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Ultra-low power techniques in energy harvesting wireless sensor networks: Recent advances and issues

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A B S T R A C T

Wireless sensor network (WSN) technology has gained increasing importance in industrial automation, agriculture, smart cities, environmental monitoring, target tracking, structural health monitoring, healthcare, military applications, and so on. WSNs powered by batteries have a problem of limited lifetime due to energy constraints. Energy harvesting technology aims to eliminate the burden of replacing or replenishing depleted batteries for the sensor nodes by harnessing energy from the environment. Ultra-low power techniques are aimed at prolonging the overall sensor network lifetime by yielding significant energy savings in the WSN. The performance and lifetime of energy harvesting wireless sensor networks (EHWSNs) can be enhanced by the development of Dynamic Power Management techniques. Energy management and conservation are critical issues in EHWSNs, hence the need to develop energy harvesting-aware protocols and algorithms that facilitate perpetual network operation. It is anticipated that advancements in miniaturization and ultra-low power techniques will drive the widespread adoption of the energy harvesting paradigm. This article provides a comprehensive review of recent advances towards ultra-low power techniques in EHWSNs. We explore some of the existing types of power management techniques in WSNs including their disadvantages. The operating principles of recently proposed applications of ultra-low power techniques in EHWSNs are reviewed along with their associated fundamental mathematical expressions and assumptions. An analysis of these recent ultra-low power schemes is also presented. For each of the techniques, a summary of strengths, weaknesses and proposed solutions is presented. We provide the research community with open research issues and future research directions as well.

1. Introduction

Recent advancements in miniaturisation have led to the manufacture of very tiny and cheap sensor nodes or motes. A Wireless Sensor Network (WSN) comprises of a number of deployed sensor nodes which are utilized for detecting environ-

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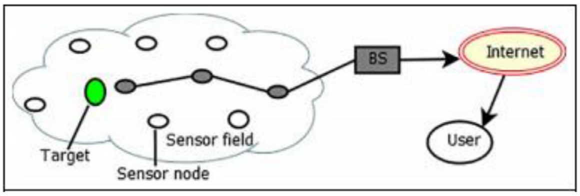

Fig. 1. Basic communication architecture of a WSN [38].

(a) (b)

Fig. 2. Snap shots of typical wireless sensor motes with (a) external solar panel (b) embedded solar panel [22]

mental conditions like motion, temperature, humidity, sound, pressure and for collectively delivering the gathered information to the intended user [39,14]. WSN technology has gained increasing importance in industrial automation, agriculture, smart cities, target tracking, structural health monitoring, healthcare, civil and military applications, and so forth [25,26].

Ultra-low power techniques are aimed at making the energy consumption in the WSN as minimum as possible. For WSNs to become truly ubiquitous and autonomous, several challenges and hurdles must be overcome [52]. In order to find a solution to the traditional finite lifetime problem, WSNs equipped with energy harvesting capabilities were recently introduced, leading to a new class of network called energy harvesting wireless sensor network (EHWSN) [43]. Some applications of WSNs require the deployment of thousands of sensor nodes. The sensor nodes usually rely on small non-rechargeable batteries as sole sources of power. However, the small batteries have limited energy storage capacity and the replacement process is very costly and inconvenient. In EHWSNs, wireless sensor nodes scavenge energy from environmental sources that include radio frequency (RF) sources, solar, vibrations and wind [26]. Energy conservation is one of the major challenges towards the successful implementation of WSNs since the tiny sensor nodes are constrained with resources such as energy, memory and processing capacities [24].

In WSNs, wireless communication may be used to deliver information between mobile sensor nodes. Mobile nodes cause rapid and dynamic change in network topology [50]. WSNs operate in stochastic (random) environments under uncertainty [30]. Therefore, these nodes are not always aware of the route to a destination. The wireless communication between the nodes may experience frequent failures and recoveries due to node mobility, additional signal propagation problems and energy constraints [40].

There are several techniques for minimizing energy consumption in a WSN that exist in literature [48,53,16]. However, the availability and quantity of energy required for uninterrupted network performance of WSNs remains a challenge. Communication between mobile sensor nodes is one of the major processes responsible for high energy consumption [28]. In WSN, routing is a very important task that has to be handled carefully [54]. Hence, proper routing between the mobile nodes is critical to avoid network failure. The greater the distance between the source nodes and the destination node, the greater the quantity of energy consumed during transmission. Several architectures of WSNs exist depending on the intended application.The basic communication architecture of a WSN is depicted in Fig. 1. Photographs of typical wireless sensor motes with solar energy harvesting capabilities are shown in Fig. 2.

Generally, it has been assumed that energy consumed during sensing is negligible compared to that consumed during communication. However, in some WSN applications the energy consumed by the sensing subsystem can be comparable or even greater than the energy consumed by the communication subsystem. So, development of ultra-low power techniques for minimizing energy consumption in EHWSNs is in progress [49].

In this article, we present a state-of-the-art review of recent ultra-low power techniques for maximizing the lifetime of EHWSNs. The main contributions of this review are as follows. The article explores some of the existing types of power management techniques in WSNs including their disadvantages. It presents the operating principles, fundamental mathematical expressions and assumptions of applications of recently proposed ultra-low power techniques in EHWSNs. An analysis of

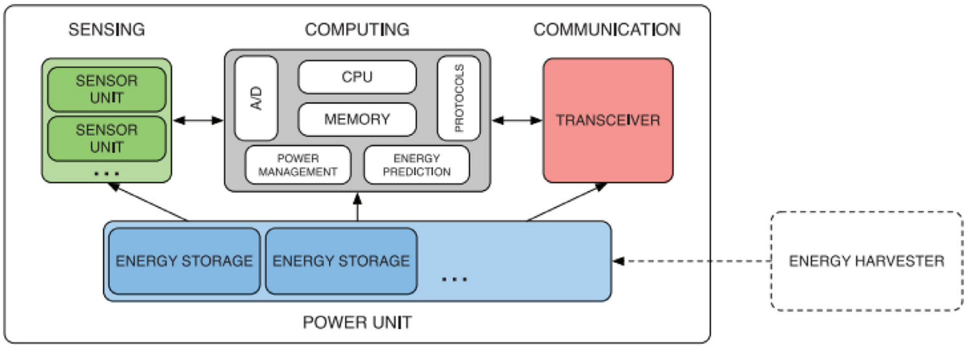

Fig. 3. Basic hardware architecture of an energy harvesting wireless sensor node. Adapted from [1].

the recent ultra-low power schemes is presented as well. The strengths and weaknesses of the recent schemes are identified. Solutions to the weaknesses of the schemes are then proposed. Open research issues and future research directions are articulated.

The rest of this paper is structured as follows. Section 2 discusses existing energy saving techniques. The operating principles, fundamental mathematical expressions and assumptions of applications of recent ultra-low power techniques in EHWSNs are then presented. An analysis of these recent ultra-low power schemes is also provided. In Section 3, open research issues and future research directions are presented. Finally, Section 4 provides the conclusion.

2. Ultra-low power techniques in EHWSNs

Traditionally, wireless sensor nodes are powered by small batteries and are hence energy constrained. In several application scenarios, these nodes are deployed in hundreds or thousands and are intended to operate for several years unattended. In such cases, manual battery replacement can be very costly, inconvenient or even impossible. Therefore, the rationale behind methods of ultra-low power consumption is to save harvested energy and prolong the overall sensor network life time. Fig. 3 shows the sensing, computing, communication and power supply subsystems of a typical energy harvesting sensor node. The major sources of energy waste in WSNs include idle listening, overhearing of unnecessary traffic, packet collision, and control packet overhead during transmitting, receiving and listening.

In this section, we review some of the existing types of power management techniques in WSNs including their disadvantages. The operating principles of recently proposed applications of ultra-low power techniques for enhancing the lifetime of EHWSNs are outlined briefly along with their respective fundamental mathematical expressions and conditions (assumptions) considered during their design. A brief analysis of each of these proposed applications is presented as well.

2.1. Existing Power Management Techniques in WSNs

In this sub-section, some of the existing power management techniques are briefly described. The disadvantages of using these energy saving techniques are also briefly explained.

2.1.1. Duty cycling

Duty cycling is a technique for reducing energy consumption in a WSN by periodically switching on and off transceivers of sensor nodes. Duty cycle refers to "the ratio between the duration when the sensor node is on and the sum of the times when the node is on and asleep" [19]. The transceivers operate in active, listen and sleep modes. Idle listening consumes a significant amount of energy [5]. The main concept behind duty cycling is to minimize energy wastage due to idle listening. Inactive nodes are put into sleep mode by switching off their radios.

However, the duty cycling approach has some disadvantages. Incoming messages may be blocked when the sensor node is in sleep mode since the receiver is switched off. Messages are also subjected to end-to-end delay during "sleep waiting". In the listening mode, the length of the queuing packets may increase. This in turn raises the chances of packet loss. Sleeping nodes may hinder the proper functioning of the entire or part of the WSN. Additional packet overhead is introduced by extra control traffic which is required during synchronization [33]. Also, the process itself of "transitioning of states" has additional power costs. Ultra-low duty cycles which save energy are not suitable for applications which require real time monitoring. Adaptive duty cycling may be exploited to minimize energy consumption. "Low power listening" is a promising technique for saving energy in low data rate scenarios.

2.1.2. Data aggregation

Data aggregation is a data reduction scheme for minimizing communication overhead. It is an approach that eliminates redundant data to reduce energy consumption and prolong the lifetime of WSNs [36]. Data aggregation is defined as the

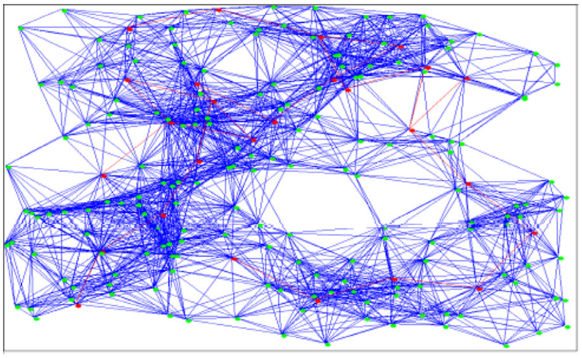

Fig. 4. Typical data aggregation tree proposed by [2].

process of "fusing data from multiple sensors to avoid redundant transmission to the sink node and, thereby, reduce the total energy cost" [32]. Neighbouring nodes may measure correlated data especially in dense sensor networks. Therefore, data aggregation saves energy by avoiding transmission of the same data by several nodes via multiple routes. A typical data aggregation tree proposed by [2] is shown in Fig. 4. The "aggregator sensor node" is shown in (red) while the "source sensor nodes" are indicated in (green).

Performance evaluation metrics used for data aggregation schemes include latency, energy consumption and data accuracy. Data aggregation has some drawbacks. All the aggregated data is lost if the CH suffers from a malicious attack. Energy consumption at the CHs responsible for data aggregation is increased. Various sensor nodes may send different versions of the same information to the node responsible for aggregating [8]. Also, this technique is not suitable for applications that demand high accuracy because recovering original data sent to the BS is a complex task.

2.1.3. Data compression

The quantity of energy consumed by a transceiver in a WSN strongly depends on the size of the transmitted data packets and the transmission distance. Data compression focusses on reducing the size of the sensed data. In this technique, information is encoded at the source nodes and decoded at the BS [27]. Communication energy is usually minimized at the expense of increased computational energy. "Compressed sensing" and "distributed compressed sensing" are potential strategies for enhancing energy efficient sensing in WSNs [34]. These strategies utilize the "sub-Nyquist sampling rate" and high accuracy of the recovered signal is guaranteed. However, energy is saved at the cost of data transmission latency especially for applications that require real time monitoring.

2.1.4. Data prediction

Data prediction is a strategy that conserves energy in WSNs by reducing the number of data transmissions [13]. In this strategy, algorithms are utilized to approximate future data values based on historical data and parameters. Energy saving is achieved in the sense that only those sensor nodes whose sensed data values considerably deviate from the predicted values are allowed to transmit. Prediction mechanisms allow certain assumptions made during data observation to be considered in the prediction models. This improves the prediction accuracy of the models. "Adaptive filters" are also employed to estimate data at both the cluster member and the CH [9]. Stochastic and "time series forecasting" algorithms are some of the examples of algorithms that are used for data prediction to minimize the frequency of data transmissions in WSNs [29]. However, reducing the frequency of transmissions may compromise the quality of the information obtained from CHs. Prediction algorithms also introduce extra computational cost.

2.1.5. Dynamic Scaling

"Dynamic voltage scaling (DVS)" and "dynamic frequency scaling (DFS)" techniques focus on adjusting the supply voltage and clock frequency of subsystems of a wireless sensor node based on the instantaneous and predicted workload [7]. The processor of a sensor node is not always required to execute scheduled tasks at its peak capacity [20]. Running the processor at peak supply voltage and frequency causes unnecessary consumption of energy. Therefore, the operating voltage and frequency of the processor should be adjusted according to the current "computational load requirements". Dynamic voltage-frequency scaling (DVFS) is a technique that utilizes software to minimize the average power consumption in a WSN by appropriately adjusting both the voltage and the frequency of operation [51]. However, reducing the operating voltage causes an increase in latency of executing scheduled tasks. Hence, power consumption should be carefully managed to avoid degrading overall performance of the WSN. In addition, complex workload prediction methods are "computation-intensive" [7] and require extra storage space which is not available in wireless sensor nodes.

2.2. Recent ultra-low power schemes in EHWSNs

In this subsection, we present the operating principles, fundamental mathematical expressions and assumptions of recently proposed applications of ultra-low power techniques in EHWSNs. An analysis of each of these schemes is also provided.

2.2.1. Achieving energy-neutral data transmission by adjusting transmission power for EHWSNs

(Tan et al.,2016) considered the issue of minimizing the overall data transmission cost by adjusting transmission power of nodes in EHWSNs. The authors considered the optimization problem of deriving the energy-neutral minimum cost paths between the source nodes and the sink node. A polynomial-time optimal algorithm for finding the optimal path from a single source node to the sink by adjusting the transmission powers was proposed. On the basis of "energy-neutral operation" [18], the authors proposed concepts of energy-neutral node, energy-neutral path, and the energy-neutral minimum cost path.

Assumptions: It is assumed that nodes are randomly deployed over a square field; the source and sink nodes are positioned at opposite sides of the field; each sensor node has an energy buffer with initial energy of 2000 J (Tan et al.,2016); the time period T is set as 1 day; source node generates 200 kB packets of the gathered data and transmits them to the sink through the selected multi-hop path; each node obtains its local information including its position by a GPS module or a localization service provided by the network [21]; the energy consumption for gathering local information is not considered; the sink node has enough energy and will not be depleted of energy. In this protocol, the authors developed three different algorithms for choosing the optimal path to a destination or sink.

Analysis: The algorithm proposed by [42] focused on obtaining optimal paths by implementing transmission power control of sensor nodes based on residual energy. The authors conducted extensive simulations to validate the algorithm. The algorithm showed improved performance by trying to achieve energy-neutral operation. It attempts to ensure that the energy consumed by a node does not exceed the scavenged energy. However, energy consumption in obtaining node location information is not considered in this algorithm.

2.2.2. Novel Energy Efficient Clustering (NEEC) algorithm

[4] proposed a "Novel Energy Efficient Clustering (NEEC)" algorithm for EHWSNs. This hierarchical routing protocol involves the handling, setup and data transmission phases. The base station (BS) is responsible for the handling phase while the other phases are performed in a distributed fashion.

Assumptions and mathematical formulations: The network comprises of randomly deployed motes; the area of the field is fixed; the BS has unlimited power supply and is part of the network; the network is homogeneous; the BS and motes are immobile; the transmission power of the motes is adjustable; a CH performs data aggregation; motes are aware of their location information; renewable energy is available and varies; sensor nodes can harvest solar energy; the harvested energy can be stored; the power consumption during data measurement and creating packages is negligible. NEEC adopted LEACH's [15] radio model for energy consumption. The authors proposed that the quantity of energy of an energy harvesting sensor node i in the r^{th} round, $E_{rem}(i, r)$ is given by eq. (1):

$$E_{rem}(i, r) = (\min(E_{max}(i),\ E_{rem}(i, r-1) + (E_{EH}(i, r-1)) \tag{1}$$

Where $E_{EH}(i, r-1)$ denotes the energy scavenged by node i in the previous round and $E_{max}(i)$ is the full energy capacity of the battery for sensor node i. The quantity of the harvested energy ($E_{EH}(i, r-1)$) and the rate of energy harvesting (μ_i) are expressed in eq. (2) and eq. (3) respectively:

$$E_{EH}(i, r-1) = \mu_i \Delta t \tag{2}$$

$$\mu_i = rand\left(P_{h,min}(r-1), P_{h,max}(r-1)\right) \tag{3}$$

Where $P_{h,min}(r-1)$ and $P_{h,max}(r-1)$ are the probable minimum and maximum energy harvesting rates for all nodes during the$(r\ -1)^{th}$ round respectively. Δt denotes the time taken by a round. The energy scavenging nodes possessing energy not exceeding a particular minimum threshold are temporarily forced to be inactive until their energy reaches the desired level.

Analysis: In the protocol for EHWSNs proposed by [4], clustering is done both in a distributed and centralised manner. The authors utilized multi-hop routing and CHs are chosen based on the current energy level of the sensor nodes. In this protocol, extra power consumption is introduced when performing computations for cluster layering and establishing neighborhood information. However, simulations performed by the authors indicated improved network throughput.

2.2.3. Joint optimal placement, routing, and energy allocation in wireless sensor networks with a shared energy harvesting module

The algorithm developed by [45][a] concurrently "minimizes the number of nodes and maximizes the data sampling quality under energy-neutral working settings (MNMQN)". MNMQN ensures the total energy consumed by nodes does not surpass the energy scavenged.

Assumptions and mathematical formulations: A single energy harvesting module together with its associated battery is shared among the deployed sensor nodes; the module is connected to a single storage battery; the harnessed energy is periodically allocated to the deployed nodes; the size of the data packets changes. In this algorithm, the authors proposed that "the ratio of the information quality to the total energy consumption (ζ)" is given by eq. (4):

$$\zeta = |Q(S)| / \sum_{i=1}^{N} \eta_i \bar{E}_i^{th} \tag{4}$$

Where E_i represents the energy ultimately allocated to node i; η_i gives a measure of the energy lost during transmission of energy to the battery and $0 \leq \eta_i \leq 1$; node i receives energy equal to $\eta E_i . \bar{E}_i^{th}$ is the energy request for every generated and selected feasible solution, $|Q(S)|$ is the "Fisher information matrix (FIM) determinant" for a certain group of elected nodes; $\sum_{i=1}^{N} \eta_i \bar{E}_i^{th}$ denotes the overall energy exhausted by N nodes. The highest figure of ζ is chosen to be the optimum value.

Analysis: [45][a] developed an algorithm in EHWSNs for structural health monitoring applications. In this algorithm, the deployed wireless sensor nodes derive energy from a shared energy harvesting node. The efficient distribution of the harvested energy among sensor nodes improves the network lifetime. One of the challenges is that the energy requests by nodes introduce extra overhead.

2.2.4. Power allocation and relay selection algorithm for energy efficient cooperation in wireless sensor networks with energy harvesting

A "power allocation and relay selection for energy efficient cooperation in wireless sensor networks with energy harvesting" algorithm (also known as COOP diversity) was proposed by [46][b]. In this algorithm, authors utilized clustering techniques proposed by [15]. Energy harvesting nodes transmit data to their respective CHs. Cooperating relay nodes are selected by CHs so as to optimise the consumption of energy harvested in the network. The source CH chooses a cooperating relay node and the CH transmissions are accomplished via multi-hop routing to the BS.

Analysis: The cooperative protocol developed by [46][b] chooses appropriate relay nodes depending on node's current energy and efficiently allocates required transmission power to nodes. The proposed approach reduces energy wastage and residual energy is increased. Accordingly, network lifetime is increased.

2.2.5. Energy Aware Distributed Clustered Routing Protocol Mechanism based on Neural network-solar energy prediction model

A novel "Energy Aware Distributed Clustered Routing Protocol Mechanism based on Neural network-solar energy prediction model" was proposed by [3]. In this protocol for EHWSNs, CHs are chosen based on the prediction of the quantity of solar energy to be harvested as well as the residual energy of a sensor node. The authors [3] utilized this prediction model to improve energy efficiency in the network. In this cluster-based protocol, matrices for solar energy prediction are built based on measurement data. CHs broadcast adverts, member nodes determine their CHs, after which, the data transmission phase begins.

Assumptions and mathematical formulations: It is assumed that the BS is static and has unlimited power supply; all sensor nodes are capable of adjusting their transmission power; all nodes have enough power for processing signals and can harvest solar energy from the environment; sensors detect physical conditions at a constant rate. The energy harnessed by a node i in a particular round (r) and day (d), $(E_{pre}(i, d, r))$ is as given in equation (5).

$$E_{pre}(i, d, r) = f_{ANN}(E_{harv}(i, d-1, r), \ldots, E_{harv}(i, d-n, r), \; E_{harv}(i, d, r-1), \ldots, E_{harv}(i, d, r-k)) \tag{5}$$

Where $E_{harv}(i, d, r-1)$ denotes the scavenged energy in the $(r-1)^{th}$ round of the i^{th} node. n and k represent the numbers of previous days and rounds respectively. CHs are selected based on probability by using eq. (6):

$$P(i, d, r) = \frac{P}{1 - P * \left(r mod \frac{1}{P}\right)} * \frac{\alpha E(i, d, r-1) + \beta E_{pre}(i, d, r) - E_{TX}(k, d_{ibs})}{E_{cap}} \tag{6}$$

$E(i, d, r-1)$ is the unused energy after $r-1$ rounds; $E_{pre}(i, d, r)$ is the predicted harnessed energy as a function of round r, day d and i; d_{ibs} is the distance between node i and the BS. $E_{TX}(k, d_{ibs})$ is the amount of energy required by node i to send k-bits of data to the BS; E_{cap} represents the "energy capacity of each node"; α and β are contributory coefficients of their respective parameters.

Analysis: The cluster-based algorithm proposed by [3] applies a neural network-based solar energy prediction model for choosing CHs in EHWSNs. The authors demonstrated that the cluster-based approach balances energy consumption among nodes and network throughput is improved. However, the intermittent nature of solar energy was ignored by the authors. The algorithm can be improved by utilizing more accurate solar prediction models.

2.2.6. Optimal Routing for Time-Driven EH-WSN under Regular Energy Sources

[10] proposed an "optimal routing protocol for Time-Driven EH-WSN under Regular Energy Sources". This protocol operates in such a way that nodes regularly detect the environmental conditions and cooperatively transmit information to a sink. The authors prioritised the concept of Minimum Hop Count (MHC). The so-called "energy-neutral condition" for EHWSN is applied in this routing protocol.

Assumptions and mathematical formulations: The authors assumed that traffic is equally shared among the nodes in the network; energy lost by nodes during transmission of the gathered data is independent of the distance to the receiver; the distance separating a source node and its destination node is irrelevant as long as it is within the transmission range; power consumption by a node is independent of time; there is a regular energy supply during an energy-harvesting period (T_s). The authors formulated the "Energy-Neutral Operation" as given in eq. (7):

$$E(T_s, X) = (E(0, X) + \int_0^{T_s} P_{out}(u, X)du - \int_0^{T_s} \frac{E_{round}}{T_{rnd}} du \tag{7}$$

Where $E(0, X)$ is node X's initial energy, P_{out} is the harvested power, T_{rnd} represents the time spent during a communication round, E_{round} is the total energy utilized during that round.

Analysis: The routing protocol for EHWSNs proposed by [10] mainly focusses on the minimum hop count to reduce network delay and increase network throughput. The author validated the results through simulations. Variation of solar energy was not considered in the protocol. Large duty cycles of sensor nodes increased the overall energy consumption and therefore significantly reduced network lifetime.

2.2.7. Energy Storage Overflow (ESO)-aware Multiple Path (EAMP) Protocol

The "Energy Storage Overflow (ESO)-aware multiple path (EAMP) protocol" by [23] utilizes a data delivery technique in which several routes from the source node to the BS are formed. The sensed data is split and transmitted through the different routes. This technique, according to the authors, assists in mitigating ESO and alleviating the "energy hungry and surplus co-existence" problem. This problem refers to a scenario where some sensor nodes are starved of energy while some other nodes within the same WSN have reached their energy storage capacity and can no longer accommodate the extra energy being harvested [23].

Assumptions and mathematical formulations: It is assumed that all nodes are capable of harnessing energy from the environment; each node can store a certain amount of the scavenged energy; the EHWSN has one sink and a number of sensor nodes; several routes from source node to the sink exist; the source node is supposed to transmit bits to the BS over several paths. According to the authors, the energy consumed when sending u bits of data to a destination node at a distance d away is expressed in eq. (8):

$$E_{Tx}(u, d) = u(\varepsilon_0 + \varepsilon_1 d^{\gamma}) \tag{8}$$

while the energy utilized in receiving u bits is given by eq. (9):

$$E_{Rx}(u) = u\varepsilon_0 \tag{9}$$

where ε_0 represents the energy consumption during digital signal processing; ε_1 is the energy utilized by the power amplifier of the transmitter; the parameter γ is a path loss exponent which varies from 2 to 4. The "energy storage overflow" at node $(i, \ j)$, $\hat{E}_{(i,j)}$ [23] is calculated using eq. (10):

$$\hat{E}_{(i,j)} = \left[P_{b(i,j)} + H_{(i,j)} - E_{\{i,j)}(\varphi) - B\right]^+ \tag{10}$$

where B represents the energy storage capacity of the node and the function "[.]$^+$" is expressed by: $[y]^+ = \{\begin{smallmatrix} y, & y > 0; \\ 0, & y < 0. \end{smallmatrix}$

After transmitting data, the remaining energy of node (i, j) is computed using eq. (11):

$$P_{a(i,j)} = P_{b(i,j)} + H_{(i,j)} - E_{\{i,j)}(\varphi) - \hat{E}_{(i,j)} \tag{11}$$

The authors [23] also proposed that after the "Data Delivering Decision", the "energy storage overflow" at node Z is expressed in eq. (12):

$$\hat{E}_{(Z)} = \left[P_{b(Z)} + H_{(Z)} - \sum_{i=1}^{k} E_i(\varphi) - B \right]^+ \tag{12}$$

where $P_{b(Z)}$ and $H_{(Z)}$ denote the residual energy of node Z before data delivery and the incoming energy during the period of data transmission at node Z, respectively. The residual energy of node Z after transmitting data is calculated using eq. (13):

$$P_{a(Z)} = P_{b(Z)} + H_{(Z)} - \sum_{i=1}^{k} E_i(\varphi) - \hat{E}_{(Z)} \tag{13}$$

Analysis: The data delivery scheme proposed by [23] addresses the problem of energy storage overflow due to overcharging of small capacity batteries in EHWSNs. The performance evaluation of the authors shows that use of a number of data delivery routes increases the quantity of residual energy and network running time. However, the source node is subjected to computation complexity when coming up with a decision on the optimal data delivery paths. This introduces additional energy consumption in the sensor network.

2.2.8. Solar Energy Harvesting for Smart Agriculture Monitoring (SHE-WSN) Protocol

The "Solar Energy Harvesting for Smart Agriculture Monitoring (SHE-WSN)" protocol proposed by [37] is based on the dynamic source routing (DSR) protocol [17] and IEEE 802.15.4 standard communication protocols. The sensed data is delivered to a gateway or sink node through a multi-hop routing technique. The sensing procedure of the nodes is guided by the duty cycle. In this protocol, batteries of the sensor nodes are recharged through solar energy harvesting. *Assumptions and mathematical formulations:* All the sensor nodes are immobile at remote sites; the destination node has unlimited power supply; there is direct communication between the gateway node and all the sensor nodes deployed in the field; The energy utilized by the WSN per day (E_n) is computed using eq. (14):

$$E_n = P_c + \lambda.E(E_s) \tag{14}$$

Where P_C denotes the power utilized by the sensor nodes in the field, λ represents the rate at which packets arrive, and $E(E_s)$ is the expected amount of energy to be consumed by all the nodes. For a WSN, the average network lifetime $E(L)$ in days [6] is expressed in eq. (15):

$$E(L) = (E_0 - E(E_w))/E_n \tag{15}$$

Where E_0 is the energy of the WSN before data transmission is initiated and $E(E_w)$ is the amount of the energy expected to remain just after network failure.

Analysis: [37] performed simulations of a zigbee-based solar energy harvesting WSN for smart agriculture. The authors demonstrated that solar energy harvesting significantly improves the network throughput and lifetime. However, increasing the duty cycle of sensor nodes reduced the network lifetime.

2.2.9. Finer Force Care-up (FFC) in underground mining

The "Finer Force Care-up (FFC) in underground mining" protocol proposed by [31] estimates the quantity of available energy for each sensor node and shares the overall collected energy in the whole WSN for underground mining. In this protocol, a sink node perceives battery power from the neighbour sensor nodes using wireless power transfer technology by means of a microwave power transmitter. The authors used the Monte-Carlo-Localization method to compute the distance between the BS and each sensor node.

Assumptions and mathematical formulations: The nodes form a random grid topology and from that, one node acts as a sink node; the sink node equally distributes perceived energy to neighboring sensor nodes; all the sensor nodes and the sink nodes are static. The energy consumed during a transmission is computed using eq. (16):

$$Sensornodeenergy\ consumption = \sum_{i=0}^{N} (Et_i + Er_i/packetsize) \tag{16}$$

Where E_t is the energy transmitted, E_r is the energy received, and N represents the total number of wireless sensor nodes. The energy E distributed to each sensor node is given by eq. (17):

$$E = AE/N \tag{17}$$

where AE is the energy available in the sink node.

Analysis: The method proposed by [31] utilizes wireless energy transfer for sharing of energy among the sensor nodes. Computations of distance between nodes and energy consumed during packet transfer are performed by a localization algorithm. These computations introduce extra energy consumption in the network. Simulation results presented by the authors showed that the algorithm improved the packet delivery ratio and network lifetime. However, the algorithm does not support mobility and the quantity of energy harvested in underground mining environments remains a challenge. Also, the wireless energy transfer technique has limited transmission range and therefore requires nodes to be very close to each other.

2.2.10. Learning automata (LA) theory-based stable and energy-efficient routing algorithm for discrete EH-mobile WSN (DEH-LA-SERA)

[11] proposed a "learning automata (LA) theory-based energy-efficient and stable routing algorithm for discrete EH-mobile WSN (DEH-LA-SERA)". In this algorithm, a relay node is chosen based on probability. LA theory is utilized to obtain the optimal path.

Assumptions: In this algorithm, the authors assumed that all sensor nodes are deployed in a 2-dimensional rectangular situation and transmit data through a shared broadcast channel using omni-directional antennas; the source node and the sink are not mobile; the network is homogeneous; the impact of an interference range is ignored.

Analysis: A learning automata theory-based algorithm proposed by [11] caters for mobile sensor nodes and discrete energy harvesting environments. However, if the speed of the mobile sensor nodes increases, end-to-end delay also increases.

2.2.11. An Energy-Efficient Cluster Head Selection Scheme for Energy-Harvesting Wireless Sensor Networks

[55] proposed a cluster-based scheme which introduced the concept of a scheduling node (SN) for each cluster to reduce CH workload. A SN keeps track of information about the residual energy of cluster members and CHs. In this proposed

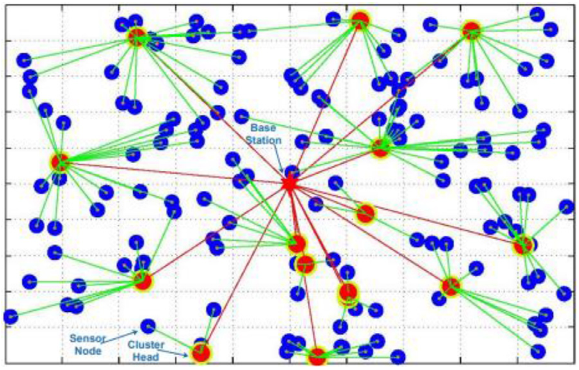

Figure 5. Typical deployment scenario of wireless sensor nodes. Source [35].

approach, residual energy is also considered in CH selection. Inorder to conserve energy, the communication radius of all the sensor nodes is adjusted dynamically. Simulations were performed in NS3 platform.

Analysis: CHs and cluster members in this approach have an option of "one-hop" routing to the BS during instances when their batteries are fully charged. Therefore, latency in the WSN is reduced. The obvious fact that energy consumption by the nodes should not exceed harvested energy was ignored in this scheme. If the energy consumed is greater than the harvested energy, the node dies.

2.2.12. A novel energy harvesting clustering protocol (NEHCP)

[35] proposed a hierarchical clustering algorithm capable of harvesting solar energy. A CH is chosen based on the residual energy and energy harvesting rate. Data is transmitted to the BS through either single-hop or multi-hop routing. A typical deployment scenario indicating sensor nodes, CHs and base station is shown in Fig. 5.

Assumptions and mathematical formulations: Nodes are randomly deployed in a large field; nodes have the same quantity of initial energy; all sensosor nodes and BS are static; each node is capable of harvesting solar energy; in most of the rounds, energy consumption rate is greater or equal to the energy harvesting rate.

LEACH's [15] radio energy model was adopted by the authors. The battery energy level of node i in the current round r, $E_{battery}(i, r)$ is given by equation

$$E_{battery}(i, r) = E_{battery}(i, r-1) - E_{active}(i, r-1) - E_{sleep}(i, r-1) + E_{har}(i, r-1) \tag{18}$$

Where $E_{battery}(i, r-1)$ is the battery energy level of node during the active mode of operation, $E_{har}(i, r-1)$ is the energy harvesting rate of the sensor node. $E_{active}(i, r-1)$ and $E_{sleep}(i, r-1)$ denote energy consumed during active and sleep modes in the previous round respectively.

Analysis: In this scheme, CHs are selected based on energy-related metrics. This enhances the the overall WSN lifetime The authors did consider the fact that solar energy harvesting rate varies according to the prevailing weather conditions. Simulation results by the authors showed improved network lifetime. However, some energy saving techniques like duty cycling of the listening mode of operation of a sensor node were not considered in this scheme.

2.2.13. Energy efficient multi-attribute based clustering scheme for energy harvesting wireless sensor networks(E^2*-MACH)*

The cluster-based E^2-MACH scheme presented by [12] elects CHs by considering the signal-to-noise ratio (SNR) of a communication link, rate of energy scavenging, remaining energy and density of surrounding nodes. The proposed scheme focusses on improving energy efficiency and communication reliability. Simulations were performed using NS2 tool.

Assumptions and mathematical formulations: All the nodes are homogeneous and are capable of scavenging energy; sensor nodes are deployed in a random manner and have the ability to perform data aggregation; the BS and nodes are immobile in the network; solar energy can be harvested 24 hours a day. The authors adopted a "first-order energy consumption model" [15] and the popular "Exponentially Weighted Moving Average" [18] as the energy harvesting prediction model which is presented in eq. 19).

$$E_{curr}(i, r) = E_{curr}(i, r-1) + E_{har}(i, r-1) \tag{19}$$

where $E_{curr}(i, r)$ represents the initial energy of sensor node i at the onset of round r, $E_{har}(i, r-1)$ is the energy scavenged by a sensor node in the preceding round $(r-1)$ and is expressed by eq. (20).

$$E_{har}(i, r-1) = HR_i(\Delta t) \tag{20}$$

where HR_i denotes the energy harvesting rate of node i during the preceding round and Δt is the round duration.

Analysis: One of the unique features in this protocol is that it considers the SNR of commucation links so as to shun the use of poor links for data transfer between sensor nodes. In that manner, energy consumption is minimized since the frequency of re-transmission of lost packets is reduced. According to the simulations conducted by the authors, the clustering scheme resulted in increased residual energy, reduced packet loss and improved WSN stability. However, in this approach extra overhead is incurred due to “message broadcasting”. The proposed cluster-based scheme assumes that sensor nodes can harvest solar energy 24 hours daily which is unrealistic. Also, the protocol is not applicable to mobile node scenarios.

A summary of the strengths, challenges and the proposed solutions for these recent techniques for improving lifetime of EHWSNs is presented in Table 1.

3. Open Issues and Future Research Directions

A number of issues and challenges still exist towards achieving unlimited lifetime of EHWSNs. In this section, we discuss some of these issues and point out the future research directions.

3.1. Stochastic Nature of Environmental Energy

Most of the existing routing techniques always assume a continuous energy harvesting mode for sensor nodes. Therefore, there is need to design techniques that take into consideration the stochastic and scarce nature of environmental energy. The techniques should be able to handle uncertainties in the harvested energy without prior knowledge of its distributions. Development of efficient techniques for the discrete energy scavenging mode and ensuring energy conservation and balance in the entire sensor network remains a major challenge that requires solutions. Different stochastic algorithms should be explored and their advantages be combined to develop optimised stochastic algorithms for power scavenging WSNs.

3.2. Mobility of Wireless Sensor Nodes

Applications that include animal tracking and intelligent transportation require mobile sensor nodes. Most of the protocols reviewed in this paper assume that the source node is static which may not always be the case in real applications. Hence, the need to explore techniques that support mobility of wireless sensor nodes and provide periodic neighbourhood information. In order to maximise the network lifetime, neighbour sensing and topology information may be utilized but, of course, with little overhead.

3.3. Use of a Hybrid of Energy Harvesting Systems

Use of a single energy harvesting source for powering WSNs is unreliable. For instance, availability of solar energy varies according to time of the day, season, location, and so forth. RF energy is available almost everywhere but the major challenges are its low power density and fluctuations. Utilization of a hybrid of energy harvesting systems significantly contributes towards achieving perpetual network operation of self-powered WSNs.

3.4. Dynamic Power Management Strategies

Utilization of Dynamic Power Management (DPM) techniques (dynamic operation modes and dynamic scaling) that force some of the subsystems to function at the most economical power modes or switch them into a sleeping mode can help extend the lifetime of EHWSNs. Dynamic voltage scaling and dynamic frequency scaling complement the dynamic operational modes approach. Most of the inefficient activities in a WSN are a result of non-optimal software and hardware configurations. For example, an idle processing or communication subsystem causes a considerable amount of power consumption. This issue of power consumption can be tackled by identifying activities in the WSN that are both wasteful and unnecessary so as to minimize their impact.

3.5. Prediction Models for Energy Harvesting

Designing of prediction models for energy harvesting in WSNs is still a challenge due to the stochastic nature of the energy harnessed from the environment. Implementation of energy-aware duty cycling mechanisms also remains difficult if the energy source of the tiny sensor nodes is the harvested energy. This introduces “erratic sleep and wake-up cycles because the level of energy remaining in the nodes may not be known a priori [5]”.

3.6. Consideration of Node Failure Probability

In inaccessible, remote and hazardous environments where sensor nodes are randomly dropped from high altitudes, the existing protocols need to consider node failure probability. The deployment process itself may result in hardware failure. The functionality of the nodes may also be affected by changes in temperature, pressure and humidity.

Table 1
Strengths, challenges and proposed solutions for recent routing protocols of EHWSNs.

Protocol, year & reference	Strengths	Challenges	Proposed solutions
"Achieving energy-neutral data transmission by adjusting transmission power for EHWSNs [42]"	Energy-neutral operation is guaranteed; high path capacity	Longer path characteristic; Stochastic nature of harvested energy is not considered; not suitable for mobile nodes	Adoption of clustering approach for largescale networks so that the proposed centralized algorithms can be applied effectively.
"NEEC algorithm [4]"	CH selection is guided by the node's current energy level and energy harvesting rate; Nodes with low energy levels are not chosen as CHs; Balanced energy consumption among all nodes; avoids direct transmission for long distances by utilizing multi-hop transmission	Extra overhead is introduced when all nodes compute their distance from the sink based on received signal strength and when all the nodes transmit messages including location information to the sink; calculations during the layering of nodes causes extra overhead processing; network performance is degraded during cloud conditions and at night; no mobility support.	Utilization of a multi-source energy harvester; Development of algorithms that consider the stochastic nature of environmental energy & rapid topological changes to handle mobility of nodes.
"Joint optimal placement, routing & energy allocation in WSNs with a shared EH module [45][a]".	Shares the scavenged energy efficiently among the nodes; reduced probability of network failure; higher quality of information	No mobility support since it is designed for structural health monitoring; When the energy required by the WSN is above the harnessed energy, the network voids and accidents may occur.	Use of multiple access control protocols for EHWSNs and consideration of clustering techniques
COOP diversity [46][b]	Energy consumption is reduced by deploying a relay node almost halfway between the source node and the sink; the amount of residual energy of the nodes is increased.	Does not achieve energy efficient network-wide cooperation. Does not cater for mobile nodes.	Integrating with other optimization algorithms; consideration of multi-objective techniques for node deployment in the cooperative EHWSN
"Energy Aware Distributed Clustered Routing Protocol Mechanism based on Neural network-solar energy prediction model [3]"	Balanced energy consumption among sensor nodes; increased network throughput	During the night, network throughput decreases; the BS may be very distant causing a high-energy transmission.	Use of a hybrid of energy harvesting systems; utilizing alternative solar energy prediction models to obtain a better prediction accuracy; consideration of seasonal change in solar irradiance.
Protocol, year & reference	Strengths	Challenges	Proposed solutions
"Optimal Routing for Time-Driven EH-WSN under Regular Energy Sources" [10]	Minimum hop count reduces the average traffic load through the network and increases the average duty cycle of the sensor nodes; better scalability; traffic load is uniformly distributed across the whole EHWSN	Does not cater for non-regular energy sources, transmission impairments and poor energy situations; there is no power control for transmit nodes.	Use of energy harvesting prediction algorithms to obtain estimates of future energy intakes; dynamic duty cycling mechanisms; appropriate adjustments of the routing topology.
EAMP [23]	Total ESO is minimized and total residual energy is maximized; Delivers more data than most existing schemes; Data is delivered over multiple routes thus enhancing network lifetime.	Performance may be degraded when several source nodes concurrently transmit data to their respective destination nodes; data delivery during the night may be interrupted because of unavailability of solar energy.	Use of a hybrid of energy harvesting systems.
SHE-WSN [37]	Reduced number of packets dropped; improved network throughput by 31.42 times due to EH; increased network lifetime of 115.75 days as compared to 5.75 days without EH.	Increased total energy consumption in the entire network; Solar alone is intermittent in nature.	Solar energy harvesting aware multiple access control protocols; techniques for reducing the energy consumed at sensor node-level; integrated circuits for power management of SEH-WSNs; renewable energy-based IoT.
FFC [31]	Energy sharing increases network lifetime; High packet delivery ratio and speed	Performance of the protocol decreases as mobility of nodes increases; For small packet sizes, performance is below that of AODV and DSR.	Utilization of mobility support mechanisms
DEH-LA-SERA, [11]	Network-wide energy balance and conservation; improved route stability; supports mobility of sensor nodes; performance is not degraded in discrete energy scavenging environments	An increase in node velocity reduces the amount of energy remaining in the node, the packets delivery ratio, route survival chance, and increases the energy variance and end-to-end latency; Only considers the case where both the source and destination nodes are static.	A cross-layer quality of service routing algorithm for discrete energy scavenging mobile EHWSNs; utilization of both solar and RF energy harvesting techniques

(continued on next page)

Table 1 (*continued*)

Protocol, year & reference	Strengths	Challenges	Proposed solutions
EECHS (Ren et al., 2020)	Energy consumption during CH selection is reduced; workload of CH is decreased; if storage battery is full, data is send directly to BS; reduced network latency; reduced packet loss	If energy consumed by a node exceeds the harvested energy, the node dies (Energy-netral operation is not considered); Mobile nodes are not catered for.	Consideration of energy-neutral operation and mobility support to cater for unmanned aerial vehicles.
Protocol, year & reference	Strengths	Challenges	Proposed solutions
NEHCP [35]	Improved network lifetime and stability; clustering reduces energy consumption; improved throughput	Solar energy is unavailable during the night; mobility of nodes is not considered	Utilization of a hybrid of efficient energy harvesters; modification to cater for mobility of nodes
E^2-MACH [12]	Reduced packet loss; enhanced WSN stability & lifetime; increased residual energy.	Message broadcasting overhead; extra energy consumption during CH selection; assumes solar energy is available 24 hours a day; No mobility support.	More accurate solar energy prediction models; utilization of multi-source energy harvesting systems; modification to support mobility.

3.7. Modification of Simulation Tools for EHWSNs

There is need for further modification of recent simulation and emulation tools like SolarCastalia Simulator [47], Network Simulator 3 (NS-3) [44], COOJA [41] and OMNeT++ [6] so that they accurately depict network behavior. Further development of simulation tools that cater for different energy harvesting techniques and transfer is still an open research area.

3.8. Hardware Implementation of the Protocols for EHWSNs

Most research conducted over the past years focused mainly on simulations and theoretical aspects without real world implementation of EHWSNs. Moreover, the few experimental evaluations of the proposed protocols were mostly implemented at small scales. Hence, large-scale practical evaluation of the already existing and new protocols for EHWSNs remains an open research area.

In light of the above, improved techniques that cater for different network scales, traffic patterns, node mobility speeds and energy harvesting environments should continue to be explored.

4. Conclusion

EHWSNs are gaining increasing importance in a wide range of new applications. Ultra-low power techniques are aimed at minimizing energy consumption in the EHWSN as much as possible. Although a number of energy management and harvesting techniques for EHWSNs have been introduced in recent years, the quantity of energy required for perpetual network operation remains a challenge. Therefore, appropriate ultra-low power techniques for the achievement of unlimited lifetime of EHWSNs in different real-life situations should continue to be developed. In this paper, we presented a concise review of recent advancements towards ultra-low power techniques that enable perpetual operation of EHWSNs. Some of the existing types of energy saving techniques were explored and analyzed. Mathematical expressions and assumptions underlying the operating principles of the various techniques were presented. For these existing techniques, we also identified strengths, weaknesses and highlighted some of the proposed solutions. Furthermore, we discussed open issues and future research directions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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