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Enhancing Network Lifetime of Duty Cycle-Based WSN With Mobile Sink Using Ambient Energy Harvesting

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ABSTRACT

In order to guarantee a successful data collection process in wireless sensor networks with mobile sinks (WSN-MS), two primary objectives must be reached: 1) enabling the mobile sink to retrieve the maximum amount of data and 2) making sure that the network operates as long as possible. The first problem has been solved previously by proposing an innovative solution HXMAC. To address the second problem, on which this paper focuses, ambient energy harvesting is used to continuously supply power to each sensor node. Thus, this paper's main contribution is to propose EH-HXMAC (HXMAC with energy harvesting), which is based on all these improvements: seamless handover, duty cycling optimization, and mainly energy harvesting capability. EH-HXMAC has been evaluated using Cooja Contiki simulator. Obtained results based on the evaluation of the proposal EH-HXMAC clearly show its suitability as a good solution to promote unlimited lifetime for WSN-MS.

KEYWORDS

Duty Cycling, Energy Harvesting, Handover, HXMAC, IoT, Wireless Sensor Networks

INTRODUCTION

Wireless sensor networks with mobile sink (WSN-MS[1]) are a set of sensor nodes that collect information of different natures from the ambient environment, such as humidity, temperature, and pressure, etc; and transmit them to a mobile sink, which in turn will transport them to a base station. Such type of networks has attracted the attention of several activity sectors, in particular those which require continuous monitoring of a certain environment such as health (Pirbhulal et al., 2016), agriculture (Ahmed et al., 2018), industry (Madni, 2008), smart cities (Zanella et al.,2014), monitoring (Ahouandjinou et al., 2017), etc.

Unfortunately, despite their realism, their robustness, and their considerable contribution, WSN are challenged by several problems due to the sensitive and vulnerable nature of nodes, such as failures, breaks, and the exhaustion of the battery whose changing is almost impossible due to the hostility or the inaccessibility of the deployment area. Thus, the solutions based on ambient energy harvesting to permanently supply the sensor nodes have appeared and have become a hot topic nowadays. Figure 1

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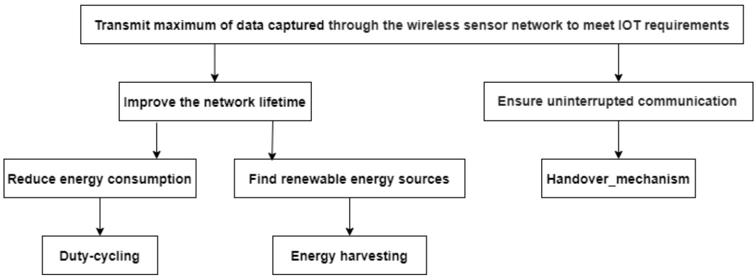
Figure 1. The main enhancements of a WSN to meet IoT applications



depicts the main conditions that a WSN should provide to meet the requirements of Internet of Things (IoT) applications.

In a WSN, the exhaustion of a node's battery implies the malfunction of the entire network and, consequently, the failure of the data collection which has sometimes sensitive nature (e.g., data used in military security applications). To overcome this problem, this paper proposes a solution that consists of improving the HXMAC protocol (Kechar & Hamamine, 2018) by integrating the collection of ambient energy from several sources. The photovoltaic energy (Beeby et al., 2010) (Kauer & Bellanger, 2020) is the most important source of energy (see Table 1). The wind (Drouilhet et al., 1995) (Slocum et al., 2019) can provide quantities of energy compared to those given by the sun. Thermal energy (Kashyap et al., 2019) (Al-Huniti & Al-Nimr, 2020) is mainly reserved for applications exploiting human energy as well as energy from machines. Vibratory energy (Mitcheson et al., 2008) (Yamane et al., 2019) varies depending on the proximity and nature of the source of vibration which is estimated at around 10 10^{-3} to 200 10^{-3} mw/cm^3. The radiofrequency radiation (Li et al., 2020) extracted from the transmitters present on the ground (2G, 3G, 4G, FM or Wi-Fi) provides a low amount of energy. Sensors have then the possibility of obtaining energy permanently from several sources, thus ensuring a longer lifetime of its battery and therefore the whole network. On the other hand, our solution integrate the duty cycling mechanism, which consists of switching between the two states (sleep/wakeup) to reduce energy consumption, if the residual energy is not sufficient, or energy extraction is difficult due to certain environmental factors (e.g., cloudy weather).

The second objective of the proposed protocol is to allow the mobile sink to gather the maximum amount of the data stored at the sensor nodes that are permanently supplied by ambient energy, using the handover mechanism (Kechar & Hamamine, 2018). This will ensure an improvement of the packets received number.

The rest of this paper has the following structure: Section 2 proposes a state-of-the-art about the newest related work. EH-HXMAC technique is described in Section 3. The results of the simulation performed using Cooja/Contiki simulator are presented in Section 4. Section 5 concludes the paper and gives some directions for future work.

STATE OF THE ART

Several research works have been carried out on ambient energy harvesting from its various sources. (Sharma et al., 2019) have proposed a new approach to address the problem of limited power availability by analyzing data communication results at the network layer level with different irradiance values. (Sharma et al., 2018a) have conducted a survey of solar energy harvesting in wireless sensor network SEH-WSN nodes on four axes: (sensing, computation, communication, and energy harvesting). (Sharma et al., 2018b) have proposed a collector which uses miniaturized photovoltaic modules, and which dynamically adapts to variations in light intensity, and its measured electrical consumption is less than 1 mW. (Sharma et al., 2018) have developed a power electronic device, which is used to convert the voltage amplitude from one level to another level for energy harvesting from WSN nodes. The simulation results have shown that the ripples of the output voltage are inversely proportional to the value of the inductance, and the duty cycle. (Fang et al., 2017) have proposed an approach regarding the use of energy harvesting in the Greens WSNs. (Ren & Yao, 2019) have proposed a technique called EECHS, which consists of dividing the set of nodes into three subsets: cluster head (CH), cluster member (CM), and scheduling node (SN). This allows reducing the energy consumption caused by the selection of (CH). (Singh et al., 2021) have proposed a complete classification of the various techniques and algorithms of energy harvesting conducted recently by various authors.

On the other hand, several works have looked at the impact of the duty cycle on the WSN efficiency. (Siddiqui et al., 2018) compares two proposed algorithms to solve scheduling sleep/wakeup problems. Other studies have proposed new approaches by acting on the duty cycle to minimize collisions (Duan et al., 2015) and energy consumption (Seo, 2015).

In terms of MAC layer protocols, (Muzakkari et al., 2020) have implemented an energy-efficient and QoS sensitive MAC protocol (EEQ), which saves energy and reduces packet latency. (Kechar & Hamamine, 2018) have proposed a transparent transfer technique based on neighborhood information which is an improvement of the XMAC protocol. This protocol enables the source node to continue providing data to the mobile sink by selecting the most appropriate neighbor as a relay node when the sink is no longer reachable. (Onwuegbuzie et al., 2019) have analyzed and compared four MAC implementations in terms of power efficiency: the Contiki_Mac, CXMAC, XMAC, and Null MAC. (Bengheni et al., 2017) compare two different types of asynchronous MAC protocols for WSN. The first is based on low-power listening (LPL), which uses the transmission of the preamble frame such as (XMAC and BMAC), and the second based on a beaconing paradigm that uses the transmission of the beacon frame such as (Receiver Initiated MAC: RIMAC). (Kaur et al., 2019) discuss EH technology in WSNs, and conduct a study of MAC protocols based on EH in a classified manner. The protocols comparison is made based on different metrics such as the energy conservation factor, latency scalability. (Kaur et al., 2020) have implemented a receiver initiated MAC protocol (HM-RIMAC) designed to adapt to weather conditions dedicated to agriculture applications. (Kochhar et al., 2020) have implemented a new multi-layer protocol (MLMAC-HEAP) which takes into account the energy harvesting criterion. The latter's performance has been evaluated based on the energy harvesting rate and the number of network nodes. Our proposed approach stands out from other works cited in the state of the art by:

- **The use of ambient energy harvesting:** (Kechar & Hamamine, 2018) did not address the problem of limited energy in the network. Once the residual energy of a node is exhausted, the node can no longer continue transmission, which implies the failure of part of the network (such as connectivity or coverage problem) or the entire network depending on the node location. To remedy this problem EH-HXMAC have resorted to energy harvesting.
- **The source of collected energy:** (Sharma et al., 2018b) used a single source of energy (solar energy) which is an unstable source and may be altered by a simple passage of clouds and does not provide energy throughout the day. This is why our approach EH-HXMAC proposes to use a hybrid energy source (solar-wind) so that when one of the sources is altered by any event, the other ensures continuity of supply.

THE PROTOCOL EH-HXMAC

This section details the design of our contribution EH-HXMAC.

Selected MAC Protocol

The authors of this paper have used HXMAC (XMAC with Handover) (Kechar & Hamamine, 2018) as a basic MAC protocol which has been enriched with ambient energy harvesting capability. In a wireless sensor network, energy efficiency is essential to minimize energy consumption and, therefore, improve the network lifetime. In recent years, several studies have been carried out on this problem, in particular those which have proposed improvements to the MAC layer protocols either synchronous (such as SMAC, TMAC) or asynchronous (such as XMAC, BMAC, RIMAC) for ensuring greater energy efficiency. In this work, the asynchronous XMAC protocol is adopted since it is simple and uses short preambles, thus ensuring low energy consumption during the listening and transmission phase. In addition to this, it has already been improved by the handover mechanism by (Kechar & Hamamine, 2018).

Selected Energy Source

After a study conducted on the various existing energy sources (Table1), it was noticed that the quantity of energy provided by vibrations, radiofrequency radiation, and heat is insufficient to ensure the sensor nodes' autonomy in several applications requiring a high amount of energy.

For that matter, EH-HXMAC protocol has adopted a hybrid energy harvesting system with two sources that have proven to be sufficient and complementary: solar (photovoltaic) energy and wind energy because they offer important energy values.

Table 2 summarizes the most recent works on unimodal/multimodal ambient energy harvesting used in WSNs. This table shows that research works that adopted multimodal ambient energy collection use two collection techniques (Individually / simultaneously). The first type of collection consists of extracting several types of energy, each separately. The second type of collection allows several types of energy to be extracted in parallel. The EH-HXMAC has adopted the second type of collection because it has the advantage of ensuring greater energy efficiency. The second remark that can be deducted from the table is that the two most used sources of energy are the sun and the wind.

Network Model

The network model of this study includes a mobile sink powered by a main supply that moves on a linear trajectory with a constant speed and a set of sensor nodes supplied with energy in a hybrid way (solar, wind). Thereby, each node has a micro solar panel to collect solar energy during sunny days, and a micro-turbine (Idriss et al., 2020) to collect wind energy, on cloudy days, or if the solar energy collected is not sufficient enough. It will also be equipped with a super capacitor

Table 1. Comparison of different ambient energy sources (Bouguera, 2019)

Energy source		Power density
Outdoor Photovoltaic		15 mW/cm^2
Indoor Photovoltaic		$100.10^{-3} mW/cm^2$
Vibrations (microwave oven)		$16.10^{-3} mW/cm^3$
Thermoelectric (for a gradient of 10 °C)		40.10^{-3} mW/cm^3
Acoustic noise (100dB)		$0.96.10^{-3}$ mW/cm^3
Ambient RF		0.08 nW-0.1µW/cm^3 (GSM 900/1800MHz) 0.01 µW /cm^3(Wi-Fi)
Wind	Turbine Triboelectric	65.2 µW /cm^3
	Generator (5m/seconds)	400 µW/cm^3

Table 2. Summary table of recent works on hybrid energy harvesting

Ref.	Type of energy used	Technique of energy harvesting	Brief description
(Wu et al., 2014)	Wind-Solar-Chemical	Simultaneously Individually	-Triboelectric nanogenerator(TENG). -Deliver a maximum power density of 16 mW/ m^2 .
(Sathiendran et al., 2014)	Wind	Individually	-Ambient wind energy harvesting system based WSN for Structural Health Monitoring. -Use Super capacitor as storage device instead of Batteries.
(Dudem et al., 2016)	Mechanical-solar-wind	Simultaneously Individually	- Hierarchical nano/micro architectured (HNMA)-polydimethylsiloxane(PDMS) film-based hybrid energy.
(Baranov et al., 2016)	Wind-solar	Individually	-The battery is used only as backup energy storage. -The switch over from the battery to the two power sources only occurs when the amount of voltage in the super capacitors exceeds 900 mV. -Each super capacitor stores energy from each source independently.
(Wu et al., 2018)	Wind	Individually	-Predictive wind energy management framework.
(Belu et al., 2018)	Wind-Solar	Individually	- Use two lithium phosphate batteries as energy storage unit.
(Bestley et al. 2018)	Wind	Individually	-Wind energy harvesters to generate power for WSN in low wind conditions. -The obtained output voltage is about 9V for 90% of rotation speed of motor.
(Iqbal et al., 2018)	Wind-Vibration	Simultaneously	- Multimodal hybrid bridge energy harvester. -Combine piezoelectric and electromagnetic conversion. - Consists of a permanent magnet, a wound coil, a piezoelectric plate, an airfoil, and two cantilever beams attached to a base support frame.
(Deng et al., 2019)	Wind-Solar-Thermal	Simultaneously	- A hardware platform for a self-powered WSN node. - Use a super-capacitor as an energy storage module. - The average daily generating capacity is 7805.09 J.
(Kang et al. 2019)	Solar	Individually	-A strategy that allows nodes that have excess solar power to communicate to other transmitting nodes the current location of the mobile receiver.
(Kaur & Butar, 2021)	Solar	Individually	-Solar EH technique with low energy adaptive clustering hierarchy protocol.
Our approach EH-HXMAC	Solar-Wind	Simultaneously	-Combines two energy sources (solar-wind). -Uses a super capacitor to ensure more storage capacity and faster charging. -Uses duty cycling to ensure greater energy efficiency.

which has the advantage of having a huge storage capacity, and charges twenty times faster than a battery (see Figure 3).

Each node has a unique identifier and its own IP address in the network. The node varies its duty cycle according to its residual energy. The emitter node starts listening; as soon as it receives a response to its request addressed to the mobile sink, it starts data transmission. When the sink leaves the node contact area, the emitter will choose the closest neighbor to the sink as a relay node and will transmit the remaining data to it (see Figure 2).

Figure 2. Class diagram required for the design of EH-HXMAC

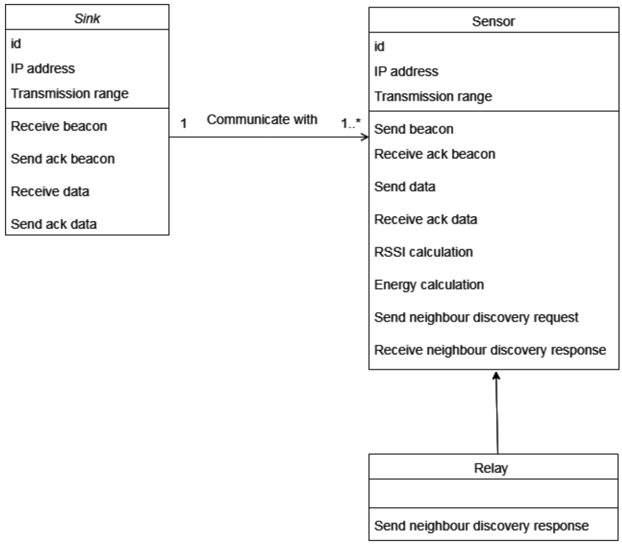
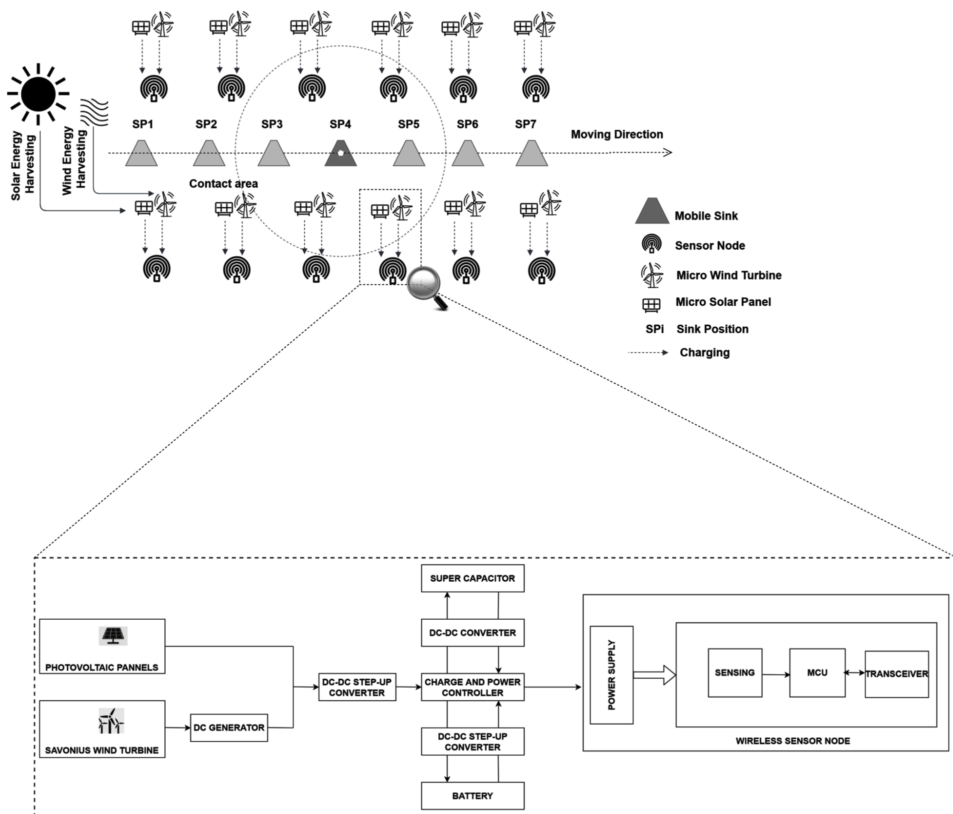


Figure 3. Energy Harvesting WSN-MS with the architecture of the sensor node



The solar panel and the wind turbine are the two input energy sources. The solar panel is intended to produce electrical energy directly from solar radiation. On the other hand, the energy generated by the wind turbine is mechanical energy, so it must pass through a DC-generator to have electrical power as output. Once the electrical energy has been collected, it passes through a DC-DC STEP-UP converter to adapt the voltage. Then comes the role of the charge and power controller which on the one hand, blocks the reverse current, thus preventing overcharging of the battery, and on the other hand it prevents over-discharging of the battery to protect it from damage (see Figure 3).

The Sensor Node Behavior

In our approach, the sensor node goes through six different states, as depicted in Figure 4, and detailed below:

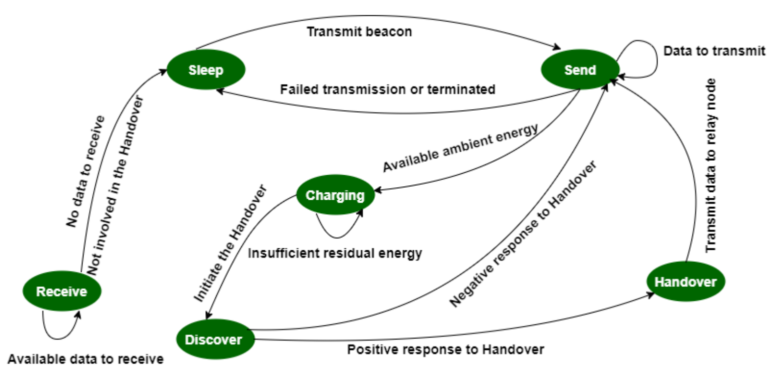
- **Sleep:** The sensor goes to sleep when there is no more data to send.
- **Send:** The sensor goes into this state to check the sink availability in its contact area by sending beacons. As soon as the sink responds, the node starts transmitting the available data to it.
- **Discover:** Before the sink leaves the contact area again, the node sends a handover request to all of its appropriate neighbors.
- **Handover:** When the closest neighbor node to the sink responds to the discovery request, the sensor transmits the data which could not be transmitted, to this neighbor node (relay).
- **Receive:** The sensor transmits beacons or data. When the packet is correctly received, the transmitter receives acknowledgment.
- **Charging:** When an amount of ambient energy is available, the sensor will be notified by this event and will charge periodically.

Proposed Algorithm of EH-HXMAC at the Source Node

The proposed EH-HXMAC protocol is an Emitter-initiated approach where the source node (sensor) takes the initiative in communication.

The sending node wakes up after a sleep period and will then test for channel availability. If the channel is not free, the node goes back to sleep mode again. Otherwise, the node starts sending a series of beacon packets (BEACON_packet). As soon as the sending node receives an acknowledgment (ACK_BEACON_packet) in response to one of its sent packet beacons, it stops the transmission of packet beacons and starts sending data packets (DATA_packet). For each data packet received by the sink, an acknowledgment must be sent to the source node. Upon each receipt of acknowledgment packet, the sending node measures the RSSI value to estimate if the mobile sink is within radio range.

Figure 4. Finite state machine diagram of a sensor node behavior using EH-HXMAC



If the value of the RSSI reaches the threshold, this means that the mobile sink has left the radio range of the transmitting node and that single-hop transmission is no longer possible.

The RSSI threshold value used is defined according to the distance d given by the following formula (Dong & Dargie, 2013):

$$d = R - \left(n - w\right)\left(\frac{N_{data}}{R_t} + \frac{N_b}{R_t} + 2T_{SIFS}\right)v \quad (1)$$

R: Radio transmission range.
n: Number of data packets stored at the sensor node.
w: The first amount of transmitted packets.
(n - w): The remaining packets at the transmitter node .
N_{data}: The data packet size.
R_t: transmission rate.
N_b: ACK beacon size.
T_{SIFS}: The time to switch the radio from transmitting to receiving mode.
v: The movement speed.

Algorithm 1: The EH-HXMAC algorithm

```
1:begin
2:if (CCA is free) then //Check the channel state
3:   Switch to active state;
4:   Send BEACON packet;   //receiver=Sink
5:   Wait for ACK_BEACON_packet;
6:   if (ACK_BEACON_packet received) then  //The sink replied
7:     Stop sending BEACON_packet;
8:     Send DATA_packet to the sink;
9:     Wait for ACK_DATA_packet;
10:    if (ACK_DATA_packet received) then //The sink replied
11:       Calculate RSSI; // Calculate the signal strength
12:       if (RSSI (ACK_DATA_packet)>threshold) then // Sink entered
13:         if (Residual_energy> 30% of Initial_energy) then
14:           Keep DC at 100%;
15:           Send DATA_packet; //receiver=Sink
16:           if (Last DATA_packet) then // There are no more data
17:             Goto 1;// Restart the procedure
18:           else Calculate RSSI;
19:              if (RSSI>threshold) then // The sink still here
20:                 Goto 13; // Check the amount of energy
21:              else Broadcast HANDOVER_REQ_packet;
22:                Wait for HANDOVER_REP_packet;
23:                if (HANDOVER_REP_packet received) then
24:                  Select the nearest neighbor to the Sink;//Relay
25:                  Send DATA packet to the relay node;
26:                else Goto 21; // Resend a Handover request
27:                  Goto 16; // All data transmitted?
28:                end if
```

```
                end if
           end if
           else reduce DC to 50%; // If the residual energy<30%
         Goto 15; // Continue data transmission
        end if
      else Goto 8; // If the transmission failed resend the data
end if
else Goto 4;// If beacon transmission failed  resend the beacon
end if
else Switch to sleep state; //If the channel is not free
end if
end
```

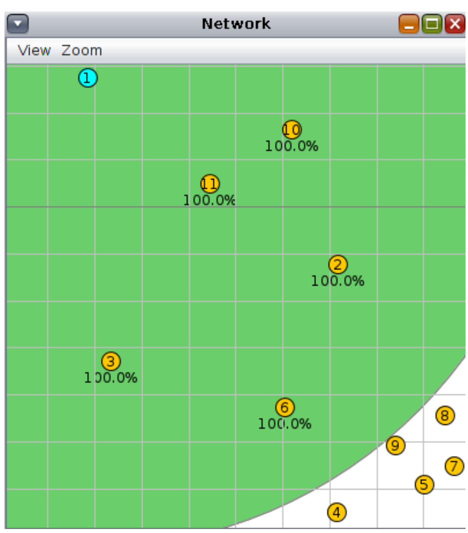
After checking that the mobile sink is indeed in the contact area of the transmitting node, the sensor must check the amount of its residual energy. As long as the amount of residual energy has not reached 30% of the initial energy, the node continues to operate with a duty cycle of 100%. Albeit the sensor node rarely reaches the minimum energy threshold thanks to the mechanism of ambient energy harvesting, if the node has reached the minimum energy threshold it must reduce its duty cycle to 50%.

When the RSSI value does not become sufficient to continue the transmission between the transmitting node and the mobile sink, this means that the sink is leaving the radio range. The sending node will then start the handover mechanism. The node will broadcast a (HANDOVER_REQ_packet) to all of its neighbors. The node to which the mobile sink is closest responds to the request with a (HANDOVER_REP_packet). This node then takes over the communication between the sender node and the sink, which will then become a 2-hop communication.

EXPERIMENTAL RESULTS

All simulations were carried out using the Cooja simulator (Figure 5) (Kugler et al., 2013). It allows emulating different kinds of sensors: (z1, Micaz, sky…) and simulates network connections and interact with the sensors. The simulation parameters, as well as the obtained results, will be presented below.

Figure 5. Illustration of the network topology using EH-HXMAC under Cooja simulator



Energy Harvesting Model

To simulate the phenomenon of ambient energy harvesting, the authors of this paper have used a framework proposed by Victorcionca[2] which has been modified to suit the needs of our work.

The framework is composed of several modules, among which the authors of this paper have used the following two.

Energy Harvester

Its function is to simulate an energy harvester's operation (micro solar panel – micro wind turbine) by receiving harvested energy values over the serial line and generates an event each time energy is harvested.

To synchronize the network time with the host time, the nodes will poll the source for values when they need them. The source should reply with an energy harvesting value representing harvested energy in the previous period.

Battery Simulator

Simulates an energy tank with a current capacity (residual energy):

- **Maximum:** If the amount of energy collected exceeds the battery's capacity, charging stops.
- **Minimum:** If the node reaches the energy threshold, it shuts down and will not resume its operation until the threshold is exceeded again.
- **Energy consumed:** The energy consumed is deducted from the current level of residual energy and the consumption of the following four modules (CPU, LPM, radio transmits and radio listen) (Hassani et al., 2019) and then multiplied by the battery consumption factor:
  - **CPU:** A power parameter that indicates the level of node processing.
  - **LPM:** Low Power Mode is a power consumption parameter that indicates the power used when in sleep condition.
  - **The radio transmits and radio listen:** Parameters related to node communication (transmit and listen).
- **Collected energy:** If a harvested energy event is generated, it will be added to the current energy.

Simulation Parameters

Table 3 summarizes the parameters that can influence the simulation.

To evaluate the performance of our approach in terms of energy consumption, network lifetime, packets received number, throughput; the authors of this paper have used a script written in JavaScript (Rhino) and developed within the COOJA/Contiki simulator. The script has been modified according to the parameters used and the expected needs.

Network Lifetime Calculation

The wireless sensor network lifetime is estimated by the period between the start of network operation until the first node dies due to energy depletion (Wu et al., 2018).

Let $E=\{ S_1,S_2,S_3,\ldots..S_n\}$ is a set of nodes in the network. Let $\mathbf{S_i}$ is a given sensor node that has a lifetime ti.

The network lifetime is given by $\mathbf{T_{net}}$ then:

$$T_{net} = \min (t_1,t_2,t_3,\ldots.t_n).$$

Each simulation repetition gives us the node consumption in 1seconde given by $ʎ_i$.

Table 3. Simulation parameters

Parameters	Values
Simulator	Cooja (Contiki) 2.7
Deployment of nodes	Random
Simulation time (s)	150
RSSI threshold (dBm)	-90
Sink transmission range (m)	100
Sensor node transmission range (m)	100
Duty cycle (Sink) (%)	100
Duty cycle (sensor node) (%)	100,50
Movement speed of sink (m/s)	1,2,3,4,5
Pause time	0
Squared area of sensor nodes deployement (m)	100*100
Average packet length (Bytes)	120
Simulation repetition for each scenario	50
MAC protocols	EH-HXMAC, HXMAC,XMAC

Sensor Node Lifetime Calculation

A sensor node S_i consumes an amount of energy $ʎ_i$ /sec.

The daily amount of energy consumed C_i is obtained by multiplying $ʎ_i$ by 86400.

The node lifetime is then calculated by the following formula:

$$t_i = \frac{Intitial\ energy\ of\ the\ node\ \left(E_i\right)}{Daily\ consumption\ of\ the\ node\ \left(C_i\right)} \tag{2}$$

The following formula calculates the throughput:

Throughput= Total_Received * Data_Length /Simulation_Time (3)

Simulation Results

See Figures 6-9.

Figure 6. Energy consumption comparison

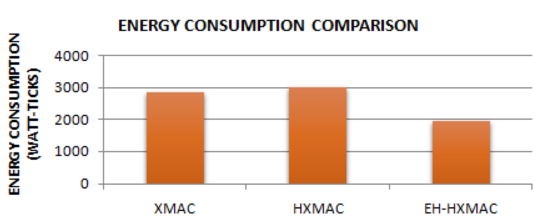


Figure 7. Network lifetime comparison

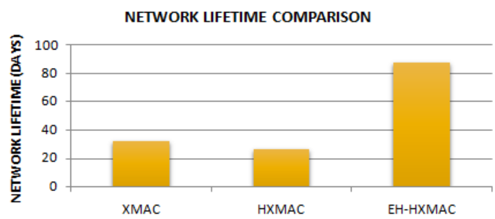


Figure 8. Network throughput comparison

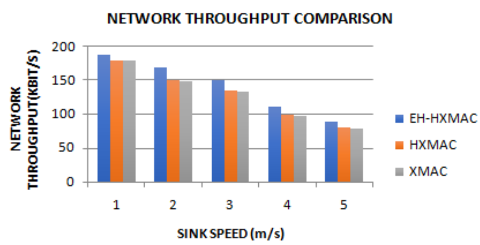
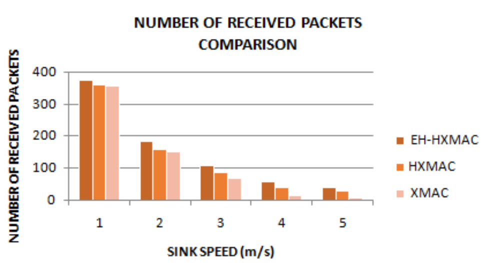


Figure 9. Number of received packets comparison



DISCUSSION OF RESULTS

To evaluate our contribution, authors propose in the following a comparison of EH-HXMAC protocol with HXMAC and XMAC protocols.

The simulation results show the impact of the combination of three techniques, namely energy harvesting, handover and duty cycling using the following four metrics: energy consumption, network lifetime, network throughput and number of received packets.

In the Figure 6, it is noticed that the EH-HXMAC provides the best results in terms of energy consumption compared to the two other protocols XMAC and HXMAC.This improvement in energy consumption is due to the duty cycle mechanism which allows the transmitter node to adapt its duty cycle by switching between the two modes (active and sleep) according to the availability of the mobile sink and to the residual energy of the node. It is also noticed that the HXMAC presents higher values in terms of energy consumption compared to the XMAC protocol because of the overactivity of the transmitter node which sometimes becomes a relay node during the handover process, without having the possibility of compensating this excessive energy expenditure because the node does not have the possibility of collecting ambient energy.

In Figure 7 the efficiency of EH-HXMAC approach is noticed in terms of network lifetime. The XMAC protocol guarantees to the transmitter node a very limited lifetime compared to the EH-HXMAC protocol. This is explained by the fact that the lifetime of the node is inversely proportional to its energy consumption, and as it was explained previously the sensor node which adopts the XMAC protocol has a much more considerable energy consumption compared to the node which adopts the EH-HXMAC protocol. The HXMAC protocol has the shortest lifetime, and this comes down to the excessive energy consumption of the transmitter node which sometimes takes the role of a relay node in the communication, which causes a rapid depletion of its energy and therefore an early death of the node. As it was explained in a previous section, the death of a node affects the lifetime of the entire network.

Figure 8 shows us that the EH-HXMAC protocol exceeds the two protocols XMAC and HXMAC which have almost the same values in terms of throughput. This is explained by the fact that unlike the two previous protocols, the EH-HXMAC protocol allows the node transmitter to operate almost permanently with a duty cycle of 100% thanks to energy harvesting, which increases the yield of the nodes and therefore improves the throughput of the network.

Figure 9 shows that the EH-HXMAC protocol has the best values of received packets number in the network compared to the two protocols XMAC and HXMAC. This is due to the combination of three mechanisms: duty cycling, energy harvesting and handover.

On the one hand, the two mechanisms: duty cycling and energy harvesting ensure the nodes a longer lifetime, so the network can operate longer and therefore can transmit a maximum of data. On the other hand, the handover mechanism allows the sending node to continue transmitting data even when the mobile sink has left its radio range.

The authors of this paper have proposed several values of the number of received packets by varying the speed of the mobile sink. It is noticed that the two protocols XMAC and HXMAC present almost the same number of received packets when the mobile sink moves with a low speed (1m/s – 2m/s) , and this is explained by the fact that when the mobile sink moves slowly the transmitter node will have enough time to send all the data packets. Therefore, the handover mechanism will not occur and the two protocols XMAC and HXMAC will have the same values in terms of the number of received packets. When the speed of the mobile sink exceeds (2m/s), the difference in the number of received packets between the XMAC protocol and the two protocols (HXMAC and EH-HXMAC), becomes more remarkable. This can be explained by the fact that when the sink moves at high speed the XMAC node will not have enough time to transmit all the data packets. On the other hand, the sending node in the two protocols HXMAC and EH-HXMAC can continue the transmission to the mobile sink by the handover mechanism.

Our EH-HXMAC approach exceeds the two XMAC and HXMAC approaches in terms of the number of received packets regardless of the speed of the mobile sink thanks to ambient energy collection, which allows the node to operate longer and therefore to transmit more data to the mobile sink.

CONCLUSION

In this paper, the authors have proposed a new EH-HXMAC protocol that improves the XMAC protocol by integrating three mechanisms: i) duty cycling which reduces energy consumption of the sensor node, ii) ambient energy harvesting which provides energy to the sensor node permanently, and iii) handover mechanism which ensures maximum data transmission to the mobile sink. The preliminary results obtained by simulation, especially in terms of network lifetime, are encouraging for further investigation in this area of high-impact research.

In future work, the authors plan to extend this work in several directions, particularly on distributing the collected energy on the nodes according to their needs to ensure greater energy efficiency and thus a longer network lifetime. Another interesting direction of research consists in using the harvested energy to wirelessly power other sensor nodes that are not provided with energy harvesting capabilities.

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ENDNOTES

1 In the rest of the paper, the authors use WSN or WSN-MS interchangeably.
2 https://github.com/victorcionca/eh_contiki/commits?author=victorcionca: Feb 2018