A Self-Powered Wireless Sensor Network

Roger N. Alegret[1,2][0000−0002−0906−8138], Raul Aragones[1,2][0000−0002−3960−6312], and Carles Ferrer[1][0000−0002−1475−8790]

[1] Autonomous University of Barcelona, 08193 Bellaterra, Barcelona, Spain
roger.nicolas@e-campus.uab.cat, {raul, carles}@uab.cat
http://www.uab.cat

[2] Alternative Energy Innovations SL, 08221 Terrassa, Barcelona, Spain
{roger,raul}@aeinnova.com
http://www.aeinnova.com

Abstract. SARSA is one of the most advanced algorithms in reinforcement learning and artificial intelligence, this algorithm lets the actor to learn about its environment and to act accordingly. Batteries are the main stopper for adopting wireless communications in the industry. Industrial processes are a source of waste energy. This paper explores the different components of the IIoT devices, which changes are needed in order to be powered by the energy on its surroundings, and finally, how those points above can be tackled using artificial intelligence.

Keywords: Energy Harvesting · Waste Heat · WSN · IIoT · Routing Protocols · Mesh Networks · Reinforcement Learning.

1 Introduction

Nowadays, Wireless Sensor Networks (WSN) are a recurrent topic of investigation, technology is towards to create smaller devices with greater computer capacity, while trying to extend the life of the device. Another important issue that is evolving a lot in recent times is the harvesting of energy from where it was not believed possible to scavenge it. This evolution has been from an experiment in a laboratory [9] unto it has become a technology to keep in mind while the process of building new devices is being done [10]. If these two topics are mixed, we find ourselves in a new paradigm called Energy Harvesting Wireless Sensor Networks (otherwise called EH-WSN) [5]. In this new paradigm, we can see the research done so far in WSN is relatively obsolete, since the main objective that was being sought so far was to extend the battery life by following different configurations and procedures: from reducing the duty cycle [8] of the device to routing protocols of packages such as LEACH and all its variants [14].But if these two concepts are combined, we can see the WSN has virtually unlimited power, since there is a generating source that can charge the battery in a relatively less time than the node will reach its depletion which, that means, it could even be possible to remove the battery of the node [9]. This opens up a new range of possibilities for operating the node that has not yet been contemplated by the date, and the main objective shifts from extending the battery life to maximize the network usage.

This harvested energy can come from many sources; technologies such as solar panels, piezoelectric components, thermoelectric generators, radio-frequency transceivers and wind turbines, to cite some of them, are able to harvest energy from the environment and power devices attached to them [4]. Thereafter, the energy harvested is stored into an energy buffer, normally a battery or a super-capacitator, and it is consumed by the node when it needs to capture, process, send or manage data to the network. Thus, the system is able to harvest energy continuously and burst it when the node requires more energy than the harvested on that concrete moment of time. This field of research, searching a way to balance the energy harvested during a period of time and the energy consumed on the same period is known as Energy Neutral Operation Nodes.

The main contribution of this paper is a novel architecture for EH-WSN adopting reinforcement learning algorithms to control the node consumption as well as selecting the channels to transmit information.

This paper presents a brief state of the art of energy harvesting wireless sensor networks and which technologies are used right now. Specially, in section 2 it goes deeper on the algorithms for prediction-free energy managers. In section 3, it dissects the different parts of an energy harvesting wireless sensor node and which responsibility takes each part in order to understand how they are related with the other parts. Following this point, in section 4, a discussion of which issues and challenges needs to be faced in order to evolve in the field of energy harvesting wireless sensor networks. Finally, in section 5 a network architecture is proposed in order fill the gap between the nodes and the network when the nodes are powered using energy harvesting techniques.

2 Related Work

In order to minimize the consumption of the node, two different approaches are used, the first one is modifying the transmission policy; the other one is modifying the duty cycle [3].

On the transmission policy side, three types of policies can be done: fixed transmission policy, variable transmission policy and using probability distribution in order to transmit data. On this field, the investigation is mainly done on the probability distribution, given as a result the LEACH protocol an all its variants, as mentioned in 1.

LEACH protocol assumes each node has enough transmitting power to reach the base station, but using it all the time would be a waste of energy; the solution goes through creating clusters inside the WSN, the nodes communicate to the cluster heads and the cluster heads compress and re-transmit the data to the sink station. Doing this, the nodes that send data to the cluster head do not need to use their radio transmitter at maximum power, allowing them o save energy. Then, in the next round a new cluster head is selected, being not possible to select the same cluster head for P rounds, where P are the number of desired cluster heads. Therefore, the probability to be the cluster head again is $1/P$.

On the duty cycle policy side, two types of policies can be done: sleep/wake-up duty cycle policies and maximum/minimum duty cycle policies. Both policies try to minimize the consumption by playing around with the duration of the duty cycles. The difference here is while sleep/wake-up duty cycle policies keep the nodes awaken while there is a connection in progress and put the nodes to sleep when there is no connection, and a scheduling is done in order to wake up the nodes; maximum/minimum duty cycle policies keep the nodes working on maximum capacities when the harvested energy is more than the energy consumed and the duty cycle is changed to a minimum performance when the energy harvested is less than the typical energy consumption on active mode, trying to prevent an energy-negative state; changing again to maximum performance when the energy harvested is more than the typical energy consumption in active mode.

The duty cycle policies are implemented in the energy managers. The energy manager is an element inside the system in charge of controlling the energy available in the buffers or collectors and to tell to the system the amount of energy able to use in a concrete moment of time. These energy managers can use previous data in order to decide the next action, this paradigm is known as predictive energy managers. The main problem of this concept is the collected information is only valid for the same region and cyclical events. On the other hand, we can find prediction-free managers, these managers have two strong points, the first one is that they have the ability to learn from their environment without any previous data, the second one is that they can be deployed anywhere, because they are not using previous captured information.

The first prediction-free energy manager was LQ-Tracker [13], proposed in 2007 by Vigorito *et al.* The main objective of this energy manager is to adapt the duty cycle using the state of charge of the energy buffer using a linear quadratic tracking. In 2014, P-FREEN [11] was proposed by Peng and Low, P-FREEN is an energy manager that maximizes the duty-cycle of the sensor node. In order to work, P-FREEN needs to know the state of charge of the energy buffer and the harvested energy in that moment. If one of these values are below a threshold, the node works using the minimum energy needed to be kept alive; otherwise, the node will be adapted to work using the combination of the energy buffer and the harvested energy. Two years later appeared Fuzzyman [2], proposed by Aoudia *et al.* This energy manager uses a set of IF-THEN rules in order to work. The input of these rules is extracted from the combination of the energy harvested in the previous cycle and the residual energy on the energy buffer. The result gives the total amount of available energy for the node on that cycle. Finally, in 2018, Aoudia *et al.* proposed RLMan [1]. This energy manager uses reinforcement learning in order to maximize the quality of the service while trying to avoid power failures. In order to work, it only needs the state of charge of the energy buffer.

The research done until this point always consider a node sending directly to the base station, without the possibility of conforming a mesh network. Also, it always consider the modification of the duty-cycle in order to work, leaving the signal power of the node or the channel used during the transmission out of the game.

3 Schema of a EH-WSN

Basically, an EH-WSN node is divided on four main pieces: the energy harvester, the energy storage, the energy manager and the node itself. Figure 1 shows a schema of a generic EH-WSN node.

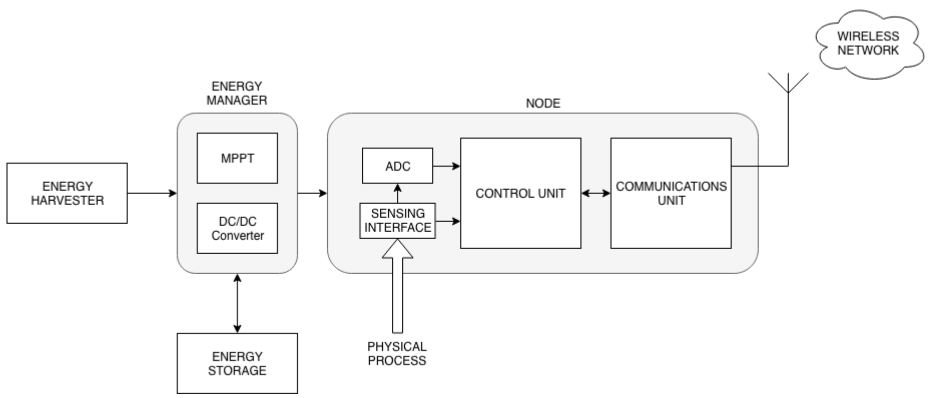

Fig. 1. Generic Energy Harvesting WSN Node

The energy harvester is the component of an EH-WSN node that scavenges energy from the environment and converts that energy harvested to electricity, commercial products can be found on the market in many forms, such as photovoltaic panels, wind and water turbines, vibrational scavengers or thermoelectric power generators.

Then, this energy is transferred to the energy manager. This component is in charge to control what to do with the energy harvested. That means it must make a decision whether charge the batteries, transfer the energy directly to the processor or power the processor using the batteries previously charged.

Finally, there is the node itself, the node is in charge of measure a physical process through a sensing interface and use the radio module in order to send the data to the network. It is also in charge of controlling the different cycles and the power consumption. The radio module can be connected to a gateway directly, creating a point to point communication, or it can be connected with other radio modules creating a mesh. When a mesh is created, the node also needs to control the time slots when the data is sent and when the radio needs to be switched as a receiver in order to retransmit data sent by the other nodes conforming the network.

4 Issues and Challenges in Energy Harvesting Wireless Sensor Networks

One of the main problems that are faced when talking about energy harvesting wireless sensor networks is the mismatch between the harvester and the node. Martinez *et al.* [7] created a tool to help hardware developers and designers in order to solve this problem. But, the problem of that tool is that it is needed to be fed with information previously captured or theoretical information if no practical data is available. So, it is only useful when the energy generated is a known value. Another big problem is that the most of the research done until now tries to solve a very specific problem, without taking in account they are part of a more complex system; and then, when two specific advances are tried to be glued in order to produce something better, they are not always compatible. Finally, in industrial sectors, when a deployment is done, it is expected to be operative for ages and this problem cannot be easily tackled. New technologies does not need to match with the previous ones, creating a barrier for accepting these advances.

On the other hand, industrial processes are a source of wasted energy. Companies are developing devices in order to recover this energy, and using it as a power source for monitoring devices is a must. The deployment of wired sensors costs around 50€/meter just for the wiring. Industrial battery-based sensors have an average live of 6-24 months, that means, every two years, batteries need to be replaced.

5 Proposed Architecture

In order to tackle all the problems mentioned above, we present a new system that tries to solve the challenges and issues exposed above. The architecture proposed consists in an undetermined number of nodes, one or more gateways, a security manager and a network manager. This structure follows the structure a of the mesh network proposed in WirelessHART standard [15]; with two differences explained below.

The main proposal is a shift on the energy manager from monitoring the level of the battery to monitoring the amount of energy that is produced in the energy harvester. This change is done because, as it is said in the introduction, if the battery is removed, the node can continue working due to the energy that comes from the energy harvester. But the problem here is the node does not know how much energy will be produced in a concrete period because of the uncertainty of the process from where the energy is extracted. In order to solve that, the node needs to learn its capabilities. This learning is done using artificial intelligence algorithms, concretely, a reinforcement learning algorithm called SARSA (State-Action-Reward-State-Action) [12]. In equation 1 we can see the SARSA prediction method

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha[r_{t+1} + \gamma Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t)] \quad (1)$$

where $Q(s_t, a_t)$ are the initial conditions, α is the learning rate and γ is the discount factor.

The reinforcement learning process can be defined as a list of states where for each state there are some actions to be done. Depending on the action, the reward will be different and will affect the probability of doing the same action in the next round of the state. This process can be split in two parts. The first one uses the amount of generated energy in one concrete period of time as a state; and the actions for each state will be related to adapt the node to consume that energy generated. The second one is related to the communication, it scans the channels that are used before doing any transmission, and selects a channel in that moment. This selection is done taking in account the energetic cost of sending a message. In both cases, an exploration or learning period is needed in order to know the environment and act accordingly.

The novelty proposed in this paper makes a change on how the network is formed. In WirelessHART there is a field that informs to the network manager the amount of remaining energy in the battery. This field is no longer used, and instead of this, the information sent is the state of the energy manager. With this information, the network manager needs to create and distribute the network paths to the nodes. This task must be repeated each time a threshold of minimum network paths is exceeded. Also, the selection of the transmission channel is new compared to the WirelessHART protocol, which is based on Time Slot Channel Hopping (TSCH), where the node knows which channel is needed to be used in advance [6]. In our proposal, just the paths are needed, but not the channel to be used.

6 Conclusions

In this paper a new architecture is presented to tackle the issues and challenges exposed in the section 4. Concretely, a new energy manager has been proposed and explained the advantages against the existing ones. In future research, this energy manager must be tested and compared with other methods focused to extend the network lifetime. Besides, this energy manager is in charge of the resilience of each node, handling power output and channel used in order to avoid interferences between nodes thanks to applying the reinforcement learning. Finally, thanks to this new energy manager, a modification of WirelessHART network has been suggested. This suggestion is necessary for two reasons: there is no existing industrial wireless protocol that handles well the energy harvesting wireless sensor nodes and because of the energy constraints of the network, one cannot delegate to the nodes the self-organizing capacity. Instead of this, it is needed an element in the network able to calculate and distribute the different paths between the nodes.

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