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ETI-MAC: An Energy-Harvested Transmitter-Initiated MAC Protocol for Wireless Sensor Networks

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***Abstract* – The paper proposes an Energy-Harvested Transmitter-Initiated MAC Protocol for WSNs (ETI-MAC). ETI-MAC takes advantage of the benefits of transmitter-initiated schemes and employs the low power listening (LPL) method with small preamble messages so that each sensor node in the network can predict its next sleep duration based on the harvested energy rate value, thereby lowering the duty cycle by making use of its accumulating residual energy. The simulation results show that the proposed protocol outperforms compared to the old PS-EHWSN scheme.**

***Keywords* – Duty-cycle, energy harvesting, low power listing, wireless sensor networks.**

I. Introduction

The field of technology known as wireless sensor networks (WSN) has advanced significantly over the past few decades in terms of micromechanics, microelectronics, and wireless communications technology. These technological developments have made it possible to produce tiny electronic components called micro-sensors, which have a volume of only a few cubic millimeters, at a competitive price. As they integrate collecting units, these micro-sensors are truly on-board systems, allowing them to gather physical quantities of various types, such as heat, and convert them to digital values. A restricted power supply (battery), computer processing and data storage device, and wireless transmission unit or modules are also included. This WSN is formed by this collection of micro-sensors (sensor nodes), which detect phenomena and direct them to a base station or collecting point (sink) responsible for transferring them to the central computer [1], [2]. Despite its novel nature, this technology nevertheless confronts several difficulties and limitations that are either related to the quality and internal efficiency of the equipment itself or to natural phenomena that occur outside, such as those present in the deployment environment. Wireless communication makes this technology more or less adaptable in areas unfriendly to people or unavailable to them, such as active volcano craters. Depending on the experience to be performed, the state of the action environment or the phenomenon to be captured, sensor nodes can be distributed in deterministic or random ways [3]. The most fundamental of all these restrictions is still the need to maintain or extend as much as possible a WSN lifetime, which can be specified to various degrees (e.g., by decommissioning a single node, a group of nodes, or the whole network). In this concept of the WSN lifetime, the theme or, let us say, the most obsessive axis for the scientific community in the field remains the management of the sensor energy [4]–[6], because both the batteries of the latter can no longer be recharged once deployed (a sensor node embedded in concrete, for example). As a result, talks are concentrated on all layers, if not all physical components of sensors, and notably on the logical functioning of sensors amongst them, namely the communication protocols of each level or layer of the OSI model, for more efficient energy consumption. Protocols of various sorts, for example, functioning at the MAC sub-layer of the OSI model, offer a fairly extensive topic of research for solutions connected to the optimization of energy usage in networks. Many MAC protocols have been established and are still being developed today, some of which are more effective than others and are devoted to the control of energy consumption in the WSN based on different methodologies, such as the duty-cycle methodology [7], which can be divided into two groups: synchronous MAC protocols and asynchronous MAC protocols [8], [9].

To increase data transmission speeds, synchronized protocols employ synchronized sleep-wake cycles. Asynchronous protocols, on the other hand, do not need to synchronize their sleep and waking times. However, the network lifetime always remains constrained. The recent development of an energy collecting system [10], [11] in each sensor node is another novel approach. In order to increase the lifetime and performance of the network, the latter harvests energy from the environment or other energy sources (footfalls, fingertip movements, etc.) and transforms it into electrical energy that can be used immediately. Therefore, in order to control the energy consumption and the way it is collected by

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the nodes in WSN, the majority of the duty-cycle is spent in the low power sleep state where the nodes can harvest more energy, leading to a reduction in the time of node activity and minimizing the duty-cycle. When several packets are delivered, excessive node activity produces significant delay and packet collisions. In this context, the present study focuses on the use of the energy harvesting technique in wireless sensor networks for the proposal of new energy management solutions in this type of network, such as the planning of the sleep and wake-up periods of a sensor on the basis of its energy level remaining in its battery so that it can harvest more energy.

In this paper, a protocol named ETI-MAC (Energy-Harvested Transmitter-Initiated MAC Protocol for Wireless Sensor Networks) is proposed, where all sensor nodes have an energy harvesting mechanism installed, and communication between them is initiated by sending a series of short preambles after the channel availability test. The sending node takes an active part in the conversation. The initiator adopts the advanced features of the issuer-initiated mechanisms developed in previous publications [12], [13]. An approach for estimating the duration of the sleep time of the nodes is also incorporated to further increase the efficiency of ETI-MAC, which will also allow defining two types of sleep duration: one is short used by the nodes of the network when the rate of energy harvesting is higher and the other is slow used when the rate of energy harvesting is low. The latter is also used to adjust their duty cycles more adaptively by function of the collected energy that will be available in the future, whose remaining energy is used to determine the duration of this next phase of sleep. This approach decreases latency and power consumption on both the source and non-target nodes, by reducing collisions, idle listening, overhearing, and over-emitting. Additionally, using the gathered energy, the primary goal of ETI-MAC is to raise the packet delivery ratio while lowering mean latency, reducing power consumption and boosting throughput in the WSN lifetime.

The layout of the remaining sections is as follows. In Section II, the literature review is provided. Section III explains the functioning of ETI-MAC protocol, while Section IV discusses the simulation-related material, including the tools and parameters. In Section V, the performance of the ETI-MAC protocol is assessed and contrasted with the PS-EHWSN scheme [26]. In Section VI, conclusions and future research areas are presented.

II. Related Works

Energy harvesting is an emerging strategy in WSNs that enables preserving energy neutrality by accounting for the influence of the rate of energy collection in order to make up for the energy used [14]. A majority of energy harvesting protocols that have been suggested for wireless sensor networks (WSNs) aim to keep the sensor node functioning in the Energy Neutral Operation (ENO) state, while ensuring that its energy consumption is either lower than or equal to the energy obtained from the environment. If energy consumption is always equal to energy collected, it achieves the ENO-Max condition otherwise. To address this issue, a wide variety of MAC protocols for energy harvesting in wireless sensor networks (EH-WSNs) have been developed that take the energy gathered into consideration while scheduling different duties, including duty cycle. The protocol that employs probabilistic polling lowers the amount of data packet collisions throughout network communication among nodes in accordance to the subsequent concept.

Each receiver node in a WSN periodically stores a contention probability P_{co}, which is used in the polling packet to determine the likelihood that a sender node will transmit its data packet. When a node receives a polling packet, it generates a random number *nbr* in [0, 1] and sends its data packet if $nbr < P_{co}$. If not, it will either remain in the receiving state to await the next polling packet or switch to the charging state if its energy is insufficient to send just one data packet and if a node buffer packet is full, it will not send a polling packet. The probability of the next polling cycle rises if the receiver does not get any data packets in response to polling. Then, it lowers the probability of contention in the event of a data packet collision. Several MAC protocols for EH that adhere to this idea are discussed below.

It has been suggested that Probabilistic Polling MAC (PPMAC) [15] for single hop WSNs will enhance network performance in terms of throughput, fairness, inter-arrival time gains from EH rate, node density, and packet collisions. The receiver node is the sink, which periodically sends the polling packet to collect the data packet from the sensor nodes.

In order to increase throughput while taking into account the different amounts of ambient energy that can be harvested from the environment at different times and locations, a medium access control protocol (EH-MAC) [16] for multi-hop EH-WSNs has been proposed. This protocol is an extension of PP-MAC to multi-hop scenarios. To lessen interference, however, it dynamically modifies the amount of polling packets, in contrast to conventional random back-off techniques.

A novel strategy for extending PPMAC to multi-hop is a Multi-tier Probabilistic Polling scheme (MTPP) [17] for multi-hop data transmission in WSNs that exclusively depends on energy harvesting for power. This protocol has a tier-based hierarchy architecture, where each tier is represented by a number (for example, tier 1, tier 2,... etc.) and is made up of a group of nodes that are spaced apart from the sink. Differently, the creators of this protocol executed the plan on commercially available hardware and empirically tested it in contrast to earlier research that relied on simulations to show the validity of the idea.

To avoid wasting bandwidth due to collisions, the authors presented in [18] an upgraded polling protocol based on PP-MAC (called Probe-Polling: A Polling Based MAC Protocol for Energy Harvesting Wireless Sensor Networks). The primary idea behind Probe-Polling is to allow sensor nodes to react to polling packets with small probe packets rather than lengthy data packets. The sink node evaluates the channel status using the received probe packet and responds with a broadcast ACK message. Only if the ACK shows that the channel is free, the sensor node will proceed to broadcast its data packet. If a collision occurs, the bandwidth used in PP-MAC is preserved,

and the network immediately begins a new polling cycle. In comparison with PP-MAC, simulation results demonstrate that Probe-Polling delivers a greater throughput and shorter inter-arrival time.

In addition to the probability polling approach, there are several MAC protocols for EH that use other distinct protocol principles present below.

Based on the idea of duty-cycle, the On Demand MAC protocol (ODMAC) [19] for EH-WSNs may enable distinct duty cycles for nodes with different energy profiles. As a result, each node has the ability to raise its performance by increasing its energy consumption until it is equal to the amount of energy gathered.

In order to achieve the optimum performance in terms of latency and energy efficiency, Energy-Harvested Receiver-Initiated MAC Protocol (ERIMAC) for WSN [20] makes use of packet concatenation and receiver-initiated approach. In addition, ERI-MAC uses a queuing mechanism to modify the functioning of a sensor node in response to the rate at which it gathers energy from its surroundings.

The data priority mechanism is used by the QoS Aware Energy-Efficient MAC Protocol for Energy Harvesting for WSNs (QAEE-MAC) [21] to choose the sender node. Periodically, a receiver node awakens, listens to sender beacon frames, and broadcasts a beacon frame with the address of the chosen sender. Depending on the priority of the sender's data, a receiver node chooses a sender node. The energy status influences how long a receiver node sleeps and how long it wakes up. As a result, the receiver node uses as little energy as possible.

An energy-harvesting user's MAC protocol in cognitive radio networks is called Energy Level based MAC (EL-MAC) [22]. In order to implement communication on a super frame basis, it employs two different user types: Primary Users (PUs) with high energy and Secondary Users (SUs) with low energy. Sensing, contention, and transmission phases are allotted discrete amount of time. In EL-MAC, the SUs were given a significant importance. They may swiftly access the channel, allowing PUs to broadcast data after SUs have finished transmitting it while still allowing SUs to enter sleep mode. Depending on the channel access likelihood based on its energy level, the SUs can determine whether or not the PUs are using it. If the channel is clear, SUs can employ CSMA/CA to transit to the contention phase; after that, the transmission period. Otherwise, SUs return to sleep quickly to avoid interfering with PU interactions. In general, EL-MAC improves energy efficiency.

The performance of energy harvesting powered WSNs is improved in three areas: relaying, scheduling, and medium access control, according to the Load and Energy Balancing MAC Protocol for Energy Harvesting Powered Wireless Sensor Networks (LEB-MAC) [23]. The transmitter node is able to lower its duty cycle and manage the active and sleep intervals in accordance with energy levels thanks to the beacons that the reception nodes send out that contain information about the next wake-up schedule. To receive a beacon from the matching receiver node, a sender node must wait for a sufficient amount of time, where the sender's maximum waiting time is application-related, if it has no knowledge of the receiver's schedule. The data packets are routed through alternative pathways when nodes require time to recharge. By distributing the load across the network in accordance with the characteristics of each node energy harvesting, this relaying approach seeks to prevent holes.

DeepSleep [24] mechanism, an IEEE 802.11 power saving mode (PSM) MAC improvement approach, enables the wireless M2M communications network [25] with extensively distributed / many autonomous energy harvesting devices. DeepSleep uses the features of energy harvesting technology to recharge the energy supply of gadgets.

An Enhanced Energy Management Scheme in Energy Harvesting WSNs (EEMEHWSN) has been suggested by the authors in [5]. The EEMEHWSN integrates an energy threshold strategy by leveraging residual energy in receiver-initiated connections to regulate sleep and active intervals in order to decrease the duty-cycle while maintaining equilibrium between energy utilized and energy harvesting capability by each sensor node in the WSN. The primary goal of EEMEHWSN is to use the energy gathered to enhance the performance of WSNs in terms of packet delivery ratio, throughput, and average delay.

A MAC protocol for Energy Harvesting WSNs (PS-EHWSN) based on a Preamble sampling Scheme is described in [26]. The PS-EHWSN system enables each sensor node inside the WSN to decide on its approaching sleep interval by utilizing its residual energy, which can rise with time, allowing it to be able to balance between its energy collection and consumption. Additionally, PS-EHWSN is built on the Low Power Listening (LPL) technology and relies on brief welcome messages received by the sender node. The primary objectives of the PS-EHWSN are to use the gathered energy to raise the WSN throughput, decrease mean latency, and boost the packet delivery ratio.

III. ETI-MAC: An Energy-Harvested Transmitter-Initiated MAC Protocol for WSNs

An Energy-Harvested Transmitter-Initiated MAC Protocol for WSNs (ETI-MAC) is presented in this section. ETI-MAC employs the strobed preamble approach, which involves broadcasting a series of short preamble packets. Fewer pauses between preamble packets allow the board recipient to transmit an acknowledgement, which ends the preamble packet series. It employs a dynamic duty-cycle scheduling system that makes use of the energy collected by the nodes.

A. Communication Scheme in ETI-MAC Protocol

ETI-MAC uses a CSMA/CA protocol, in which the transmitter employs a carrier wave to make the wireless channel busy and the receiver monitors the channel to prevent collisions. Each time the short preamble is sent, all nodes in the ETI-MAC network that have queued packets that need to be transmitted to the sink are listening to the channel and waiting for an appropriate acknowledgement (ACK). The transmission of the data packet is started as soon as the relevant ACK is received.

The suggested scheme is based on duty-cycling, which alternates active and sleep phases. This method gives energy harvesters a decent opportunity to replenish the energy source before entering an unloading mode, in which the sensor node uses the stored energy. The communication foundation of ETI-MAC is described below.

1. The proposed protocol nodes regularly wake up to do the transmission operation if there are data to be sent, and they move to sleep mode when there is no network activity after a listening period or after each subsequent data transfer.

2. In the beginning, all nodes go into sleep mode and then move to listening mode on their own timetable to listen to the traffic in the network.

3. When a sender node S wants to send data, it starts a preamble session by sending several short preamble packets Pr to its nearby nodes on broadcast after using the CCA (Clear Channel Assessment) to determine whether the medium is available. It then pauses after each transmission of the short preamble to listen for the carrier. Upon receiving a brief preamble and if their backoff is expired, an awake receiver node R answers to the sender by sending an ACK (acknowledgement preamble) packet in unicast mode.

4. If the channel is free, the sender S stops sending the remaining Pr short preambles and starts sending the data packet to the intended recipient, which will be acknowledged by R with ACK; otherwise, it goes to sleep state after a predefined amount of time allotted to sending many short preambles Pr.

5. After receiving the transmitted ACK acknowledgment by data packet, the sender S goes into sleep mode.

Then, the receiving node instantly begins broadcasting the data to the next node by carrying out Steps 3–5.

B. The Technique Described for Predicting the Next Sleep Period

The sensor node architecture used. We take into account one kind of periodic energy harvesting, where each node *i* is made up of a set of units: an environment detection unit (sensors), an analogue-to-digital converter (ADC), processing unit, multiple types of memory (program, data, and flash memories), communication unit (transmitter/receiver), a power unit (battery) of maximum capacity (E^{MAX}), and an energy harvesting system. Furthermore, each node employs an energy threshold (E_{thre}) to maintain a balance between energy consumption and energy collecting capability. An energy-harvesting and energy-to-electrical-energy-transformation system can come in two different architectures with or without storage capability [27], [28]: (a) recover-spend: the harvested energy is used directly and (b) recover-recharge-spend: the harvested energy is stored for later use. In the present study, we rely on the use of architecture (b).

Mathematical modelling. Let us assume that we have a network of *N* nodes and explore one sort of periodic traffic production in which each node *i* generates data at a predetermined periodic interval. Table I contains all of the notations for network, energy, and delay models that will be used throughout this section.

Energy model. To assess the energy efficiency of the ETI-MAC protocol, the quantity of energy ($\mathrm{E}_{\mathrm{Total}}^{\mathrm{ETI\text{-}MAC}}(\mathrm{i},\mathrm{t})$) spent by node *i* during data transmission, reception, and during the absence of any data to be sent or received (in the carrier sensing and in the environment sensing) at time *t* is stated as a formula, and after an analysis, it can be determined by ETI-MAC in the following manner.

TABLE I
SYMBOLS USED IN MATHEMATICAL MODELLING OF ETI-MAC

Symbol	Description
$E_{\text{Abs-Data}}^{\text{ETI-MAC}}$	The sum of two types of sense energy used (sense and carrier)
$E_{\text{Reception}}^{\text{ETI-MAC}}$	Receiving energy
$E_{\text{Transmission}}^{\text{ETI-MAC}}$	Transmitting energy
$R_{\text{data}}^{rx/tx}$	Rate to RX/TX data packets
R_{sense}	Rate of environment sense
P_i^{tx}	Transmission power
P_i^{rx}	Reception power
P_i^{carrier}	Carrier sense power
P_i^{sense}	Environment sense power
$L_{\text{spreamble}}$	Length of short preamble
L_{packet}	Length of data packet
L_{ack}	Acknowledgement length of data packet
T_i^{carrier}	Time of carrier sense
T_i^{acarrier}	Average time of carrier sense
T_i^{sense}	Time of environment sense
T_i^{asense}	Average time for sampling of data
T_i^{rx}	Time of reception
T_i^{tx}	Time of transmission
$T_{\text{byte}}^{rx/tx}$	Time of Tx/Rx (byte)
$T_{\text{switching}}$	Radio switching time
T_i^{que}	Time of queuing
T_i^{pro}	Time of processing

1. *The amount of energy used for data transmission at time t* ($E_{\text{Transmission}}^{\text{ETI-MAC}}(i,t)$) :

$$E_{\text{Transmission}}^{\text{ETI-MAC}}(i,t) = T_i^{tx} \times P_i^{tx}. \quad (1)$$

The time required to send data packets, short preambles, and acknowledgements (of short preamble and data packet) is collectively referred to as the node *i* transmission time (T_i^{tx}). When it has data to communicate, it sends a brief preamble and immediately switches its radio to listening mode in order to receive an acknowledgement. This procedure must be followed until the destination node acknowledges it. *K* is the number of times a node *i* sends a brief preamble and changes its radio frequency in order to get an acknowledgment (ack). After

receiving the data packet, the receiver modifies its radio to transmit an ack.

$$T_i^{tx} = \left(R_{\text{data}}^{rx/tx}\left(L_{\text{packet}} + 2L_{\text{ack}}\right) + KL_{\text{spreamble}}\right) \times T_{\text{byte}}^{rx/tx} + (K+2) \times T_{\text{switching}}. \quad (2)$$

2. *The amount of energy used to receive data at time t* $(E_{\text{Reception}}^{\text{ETI-MAC}}(i,t))$:

$$E_{\text{Reception}}^{\text{ETI-MAC}}(i,t) = T_i^{rx} \times P_i^{rx}. \quad (3)$$

During a given time period, a node may receive several ($\sum$) preambles. When it becomes a target node for a given preamble, it instantly sends an acknowledgement to the sender and gets its packet, after which it sends an acknowledgement to the latter. This is called the node *i* reception time (T_i^{rx}).

$$T_i^{rx} = \left(R_{\text{data}}^{rx/tx}\left(L_{\text{packet}} + 2L_{\text{ack}}\right) + \sum L_{\text{spreamble}}\right) \times T_{\text{byte}}^{rx/tx} + 2T_{\text{switching}}. \quad (4)$$

3. *The amount of energy used in the absence of any data to send or receive at time t* $(E_{\text{Abs-Data}}^{\text{ETI-MAC}}(i,t))$:

$$E_{\text{Abs-Data}}^{\text{ETI-MAC}}(i,t) = T_i^{\text{carrier}} \times P_i^{\text{carrier}} + T_i^{\text{sense}} \times P_i^{\text{sense}}. \quad (5)$$

Before delivering a preamble, a node *i* senses the carrier at each wake-up state for a period time (T_i^{carrier}). It also senses its surroundings in order to measure physical quantities for a period time (T_i^{sense}).

$$T_i^{\text{carrier}} = T_i^{\text{acarrier}} \times R_{\text{data}}^{rx/tx}. \quad (6)$$

$$T_i^{\text{sense}} = T_i^{\text{asense}} \times R_{\text{sense}}. \quad (7)$$

4. *The total amount of energy consumed at time t* $(E_{\text{Total}}^{\text{ETI-MAC}}(i,t))$:

$$E_{\text{Total}}^{\text{ETI-MAC}}(i,t) = E_{\text{Transmission}}^{\text{ETI-MAC}}(i,t) + E_{\text{Reception}}^{\text{ETI-MAC}}(i,t) + E_{\text{Abs-Data}}^{\text{ETI-MAC}}(i,t). \quad (8)$$

Latency model. After each packet processing and queuing in each node *i*, each data packet in ETI-MAC is preceded by a number of preambles, and the node transmits an acknowledgment after it has received the packet. The predicted delay is determined by (2), (4) and (6), and is as follows:

$$\begin{aligned} L_i^{\text{ETI-MAC}} &= T_i^{\text{que}} + T_i^{\text{pro}} + T_i^{\text{carrier}} + T_i^{tx} + T_i^{rx} \\ &= T_i^{\text{que}} + T_i^{\text{pro}} + \Big((K+1)L_{\text{spreamble}} + 2 \times \left(L_{\text{packet}} + 2L_{\text{ack}}\right)\Big) \times T_{\text{byte}}^{rx/tx} \times R_{\text{data}}^{rx/tx} + (K+4)T_{\text{switching}}. \end{aligned} \quad (9)$$

The calculation of the residual energy at the check time t_{ch}. The following equation is used to determine the residual energy for node *i* at check time t_{ch} (noted by: $E_i^{\text{res}}(t_{ch})$) after the previous checking at check time t'_{ch} (with $(t_{ch} > t'_{ch})$):

$$E_i^{\text{res}}(t_{ch}) = \left[E_i^{\text{cur}}(t'_{ch}) + E_i^{\text{har}}(t_{ch} - t'_{ch})\right] - E_i^{\text{spe}}(t_{ch} - t'_{ch}), \quad (10)$$

where

$E_i^{\text{cur}}(t'_{ch})$ – the current energy at the previous verifying time t'_{ch} of the node *i*.

$E_i^{\text{har}}(t_{ch} - t'_{ch})$ – the total quantity of energy harvested during the time $(t_{ch} - t'_{ch})$ by the node *i*.

$E_i^{\text{spe}}(t_{ch} - t'_{ch})$ – the amount of energy expended during the time $(t_{ch} - t'_{ch})$ by the node *i* and that is computed using (8).

Duty cycles. The duty-cycling of a node activity is fixed in the beginning, where the active time and sleep time are fully determined by the administrator, and it becomes dynamic depending on the rate at which energy can be harvested once the residual energy $E_i^{\text{res}}(t_{ch})$ *at* t_{ch} instant is less than E_{thre} ($E_i^{\text{res}}(t_{ch}) < E_{\text{thre}}$). Regularly, nodes with superior energy supplies wake up more frequently, sleep for shorter periods of time, and, as a result, receive and transmit more packets. Additionally, this approach lessens collisions brought on by nearby nodes waking up simultaneously and vying for the channel. The node sleep durations are determined deterministically by ETI-MAC as a function of the node energy availability, which cannot be same for a collection of nodes. As a result, a node with a lower energy level chooses extended sleep duration in order to harvest as much energy as possible and stock an assured energy level. Trough ETI-MAC, the sleep time (long or short) for node *i* (T_i^{sleep}) is computed by the following procedure which is detailed below.

a. Each node *i* in the waking state checks its residual energy right before it enters the sleep state.

b. In the sleep state, if ($E_i^{\text{res}}(t_{ch}) < E_{\text{thre}}$), node *i* computes the amount of time that has passed (T_i^{ste}) until its residual energy first reached E_{thr} by utilizing the following equation:

$$T_i^{\text{ste}} = \min\left[T_i^{\text{ste}}, 1\right]. \quad (11)$$

In the following wake-up states, node *i* computes its sleep time (T_i^{sleep}) using (12) (regarding the long sleep time) or (13) (regarding the short sleep time) while ($E_i^{\text{res}}(t_{ch}) \geq E_{\text{thre}}$); otherwise, node *i* performs steps (a), (b), then (c), in that order.

Long sleep time :

$$T_i^{\text{sleep}}(E_i^{\text{res}}(t_{ch})) = \frac{E^{\text{MAX}} - E_i^{\text{res}}(t_{ch})}{E^{\text{MAX}} - E_{\text{thre}}} \times T_i^{\text{ste}}. \quad (12)$$

When T_i^{ste} is calculated

(In this case: we use the new calculated T_i^{ste} value)

Short sleep time :

$$T_i^{\text{sleep}}(E_i^{\text{res}}(t_{ch})) = \log_2\left(\frac{E^{\text{MAX}} - E_i^{\text{res}}(t_{ch})}{E^{\text{MAX}} - E_{\text{thre}}} \times T_i^{\text{ste}}\right) \quad (13)$$

When T_i^{ste} is not calculated and $E_i^{\text{res}}(t_{ch}) < E^{\text{MAX}}$

(In this case: we use the old calculated T_i^{ste} value)

$$T_i^{\text{sleep}}(E_i^{\text{res}}(t_{ch})) = 0 \quad when \quad E_i^{\text{res}}(t_{ch}) = E^{\text{MAX}}$$

Formulation of optimization problem (OP). In order to optimize the performance of ETIMAC especially in terms of energy efficiency and latency based on minimizing the duty cycle of each node *i* within the network more adaptively, a optimization problem (OP) is formulated by reducing the duty cycle in the WSN for the cyclic amount of power harvested and for different cyclic traffic scenarios.

The activity node duty-cycle in ETI-MAC ($Dutyc_i^{\mathrm{ETI-MAC}}$) is defined as the ratio of active time (T_i^{active}) to the sum of active time (T_i^{active}) and sleep time (T_i^{sleep}) [4].

$$Dutyc_i^{\mathrm{ETI-MAC}} = \frac{T_i^{\mathrm{active}}}{T_i^{\mathrm{active}} + T_i^{\mathrm{sleep}}}. \quad (14)$$

$$\text{minimize} \quad Dutyc_i^{\mathrm{ETI-MAC}} \quad \forall i \in \{1, \ldots, N\}. \quad (14a)$$

Subject to:

$$T_i^{\mathrm{active}} \leq T_i^{\mathrm{active}} + T_i^{\mathrm{sleep}}. \quad (14b)$$

$$T_i^{\mathrm{active}} + T_i^{\mathrm{sleep}} \neq 0. \quad (14c)$$

$$E_{\mathrm{thre}} \leq E_i^{\mathrm{res}} \leq E^{\mathrm{MAX}}. \quad (14d)$$

$$E_{\mathrm{thre}} < E^{\mathrm{MAX}}. \quad (14e)$$

$$T_i^{\mathrm{active}}, T_i^{\mathrm{sleep}} \geq 0 \,;\; E_{\mathrm{thre}},\; E_i^{\mathrm{res}},\; E^{\mathrm{MAX}} > 0. \quad (14f)$$

IV. Simulation

A. Simulation with OMNeT++/MiXiM

For the implementation of the suggested protocol ETI-MAC, the OMNeT++ simulator was employed with the MiXiM simulation framework [29]–[31]. The primary ETI-MAC implementation is the ETIMACLayer, which is a MAC layer module built within the new network interface NicETIMAC (based on WirelessNicBattery [32]); which is made up of a number of distinct modules, including the power supply SimpleBattery, the network interface WirelessNic-Battery, and the BatteryStats, which calculates the energy usage for each module.

B. Simulation Parameters

To test the ETI-MAC protocol, a WSN was created using the MiXiM-2.3 framework and the OMNeT++-4.6 simulator version. Table II lists many simulation-related settings that were defined in the omnetpp.ini file. Additionally, the config.xml file declares physical layer settings like analogue models and decision type, and the Nic.ned file specifies the MAC type. The maximum duration between two packet transmissions, stated in seconds, is the Traffic Parameter in this case. Numerous scenarios are constructed and evaluated, ranging from 10 mobile sensor nodes deployed in an area of 400 m × 400 m to 100 mobile sensor nodes deployed in an area of 1100 m × 1100 m, where the distance between two neighbours is 100 m for 1000 simulated seconds. EH rate is periodic with Harvesting Param (is the maximum time interval between two harvesting energy moments expressed in seconds), which is equal to 0.1 s for each sensor node randomly set between [0 mW...50 mW]. Each mobile sensor node has a starting energy value of 50 J, a maximum energy value of 100 J, and an energy threshold (E_{thre}) value of 30 J.

TABLE II
Simulation Parameters at Different Layers

Layer	Parameter	Value
General	Number of nodes	10, 25, 50, 75, 100
	Simulation time/run	1000 s
	Playground size (*x*, *y*)	(400 m, 400 m), (600 m, 600 m), (800 m, 800 m), (950 m, 950 m), (1100 m, 1100 m)
	Mobility type	ConstSpeedMobility
	Mobility speed	2 mps
	Initial residual energy E_i^{res}	50 J
	Energy threshold E_{thre}	30 J
	Max attempts	2
Layer of Application	Application type	Sensor App Layer
	Traffic type	Periodic
	Traffic param	0.1 s, 0.5 s
	Number of packets sent	500, 1000
Layer of Network	Network type	BaseNetwLayer
	Destination node	9, 24, 49, 74, 99
Layer of Mac	Type of Mac	ETIMACLayer PSEHMACLayer BMACLayer
	Size of queue	6 packets
	Max attempts	2
Layer of physical	Power of transmission	0.05 W
	Carrier frequency	2.412e + 9 HZ
	Propagation model	SimplePathlossModel
Battery (Power)	Nominal of battery	100 J
	Capacity of battery	100 J
	Num devices of battery	1
Harvesting	Harvesting type	Periodic
	Harvesting param	0.1 s
	Harvesting rate randomly	[0 mW…50 mW]

V. Performance Evaluation

The ETI-MAC protocol is compared to the PS-EHWSN [26] protocol, which uses a dynamic duty-cycle like ETI-MAC and also to a static duty-cycle scheduling scheme BMAC [12], which is the basis of all protocols based on communication through preamble sampling using extensive simulations utilizing the OMNeT++ simulator with the MiXiM framework. To compare the two protocols, the performance measures listed below were used.

Mean Packet Latency: The time taken by the packet to reach the target node is averaged over all packets. This should be reduced.

Packet Delivery Ratio (PDR): It reflects the number of packets successfully received (N_r^{pktS}) by the sink to total packets sent by all network source nodes (Nbr_s^{Tpkt}) which should be maximized. The formula is as follows:

$$PDR = \frac{N_r^{pktS}}{Nbr_s^{Tpkt}}. \quad (15)$$

Throughput: The total transfer rate measured in bits per second that should be maximized. The formula is as follows:

$$Throughput = \frac{N_{tr}^{pkt} \times \text{packetsize}}{\text{simulation time}}, \quad (16)$$

where N_{tr}^{pkt} — the number of transferred packets.

Average Energy Consumption per node: It is equal to the total average energy spent (MCS) by each node in the WSN divided by the number of nodes (Nbr) shown by Avge (MCS) in (17), which should be minimized:

$$Avge(MCS) = (\sum_{i=1}^{Nbr} MCS_i)/Nbr, \quad (17)$$

where

$$MCS_i = \text{consumed energy per node } i/simulation\ time. \quad (18)$$

Network lifetime: It is defined as the period of time when all of the power from the initial sensor has been used up or when there is no power left for the sensor to transmit data during data collection, which must be expanded.

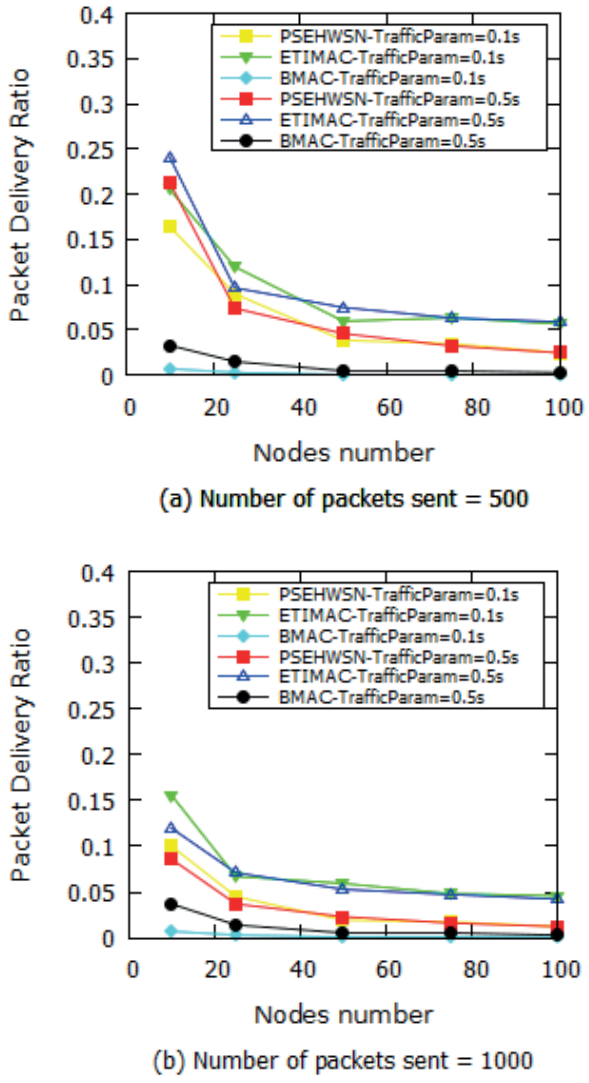


Fig. 1. Packet delivery ratio.

The simulation results for the delivery rate metric are shown in Fig. 1 for two values of TrafficParam (0.1 s and 0.5 s) and varied quantities of delivered packets (500 and 1000), where the number of nodes is made up of between 10 and 100. The findings show that as the number of nodes increases, the packet delivery rate falls. Additionally, the results demonstrate that ETIMAC is capable of providing a high packet delivery rate in comparison with PSEHWSN for various energy harvesting rates by employing a novel method for anticipating the next sleep period based on the energy harvesting rate, which may be either long or short and it may not be the same throughout the network and although both protocols employ the stroboscopic preamble approach and dynamic adjustment of duty cycles more adaptively of nodes in WSN, they do so by taking advantage of the rise in residual energy over time. This lowers packet collision and retransmission rates. As a result, the chance of packet loss due to collision rises when data packets are sent. This mostly results in increased energy consumption, which seriously interrupts transmission in WSN. For example, in case the number of packets sent is set to 500 and the number of nodes increases from 10 to 50 as shown in Fig. 1(a), ETIMAC outperforms PSEHWSN in packet delivery rate between approximately 20 % and 35.34 % when the TrafficParm is set to 0.1 s and between 11.52 % and 38.61 % when the TrafficParm is set to 0.5 s. Therefore, it can be seen that significant performance gains in the delivery ratio are achieved with ETIMAC compared to PSEHWSN.

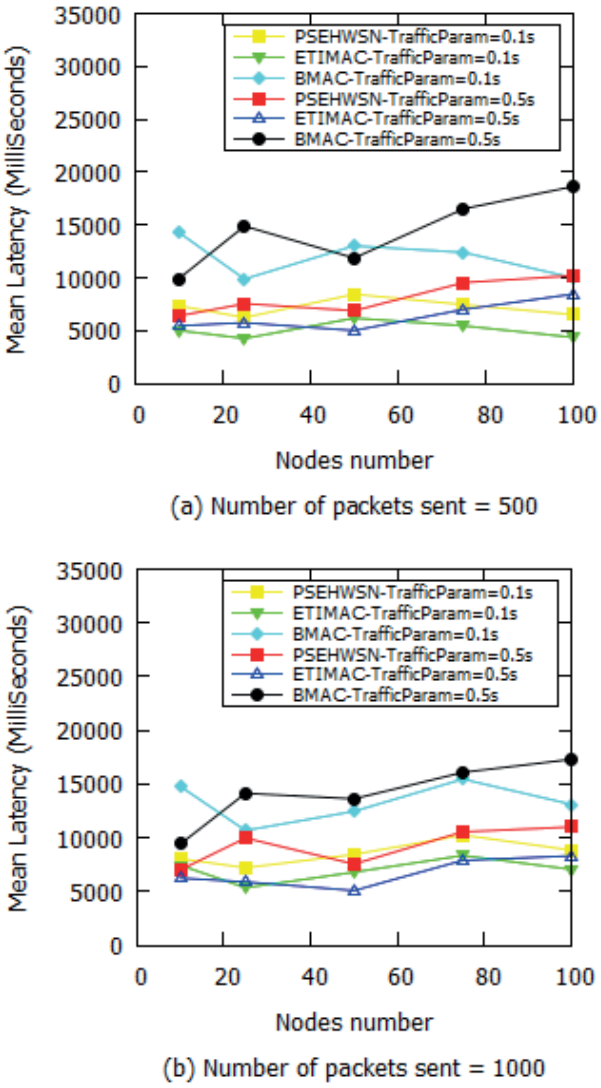
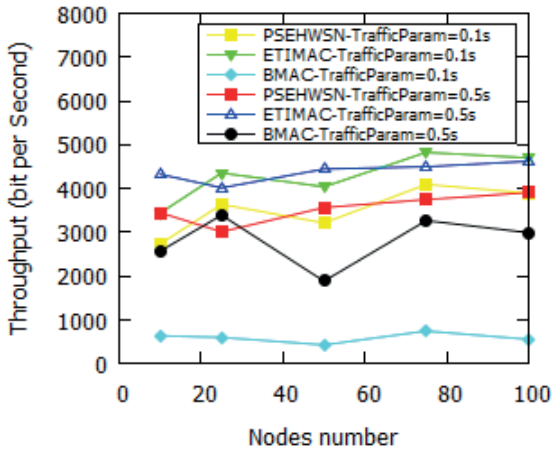


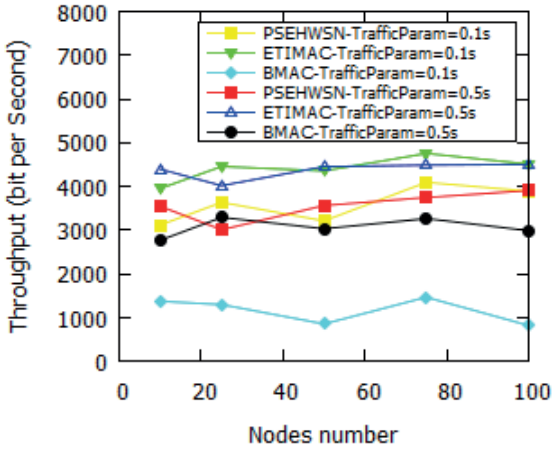
Fig. 2. Mean latency.

Figure 2 shows that as the number of nodes increases, ETIMAC outperforms PSEHWSN. Furthermore, the average latency of ETIMAC is lower than that of PSEHWSN. This is because the proposed ETIMAC protocol uses the new next sleep period prediction technique to provide load balancing between nodes in WSN where it favours nodes with higher energy level to be active thanks to their short sleep period duration, which is calculated based on (13) in case the residual energy increase is somewhat rapid compared to PSEHWSN and using the strobe preamble technique. This increases the likelihood that data packets are not buffered and greatly decrease average latency. Alternatively, the suggested protocol uses a technique for predicting the duration of the upcoming sleep period to adjust the duty cycle of the nodes more adaptively than the PSEHWSN based on the harvested energy presented in the future. Figure 2(a) shows that ETIMAC achieved a lower average latency gain of about 33.08 % when Traffic Param = 0.1 s and 17.16 % when Traffic Param = 0.5 s compared to PSEHWSN when thw number of nodes is 100 and packets sent = 500.

As seen in Fig. 3, ETIMAC outperforms PSEHWSN in terms of throughput achieved. This is because the active period of the sensor nodes is dynamically reduced significantly due to the use of the proposed technique for predicting the next period of sleep, which is based on the quantity of different energies collected and allows dynamic adjustment of the duty cycles more adaptable than PSEHWSN, as well as owing to the use of the stroboscopic preamble technique. This lowers the maximum number of retransmissions and collisions because the more collisions there are, the longer it takes for a transmission to be successful, which leads to dropped packets and primarily increases power consumption while severely paralyzing the data transmission operation in WSN. As shown in Fig. 3(a), for instance, if the number of packets sent is set to 500 and the number of nodes rises from 10 to 50, ETIMAC outperforms PSEHWSN in throughput by roughly 20.55 % to 20.47 % when the TrafficParm is set to 0.1s and by 20.30 % to 19.78 % when the TrafficParm is set to 0.5 s. As a result, it is clear that ETIMAC achieves substantial performance improvements in the throughput when compared to PSEHWSN.

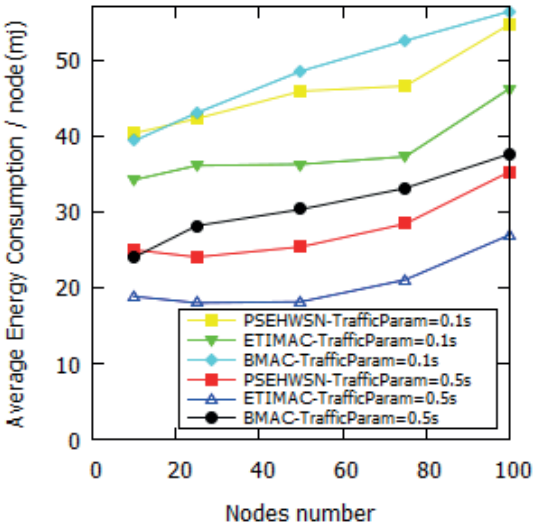


(a) Number of packets sent = 500

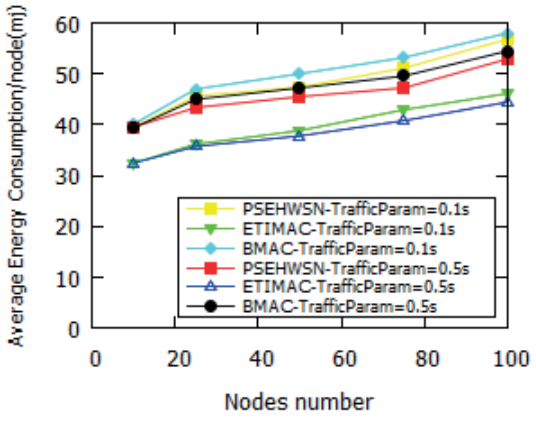


(b) Number of packets sent = 1000

Fig. 3. Throughput.



(a) Number of packets sent = 500



(b) Number of packets sent = 1000

Fig. 4. Average energy consumption.

According to Fig. 4, ETIMAC outperforms PSEHWSN in terms of energy performance for various EH rates. This is due to the fact that the ETIMAC employs the stroboscopic preamble method, each sensor node can dynamically adjust its duty cycle more adaptively, and it is more adaptive than the PSEHWSN based on residual energy which may increase over time, where the ETI-MAC purposefully chooses sleep periods (short or slow) that are not likely to be identical for a neighbourhood in the WSN for the sensor nodes, thereby minimizing collision and retransmissions, which are regarded as some of the primary causes of increasing power use and frequent failures during the process of data transmission within the network. Figure 4 shows that when the traffic parameter is set to 0.1 or 0.5 s, per-node energy preservation in ETIMAC is mainly successful over the whole simulation chain when compared to PSEHWSN. For example, in Fig. 4(a) when Traffic Param = 0.5 s, ETIMAC outperforms PSEHWSN in energy saving by about 15.20 % when the number of nodes = 10 and by about 15.46 % when the number of nodes = 100.

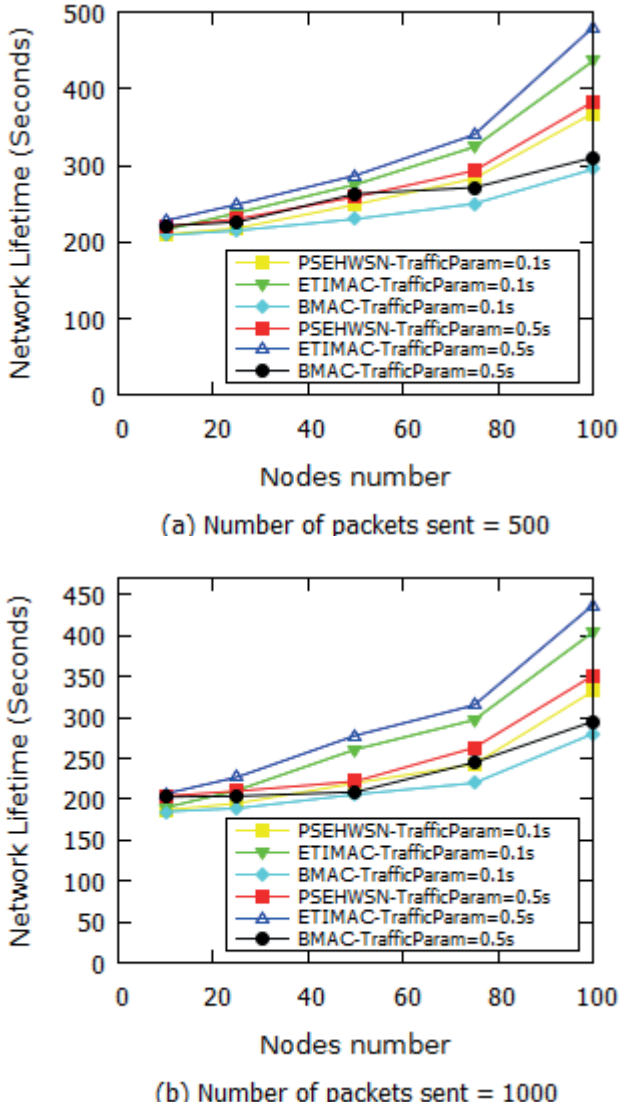


Fig. 5. Network lifetime.

According to the results obtained for the network lifetime metric, the latter increases with the increase in the number of nodes with these two protocols ETIMAC and PSEHWSN for different EH rates. This is because they employ the strobe preamble technique and each sensor node is capable of dynamically adjusting its duty cycle by determining the length of its subsequent slumber. Which may be either short or long depending on two equations (13) and (12), respectively in ETIMAC. As can be seen from the results in Fig. 5, ETIMAC outperforms PSEHWSN because it uses the newly proposed method to predict the duration of the next sleep period in order to provide load balancing between nodes in WSN and because it considers dynamic adjustment of duty cycles in a more adaptive manner than PS-EHWSN where it ensures that the relay nodes do not depart or totally run out of energy after engaging in cooperation and therefore extends the lifetime of the network. It also encourages the activity of nodes with a greater energy level owing to their reduced sleep time. As shown in Fig. 5(a), ETIMAC outperforms PSEHWSN in terms of network lifetime increase as the number of nodes increases from 10 to 100 and the number of packets sent equals 500 of 2.78 % and 15.60 % respectively with the Traffic Param equal to 0.1s and between 3.51 % and 20.21 % with the Traffic Param equal to 0.5 s.

As a result, in order to improve WSN performance in terms of energy efficiency, packet delivery ratio, mean latency, throughput, and WSN lifetime in the area of EH, duty-cycle reduction is critical to avoid energy consumption caused by collision and high node activity. Because of the variable duty-cycle reduction, it is dynamic which makes there a guarantee of load balance in the WSN. Furthermore, sleep times are deliberately chosen that are unlikely to be identical for a neighbourhood, which can be short or long, reducing retransmissions and collisions. ETIMAC outperforms the PSEHWSN, which uses a dynamic duty-cycle that may be the same as ETIMAC but not more adaptively. Overall, by observing the results of the above scenario, we can conclude that BMAC has lower performance than PSEHWSN and ETIMAC protocols since it gets low ratios in packet delivery ratio, throughput and WSN lifetime and high ratios in average latency and energy consumption because of its use of the fixed duty cycle.

VI. Conclusions and Future Research Areas

Mobile wireless sensor networks are distinguished by their absence of infrastructure, their dynamic nature, and their limited availability of resources, including computing power, storage, and most significantly energy because they are frequently powered by batteries. Because of their inaccessible positions, it is often hard to recharge the sensor batteries. This paper proposes ETI-MAC, a MAC protocol for energy harvesting WSN, which represents a new EH-based approach to low-power communication in WSNs. It addresses applications that need a lot of time and energy while keeping sensible system fairness. ETIMAC uses a dynamic duty-cycle scheduling method with a strobed preamble technique, broadcasting a succession of short preamble packets. This work

has one significant contribution. The proposed protocol uses a residual energy level to predict two different types of future sleep period durations: short and long, which can be estimated using (13) and (12), respectively where each node can adjust its duty-cycle dynamically more adaptively by function of the collected energy that will be available in the future. When compared to PSEHWSN protocol, this idea enhances the network performance. ETI-MAC is able to control the energy collected from a sensor node utilized for detection, transmission, reception, and processing by comparing its performance with that of the PSEHWSN protocol. The ETI-MAC is assessed by simulations using OMNeT++ through several test scenarios with different traffic flows. In every experiment, ETI-MAC performs much better than the PSEHWSN protocol in terms of energy efficiency, packet delivery ratio, mean latency, throughput, and WSN lifetime. Future work will involve a more complete study of the proposed ETI-MAC protocol with varied traffic situations and duty-cycles, as well as a variable energy threshold that will be utilized by all nodes and which can be determined based on the node mobility and residual energy.

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