-nodes (low energy level) and the sink with unlimited energy. H-nodes provide a longer transmission range and higher data rate than L-nodes. Compared with HARP and RAHMoN, its cluster head is fixed and provides a single hop data transmission. It uses particle swarm optimization to optimize the sink's moving trajectory among cluster heads. It is thus applicable to large-scale WSNs. The simulation results show that it is more energy-efficient than WSNs with a static sink. They also verify that the loss of data occurs when the speed of the mobile sink increases.

3) DISCUSSION

Similar to routing protocols for homogeneous WSN, introducing mobile nodes to heterogeneous WSN can avoid energy holes, achieve high energy efficiency and balance energy consumption among nodes. Table 8 provides a comparative summary of the characteristics of routing protocols for mobile heterogeneous WSN as discussed above with respect to different parameters. Note that, protocols in this class do not assume any special energy models, except HSN [61]. HSN uses the same energy model as that in [11].

V. CONCLUSIONS AND OPEN ISSUES

In this paper, we have surveyed the main routing protocols to realize energy-efficient routing for WSNs. We categorize them into homogeneous WSNs and heterogeneous ones, each of which can be further divided into static or mobile ones. We also highlight critical characteristics influencing routing protocol design and applications, and give a comparative summary of the current routing protocols in each class.

Routing protocols for homogeneous WSNs are more widely investigated than heterogeneous ones. More studies of the latter are foreseen in order to meet diverse application requirements. As compared with static WSN's, routing protocols for mobile WSNs promise to bring more benefits to real-time delivery guarantee as well as high coverage, energy efficiency and energy balance but require high implementation and deployment cost.

According to the discussion of their characteristics in different WSNs, we conclude this paper with the following open issues.

New Routing Metrics: Creating and using a reliable routing metric is important in routing design. It should measure routing overhead and routing capability from different aspects due to the diversity of WSNs. New routing metrics such as spatial reusability [62] should be taken into consideration in order to increase the network throughput performance with affordable energy overhead. For heterogeneous WSN, besides energy heterogeneity, link heterogeneity is also important and requires further study.

QoS Routing: Many existing QoS routing protocols are restricted into some particular applications and only take one or two QoS metrics. They tend to lose the balance between QoS guarantee and energy efficiency. In this regard, energy efficient routing with QoS guarantee in different applications or diverse WSNs can be viewed as an interesting area for future investigation [63].

Secure Routing: In WSNs, each node acts as both perceived role and a router and thus makes itself vulnerable to attack. Hence, secure routing [64], [65] is an important issue that needs further attention. Clearly a security mechanism incurs additional energy cost. Designers must make a proper tradeoff between security levels and energy consumption for different applications.

Application-Specific Routing: Since the application of WSN is wide, the process of routing implementation varies significantly from one WSN to another. Thus, application-specific routing protocols are needed for such situations as vehicles, underwater, space, volcanoes, exploration, epidemic, human body, water and oil pipelines, microgrid, system monitoring and diagnosis, and robots [66]–[77]. Their applications in Internet of Things and body sensor networks [78]–[82] should be actively sought.

WSN Hardware Implementation: To evaluate the performance of proposed protocols, simulation platform or software can be TinyOS [26], [44], NS-2 [27], [36], [44], [61], OPNET [38], Java [48], J-Sim [50], MATLAB [53]–[55], [57], [59], CPLEX [58], Berkeley mote platform [47], SiNAlgo [60], and so on. More implementations should be realized not only in simulations, but also on real WSN hardware as shown in [44] and [49].

Benchmark Studies/Comparisons: Almost every protocol proposed claims to be better than the earlier ones in energy efficiency. However, comparing with each other, i.e., especially those in [49], [50], [53], [54], [57], and [58], is missing. There is a strong need to create some benchmark problems to facilitate their comparisons by simulation and hardware implementations.

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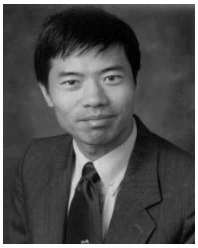
JINGJING YAN received the B.S. degree from the Shandong University of Science and Technology, Qingdao, China, in 1999, and the M.S. degree from Tianjin University, Tianjin, China, in 2006. She is currently pursuing the Ph.D. degree with the Department of Computer Science and Technology, Tongji University, Shanghai, China. She is also a Lecturer with Taizhou Vocational and Technical College, Zhejiang, China. Her current research interests include wireless sensor networks and design optimization.



MENGCHU ZHOU (S'88–M'90–SM'93–F'03) received the B.S. degree in control engineering from the Nanjing University of Science and Technology, Nanjing, China, in 1983, the M.S. degree in automatic control from the Beijing Institute of Technology, Beijing, China, in 1986, and the Ph.D. degree in computer and systems engineering from the Rensselaer Polytechnic Institute, Troy, NY, in 1990. He joined the New Jersey Institute of Technology, Newark, NJ, in 1990, where he is currently a Distinguished Professor of Electrical and Computer Engineering. His research interests include Petri nets, Internet of Things, big data, web services, manufacturing, transportation, and energy systems. He has authored over 680 publications, including 12 books, over 360 journal papers (over 260 in IEEE Transactions), and 28 book-chapters. He is the Founding Editor of the IEEE Press Book Series on Systems Science and Engineering. He is a recipient of the Humboldt Research Award for U.S. Senior Scientists, the Franklin V. Taylor Memorial Award and the Norbert Wiener Award from the IEEE Systems, Man and Cybernetics Society. He is a Life Member of Chinese Association for Science and Technology, USA and served as its President in 1999. He is a Fellow of the International Federation of Automatic Control and American Association for the Advancement of Science.

ZHIJUN DING received the M.S. degree from the Shandong University of Science and Technology, Qingdao, China, and the Ph.D. degree from Tongji University, Shanghai, China, in 2001 and 2007, respectively.

He is currently a Professor with the Department of Computer Science and Technology, Tongji University. His current research interests include formal engineering, Petri nets, services computing, and workflows. He has authored over 50 papers in journals and conference proceedings.

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