

Sleep Scheduling for Unbalanced Energy Harvesting in Industrial Wireless Sensor Networks

Mithun Mukherjee*, Lei Shu*[†], R. Venkatesha Prasad[‡], Di Wang*[§], and Gerhard P. Hancke[¶]

*Guangdong Provincial Key Lab of Petrochemical Equipment Fault Diagnosis,
Guangdong University of Petrochemical Technology, China

[†]School of Engineering, University of Lincoln, UK

[‡]Department of Telecommunications, Delft University of Technology, Delft, The Netherlands

[§]College of Information and Computer Engineering, Northeast Forestry University, Harbin, China

[¶]Department of Electrical, Electronic & Computer Engineering,
University of Pretoria, 0002 PRETORIA, South Africa

Email: m.mukherjee@ieee.org, lei.shu@ieee.org, r.r.venkateshaprasad@tudelft.nl, dididi.wang@live.cn, g.hancke@ieee.org

Abstract—Energy harvesting from ambient energy sources has gained increased attention due to its advantage of less maintenance and for removing the dependency on batteries in Industrial Wireless Sensor Networks (IWSNs). However, due to the dynamic nature of the ambient energy sources and position of harvesting nodes, energy-harvesting is not always available, resulting in unbalanced energy-harvesting in IWSNs. Although, some battery operated nodes are used, the limited lifetime problem still exists due to the non-harvesting nodes. In this paper, a scheme that combines the advantages of energy-harvesting and sleep-scheduling in hybrid solar energy-harvesting IWSNs and non-harvesting nodes is proposed. We present a model of the harvesting-node using a three-state Markov chain. The proposed harvest-use-store type architecture aims to guarantee an energy-neutral condition to avoid energy harvesting nodes from early energy exhaustion. The proposed approach allows to wake up a few more non-harvesting nodes to handle network coverage and connectivity during less-energy-harvesting intervals. Similarly, non-harvesting nodes are allowed to sleep by increasing the default transmission range of the solar-harvesting nodes during higher energy harvesting intervals prolonging network lifetime.

I. INTRODUCTION

With the unprecedented growth in wireless data services in the emerging Industrial Internet-of-Things (IIoT), Industrial Wireless Sensor Networks (IWSNs) play a leading role in its development of large-scale industries. Before IIoT can be widely adopted in various industrial applications, resource management – in terms of sensor deployment, residual energy management, and scheduling techniques – is one of the major challenges that must be overcome. Typically, in IWSNs, it is not always possible to replace the batteries of wireless nodes in difficult-to-access areas or harsh environments, e.g., the presence of toxic gas, rotating machines, gas pipelines, etc. Thus, IWSNs also inherited the limited-lifetime disadvantage from traditional WSNs.

A. Energy-Harvesting in IWSNs

There is a paradigmatic shift with respect to the utilization of renewable energy sources like motion, vibration, pressure and electromagnetic radiation, wind, chemical process, and solar to prolong network lifetime [1]–[3]. Energy harvesting techniques are broadly categorized into *harvest-use*- and *harvest-store-use*-based architectures. In the harvest-use approach, the harvested energy is directly fed to sensor devices for sensing and transmission. Alternatively, energy-harvesting sensor nodes do not work when the harvesting source is not available (e.g., bad weather and night in solar-based harvesting and no wind in wind-based harvesting). The energy-storage devices are utilized during this interval. Such architecture, called as the harvest-storage-use, employs a storage device to store harvested energy first before used by the sensor devices. In addition, with the advancement in rechargeable devices, Lithium-ion (Li-ion) batteries it is possible to be integrated with *harvest-storage-use*-based architectures due to

its low leakage, a higher number of charging cycles, and smaller size compared to traditional bigger size batteries.

As the efficiency of solar energy harvesting has significantly been improved in recent years, solar-harvesting is widely used in many applications ranging from remote environmental monitoring, consumer electronics, to industry. Most recently, the Molybdenum disulfide (MoS)-based ultra-thin solar panel – which is expected to be widely used as a powerful and flexible device with improved efficiency – is one of the latest advancements in energy-harvesting optoelectronic devices. This paper is based on solar harvesting as a test case. However, the schemes and techniques could be replicated with another type of harvesters too.

B. Unbalanced Energy Harvesting in Industry

Renewable energy is ideally infinite but instantaneous power is limited. Furthermore, ambient sources are not always suitable for the industrial environment. For example, the solar harvesting is fundamentally restricted by the location (e.g., inside manufacturing buildings) and the direction against the sun light. In addition, due to the harsh environment of the industrial area, the energy-transfer ratio is limited in wireless energy harvesting. Moreover, the deployment conditions restrict the energy harvesting from mechanical sources. This results in *unbalanced* energy-harvesting in large-scale industries. Although energy-conversion efficiency is significantly improved in optoelectronic devices, it is still the main bottleneck in harvest-storage-use type architectures.

To cater to the above situation, IWSNs will mostly consist of both harvesting and non-harvesting nodes¹, sleep scheduling – which is one of the efficient and well-studied approaches to extend network lifetime – still can be applied to hybrid IWSNs. The main idea of sleep scheduling is to allow a subset of sensor nodes into the sleep state, where the sensor node turns off its sensing and/or data transmission tasks while guaranteeing coverage, connectivity, and throughput of a network.

In this article our contributions are as follows:

- The advantages of sleep scheduling and energy-harvesting are combined with an aim to prolong network lifetime. The unbalanced nature of energy-harvesting, mainly, less energy harvesting interval is handled by changing the current state of a few more non-harvesting sensor nodes to awake-state with the aim to guarantee the network coverage and connectivity. Nevertheless, during high energy harvesting, the proposed scheme allows more non-harvesting sensor nodes to go to sleep-state to save their remaining energy, thereafter, prolonging the network lifetime.

¹The replacement of all non-harvesting sensor nodes in large-scale IWSNs results huge deployment cost.

- The state of the solar energy harvesting nodes (in short, solar nodes) is modelled as a three-state Markov chain in which the node's state depends on the current harvested energy, energy consumption, and the residual energy. We use a Markov model and the state-transitions to maintain energy-neutral condition with an aim to avoid solar-harvesting nodes from early energy depletion are explained.

II. A RELOOK AT THE LITERATURE ON DUTY-CYCLED WSNs

A. Duty-cycled WSNs

Sleep scheduling must guarantee network *coverage* and *connectivity* in duty-cycled WSNs. Several papers discussed duty-cycled WSNs for satisfying point- and node-coverage with the global connectivity. In global connectivity, each node (awake or asleep) has at least one 1-hop awake-node. For example, a distributed sleep scheduling scheme is proposed in [4], where a node goes to sleep-state if its sensing area is completely covered by its neighbours' sensing areas. In the coverage-aware sleep scheduling scheme [5], the sleep period is proportional to the size of the common sensing area. Among several works on duty-cycled WSNs, the Connected K -Neighborhood (CKN) [6] algorithm is widely used in a duty-cycled network because it allows the network to be k -connected with a minimum awake nodes. Here, k -connectivity refers to any node u with N_u number of 1-hop neighbors has at least $\min(N_u, k)$ awake neighbors in each epoch, where k is any positive integer.

In CKN-based sleep scheduling schemes, the set of awake and asleep nodes changes dynamically to conserve energy over the network. Among several CKN-based sleep scheduling schemes in duty-cycled WSNs, the Energy-Consumption-based CKN (EC-CKN) [7] sleep scheduling considers node's residual energy to select active- or sleep-mode, therefore, EC-CKN aims to balance energy consumption over the network. Note that the CKN-based algorithms [6], [7] are distributed approaches that require only 1-and 2-hop neighbour's information rather than the global information of a network topology. Although, the centralized approach has its own benefits, suffers from additional messages circulating over the network.

B. Energy Harvesting in Duty-cycled WSNs

Existing sleep scheduling schemes for energy harvesting WSNs focused on either adjusting the percentage of duty-cycle to control the amount of awake duration or how to schedule the active time-slots in the energy-efficient networks. For example, the node's duty-cycle is adjusted in a dynamic approach [8] based on the deviation in energy input compared to the estimated energy. This model assumes a periodic energy-harvesting model, however, in a real situation, ambient energy sources are dynamic and often unpredictable. Therefore, a model-free approach is discussed in [9] which does not need *a priori* information about energy sources. Recently, another opportunistic duty cycling approach was introduced based on a new concept of Value-of-Information (VoI) of the sensory data [10]. However, it is not always possible that all the sensor nodes in IWSNs must have energy harvesting capability. A greedy scheduling algorithm was proposed in [11] with both harvesting and non-harvesting sensor nodes for network coverage, however, the network connectivity issue is not considered in the model. The main focus of the article is to design a CKN-based sleep scheduling algorithm that considers the unbalanced nature of energy harvesting in IWSNs.

III. SYSTEM MODEL

A. Energy Harvesting Models

To understand the nature of solar harvesting, firstly, data of harvested energy are collected from solar nodes in different locations. For our case study, data are collected every day from sunrise to sunset over 30 days. Each solar panel is placed in different directions

toward the sun. From these data (see Fig. 1), it is observed that the position, intensity of received light, and weather significantly affect the harvested energy. This verifies the dynamic nature of harvested energy [12]. To consider these variations in energy-harvesting, several research efforts have been carried out based on statistical average and various prediction models. Although such energy-harvesting model-based approaches are in infancy, they are, however, used to design an energy-efficient wireless network, while exploiting the prior information about ambient energy sources.

The Holt-Winters (HW) model is one of the earliest methods of forecasting. It uses a modified exponential-smoothing method. This model mainly consists of three smoothing equations for average, trend, and seasonal components. After almost 50 years, this method is still popular and is being widely applied in several areas including prediction of harvested energy due to its simplicity, low-storage requirement, and ease-of-integration with existing systems. This HW model acts as a key prediction model and has been used by several researchers to design improved prediction models in recent years. An energy-harvesting framework [1], which is one of the widely applied energy prediction models, uses an auto-regressive filter over a finite number of previous epochs assuming a day as a single-epoch. This prediction model provides a distributed framework that helps the energy-aware task assignment for load balancing, cluster-head selection, and routing schemes. Another type of prediction scheme, called as Exponentially Weighted Moving-Average (EWMA), based on a moving-average was proposed in [8]. This scheme predicts the harvested energy with an assumption that harvested energy at a time of the current day is almost similar to the same time of the previous day. Therefore, the predicted energy is approximated using properly weighted average of the estimated energy of the previous time slot of the same day, as well as the same time slot of the previous day. Zhang et al. [13] considered the solar profile provided by the Solar Radiation Research Laboratory to evaluate the performance of distributed data gathering in rechargeable WSNs.

Subsequently, a series of prediction models were presented to further minimize the estimation error in the EWMA model. For example, since the estimation accuracy decreases on alternating sunny and cloudy days, an approach, called Weather-Conditioned Moving Average (WCMA) [14] introduced a weight that depends on how much the weather changes compared to the previous day. Most recently, an approximated one-day energy-harvesting model was proposed in [2] using quadratic curve-fitting on field data measurements. Fig. 1(c) shows the charging pattern using the above curve-fitting in [2] on our experimental data.

B. Network Model

The network consists of normal sensor nodes (temperature, humidity, wind speed, wind direction, PM_{2.5}, see footnote², GPS, atmospheric pressure, and gas sensors: CO, CO₂, SO₂, and H₂S) and sensor nodes with solar panels³. Since the solar nodes have the opportunity to harvest solar energy, an increased sensing and transmission range can save energy consumption, while still guaranteeing network coverage and connectivity. An example of sleep scheduling in a solar-harvesting network is shown in the Fig. 2. Node ⑥ gets a chance to sleep as it is covered by awake node ③ or ⑦ while maintaining $k = 1$ connectivity among all the awake nodes.

A multihop IWSN, represented as a network graph, is considered with both uniformly and randomly deployed sensor nodes in a large-scale 2-dimensional industrial sensing area. Fig. 2 depicts the system

²PM_{2.5} particle sensor is used to detect and count particle size of $< 2.5 \mu\text{m}$.

³Solar node storage specification: Valve-regulated lead-acid battery, voltage 12 V, capacity 20 A h, volume $180 \times 75 \times 165 \text{ mm}^3$, weight 5.2 kg. Normal sensor node's storage specification: voltage 12 V, capacity 3000 mA h, volume $54 \times 18 \times 70 \text{ mm}^3$, and maximum discharge current 2 A.

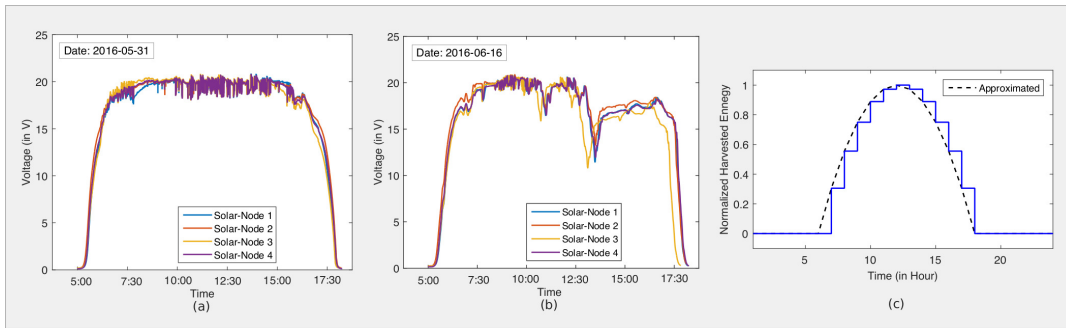


Fig. 1. (a)-(b) Field data on harvested energy from solar nodes and (c) approximated charging pattern using quadratic curve-fitting [2] on the experimental data.

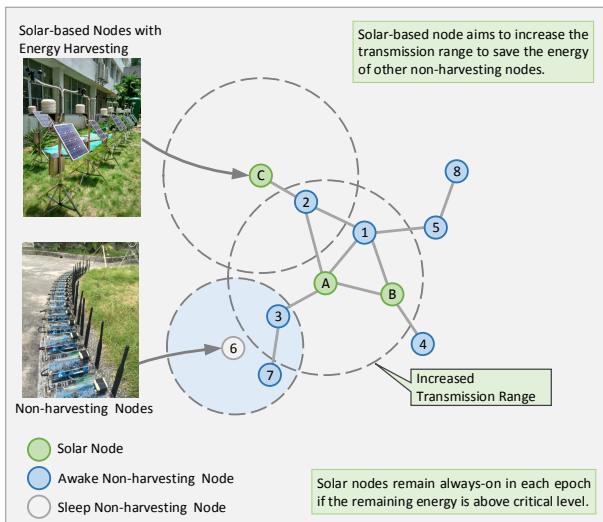


Fig. 2. An illustration of solar energy harvesting in WSNs.

model of hybrid IWSNs with both solar and non-harvesting sensor nodes. Two nodes are called 1-hop neighbours to each other if they are within the transmission range of each other. Bi-directional communications are assumed between 1-hop neighbours. Global Positioning System or localization technique is used to obtain the sensor node's location. Let us neglect the noise and interference issues to first find the theoretical aspects of this problem. Let r be the transmission range, which is the same for all the non-harvesting sensor node. Without loss of generality, we take the transmission range to be the same as sensing range. Assume that each non-harvesting node has the same functionality and capability. In addition, solar nodes have a similar type of solar panels with the same specification.

C. Energy Consumption Model

In a duty-cycled network, any sensor node has two states namely, awake and sleep states. In an awake state, energy consumption mainly includes message transmission and running sleep scheduling algorithms. The distance square path loss model is considered in channel transmission for the calculation of energy consumption [7] to transmit and receive a packet. Note that the energy consumption in any sleep scheduling mainly depends on message exchange between neighbours.

Compared to the awake-state, the sleep-state consumes less energy, as most of the circuitry is in hibernating mode. As some triggering mechanism is always running to wake up the sleep sensor node whenever necessary, the wake-up radio mainly consumes the energy.

Recently, Spenza et al. [15] suggested a wake-up with short wake-up latency and low current consumption in idle-state. This ultra-low-power radio will be a suitable choice for duty-cycled IWSNs.

D. Energy Neutral Condition

It is observed that the charging efficiency η of the storage device is about 75%, thus 25% of the harvested energy is wasted during charging. A *harvest-use-store* type harvesting model, which is a combination of both the *harvest-store-use* and the *harvest-use* models is considered. In our model, the harvested energy is directly used for the sensors, and the remaining energy is stored for future use. This procedure minimizes the loss of harvested energy due to energy conversion in storage devices.

We make a generalization here.

- 1) *when the harvested energy is above the consumed energy*, then the solar harvested energy is first used for the sensor nodes, and the remaining energy $E_s - E_c$ is stored in the storage devices, where E_s and E_c are the harvested energy and the consumed energy, respectively.
- 2) *when the harvested energy is lower than the consumed energy*, then an additional $E_c - E_s$ amount of energy is consumed from the storage device with a condition that the remaining energy of the storage device is above the critical limit of the storage device. We assume that any sensor node becomes non-functional if the remaining energy of the storage device is less than its critical level.

Fig. 3(c) illustrates the above two conditions for the energy neutral operation [8] in our *harvest-use-store* type energy-harvesting architecture for the solar nodes.

IV. SOLAR NODE STATES: A THREE-STATE MARKOV MODEL

Each solar node compares its own residual energy with a predefined critical energy level. Basically, this critical energy level mainly depends on the physical property of the storage element (e.g., number of elapsed re-charging cycle of the storage element), data sampling frequency, leakage energy for the storage device, and initial energy stored in the battery. Finding the optimized value of this critical level is an important research issue, however, is not addressed in the context of present focus of this article. If the residual energy is higher than the critical energy level, then the solar node remains awake and follows the *harvest-use-store* type architecture. However, when the residual energy becomes lower than the critical energy level, then the solar node normally goes to sleep. Although the leakage energy is low, it is still a reasonable value compared to other energy consumption in sleep-mode for solar nodes with large storage capacity. Thus, to make the solar nodes (with harvested energy) awake as long as possible, the following ways are suggested: The solar node remains awake until the harvested energy is above

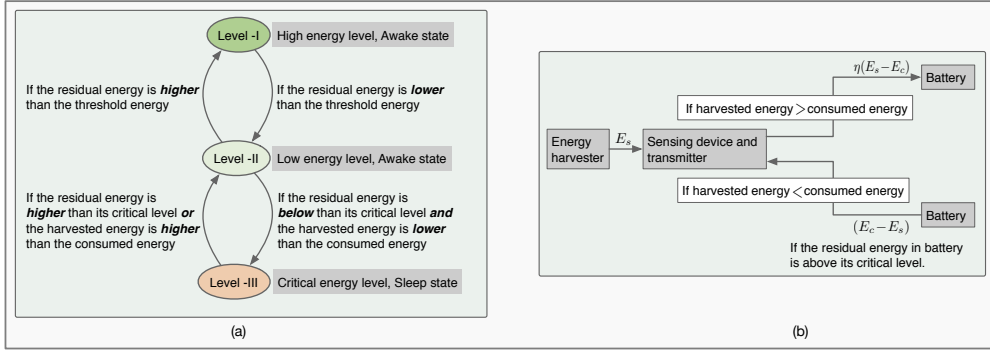


Fig. 3. (a) Three-state Markovian model with state-transitions for solar nodes. (b) Energy-neutral operation in the harvest-use-store type architecture.

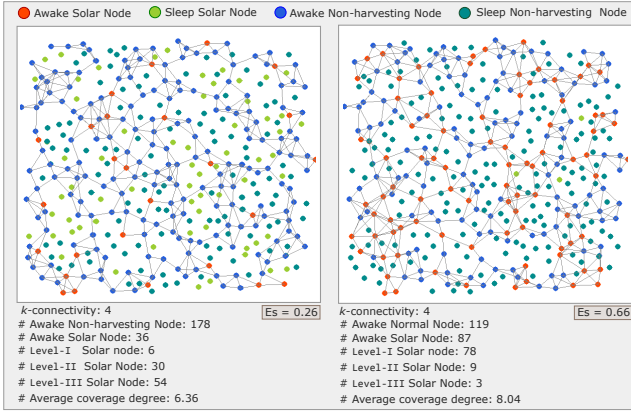


Fig. 4. Snapshots of network topology with two different energy-harvesting using NetTopo, an open-source software for simulating and visualizing WSNs (online at <http://sourceforge.net/projects/nettopo/>) with non-harvesting nodes = 300 and solar nodes = 90.

energy consumption, otherwise, it goes to sleep. This is similar to the *harvest-use* type architecture.

Thus, the solar node's state is modelled as a Markov chain with following state-space $\{\text{Level-I}, \text{Level-II}, \text{and Level-III}\}$. Fig. 3(d) illustrates these states with state-transition probabilities. The solar node in the Level-I state remains in the same state with a probability λ until its residual energy is above a pre-defined energy level E_{th} , which is about 20%th of the energy storage limit. Due to a high energy consumption and a low harvested energy, any solar node with Level-I state goes down to a Level-II state with probability $1 - \lambda$ when the residual energy is above than E_{th} . Any node in a Level-II state returns back to the Level-I state if the residual energy is above the threshold with a probability α . A solar node in Level-II state remains in either awake-mode or sleep-mode with a probability γ and $1 - \alpha - \gamma$, respectively, based on the energy consumption as well as harvested energy. All the solar-nodes in the Level-III state remain in the sleep-mode with a probability β until either the harvested energy is higher than the consumed energy or the residual energy becomes above than its critical level.

V. PROPOSED ENERGY HARVESTING-CONCERNED CKN SLEEP SCHEDULING

We describe the sleep scheduling scheme that satisfies network demand while maintaining an energy neutral condition with minimal awake non-harvesting nodes for energy-harvesting hybrid IWSNs. We sketch the procedure here:

Step 1: Estimate the harvested energy:

Firstly, harvested energy is estimated. For simplicity, the same harvested energy is assumed for all solar nodes.

Step 2: Determine solar node's state in the Markov chain:

Any solar node determines its state based on the residual energy, the harvested energy, and the energy consumption in the current harvesting time-slot.

Step 3: Set $k = 1$ connectivity for the EC-CKN:

Each solar and non-harvesting node broadcasts HELLO message that contains its ID and residual energy status. In the same way, each node also receives the residual energy status of its 1-hop neighbors including the current state (from state-space in the Markov chain) of the solar nodes. Subsequently, each node u broadcasts R_u , the residual energy status of its 1-hop neighbors and receives $R_v \forall v \in N_u$ from its 1-hop neighbors.

The connectivity parameter is set as $k = 1$ in the EC-CKN-based algorithm. This allows a node u to be awake when either the node u has only one 1-hop neighbour or its 1-hop neighbour has only one 1-hop neighbour, i.e., $|N_v| = 1 \forall v \in N_u$. In this way, the network is globally connected with a minimum number of awake non-harvesting nodes. Note that each solar or non-harvesting node (either awake or sleep) has at least one awake 1-hop neighbour with $k = 1$ connectivity over the network.

Step 4: Check the network demand:

The network demand is obtained at $k = 1$ for EC-CKN-based sleep scheduling. For example, the average coverage degree is measured as a network demand⁴. The average coverage degree D is obtained as follows. First, we divide the entire network into small square grids. The average coverage degree is obtained as the average number of sensor nodes that cover the center points of these square grids.

Step 5: Boost the transmission power of solar nodes:

If the current average coverage degree does not satisfy with its target value D_{target} , then the network normally needs to wake up more nodes. Since almost all the solar nodes (with sufficient residual energy and harvested energy) are already awake, waking up additional nodes mainly affects the non-harvesting node's energy consumption. Therefore, it is a better approach to utilize the solar-harvested energy rather waking up non-harvesting nodes directly. In this context, the transmission range of the solar-nodes with high residual energy (in the Level-I state) is increased as $r^{new} = r \times (1 + E_{residual}/E_0)$, where $E_{residual}$ and E_0 are the residual and initial energy in the solar node's battery, respectively. This has a two-fold advantage: (1) the network coverage is further increased and (2) non-harvesting nodes go to sleep more in the next epoch.

⁴Either way, when the network demand is a 'low-latency' as well as a 'time-critical' message, any node must have at least k - neighbours if possible, leading to k -connectivity.

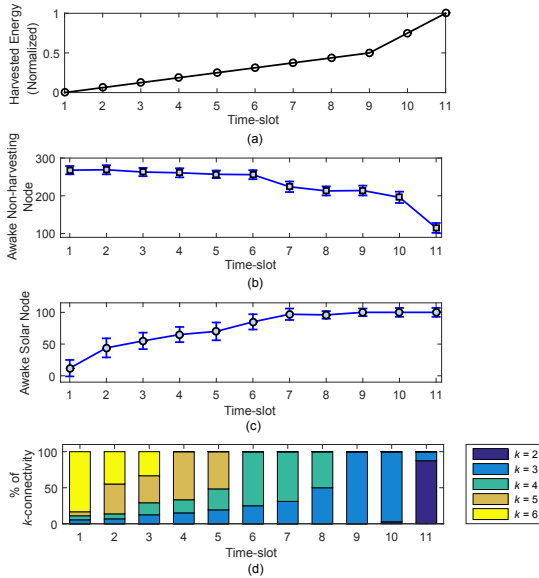


Fig. 5. (a) Expected solar harvested energy (normalized), number of awake (b) non-harvesting and (c) solar nodes at different time-slots. (d) percentages of k -connectivity to satisfy $D_{\text{target}} = 7$.

Step 6: Update the k -connectivity in EC-CKN:

Afterwards, the k -value is increased in the EC-CKN algorithm which allows more awake nodes, particularly, non-harvesting nodes. Subsequently, repeat from *Step 1* with updated harvested energy and continue the process. If the current average coverage degree satisfies D_{target} , then the k -connectivity in EC-CKN remains as previously the case.

VI. SIMULATION RESULTS

This section evaluates the impact of solar energy-harvesting in hybrid IWSNs on 1) the number of awake non-harvesting and solar nodes with different states and 2) the network coverage degree and k -connectivity⁵ for EC-CKN-based sleep scheduling are considered.

Simulation Setup: Extensive simulations were conducted using NetTopo with a network size of $600 \times 600 \text{ m}^2$. Each of the results is averaged over 100 different topologies. The number of non-harvesting nodes ranges from 200 to 400. The percentage of solar nodes is varied from 10% to 30%. The initial energy of the non-harvesting nodes and solar nodes are 80 J and 100 J, respectively. We set the energy consumption to run the transceiver circuitry is 50 nJ/bit. Besides, 50 pJ/bit/m² is consumed in transmitter amplifier to send a packet over an unit distance and $E_{\text{critical}} = 2.5 \text{ mJ}$. The default transmission range of each non-harvesting node and solar-node (in the Level-II state) is 60 m. In each epoch of duration 1 min, 1000 packets of size 12 byte are sent. A grid-size of $0.5 \times 0.5 \text{ m}^2$ is used over the entire area to calculate D .

A. Sleep Schedules in Energy-Harvesting Networks

Two scenarios are considered with different energy-harvesting for the same network topology that consists of 300 non-harvesting nodes and 90 solar nodes. We show snapshots after the 15th round of each case in Fig. 4. It is observed that when the normalized energy-harvesting is low, i.e., harvested energy = 0.26, more than 50% of the solar nodes, (i.e., 54 solar nodes) remain in the Level-III state

⁵Goodput is one of the widely used metrics in energy-harvesting networks, however, in this work, only network coverage and connectivity that are important metrics in sleep-scheduling are considered.

sleep-mode due to low residual energy. On the contrary, as energy-harvesting increases, i.e., harvested energy = 0.66, the number of solar nodes in Level-I increases from 6 to 78. By increasing the transmission range of more Level-I state solar nodes, it is observed that: 1) the average coverage degree increases and 2) more non-harvesting nodes go to sleep-mode while maintaining $k = 4$ connectivity over the network.

B. Performance with Unbalanced Energy-Harvesting

To see the impact of energy-harvesting, simulation results with 100 solar nodes and 300 non-harvesting are shown in Fig. 5 to guarantee target average coverage degree $D_{\text{target}} = 7$ over the network. Fig. 5(a) shows the energy-harvesting in different time-slots. Fig. 5(b)-(c) illustrate the average number of awake non-harvesting and solar nodes with different harvested energy. It is observed that the number of awake solar-nodes is low when the harvested energy is less than about 30% of its maximum value. When the harvested energy is low, a significant number of solar nodes change their state from Level-II to the Level-III. In addition, during that low energy harvesting interval, a solar node in the Level-III state remains in the same state with sleep-mode. Therefore most of the solar nodes change their state from Level-I to Level-II and afterwards Level-III, resulting in less awake solar nodes.

Effect on k -connectivity: Fig. 5(d) illustrates the effect on the k -connectivity parameter for the EC-CKN-based sleep scheduling in energy-harvesting IWSNs. To satisfy the target coverage degree, when harvested energy is low, the network needs to wake up additional non-harvesting nodes, therefore, the k -connectivity parameter for EC-CKN increases. On the contrary, while harvesting high energy, most of the solar nodes that remain at the Level-I state increase their transmission range to guarantee the target average coverage degree. Thus, these solar nodes allow sleeping of additional non-harvesting nodes, resulting in low k -connectivity in sleep scheduling.

C. Performance of the Average Coverage Degree with a Different Number of Solar nodes

Fig. 6(a) illustrates the average coverage degree for different ratios of solar nodes to non-harvesting nodes for a normalized harvested energy = 0.66 with a fixed number of non-harvesting nodes. It is observed that the average coverage degree increases with the number of solar nodes in both deployments with 200 and 300 non-harvesting nodes. As expected, a higher value of k -connectivity results in more awake nodes, particularly, non-harvesting nodes, and the average coverage degree increases. In addition, it is observed that the average coverage degree increases with a higher number of non-harvesting nodes, however, at a high deployment cost.

D. State-transition with Different Energy-Harvesting

The state-transition probability of the Markov chain is illustrated in Fig. 6(b). During low energy harvesting times, most of the solar nodes remain in the Level-III state, thus the sleep probability of solar nodes (i.e. λ) is higher than other state-transition probabilities. As energy-harvesting increases, transition from Level-III to Level-II (i.e., $(1 - \beta)$) and from Level-II to Level-I (i.e., α) increase. As a result, almost all the solar nodes remain in either Level-I or awake-mode in Level-II, thus the sleep-mode probability of the Level-II state (i.e., β) decreases. Note that at the maximum energy harvesting times, the solar nodes in Level-II moves toward Level-I, resulting in a lower number of solar nodes in the Level-II state that leads to *slightly low* awake-probability in Level-II (i.e., γ). However, the overall awake-probability of solar nodes is higher with either Level-II or Level-I. In this way, the energy neutrality is maintained to avoid harvesting-nodes from energy exhaustion and enhance the benefits of energy-harvesting.

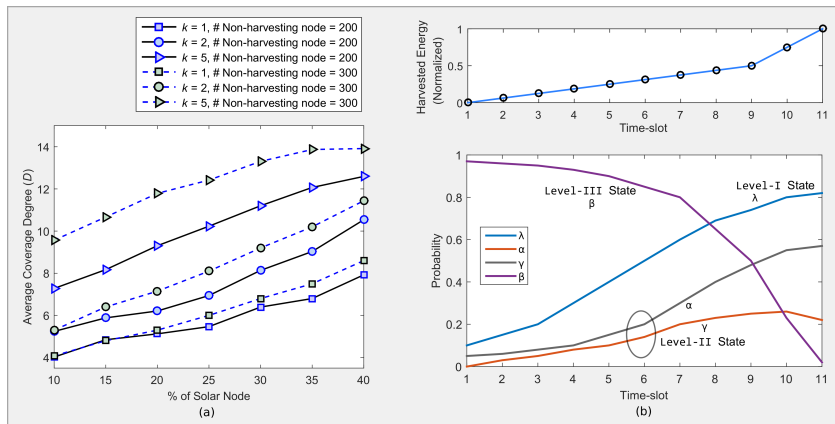


Fig. 6. (a) Performance of average coverage degree with various percentages of solar nodes for 200 and 300 non-harvesting nodes. (b) Solar node's state transition probability at different energy-harvesting for 60 solar nodes and 300 non-harvesting nodes.

E. Discussions and Future Work

1) The Big Picture:

Residual energy management is an essential requirement for the power-limited IWSNs. Energy harvesting from the ambient energy sources is one of the approaches that minimize the dependency on the batteries for wireless sensor nodes. However, on one hand, due to the typical nature of industrial environments, such as hard-to-access areas, a location of sensor node inside the buildings, and chemical plants, etc., energy harvesting from the ambient sources is not always suitable. How to address the unbalanced nature of energy harvesting mainly, during less energy harvesting intervals is becoming increasingly important. On the other hand, replacing the non-harvesting sensor node with energy harvesting node demands enormous deployment cost in a large-scale industrial area.

2) Takeaway Message:

One of the solutions that can work incrementally with the already existing deployed sensors is to consider the sleep scheduling for both harvesting and non-harvesting sensor nodes to prolong the network lifetime. With an energy-balanced approach, in less energy harvesting intervals, we aim to wake up a minimum number of battery/mains powered nodes to guarantee the network connectivity and coverage requirements. On the other hand, in high energy harvesting intervals, the proposed scheme allows more non-harvesting sensor nodes to go to sleep-state to save their remaining energy, thus prolonging the network lifetime.

3) *Envisioned Future Directions:* Even though we have many energy harvesting technologies available, it is not easy to deploy them widely in practice. There are many associated challenges still. We briefly enumerate a few of them here:

- 1) The network built using energy harvesting sources is unreliable. The required high reliability for IIoT is not easy to achieve.
- 2) The use of the backup battery and secondary nodes with sufficient energy that has been used here could also be an alternative, however, the complexity and form factor become the issues and thus discouraging widespread use of this technique.
- 3) A tradeoff between reduction in form factor and requirement of sufficient energy is a holy grail for energy harvesting networks.
- 4) Hitherto the protocols designed are all considering nodes with batteries; thus, there is a need to evolve stable yet versatile protocols for energy harvesting networks.
- 5) Dynamically adaptable applications and secondary sources of sensors for redundancy are also needed to allow this technology in IIoT.

VII. CONCLUSION

In this article, a sleep scheduling framework is proposed for an unbalanced energy-harvesting IWSNs. Under the limitation of unbalanced energy harvesting in industrial domains, the proposed scheme exploits the energy of the non-harvesting nodes to meet the connectivity and coverage issues of a network in less-energy harvesting times. At the same time, these non-harvesting nodes save their energy while going to sleep state due to the increased transmission range of harvesting nodes with high remaining energy. We also provided a Markov model of our scheme that helps in handling the energy neutrality over the network and to enhance the benefits of energy-harvesting in IWSNs. The proposed scheme is very promising to extend the network lifetime by combining the advantages of both duty-cycling and energy-harvesting in industrial applications.

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