Wireless Netw
DOI 10.1007/s11276-015-1150-6

Energy harvesting and battery power based routing in wireless sensor networks

Mohammad Hossein Anisi[1] · Gaddafi Abdul-Salaam[2,3] · Mohd. Yamani Idna Idris[1] · Ainuddin Wahid Abdul Wahab[1] · Ismail Ahmedy[1]

Abstract Wireless sensor networks (WSNs) are a collection of several small and inexpensive battery-powered nodes, commonly used to monitor regions of interests and to collect data from the environment. Several issues exist in routing data packets through WSN, but the most crucial problem is energy. There are a number of routing approaches in WSNs that address the issue of energy by the use of different energy-efficient methods. This paper, presents a brief summary of routing and related issues in WSNs. The most recent energy-efficient data routing approaches are reviewed and categorized based on their aims and methodologies. The traditional battery based energy sources for sensor nodes and the conventional energy harvesting mechanisms that are widely used to in energy replenishment in WSN are reviewed. Then a new emerging energy harvesting technology that uses piezoelectric nanogenerators to supply power to nanosensor; the type of sensors that cannot be charged by conventional energy harvesters are explained. The energy consumption reduction routing strategies in WSN are also discussed. Furthermore, comparisons of the variety of energy harvesting mechanisms and battery power routing protocols that have been discussed are presented, eliciting their advantages, disadvantages and their specific feature. Finally, a highlight of the challenges and future works in this research domain is presented.

Keywords Energy harvesting · Battery power · Routing · Piezoelectric nanogenerators · Sensor nodes

✉ Mohammad Hossein Anisi
anisii@gmail.com; anisi@um.edu.my

Gaddafi Abdul-Salaam
agaddafi2@live.utm.my

1 Department of Computer Systems and Technology, Faculty of Computer Science and Information Technology, University of Malaya, 50603 Kuala Lumpur, Malaysia

2 Department of Computer Science, Faculty of Computing, Universiti Teknologi Malaysia (UTM), 81310 Johor Baharu, Johor, Malaysia

3 University Information Technology Services, Vice Chancellor's Office, Kwame Nkrumah University of Science and Technology (KNUST), PMB, University Post Office, Kumasi, Ghana

1 Introduction

Wireless sensor networks (WSNs) comprises of wireless networks of tiny devices that are equipped with sensors, and it is used to monitor physical conditions. They have been suggested for many applications such as medicine, military, smart cities, and environmental monitoring. In such applications, several small sensor nodes are deployed in the region of interest to monitor, detect and collect required phenomena, which they transmit to a base station (BS) [80, 90, 106]. WSN belongs to the category of ad hoc networks and therefore, has the same challenges of ad hoc networks. However, it has additional specific challenges that include small memory, throughput, routing, connectivity, security, synchronization and localization [30, 92, 112]. The primary aim in WSN is the collection of data from the environment. However, due to resource constraint, transmitting the gathered data by the sensor nodes to the BS requires an efficient solution.

In fact, routing plays the main role in WSNs applications. For instance, in health monitoring, biological wireless sensors can be used to monitor patients' body [87]. In such applications, patient's data must be routed reliably and in a certain period; otherwise, they are not useful [15].

Published online: 15 December 2015

In military applications, required information about enemy tracking, battlefield surveillance or target classification needs to be perfectly routed back toward the BS. Furthermore, WSN is used to help rescue teams in case of natural disasters, by way of finding people buried in avalanches [81, 95]. Again, successful routing of information towards the rescuers is necessary. In civil infrastructure, it is used to monitor and detect cracks, structural defects, and fire outbreaks. Such applications necessitate energy-efficient and real-time routing solution [102]. Consequently, routing is an important technical problem in WSNs and should be carefully considered.

The challenges of routing in WSNs are due to some characteristics that separate it from the other communication in wireless ad-hoc networks [21, 38, 61]. Dense deployment of several sensor nodes and a high predisposition to failure, due to limited energy supply, are some of the challenges. In designing a routing approach, several technical challenges should be taken into consideration [9, 45]. However, based on the energy-constrained nature of WSNs [96] and the direct impact of energy on network lifetime, energy consumption becomes the most important routing challenge [26, 35, 43, 66, 71, 104]. Usually, the deployment of sensor nodes is carried out once and expected to operate for a long period. Hence, during a routing process, it is important for energy supply to the nodes to be sufficient [67, 108]. This will sustain the nodes to operate over a long term to carry out the transmission and routing of packets. In addition to saving residual energy of nodes, balancing energy consumption among sensor nodes also reduces energy consumption. Therefore, finding and selecting the optimal paths is essential.

In this paper, after a brief summary of routing and related issues in WSNs, the most recent energy-efficient data routing approaches are categorized and reviewed based on their aims and methodologies. We discuss the traditional battery based energy sources for sensor nodes and the conventional energy harvesting mechanisms that are widely used to replenish energy of nodes in WSN. We also present an emerging energy harvesting technology that uses piezoelectric nanogenerators to supply power to nanosensor; the type of sensors that cannot be charged by conventional energy harvesters. Again, we explain in details, the energy consumption reduction routing strategies in WSN. Then we compare the variety of energy harvesting mechanisms and battery power routing protocols that have been discussed, eliciting their advantages, disadvantages and their specific features. Finally, we highlight on the challenges and future works in this research domain.

The rest of this paper is organized as follows. Section 2 introduces energy-efficient routing in WSN. Section 3 presents details of energy harvesting mechanisms for WSN. Section 4 discusses details of battery power based routing approaches. Section 5 compares and discusses the variety of energy harvesting mechanisms studied. Finally, Sect. 6 concludes and discusses future works.

2 Energy-efficient routing in WSNs

There are several challenges that must be considered in designing a routing protocol in WSN. These include: ad hoc deployment [52, 76, 122], energy consumption [27, 30, 32, 54, 55, 130], computation capabilities, communication range, fault tolerance [14, 17, 50, 60, 65, 94, 109], scalability [40, 107], hardware constraints [19], transmission media [41, 111], connectivity [57, 132] and quality of service (QoS) [36, 37, 86]. Among these challenges, the limited lifespan of the sensor node creates a strong dependence on the battery lifetime, energy consumption is therefore, considered the most important challenge of routing in WSNs.

Any routing mechanism that exhausts the energy supply of the nodes will result in serious problems. The malfunction of certain nodes due to power failure can affect the accuracy of the results or create considerable topological changes. Moreover, it might require rerouting of data packets and reorganization of the network. Several approaches are available with the goal of enabling energy-efficient routing to increase the network lifetime [42, 63, 72, 73, 79, 93, 110, 111, 116, 120]. In general, energy-efficient routing for extending the network lifetime is based on two classes: (1) energy harvesting, and (2) battery power. In the following Sections, the two methods are described, and the most recent methods in each of the classes are reviewed and discussed.

3 Energy harvesting routing approaches

Energy harvesting or scavenging involves the extraction of small amount of energy from ambient environment sources such as solar, thermal, wind and vibration. These mechanisms are effective in improving the network lifetime of WSN [47]. In energy harvesting, a battery is periodically recharged to keep the sensor node continuously working in the network-wide operation rather than being centered on minimizing energy consumption. However, to efficiently use harvested energy, the harvest process ought to be incorporated into the network style. Some routing protocols that have done work in this category consider various network factors such as topology, energy consumption rate and prediction errors. These factors affect energy savings by considering wastage awareness and most of them use the recharging ability to boost network-wide performance. In the following sections, we discuss current state of the art routing approaches that utilize energy harvesting approaches.

3.1 Conventional based energy harvesting

An intelligent solar energy harvesting (ISEH) system is proposed in [68] for the supply of long-term and stable power in WSN. A solar panel, lithium battery and a control circuit work together and the charging system depends on the hardware. The solar energy is used when there is enough sunlight while the lithium battery is used when sunlight is not available. The proposed ISEH system adapts a maximum power point tracking circuit to take full advantage of solar energy, and it guarantees the lithium battery with an appropriate charging method for long-term operations. This reduces the frequency of the battery charge–discharge cycle. RS triggers are used to implement the charging controls of the battery which according to the authors is more reliable and stabilizes the software implementation. Figure 1 shows a schematic diagram of the ISEH system showing the interconnections of the functional components, including three input branches (i.e. a solar panel, a lithium battery, a mini-USB interface) and an output USB interface. There are many different rechargeable batteries that can be used for such systems. Among them are the lead-acid battery and lithium-polymer battery. The capacity of any one of them informs how it is used. For example, the lithium-polymer is more useful for a system that depends on the load. The capacity of whatever battery is used can be determined by the formula stated in Eq. (1)

$$BC = A \times QL \times TO/(cc \times V)Wh \tag{1}$$

where A is a safe factor between 1.1 and 1.4, QL depicts average daily power consumption of the load in Wh, NL denotes longest continuous rainy days, set 7 according to experience, TO represents temperature correction factor, which is set to 1 and cc is a depth of the battery discharge. This system can be implemented with small power equipment that is especially suitable for outdoor-based wireless sensor nodes in the internet of things (IoT). Results by Li and Shi [68] show that the system performs stably and safely with higher reliability and efficiency.

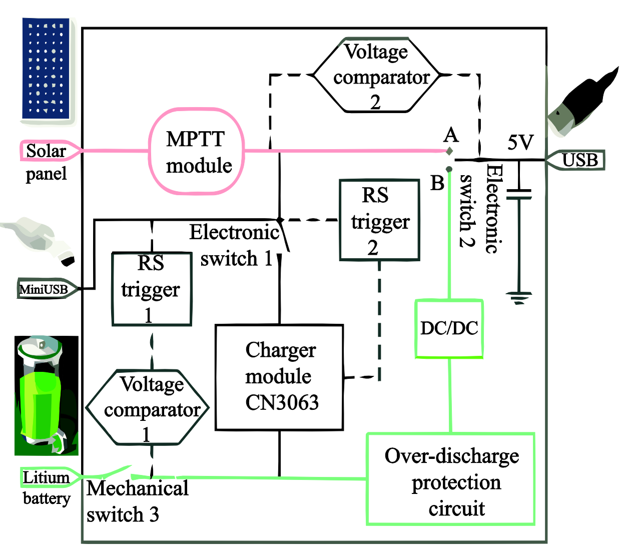

Fig. 1 ISEH system schematic diagram [68]

Harvesting aware speed selection (HASS) algorithms is proposed in [126], to maximize energy reserves of nodes in the network while meeting application performance requirements in WSN. HASS is an epoch-based method for energy controlling in performance-constrained WSNs that exploits energy harvesting. It uses dynamic voltage scaling technique to save computation energy by concurrently decreasing CPU supply voltage and frequency, and also uses the dynamic modulation scaling technique to save communication energy by decreasing radio modulation level. HASS problem is formulated as an optimization problem and solved with a centralized and distributed algorithms. In HASS, the energy level Γ_i of a node V_i at the end of an epoch is given in Eq. (2)

$$\Gamma_i = \Gamma_i^{\text{init}} + P_i \cdot S - \left\lfloor \frac{S}{\pi} \right\rfloor \cdot e_i^c \tag{2}$$

where Γ_i^{init} is the initial energy level of V_i, S is epoch length, $\left\lfloor \frac{S}{\pi} \right\rfloor$ are some frames in an epoch, the energy consumption is e_i^c and P_i is the harvested power of epoch i. Results of simulation [126] shows that HASS performance is significantly higher than the baseline approaches.

Ren et al. [89] devised a centralized and distributed algorithms for quality-aware target coverage problem in an energy harvesting sensor network. An energy harvesting plan is expected to be perfect throughout the network operations. However, such an assumption is noted to be problematic in realistic applications. For this reason, the authors suggested an adaptive framework for energy prediction fluctuations (AFEPF). It aims to plan sensor activities by dynamic interval concept. AFEPF comprises of sequential time slots that is not more than L. It counts the number slots to attain before another recharging occurs. The charging of the solar energy depends on the weather conditions, and the interval length is adaptively planned by the correctness of energy focus. Thus, the whole operational period of L time slots consists of some intervals. Then a suggested Greedy–Heuristic is applied in every interval. The accuracy of the predicted energy $\theta_i(v)$ of a sensor $v \in V(I_i)$ in an interval I_i is formulated a $\theta_i(v) = \frac{|Q_v - \acute{Q}_v|}{Q_v}$ Where Q_v and $\acute{Q}_v$ represent the actual and forecast values of harvested energy. The average forecast correctness of nodes in the interval is denoted by the energy prediction correctness of interval I_i. This is the average energy forecast correctness in active nodes in the interval given by $\theta_i = \sum_{v \in V(I_i)} \theta_i(v)/|V(I_i)|$. The results on experimental simulation show the proposed solutions are promising.

3.2 Energy harvesting from piezoelectric nanogenerators

The conventional energy harvesting mechanisms mentioned in Sect. 3.1 are not useable in the case of very tiny sensor nodes devices, such as the ones used in wireless nanosensor networks (WNSN) [58] that are used for applications such as drug delivery systems [7] or tactile sensors [119]. The reasons are that: (1) the solar energy harvesting contains a low efficient photovoltaic nanocell which does not improve even if novel nanocomponents such as carbon nanotubes are used to improve their sensitivity [59]. (2) Usually, the sunlight is not available in many WNSN's applications, and (3) the mechanisms to harvest kinetic energy from wind is not feasible in the nanoscale due to limitations of current technology [5]. To overcome the problem of limited energy capacity of nanosensor nodes, researches have proposed the use of piezoelectric nanogenerator to recharge the energy of the nanodevices as in [114, 115, 127]. In the following, we describe some works that have exploited the piezoelectric effect to power nanosensors.

A novel routing framework based on Terahertz Band communication and nano-scale energy harvesting is proposed in [85]. The framework, constructed in hierarchical cluster architecture divides the nonasensor network into clusters. In each cluster, there is a nano-controller with more capabilities that coordinates and gather the data of the nanosensors. The framework presents a procedure that conserves harvested energy by the nanosensors, and also increases the throughput in transmitting data from the nanosensor to the nano-controller. To transmit data, a nanosensor first makes a request to the nanocontroller specifying the amount of data. Then based on the distance apart, and the density of nanosensors, the nanocontroller decides whether the nanosensor should transmit in single-hop or in multi-hop. The average energy required in transmitting a bit of data through a given distance l is formulated in Eq. (3)

$$E_{bit}(l) = \left(\frac{4\pi f_0}{C}\right)^2 \frac{N_0 SNR}{\log_2(1+SNR)} l^2 \tag{3}$$

where N_0 represents a constant, l is a distance and f_0 is the design center frequency, c is the speed of light in the vacuum, and SNR is the constant signal-to-noise ratio guaranteed at the receiver.

Also, the average energy to transmit a bit $\hat{E}_{bit}(x_n, \varphi)$ from a neighbor nanosensor to the nanocontroller is modeled in Eq. (4)

$$\hat{E}_{bit}(x_n, \varphi) = \left(\frac{4\pi f_0}{C}\right)^2 \frac{N_0 SNR}{\log_2(1+SNR)} \left(x_n^2 + z_n^2 - 2x_n z_n \cos\varphi\right) \tag{4}$$

where z_n is the distance between the nanosensor n and the nano-controller, x_n is the distance between the nanosensor n and a random neighbor, and φ is the angle between the line connecting the nanosensor n and the nano-controller and the line connecting the nanosensor n and the neighbor. Performance evaluation [85] shows the merit of the proposed framework over basic single hop communication.

A technique to maximize the utilization of harvested energy in nanosensor networks is proposed in [82]. Maximizing energy utility is based on switching between two states. An action that causes a higher level energy state indicates energy consumption, and it is assigned with negative rewards. On the other hand, if the action leads to lower energy state, then a positive reward is assigned. An *out of energy* state leads to packet loss reception due to lack of energy. Similarly, there is loss of packet reception at *full energy* state, for lack of empty space in the storage. The transition function between the different states is proportional to the energy consumption and it is defined in Eq. (5)

$$J(S_i, S_j, a_k) = \begin{cases} i - j & j \neq 1, s \\ -(S+1) & j = 1, s \end{cases} \tag{5}$$

where a_k represents the action taken, S_i and S_j represent the different system states and s is the energy storage capacity. Simulation results of the proposed technique shows that it has near optimal performance.

In Table 1, the energy harvesting routing approaches for WSN is summarized indicating the advantages and disadvantages of each category.

4 Battery power based routing approaches

In general, energy efficiency for battery power based routing approaches is provided by two methods: (1) energy balancing, and (2) energy consumption reduction [10, 12, 13, 24, 70]. In the following sections, the two methods are described, and most recent approaches in each are reviewed and discussed.

4.1 Energy balancing

In WSNs, balancing of energy among nodes during routing of data packets toward the BS is very important.

Table 1 Summary of energy harvesting mechanisms WSN

Mechanism	Source	Feature	Advantages	Disadvantages	Application field
Conventional energy harvesting	Solar	Light energy is transformed into electrical energy	Established technology	High installation cost	Environment [13], agriculture [53, 100]
	Wind	Kinetic energy of wind is transformed into mechanical energy then into electrical energy		Sunshine is not available at all times	
Piezoelectric nanogenerators energy harvesting	Vibration	Energy from movement or vibration is converted into electrical energy	No limit to harvested energy limit [28]	Still an emerging technology Amount of energy is small	Biomedical, industrial and military [4]. Drug delivery systems [28]

Overloading of specific nodes gradually exhausts their energy and leads to failure. Therefore, several routing approaches capable of balancing and distributing energy among the nodes have been proposed in the literature. The following sections describe some of the energy balancing approaches.

4.1.1 Single-path approaches

This class of energy balancing makes use of only direct route from the source node to the sink in its data transmission. The approach considers a set of nodes with maximum remaining energy along the path to the sink. If the energy level of a particular node "drops", the approach selects other nodes that have higher energy. The single-path approach varies among different paths thereby balancing the energy depletion among the nodes and extending the network lifetime.

In [46], a heuristic method is proposed to explore a balanced and lower-weight spanning trees with larger diameters that can be used in WSN to balance the energy consumption. The proposed scheme can be applied in parallel as simple algorithms scattered in the neighborhood. The method represents an adjustment of the classical Kruskal's algorithm, which finds the routing spanning tree with satisfactory performance. The distributed algorithm requires input graph representation via the adjacent matrix. One of the main objectives of the heuristic method is the discovery of a routing spanning tree that reduces the consumption of maximum energy in all sensor nodes. To demonstrate the operation of the algorithm in an instinctive manner, and to describe its dispersed computational structure, the authors studied an adjacency matrix (M) graph. The manner in which the algorithm treats M when k = 0, 1 and 2, i.e. with 1, 2 and 4 initial clusters, respectively as shown in Fig. 2, the authors take $2^0 = 1$ as

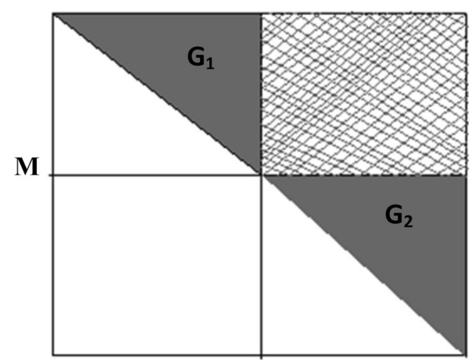

Fig. 2 Adjacency matrix with two clusters

the initial cluster when k = 0, and the algorithm is the same as that of Kruskal. In this case, the algorithm simply browses the upper right triangle over the main diagonal of *M* to find the smallest weight edge to add to the minimum spanning tree of *T* (whenever this is possible), which is under construction. The authors' results show that the proposed methods prolong lifetime of WSN by a factor of 3–4 by reducing the energy of transmission. Additionally, it shows that the results can be enhanced by the use of initial clustering of the input network.

Due to the ability of this method to save the energy of the nodes and extend the network lifetime, it can be suitable for applications that require long-term data collection such as habitat monitoring. In such applications, sensor nodes must stay alive to perform continuous monitoring of the environment.

An energy-efficient clustering routing protocol based on weight (ECRPW) is proposed in [101] to reduce the energy consumption and increase the network lifetime. In ECRPW, after the formation of clusters, the data transmission is performed on a routing tree (Fig. 3). In the proposed mechanism, cluster heads (CHs) first disseminate a weight message containing an ID of the node and its

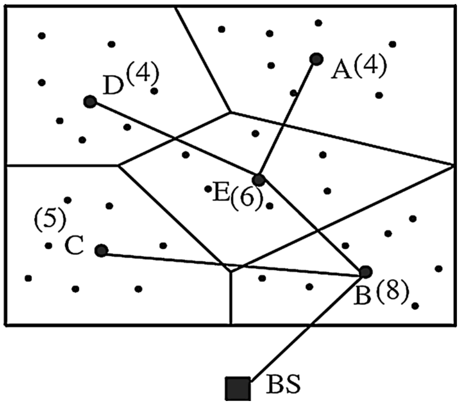

Fig. 3 Data routing in ECRPW

weight (W). When a cluster head receives a weight message, it compares its weight with the weight in the message.

If it finds that its weight is greater than the weight in the received message, it sends a child message to that node, and the node with the greater weight will be elected as the parent node. Additionally, the node with the maximum weight is selected as the root of the tree. If the node receives no message from other nodes, it transmits its packet directly to a BS. This mechanism is illustrated in Fig. 3. Nodes A–E are the CHs and their weights are shown in the parentheses. According to Fig. 2, node E receives the Weight message from all other nodes, but it selects node B as its parent due to its greater weight, 8. Similarly, nodes D and A select node E as their parent, while node C is selects node B as its parent.

The calculation of the weight is by the remaining energy of nodes and their distances to the sink as shown in Eq. (6)

$$W_i = E_i(r)/E_{start} \times RSSI \tag{6}$$

where $E_i(r)$ is the average energy at round r of the network, E_{start} denotes the initial energy and RSSI is the received signal indicator, which is achieved at the network initialization by broadcasting a test signal.

The approach is suitable for safety monitoring of small areas, and for underground coal mines where there are difficult tasks due to natural circumstances. The proposed energy-efficient clustering routing method can extend the network lifetime and reduce the maintenance cost of the system. The ECRPW protocol demonstrates that it is energy efficient by the adoption of clustering which ensures that only a few nodes contribute traffic into the network. Again, data transmission is biased towards nodes with higher residual energy that balances energy consumption among nodes. We believe that the two methods adopted in the ECRPW protocol indeed helps to conserve energy and prolongs the network lifetime.

An energy-efficient routing protocol with static clustering and dynamic structure (ERP-SCDS) is proposed in [44]. ERP-SCDS balances the energy consumption of sensor nodes during the cluster formation. It forms several static clusters with equal sizes to increase the network lifetime. Firstly, it undergoes an initialization phase whereby the sink distributes several virtual points in the network in a balanced way that is further used as the center of the cluster. By balancing the distribution of the virtual points, it balances the distribution of the clusters and reduces the energy consumption. Figure 4 presents the placement and selection of the virtual points.

In forming the clusters, each node selects the nearest virtual point, and the nodes with the same virtual point ID are considered to belong to the same cluster. Moreover, the CH selection depends on the residual energy and distance of nodes from the virtual points to ensure connectivity of the network. Similarly, for data transmission from the CH to the sink, each CH chooses the relay node that has the highest remaining energy and the shortest distance to the sink.

Energy-balanced routing protocol (EBRP) studied in [88] proposes a routing protocol that balances power consumption in WSN with the assistance of the concept of "potential" in physics. The EBRP constructs a mixed field of potential that can forcibly move packets towards a sink via denser energy, and prevents energy depletion of the nodes that have low residual energy. Additionally, it makes a classification for routing loops and considers a technique for the identification and removal of routing loops. The authors formulate a potential field that uses concepts from classical theory. A positive electrical charge Q located at the point (x_0, y_0) causes an induction of a field of electrical potential $V(x, y)$ at position (x, y) about itself. The electrical potential field is formulated in Eq. (7)

$$V(x,y) = Q/_{4\pi\varepsilon_0}\sqrt{(x-x_0)^2+(y-y_2)^2} \tag{7}$$

where ε_0 is taken as a constant such that the strength of the field can be written as

$$\mathrm{S(x,\ y) = (dv/dx, dv/dy).} \tag{8}$$

In this representation, the force **F** and the field strength with the negative charge are oriented in the same direction. Again, it is understood from Eq. (8) that the direction of the gradient and the strength of the field share the same direction, which signifies that the negative charges will be forcibly moved according to the gradient direction, and the speed of variation of the electric potential. The proposed protocol is related to the class of data gathering grounded algorithms for routing and is not suitable for point-to-point network transmission and data dissemination. The protocol is also limited with respect to the dynamics of time variation, which is a challenging issue for future work. EBRP forwards packets along the most energy-efficient path to

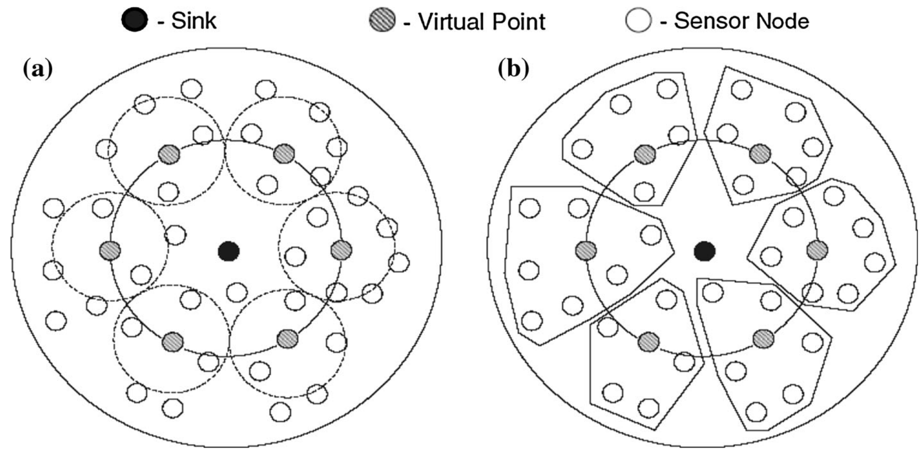

Fig. 4 Placement and selection of virtual points

the BS. Therefore, energy depletion rate of nodes with low residual energy decreases.

4.1.2 Multi-path approaches

Multi-path approaches can balance the load among routing paths. Load balancing can distribute the energy consumption among nodes in WSNs which can extend the network lifetime. Moreover, load balancing can prevent bottlenecks and congestion in the network.

In the grid-based multipath with congestion avoidance routing protocol (GMCAR) in [16], the authors state that congestion occurs in a network when the existing traffic burden surpasses the maximum bandwidth capacity limit of the network. Based on such observation, a congestion avoidance protocol based on multi-path grid routing is proposed. The protocol can be used in grid-based sensor networks whereby the network field is divided into different multiple grids and one node selected as a master in every grid. To avoid congestion in the network, an algorithm is used to identify emerging congestion and prevent its occurrence. The buffer tenure is often used to monitor the emerging traffic load. However, this approach does not rely only on embedded avoidance because each node in each grid might not have the ability to assess the traffic load of the entire network. GMCAR diagonally creates multiple paths between the sink and each master node. The GMCAR mechanism arranges the network topology to split the network into grids with predefined sizes (Fig. 5). The novelty of GMCAR is based on two different concepts. First is the idea of dividing the network and second is the consideration of the node density.

The authors consider the location of the BS at the corners of the topology such that two types of grids can be distinguished: boundary and non-boundary grids.

The grids that lie horizontal or vertical to the sink are boundary grids whereas the non-boundary grids lay further

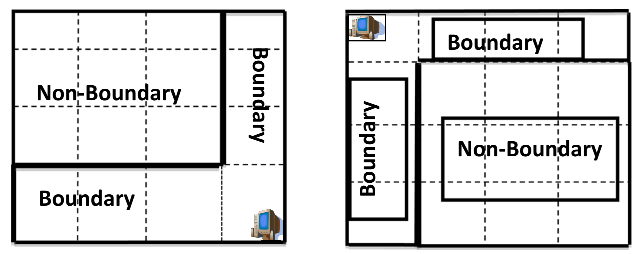

Fig. 5 Boundary and non-boundary grids in GMCAR

away, as shown in the Fig. 5. The GMCAR protocol can support packet delivery ratio, bandwidth, and end-to-end delay, and it is suitable for applications in which quality of service must be guaranteed. Examples of such applications include reporting imaging data in hostile areas and intrusion detection.

In [113], a multipath node-disjoint routing (MNR) method is discussed to minimize energy consumption with the use of multi-mode assistance and resource allocation. The MNR algorithm comprises of novel characteristics of communication that can efficiently reduce power consumption through resource allocation and multimode cooperation. The authors study multi-path routing with energy-efficient node disjoints for a sender-to-receiver pair given by the construction of a joint route, the methods of power techniques and the relay assignment. In the first phase, MNR defines a new problem of bandwidth power-aware cooperative multi-path routing (BP-CMPR) and formally proves its NP-hardness. The second phase of the study proposes an experimental algorithm for the polynomial-time CMPR to overcome the issues associated with the fist. Furthermore, a distributed version of the CMPR known as DCMPR is proposed. The algorithm is adopted on a weight diagram from the sender to the end point to find the K minimal-weight routes with the node disjoint. Again, dynamic concept of programming is used to deploy relay assignment and power resources allocation. Comparisons of the CMPR and DCMPR that have the same cooperative multi-path routing construction demonstrate a performance that is 15 % better than the traditional path routing scheme. The MNR approach is proposed for video surveillance applications using wireless multimedia sensors such as in the battlefields. In such applications, minimizing energy consumption and achieving a sufficient bandwidth to improve the quality of a video is desirable.

An energy-efficient and QoS-based multi-path routing (EQSR) is proposed in [18]. EQSR balances loads in the network. In the approach, a discovery procedure initially begins at the sink and selects a set of neighboring nodes capable of forwarding data from the source nodes to the BS. The selected paths are maximally disjoint, which means that there are no minimum common nodes between the nodes; thus, the failure of a single node cannot affect all of the paths. This achieves the fault tolerant level. The path discovery procedure in the EQSR consists of three phases. The first is an initialization phase in which each node finds its best 'next hop' neighbors by broadcasting a Hello message. Second is the Primary path discovery phase, in which a set of nodes with appropriate link quality metrics are selected as the primary path, and the third is Alternative path discovery phase in which another path is chosen as a backup path for the primary route. After the phases of path discovery and construction, two sets of paths are selected for different types of traffic (real-time and non-real-time) to guarantee transmission of real-time data with minimum delay. After selecting the set of paths, a weighted traffic allocation mechanism is used to distribute and balance the data packets among the paths. For data transmission, the EQSR divides the data packet into several segments of the same size and sends the packet over multiple paths simultaneously. As a result, this approach balances traffic among the nodes and reduces the loads on specific nodes. Mission critical and multimedia applications are challenged by data traffic that may be delay sensitive or delay tolerant. The need for QoS routing of the data packets cannot therefore be overlooked. Hence, the capability for EQSR to provide efficient and QoS-aware multi-path routing is suitable for the objective function.

4.2 Energy consumption reduction

One of the most important design targets of WSNs is the use of energy reduction mechanisms to prolong the lifespan of the network using efficient energy conservation techniques. The main duty of a routing protocol in WSNs is data gathering from sensor nodes that are distributed in an interesting environment. Each sensor node captures data from the environment and transfers the collected data to the BS. However, in line with the resource-constrained nature of WSNs, routing of the data packets toward the BS with minimal consumption of energy is of great importance. Certain energy-efficient techniques are employed to achieve this goal. One of such efficient techniques is data aggregation, which is explained in the next Section.

4.2.1 Data aggregation techniques

Data aggregation (Fig. 6) is a famous and efficient technique used during routing process to reduce the volume of data and the number of transmissions across a network [6, 98].

Data aggregation technique is a process in which a node obtains data from other nodes, combines its data with it, removes any redundant data and sends only a single summary packet toward the BS. Only the maximum, average or minimum data is transmitted to the sink [2, 131]. The process continues for all subsequent nodes until the sink receives the final summarized packet. The technique greatly reduces communication traffic, conserves energy of nodes and increases network lifetime. Previous works such as in [3, 23, 33, 56, 74] have used data aggregation to decrease the energy depletion of the network. Moreover, TinyDB [75] and Cougar [121] have been developed as query processors to manage data aggregation in WSNs. These systems maintain the network in the form of a data aggregation tree for data routing and aggregation.

4.2.2 Energy consumption reduction routing approaches

The energy consumption reduction routing approaches can be classified into two: (1) stationary approaches that do not support mobility, and (2) mobility-enabled routing approaches in which sink(s) or sensor nodes are mobile. There are applications in which the nodes are mobile and can reorganize their locations to redistribute traffic-congested regions, thereby balancing the energy consumption among the nodes, and easing the network partitioning [31, 51]. In the scenario where the BS is mobile, as in [8, 11], it can traverse the network field to gather data from nodes. It then balances the energy consumption among the nodes in the entire network field. In such a scenario, data is either

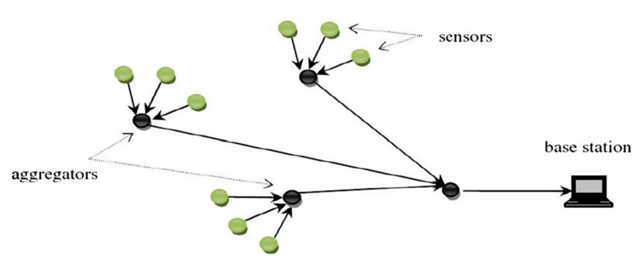

Fig. 6 Data aggregation in WSNs

sent periodically or stored until the mobile entity is closer to the sending node. The decrease in the transmission range reduces the energy consumption.

4.2.2.1 Stationary nodes routing approaches Clustering is a popular technique for energy-efficient data routing in WSNs. Hierarchal multi-hop based routing protocols have effectively implemented data aggregation to reduce data volumes transmissions over the network. Several kinds of research have made use of the clustering techniques in their data routing approaches. Examples of some of them are described in the following.

In [105], a novel spatial-correlation-aware (SCA) algorithm for dynamic and scalable data gathering in WSNs is proposed. The work first addressed the objectives of developing a spatial correlation of the data in WSN. Then, the preliminary motivation of the proposed method is discussed to demonstrate energy consumption of nodes during the data collection process in two dissimilar types of routing tactics. Figure 7 illustrates that if the sink node is placed at point (0, 0), it obtains data from a detected event with a radius of 70 m positioned at the point (600, 600). Figure 8a shows a simple method the collected sensed data is sent to the sink. The procedure in Fig. 8b presents a more refined approach that implies the use of spatial correlation for the energy conservation. In this method, only subsets of the nodes that sense events transmit their data to the sink. At every second, notification is performed in both approaches. The difference between these approaches is that Fig. 7(a) sends 32,157 notifications, whereas Fig. 7(b) sends 5667 notifications. The latter approach can conserve more energy and prolong the network lifetime. The results of the approaches put the proposed algorithm ahead of similar existing algorithms in terms reducing the required energy for data collection.

Dense and large scale WSNs are used in different classes of applications for accurate monitoring. However, according to the high density of nodes in such systems, some sensor nodes can perceive both redundant and spatially correlated data. Therefore, the proposed data collection method in [105] can be a good solution for such applications.

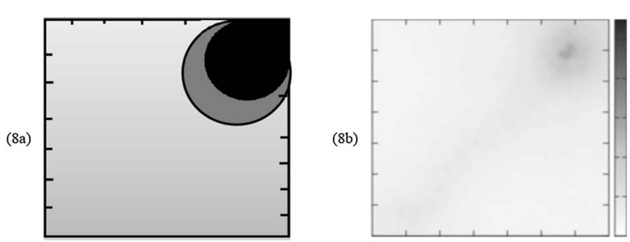

Fig. 7 Ring topology in multi-path data aggregation

In [29], the authors proposed an integrated data gathering and interest dissemination system (IRIS) for WSN. Figure 9 illustrates the IRIS system and its components. In IRIS, convergence casting and integrated dissemination of solutions are presented for WSNs in which the first approach is used for the data collection process and deployment of network sink, while the latter builds and maintains the network topology. The IRIS system performs the integration process with the diverse and desired features of WSN communications. The IRIS deployment mechanisms contains awake and asleep schedules, convergence casts using cross layers, dissemination of interest and an estimation process for the number of neighbors of every sensor, all these are shown in Fig. 8. In IRIS system, the sensors communicate for three reasons: (1) to estimate the number of sensor nodes in the transmission range, (2) to propagate the signal of interest received by the network sink, and (3) to send the data packets to the sink. All of

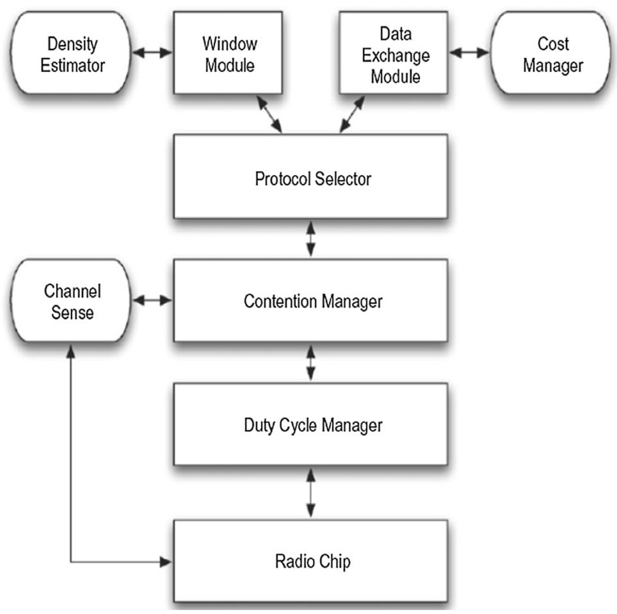

Fig. 8 IRIS system

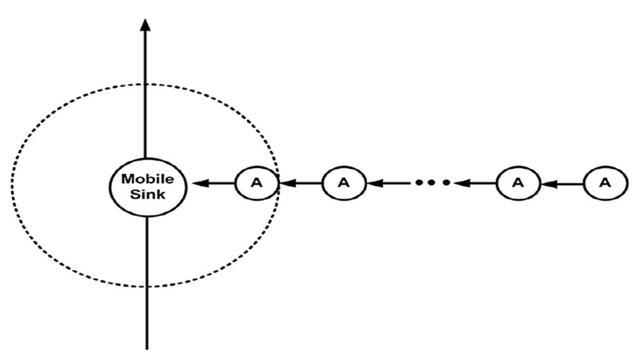

Fig. 9 K-hop relay mechanism

these tasks are performed during the sensor lifetime and can be dynamically altered according to the status and the requirements of the network.

Applications that consider energy and delay of data delivery as issues can employ IRIS. For instance, IRIS has been used in WSNs for city-wide ambient intelligence (WISE-WAI). It is an application that looks for definition and deployment of integrated solutions for environmental intelligence in large, urban scenarios.

The work in [64] state that the CHs with proximity to the BS must relay additional data. Therefore, a routing protocol based on the size of the clusters is proposed for minimizing the sizes of clusters located near BS. Each CH is allowed to use nearly the same amount of energy such that energy consumption of the CHs nearer to the BS is controlled. Moreover, the network topology is separated into numerous hierarchical stages to prolong the lifetime of the network. Also, to transmit data through multiple CHs, the authors propose a routing methodology that is capable of using multi-hop communications. The method dynamically changes the transmission distance such that energy of the nodes is not rapidly exhausted. The second purpose of the proposed protocol is to separate the topology into several stages with different sizes. To avoid excessive transmission loads on CHs located closer to BS. The clusters near the BS are smaller than those away from the BS. The other phase of the work involves the use of cluster maintenance to lengthen the network lifetime. Maintenance of cluster (which contains the CH revolutions and cross-level transmissions) is proposed to eliminate the recurrent topology reconfiguration. Future directions are also given in this work as a guideline for formulating coverage issue in an integer linear programming problem (ILP). The authors intend to implement the optimization problem using a C simPLEX (CPLEX) solver, commercial optimization software from IBM. Their simulation results show that their proposed scheme enhances the lifetime of the network better than related approaches.

In harsh environments in which monitoring cannot be easily managed, grouping the nodes into clusters can be very effective. However, in homogenous clustered networks, controlling the energy of the CHs and keeping them alive is the main issue. By calculating cluster radius to balance the energy dissipation of each CH, the proposed mechanism, can prolong the network lifetime, thereby, offering a good solution for such applications.

4.2.2.2 Mobility-enabled routing approaches In [62], the authors proposed a new protocol known as Mobicluster in which mobile sinks retrieve data from isolated portions of WSNs. The protocol aims is to maximize connectivity and throughput of data, balances energy among sensor nodes, and minimizes overhead across the entire network. The algorithm constructs a structure of unequal clusters in the first phase. It subsequently builds two separate sizes of clusters based on the distance between the CHs from the mobile sink trajectories. In Mobicluster, a filtering process is performed on the raw data, and the obtained information is forwarded to the appropriate endpoints that have sufficient residual energy. Then the endpoints are placed in proximity to the mobile sink trajectories. All of the processes of data collection are accomplished via the construction of several clusters in which the data of the cluster members are sent to allocated CHs. To avoid energy depletion of nodes and potential data loss, a selection model is proposed in which a group of cluster members from every cluster are registered as rendezvous nodes. Then, the best applicants of the rendezvous nodes that are selected are the ones that contain sufficient residual energies, can receive a maximum number of BEACON packet, and are located within a small distance from the mobile sink trajectories. To calculate the number of acknowledged BEACON packets, the sensor node, *v,* raises BEACON counter, *nb*, by one, and retains the record of the receiving time, *ti.* It also retains the signal strength, *si* and reboots a “Link Drop Timer”. The sensor node also stores this information, denoted as *v.Tfirst* and *v.Tlast*.

Mobicluster has been suggested for a class of WSN applications in isolated urban areas such as building blocks or urban parks covered by plenty of nodes monitoring the environment. In such areas, some vehicles such as buses can be equipped with mobile sinks to perceive sensory information from the deployed nodes. The utilization of multi-hop data retrieval process of Mobicluster decreases network overhead and lengthen the network life.

The authors in [97] proposed a data gathering approach that collects data from static sensor nodes using a mobile sink. There are two data gathering protocols called the infrastructure-based data gathering protocol (IDGP) and the distributed data gathering protocol (DDGP) that plan the data collection route for a mobile sink. Both protocols use a K-hop relay strategy to reduce the number of hops. In this mechanism, k is set by the users and is defined as the maximum number of hops needed to perform data transmission from the nodes to the mobile sink. In Fig. 9, the mobile robot, which is a located k hop away from node *A*, gathers the data from the other nodes.

Moreover, by the k-hop relay strategy, a layer value between 0 and $k-1$ is assigned for each sensor node. If v is considered to be the layer value of a node and $v < k$, then the node relays its data to a node with a layer value >l.

The IDGP enables the mobile sink to gather data from the routes with fewer numbers of hops. Thus, the approach reduces the energy consumption of the network. In DDGP protocol, the mobile sink determines its data collection route and disseminates a control message to all sensor nodes with the value of k. When the nodes receive the control message, they determine their layer value based on the collected information. Also, the DDGP builds a distributed data collection route and enables the mobile sink to navigate the data collection route. Moving the sink for gathering data of sensor nodes can be useful for applications involving real-time traffic. However, delay, relocation of the sink and data traffic must be taken into consideration. Due to the ability of the proposed approach to plan and reduce the data gathering path for mobile sink along with the mitigation of energy consumption, it can be suitable for such applications.

In the minimum Wiener index spanning tree (MWST) in [49], the authors proposed a data routing mechanism for WSNs based on multiple mobile sinks. In the MWST, the transmission distance is reduced compared with other tree approaches; hence, the energy consumption of the nodes decreases. Additionally, this approach reduces the number of hops required for data transmission to save additional energy. Multiple mobile sinks approach the nodes and collect their information in the networks. In addition, it is assumed that all the nodes and mobile sinks possess prior information on the network. Thus the mobile sinks can move around the network, and sensor nodes know how to select the nearest mobile sink for data transmission. The MWST proposes a branch-and-bound algorithm for finding the optimal solution for the minimum Wiener index spanning tree problem in small-scale WSNs. The duty of the branch-and-bound algorithm is to remove the redundant sub-trees from the solution space and minimize the search space. Also, this method proposes a simulated annealing approach to finding the optimal solution to the problem mentioned above. The simulated annealing approach is used to minimize a search space with many sensor nodes in the network. When the number of sensors in the WSN is >10 nodes, the branch-and-bound algorithm is applied, but when the number of nodes exceeds ten, the simulated annealing algorithm is recommended.

In some applications such as physical intrusion detection systems, the low latency is considered as significant as the energy consumption. Hence, the proposed mechanism that works on the basis of tree topology with mobile sinks designed to improve packet transmission latency as well as energy efficiency.

A virtual infrastructure-based energy-efficient routing (VIBE) scheme is studied in [84]. The scheme extends the network lifetime by minimizing the average energy expense of the network. In VIBE, information from distant areas is transferred to sink by dispersion of sufficient self-configured mobile sensor nodes (Fig. 10).

VIBE protocol can address the mobility necessities because it is fully independent of any control messages and topological knowledge. Each sensor node only needs to know its position and the position of the sink to contribute to the routing process. When a node collects information on the disseminated topic of interest and decides to inform the sink, a message is sent to an outside fixed infrastructure in the name of the message to a centralized storage device. The storage device then processes the messages together with other messages transmitted from other sensor nodes.

VIBE can be used in high density application. Examples include large scale and high mobility deployments such as battlefield surveillance and environment monitoring. In such applications, some self-configure mobile sensors must report information from unreachable environments with the least delay and packet loss. Thus, the contributions of this method including energy-efficient packet transmission, scalability, high speed and mobility adaptability are suitable for such applications.

5 Comparison and discussion

Several challenges remain for routing data in WSNs, such as the ad hoc deployment of nodes, scalability, and energy consumption [48, 99, 125]. However, energy consumption can be considered the most important technical challenge for routing in WSNs. The limited battery capacity constraints the performance of sensor nodes and decreases the lifespan of sensor networks, nevertheless it remains the primary source of energy for sensor nodes. The advantages of the battery are that it is convenient, low-cost and provides high energy density. However, the advancement of battery technology has lagged behind the fast pace of electronics [83]. Moreover, the physical size of batteries

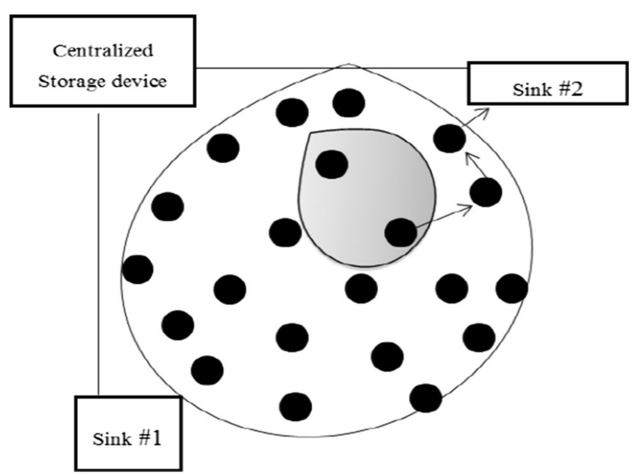

Fig. 10 Data routing in the area of interest in VIBE

Table 2 Features and goals of energy-efficient data routing protocols in WSN

Protocol	Classification	No. of sinks	Mobility	Data aggregation	Single/ multiple path	Energy balancing	Energy reduction
ECRPW [63]	Hierarchical	1	No	Yes	Single	√	
IRIS [78]	Data-centric	1	No	Yes	Single		√
GMCAR [10]	Data-centric	1	No	No	Multiple	√	
Mobicluster [8]	Hierarchical	Multiple	Yes	Yes	Single		√
ERP-SCDS [91]	Hierarchical	1	Possible	Yes	Single	√	
IDGP-DDGP [11]	Data-centric	1	Yes	No	Single		√
EBRP [24]	Data-centric	1	No	No	Single	√	
BP-CMPR [46]	Data-centric	1	No	Yes	Multiple	√	
MWST [105]	Data-centric	One or more	Yes	No	Single		√
EQSR [101]	Data-centric	1	No	No	Multiple	√	
VIBE [20]	Hierarchical	One or more	Yes	Yes	Single		√
YEAST [22]	Hierarchical	1	No	Yes	Single		√
ACT [51]	Hierarchical	1	No	Yes	Single		√
Hierarchical search [42]	Hierarchical	1	No	No	Single	√	
Energy-efficient and reliable [70]	Hierarchical	1	No	Yes	Single	√	

also limits their usages in the ever growing miniaturizing devices such as nanosensors. Replacement, recharging and disposal of batteries also present another set of challenges and may not be possible in some application.

An alternative to overcoming the problems of battery usage in WSN is by harvesting the energy from the environment, such as solar energy from the sunlight, and wind energy from windmills. These mechanisms are established technologies that are used in the replenishment of energy of the battery in various applications of WSN. For instance, solar energy is harvested to power greenhouses [1, 13]. Different from batteries, energy harvesting mechanisms offer very important advantage, whereby for sensor nodes can replenish their energy when needed. Energy harvesting is, therefore, a promising approach to providing perpetual operations for WSN [129]. In spite of its usefulness, the established energy harvesting mechanisms such as solar and wind energy, have reputation for unreliability and providing the needed energy. Also, these conventional energy harvesters cannot be utilized for replenishing energy of sensor nodes in the nano-scale, mainly due to their nano-scale sizes.

A reliable alternative to the conventional energy harvesting for nanosensors is the utilization of piezoelectric nanogenerators. By direct piezoelectric effect, mechanical vibrations can be converted into electrical energy for the prospect of being used for small energy requirements as in nanosensors [25]. Compared to the conventional energy harvesting mechanism, piezoelectric energy is always guaranteed from the source. The key advantage of the piezoelectric mechanism is that the material used can be formed in any shape or size to fit in any applications. Furthermore, the piezoelectric materials are resilient, chemically inert and resistant to high temperatures and atmospheric pressures.

Another way of sustaining the battery working life is by implementation of efficient routing protocols to reduce energy consumption. Largely; the two main methods that save energy during routing in WSN are energy balancing among the sensor nodes and energy consumption reduction of the nodes (Table 2). These goals are achieved by integrating energy saving techniques or heuristics into the routing algorithms. Examples include routing data packets via the sensor nodes with the highest remaining energy, controlling the data packet transmission over shortest path, topology control and transmitting compressed data packets. The combination of energy-efficient routing strategies with appropriate energy harvesting mechanism can prolong network lifetime for all applications of sensor networks. The specific techniques are shown in Tables 2 and 3.

As shown in Table 2, the routing algorithms in WSN contain working features that are effective in achieving the required objectives. In this work, the reviewed routing approaches in the literature are compared according to their features and selected working factors that are effective in data routing strategies such as mobility [23, 39, 75, 103, 117, 118, 121, 128], number of sinks [51, 52, 77, 124] and data aggregation [36, 69, 123]. Moreover, in Table 3, the problem, method, advantages and drawbacks of popular

Table 3 Summary of energy-efficient data routing protocols in WSN

Protocol	Problem	Method	Advantage	Drawback
ECRPW [63]	Deployment Restrictions	Single-path	Optimum clusters	High setup cost
IRIS [78]	Reliability	Stationary nodes	Multiple performance goals	Computational overhead
GMCAR [10]	QoS requirements	Multi-path	Multi-traffic classes	Maintains routing table
Mobicluster [8]	Connection failure	Mobility-enabled	Cover isolated areas	Long distance delay
ERP-SCDS [91]	Cluster size	Single-path	Avoid re-clustering	Collision
IDGP-DDGP [11]	Real-time data	Mobility-enabled	Minimize packet loss	End-to-end delay
EBRP [24]	Network partition	Single-path	Relieve low energy nodes	Routing loop
BP-CMPR [46]	Channel fading	Multi-path	Satisfy bandwidth requirement	Transmission delay
MWST [105]	Routing topology	Mobility-enabled	Efficient transmission distance	Relatively poor network lifetime
EQSR [101]	QoS requirements	Multi-path	Avoid congestion	Route coupling
VIBE [20]	Communication overhead	Mobility-enabled	Minimize control traffic	Delay
YEAST [22]	Low quality routing trees	Multi-path	Best aggregation quality	High density of nodes
ACT [51]	Power consumption	Unequal clustering	Cross level transmission	Poor coverage
Hierarchical Search [42]	Routing topology	Tree-based	Relatively simple and general	Consider only transmission matrix
Energy-efficient and Reliable [70]	Packet loss	Multi-path	Increase data delivery at BS	Not suitable for all number of nodes

and recent data routing approaches in WSN are shown and compared. Although a particular data routing approach may contain other contributions, advantages and drawbacks, the table specifies only the main ones.

6 Conclusion and future works

This paper presented energy harvesting routing based and battery power based routing approaches in WSN. The state-of-the-art energy harvesting mechanism for WSN is discussed in details and the most recent energy-efficient data packet routing approaches are reviewed. Then comparisons of the studied methods based on the main features are made. According to the literature, balancing of the energy among the nodes is usually obtained in two ways, single-path, and multi-path methods. In single-path methods, the best path that can satisfy the required energy consumption and the QoS requirements is selected for each data delivery. The load is divided amongst the paths, to ensure energy balancing among nodes in multi-paths methods. Approaches aimed at reduction of energy consumption in WSNs are categorized according to the movement ability of the BS(s) or the nodes. The movement of the BS or the nodes moderates the energy depletion of the network to create more efficient data routing among the nodes; however, the cost of such mobility must be considered in the desired applications.

Currently the energy harvesting equipment is bigger in size and thus, further research is needed to reduce the size of the components for easier integration with tiny sensor nodes. Also, it is financially costly to convert harvested energy into useable power and this challenges its usage in low cost WSN. Considerable research is therefore, necessary to reduce the financial cost while enhancing the conversion efficiency. There has to be effective controlling of the harvested energy among the sensor nodes. For example includes the optimum data routing decisions and judicious use of the extra power harvested [34]. In summary, this paper covers detailed review of the state-of-the-art of energy harvesting and battery power based routing protocols in WSN.

Acknowledgments The authors thank University of Malaya for the financial support (UMRG Grant RP036A-15AET, RP036B-15AET, RP036C-15AET, RG325-15AFR) and facilities to carry out the work.

References

1. Abbasi, A. Z., Islam, N., & Shaikh, Z. A. (2014). A review of wireless sensors and networks' applications in agriculture. *Computer Standards & Interfaces, 36*(2), 263–270.

2. Abdul-Salaam, G., Abdullah, A. H., Anisi, M. H., Gani, A., & Alelaiwi, A. (2015). A comparative analysis of energy conservation approaches in hybrid wireless sensor networks data collection protocols. *Telecommunication Systems,* 1–21. doi: 10.1007/s11235-015-0092-8.
3. Acampora, G., Gaeta, M., Loia, V., & Vasilakos, A. V. (2010). Interoperable and adaptive fuzzy services for ambient intelligence applications. *ACM Transactions on Autonomous and Adaptive Systems (TAAS), 5*(2), 8.
4. Akyildiz, I. F., Brunetti, F., & Blázquez, C. (2008). Nanonetworks: A new communication paradigm. *Computer Networks, 52*(12), 2260–2279.
5. Akyildiz, I. F., & Jornet, J. M. (2010). Electromagnetic wireless nanosensor networks. *Nano Communication Networks, 1*(1), 3–19.
6. Al-Karaki, J. N., Ul-Mustafa, R., & Kamal, A. E. (2009). Data aggregation and routing in wireless sensor networks: Optimal and heuristic algorithms. *Computer Networks, 53*(7), 945–960.
7. Allameh, S., Akogwu, O., Collinson, M., Thomas, J., & Soboyejo, W. (2007). Piezoelectric generators for biomedical and dental applications: Effects of cyclic loading. *Journal of Materials Science Materials in Medicine, 18*(1), 39–45.
8. Alsalih, W., Hassanein, H., & Akl, S. (2010). Placement of multiple mobile data collectors in wireless sensor networks. *Ad Hoc Networks, 8*(4), 378–390.
9. Alwan, H., & Agarwal, A. (2009). A survey on fault tolerant routing techniques in wireless sensor networks. In *Third international conference on sensor technologies and applications (SENSORCOMM '09)* (pp. 366–371).
10. Alzoubi, K., Li, X.-Y., Wang, Y., Wan, P.-J., & Frieder, O. (2003). Geometric spanners for wireless ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems, 14*(4), 408–421.
11. Angelopoulos, C. M., & Nikoletseas, S. (2011). Aggregated mobility-based topology inference for fast sensor data collection. *Computer Communications, 34*(13), 1570–1579.
12. Anisi, M. H., Abdullah, A. H., Coulibaly, Y., & Razak, S. A. (2013). EDR: Efficient data routing in wireless sensor networks. *International Journal of Ad Hoc and Ubiquitous Computing, 12*(1), 46–55.
13. Anisi, M. H., Abdul-Salaam, G., & Abdullah, A. H. (2015). A survey of wireless sensor network approaches and their energy consumption for monitoring farm fields in precision agriculture. *Precision Agriculture, 16*(2), 216–238.
14. Asim, M., Mokhtar, H., & Merabti, M. (2009). A cellular approach to fault detection and recovery in wireless sensor networks. In *Third international conference on sensor technologies and applications (SENSORCOMM'09)* (pp. 352–357).
15. Bangash, J. I., Abdullah, A. H., Anisi, M. H., & Khan, A. W. (2014). A survey of routing protocols in wireless body sensor networks. *Sensors, 14*(1), 1322–1357.
16. Banimelhem, O., & Khasawneh, S. (2012). GMCAR: Grid-based multipath with congestion avoidance routing protocol in wireless sensor networks. *Ad Hoc Networks, 10*(7), 1346–1361.
17. Bari, A., Jaekel, A., Jiang, J., & Xu, Y. (2012). Design of fault tolerant wireless sensor networks satisfying survivability and lifetime requirements. *Computer Communications, 35*(3), 320–333.
18. Ben-Othman, J., & Yahya, B. (2010). Energy efficient and QoS based routing protocol for wireless sensor networks. *Journal of Parallel and Distributed Computing, 70*(8), 849–857.
19. Benini, L., Farella, E., & Guiducci, C. (2006). Wireless sensor networks: Enabling technology for ambient intelligence. *Microelectronics Journal, 37*(12), 1639–1649.
20. Bhattacharyya, D., Kim, T.-H., & Pal, S. (2010). A comparative study of wireless sensor networks and their routing protocols. *Sensors, 10*(12), 10506–10523.
21. Bhuiyan, M., Wang, G., & Vasilakos, A. (2015). Local area prediction-based mobile target tracking in wireless sensor networks. *IEEE Transactions on Computers, 64*(7), 1968–1982.
22. Biswas, S., & Morris, R. (2005). ExOR: Opportunistic multi-hop routing for wireless networks. *ACM SIGCOMM Computer Communication Review, 35*(4), 133–144.
23. Bo, W., Han-Ying, H., & Wen, F. (2008). An improved leach protocol for data gathering and aggregation in wireless sensor networks. In *International conference on computer and electrical engineering (ICCEE 2008)* (pp. 398–401).
24. Boukerche, A., Turgut, B., Aydin, N., Ahmad, M. Z., Bölöni, L., & Turgut, D. (2011). Routing protocols in ad hoc networks: A survey. *Computer Networks, 55*(13), 3032–3080.
25. Bowen, C., Kim, H., Weaver, P., & Dunn, S. (2014). Piezoelectric and ferroelectric materials and structures for energy harvesting applications. *Energy & Environmental Science, 7*(1), 25–44.
26. Busch, C., Kannan, R., & Vasilakos, A. V. (2012). Approximating congestion+ dilation in networks via" quality of routing&# X201D; games. *IEEE Transactions on Computers, 61*(9), 1270–1283.
27. Byun, J., & Park, S. (2011). Development of a self-adapting intelligent system for building energy saving and context-aware smart services. *IEEE Transactions on Consumer Electronics, 57*(1), 90–98.
28. Caliò, R., Rongala, U. B., Camboni, D., Milazzo, M., Stefanini, C., De Petris, G., & Oddo, C. M. (2014). Piezoelectric energy harvesting solutions. *Sensors, 14*(3), 4755–4790.
29. Camillò, A., Nati, M., Petrioli, C., Rossi, M., & Zorzi, M. (2013). IRIS: Integrated data gathering and interest dissemination system for wireless sensor networks. *Ad Hoc Networks, 11*(2), 654–671.
30. Cano, C., Bellalta, B., Sfairopoulou, A., & Oliver, M. (2011). Low energy operation in WSNS: A survey of preamble sampling MAC protocols. *Computer Networks, 55*(15), 3351–3363.
31. Cao, X., Chen, J., Gao, C., & Sun, Y. (2009). An optimal control method for applications using wireless sensor/actuator networks. *Computers & Electrical Engineering, 35*(5), 748–756.
32. Challal, Y., Ouadjaout, A., Lasla, N., Bagaa, M., & Hadjidj, A. (2011). Secure and efficient disjoint multipath construction for fault tolerant routing in wireless sensor networks. *Journal of Network and Computer Applications, 34*(4), 1380–1397.
33. Chatterjea, S., Nieberg, T., Meratnia, N., & Havinga, P. (2008). A distributed and self-organizing scheduling algorithm for energy-efficient data aggregation in wireless sensor networks. *ACM Transactions on Sensor Networks (TOSN), 4*(4), 20.
34. Chen, S., Sinha, P., Shroff, N. B., & Joo, C. (2014). A simple asymptotically optimal joint energy allocation and routing scheme in rechargeable sensor networks. *IEEE/ACM Transactions on Networking (TON), 22*(4), 1325–1336.
35. Chilamkurti, N., Zeadally, S., Vasilakos, A., & Sharma, V. (2009). Cross-layer support for energy efficient routing in wireless sensor networks. *Journal of Sensors, 2009*, 1–9.
36. Chipara, O., He, Z., Xing, G., Chen, Q., Wang, X., Lu, C., et al. (2006). Real-time power-aware routing in sensor networks. In *14th IEEE international workshop on quality of service (IWQoS 2006)* (pp. 83–92).
37. Choe, H. J., Ghosh, P., & Das, S. K. (2010). QoS-aware data reporting control in cluster-based wireless sensor networks. *Computer Communications, 33*(11), 1244–1254.
38. Clementi, A. E., Penna, P., & Silvestri, R. (2004). On the power assignment problem in radio networks. *Mobile Networks and Applications, 9*(2), 125–140.
39. Considine, J., Li, F., Kollios, G., & Byers, J. (2004). Approximate aggregation techniques for sensor databases. In

Proceedings of the 20th international conference on data engineering (pp. 449–460).
40. Das, S. M., Pucha, H., & Hu, Y. C. (2008). Distributed hashing for scalable multicast in wireless ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems, 19*(3), 347–362.
41. Díaz-Anadón, M. O., & Leung, K. K. (2011). TDMA scheduling for event-triggered data aggregation in irregular wireless sensor networks. *Computer Communications, 34*(17), 2072–2081.
42. Dimokas, N., Katsaros, D., & Manolopoulos, Y. (2010). Energy-efficient distributed clustering in wireless sensor networks. *Journal of Parallel and Distributed Computing, 70*(4), 371–383.
43. Dvir, A., & Vasilakos, A. V. (2011). Backpressure-based routing protocol for DTNS. *ACM SIGCOMM Computer Communication Review, 41*(4), 405–406.
44. Ferng, H.-W., Tendean, R., & Kurniawan, A. (2012). Energy-efficient routing protocol for wireless sensor networks with static clustering and dynamic structure. *Wireless Personal Communications, 65*(2), 347–367.
45. Förster, A., & Murphy, A. L. (2010). A critical survey and guide to evaluating WSN routing protocols. In *The first international workshop on networks of cooperating objects (CONET), Stockholm.*
46. Gagarin, A., Hussain, S., & Yang, L. T. (2010). Distributed hierarchical search for balanced energy consumption routing spanning trees in wireless sensor networks. *Journal of Parallel and Distributed Computing, 70*(9), 975–982.
47. Guo, S., Wang, C., & Yang, Y. (2014). Joint mobile data gathering and energy provisioning in wireless rechargeable sensor networks. *IEEE Transactions on Mobile Computing, 13*(12), 2836–2852.
48. Han, K., Luo, J., Liu, Y., & Vasilakos, A. V. (2013). Algorithm design for data communications in duty-cycled wireless sensor networks: A survey. *IEEE Communications Magazine, 51*(7), 107–113.
49. Han, S.-W., Jeong, I.-S., & Kang, S.-H. (2013). Low latency and energy efficient routing tree for wireless sensor networks with multiple mobile sinks. *Journal of Network and Computer Applications, 36*(1), 156–166.
50. Hassanein, H., & Luo, J. (2006). Reliable energy aware routing in wireless sensor networks. In *2nd IEEE workshop on dependability and security in sensor networks and systems* (*DSSNS 2006*) (pp. 54–64).
51. He, S., Chen, J., Sun, Y., Yau, D. K., & Yip, N. K. (2010). On optimal information capture by energy-constrained mobile sensors. *IEEE Transactions on Vehicular Technology, 59*(5), 2472–2484.
52. Heinzelman, W. R., Kulik, J., & Balakrishnan, H. (1999). Adaptive protocols for information dissemination in wireless sensor networks. In *Proceedings of the 5th annual ACM/IEEE international conference on mobile computing and networking* (pp. 174–185).
53. Hou, J., & Gao, Y. (2010). Greenhouse wireless sensor network monitoring system design based on solar energy. In *International conference on challenges in environmental science and computer engineering (CESCE)* (pp. 475–479).
54. Huang, H., Hu, G., Yu, F., & Zhang, Z. (2011). Energy-aware interference-sensitive geographic routing in wireless sensor networks. *IET Communications, 5*(18), 2692–2702.
55. Huang, P., Wang, C., & Xiao, L. (2012). Improving end-to-end routing performance of greedy forwarding in sensor networks. *IEEE Transactions on Parallel and Distributed Systems, 23*(3), 556–563.
56. Intanagonwiwat, C., Govindan, R., & Estrin, D. (2000). Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *Proceedings of the 6th annual international conference on mobile computing and networking* (pp. 56–67).
57. Jing, Q., Vasilakos, A. V., Wan, J., Lu, J., & Qiu, D. (2014). Security of the internet of things: Perspectives and challenges. *Wireless Networks, 20*(8), 2481–2501.
58. Jornet, J. M., & Akyildiz, I. F. (2012). Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band. *IEEE Transactions on Nanotechnology, 11*(3), 570–580.
59. Kamat, P. V. (2006). Harvesting photons with carbon nanotubes. *Nano Today, 1*(4), 20–27.
60. Khanna, G., Bagchi, S., & Wu, Y.-S. (2004). Fault tolerant energy aware data dissemination protocol in sensor networks. In *International conference on dependable systems and networks* (pp. 795–804).
61. Kiess, W., & Mauve, M. (2007). A survey on real-world implementations of mobile ad-hoc networks. *Ad Hoc Networks, 5*(3), 324–339.
62. Konstantopoulos, C., Pantziou, G., Gavalas, D., Mpitziopoulos, A., & Mamalis, B. (2012). A rendezvous-based approach enabling energy-efficient sensory data collection with mobile sinks. *IEEE Transactions on Parallel and Distributed Systems, 23*(5), 809–817.
63. Koutsonikolas, D., Das, S. M., Hu, Y. C., & Stojmenovic, I. (2010). Hierarchical geographic multicast routing for wireless sensor networks. *Wireless Networks, 16*(2), 449–466.
64. Lai, W. K., Fan, C. S., & Lin, L. Y. (2012). Arranging cluster sizes and transmission ranges for wireless sensor networks. *Information Sciences, 183*(1), 117–131.
65. Lee, J.-H., & Jung, I.-B. (2010). Speedy routing recovery protocol for large failure tolerance in wireless sensor networks. *Sensors, 10*(4), 3389–3410.
66. Li, M., Li, Z., & Vasilakos, A. V. (2013). A survey on topology control in wireless sensor networks: Taxonomy, comparative study, and open issues. *Proceedings of the IEEE, 101*(12), 2538–2557.
67. Li, P., Guo, S., Yu, S., & Vasilakos, A. V. (2014). Reliable multicast with pipelined network coding using opportunistic feeding and routing. *IEEE Transactions on Parallel and Distributed Systems, 25*(12), 3264–3273.
68. Li, Y., & Shi, R. (2015). An intelligent solar energy-harvesting system for wireless sensor networks. *EURASIP Journal on Wireless Communications and Networking, 2015*(1), 1–12.
69. Liu, B.-H., & Jhang, J.-Y. (2014). Efficient distributed data scheduling algorithm for data aggregation in wireless sensor networks. *Computer Networks, 65*, 73–83.
70. Liu, H., Jia, X., Wan, P.-J., Liu, X., & Yao, F. F. (2007). A distributed and efficient flooding scheme using 1-hop information in mobile ad hoc networks. *IEEE Transactions on Parallel and Distributed Systems, 18*(5), 658–671.
71. Liu, L., Song, Y., Zhang, H., Ma, H., & Vasilakos, A. V. (2015). Physarum optimization: A biology-inspired algorithm for the steiner tree problem in networks. *IEEE Transactions on Computers, 64*(3), 819–832.
72. Liu, X.-Y., Zhu, Y., Kong, L., Liu, C., Gu, Y., Vasilakos, A. V., et al. (2015). CDC: Compressive data collection for wireless sensor networks. *IEEE Transactions on Parallel and Distributed Systems, 26*(8), 2188–2197.
73. Liu, Y., Xiong, N., Zhao, Y., Vasilakos, A. V., Gao, J., & Jia, Y. (2010). Multi-layer clustering routing algorithm for wireless vehicular sensor networks. *IET Communications, 4*(7), 810–816.
74. Madden, S., Szewczyk, R., Franklin, M. J., & Culler, D. (2002). Supporting aggregate queries over ad-hoc wireless sensor networks. In *Proceedings of the fourth IEEE workshop on mobile computing systems and applications* (pp. 49–58).

75. Madden, S. R., Franklin, M. J., Hellerstein, J. M., & Hong, W. (2005). TinyDB: An acquisitional query processing system for sensor networks. *ACM Transactions on Database Systems (TODS), 30*(1), 122–173.
76. Manjeshwar, A., & and Agrawal, D. P. (2001). TEEN: A routing protocol for enhanced efficiency in wireless sensor networks. In *International parallel and distributed processing symposium* (p. 30189a).
77. Manjeshwar, A., & Apteen, D. A. (2002). A hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks. In *1st IEEE international parallel and distributed processing symposium, Fort Lauderdale, FL, USA*.
78. Manjhi, A., Nath, S., & Gibbons, P. B. (2005). Tributaries and deltas: Efficient and robust aggregation in sensor network streams. In *Proceedings of the ACM SIGMOD international conference on management of data* (pp. 287–298).
79. Meng, T., Wu, F., Yang, Z., Chen, G., & Vasilakos, A. (2015). Spatial reusability-aware routing in multi-hop wireless networks. IEEE Transactions on Computers. doi:10.1109/TC.2015.2417543.
80. Merck, M. (2010). The icecube detector: A large sensor network at the south pole. *IEEE Pervasive Computing, 9*(4), 43–47.
81. Michahelles, F., Matter, P., Schmidt, A., & Schiele, B. (2003). Applying wearable sensors to avalanche rescue. *Computers & Graphics, 27*(6), 839–847.
82. Mohrehkesh, S., & Weigle, M. C. (2014). Optimizing energy consumption in terahertz band nanonetworks. *IEEE Journal on Selected Areas in Communications, 32*(12), 2432–2441.
83. Nechibvute, A., Chawanda, A., & Luhanga, P. (2012). Piezoelectric energy harvesting devices: An alternative energy source for wireless sensors. *Smart Materials Research, 2012*, 1–13.
84. Papadopoulos, A., Navarra, A., Mccann, J. A., & Pinotti, C. M. (2012). VIBE: An energy efficient routing protocol for dense and mobile sensor networks. *Journal of Network and Computer Applications, 35*(4), 1177–1190.
85. Pierobon, M., Jornet, J. M., Akkari, N., Almasri, S., & Akyildiz, I. F. (2014). A routing framework for energy harvesting wireless nanosensor networks in the terahertz band. *Wireless Networks, 20*(5), 1169–1183.
86. Pothuri, P. K., Sarangan, V., & Thomas, J. P. (2006). Delay-constrained, energy-efficient routing in wireless sensor networks through topology control. In *Proceedings of the IEEE international conference on networking, sensing and control (ICNSC'06)* (pp. 35–41).
87. Pradhan, G. N., & Prabhakaran, B. (2008). Storage, retrieval, and communication of body sensor network data. In *Proceedings of the 16th ACM international conference on multimedia* (pp. 1161–1162).
88. Ren, F., Zhang, J., He, T., Lin, C., & Ren, S. K. (2011). EBRP: Energy-balanced routing protocol for data gathering in wireless sensor networks. *IEEE Transactions on Parallel and Distributed Systems, 22*(12), 2108–2125.
89. Ren, X., Liang, W., & Xu, W. (2015). Quality-aware target coverage in energy harvesting sensor networks. *IEEE Transactions on Emerging Topics in Computing, 3*(1), 8–21.
90. Ritchie, L., Deval, S., Reisslein, M., & Richa, A. W. (2009). Evaluation of physical carrier sense based spanner construction and maintenance as well as broadcast and convergecast in ad hoc networks. *Ad Hoc Networks, 7*(7), 1347–1369.
91. Sanchez, J., Ruiz, P. M., & Stojmenovic, I. (2006). GMR: Geographic multicast routing for wireless sensor networks. In *3rd annual IEEE communications society on sensor and ad hoc communications and networks (SECON '06)* (pp. 20–29).
92. Seema, A., & Reisslein, M. (2011). Towards efficient wireless video sensor networks: A survey of existing node architectures and proposal for a flexi-WVSNP design. *IEEE Communications Surveys & Tutorials, 13*(3), 462–486.
93. Sengupta, S., Das, S., Nasir, M., Vasilakos, A. V., & Pedrycz, W. (2012). An Evolutionary multiobjective sleep-scheduling scheme for differentiated coverage in wireless sensor networks. *IEEE Transactions on Systems, Man, and Cybernetics Part C: Applications and Reviews, 42*(6), 1093–1102.
94. Seo, J., Kim, M., Hur, I., Choi, W., & Choo, H. (2010). DRDT: Distributed and reliable data transmission with cooperative nodes for lossywireless sensor networks. *Sensors, 10*(4), 2793–2811.
95. Sha, K., Shi, W., & Watkins, O. (2006). Using wireless sensor networks for fire rescue applications: Requirements and challenges. In *IEEE international conference on electro/information technology* (pp. 239–244).
96. Sheng, Z., Yang, S., Yu, Y., Vasilakos, A., Mccann, J., & Leung, K. (2013). A survey on the IETF protocol suite for the internet of things: Standards, challenges, and opportunities. *IEEE Wireless Communications, 20*(6), 91–98.
97. Sheu, J.-P., Sahoo, P. K., Su, C.-H., & Hu, W.-K. (2010). Efficient path planning and data gathering protocols for the wireless sensor network. *Computer Communications, 33*(3), 398–408.
98. Sicari, S., Grieco, L. A., Boggia, G., & Coen-Porisini, A. (2012). DYDAP: A dynamic data aggregation scheme for privacy aware wireless sensor networks. *Journal of Systems and Software, 85*(1), 152–166.
99. Song, Y., Liu, L., Ma, H., & Vasilakos, A. V. (2014). A biology-based algorithm to minimal exposure problem of wireless sensor networks. *IEEE Transactions on Network and Service Management, 11*(3), 417–430.
100. Srbinovska, M., Gavrovski, C., Dimcev, V., Krkoleva, A., & Borozan, V. (2015). Environmental parameters monitoring in precision agriculture using wireless sensor networks. *Journal of Cleaner Production, 88*, 297–307.
101. Sun, Y., He, Y., Zhang, B., & Liu, X. (2011). An energy efficiency clustering routing protocol for WSNS in confined area. *Mining Science and Technology (China), 21*(6), 845–850.
102. Sung, J., Ahn, S., Park, T., Jang, S., Yun, D., Kang, J., et al. (2008). Wireless sensor networks for cultural property protection. In *22nd international conference on advanced information networking and applications-workshops (AINAW 2008)* (pp. 615–620).
103. Vasilakos, A. V., Li, Z., Simon, G., & You, W. (2015). Information centric network: Research challenges and opportunities. *Journal of Network and Computer Applications, 52*, 1–10.
104. Vasilakos, A. V., Zhang, Y., & Spyropoulos, T. (2011). *Delay tolerant networks: Protocols and applications*. Boca Raton: CRC Press.
105. Villas, L. A., Boukerche, A., De Oliveira, H. A., De Araujo, R. B., & Loureiro, A. A. (2014). A Spatial correlation aware algorithm to perform efficient data collection in wireless sensor networks. *Ad Hoc Networks, 12*, 69–85.
106. Wang, Y.-C., Peng, W.-C., & Tseng, Y.-C. (2010). Energy-balanced dispatch of mobile sensors in a hybrid wireless sensor network. *IEEE Transactions on Parallel and Distributed Systems, 21*(12), 1836–1850.
107. Watfa, M. K. (2012). A position-based routing algorithm in 3D sensor networks. *Wireless Communications and Mobile Computing, 12*(1), 33–52.
108. Wei, G., Ling, Y., Guo, B., Xiao, B., & Vasilakos, A. V. (2011). Prediction-based data aggregation in wireless sensor networks: Combining grey model and Kalman filter. *Computer Communications, 34*(6), 793–802.

109. Wu, G., Lin, C., Xia, F., Yao, L., Zhang, H., & Liu, B. (2010). Dynamical jumping real-time fault-tolerant routing protocol for wireless sensor networks. *Sensors, 10*(3), 2416–2437.
110. Xiang, L., Luo, J., & Vasilakos, A. (2011). Compressed Data aggregation for energy efficient wireless sensor networks. In *8th annual IEEE communications society conference on sensor, mesh and ad hoc communications and networks (SECON)* (pp. 46–54).
111. Xiao, Y., Peng, M., Gibson, J., Xie, G. G., Du, D.-Z., & Vasilakos, A. V. (2012). Tight performance bounds of multihop fair access for mac protocols in wireless sensor networks and underwater sensor networks. *IEEE Transactions on Mobile Computing, 11*(10), 1538–1554.
112. Xiong, N., Vasilakos, A. V., Yang, L. T., Song, L., Pan, Y., Kannan, R., & Li, Y. (2009). Comparative analysis of quality of service and memory usage for adaptive failure detectors in healthcare systems. *IEEE Journal on Selected Areas in Communications, 27*(4), 495–509.
113. Xu, H., Huang, L., Qiao, C., Zhang, Y., & Sun, Q. (2012). Bandwidth-power aware cooperative multipath routing for wireless multimedia sensor networks. *IEEE Transactions on Wireless Communications, 11*(4), 1532–1543.
114. Xu, S., Hansen, B. J., & Wang, Z. L. (2010). Piezoelectric-nanowire-enabled power source for driving wireless microelectronics. *Nature Communications, 1*, 93.
115. Xu, S., Qin, Y., Xu, C., Wei, Y., Yang, R., & Wang, Z. L. (2010). Self-powered nanowire devices. *Nature Nanotechnology, 5*(5), 366–373.
116. Xu, X., Ansari, R., Khokhar, A., & Vasilakos, A. V. (2015). Hierarchical data aggregation using compressive sensing (HDACS) in WSNS. *ACM Transactions on Sensor Networks (TOSN), 11*(3), 45.
117. Yan, Z., Zhang, P., & Vasilakos, A. V. (2014). A survey on trust management for internet of things. *Journal of Network and computer Applications, 42*, 120–134.
118. Yang, M., Li, Y., Jin, D., Zeng, L., Wu, X., & Vasilakos, A. V. (2014). Software-defined and virtualized future mobile and wireless networks: A survey. *Mobile Networks and Applications, 20*(1), 4–18.
119. Yang, Y., Zhang, H., Lin, Z.-H., Zhou, Y. S., Jing, Q., Su, Y., et al. (2013). Human skin based triboelectric nanogenerators for harvesting biomechanical energy and as self-powered active tactile sensor system. *ACS Nano, 7*(10), 9213–9222.
120. Yao, Y., Cao, Q., & Vasilakos, A. V. (2013). EDAL: An energy-efficient, delay-aware, and lifetime-balancing data collection protocol for wireless sensor networks. In *IEEE 10th international conference on mobile ad hoc and sensor systems (MASS)* (pp. 182–190).
121. Yao, Y., & Gehrke, J. (2002). The cougar approach to in-network query processing in sensor networks. *ACM Sigmod Record, 31*(3), 9–18.
122. Younis, M., Youssef, M., & Arisha, K. (2002). Energy-aware routing in cluster-based sensor networks. In *Proceedings of the 10th IEEE international symposium on modeling, analysis and simulation of computer and telecommunications systems (MASCOTS 2002)* (pp. 129–136).
123. Yousefi, H., Yeganeh, M. H., Alinaghipour, N., & Movaghar, A. (2012). Structure-free real-time data aggregation in wireless sensor networks. *Computer Communications, 35*(9), 1132–1140.
124. Yu, Y., Govindan, R., & Estrin, D. (2001). *Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks*. Technical report UCLA/CSD-TR-01-0023. Computer Science Department: UCLA.
125. Zeng, Y., Xiang, K., Li, D., & Vasilakos, A. V. (2013). Directional routing and scheduling for green vehicular delay tolerant networks. *Wireless Networks, 19*(2), 161–173.
126. Zhang, B., Simon, R., & Aydin, H. (2013). Harvesting-Aware energy management for time-critical wireless sensor networks with joint voltage and modulation scaling. *IEEE Transactions on Industrial Informatics, 9*(1), 514–526.
127. Zhang, C. (2013). *Nonlinear oscillator for vibration energy harvesting*. Google Patents.
128. Zhang, X. M., Zhang, Y., Yan, F., & Vasilakos, A. V. (2015). Interference-based topology control algorithm for delay-constrained mobile ad hoc networks. *IEEE Transactions on Mobile Computing, 14*(4), 742–754.
129. Zhao, M., Li, J., & Yang, Y. (2014). A framework of joint mobile energy replenishment and data gathering in wireless rechargeable sensor networks. *IEEE Transactions on Mobile Computing, 13*(12), 2689–2705.
130. Zheng, G., Liu, S., & Qi, X. (2012). Clustering routing algorithm of wireless sensor networks based on Bayesian game. *Journal of Systems Engineering and Electronics, 23*(1), 154–159.
131. Zhou, L., Naixue, X., Shu, L., Vasilakos, A., & Yeo, S.-S. (2010). *Context-aware middleware for multimedia services in heterogeneous networks*. IEEE Intelligent Systems, 25(2), 40–47. doi:10.1109/MIS.2010.48.
132. Zhu, C., Zheng, C., Shu, L., & Han, G. (2012). A survey on coverage and connectivity issues in wireless sensor networks. *Journal of Network and Computer Applications, 35*(2), 619–632.

Mohammad Hossein Anisi is a senior lecturer at the Department of Computer System and Technology, Faculty of Computer Science and Information Technology, University of Malaya. He obtained his Ph.D. from Universiti Teknologi Malaysia (UTM) while being awarded as the best postgraduate student. He worked as post-doctoral research fellow at UTM and was a member of pervasive computing research group (PCRG), a research group under K-Economy Research Alliance in Malaysia. His research interests lay in the area of internet of things, wireless sensor networks and their applications, mobile ad hoc networks and intelligent transportation systems. He has also collaborated actively with researchers in several other disciplines of computer science.

Gaddafi Abdul-Salaam is currently pursuing his Ph.D. degree in the pervasive computing research group (PCRG) laboratory at the Faculty of Computing, Universiti Teknologi Malaysia, Johor, Malaysia. He received his M.Sc. degree in Advanced ICT studies from the Institute for Advanced ICT Studies, Ghana in 2009, and B.Sc. degree in Computer Engineering from the Kwame Nkrumah University of Science and Technology (KNUST), Ghana in 2005. He was also head of the ICT Centre in KNUST from 2010 to 2013. His research interests include wireless sensor network, hybrid WSN and energy efficient data collection protocols in WSN.

Mohd. Yamani Idna Idris currently is a senior lecturer at the Faculty of Computer Science and Information Technology, University of Malaya. He has been serving the university for more than 15 years. His research interests are in the area of sensor network, embedded system and image and signal processing.

Ainuddin Wahid Abdul Wahab earned his Ph.D. degree in Computing from University of Surrey, United Kingdom. He is currently a Senior Lecturer at the Department of Computer System and Technology, University of Malaya, Kuala Lumpur, Malaysia.

Ismail Ahmedy is one of the academic members in Department of Computer System and Technology, University of Malaya since 2007. He received his B.Sc. (Computer Science) from University Teknologi Malaysia in 2006. After completing his study, he has been granted a full scholarship to pursuing his studies in Master degree where he receives his M.Sc. (Computer Science) from University of Queensland, Australia. He obtained his Ph.D. in Universiti Teknologi Malaysia in Wireless Networks System specializing in wireless sensor networks in routing system.